BENCHMARKING HEAVY VEHICLE PRODUCTIVITY AND SAFETY PERFORMANCE

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ABSTRACT

Both Land Transport Safety Authority (LTSA) and Transit New Zealand are committed to developing a road transport system that achieves world's best practice. However, changes to the system are usually evaluated in terms of how they improve upon current practice, because there is limited information available on what constitutes world's best practice. This study takes a typical road transport task and compares the safety and productivity performance of the vehicles that are used to undertake this task in different jurisdictions internationally.

The selected transport task is the haulage of standard intermodal containers of 40 ft length and a range of weights. This is a key transport task undertaken in all countries and provides the backbone of international trade and freight flows. This task also has great future significance as it links rail, sea and road freight transportation world-wide. Annual container movements are increasing steadily in all countries.

The objectives of the study are:
- to determine world's best practice for the transport task
- to benchmark New Zealand practice against this standard
- to identify options for improving New Zealand practice.

The benchmarking process addresses three attributes (dynamic stability, pavement wear and bridge loading) by developing a performance indicator for each attribute. The performance indicators are normalised to current New Zealand practice as a means of setting a benchmark with which to compare other practices from around the world.

LITERATURE REVIEW

International benchmarking of vehicle performance

A 1992 paper by Billing [1] provided the basis for what is known today as Performance Based Standards (PBS). This paper laid out a definitional framework for performance measures and standards, suggested a number of relevant measures and identified the vehicle and highway factors which affect each of these standards. Billing also brought forward the probabilistic notion of "demand" exceeding "performance" and thereby creating a safety or infrastructure damage issue.

An international study in the early 90s [2] attempted to develop an overall efficiency measure for various configurations of tractor-semi-trailer at various weights. This work showed that, provided certain dynamic performance measures are satisfied, "operational performance" is the key attribute which may be used to rank vehicles. Operational performance was quantified in terms of indices such as Equivalent Standard Axle Loads (ESALs) per unit payload. This provides an efficiency measure of pavement wear per unit payload transported and gives a higher rating to vehicle configurations which carry more payload on more axles (with corresponding lower ESALs). In this study, stability measures such as Static Rollover Threshold (SRT) were quantified and needed to meet a minimum standard; the comparative figure of merit for the vehicle was then based on operational performance.

The 1996 FHWA Highway Commercial Vehicle Scanning Tour [3] contrasted the overloaded US 5-axle combinations hauling containers under permit with the 44 t combinations allowed in Europe for combined (or intermodal) transport. Subsequently, the US FHWA Comprehensive Truck Size and Weight Study of 1998 [4] included a "NAFTA scenario" which would provide for the legal transportation of 40 ft containers loaded to maximum international weight limits (30 t). This was a 6-axle combination with GCM of 44 t. This would replace the existing overloaded 5-axle US combination operating under non-divisible load permits. This option was compared with Canada allowing 46.5 t on a 6-axle vehicle, Mexico with 48.5 t and the EC with 44 t on a 5-axle or 6-axle combination for international trade.

Fekpe and El-Gindy [5] looked at "less common" vehicle configurations in the US and Canada, including a 47.3 t 8-axle tractor-semi-trailer (4-S4) for heavy containers. The operational efficiency of this vehicle was found to be high (in terms of ESAL per unit payload).

A paper by Koskinen [6] compared a Nordic configuration with the Central European norm, in terms of fuel consumption, emissions, operating costs and road wear and concluded that the heavier Nordic concept was much more efficient. Engines were characterised in terms of generation with regard to emissions controls (eg Euro2) and power capacity.

In summary, some international comparisons of heavy vehicle performance have been done, based mainly on operational efficiency, and containers have received some attention. Dynamic performance has also been compared, but has proven too multi-dimensional to produce straightforward comparisons.

Recent developments

A recent Transit NZ investigation [7] of the safety and economic consequences of size and weight limits, including the possibility of larger combinations on designated routes, examined a 7-axle tractor-semi-trailer with quad axle semi-trailer which may operate at a Gross Combination Mass (GCM) of 44 t.

In Australia, some States are currently issuing permits for vehicles outside current general limits, based on PBS assessment. This includes 7-axle tractor-semi-trailers with quad axle semi-trailers for hauling 35 t 40 ft containers. There are also proposals for an 8-axle combination which would carry a 40 t 40 ft container under PBS permits. This would allow the road transport of containers which equate to the maximum current capacity of port container handling facilities.

Performance-based standards

The Australian National Road Transport Commission (NRTC), in conjunction with Austroads (representing Australian and New Zealand road agencies), is well-advanced in developing a performance based regulatory system to serve alongside, and as an alternative to, current prescriptive regulations. Appropriate safety standards [8] and infrastructure standards [9] have been developed and refined. While the safety measures are universal, the infrastructure measures tend to be dependent on local pavement design procedures.

The Australian and New Zealand PBS safety measures have been soundly based on the international literature and will be adopted in this study. These measures include the key Static Rollover Threshold (SRT) measure among a well-established group of measures which originally derive from research carried out by the University of Michigan Transportation Research Institute (UMTRI) for the Roads and Traffic Association of Canada (RTAC) Mass and Dimension Study [10].

Infrastructure measures will be based on best international practice as represented by the OECD DIVINE study [11] and the more recent COST 334 study [12], as well as the Australian and New Zealand PBS infrastructure measures. The base pavement wear measure to be used will be the time-honoured ESAL. Because the load equivalencies used for axle groups can vary significantly between countries, the more universal and simple approach of calculating ESALs for each axle, irrespective of the axle's presence in a single, tandem, tridem or quad group will be used. According to a recent survey [13], single axle equivalencies currently in use vary from 8.2 t (US, Canada, South Africa and Australia) to 13.3 t in France. While the actual value of single axle equivalency is not of significance for comparative purposes, 8.2 t will be used because it is relatively common and has a lineage back to the AASHO Road Test of the nineteen fifties.

With regard to bridges, most countries utilise axle mass schedules (sometimes called bridge formulae) for design and regulatory purposes. These schedules vary significantly between countries and an individual country may operate with several different schedules. The Australian and New Zealand PBS infrastructure measures include a relatively fundamental bridge measure in the form of Maximum Effect Relative to Reference Vehicle (MERRV) [9]. This requires the calculation of maximum bending moment and shear force for simply-supported spans ranging from 5 m to 50 m, and comparing these maximum values with those generated by appropriate reference vehicles. The MERRV approach will be used in this study, for short span (10 m) and longer span (50 m) bridges.

Additional standards

In recent years, heavy vehicle fuel consumption and emissions have become major issues and there has been significant rule-making activity to control emissions. The main sources of such standards are the European Commission and the US EPA. Various generations of these standards have been developed and many countries are seeing a phased introduction of increasingly stringent emission standards.

The differences between these generations of engines are likely to far outweigh the effects of vehicle configuration, mass etc on vehicle emissions. While this study will comment on the environmental benefits of the new generation engines, the analysis of each vehicle option will not extend to quantitative emissions indices.

Accident rates

A recent international benchmarking study of heavy vehicle accident rates [14] found that the number of persons killed in crashes involving a truck per 100 million km of truck travel is lowest in the United States (1.7) and Great Britain (1.8), while the rate is somewhat higher in Canada (2.1), Germany (2.2) and Australia (2.5), with France (4.4) and New Zealand (5.5) having considerably higher rates.

About two-thirds of fatal truck crashes involved articulated trucks in Australia (63%), Canada (64%) and the United States (70%). The percentages were much lower in Great Britain (38%) and New Zealand (19%), which may reflect the greater use of truck-trailer combinations in these countries.

In considering possible reasons for the significant variations in truck accident rates between countries, the benchmarking study reported a number of vehicle, road and environment factors whose effect on truck accident risks have been quantified in a limited way. These included a US study which found that the truck fatal crash rate on rural limited access roads was 4.5 times less than on "other rural roads". In urban areas the rate was approximately 2.8 times less on the limited access roads. Similarly the truck fatal crash rates were more than 3 times greater at night than in the daytime. The effect of truck configuration was not large, except for bobtail tractors. The rate for a semi-trailer was 31% greater than for a rigid truck, but 17% less than that of a truck and trailer combination.

The available research on truck accident rates therefore indicates relatively large variations in overall rates between countries, and the reasons for such variations could include differences in:
- Road standards and truck travel patterns on divided and undivided roads
- Proportions of urban and rural travel
- Proportions of night-time travel
- Truck configurations
- Traffic rules and enforcement, including speed limits and driving hours.

The benchmarking study also noted some concerns about the differing methods of truck accident data collection and, especially, the means of estimating truck travel for the purposes of quantifying exposure to accidents.

Given the relatively strong effects of road, environmental, and possibly enforcement factors on truck accident rates, it is not possible to identify international accident rate variations with differences in truck configuration and dynamic performance.

Following the Australian PBS project's review of known relationships between truck accident rates and truck performance [15], the category of truck accidents with the best established performance relationship is rollovers.

CONTAINER VEHICLE OPTIONS

All vehicles selected for the study are capable of carrying a standard ISO 40 ft container. The vehicles selected represent:
- Current NZ practice of A123 carrying a 24 t container at a GCM of 39 t
- Possible future NZ practice of A224 carrying a 30 t container at a GCM of 50.8 t
- Current Australian practice of A123 carrying a 30 t container at a GCM of 42.5 t
- Australian trial practice of A124 carrying a 34 t container at a GCM of 50 t
- North American proposed A123 carrying a 30 t container at a GCM of 44 t
- North American proposed A134 carrying a 34 t container at a GCM of 51.5 t
- European practice of A123 carrying a 30 t container at a GCM of 44 t
- Asia-Pacific practice of A112 carrying a 30 t container at a GCM of 43 t.

These vehicles have been considered with the most typical specifications for the countries nominated. The vehicle specifications include the following elements:
- Suspension type (mechanical or air)
- Tyre configuration (dual or single) and size designation.

Layout drawings of each of the selected vehicles are shown in the Appendix.

PERFORMANCE ASSESSMENT

The performance of each vehicle configuration was assessed in terms of safety-related and infrastructure-related measures adapted from the Australian Performance-Based Standards for Heavy Vehicles (PBS). The safety-related measures were selected to cover the key dynamic safety aspects of the vehicle, while the infrastructure-related measures were selected to cover each vehicle's efficiency in using the road network.

Safety-related performance
Safety-related performance was assessed for each vehicle configuration according to Australian performance-based standards as current at the time of writing.

The following set of safety-related standards was assessed for each vehicle using Roaduser Autosim Truck Engineering Dynamics (RATED) computer simulation models:
- Tracking ability on a straight path (TASP)
- Low-speed offtracking (LSO)
- Steer tyre friction demand (STFD)
- Static rollover threshold (SRT)
- Rearward amplification (RA)
- High-speed transient offtracking (HSTO)
- Yaw damping coefficient (YDC)

Geometric variations are most likely to affect low-speed offtracking, so it is expected that there would be a contrast in LSO performance between the long-wheelbase US vehicles and the short-wheelbase European vehicles.

Axle load variations are most likely to affect static rollover threshold and high-speed transient offtracking, so there would be a contrast in SRT and HSTO performance between the lightly-laden NZ vehicles and the heavily-laden Asia-Pacific vehicles.

A summary of performance results for the above standards is contained in Table 1.

Table 1. Simulation results.

PBS measure	Performance target (Level 1 PBS)	Vehicle ID							
		#1	#2	#3	#4	#5	#6	#7	#8
TASP	≤ 2.90 m	2.72 m	2.72 m	2.73 m	2.67 m	2.74 m	2.72 m	2.76 m	2.84 m
LSO	≤ 7.40 m	6.34 m	6.13 m	6.10 m	6.64 m	6.79 m	6.34 m	5.88 m	6.04 m
STFD	≤ 0.80	0.49	0.53	0.49	0.47	0.53	0.67	0.48	0.22
SRT	≥ 0.35 g	0.36 g	0.35 g	0.36 g	0.32 g	0.34 g	0.36 g	0.35 g	0.24 g
5.7×SRT		*2.05*	*2.00*	*2.05*	*1.82*	*1.94*	*2.05*	*2.00*	*1.37*
RA	≤ 5.7×SRT	1.55	1.32	1.50	1.59	1.46	1.27	1.53	1.54
HSTO	≤ 0.60 m	0.23 m	0.28 m	0.26 m	0.26 m	0.26 m	0.27 m	0.28 m	0.42 m
YDC	≥ 0.15	0.58	0.57	0.62	0.62	0.53	0.68	0.50	0.70

In general, performance of all selected vehicles was found to be acceptable in almost all areas. The Asia-Pacific example demonstrated performance levels slightly below those of the other vehicles, primarily due to the greater load per axle compared with the other vehicles.

The geometric differences between the vehicles did not affect LSO greatly; performance was well within the acceptable range for all vehicles. The NZ vehicles demonstrated middle-of-the-road performance in LSO.

While almost all standards were easily satisfied, SRT was found to be the most difficult to achieve. This was especially the case for those vehicles with high load per axle, as axle loads tend to have a large influence on SRT and HSTO. The NZ vehicles demonstrated the best performance in SRT and HSTO, with the proposed high-productivity option not performing quite as well as current NZ practice.

Performance in the remaining measures did not highlight any major trends, although the NZ vehicles performed well in comparison with the other vehicles.

Infrastructure-related performance

The infrastructure effects of the selected vehicles have been quantified in terms of their effects on both pavements and bridges. Pavement effects have been examined using analysis against Equivalent Standard Axle Load (ESAL) and bridge effects have been examined using the new PBS bridge standard Maximum Effect Relative to Reference Vehicle (MERRV).

Table 2 lists the results obtained from the pavement effect analysis. As described earlier, the total number of standard axle repetitions (SARs) was calculated for each vehicle assuming all axles were single axles with an ESAL of 8.2 t. A 4th power relationship was applied to the ratio of axle load to ESAL. The measure was also expressed as Payload/SAR to include an efficiency aspect that more clearly quantifies the effect of the vehicle on the road network for a given freight task.

It can be seen that the high load per axle present in the Asia-Pacific vehicle has a marked effect on pavement wear performance for that vehicle. All other vehicles demonstrate similar performance, with the current NZ practice offering excellent performance. While the proposed high-productivity NZ vehicle has reduced performance compared with current practice (ie. greater SAR), it maintains a position at the better end of the spectrum.

Table 2. Pavement effect analysis.

Vehicle ID	Total SARs per vehicle pass	Payload per SAR (tonnes)
#1	3.78	6.35
#2	4.96	6.05
#3	4.88	6.15
#4	5.67	6.00
#5	4.96	6.05
#6	4.34	7.83
#7	5.32	5.64
#8	16.88	1.78

Table 3 lists the results obtained from the bridge effect analysis. The MERRV standard was used to calculate the peak shear forces and bending moments induced in simply-supported spans of 10 metres and 50 metres by moving each vehicle incrementally along the span to capture the worst case position.

Table 3. Bridge effect analysis.

Vehicle ID	10 metre span (simply-supported)		50 metre span (simply-supported)	
	Max shear (kN)	Max bending (kNm)	Max shear (kN)	Max bending (kNm)
#1	164	360	333	3912
#2	203	438	431	5111
#3	182	401	365	4289
#4	217	494	248	5006
#5	203	468	380	4393
#6	212	455	434	5177
#7	211	468	382	4476
#8	224	493	379	4345

The current NZ and Australian practices offer the best performance of all vehicles. It can be seen that the loads induced in the 50 metre span are much greater than for the 10 metre span. The 50 metre span, however, is not common in all parts of the world, and tends to give bending moment results that correlate closely with GCM for short vehicles. Figure 1 shows the correlation between GCM and maximum bending moment in the 50 metre span for all vehicles assessed. This enforces the fact that a relatively short vehicle on a relatively long span approaches a point load scenario, where internal axle locations do not play as large a part in the bridge loading as does the GCM.
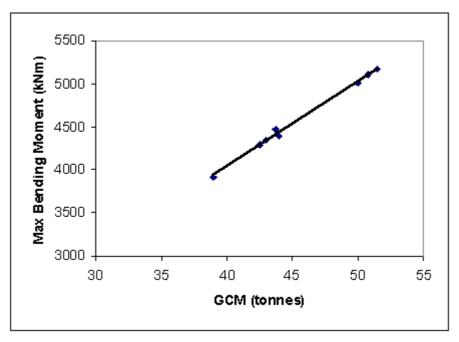
Figure 1. Correlation between GCM and bending moment (50m span).

Performance comparisons

The assessments conducted thus far have produced a large set of numerical results which are considered to make clear comparison between vehicles difficult to achieve.

It is proposed that the following three measures are developed to reduce the results down to a manageable size:

- DYNAMICS

  Captures the dynamic "fingerprint" of the vehicle expressed in terms of static rollover threshold (SRT) and rearward amplification (RA). While SRT is the cornerstone stability measure of a vehicle, it does not address the role that vehicle dynamics play in the overall stability performance of the vehicle. RA can be related to SRT using the prescribed PBS performance level of 5.7xSRT. Therefore a higher level of SRT in effect authorises a higher level of RA as being acceptable for a given vehicle. The ratio (5.7xSRT)/RA effectively describes the vehicle's dynamic stability in terms of its propensity to dynamic rollover. The payload capacity of the vehicle is addressed by arriving at a final value which is the product of payload capacity and the ratio (5.7xSRT)/RA. Therefore, a higher payload vehicle is given greater credit for the same dynamic stability. A higher value for this measure indicates a better-performing vehicle.

- PAVEMENTS

  Captures the vehicle's effect on pavements in terms of payload per SAR as calculated in Table 2. The payload aspect is included so that road wear can be assessed in terms of a vehicle's effect on the road network resulting from execution of a given freight task. For example, a task of 1,000 tonnes would require 33 trips of a vehicle having 30 tonne payload capacity; another vehicle having 34 tonne payload capacity would only require 29 trips and is therefore considered more efficient for the same total SAR. A higher value for this measure indicates a better-performing vehicle.

- BRIDGES

  Captures the vehicle's effect on bridge infrastructure in terms of maximum bending moment on a 10 metre span. The 50 metre span was previously found to correlate very closely with GCM and therefore was not considered to be useful in this exercise. The 10 metre span is a more common bridge span which also provided a degree of variety between the performance levels obtained by the set of vehicles. The maximum bending moments obtained and shown in Table 3 are inverted so that a higher value for this measure indicates a better-performing vehicle. In the same fashion as for DYNAMICS, the payload capacity was included to give higher payload vehicles more credit for the same bending moment.

All performance results for these measures have been normalised to the current NZ practice so that a true benchmark can be set for the remaining vehicles to be compared against. A value greater than 1.00 indicates better performance than the current NZ practice.
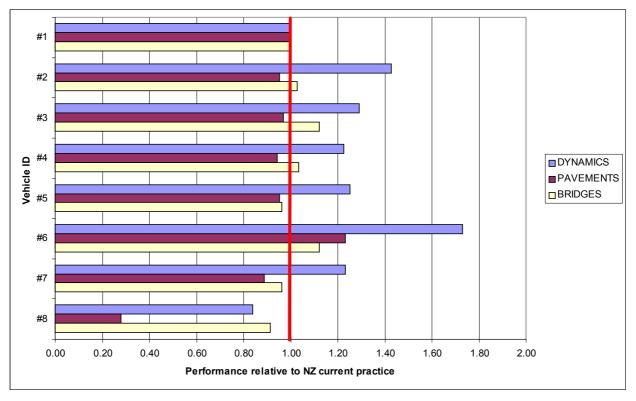

Figure 2. Performance comparisons (dynamics, pavements, bridges).

CONCLUSION

The haulage of standard ISO 40 ft containers is a key transport task undertaken in all countries, providing the backbone of international trade and freight flows. This task also has great future significance as it links rail, sea and road freight transportation world-wide. Annual container movements are increasing steadily in all countries.

Both Land Transport Safety Authority (LTSA) and Transit New Zealand are committed to developing a road transport system that achieves world's best practice. Part of this task needs to focus on the transport of 40 ft containers, so current international practice in the haulage of 40 ft containers has been surveyed. Several solutions from New Zealand, Australia, North America, Europe and Asia have been collated and assessed to determine "world's best practice"; this provided a benchmark with which to compare the performance of NZ current practice and potential future options. The set of comparison vehicles covered the transport of containers of 30 t and 34 t gross mass. The current NZ practice of carrying 24 t containers is potentially to be replaced by a solution for carrying 30 t containers.

Performance-based standards (PBS) have come to be regarded as an effective means of comparing vehicle performance. Since the performance targets may vary between countries, direct comparison of vehicles against each other (rather than against performance targets) is a valid means of benchmarking performance. While performance-based standards cover many aspects of vehicle performance, the vehicle dynamics aspects have often been considered too multi-dimensional for performance comparison, and the simpler infrastructure measures used in isolation to determine cost to society.

Comparison of the dynamic performance of the group of international vehicles was undertaken by assessing each vehicle against a selection of safety-related performance-based standards capturing the essential safety-performance characteristics. The NZ vehicles compared well with the other vehicles in terms of geometric performance in Low-Speed Offtracking (LSO), and demonstrated the best performance in the

stability-related measures Static Rollover Threshold (SRT) and High-Speed Transient Offtracking (HSTO). Based on the details presented, it could be considered that the NZ vehicles demonstrate world's best practice in dynamic stability.

Pavement effects were assessed using the time-honoured ESAL, where it was found that the current NZ practice was the best performer on a total SAR per vehicle basis. The potential NZ option for increased mass was also at the high end of the spectrum.

Bridge effects were assessed using the newly-developed PBS standard Maximum Effect Relative to Reference Vehicle (MERRV). Again, the NZ vehicles were found to offer the best performance.

Three performance indicators were proposed, which capture the essential vehicle characteristics as they pertain to Dynamics, Pavements and Bridges. These indicators were normalised to current NZ practice so that comparisons could be made between the vehicles. Payload capacity was also factored in so that vehicles carrying a greater payload were given more credit for the same performance. The proposed future NZ vehicle was found to be close to world's-best-practice in all three measures.

The success of the NZ vehicles in this comparative study is primarily attributed to the use of low axle loads (ie. reduced load per axle in comparison with the other vehicles). By using a greater number of lightly-laden axles, stability and dynamic performance can be greatly enhanced, while pavement effects and bridge loading can also be substantially mitigated.

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APPENDIX

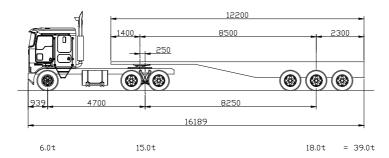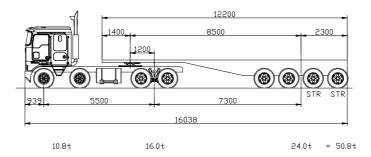Figure A1. Vehicle ID #1 – Current NZ A123.

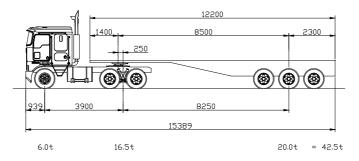Figure A2. Vehicle ID #2 – Potential future NZ A224.
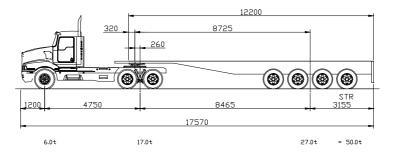

Figure A3. Vehicle ID #3 – Current Australian A123.

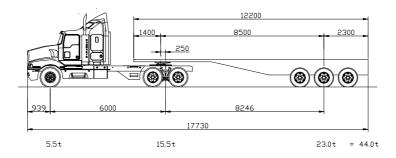Figure A4. Vehicle ID #4 – Potential Australian A124.
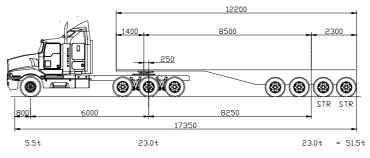
Figure A5. Vehicle ID #5 – Proposed US A123.

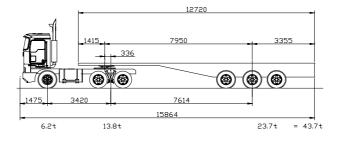Figure A6. Vehicle ID #6 – Potential US A134.
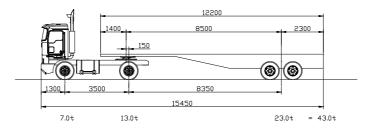

Figure A7. Vehicle ID #7 – Current European A123.

Figure A8. Vehicle ID #8 – Current Asia-Pacific A112.