A COMPARATIVE ANALYSIS OF THE PERFORMANCE OF HEAVY VEHICLE COMBINATIONS FROM OECD MEMBER COUNTRIES BY COMPUTER SIMULATION

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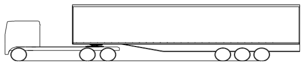
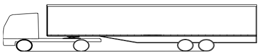
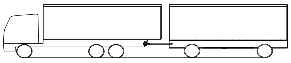
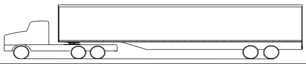
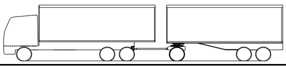
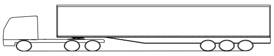
Introduction

Presently there is a broad range of heavy vehicle combinations in operation throughout the world. At one end of the spectrum, these vehicles are single unit trucks with two or more axles, transporting goods short distances within cities, while at the other end of the spectrum, multi-unit combinations weighing in excess of 60 tonnes move freight in remote areas. Sometimes, vehicle combinations are designed according to the requirements of a particular transport task, but are most often operated for reasons of convenience to the operator, in terms of availability of equipment. Some examples of typical articulated combinations, and their gross combination mass (GCM), total allowable payload and overall length are provided in Table 1.

While some of the examples above appear to be similar in terms of their overall length and mass, there are important differences between some of these vehicles. For example, the European rigid truck and full-drawbar trailer has a GCM of 40 tonnes, while a similar vehicle of Danish design, and identical length, is permitted a maximum mass of 48 tonnes. In most instances, differences such as these reflect the allowable limits under local regulations. Additionally, it is also important to note that specific differences exist with regards to vehicle geometry, (e.g. truck wheelbase, trailer length, and inter-axle spacing), equipment (e.g. suspension type and tyre size), and the nature of the coupling between the truck and the trailer.

Table 1: Variations in truck size and dimensions (Woodrooffe et al., 2010)

Picture	Description	GCM (t)	Payload (t)	Length (m)
	Australian truck and semi-trailer	45.5	29.0	19.0
	European truck and semi-trailer	38.0	24.0	16.5
	European rigid truck and full-trailer	40.0	25.0	18.75
	American truck and semi-trailer	36.35	21.5	19.8
	Danish rigid truck and dolly-trailer	48.0	32.0	18.75
	South African truck and semi-trailer	49.3	31.9	17.75

These differences lead to the potential for substantial variation in the on-road dynamic performance and stability of these vehicles, and vehicle combinations may exist which meet regulatory limits but can be shown to demonstrate a lower level of safety than other vehicles in dynamic measures. The challenge that this situation presents is how to effectively quantify vehicle performance and analyse vehicle designs in terms of on-road dynamic behaviour and safety. Associated with this is the requirement to compare the safety performance of new and innovative vehicle designs to existing vehicles.

Australia's innovative performance based standards (PBS) vehicle assessment scheme is considered to offer an effective framework to address this requirement. Under this regulatory scheme, vehicle designs are assessed in a range of safety and infrastructure-related standards using computer simulation, modelling techniques and physical field tests. These capabilities are described in the context of a recent project conducted by ARRB Group Ltd (ARRB) for the Joint OECD/ITF Transport Research Centre (JTRC), which benchmarked the safety performance of 39 heavy vehicles across 10 OECD member countries. The PBS scheme and key vehicle performance measures, the simulation and modelling methods and the results of the benchmarking project are the discussed in this paper.

The performance-based approach

Typical heavy vehicle regulatory schemes focus on prescriptive vehicle requirements, such as the maximum laden mass for a single axle or axle group, or the maximum overall vehicle length. While such schemes are able to effectively regulate heavy vehicle operations, various economic and environmental factors are presently demanding improved freight efficiency and better utilisation of the available road network. To address this requirement, regulators in Australia have developed a 'performance based' approach to heavy vehicle regulation, known as the Performance Based Standards (PBS) scheme.

PBS allows the potential for transporters to achieve higher levels of productivity and operational safety via innovative vehicle designs. In this context, the term 'innovative' can refer to improvements to existing vehicles, the employment of new technologies to overcome safety or operational concerns, or completely new equipment designed for specific transport tasks. The benefits that this approach allows are generally not accessible under a conventional framework of prescriptive regulations.

The central requirement of the PBS process is an individual study of the on-road performance and behaviour of the vehicle and its load configurations. While the scheme provides the scope for performance studies to be conducted via computer simulation or physical testing of an exemplar vehicle in the field, the former is usually preferred due to the reduced cost and simplicity offered. Within the study of vehicle performance, each vehicle is assessed in sixteen safety-related, and four infrastructure-related standards. Primarily, the safety-related standards focus on the dynamic aspects of vehicle behaviour while travelling at highway speeds, the vehicle's lateral stability limit, and the low-speed turning requirements (swept area). The infrastructure standards address vehicle performance in the areas of vertical and horizontal tyre forces, tyre contact pressure distribution, and the impact of the vehicle on bridges, but at present mainly refer to prescriptive controls.

From the set of twenty standards offered by PBS, only seven were selected for investigation in the JTRC benchmarking project, and for brevity, only the vehicle performance measures that provided the most interesting results will be discussed in this paper. For more information, interested readers should refer to the JTRC benchmarking project report (Woodrooffe et al., 2010) for a description of the seven standards used in that study, and Australia's National Transport Commission (NTC) PBS assessment rules (NTC, 2008) for a description of each of the twenty PBS standards.

Computer simulation method

Within the PBS scheme, the role of ARRB as a vehicle assessor is to conduct individual studies of vehicle performance. To achieve this, ARRB utilises AutoSIM, a custom-code vehicle simulation and modelling package which models the forces and moments involved in complex multi-body dynamic interactions. ARRB's software allows the definition of the vehicle and its components at a mathematical level, which provides the required level of detail to accurately model innovative vehicle designs, which can differ substantially to existing vehicles in their configuration, coupling type and steering system. ARRB's vehicle simulations and modelling techniques have been validated in numerous field tests and comparative studies conducted over the last twelve years.

These capabilities provide other opportunities which are separate to assessing vehicle performance under a regulatory framework, as demonstrated in the recent investigation conducted by ARRB for the JTRC research working group. The study investigated the safety, environmental and productivity impacts of current and future heavy vehicle operations, in the context of seeking to increase road freight efficiency. ARRB's role in the project was to conduct the individual vehicle performance assessments by computer simulation, using the PBS assessment methods, and therefore 'benchmark' the safety performance of each vehicle from the selected OECD member countries.

Assessing heavy vehicle dynamic performance

As discussed earlier, a total of seven of the performance measures defined under Australia's PBS scheme were used in the JTRC benchmarking project. However, for brevity, only the vehicle performance measures that provided the most interesting results will be discussed in this paper. These performance measures are:

– static rollover threshold;

– tracking ability on a rough road;

– low speed off-tracking (vehicle and trailer swept path);

– high speed steering input amplification.

Static rollover threshold (SRT) is arguably the most critical safety measure for heavy vehicles, as it describes their inherent resistance to experiencing rollover. Heavy vehicles can experience rollover if subjected to high lateral forces during transient manoeuvres, such as swerving to avoid an object while travelling at high speed, and also during steady-state manoeuvres such as cornering. Key factors which influence rollover performance are the centre of gravity (CoG) height of the vehicle's trailers, the relationship between the CoG height and the vehicle's track width, the type of coupling between vehicle units, and the roll stiffness of the suspension. SRT performance is quantified using the level of lateral acceleration that the vehicle's units can sustain without experiencing rollover, and is measured using a standardised simulation or field test manoeuvre.

Tracking ability on a rough road refers to the capability of a vehicle combination to remain within the confines of a traffic lane when travelling over a 'rough' road of defined geometry at highway speeds. The road geometry data used in this assessment is considered to be representative of typical Australian rural highways, but could be adapted to be representative of any type of road, provided that the road profile and geometry data was available. This performance measure is particularly applicable to articulated vehicles with one or more trailers, as they can demonstrate a tendency to 'amplify' small lateral accelerations experienced by the hauling unit, and can result in considerable lateral off-tracking or 'sway' of each of the trailers.

Performance in this area is an important safety consideration for heavy vehicle combinations, as adverse behaviour can present a safety issue for other road users, particularly passing or overtaking vehicles. If the level of off-tracking is sufficiently severe, and the roadway particularly narrow, the wheels of one side of the trailer may leave the paved road surface, which could initiate a rollover.

Low-speed off-tracking identifies the road area required for a vehicle to complete a standard turning manoeuvre, and is implemented to ensure the safety and protection of infrastructure for vehicles operating in urbanised areas. The test procedure (NTC, 2008), and simulation outputs (Woodrooffe et al. 2010), are shown in Figure 1.

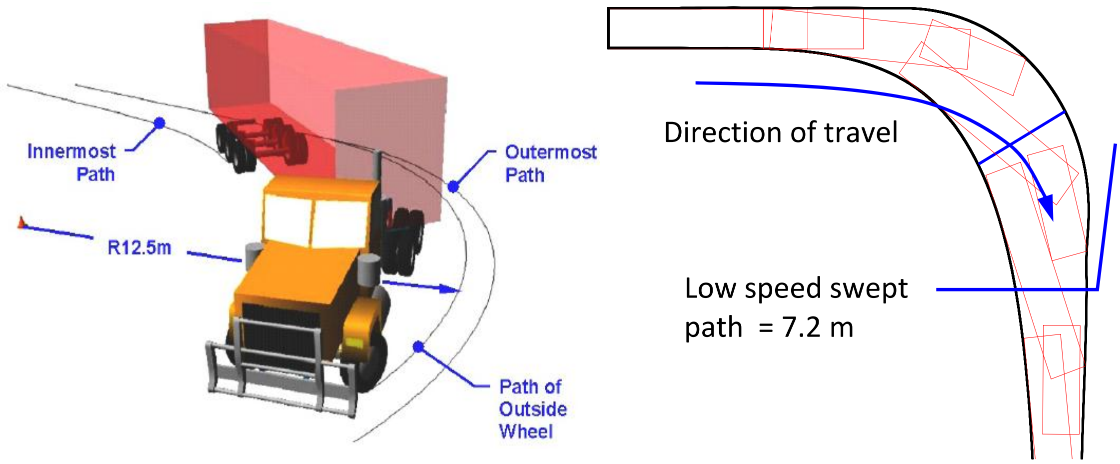


Figure 1: Low speed off-tracking manoeuvre (left), and simulation results (right)

High-speed steering input amplification describes the tendency for the rear-most trailer of an articulated combination to experience a higher level of lateral acceleration than the hauling unit during a dynamic manoeuvre, such as swerving to avoid an object on the roadway. Performance in this area is assessed in PBS using the 'lane-change manoeuvre', identical to that specified in the international standard (ISO) 14791:2000. Performance is quantified by the calculation of 'rearward amplification' (RA) which is the ratio of the peak lateral acceleration at the rear-most trailer unit to that at the steer axle of the hauling unit experienced during the lane change manoeuvre. Acceptable RA performance is considered to be critical to the safe operation of heavy vehicles, as adverse performance in this area can render the vehicle susceptible to rollover, and endanger the safety of other road users.

Subject vehicles in the JRTC benchmarking study

Ten OECD member countries were invited to submit representative vehicles for evaluation in the study, and to provide technical data for each. From the data provided, a total of 39 vehicle designs were generated, representing both existing vehicles, and longer and heavier vehicles which could be created using combinations of existing equipment. Vehicles were classified in three general categories: 'workhorse' vehicles, 'higher capacity' vehicles, and 'very high capacity' vehicles. Workhorse vehicles were defined as the vehicle most commonly used within the member country for long haul transport. The vehicle designs generally represent the upper end of the weight and dimension range that is permitted access to the majority of the road network. These vehicles were defined in the study as having a gross mass of less than 50 tonnes and a length of less than 22 metres. Of the 39 vehicles in the study, 22 were classified as workhorse vehicles.

Higher capacity vehicles were defined as the vehicle typically operated under restricted access conditions, dependent on the suitability of the road network. This vehicle is usually heavier and/or longer than the workhorse vehicle, having a gross mass of up to 70 tonnes and a maximum length of 30 metres. In the study, 13 vehicles were classified as higher capacity vehicles. Very high capacity vehicles designs represent vehicles typically operating under permit conditions and often in rural or remote areas, and typically heavier and/or longer than the higher capacity vehicle, having a gross mass of at least 52 tonnes and a length of over 30 metres. In the study, 5 vehicles were classified as very high capacity vehicles. Details of the 39 vehicle designs, including the country of origin, a diagram, the maximum GCM, payload and overall length of the vehicle are provided in Appendix A.

Key results from the JTRC benchmarking study

One of the key observations of the study was the distribution of static rollover threshold (SRT) performance within the studied fleet. The distribution of SRT results for the three vehicle classes is shown in Figure 2. The minimum performance requirement set in Australia's PBS scheme is 0.35 g, which is highlighted by a red line. Evidently, the SRT results were recorded within the range of 0.28 g (lowest level of performance) to 0.43 g (highest level of performance).

Overall, 28 of the 39 vehicles satisfied the performance requirement, and the results demonstrate a slight trend in increasing SRT result (better performance) with increasing vehicle payload capacity. All 5 of the very high capacity vehicles, 10 of the 13 high capacity vehicles and 14 of the 22 workhorse vehicles passed the SRT performance measure. This demonstrates that high-capacity vehicles can be designed to satisfy on-road safety requirements, and simultaneously deliver productivity gains.

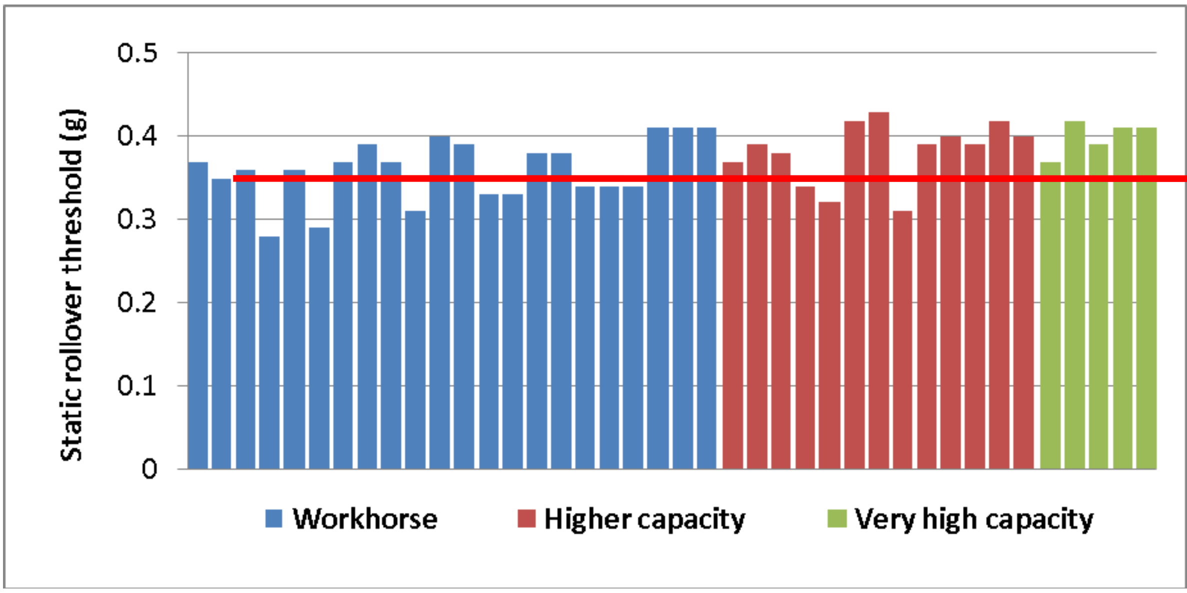


Figure 2: Distribution of SRT results among the three vehicle classes

The performance results represent the extra road width required (above the vehicle's width of 2.5 m) while travelling down a rough road considered typical of Australian conditions. The performance requirement for this measure varies according to the desired level of network access, so while no distinct criteria is defined, a lower result is indicative of a higher, safer level of vehicle performance.

The results show a general trend of increasing road space requirement (lower performance) with increasing vehicle length. It is important to note that this result does not indicate that high capacity and very high capacity vehicles demonstrate unsafe behaviour, only that care should be taken regarding the roads on which such vehicles are permitted to operate, so it can be ensured that such vehicles are only operated on roads wide enough to safely accommodate them. It is also interesting to note that some higher and very high capacity vehicles require less road space the workhorse vehicles, again indicating that these vehicles can be designed to simultaneously deliver on-road safety requirements and productivity gains.

The distribution of low-speed off-tracking results for the three vehicle classes is shown in Figure 3. The performance results represent the width of the road area required during the completion of the standard manoeuvre described earlier. Again, the performance requirement for this measure varies according to the desired level of network access, so while no distinct criteria is defined, it is clear that a lower result is indicative of a higher level of vehicle performance. Again, there is a general trend of increasing road space requirements with increasing vehicle length.

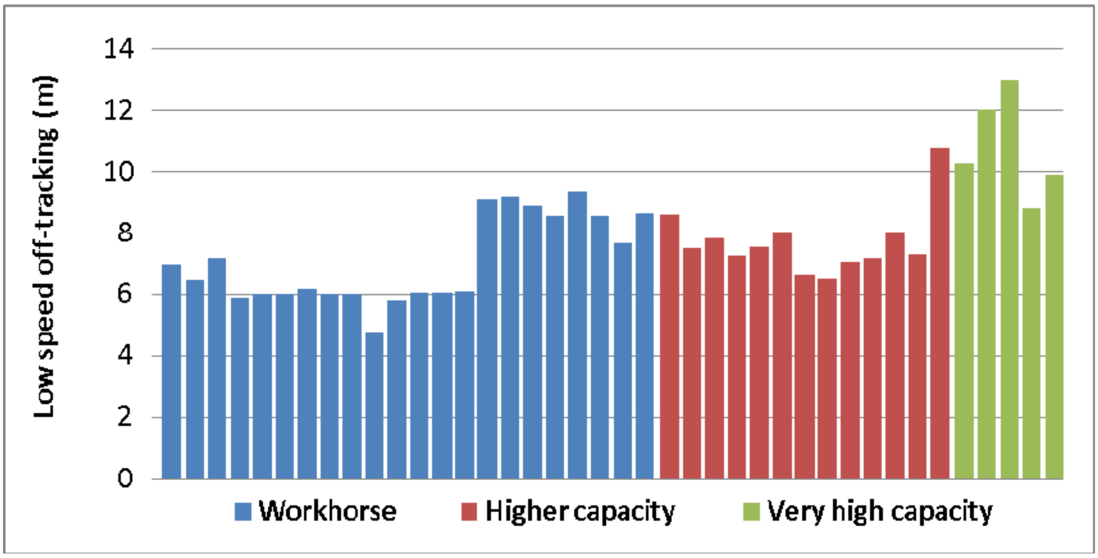


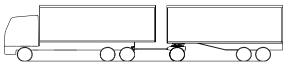
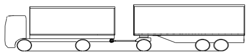
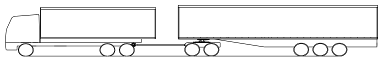
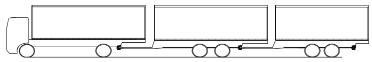
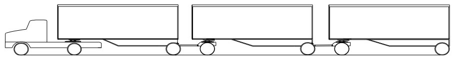
Figure 3: Distribution of low-speed off-tracking results among the three vehicle classes

However, it is again important to note that while this result clearly demonstrates the inability of very high capacity vehicles to negotiate urban areas, it does not indicate that longer and heavier vehicles demonstrate unsafe behaviour. Care should be taken regarding the access arrangements for such vehicles, and it would be prudent to ensure that the road area available for turning manoeuvres at intersections and other facilities such as freeway on-ramps is sufficient.

As described earlier, the performance results represent the ratio of the peak lateral acceleration at the rear-most trailer unit to that at the steer axle of the hauling unit during experienced during the lane change manoeuvre. Evidently, the majority of performance results are similar, however some vehicles from each class demonstrate a very high level of RA. The performance requirement defined under PBS is that the maximum RA during the lane change manoeuvre be no greater than 5.7 times the vehicle's SRT. Hence, some vehicles, while having a seemingly high level of RA (thus implying poor performance), may actually demonstrate an acceptably safe level of performance in this regard.

Inspection of the results indicates that only five vehicles fail this performance requirement under the PBS definition. These vehicle designs are shown in Table 2. It is important to note that the first two vehicles are from the 'workhorse' category, and represent vehicles similar to those presently operating. The next two vehicles are higher capacity vehicles, and are also in operation under local regulations in Denmark and the Netherlands. The final vehicle is only a proposed design, and is not presently in operation. However, a key finding is that designs which may be safety deficient in this dynamic performance measure are present in each category, not only restricted to the very high or higher capacity vehicle categories.

Table 2: Vehicle designs failing the RA performance measure

Picture	Description	GCM (t)	Payload (t)	Length (m)
	Danishrigid truck and dolly-trailer	48.0	32.0	18.75
	European rigid truck and dolly-trailer	40.0	27.0	16.90
	Danish rigid truck and semi-trailer	60.0	40.7	25.25
	Dutch rigid truck and rigid trailers	50.0	33.4	24.2
	American truck and dolly-trailers	53.7	37.3	31.6

Discussion and conclusion

An important finding of the study was the focus placed on certain performance criteria across different geographic regions, which was often highly dependent upon the individual transport requirements of that region. In other words, vehicle performance was found to reflect the requirements of the freight task for the region in which the vehicles were designed to operate. As an example, European vehicles tended to focus upon improving low speed turning performance (lowering swept path) while the Australian, South African and North American vehicles tended to demonstrate improved high-speed dynamic performance.

Based on these results presented, several key conclusions regarding the variations in performance between vehicles of different category can be drawn. Primarily, it is clear that longer and heavier vehicles require more road space in terms of lateral lane width and clear area for turning manoeuvres, as shown in the high and low speed off-tracking results. However, it is important to note that these results do not indicate that these vehicles demonstrate unsafe behaviour, only that care should be taken regarding the access arrangements for such vehicles, and efforts should be made to match vehicles to roads.

The key stability results (SRT and RA) display two important trends:

– performance deficiencies exist across all vehicle classes;

– longer and heavier vehicle designs are available which can demonstrate similar performance levels to existing ‘workhorse’ vehicle designs.

The first of these trends implies that some vehicle designs which are currently in operation, while meeting applicable prescriptive regulatory requirements, can demonstrate a lower level of safety than other vehicles in dynamic measures. In these instances, Australia’s PBS scheme and the computer simulation method was able to successfully highlight the performance deficiencies, and can be an effective tool in quantifying the relative safety of varying vehicle designs. The second trend gives a strong indication that longer and heavier vehicle designs may be able to replace existing ‘workhorse’ vehicles for some transport tasks, and therefore allow productivity gains, reduce congestion, and deliver economic and environmental benefits, while simultaneously maintaining the same level of infrastructure wear, and improving heavy vehicle safety outcomes.

References

Woodrooffe et al. (2010), Safety, Productivity, Infrastructure Wear, Fuel Use and Emissions Assessment of the International Truck Fleet: A Comparative Analysis, Joint OECD/ITF Transport Research Centre (JTRC), International Transport Forum, France.

National Transport Commission (2008), Performance based standards scheme, the vehicle standards and assessment rules. National Transport Commission (NTC), Melbourne, Australia.

Appendix A: Table of vehicle designs

Vehicle designs from each category within the JTRC study are shown in the following series of tables. Table A-1 shows each of the workhorse vehicle designs.

Table A-1: 'Workshorse' vehicle designs from the JTRC study

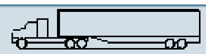
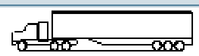
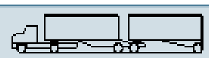
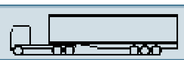
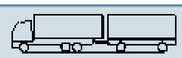
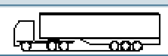
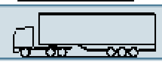
Vehicle origin and number	Vehicle description	GCM (t)	Payload (t)	Length (m)	Schematic
South Africa 1	Tractor semi-trailer	43.500	28.140	15.313	
South Africa 2	Tractor semi-trailer	49.300	31.900	17.745	
Canada 1	Tractor semi-trailer	39.500	25.300	21.550	
Canada 2	Tractor semi-trailer	46.500	31.300	21.550	
Mexico 1	Tractor semi-trailer	44.000	28.649	20.800	
Mexico 2	Tractor semi-trailer	48.500	32.349	20.800	
Mexico 3	Tractor semi-trailer	44.000	28.649	21.565	
United States 1	Tractor semi-trailer	36.350	21.150	19.770	
United States 2	B-double	36.360	23.460	21.980	
United States 3	Tractor semi-trailer	41.900	26.700	19.770	
Australia 1	Tractor semi-trailer	45.500	29.000	19.000	
Belgium 1	Tractor semi-trailer	39.000	25.000	16.200	
Denmark 1	Tractor semi-trailer	44.000	30.000	16.480	
Denmark 2	Rigid truck trailer	48.000	32.000	18.750	
Denmark 3	Tractor semi-trailer	48.000	32.300	16.500	
Europe 1	Tractor semi-trailer	38.000	24.000	16.500	
Europe 2	Tractor semi-trailer	40.000	26.000	16.480	
Europe 3	Truck trailer	40.000	27.000	16.895	
Europe 4	Rigid truck with rigid drawbar trailer	40.000	25.000	18.750	
United Kingdom 1	Tractor semi-trailer	44.000	29.109	16.500	
United Kingdom 2	Tractor semi-trailer	44.000	28.000	16.500	
South Africa 3	B-double	56.000	33.800	21.972	

Table A-2 shows each of the higher capacity vehicle designs.

Table A-2: 'Higher capacity' vehicle designs from the JTRC study

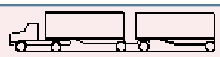
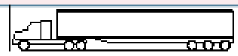
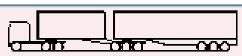
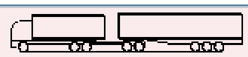
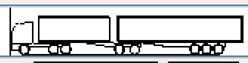
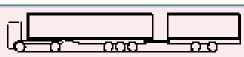
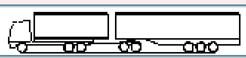
Vehicle origin and number	Vehicle description	GCM (t)	Payload (t)	Length (m)	Schematic
South Africa 3	B-double	56.000	33.800	21.972	
South Africa 4	B-double	56.000	34.240	21.983	
Canada 3	B-double	62.500	42.300	20.430	
United States 4	'A' train double	36.360	23.586	22.060	
United States 5	Tractor semi-trailer	44.100	28.900	25.120	
Australia 2	B-double	68.000	44.500	25.010	
Belgium 2 (European Modular)	Tractor semi-trailer with rigid drawbar trailer	60.000	39.300	25.250	
Denmark 4 (European Modular)	Truck trailer	60.000	40.700	25.250	
Denmark 5 (European Modular)	B-double	60.000	38.000	25.100	
Germany 1 (European Modular)	Tractor semi-trailer with rigid drawbar trailer	40.000	25.000	25.235	
Netherlands 1	Rigid truck with two rigid drawbar trailers	50.000	33.410	24.200	
Netherlands 2 (European Modular)	Tractor semi-trailer with rigid drawbar trailer	60.000	37.702	25.250	
Netherlands 3	Rigid truck trailer	60.000	39.720	25.240	

Table A-3 shows each of the very high capacity vehicle designs.

Table A-3: 'Very high capacity' vehicle designs from the JTRC study

Vehicle origin and number	Vehicle description	GCM (t)	Payload (t)	Length (m)	Schematic
Netherlands 3	Rigid truck trailer	60.000	39.720	25.240	
Canada 4	A' train double	62.500	37.300	38.330	
Mexico 4	'A' train double	66.500	42.849	39.080	
United States 6	'A' train triple	53.752	37.287	31.570	
United States 7	'A' train double	57.040	32.840	30.960	
Australia 3	B-triple	90.500	60.000	33.310