TERNZ
TRANSPORT RESEARCH

The Development of Pro-Forma Over-Dimension Vehicle Parameters

Prepared for:
The New Zealand Transport Agency
April 2010

Transport Engineering Research New Zealand Limited (TERNZ) is a research organisation providing high quality independent research services to the transport industry. TERNZ has expertise across a broad range of transport-related areas including vehicle safety, vehicle dynamics, vehicle-infrastructure interaction, fuel efficiency, driver behaviour, driver performance, impacts on communities and other social issues. Our customers also span the range of industry stakeholders and include government agencies, vehicle manufacturers and suppliers, industry associations, individual transport operators and community groups.

TERNZ prides itself on the quality, timeliness and independence of its work.

Authorship: This document was written by John de Pont. For further information, please contact John at j.depont@ternz.co.nz or by phone on 09 337 0542.

TERNZ
TRANSPORT RESEARCH

TERNZ Ltd
Telco House | 16 Kingston St | Auckland
PO Box 106573 | Auckland 1143
Phone +64 9 337 0542

info@ternz.co.nz
www.ternz.co.nz

CONTENTS

INTRODUCTION

The proposed amendment to the Vehicle Dimensions and Mass (VDAM) Rule 41001 provides for heavier and longer vehicles to be operated, subject to Road Controlling Authority approval, on sections of the highway network that have the capacity to accommodate these vehicles. As well as increasing the maximum allowable weight on some axle groups, the amendment contains a revised and extended version of the table of maximum allowable weight for a given axle spread. This is often referred to colloquially as the “bridge formula” because its main purpose is to prevent the overloading of bridges. In the current Rule the “bridge formula” only goes up to 44 tonnes and to achieve this, the axle spread must be greater than 16m. The axle spread required for higher weights is not defined. In the proposed amendment an allowable weight of 44 tonnes is achieved when the axle spread exceeds 13m. A supplementary table defines the axle spreads required for weights up to more than 62 tonnes. The rate of increase is linear at 0.5m per tonnes. Hence for 45 tonnes the axle spread must exceed 13.5m, for 46 tonnes 14m and so on.

Currently the maximum allowable combination weight is 44 tonnes and to achieve this, the axle spread must exceed 16m. The maximum overall vehicle length is 20m for B-trains and truck and trailer combinations and 18m for semitrailer combinations. Under the proposed new “bridge formula” an axle spread of 16m-16.5m would enable a maximum gross weight of 50 tonnes. For the most commonly used B-train and truck and trailer combinations the sum of the axle group weight limits is greater than 50 tonnes and thus higher weights could be possible but this would require increasing the axle spread. Although it is possible to increase the axle spread a little without increasing overall length by reducing the front and rear overhangs, but this is not always desirable. For example, European trucks that incorporate the latest frontal underrun protection systems have a greater front overhang than trucks without this safety feature. It would be undesirable to discourage the use of these vehicles by making them less productive than vehicles without the safety equipment.

Some freight tasks are volume-constrained rather than weight-constrained. For vehicles performing these task and increase in weight limits provides no productivity gains at all. Increases in length are necessary for productivity gains to be realised.

There are also safety benefits from increasing the allowable length in conjunction with increasing the allowable weight. Generally, for a given transport task, if the payload weight is increased but the length of the payload space is not increased, the height of the payload and hence the height of its centre of gravity will increase. This reduces the rollover stability of the vehicle. The current VDAM Rule requires all large heavy vehicles to achieve a minimum level of rollover stability and there is no suggestion that the heavier vehicles would not have to meet the same minimum rollover stability requirements. However, at the lower acceptable levels of rollover stability, a reduction in stability leads to relatively rapid increase in rollover risk (de Pont et al. 2000; Mueller et al. 1999). For example, a 10% reduction in rollover stability from 0.39g to 0.35g (the minimum acceptable level) increases the rollover risk by just over 40%. For a full trailer the increase in payload to produce this level of rollover stability reduction is about 15% and this should result in 15% fewer truck trips which will reduce the crash risk by 15% but this is not sufficient to offset the poorer truck performance. However, if we also increase the length of the vehicle we can reduce the negative impact of adding additional payload weight on rollover stability. It should be noted that this argument is most relevant for vehicles approaching the lowest acceptable level of rollover stability. For vehicles with very good rollover stability, the effect on rollover crash risk of reducing it by a modest amount is much less. As well as facilitating better rollover stability, increased length allows for longer wheelbase trucks and trailers which results in improved dynamic stability during evasive manoeuvres.

The main disadvantage of longer combination vehicles is that they require more road space for low speed turning than the current maximum length vehicle of the same configuration. However, different vehicle configurations perform differently in this regard. Generally, for the same overall length, truck and full trailer combinations are more manoeuvrable and require less road space than B-trains which in turn require less space than tractor-semitrailer combinations. The current road network can generally accommodate the poorest performing maximum length vehicles. This does not mean that residential cul-de-sacs are designed to allow an 18m tractor semitrailer to be able to turn around in them. However, the roads, intersections, roundabouts and curves that these vehicles would reasonably be expected to use should be designed to accommodate them.

In designing the longer vehicles that the amendment to the VDAM Rule would permit to operate on approved routes one could evaluate each design on its proposed route to determine whether or not it would fit. This would be a costly and time-consuming exercise. The approach can be simplified by comparing the performance of the proposed design with that of a worst-case standard vehicle using a standardised manoeuvre or set of manoeuvres. If the performance of the proposed vehicle was better than that of the standard vehicle we could assume that it would fit on the network. This approach requires fewer manoeuvres to be evaluated but still requires each vehicle design to be tested and thus is still quite costly and time-consuming. Further simplification is possible by developing pro-forma designs that have been tested and found to achieve satisfactory performance. Operators could then build vehicles that conform to the pro-forma designs and have them approved to operate on the designated routes without the need for further testing for low speed performance. Vehicles outside the pro-forma design envelope could potentially still be used but they would have to go through an evaluation process to check their performance characteristics.

This report describes the development of the proposed pro-forma designs. It explains the methodology used to identify the design, the evaluation process and the performance characteristics of the designs. This project was commissioned by the New Zealand Transport Agency who consulted with the Truck and Trailer Manufacturers' Federation (TTMF) to identify the desired vehicle configurations.

METHODOLOGY

Performance Requirements

The starting point for the proposed pro-forma vehicles was that their low speed performance should not be worse than the poorest-performing standard vehicle. This was deemed to be a quad-axle semi-trailer. In the current VDAM Rule, this vehicle is required to have two self-steer axles which for practical reasons are almost always the last two axles[1]. The VDAM Rule defines the axis of the quad axle set as midway between the two non-steering axles. Effectively this assumes that the two steering axles castor freely and generate no cornering force at all. In practice, to achieve high-speed dynamic stability the self-steer axles need to have a moderate level of centring force. With the two rear axles steering this has the effect of moving the effective axis rearwards which increases the offtracking of the vehicle during low speed turns. Tests commissioned by NZTA's predecessor organisation showed that this rearward movement of the axis was of the order of 0.7m. Thus, although the VDAM Rule specifies that the maximum forward length[2] of a semi-trailer is 8.5m, the effective forward length for the typical quad semitrailer in approximately 9.2m. This results in the quad semitrailer being the most demanding standard vehicle in terms of road space requirements during low speed turning. Thus it was chosen by NZTA as the reference vehicle for benchmarking the pro-forma vehicles against.

Several performance measure variations have been used in the past to characterise the road width requirements of a vehicle during low speed turning. Variations in the test manoeuvre include different turn radii and whether the turn should be undertaken on "kerb-to-kerb" basis or a "wall-to-wall" basis. For a "kerb-to-kerb" turn limits are placed on the path of the outside wheel of the steer axle of the vehicle – the front corner of the vehicle may cross these limits. For a "wall-to-wall" turn no part of the vehicle may cross the prescribed limits and thus the trajectory of the vehicle is controlled by the path of the front outside corner. Most low-speed turning performance measures specify a 90° turn with straight tangents at the entry and exit. However, for this analysis NZTA specified a 120° wall-to-wall turn at 12.5m radius. The reason for the increased turn angle was to simulate a worst case situation which might typically be experienced during a right hand turn at a roundabout. In this situation the driver must initially turn to the left before then proceeding around the roundabout turning right. The total angle turned through by the vehicle is greater than 90°.

NZTA simulated the turning performance of the quad-axle semitrailer undertaking this turn using software they have in-house and found that it could negotiate the turn while not crossing a concentric inner circle with a radius of 4.9m. This effectively means a maximum swept width of 7.6m for this manoeuvre and these conditions were specified as the performance requirements for the pro-forma vehicles. Note that this swept width limit is greater than the Australian PBS level 1 limit but this is because the manoeuvre is more severe. If the turn angle were reduced to 90°, the swept width of the quad semitrailer would reduce significantly.

Vehicle Configurations

There are three principal combination vehicle configurations in widespread use in New Zealand. They are: the truck and full trailer, the tractor semitrailer and the B-double. In addition there are a number of truck and simple trailer configurations in use primarily for specialist applications such as car carriers. As noted in the previous section the current tractor semitrailer represents the limit case for road space requirements and thus there is no scope for longer tractor semitrailer combinations. All of the other three combinations could be made longer without exceeding the road space requirements of a tractor semitrailer. Thus the aim of the project was to develop three pro-forma vehicles: a truck and trailer, a B-train and a truck and simple trailer.

---

[1] The Rule allows either the last two axles or the first and last axles of the quad group to be self-steering. However, in order to achieve sufficient axle spread to be able to utilise the weight capacity of the vehicle it is necessary to make the last two axles steering.

[2] Forward length for a semitrailer is the distance from the kingpin or coupling point to the centre of the rear axis of the vehicle.

Members of the TTMF were asked to put forward proposed vehicle configurations in each or any of these three categories for consideration. Twelve designs were forwarded from NZTA to TERNZ for analysis. These consisted of three truck and trailer combinations, eight B-trains and one truck and simple trailer. Five different vehicle designers produced the designs.

Although the low speed turning performance requirements had been communicated to the designers at the time of requesting them to propose vehicle designs, only some of them took this into account. It would appear that the others did not have any in-house capability for evaluating low speed turning performance. This is not surprising because for vehicles that comply with the VDAM Rule there is no need to undertake any assessment. Several of the designers appear to have gained the impression that the maximum length and weight that will be acceptable under the proposed amendment to the VDAM Rule are about 25m and 62t and have based their designs on utilising these limits to the full. The designers who did undertake some low speed turning analysis realised that this length, in particular, is not achievable if the low speed turning criterion is to be satisfied and thus proposed more modest length and weight options.

Because several of the designs were quite similar to each other a subset of eight vehicle configurations was selected for analysis. In addition an 18m quad tractor-semitrailer combination with two self-steering axles and a 19m quad tractor-semitrailer combination with one self-steering axle were analysed. In terms of low speed turning performance the 18m variant is the worst case as-of-right vehicle under the current VDAM rule and the 19m variant is the worst case under the proposed amendment. The latter is the reference vehicle and it was included to ensure that the results obtained by the analysis methods used in this study are comparable with those used by NZTA in determining the acceptability criterion.

The vehicles were loaded to the weights indicated on the design drawings. The centre of gravity heights of the payload were chosen somewhat arbitrarily but with the intention of achieving a level of rollover stability close to the minimum allowable. The low speed turning manoeuvre was undertaken at 8km/h which is sufficiently slow for there to be minimal vehicle dynamics effects. Thus the payload weight should have very little effect on the low speed turning performance. There is a small effect due to the non-linearities of the tyre response which will be discussed further in the results section. For all vehicles it was assumed that the width at the front of the vehicle is 2.4m.

Analysis Method

The main tool used for analysing these vehicles was multibody computer simulation. The software package used was Yaw-Roll (Gillespie 1982) which was developed by the University of Michigan Transportation Research Institute (UMTRI). A computer model of each of the nine vehicle configurations was built and the required test manoeuvre was simulated. The vehicle designs that satisfied the low speed turning criterion were identified. Those that failed were investigated further to see whether some minor tweaking of their geometry could be applied to improve their performance and achieve a pass.

One variant of each of the three configurations – truck and full trailer, B-train and truck and simple trailer – that had satisfactory low speed performance was identified. The other standard performance measures were then evaluated for each of these three vehicles to ensure that their overall performance was satisfactory. The geometric parameters of these three configurations were then varied to see what range of values was possible without exceeding the performance criterion. Sketch diagrams were prepared for each of the vehicle configurations showing the key dimensions and the range of acceptable values for these dimensions.

RESULTS AND DISCUSSION

Before considering the results of the simulations it is useful to review how low speed off-tracking occurs and how it is affected by the vehicle parameters. This will help to explain the results and to provide insights for determining the pro-forma vehicle dimension limits.

Consider a 2-axle vehicle such as a car or small truck. The simplest model that is used is the so-called "bicycle model" where the front and rear axles are each represented by a single wheel on the centreline of the vehicle. During a steady state low speed turn there is no slip angle at the tyres and the vehicle wheels follows the paths shown in Figure 1. Clearly the radius of the path followed by the front axle is greater than the radius of the path followed by the rear axle and the difference is the offtracking. Because R_1, R_2 and WB form a right angle, R_2 can easily be calculated from R_1 and WB using Pythagorus' theorem.

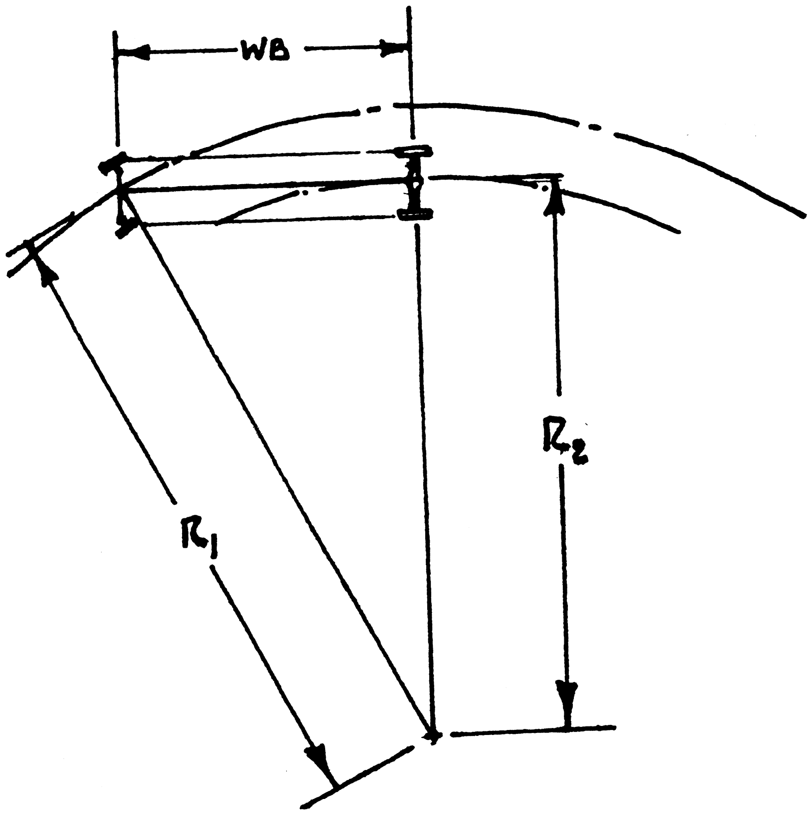

Figure 1. Steady state low speed turning path of a 2-axle vehicle.

The situation becomes a little more complicated when the rear axle is not a single axle but an axle group. In this case it is no longer possible to draw lines from the centre of turn perpendicular to both of the rear axles. So the perpendicular line is drawn through the rear axis. Axle(s) in front of the rear axis will then have a slip angle which will tend to steer the rear of the vehicle outboard of the path while axle(s) behind the rear axis will tend to steer the rear of the vehicle inboard of the path. These two effects must balance for the rear of the vehicle to follow the path shown. Because of the geometry of the vehicle, the position of the rear axis needed to achieve this balance is a little behind the geometric centre of the axle group. When modelling a wall-to-wall turn the path of the front of the vehicle is specified rather than the path of the steer axle. The same result would be achieved if the steer axle was moved to the very front of the vehicle. Thus for a wall-to-wall turn the “wheelbase” of the vehicle is the forward length, i.e. the distance from the rear axis to the front of the vehicle.

When we consider combination vehicles we can apply the same bicycle model approach to each vehicle unit in turn. Thus given the path of the front of the towing vehicle we can solve for the path of the rear. This enables us to determine the path of the coupling point which is the path of the front of the first towed unit. From here we can solve for the path of the rear of the first towed unit and get the path of its coupling point and so on. When we do this we find that we can represent a combination vehicle as a rigid vehicle with an equivalent wheelbase. The equation for the equivalent wheel base is:

$$WB_{equivalent} = \sqrt{\sum_i (WB_i)^2 - \sum_i (Hitch\_Offset_i)^2}$$

where WB_i is the wheelbase of vehicle unit I,
$Hitch\_Offset_i$ is the distance between the rear axis and the coupling on vehicle unit i.

A lower equivalent wheelbase results in less offtracking. So from the equivalent wheelbase equation we can deduce some of the factors that will increase or decrease offtracking:

- A larger number of vehicle units reduces equivalent wheelbase and offtracking. For example, if the total wheelbase length is 12m, then three 4m units will produce a significantly lower equivalent wheelbase than two 6m units.
- More equal unit wheelbases produce less offtracking than combinations with large wheelbase differences. For example two 6m units produce a lower equivalent wheelbase than an 8m unit and a 4m unit.
- Larger hitch offsets reduce offtracking. Interestingly the sign of the hitch offset makes no difference just its size. This is the main reason than truck and trailer combinations generally have less offtracking than B-trains.

With respect to the hitch offset values, as noted by Fancher and Winkler (2007), there is a trade off between high speed and low speed performance. Larger hitch offsets improve low speed turning performance but have a negative impact on high speed dynamic stability.

All of the previous discussion relates to the steady state turning performance which occurs when the vehicle is going round in circles. When a vehicle enters a low speed turn it takes some time to reach this steady state situation (up to 270° of turn or more). Furthermore the amount of turn required to reach steady state is not constant for all vehicle configurations – it is generally greater for long combination vehicles than for shorter rigid vehicles. Thus for the standard performance measure turns (90° or in this case 120°) the vehicles have not reached the steady state offtracking condition before they are straightening up to exit the turn. For these reasons, equivalent wheelbase cannot be used as the predictor of low speed turning performance although it is useful for identifying options and improvements for individual vehicle combinations.

The nine vehicles identified earlier were modelled using the Yaw-Roll multibody simulation software and the models were driven through a 120° 12.5m radius wall-to-wall turn. The maximum radius of the inner circle that the vehicles do not cross is shown in Table 1. Also shown in Table 1 is the equivalent wheelbase calculated using the equation above. The reference vehicle has a maximum inner radius of 4.86m which is slightly less than the 4.9m specified by NZTA. One possible reason for this is differences in the calculation method. The software used by NZTA requires the user to specify the position of the rear axis. The Yaw-Roll software used in this analysis models the forces at each wheel and does not require the user to estimate the axis position. Configurations with a maximum inner radius greater than 4.86m (using Yaw-Roll) are considered to meet the low speed turning performance required by NZTA.

From Table 1 it can be seen that only two of the vehicle designs proposed achieved the required low speed performance standard but two of the others were relatively close and could be expected to meet the standard with some minor tweaking of dimensions. The three poorest performing vehicles are so far from achieving the standard that major redesign would be required. The Jackson58, which is the vehicle between these groups, is the same vehicle configuration as the Domett22mB but slightly longer and with a larger difference in trailer wheelbases. It is expected that the pro-forma vehicle based on the Domett22mB will specify the range of dimensions possible for a B-train that complies with the performance requirements. Using the Jackson58 as the starting point will not change the outcome.

Table 1. Results of low speed turning performance simulations.

Vehicle Configuration	Maximum Inner Radius (m)	Equivalent wheelbase (m)
18m 4-axle tractor quad semitrailer – 2 steerers	4.94	11.176
19m 4-axle tractor quad semitrailer-1 steerer	4.88	11.176
Domett22mB - 22m 6x4 B-train	4.93	10.943
Domett22mTT - 5 X 5 22m truck -trailer	5.35	10.191
Domett24mTT - 5 X 5 24m truck -trailer	4.64	11.159
Jackson58 - 22.7m 9-axle B-train	4.46	11.523
KraftB - 25m 10-axle B-train	2.72	12.906
Maxitrans25mTT - 25m 8-axle truck-trailer	3.84	12.185
MaxitransB- 25m 9-axle B-train	3.07	12.971
Scania24m36t - stinger steer car carrier	4.88	11.166

It can also be seen that the equivalent wheelbase measure is a reasonable indicator of low speed turning performance but it is not perfect. For example the KraftB vehicle has a slightly worse performance than the MaxitransB but has a slightly smaller equivalent wheelbase.

The geometries of the vehicles using the notation of the equivalent wheelbase equation are shown in Table 2. From this it is reasonably clear why, for example, the Domett22mB has better low speed performance than the Jackson58. The wheelbases are more similar and the hitch offsets are greater. This geometry data can be used to identify opportunities for improving the performance of the vehicles that failed to meet the performance requirement by only a small amount.

Table 2. Vehicle Geometries.

Vehicle Configuration	WB_1 (m)	WB_2 (m)	WB_3(m)	Hitch $Offset_1$	Hitch $Offset_2$
18m 4-axle tractor quad semitrailer – 2 steerers	6.410	9.200[3]		0.910	
19m 4-axle tractor quad semitrailer – 1 steerer	6.410	9.200[4]		0.910	
Domett22mB - 22m 6x4 B-train	5.636	6.860	6.526	0.254	1.261
Domett22mTT - 5 X 5 22m truck -trailer	7.355	2.810	6.990	2.645	0.000
Domett24mTT - 5 X 5 24m truck -trailer	7.845	2.910	7.990	3.055	0.000
Jackson58 - 22.7m 9-axle B-train	5.770	6.400	7.660	0.350	0.150
KraftB - 25m 10-axle B-train	6.500	8.500	7.400	1.000	1.300
Maxitrans25mTT - 25m 8-axle truck-trailer	8.534	3.200	8.500	2.617	0.000
MaxitransB- 25m 9-axle B-train	5.636	8.026	8.500	0.400	0.000
Scania24m36t - stinger steer car carrier	7.890	8.500		3.135	

[3] This value is based on the estimated position of the effective rear axis. The wheelbase based on the geometric rear axis where the steering axles are considered to have no effect is 8.5m.
[4] This is based on the geometric rear axis which ignores the effect of the steering axle. The effective rear axis is further rearward which is why the low speed turning performance is slightly worse than that of the 18m vehicle.

The aim of this study is to develop a pro-forma design for each of three vehicle configurations, the truck and full trailer, the B-train and the truck and simple trailer.

Beginning with the truck and full trailer: the Domett22mTT comfortably passes the performance requirement. This combination uses a 5-axle truck and a 5-axle full trailer. The reason for this is to maximise the weight capacity and minimise the Road User Charges (RUC) liability. While this is a logical aim for a vehicle manufacturer it is not a requirement for the pro-forma vehicle design. A 4-axle truck and 4-axle trailer with the same geometry would achieve the same low speed performance. Therefore it is proposed that the pro-forma vehicle could use a 4-axle or 5-axle truck towing a 4-axle or 5-axle trailer. Because the vehicle comfortably exceeds the performance requirement there is some scope to vary the geometric parameters while still meeting the performance requirement. It was found that the truck forward length and the trailer wheelbase (WB_1 and WB_3) could be increased to 7.5m simultaneously provided the first hitch offset was not reduced below 2.6m and the drawbar length (WB_2) was limited to 2.9m. This configuration achieved a maximum inner radius of 4.95m and thus still comfortably achieves the performance requirement. Because the hitch offset may not be more than 45% of the truck wheelbase (increased from 40% in the amendment to the VDAM Rule) the minimum hitch offset also defines a minimum wheelbase of 5.8m. Having a large hitch offset and a short drawbar has a negative impact on high speed dynamic stability. We therefore propose imposing a minimum drawbar length of 2.5m. Increasing the drawbar length is desirable for high speed stability but will degrade the low speed turning performance. However, this can be offset by simultaneously reducing the trailer wheelbase. We therefore propose imposing a limit for the distance from the trailer coupling to the trailer rear axis of 10.4m. This is equal to the dimensions of the base case (2.9m + 7.5m = 10.4m) but allows for a range of options. It can be shown from the equivalent wheelbase formula that the options should all have better low speed performance than the base case. A sketch of the pro-forma truck and trailer is shown in Figure 2.

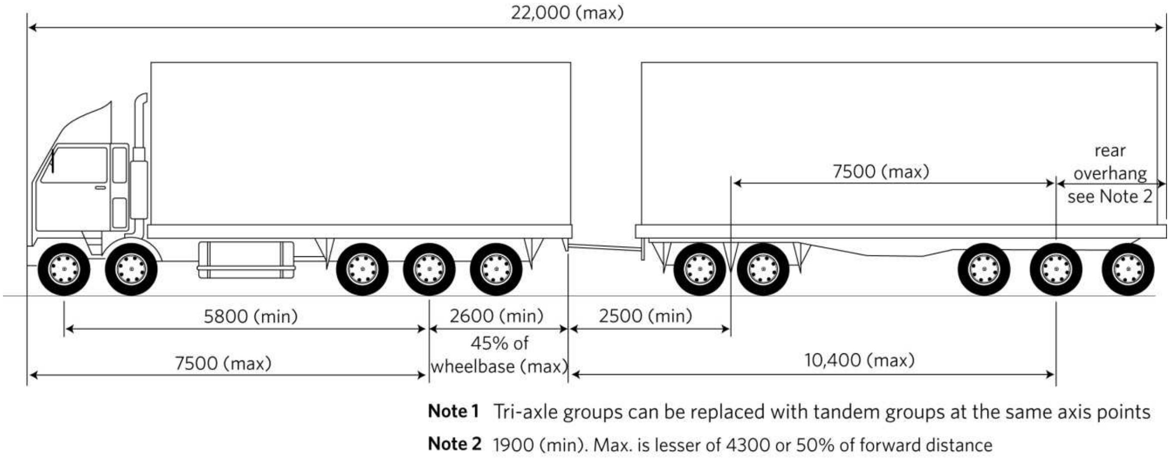

Figure 2. Sketch of pro-forma truck and trailer.

For the B-train, the Domett22mB has a low speed performance that is the same as the reference quad semitrailer. Thus it could be the base case. However, its dimensions are given to the millimetre and this is too precise for a pro-forma design. We therefore used this design as a guide rather than as a base. The Domett22mB that we analysed used a 3-axle tractor unit. However, several other designs with 4-axle (twin steer) tractors were also submitted. Provided the second steering axle is correctly configured there is no difference in low speed turning performance between a 3-axle and a 4-axle tractor. We therefore propose that the pro-forma vehicle could use either. As noted in the discussion of equivalent wheelbase the best low speed performance is achieved when the trailer wheelbases are equal. From the Domett22mB design we see that a trailer wheelbase of about 6.9m was desired. It is not possible to make both trailers with 6.9m wheelbases but there is no reason to prefer one over the other. Under the current VDAM rule the maximum trailing length (distance from the first hitch to the rear of the second trailer) of a 20m B-train is 14.5m. As this vehicle is 2m longer it seems reasonable to increase the maximum trailing length to 16.5m thus allowing exactly the same tractors to be used as currently. To maintain low speed turning performance we need to maintain the hitch offset at the hitch between the first and second trailers. We have set a minimum value at 1.25m. To further control the trailer wheelbases we specify a minimum rear overhang on the second trailer of 1.9m. This combination of restrictions means that if the first trailer is at the maximum wheelbase length of 6.9m then, with minimum hitch offset and minimum rear overhang, the second trailer will have a maximum wheelbase of 6.45m. This vehicle achieves a maximum inner circle radius of 4.88m which is just better than the reference vehicle. Any variations from the limit values of the critical dimensions will improve the low speed turning performance. A sketch of the pro-forma B-train is shown in Figure 3

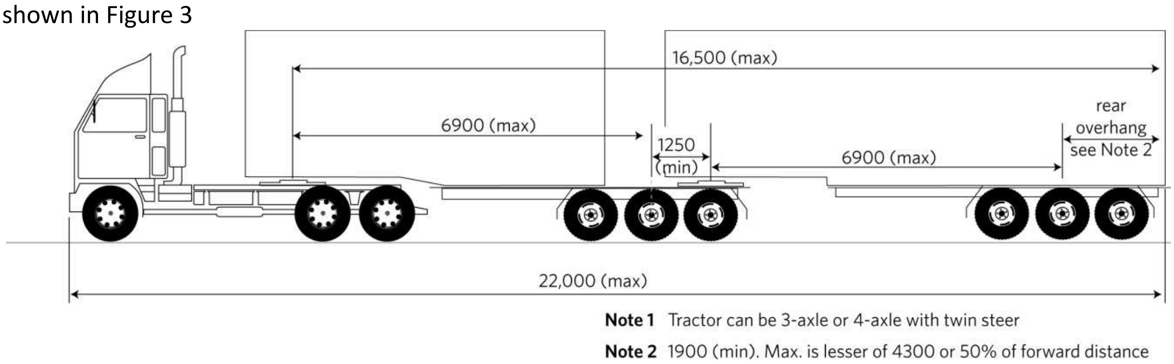

Figure 3. Sketch of pro-forma B-train.

The truck and simple trailer that was analysed just failed to meet the low speed turning criterion. It is clear looking at the dimensions that its low speed turning performance can easily be improved by reducing the trailer wheelbase. The vehicle was well below the maximum allowable rear overhang so this can be increased to offset the reduction in wheelbase and thus there is no loss of carrying capacity by doing this. It is also possible to increase the hitch offset a little to improve the performance. We therefore specified a minimum hitch offset of 3.15m and a maximum trailer wheelbase of 8.4m. Because the hitch offset may not be greater than 50% of the truck wheelbase the minimum hitch offset also defines a minimum truck wheelbase of 6.3m. This limit vehicle was simulated and found to have a maximum inner circle radius of 4.88m which again meets the performance criterion. Departures from the limit dimensions will result in improved low speed performance. It should be noted that this particular configuration was 23m long where the other two pro-forma vehicles were both 22m. However, the truck and simple trailer is weight restricted to 36t and thus it is not likely that there will be a significant swing to using this configuration in preference to truck and trailers or B-trains. For the car carrier application the capacity can be increased by overhanging the load at both the front and the rear. The design submitted had 0.6m overhang at the front and 0.7m overhangs at the rear. Because these loads are significantly narrower than the truck they have no effect of the performance measures analysed. That is, the path of the vehicle during the low speed turn is still determined by the front corner of the truck not the front corner of the load and the maximum tail swing at the rear of the vehicle comes from the trailer body not the load. Thus we have proposed that the pro-forma vehicle can have front or rear overhangs of up to 1m but the total overall length including overhangs should not exceed 24.3m. A sketch of the pro-forma truck and simple trailer is shown in Figure 4.

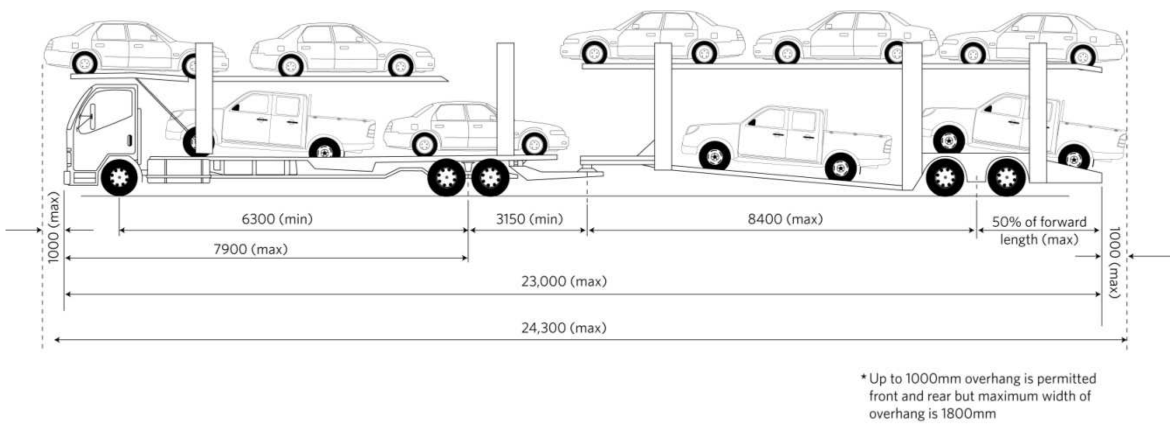

Figure 4. Sketch of pro-forma truck and simple trailer.

For all three pro-forma vehicles it is assumed that where a dimension is not specified they will be required to meet the requirements of the amended VDAM Rule. Thus inter-vehicle spacing is not explicitly specified nor are the axle spacings required to achieve the desired gross weight capabilities. Care needs to be taken in determining the maximum allowable gross combination weight for the pro-forma designs to ensure that European tractors with safety features such as frontal underrun protection are not disadvantaged relative to other tractors with a smaller front overhang.

As a cross-check a range of performance measures were evaluated for the three limit case pro-forma vehicles as well as the two reference quad semitrailers. The truck and full trailer and the B-train were loaded to 57t while the truck and simple trailer was loaded to 36t and the two semitrailer combinations were loaded to 44t. The results are shown in Table 3. The performance measures shown are all evaluated used the manoeuvres specified in the Australian Performance-Based Standards (PBS) scheme (National Transport Commission 2007). The results are indicative only. The pro-forma designs do not specify tare weights, centre of gravity heights, tyre sizes or suspension characteristics, all of which will impact performance. The centre of gravity height of the payload for the truck and full trailer and for the B-train was arbitrarily chosen to give a low static rollover threshold close to the legal minimum. For many freight tasks at higher weight this is likely to be the case. Overall the indicative performance characteristics of the pro-forma vehicles is quite good and meet generally accepted target levels. The dynamic load transfer ratio of the truck and full trailer is just above the common maximum desired level of 0.6 but is better than many truck and full trailer currently operating at 20m and 44t. Note that the Australian PBS system does not have a standard for dynamic load transfer ratio.

Table 3. Performance Characterisation of pro-forma limit-case vehicles.

Performance Measure	Vehicle Configuration				
	Quad Semitrailer		Truck-Full Trailer	B-train	Truck-Simple Trailer
	18m	19m			
Low Speed Offtracking (m)	3.65	3.68	3.60	3.77	3.61
Steer Friction Utilisation (%)	25	24	14	28	16
Tail Swing (m)	0.05	0.20	0.12	0.02	0.08
Static Rollover Threshold (g)	0.37	0.37	0.36	0.37	0.46
Rearward Amplification	1.12	1.04	1.74	1.69	1.35
High Speed Transient Offtracking (m)	0.18	0.23	0.46	0.51	0.15
Dynamic Load Transfer Ratio	0.41	0.37	0.62	0.46	0.28
Yaw Damping Ratio (%)	>30	>30	>30	>30	>30
High Speed Offtracking (m)	0.32	0.40	0.47	0.48	0.27
High Speed Friction Utilisation (%)	35	46	46	43	36

REFERENCES

de Pont, J. J., Mueller, T. H., Baas, P. H., and Edgar, J. P. "Performance measures and crash rates." *6th International Symposium on heavy vehicle weights and dimensions*, Saskatoon,Saskatchewan, Canada, 1 - 10.

Fancher, P. and Winkler, C. (2007), "Directional performance issues in evaluation and design of articulated heavy vehicles", *Vehicle System Dynamics, 45(7-8), 607-647*.

Gillespie, T. D. (1982). "Constant velocity yaw/roll program - User's manual." *UMTRI - 82 - 39*, University of Michigan Transportation Research Institute, Ann Arbor.

Mueller, T. H., de Pont, J. J., and Baas, P. H. (1999). "Heavy vehicle stability versus crash rates. A report prepared for the LTSA July 9th, 1999." TERNZ Ltd, Auckland.

National Transport Commission (2007) "PBS Scheme – The Standards and Vehicle Assessment Rules", National Transport Commission, Melbourne.