Optimisation of heavy vehicle performance
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Abbreviations and acronyms

BL	Bulk liquids
BM	Bulk materials
CG or cg	Centre of gravity
CML	Concessional mass limits
GCW	Gross combination weight
GML	General mass limits
HML	Higher mass limits
HSO	High-speed offtracking
HSTO	High-speed transient offtracking
IC	Intermodal containers
ISO	International Standards Organisation
kg	kilogram: measure of mass
kNm	Kilo Newton metres: measure of torque or moment of force
LS	Livestock
LSO	Low-speed offtracking
LTR	Load transfer ratio
m	Metre: measure of distance
NA	Not applicable
NHVAS	National Heavy Vehicle Accreditation Scheme
NZTA	New Zealand Transport Agency
OAL	Overall length
OAS	Overall axle spacing (distance from first to last axle)
PBM	Peak bending moment
PBS	Performance based standards
PC	Passenger coach
PLD	Payload weight
RA	Rearward amplification
RG	Refrigerated goods
SAR	Standard axle repetitions
SRT	Static rollover threshold
t	Tonne: measure of mass (one thousand kilograms)
TAC	Tyre-axle-coupling sequence
YDR	Yaw damping ratio

Contents

Executive summary

Operational requirements, vehicle dimensions and mass limits, other regulations and road user charges all influence the type of vehicle used for passenger and freight transport in New Zealand. The aim of this research was to improve the performance of New Zealand's heavy vehicle fleet in protecting the road and bridge infrastructure, improving safety, reducing environmental impact and reducing congestion. To achieve this aim, typical vehicles used in six transport tasks in New Zealand were benchmarked against vehicles undertaking those same tasks in Australia, Canada, Southeast Asia and the United Kingdom. Care was taken to ensure that the vehicle models complied with the current weight and dimension rules of their country of operation. In the report a more optimal New Zealand truck and full trailer is presented, and ways to optimise other vehicle configurations are discussed.

The benchmarking analysis considered four aspects of heavy vehicle performance: pavement wear, bridge wear, road space and safety. Pavement wear performance was determined by the amount of accumulated pavement wear (based on the fourth power of the axle loads) and payload. Bridge wear performance was determined by the amount of accumulated bridge wear (based on the third power of the peak bending moment when traversing a reference bridge spanning 12.5m) and payload. Road space performance was determined by the amount of road width occupied on low- and high-speed turns (vehicle width and low- and high-speed offtracking) and payload. Safety performance was based on relating the vehicle's rollover stability (static rollover threshold (SRT)) and high-speed dynamic stability characteristics (load transfer ratio, rearward amplification, high-speed transient offtracking) to the relative likelihood of being involved in a stability-related crash. The safety performance measure included payload as a measure of vehicle exposure. Payload was also used as a measure of environmental impact where more productive vehicles result in fuel and emissions savings and in reduced congestion.

General conclusions

The New Zealand vehicles caused the least amount of pavement wear and were sufficiently productive to achieve the best pavement performance in every transport task. The main reason for this is that road tax on heavy vehicles in New Zealand is collected through road user charges which includes a component for pavement wear based on the fourth power of the axle loads. This tax has created a situation unique to this country by encouraging operators to fit more axles to carry a given load than is necessary to comply with the axle group weight limits. Encouraging operators in New Zealand to fit more axles to reduce pavement wear also contributes to reduced bridge wear, particularly for short bridges.

A large number of transport tasks in New Zealand are undertaken by truck and full trailers compared with the other countries which tend to use mainly tractor semi-trailers and to a lesser extent B-trains for the same tasks. Truck and full trailers have good low-speed manoeuvrability and thus perform well in terms of road space requirements. With the axle weights used in New Zealand they have relatively low impact on the pavement and bridge infrastructure and also perform well in this regard. However, their safety performance can be worse than other vehicle configurations if they are not designed well. The New Zealand size and weight regulations do include some requirements aimed at truck and full trailer design for improved safety. Specifically, there is a minimum SRT requirement of 0.35g for all large heavy vehicles; the distance between the rear axis of the truck and the coupling hitch must be less than 40% of the truck's wheelbase; and the trailer:truck mass ratio must not be more than 1.5:1.

There are unique road geometry challenges in New Zealand in both low- and high-speed operations. Of particular risk is the frequency of high-speed tight radius curves that challenge drivers and vehicles. Such conditions do not exist at the same level in the benchmark countries. This unique condition argues for rigorous heavy vehicle safety performance evaluation as outlined in this report. As an additional countermeasure, crash avoidance technology such as electronic stability systems and roll stability systems should be considered as a requirement for higher productivity vehicles including motor coaches.

Heavy vehicle optimisation

The overall performance of passenger coaches in New Zealand can be improved by operating 13.5m or 14.5m coaches under permit. The advantages of longer coaches over the 12.6m coach currently used in New Zealand are as follows:

- Although longer passenger coaches are generally heavier in tare weight than shorter coaches they are also more productive as they can seat more passengers.
- As 12.6m coaches have both good pavement and bridge wear performance, it is possible for longer and more productive coaches to operate without their corresponding axle weight increases impacting significantly on their respective ranking. One benefit of operating longer coaches is that by distributing their weight over a greater span they have less impact on the bridge infrastructure.
- Road space performance of passenger coaches can be improved by operating longer and more productive coaches as the occupied road width is still much less than that used by combination vehicles on the same road network.
- The safety performance of passenger coaches can be improved by operating longer coaches because an increase in productivity results in reduced on-road vehicle exposure thus improving safety, and the increase in overall length (OAL) results in improved stability on high-speed path changes or evasive manoeuvres due to the tyres encountering smaller slip angles.

The overall performance of truck and full trailers in New Zealand can be improved with moderate increases in both gross combination weight (GCW) and OAL limits for the following reasons:

- As these vehicles have good pavement wear performance, a moderate increase in GCW is possible without it impacting significantly on their respective rankings.
- As these vehicles have good bridge wear performance, increases in both GCW and OAL are possible without impacting significantly on their respective rankings since they distribute their weight more uniformly on bridges than other combination vehicles, and because longer vehicles have less impact on the bridge infrastructure.
- As these vehicles have good road space performance, moderate increases in both GCW and OAL are possible without these increases impacting significantly on their respective rankings.
- The safety performance of these vehicles can be improved with moderate increases in both GCW and OAL, as an increase in GCW results in greater productivity and reduced on-road vehicle exposure thus improving safety; an increase in OAL results in improved stability on high-speed path changes or evasive manoeuvres; and moderate increases in both GCW and OAL can be managed so that the rollover stability of these vehicles is no worse or even better than the current vehicle configurations.

An increase in GCW limit for truck and full trailers can be achieved without necessarily increasing their axle group weight limits since these vehicles currently operate with their axle groups weights below the legal maximum. A more optimal New Zealand truck and full trailer is presented in section 5.8 and discussed in section 6.1.

The overall performance of tractor semi-trailers can be improved with moderate increases of their tri- and quad-axle trailer group weight limits for the following reasons:

- As these vehicles have good pavement wear performance, these weight increases are possible without impacting significantly on their respective rankings. This is because the current weight limits for the tri- and quad-axle groups are less than those reference axle group weights deemed to generate the same amount of pavement wear as one standard axle.
- Although these vehicles do not perform as well as other combination vehicles in terms of bridge wear performance, these weight increases will improve their respective rankings as it is the axle loads on the tractor units, the tandem drive axles in particular, that impact the most on the bridge infrastructure and not their trailer axles.
- As these vehicles do not perform as well as other combination vehicles in terms of road space performance, the best way to improve this is with a moderate increase in productivity through adopting these weight increases.
- The safety performance of these vehicles is generally better than that of other combination vehicles as they each have only one coupling, and because the fifth wheel provides roll coupling between both vehicle units every axle contributes to the rollover stability of the combination. These weight increases result in greater productivity and reduced on-road vehicle exposure, thus improving safety.

An increase in the weight limits of tri- and quad-axle trailer groups on tractor semi-trailers also requires a corresponding increase in the GCW limit since many configurations operate their axle groups at full capacity, and some configurations already operate at the current GCW limit.

For the same vehicle configuration, an increase in weight will mean more pavement wear but this will be recovered by the increased road user charges for this vehicle. An increase in New Zealand’s GCW limit will require a new weight limit schedule (or bridge formula) to be developed and implemented. The fundamental principle behind any weight limit schedule is to protect the bridge infrastructure from overstress by only allowing longer vehicles more weight. This is because longer vehicles distribute their weight over longer spans which lessen their impact on the bridge infrastructure. However, longer vehicles must also be more manoeuvrable to successfully negotiate the road network. As truck and full trailers are longer and more manoeuvrable than other combination vehicles, an increase in both GCW and OAL limits observes the principles of the weight limit schedule and can be accommodated by linear extrapolation of the current schedule. Conversely, tractor semi-trailers are generally shorter and have relatively poor manoeuvrability compared with other combination vehicles, so if their OAL is maintained at the current limit, increasing the GCW limit alone will contravene the principles of the weight limit schedule and cannot be accommodated by extrapolation of the current schedule in the same way. An increase in weight allowance would be required.

An increase in the OAL limit of heavy vehicles in New Zealand will mean that longer vehicles will inevitably occupy more road space than vehicles at the current length limit. An increase in the OAL limit will also impact on other road users in terms of increased overtaking and intersection clearance times, and increased stacking length at intersections and on right-turning bays. A report by de Pont and Baas (2002) on similar matters states that although no good data is available on the safety impacts of such changes, it is reasonable to assume they would be negligible.

Since B-trains have relatively low usage in New Zealand compared with other more popular combination vehicles, their performance was not included as part of this benchmarking study. In general however, the performance of B-trains can be viewed as a trade-off between truck and full trailers and tractor semi-trailers. That is, B-trains generally perform better than tractor semi-trailers but worse than truck and full trailers in terms of road space, and they generally perform better than truck and full trailers but worse than tractor semi-trailers in terms of safety. B-trains in NZ have the same OAL limit as truck and full trailers, but they can often distribute their weight more uniformly on bridges than truck and full trailers, thus B-trains generally have slightly less impact on the bridge infrastructure than truck and full trailers. What these comparisons mean in terms of optimisation is that the performance of B-trains can be improved with moderate increases in both GCW and OAL for similar reasons as the truck and full trailers. However, the road space performance criteria will mean that the potential length increase of a B-train is less than that of a truck trailer.

Regarding the types of transport tasks undertaken, those that transport high-density product are safer than those that transport low-density product for the same vehicle and GCW. This result is mainly due to their differences in payload centre of gravity (cg) heights, where high-density products have lower cg heights than low-density products. Payload cg height has a significant impact on safety performance since lower cg heights result in better rollover stability. Therefore vehicles that transport high-density product can operate at heavier weights than those that transport low-density product for the same level of rollover stability, but with improved safety performance because of their greater productivity and reduced levels of on-road exposure. In addition, these more productive vehicles will also have improved road space performance, but these performance improvements will be at the expense of infrastructure performance.

For weight-constrained loads, increasing the allowable vehicle weight limits increases payload capacity, while for volume-constrained loads, increasing the allowable length will improve payload capacity. All of the compound performance measures incorporate payload in the calculation and so that aspect of performance will improve in proportion to the payload increase. However, increasing weight and/or length will also have negative effects on some aspects of performance. For example, increasing weight will worsen pavement performance in proportion to the fourth power of axle loads. Other aspects of performance may improve. For example, increasing weight and length proportionately so that the cg height of the vehicle does not change, should improve the safety performance since longer vehicles have better dynamic stability and because more productive vehicles result in reduced on-road vehicle exposure.

Abstract

Operational requirements, vehicle dimensions and mass limits, other regulations and road user charges all influence on the type of vehicle used for passenger and freight transport in New Zealand. The aim of this research was to improve the performance of New Zealand's heavy vehicle fleet in protecting the road and bridge infrastructure, improving safety, reducing environmental impact and reducing congestion. To achieve this aim, typical vehicles used in six transport tasks in New Zealand were benchmarked against vehicles undertaking those same tasks in Australia, Canada, Southeast Asia, and the United Kingdom. The six transport tasks analysed were passenger coach transport, bulk liquids and materials transport, 40 foot ISO intermodal container transport, and livestock and refrigerated goods transport. A more optimal New Zealand truck and full trailer is presented, and ways to optimise other vehicle configurations are discussed.

1 Introduction

Operational requirements, vehicle dimensions and mass limits, other regulations and road user charges[1] all influence the type of vehicle used for passenger and freight transport in New Zealand. The aim of this research was to improve the performance of New Zealand's heavy vehicle fleet in protecting the road and bridge infrastructure, improving safety, reducing environmental impact and reducing congestion. To achieve this aim, the research:

- identifed six typical road transport tasks and established the typical vehicle configuration used to undertake those tasks in New Zealand
- identified the vehicle configurations used to undertake the tasks in Australia, Canada, Southeast Asia, and the United Kingdom
- selected a set of performance measures that characterised infrastructure wear, road space, safety, efficiency and the environmental impact of a heavy vehicle
- benchmarked the performance of New Zealand vehicles against overseas vehicles
- determined the factors that prevented the best vehicles from currently being used
- identified new initiatives that could be introduced to produce the greatest benefits in terms of meeting the Road Safety to 2010 Strategy and the NZ Transport Strategy[2].

1.1 Road transport tasks

The six road tasks selected for the comparison of performance between vehicles from New Zealand and other countries were the transportation of:

- people by passenger coach (PC)
- bulk liquids (BL)
- bulk materials (BM)
- 40 foot ISO intermodal containers (IC)
- livestock (LS)
- refrigerated goods (RG).

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[1] The road tax on heavy vehicles is collected through road user charges which apply to all vehicles powered by diesel fuel and all others with gross weights over 3.5 tonnes. It is allocated according to gross vehicle mass, axle configuration and distance travelled. This tax has created a situation unique to this country by encouraging operators to fit more axles to carry a given load than is necessary for compliance with the weigh limits.

[2] The Road Safety to 2010 Strategy addresses road safety on three fronts: engineering, education and enforcement. The strategy is a key component in achieving the NZ Transport Strategy goal of having an affordable, integrated, safe, responsive and sustainable transport system.

1.2 Vehicle performance measures

Vehicle performance was assessed in terms of nine fundamental measures and four compound measures. The compound measures quantified four aspects of heavy vehicle performance: pavement wear, bridge wear, road space and safety. Pavement wear performance was determined by the amount of accumulated pavement wear and payload. Bridge wear performance was determined by the amount of accumulated bridge wear and payload. Road space performance was determined by the amount of road width occupied on low- and high-speed turns and payload. Safety performance was based on relating the vehicle's rollover stability and high-speed dynamic stability characteristics to the relative likelihood of being involved in a stability-related crash. The safety performance measure included payload as a measure of vehicle exposure. Payload was also used as a measure of environmental impact where more productive vehicles result in fuel and emissions savings and in reduced congestion.

1.3 Structure

This report is structured as follows:

- Chapter 2 reviews the literature on the types of vehicle equipment and usage in each of the countries studied. The bridge formulae applicable to some of the countries studied is reviewed. This chapter also reviews the literature relating vehicle performance to crash risk. The definitions and the significance of each of the fundamental performance measures and their target values are discussed.
- Chapter 3 outlines some of New Zealand's land transport rules. The main coupling types and self-steering axles are also discussed. This chapter also presents an overview of the weight and dimension limits in each of the countries studied together with a description of the vehicles used to undertake each of the transport tasks studied. This chapter concludes with an overview of the numerical simulation software used in this benchmarking study.
- Chapter 4 discusses the methodology behind the development of the four compound performance measures.
- Chapter 5 presents the results of the study beginning with an analysis of the amount of bridge wear caused by New Zealand baseline vehicles traversing a range of different bridge spans, followed by the benchmarking results by transport task and country of operation.
- Chapter 6 discusses the results of the study as they relate to the main vehicle parameters. This chapter includes a section on a more optimal New Zealand truck and full trailer.
- Chapter 7 draws conclusions based on previous sections and identifies ways to optimise the performance of heavy vehicles.
- The report concludes with the following appendices:
    - Appendix A reproduces the bridge formulae used in some of the countries studied
    - Appendix B defines the manoeuvres used to undertake the road space and safety performance analysis
    - Appendix C presents the weights and dimensions of the vehicles modelled in this study

- Appendix D presents the bending moment versus front axle location of New Zealand vehicles as they traverse a simply-supported bridge spanning 12.5m
- Appendix E presents figures of some of the fundamental performance measures and their relationships with each other.

2 Literature review

2.1 Heavy vehicle equipment and usage

In 1997, New Zealand's fleet of 72,700 heavy vehicles (vehicles over 3.5 tonnes) comprised 75.1% rigid trucks, 15.2% truck and full trailers, 7.3% tractor semi-trailers, 2.1% B-trains and 0.3% A-trains (Baas 1999). It was also estimated that rigid trucks, truck and full trailers, tractor semi-trailers, B-trains and A-trains accounted for 61.3%, 21.2%, 12.1%, 4.2% and 1.2% of the 1.85 billion heavy vehicle-kilometres travelled (Baas 1999). In 2003, there were 6800 registered buses and coaches in revenue service operated by the licensed industry. About 85% of the licensed bus operators in New Zealand are members of the Bus and Coach Association, running 80% of the nation's bus fleet. In that same year, 44% of the 140 million vehicle-kilometres travelled by buses (and coaches) belonging to members of the Bus and Coach Association were undertaken in urban areas, 32% on tours, 16% on school routes, and 8% on charter and limousine travel (Bus and Coach Association 2005).

In March 2006, Australia's fleet of 456,000 heavy vehicles comprised 84% rigid trucks (excluding light commercial vehicles) and 16% articulated trucks (tractor semi-trailers, B-doubles and road trains). In the year ending October 2005, rigid trucks and articulated trucks accounted for 54% and 46% of the 13.68 billion heavy vehicle-kilometres travelled. In March 2006, Australia's bus fleet comprised 75,000 buses. In the year ending October 2005, 49% of the 1.86 billion vehicle-kilometres travelled by buses were undertaken in city centres, 20% in urban areas, 27% in other areas of the state/territory, and 4% on interstate travel (Australian Bureau of Statistics 2008).

In 2006, Canada's fleet of 633,000 heavy vehicles (trucks with gross weights of at least 4.5 tonnes) comprised 52% straight (or rigid) trucks, 33% tractor semi-trailers, and other heavy vehicles made up the remaining 15%. In the same year, straight trucks, tractor semi-trailers, and other heavy vehicles accounted for 27%, 64% and 9% of the 29.1 billion heavy vehicle-kilometres travelled. Of the heavy vehicle-kilometres undertaken by tractor semi-trailers: those operating in a bobtail configuration (tractor not towing a semi-trailer) accounted for 6%; tractors hauling one semi-trailer (18 wheelers) accounted for over 77%; those hauling two semi-trailers accounted for over 17%; and tractors hauling three semi-trailers made up the remaining share (Transport Canada 2007). In 2000, Canada's bus fleet comprised 72,000 buses. In this same year, 50% of the 1.89 billion vehicle-kilometres were undertaken by school buses, 25% from urban transit, 20% from charter and other activities, and 5% from intercity highway activity (Transport Canada 2001).

In 2006, the fleet of 446,000 heavy goods vehicles in the United Kingdom comprised 73% rigid trucks and 27% articulated trucks. In the same year, rigid and articulated trucks accounted for 46% and 54% of the 25.37 billion heavy vehicle-kilometres travelled (Department for Transport 2007). In 2007/2008, there were 80,400 buses in the United Kingdom. In this same period, 65% of the 4.31 billion vehicle-kilometres travelled by buses were on local service runs, and 35% on non-local service runs (Department for Transport 2008).

The use of combination vehicles is less significant in the developing countries of Southeast Asia which tend to use a large proportion of two- and three-axle rigid trucks (World Bank 2005). One reason for this is the relatively high capital costs associated with combination vehicles compared with the low cost of labour. To the author's knowledge, there is no accurate or complete data on the types of heavy vehicle equipment or their usage in the developing Southeast Asian countries.

2.2 Bridge formulae

Some countries, including New Zealand, Australia and the United States of America specify weight limits for groups of axles that depend on axle spread to protect their bridges from overstress. These limits are in addition to the prescriptive axle group weight and gross combination weight limits. In some jurisdictions, these axle group weight limits are presented in tabular form while in others they are presented as formulae. Because of its role in protecting bridges, this type of weight limit is usually called a bridge formula even when it is presented in tabular form. Other countries including Canada (Council of Ministers 2005) and the European Community (European Communities 1996; 2002) rely on prescriptive weight and dimension limits to protect their bridges from overstress.

Although New Zealand's bridge formula is presented in tabular form, Sleath and Pearson (2000) give a piecewise linear approximation of the mass limits relating to axle spread (table 6 of the Land Transport Rule: Vehicle Dimensions and Mass 2002 – Rule 41001 (LTSA 2002)). The current bridge formula effectively precludes any increase in weight limits without an increase in length. To overcome this, Sleath and Pearson (2000) proposed an alternative bridge formula in place of the current limits that would enable higher productivity vehicles to operate in New Zealand under two different scenarios: increasing heavy vehicle weights on the entire road network (scenario A), and increasing both heavy vehicle weights and dimensions for selected routes only (scenario B). The research included estimating the economic impact of increasing the mass limits on bridges based on a reduction in the overall service life and the additional cost due to their earlier replacement. These bridge formulae are given by equation A.1 and equation A.2 in appendix A. Neither scenario nor any changes relating to mass limits and axle spread have been implemented in law to date.

The bridge formula given in the Australian Performance Based Standards (PBS) Scheme[3] – the Standards and Vehicle Assessment Rules (National Transport Commission 2007), is a linear approximation of the mass limits relating to axle spacing given in table 2 of the Road Transport Reform (Mass and Loading) Regulations Statutory Rules 1995 (AGAGD 1999). This formula forms the first part of a two-part piecewise linear formula which, if met, allows the qualifying PBS (or SMART) vehicles access to the PBS level 1 road network. To gain access to the PBS level 2, 3 and 4 road networks, the bridge formulae relating to those roads must be met by the qualifying PBS vehicles. The bridge formulae for PBS level 1 through to level 4 are reproduced by equation A.3 through to equation A.5 in appendix A.

The Federal Highway Administration of the United States of America developed the Federal Bridge Formula B to regulate truck size and weight. A new bridge formula known as the TTI-HS20 formula was proposed to protect the inventory of HS20 bridges (James et al 1986). The TTI-HS20 formula offers some advantages over the Federal Bridge Formula B in that it only depends on one variable (axle spacing), and the gross vehicle weight limit of 36.29 tonnes (80,000 pounds) is removed thus allowing heavier and more

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[3] PBS is an alternative compliance regime to the conventional prescriptive size and weight regulations of heavy vehicles in Australia. PBS offers the potential for heavy vehicle operators to achieve higher productivity and safety through innovative vehicle design (National Transport Commission, Fact sheet A). A potential SMART vehicle is evaluated by an accredited PBS assessor and an application is made to the PBS review panel for approval. If approved, the operator must formally apply for road network access with the relevant state road authorities. The SMART vehicle may also require an exemption from the Australian Design Rule. The National Transport Commission has published a limited number of SMART blueprint vehicle designs that already comply with the PBS standards thus saving the applicant assessment costs. Road use costs for SMART heavy vehicles will be set through the 2007 Charges Determination and annual indexation mechanism on a cost recovery basis (National Transport Commission, Fact sheet B).

productive trucks to operate. The TTI-HS20 formula is recommended by the American Road and Transportation Builders Association and in the NCHRP Special Report 225 but has not been implemented in law to date (Jaykishan 2005). The Federal Bridge Formula B and the TTI-HS20 formula are reproduced by equation A.6 and equation A.7 in appendix A.

2.3 Performance measures and crashes

A performance measure characterises the behaviour of a vehicle in response to a standardised vehicle manoeuvre which usually reflects some aspect of a vehicle's performance that is considered important. With regard to vehicle stability and crashes, the premise is that vehicles that achieve better performance relating to stability would have a lower risk of being involved in stability-related crashes. To quantify the benefits associated with any performance measures introduced to improve vehicle stability, the relationship between vehicle performance and crash risk must be known.

A paper by de Pont et al (2000) calculated the relative crash rates for different performance measures in relation to New Zealand's heavy vehicle fleet. The paper considered four stability-related performance measures: static roll threshold (SRT), load transfer ratio (LTR), high-speed transient offtracking (HSTO) and yaw damping ratio (YDR). The performance results for a set of heavy vehicles involved in rollover or loss-of-control crashes were compared with those of the fleet in general. By comparing these distributions, the relative crash rates for the performance measures were calculated.

The relative crash rates versus SRT, LTR and HSTO are shown in figures 2.1, 2.2 and 2.3. These figures show that vehicles with lower SRT, higher LTR and higher HSTO have a higher likelihood of being involved in a stability-related crash. There was also some indication that a poor value of YDR increases crash risk. Note that LTR and HSTO and SRT are causally related.

Figure 2.1 **Relative crash rate versus static roll threshold (de Pont et al 2000)**

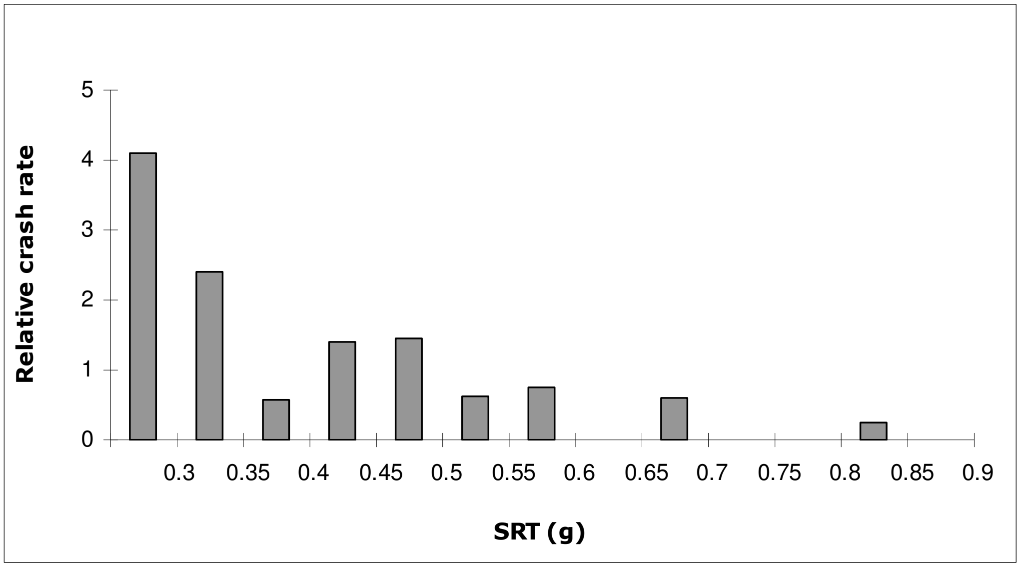


Figure 2.2 Relative crash rate versus load transfer ratio (de Pont et al 2000)

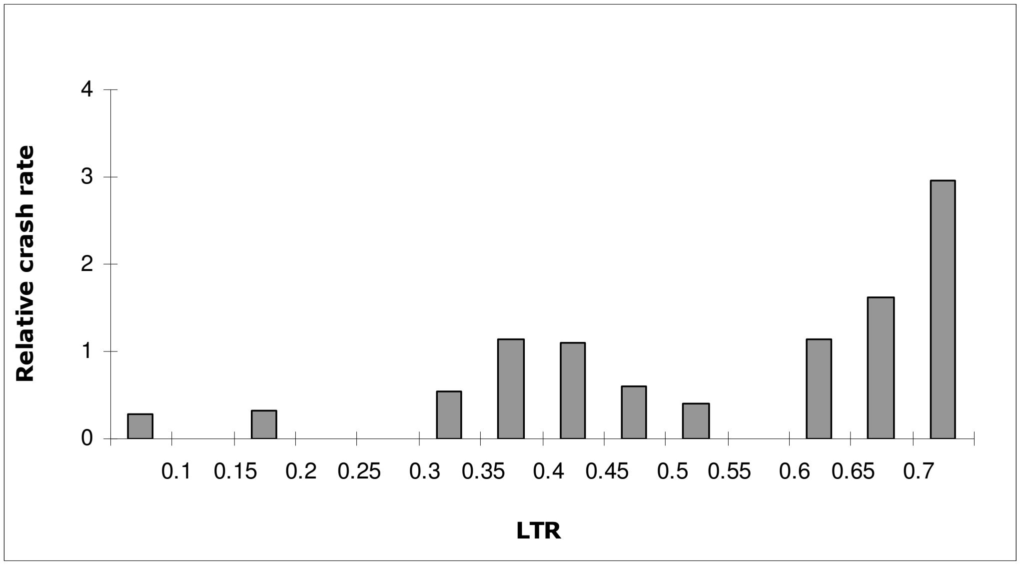
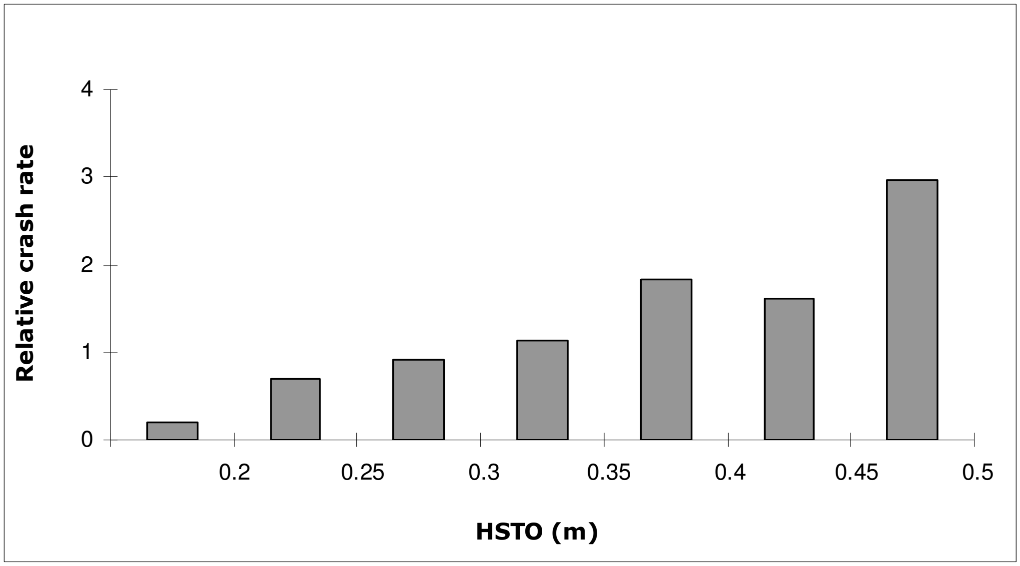


Figure 2.3 Relative crash rate versus high-speed transient offtracking (de Pont et al 2000)



To create a performance standard, a limit value for that performance measure must be defined. The level of the target values typically used for SRT, LTR and YDR as shown in table 2.1 seem reasonable given that the crash rate rises steeply when these values are not achieved. For HSTO, the target value is substantially higher than the values of the existing fleet but there is a trend showing that higher HSTO values have increased crash risk.

It is clear from table 2.1 that a small percentage of poor-performing vehicles contribute disproportionately to the crash rate. For example, although only 15% of the fleet had an SRT below the target 0.35g, 40% of these vehicles were involved in stability-related crashes. Similarly, only 35% of the fleet had an LTR greater than the target 0.6, yet 58% of these vehicles were involved in stability-related crashes.

Table 2.1 Performance measure results summary (de Pont et al 2000)

Performance measure	Target value	Target value not met	
		Fleet performance	Crashed vehicles
SRT	≥ 0.35g	15%	40%
LTR	≤ 0.6	35%	58%
HSTO	≤ 0.8 metres	0%	0%
YDR	≤ 0.15	1.2%	4.7%

2.4 Performance measures

Table 2.2 shows the typical target values (or performance standards) for the nine fundamental performance measures which are grouped into the infrastructure, road space and safety categories. The definitions and significance of these measures and their target values are discussed in the following sections. A detailed description of the manoeuvres used to obtain the road space and safety performance measures is given in table B.1 in appendix B.

Table 2.2 Target values of the eight fundamental performance measures by category

Category	Fundamental measure	Abbreviation	Target value
Infrastructure	Peak bending moment	PBM	≤ baseline vehicle
	Standard axle repetitions	SAR	≤ baseline vehicle
Road space	Low-speed offtracking	LSO	≤ 4.2 metres
	High-speed offtracking	HSO	≤ 0.5 metres
Safety	Static roll threshold	SRT	≥ 0.35g (0.7g for coaches)
	Load transfer ratio	LTR	≤ 0.6
	High-speed transient offtracking	HSTO	≤ 0.8 metres
	Rearward amplification	RA	≤ 2
	Yaw damping ratio	YDR	≥ 0.15

Note that road space and safety performance can become an infrastructural performance issue if the inadequacies of a vehicle's road space or safety performance result in wear to the road or bridge infrastructure. Similarly, infrastructural and road space performance can become a safety performance issue if the structural integrity of pavements or bridges is compromised, or if inadequate lane-keeping or intrusions onto footpaths or road shoulders by a vehicle occurs. Nevertheless, the grouping of these fundamental measures into these categories is needed to facilitate the development of the four compound measures. The development of these compound measures is discussed in chapter 4.

2.4.1 Infrastructure

2.4.1.1 Standard axle repetitions

Pavement wear is quantified in terms of standard axle repetitions (SAR) which account for the amount of accumulated pavement wear. A lower value of SAR indicates a reduction in pavement wear. The total SAR of a vehicle is the sum of the individual SAR produced by every one of its axle groups. The SAR for a given tyre and axle group configuration is calculated by taking its load and dividing it by the reference load for that group, then raising the result to the fourth power. The reference load for an axle group is the load that is deemed to generate the same amount of pavement wear as one standard axle. Table 2.3 shows the reference weights for the given tyre and axle group configuration. For six-tyred tandem axle groups with four standard tyres on one axle and two wide-single tyres on the other axle, a reference weight of 13 tonnes is used.

Table 2.3 Reference weights, in tonnes, for given tyre and axle group configurations

Tyre configuration	Axle configuration			
	Single	Tandem	Tridem	Quadem
Single	5.4[a]	9.2[b]	12.3[b]	14.9[b]
Wide-single	7.2[a]	12.1[b]	16.2[b]	19.8[b]
Dual	8.2[a]	13.8[a]	18.5[a]	22.5[a]

Notes:

[a] Austroads (2004).

[b] Reference weight values obtained by scaling the corresponding dual tyre axle group values by the single or wide-single tyre values relative to the dual tyre value for a single axle.

Road user charging in New Zealand includes a pavement wear component based on this fourth power rule[4] for flexible asphaltic concrete pavements. The fourth power rule has never been validated on New Zealand's thin surfaced unbound granular pavements.

2.4.1.2 Peak bending moment

Based on experimental data and fracture mechanics principles, bridge wear of steel bridge components is proportional to the magnitude of the stress cycles raised to the third power (Transportation Research Board 2003). The amount of accumulated wear may then be formalised by a third power wear accumulation law based on constant stress cycles. However, in cases where one stress cycle dominates the others, the amount of accumulated wear can be approximated by the maximum stress cycle raised to the third power. For girder bridges, the stress is proportional to the bending moment. Thus the maximum stress cycle is represented by the peak bending moment (PBM).

In this report, bridge wear is quantified in terms of the magnitude of the PBM raised to the third power. Lower values indicate better performance in terms of reducing the wear caused to the bridge

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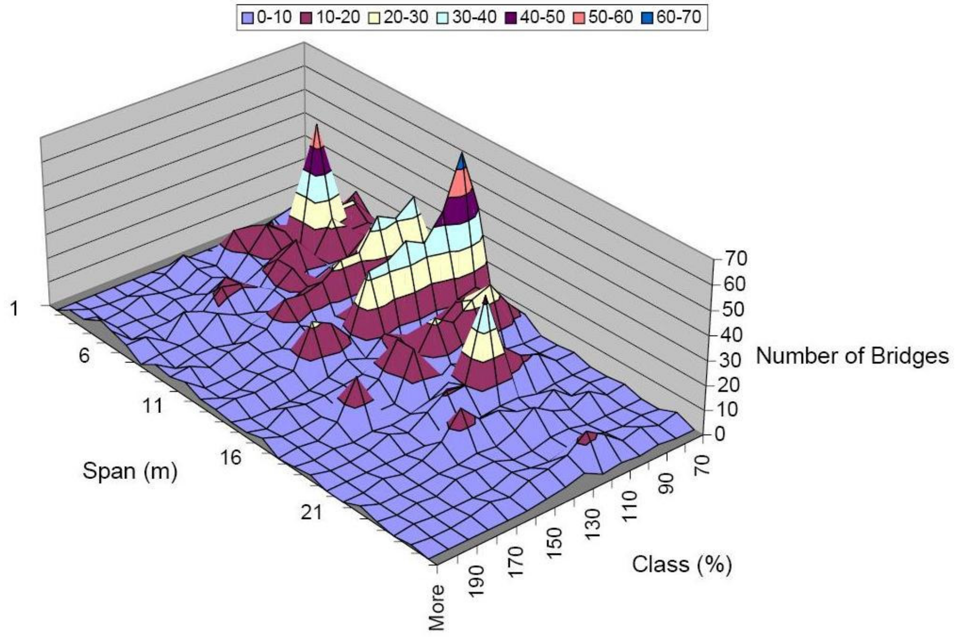
[4] The American Association of State Highway Officials road test conducted back in the 1950s and 1960s studied the performance of highway pavement structures under moving loads of known magnitude (American Association of State Highway Officials 1962). The study found that pavement wear was largely related to axle load rather than gross vehicle mass. The study also found that the relationship of pavement wear to axle load was highly non-linear and the so-called fourth power rule for flexible asphaltic concrete pavements emerged (Johnsson 2004).

infrastructure. Figure 2.4 presents an inventory of 2358 state highway bridges in New Zealand by span and class[5] (Roberts and Heywood 2001). These bridges are characterised as follows:

- half are constructed from steel reinforced concrete
- a large number were built in the 1940s and the 1960s
- a signification number were designed to carry loads lower than the current design standard
- there are a significant number in the 12-13m span range, and a number of these bridges have a low class or strength value.

Figure 2.4 Distribution of state highway bridges by span and class (Roberts and Heywood 2001).



Given that there are a significant number of bridges in the 12-13m span range, and because a number of these bridges have a low class or strength value, a span of 12.5m is used as the reference bridge span, although other bridge spans were also considered. The bridges are assumed to be simply-supported beams[6], and the axle loads applied to these bridges are assumed to be point loads.

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[5] The class or strength value of a bridge is defined as the percentage of the rated load that a bridge can withstand under the overload criteria as defined by the Transit New Zealand *Bridge manual* (Transit NZ 2003).

[6] A simply supported beam is free to rotate at both attachment points, and is free to expand longitudinally. These attachment points do not transmit bending moments or longitudinal forces into the beam.

2.4.2 Road space

2.4.2.1 Low-speed offtracking

Low-speed offtracking (LSO) is the maximum distance between the path of the steer axle centre and the path of the most inboard trailing axle centre when negotiating the prescribed low-speed turn. Lower values of LSO indicate better performance in terms of the occupied road width on low-speed turns.

The LSO manoeuvre defined in Schedule 8 of New Zealand's Vehicle Dimensions and Mass Rule 41001 is used in this report. It is based on that used in the weights and dimensions study on heavy trucks in Canada (LTSA 2002, Roads and Transportation Association of Canada 1986). The Canadian study used a LSO target of no greater than 6m. Although Schedule 8 specifies how LSO is to be calculated, it does not specify how much LSO is acceptable for negotiating the road network. A LSO target in New Zealand of no greater than 4.2m is used in the absence of an official value for acceptable performance. This value is typical of the LSO of the worst-case vehicles that are currently permitted on New Zealand's roads.

2.4.2.2 High-speed offtracking

High-speed offtracking (HSO) is the maximum distance between the path of the steer axle centre and the path of the most outboard trailing axle centre when negotiating the prescribed high-speed turn. Lower values of HSO indicate better performance in terms of the occupied road width on high-speed turns.

The Roads and Transportation Association of Canada (1986) vehicle weights and dimensions study of heavy trucks used a HSO target of no greater than 0.46m. Transit NZ's heavy vehicle limits study used a HSO target of no greater than 0.5m (Milliken et al 2001). This report will use the same HSO target as that used in the Transit NZ's heavy vehicle limits study of no greater than 0.5m for acceptable performance.

2.4.3 Safety

2.4.3.1 Static roll threshold

The performance measure used to determine a vehicle's roll over stability is called the static rollover threshold (SRT). The SRT is the maximum level of lateral acceleration that a vehicle can sustain when cornering before all wheels on one side lift off the ground. The SRT is given in units of g, where 1g is the acceleration due to gravity or 9.807m/s^2. Higher values of SRT indicate better performance in terms of rollover stability. For combination vehicles, the worst performing vehicle unit with the lowest value of SRT determines the SRT of the combination. Roll-coupled vehicles such as tractor semi-trailers and B-trains are considered to be one vehicle unit because the vehicle does not roll until the whole combination rolls.

All heavy vehicles in New Zealand are required to have an SRT of at least 0.35g (LTSA 2002). For general goods transport, SMART heavy vehicles in Australia must also have an SRT of at least 0.35g (National Transport Commission 2007). The certificate of initial fitness, equipment and use regulations for passenger service vehicles in the United Kingdom stipulates that single deckers are required to meet a static tilt test of at least 35 degrees (0.70g SRT), and double deckers of at least 28 degrees (0.53g SRT) (Department for Transport 2003). Passenger coaches in NZ with floor heights of 2m or more must have an SRT of no less than 0.53g, but if they have floor heights of less than 2m they must have an SRT of no less than 0.7g (LTSA 1999). Buses, coaches and SMART tankers transporting hazardous substances in Australia are required to have an SRT of at least 0.40g (National Transport Commission 2007). Tankers transporting hazardous substances that conform to ECE 111 regulations must have an SRT of at least 0.42g (United Nations Economic Commission for Europe 2005), while tankers transporting hazardous substances in

New Zealand are required to have an SRT of at least 0.45g (Ministry for the Environment 2007). For acceptable performance, passenger coaches have an SRT target of at least 0.7g, and all other vehicles have a target of at least 0.35g.

2.4.3.2 Load transfer ratio

The load transfer ratio (LTR) is the proportion of the axle load that is transferred from one side of the vehicle to the other when negotiating the prescribed high-speed path-change or evasive manoeuvre. Lower values of LTR indicate better performance in terms of rollover stability on high-speed path changes. For combination vehicles, the worst performing vehicle unit with the highest LTR determines the LTR of the combination. Roll-coupled vehicles such as tractor semi-trailers and B-trains are considered to be one vehicle unit.

The Roads and Transportation Association of Canada (1986) vehicle weights and dimensions study of heavy trucks used a LTR target no greater than 0.6. Transit NZ's heavy vehicle limits study used a LTR target of no greater than 0.6 (Milliken et al 2001). Tankers transporting hazardous substances in New Zealand are required to have a LTR of no greater than 0.6 (Ministry for the Environment 2007). For acceptable performance, a target LTR of no greater than 0.6 is used.

2.4.3.3 High-speed transient offtracking

High-speed transient offtracking (HSTO) is the maximum lateral excursion of the path of the most outboard trailing axle centre relative to the path of the steer axle centre when negotiating the high-speed path-change or evasive manoeuvre. Lower values of HSTO indicate better performance in terms of lane keeping with less intrusion into an adjacent lane or shoulder.

In Australia, SMART heavy vehicles that have an HSTO of no greater than 0.6m are permitted on general access (Level 1)[7] routes (National Transport Commission 2007). The Roads and Transportation Association of Canada (1986) vehicle weights and dimensions study of heavy trucks used an HSTO target of no greater than 0.8m. Transit NZ's heavy vehicle limits study used an HSTO target of no greater than 0.8m (Milliken et al 2001), while tankers transporting hazardous substances in New Zealand are required to have an HSTO of no greater than 0.8m (Ministry for the Environment 2007). This report will use the same HSTO target as that used in the Transit NZ's heavy vehicle limits study of no greater than 0.8m for acceptable performance.

2.4.3.4 Rearward amplification

Rearward amplification (RA) is the ratio of the peak lateral acceleration of the rearmost vehicle unit's sprung mass to that of the peak lateral acceleration of the steer axle's unsprung mass when negotiating the prescribed high-speed path-change or evasive manoeuvre. Lower values of RA indicate better performance in terms of a vehicle's reduced tendency of whipping.

The National Transport Commission (2007) of Australia requires SMART heavy vehicles in Australia to have a RA of no greater than 5.7 times the SRT of the rearmost roll-coupled vehicle unit. Transit NZ's heavy

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[7] As part of the PBS scheme, parts of the road network in Australia are categorised into four levels of accessibility. The performance of a SMART vehicle determines its level of accessibility to those designated parts of the road network. In general, a longer and heavier SMART vehicle is restricted to fewer parts of the road network. The operator of an approved and certified SMART vehicle must formally apply for road network access with the relevant state road authorities. For access to a non-designated route, a route assessment must be undertaken to obtain its level of accessibility (National Transport Commission, Fact sheet A).

vehicle limits study used a RA target of no greater than two (Milliken et al 2001). This report will use the same RA target as in Transit NZ's heavy vehicle limits study of no greater than two for acceptable performance.

2.4.3.5 Yaw damping ratio

Yaw damping ratio (YDR) is the rate at which yawing oscillations of the rearmost vehicle unit decay following the prescribed high-speed steering pulse input. Higher values of YDR indicate better performance in terms of how quickly a vehicle's yawing oscillations are brought under control. Low values of YDR can contribute to increased driver fatigue and in extreme cases can cause loss of control. Drivers often refer to this vehicle characteristic as snaking.

SMART heavy vehicles in Australia must have a YDR of no less than 0.15 (National Transport Commission 2007), and Transit NZ's heavy vehicle limits study in New Zealand also used a YDR limit of no less than 0.15 (Milliken et al 2001). Thus for acceptable performance, a target YDR of no less than 0.15 is used. Vehicles with a YDR value greater than 0.3 are quoted at this value because it is impossible to calculate YDR accurately when it is higher than 0.3.

3 Vehicle models

3.1 Emissions

Heavy vehicle fuel consumption and emissions are an important consideration with many countries adopting a phased introduction of increasingly stringent emissions standards. In New Zealand, the Land Transport Rule: Vehicle Exhaust Emissions 2007 – Rule 33001/2 (Land Transport NZ 2007) requires compliance with ADR 80/02 and ADR 30/01, Euro 4, Japan 05 or US 2004 emissions standards. The intention of the rule is that new standards, such as the proposed Euro 5 and Japan 09 standards, be progressively introduced in the coming years following their adoption in their relevant jurisdictions (Land Transport NZ 2007). The vehicles in this study are assumed to comply with the minimum standards set by the rule. This study does not explicitly undertake any quantitative emissions analysis.

3.2 Brake rule

New Zealand’s Brake Rule is based on the United Nation Economic Commission of Europe Regulation Number 13 (UN/ECE 13) although vehicles complying with other international brake codes such as those from the Australia, Japan and the United States of America are acceptable. Any vehicle first registered after 1 July 1994 with a gross mass exceeding 3.5 tonnes must comply with UN/ECE 13 plus special annexes; or an approved vehicle standard for brakes plus special requirements. The selected vehicles are assumed to comply with minimum standards set by Land Transport Rule: Heavy-vehicle Brakes – Rule 32015 (Land Transport NZ 2006). This study does not include any quantitative brake performance analysis.

3.3 Coupling types

The three main coupling types used to connect individual vehicle units in combination vehicles are fifth wheel, turntable and tow-eye couplings. The fundamental difference between these coupling types is the number of rotational degrees of freedom they permit, although in practice there is typically a difference in the amount of coupling offset.

3.3.1 Fifth wheel

A fifth wheel coupling is used for semi-trailer connections and is often referred to as a B-coupling. It consists of a kingpin that interlocks with a U-shaped skid plate. The coupling allows a semi-trailer to yaw with respect to the towing vehicle. A conventional single oscillating fifth wheel coupling allows some moments about the roll and pitch axis to be transmitted between these two vehicles. The magnitude of these components depends on the articulation between the vehicles, with the roll and pitch components being proportional to the cosine and sine of the articulation angle, respectively. Thus at zero articulation angle, only the roll moment is transmitted.

3.3.1.1 Turntable

A turntable coupling consists of a ball race system that connects a semi-trailer to a dolly to form a full trailer. A turntable allows only yaw motion between these vehicles. Both roll and pitch moments are transmitted between these units. A hinge connects the dolly’s bogey to the dolly’s drawbar. This prevents pitch moments generated at the dolly from applying vertical loads at the tow-eye coupling. The dolly's turntable, bogey and drawbar assembly is often referred to as an A-coupling.

3.3.1.2 Tow-eye coupling

A tow-eye coupling consists of a towing eye that interconnects with a pin or a hook. It is functionally equivalent to the ball and cup arrangement used on light trailers. The coupling provides no restraint on rotational motion. The two vehicle units connected by a tow-eye coupling are free to yaw, roll and pitch with respect to one another.

3.4 Self-steering axles

The purpose of self-steering or castoring axles is to reduce the transverse pavement scuffing and tyre scrubbing forces generated by the tyres of multi-axle groups on low-speed turns (Latto and Baas 2002). Self-steering axles are steered passively about the kingpin by the cornering force applied at the pavement–tyre interface at a trailing distance behind the kingpin. The Land Transport Rule: Vehicle Dimensions and Mass 2002 – Rule 41001 (LTSA 2002) requires that quad-axle groups in New Zealand have two self-steering axles.

Well designed self-steering axles have mechanisms that provide a steering stabilisation or centring force. In some cases, undulating pressure bearings are used to provide a weight dependent centring force. In other cases, steel and air springs are used to provide a centring force (Latto and Baas 2002). Air springs have the potential to provide a variable centring force by altering the airbag pressure. Locking mechanisms are used to provide very large centring forces and are often used when the vehicle is reversing, but can also be used at higher speeds. Having a weight and speed dependent centring force can provide a mechanism for improved low-speed and high-speed performance. The foremost of the two self-steering axles on quad-axle groups in New Zealand may be locked in the straight-ahead position at a speed of 30km/h or more (Land Transport NZ 2007) which improves high-speed dynamic performance.

The self-steering axles modelled in this report are based on Ceschi axles. These axles were given a maximum steer angle of 15 degrees which is the minimum requirement set by the Land Transport Rule: Vehicle Dimensions and Mass 2002 – Rule 41001 (Land Transport NZ 2007).

3.5 Weights and dimensions

Care was taken to ensure that the vehicle models in this study complied with the current weights and dimensions rules of their country of operation (see table 3.1), including their weight limit schedule or bridge formula requirements. Table 3.2 summarises the weight limits for different axle group and tyre configurations, and table 3.3 summarises the overall length (OAL) and gross combination weight (GCW) limits for the given vehicles.

Most developing countries in Southeast Asia have limited regulations for weights and dimensions and there is a high level of non-compliance with these rules (World Bank 2005; Marketing and Development Research Associates 2006). As many of the trucks in Southeast Asia are sourced from Europe, it will be assumed that countries in Southeast Asia abide by the weights and dimensions rules of the European Community. At least one Malaysian heavy vehicle manufacturer designs their vehicles to rated loads equivalent to that of the European Community.

In Australia (Au) and in the European Community, additional weight allowances[8] are permitted on vehicles fitted with road-friendly suspension[9] (National Transport Commission 2007, European Community 1996). It was assumed that all United Kingdom (UK) vehicles modelled in this research complied with the council directives of the European Community. No weight benefits are granted to vehicles fitted with road-friendly suspension in New Zealand (NZ), Canada (Ca) or in Southeast Asia (SEA). Furthermore, all axle groups on heavy vehicles in New Zealand must be fitted with load-sharing[10] suspensions except for twin-steer axle groups on powered units (LTSA 2002). In Australia, additional weight allowances are permitted on vehicles fitted with load-sharing suspension on twin-steer axle groups on powered units. Tables 3.2 and 3.3 reflect these constraints. Limits on vehicle width and height are different between the countries studied (see table 3.4).

Table 3.1 Weights and dimensions rules

Country	Weighs and dimensions rules
Au	Road Transport Reform (Mass and Loading) Regulations 1995 (Australian Government Attorney-General's Department 1999)
Ca	Heavy Truck Weight and Dimension Limits for Interprovincial Operations in Canada, Summary Information August 2005 (Council of Ministers 2005)
NZ	Land Transport Rule: Vehicle Dimensions and Mass 2002 – Rule 41001 (LTSA 2002)
UK	Council Directive 96/53/EC of 25 July 1996 (European Communities 1996), Council Directive 2002/53/EC of 18 February 2002 (European Communities 2002)

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[8] Under the implementation of the Australian PBS Scheme, axle group mass limits are determined by general mass limits (GML), concessional mass limits (CML) and higher mass limits (HML) schemes. Only operators accredited under the National Heavy Vehicle Accreditation Scheme (NHVAS) Mass Management Module may operate their vehicles at CML and HML. Truck and simple-trailer configurations are excluded from both CML and HML. Vehicles operating at CML have access to GML routes. Vehicles operating at HML must be fitted with road-friendly suspensions, and can only operate on HML routes. Operating conditions for these schemes also apply to SMART heavy vehicles (National Transport Commission, Fact Sheet B). The European Community permit increased mass limits on heavy vehicles fitted with road-friendly suspensions (European Community 1996).

[9] A road-friendly suspension system means an air suspension system or an equivalent thereof as defined in Annex II of the Council of the European Union Directive 96/53/EC of 25 July 1996. In Australia, the road-friendly suspension requirements are based on those of the Council Directive 96/53/EC (Department of Transport and Regional Services 2004) but they specify a 5% static load share requirement; and the use of dual tyres an all axles within an axle group that does not belong to a six-tyred tandem axle group.

[10] In New Zealand, a load-sharing axle group is one that has effective damping characteristics on all axles and proportions its load to within 10% of that specified (LTSA 2002). In Australia, static load share between axles in an axle group must be within 5% (Department of Transport and Regional Services 2004).

Table 3.2 Weight limits for the given axle group and tyre configurations

Country	Tyre	Gross axle group weight (t)					
		Steer		Single	Tandem	Tridem	Quadem
		Single	Twin				
Au	Singles	6(a)	10(c)	6.7(d)	13.3(d)	20(j)	NA
	Duals	NA	NA	9(e)	16.5(g)	20(k)	27
Ca	Singles	5.5(b)	NA	NA	NA	NA	NA
	Duals	NA	NA	9.1	17	24	NA
NZ	Singles	6	10.8	7.2	13	18	20
	Duals	NA	NA	8.2	15(h)	18	20
UK	Singles	6.5	13	NA	NA	24	NA
	Duals	NA	NA	10(f)	18(i)	24	NA

Notes:

(a) tyre width < 375mm

(b) 7.25t for a straight truck

(c) 11t with load-sharing suspension

(d) 375mm ≤ tyre width < 450mm

(e) 8.5t for pig trailer, 10t for HML buses or coaches

(f) 11.5t drive axle only

(g) 15t for a pig trailer, 17t for CML and HML vehicles

(h) 15.5t if axle group spread is at least 1.8m

(i) 19t if drive axle group is spread at least 1.3m and are air suspended or has eight tyres, and 20t if trailer axle group spread is at least 1.8m.

(j) tyre width ≥ 375mm.

(k) 18t for a pig trailer, 21t for CML vehicles, 22.5t for HML vehicles.

Table3.3 Overall vehicle length and gross combination weigh limits for the given vehicles

Country	Parameter	Vehicle					
		Tractor semi-trailer	B-train	Truck	Truck and simple-trailer	Truckand full-trailer	Coach
Au	OAL (m)	19	26	12.5	19	19	12.5
	GCW (t)	42.5(a)	62.5(c)	26.5(d)	42.5	42.5(f)	19(g)
Ca	OAL (m)	23	25	12.5	23	23	14
	GCW (t)	46.5	62.5	24.25	45.25	53.5	20.9
NZ	OAL (m)	18	20	11.5(e)	20	20	12.6(h)
	GCW (t)	44	44	26	32	44	21
UK	OAL (m)	16.5	NA	12	18.75	18.75	13.5(i)
	GCW (t)	40(b)	NA	32	40	40	28

Notes:

(a) 43.5t for CML vehicles, 45.5t for HML vehicles

(b) 44t permitted for 40ft ISO intermodal container transport

(c) 64.5t for CML vehicles, 68t for HML vehicles

(d) 27.5t with load sharing twin-steer suspension, 28t for CML vehicles

(e) 12.6m not towing

(f) 43.5t for CML vehicles; 50t for HML vehicles in some states

[g] 20t for an HML bus or coach

[h] The NZTA has introduced provisions for coaches to be permitted to operate at 13.5m or 14.5m of OAL with approval from the road controlling authorities subject to a number of conditions

[i] 15m with more than two axles.

Table3.4 Vehicle width and height by country

Country	Vehicle	
	Width (m)	Height (m)
Au	2.5	4.3[a]
Ca	2.6	4.15
NZ	2.5	4.25
UK	2.55	4

Notes:

[a] Provided they meet certain specifications, some 4.6m high vehicles in Australia including car-carriers, livestock trucks, and special purpose vehicles are permitted to operate on approved 4.6m high vehicle routes.

Vehicles over 26m in length, such as road-trains in Australia and Rocky Mountain and Turnpike Doubles in Canada, were not considered because their use is restricted to a small proportion of the network and it is unlikely that such vehicles would be permitted full access to New Zealand's public road network. Special purpose vehicles in New Zealand such as those issued with overweight or over dimension permits were also not considered in this study.

3.6 TAC sequence

To represent the vehicles in a descriptive and compact form, a shorthand code called the tyre axle coupling (TAC) sequence was developed. The TAC sequence is a string of case-sensitive context-dependent characters used to encode a vehicle's couplings, axles and tyre configurations. Table 3.5 describes the different types of axles and tyre configurations with their designated TAC characters, and table 3.6 describes the different types of couplings with their designated TAC characters.

Table 3.5 Description of the different types of axles and tyre configurations with their designated TAC characters.

Axle type	Tyre configuration	
	Single	Dual
Actively steered axle (eg steer axle)	a	A
Passively steered axle (self-steering axle)	p	P
Non-steering drive axle	d	D
Non-steering fixed axle (eg pusher or tag axle)	f	F

For example, the TAC sequence **aa-DD^ffpp** denoted a twin-steer tandem-drive tractor in combination with a quad-axle semi-trailer with two rear-mounted self-steering axles. The tyres on the drive axles were in dual configuration, and the remaining axles were configured with single tyres. The TAC sequence **a-DD_F-FF** denoted a three-axle tandem-drive truck in combination with a three-axle full trailer with a single-axle dolly. All tyres on the truck and full trailer combination were in dual configuration except for the steer tyres which were configured as singles.

Table 3.6 Description of the different coupling types and the designated TAC character

Coupling type	Coupling
Chassis	-
Fifth wheel, kingpin and semi-trailer chassis	^
Pin, tow-eye, drawbar and turntable (fixed dolly assembly)	_

3.7 Selected vehicles

Table 3.7 describes the selected vehicles and their TAC sequences. The active steering axles of the powered vehicles were modelled with single 11R22.5 tyres, and the drive axles were modelled with the same tyres in dual configuration. The single-tyred pusher, tag and trailer axles were modelled with 385/65R22.5 wide-single tyres. The dual-tyred trailer axles were modelled with 11R22.5 tyres, with the exception of the New Zealand dual-tyred trucks and full trailers which were modelled with 245/70R19.5 tyres since this is the most common configuration for these vehicles.

Table 3.7 Description of the selected vehicles and their TAC sequences

Country	TAC sequence	Description
Au	a-DD^FFF	Six-axle tractor semi-trailer
	a-DD^FFF^FFF	Nine-axle B-train
	a-DD_F-FF	Six-axle truck and full trailer
Au50	a-Df	50-passenger three-axle coach with tag axle
Ca	a-DD^FF	Five-axle tractor semi-trailer
	a-DD^FFF	Six-axle tractor semi-trailer
Ca55	a-Df	55-passenger three-axle coach with tag axle
NZ	a-DD^FFF	Six-axle tractor semi-trailer
	aa-DD^ffpp	Eight-axle tractor semi-trailer with twin rear-mounted self-steering axles
	a-DD^FFF^FF	Eight-axle B-train*
	aa-DD_FF-FF	Eight-axle truck and full trailer
NZ50	a-Df	50-passenger three-axle coach with tag axle
SEA	a-DD^FF	Five-axle tractor semi-trailer
	a-DD	Three-axle rigid truck
SEA44	a-D	44-passenger two-axle coach
UK	a-D^fff	Five-axle tractor semi-trailer
	a-fD^fff	Six-axle tractor semi-trailer with pusher axle and wide-single trailer tyres
	a-DD_F-FF	Six-axle truck and full trailer
UK52	a-Df	52-passenger three-axle coach with tag axle

Note:
* New Zealand's B-train is not the most popular choice of vehicle used in the any of the selected transport tasks so its performance was not thoroughly analysed in this study. For comparative purposes, however, the impact of this vehicle

on bridges for different span lengths was analysed alongside New Zealand's more popular vehicles. The transport task allocated to this B-train was refrigerated goods.

The Southeast Asian vehicles were modelled with steel-leaf DAF 85CF OEM springs on the steer and drive axles, and steel-leaf Hutch 9600 354 springs on their trailer axles. The remaining vehicles were modelled with steel-leaf DAF 85CF OEM springs on the steer axle, Freightliner air springs on the drive axles, and BPW ALO/D30K air springs on the trailer axles. Canadian vehicles were modelled with 2.59m (102 inch) wide trailer axles. All other vehicles were modelled with 2.44m (96 inch) wide axles. The axle group weights on Australia's bulk liquids, livestock and refrigerated goods B-doubles were configured to higher mass limits (HML) since they often operate on HML routes. The axle group weights on Australia's remaining vehicles were configured at general mass limits (GML).

Table 3.8 Description of the selected vehicles by country and transport task

Task description	Task ID	Country				
		Au	Ca	NZ	SEA	UK
Passenger coach	PC	a-Df	a-Df	a-Df	a-D	a-Df
Bulk liquids	BL	a-DD^FFF^FFF	a-DD^FF	aa-DD_FF-FF#	a-DD	a-D^fff
Bulk materials	BM	a-DD_F-FF	a-DD^FFF	a-DD_FF-FF	a-DD	a-D^fff
Intermodal containers	IC	a-DD^FFF	a-DD^FFF	a-DD^FFF	a-D^FF	a-fD^fff
Livestock	LS	a-DD^FFF^FFF	a-DD^FF	aa-DD_FF-FF	a-DD	a-D^fff
Refrigerated goods	RG	a-DD^FFF^FFF	a-DD^FF	aa-DD^ffpp	a-DD	a-D^fff

Note:
Two other variants on New Zealand's truck and full trailer bulk liquids tanker were also modelled and their performances compared with other tankers. These variants demonstrate how heavy vehicle optimisation can be achieved.

The same floor height and seat height was modelled on every passenger coach. For the remaining transport tasks and for each of the remaining vehicles, the allocated payload height could be different depending on the transport task, the vehicle performing the transport task and in which country the transport task was undertaken. Payload height was calculated from the mass and density of the product being transported and from the shape of the payload space. The products for each of the transport tasks were modelled uniformly within the confines of their payload spaces. Table C2 in appendix C gives the product densities for each transport task, while table C3 in appendix C lists the weights and dimensions of the vehicle models used in this study.

The bulk liquid tankers were modelled as petroleum tankers. The transverse cross-sectional area of each tank was modelled as an ellipse that was constant along the length of the tank. The internal width of the tank modelled on the Canadian tanker was 2.5m, and the internal widths of the tanks modelled on the remaining tankers were 2.4m. The nominal internal length of a particular tank depended on the dimensions and configuration of that vehicle. From this information, the payload height for each tanker was determined.

The bulk material vehicles were modelled with dry earth material contained inside rectangular bins. The internal width of the bins modelled on the Canadian vehicle was 2.5m, and the internal widths of the bins modelled on the remaining vehicles were 2.4m. The nominal internal length of a particular bin depended on the dimensions and configuration of that vehicle. From this information, the payload height for each bulk materials vehicle was determined.

The intermodal container vehicles were modelled with a generic uniform density product inside a 40 foot ISO container. The tare weight of the container was assumed to be 4.1 tonnes and the maximum gross weight of the container was 30.4 tonnes. Thus the density of the product modelled inside the containers was based on these weights and on the internal dimensions of the container. The internal dimensions of the container were 12.015m long, 2.33m wide and 2.365m high. Australian, Canadian and United Kingdom vehicles were modelled with containers at the maximum gross weight limit. Due to the lower weight limit, some of the product inside the container of the New Zealand six-axle vehicle was offloaded which resulted in a reduced payload weight and payload height. Some of the product inside the container of the Southeast Asian four-axle vehicle was also offloaded which resulted in reduced payload weight and payload height.

Livestock vehicles in New Zealand are used primarily to transport cattle or sheep. Typically, cattle have a higher density, and higher payload weights can be achieved. Thus, the livestock vehicles were modelled with cattle contained within their crates. The density of cattle contained within a crate was determined by the payload weight and crate dimensions of the United Kingdom livestock vehicle. This ensured that the maximum gross weight of the livestock vehicles, with the exception of the Southeast Asian rigid truck, was maintained while containing the cattle within the dimensions of their crates. The internal width of the crate modelled on the Canadian vehicle was 2.5m, and the internal widths of the crates modelled on the remaining vehicles were 2.4m. The nominal internal length of a particular crate depended on the dimensions and configuration of that vehicle. From this information, the payload height for each livestock vehicle was determined.

The refrigerated goods vehicles were modelled with a processed product contained within their refrigerated van bodies. The density of the product was determined by the payload weights and dimensions of the Australian B-double. This ensured that the maximum gross weight of the refrigerated goods vehicles, with the exception of the Southeast Asian rigid truck, was maintained while containing the product within the dimensions of their van bodies. The internal width of the van body modelled on the Canadian vehicle was 2.5m, and the internal widths of the van bodies modelled on the remaining vehicles were 2.4m. The nominal internal length of a particular van body depended on the dimensions and configuration of that vehicle. From this information, the payload height for refrigerated goods vehicle was determined.

3.8 Software

The software used to calculate the swept-path and safety performance of the vehicles was the Constant Velocity Yaw-Roll Multi-Body simulation package from the University of Michigan Transportation Institute. The software has been used extensively in New Zealand and internationally to undertake performance assessments of heavy vehicles. It has been experimentally validated both internationally and in New Zealand. In this report, this software is referred to as Yaw-Roll. Some simplifying mathematical assumptions were employed by this software (Gillespie and MacAdam 1982):

- Constant velocity meant that no tractive or braking forces were incorporated in the model.
- The vehicle models traversed a horizontal pavement with uniform friction characteristics.
- A single peak friction coefficient defined the friction model. This implied that the static friction coefficient was equal to the kinetic friction coefficient.
- Camber thrust was not incorporated in the model.

- The small angle approximation held for the pitch motion of the sprung mass and for the relative roll angle between the sprung mass and unsprung mass.
- The relative roll motion between the sprung mass and unsprung mass took place about the roll centre, which was at a fixed distance beneath the sprung mass.
- Forces acting on each axle were treated independently. Therefore, no inter-axle load transfer effects were incorporated in the model. The axles were modelled as solid axles.

4 Simulation methodology

A vehicle's performance was evaluated in terms of the nine fundamental performance measures. For a given transport task, a vehicle's performance was compared with the New Zealand baseline vehicle. When compared with the baseline, the vehicle with a higher level of:

- SAR caused more pavement wear and was thus more damaging to the pavement infrastructure
- PBM caused more bridge wear and was thus more damaging to the bridge infrastructure. A reference span of 12.5m was used
- LSO occupied more road width on the prescribed low-speed turn
- HSO occupied more road width on the prescribed high-speed turn
- HSTO occupied more road width during the prescribed high-speed path change
- SRT was more roll-stable or had better rollover stability
- LTR was less roll stable in the prescribed high-speed path change
- RA whipped out more during the prescribed high-speed path change
- YDR snaked less or attenuated high-speed snaking with fewer oscillations
- PLD was more productive.

A vehicle's performance was also evaluated in terms of four compound measures defined by equations 4.1 to 4.4. These compound measures quantified a vehicle's overall pavement wear, bridge wear, road space and safety performance in terms of one or more fundamental measures. Higher values of these measures indicated a better performing vehicle. These compound measures incorporated a vehicle's productivity in terms of the amount of payload (PLD) tonnes carried. Higher PLD vehicles were given more credit for the same amount of pavement wear, bridge wear and road space. The vehicle's PLD was also used as a surrogate measure for vehicle exposure and environmental impact. That is, the higher the vehicle's PLD, the fewer number of vehicle journeys it needed to move the same amount of product by tonne. This resulted in exposure related safety gains and in fuel and emissions savings. For a given transport task, these four compound performance measures would be normalised by the performance of the New Zealand baseline vehicle. The development of these compound measures is discussed in the following sections.

$$\text{Pavements} = \frac{1}{\text{SAR}} \times \text{PLD} \qquad \text{(Equation 4.1)}$$

$$\text{Bridges} = \frac{1}{\text{PBM}^3} \times \text{PLD} \qquad \text{(Equation 4.2)}$$

$$\text{Road space} = \frac{1}{\left((\text{LSO}_{2.9} + \text{VW}) \times (\text{HSO}_{0.345} + \text{VW})\right)^2} \times \text{PLD} \qquad \text{(Equation 4.3)}$$

$$\text{Safety} = \frac{\text{SRT}^{3/2}}{\left(\text{RA} \times \text{HSTO} \times \text{LTR}\right)^{1/3}} \times \text{PLD} \qquad \text{(Equation 4.4)}$$

For consistency, the productivity of the coaches was also reflected by the amount of PLD they carried although the number of passengers they carried can be inferred from their PLD. The weight of one passenger and their luggage was assumed to be 105kg.

4.1.1.1 Pavements

For the same amount of PLD, equation 4.1 determines a vehicle's pavement performance in relation to the amount of accumulated pavement wear, which is equivalent to the total amount of SAR. The overall pavement performance used in this study was based on that used in Sweatman et al (2004). The ratio of axle group load to the reference load for every axle group was raised to the fourth power to calculate the total SAR. The total amount of SAR was inverted so that a higher value for this measure indicated a better performing vehicle.

4.1.1.2 Bridges

For the same amount of PLD, equation 4.2 determines a vehicle's bridge performance in relation to the amount of accumulated bridge wear it caused when traversing a simply-supported bridge spanning the reference length of 12.5m. The amount of accumulated wear of steel bridge components, which was approximately equal to the PBM raised to the third power for girder bridges, was inverted so that a higher value for this measure indicated a better performing vehicle.

Figure D.1 through to figure D.7 in appendix D show the bending moment versus front axle location of the New Zealand vehicles as they traversed the reference bridge. These figures illustrate the effect that each axle load and the combined effect of these axles had on the reference bridge. To demonstrate the accuracy of using only the PBM to calculate the accumulated bridge wear as opposed to using stress cycles, figure D.7, which presents the greatest deviation from these, will be used as an example.

Figure D.7shows the bending moment versus front axle location of the New Zealand refrigerated goods eight-axle tractor semi-trailer as it traversed the reference bridge. The peak moment of 527kNm happened when the front steer axle advanced 10.25m onto the bridge. It reduced to 287kNm after the front axle cleared the far side of the bridge by about 2.5m, and then rose to 479kNm when the front axle cleared the bridge by about 7.5m. These two stress cycles correspond to an accumulated bridge wear proportional to 527kNm cubed plus 192kNm (479kNm minus 287kNm) cubed. Comparing this value with that calculated by using only the PBM cubed (527kNm cubed) gives only a 4.6% underestimation.

Note that the PBM values given in figure D.2 through to figure D.7 in appendix D are less accurate than those presented later in chapter 5 of this report. This is because relatively coarse spatial increments were needed to provide these figures with good graphical legibility. The PBM values presented in chapter 5 are not constrained in the same way so fine spatial increments were employed.

4.1.1.3 Road space

For the same amount of PLD, equation 4.3 determines a vehicle's road space performance in relation to the amount of road width it occupied on the prescribed low- and high-speed turns. The amount of road width that a vehicle occupied was defined in terms of the LSO and HSO measures and vehicle width. Vehicle width was added to each of the measures to estimate the total swept width occupied by the vehicle when undertaking the prescribed turns. The inclusion of vehicle width meant that wider vehicles would be penalised more than narrower vehicles for the same amount of offtracking. The product of these road width measures was situated in the denominator of the expression so that a higher value for this measure indicated a better performing vehicle in terms of its adequacy or ease with which it could negotiate the road network.

LSO and HSO are related since they both depend on wheelbase and, where applicable, on the number of couplings and their offsets. Of the vehicles studied in this report[11], 59% of total variance in HSO was accounted for by LSO (r-squared value of 0.59, see figure E.1 in appendix E). The product of LSO and HSO was raised to the fourth power. The justification for this power term was that any vehicle with excessive offtracking would encounter problems when negotiating the network and should be penalised to an extent that was more than linear but was also fair and reasonable. A second power relationship was deemed to provide a fair and reasonable penalty.

Note the subscripts of 2.9 and 0.345 associated with the LSO and HSO measures. These subscripts represented the penalty thresholds. These thresholds were the lower bounds of offtracking in metres where the offtracking of any vehicle that was below these limits was set to these limits. The justification for this was that any vehicles with offtracking at these limit values should not encounter any road space problems when negotiating the network. Vehicles with less offtracking would not have fewer problems and should not be excessively rewarded. The product of these subscripts was equal to one.

4.1.1.4 Safety

Equation 4.4 determines a vehicle's overall safety performance in relation to its rollover stability on the prescribed high-speed turns (SRT) and path changes (LTR), and in terms of its whipping behaviour (RA) and by the amount of road width it occupied (HSTO) on the prescribed high-speed path change.

This safety measure reflected the relative crash rate of heavy vehicles in New Zealand involved in stability-related crashes versus SRT as reported by de Pont et al (2000). Since a higher value for this measure indicated a better performing vehicle, the SRT measure was in the numerator of the equation thus increasing SRT improved safety performance. The product of the RA, HSTO and LTR measures was in the denominator of the equation thus reducing improved safety performance.

RA, HSTO and LTR are related since these measures characterise different aspects of a vehicle's dynamic stability as it undertakes the prescribed high-speed path change. Of the vehicles studied in this report[11], 74% of total variance in LTR and 71% of total variance in HSTO was accounted for by RA (see figure E.2 and figure E.3 in appendix E). To avoid the safety losses or gains from being overemphasised, their product was raised to the power of one third.

A relationship exists between SRT and the ratio of RA to LTR. By definition, RA is the ratio of the peak lateral acceleration of the rearmost vehicle unit's sprung mass to that experienced by the lead steer axle's unsprung mass as it negotiates the prescribed high-speed path change. Also by definition, LTR is the proportion of the axle load that is transferred from one side of the vehicle to the other as the vehicle undergoes the same manoeuvre. For combination vehicles, the worst performing vehicle unit with the highest LTR determines the LTR of the combination. Similarly, the worst performing vehicle unit with the lowest SRT determines the SRT of the combination. For combination vehicles that are not roll-coupled together such as truck and full trailers, it is the rearmost vehicle unit or trailer that often experiences the greatest amount of LTR and has the lowest SRT.

From the vehicles studied in this report[11], 96% of total variance in SRT was accounted for by the ratio of RA to LTR (see figure E.4 in appendix E). Other studies, including the study of the performance characteristics of the Australian heavy vehicle fleet by Prem et al (2002), have shown that these safety measures can be

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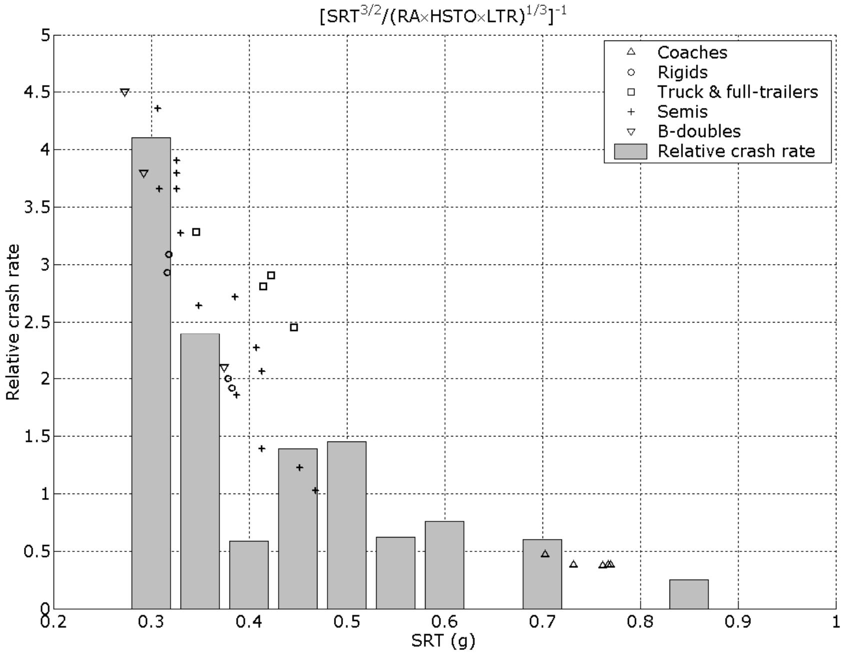
[11] With the exception of the two New Zealand truck and full trailer variants (NZ1 and NZ2) used to demonstrate how heavy vehicle optimisation can be achieved (see sections 5.8 and 6.1).

predicted from each other with varying levels of accuracy. Because these fundamental safety measures are related, the SRT in the numerator required a power term so that the compound measure could approximate the relative crash rate versus SRT as reported by de Pont et al (2000). Raising the SRT value to the power of three over two provided the best match. Figure 4.1 shows the relative crash rate versus SRT that is representative of New Zealand's heavy vehicle fleet. Overlaid on top of this are the results of the reciprocal of the compound safety measure applied to the performance results of the vehicles studied multiplied by PLD. This compound safety measure indicates how vehicles from other countries would perform if they were to operate on New Zealand's roads. It does not account for the safety impacts associated with the different road terrain profiles of other countries. Much of New Zealand's road terrain is mountainous and is demanding for its heavy vehicle fleet to operate safely. The terrain profile of New Zealand's roads is summarised in Baas (1999).

Of the combination vehicles, the truck and full trailers generally had the same relative crash rate as tractor semi-trailers and B-doubles for higher values of SRT. This result was consistent with the fact that truck and full trailers usually had higher levels of RA, HSTO and LTR than tractor semi-trailers and B-doubles implying that truck and full trailers were relatively less safe. Of the single-unit configurations, the rigid trucks had a much higher relative crash rate than the passenger coaches. The passenger coaches had the lowest relative crash rate of all the vehicles.

Figure 4.1 Relative crash rate versus SRT overplayed with the results of the reciprocal of the compound safety measure multiplied by PLD



All of the vehicles studied in this report had YDR values greater than the target value. The study by De Pont et al (2000) found that only a very small proportion of the vehicles they studied had YDR values below the target. Although their analysis indicated a high relative crash rate for these vehicles, the numbers in this category was too small to be confident of a relationship. They also reported that for higher values of YDR, there was no clear trend relating crash rate to YDR. For this reason, YDR was not included as part of the compound safety measure.

5 Results

The results section is structured as follows:

- Section 5.1 Bridge effects. This compares the amount of bridge wear caused by New Zealand vehicles on various bridge spans.

Section 5.2 through to section 5.7 give the performance results for the different countries by transport task:

- Section 5.2 Passenger coach
- Section 5.3 Bulk liquids
- Section 5.4 Bulk materials
- Section 5.5 Internodal containers
- Section 5.6 Livestock
- Section 5.7 Refrigerated goods.

Section 5.8 demonstrates how a more optimal New Zealand truck and full trailer can be achieved.

5.1 Bridge effects

Figure 5.1 shows the PBMs of New Zealand vehicles traversing a range of simply supported bridges spanning 1m through to 25m in length. Figure 5.2 shows these PBMs normalised by half the bridge span giving the shear forces that would result if point loads were placed mid-span on these bridges to produce the same PBM. This normalising contrasts the relative impacts of these vehicles for easier comparison. This section discusses bridge effects in terms of the PBM rather than the amount of accumulated wear (or the PBM raised to the third power for steel girder bridge components) since it provides a greater visual separation when plotted against bridge span. The relative order in terms of which vehicle configurations are the most damaging is also preserved. Based on figures 5.1 and 5.2, the following observations can be made:

- On short bridges with spans no greater than about twice the shortest spacing between axle groups:
    - single- and double-unit vehicles (eg passenger coaches and tractor semi-trailers) generally cause more bridge wear than the triple-unit vehicles (eg truck and full trailers and B-trains) because of their higher axle weights
    - the PBM increases with increasing axle weight. Note that the point-load approximation is less valid for very short bridges as the length of the tyre contact patch becomes more significant
- On medium bridges with spans ranging from about twice the shortest axle spacing between axle groups to about the overall length (OAL) limit:
    - for the same number of axles and GCW, vehicles with longer wheelbases can distribute their weight over a greater length thus they, in general, cause less bridge wear than vehicles with shorter wheelbases

  - for the same number of axles and GCW, vehicles that distribute their weight more uniformly over their lengths generally cause less bridge wear than vehicles that distribute their weight non-uniformly

- On bridges spanning the reference length of 12.5m:
  - the passenger coach caused the least amount of bridge wear followed by the refrigerated goods B-train, then truck and full trailers hauling bulk materials, livestock and bulk liquids; and finally by the tractor semi-trailers hauling intermodal containers and refrigerated goods

- On long bridges spanning more than the OAL limit:
  - triple-unit vehicles generally cause more bridge wear than the single- and double-unit vehicles because of their higher gross combination weights (GCWs)
  - the PBM increases with increasing GCW. Note that the point-load approximation is valid for short vehicles on long bridge spans.

Figure 5.1 Peak bending moments of New Zealand vehicles over a range of bridge spans

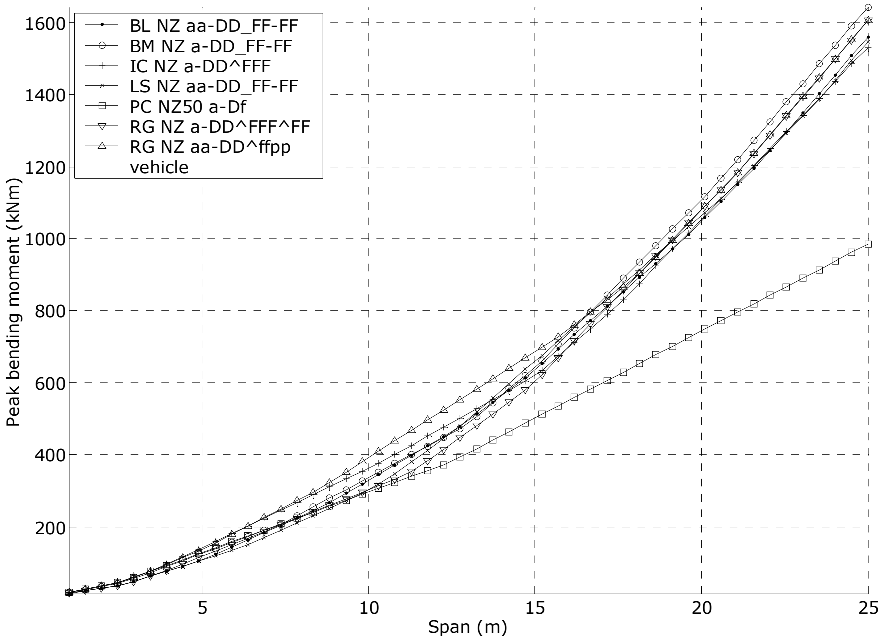
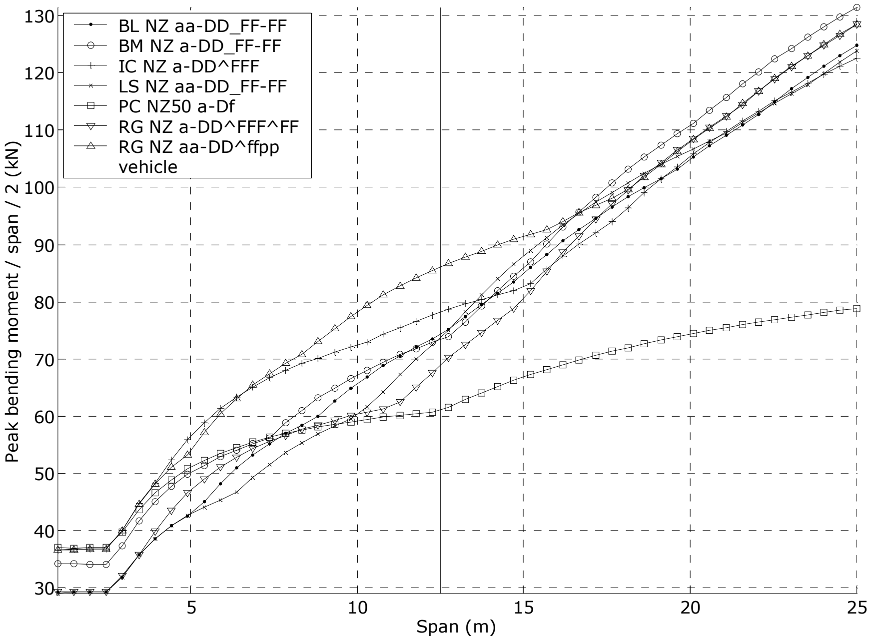


Figure 5.2 Peak bending moments/span/2 of New Zealand vehicles over a range of bridge spans



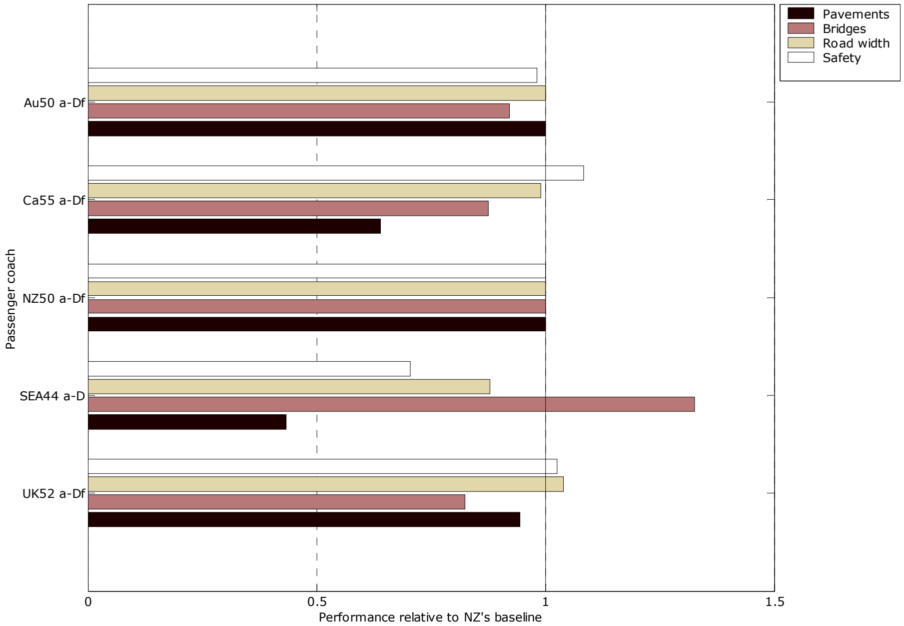
5.2 Passenger coach

Table 5.1 gives the performance results of the passenger coaches in terms of the fundamental measures, and figure 5.3 shows these results in terms of the compound measures relative to the New Zealand baseline vehicle.

Table 5.1 Performance of the passenger coaches

Vehicle	**LSO (m)**	**HSO (m)**	**HSTO (m)**	**YDR (-)**	**RA (-)**	**LTR (-)**	**SRT (g)**	**SAR (-)**	**PBM (kNm)**	**PLD (t)**
Target	**≤4.2**	**≤.5**	**≤.6**	**≥.15**	**≤2**	**≤.6**	**≥.7**	**-**	**-**	**-**
Au50 a-Df	2.03	0.14	0.09	0.30	1.04	0.19	0.77	2.78	391	5.25
Ca55 a-Df	2.64	0.15	0.08	0.30	0.97	0.18	0.73	4.77	410	5.77
NZ50 a-Df	2.11	0.13	0.08	0.30	1.03	0.19	0.76	2.78	380	5.25
SEA44 a-D	1.70	0.13	0.10	0.30	1.08	0.20	0.70	5.64	332	4.62
UK52 a-Df	2.24	0.15	0.09	0.30	1.02	0.19	0.77	3.05	411	5.46

Figure 5.3 Performance of the passenger coaches relative to the New Zealand baseline vehicle



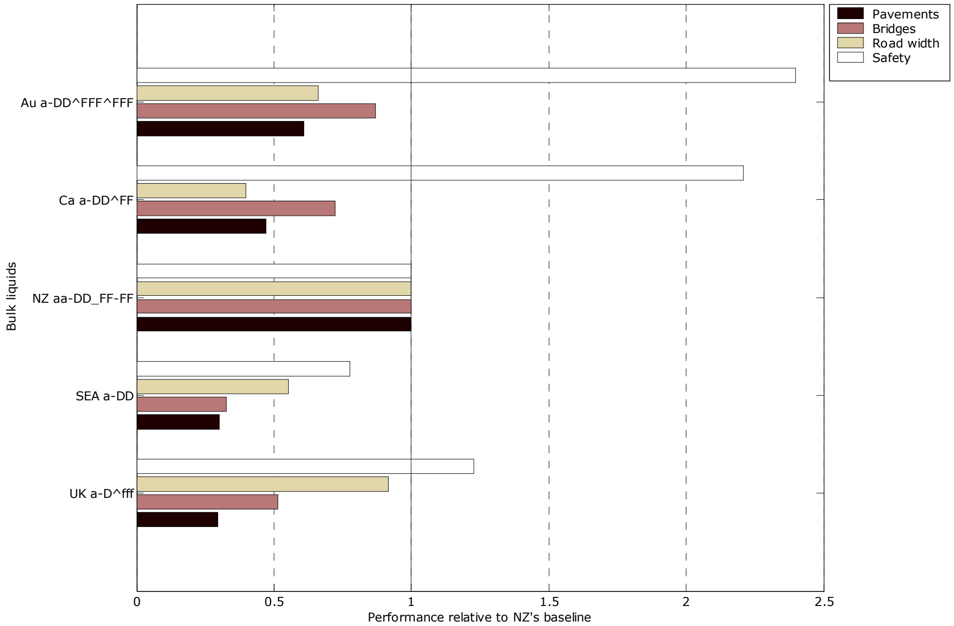
5.3 Bulk liquids

Table 5.2 gives the performance results of the bulk liquid tankers in terms of the fundamental measures, and figure 5.4 shows these results in terms of the compound measures relative to the New Zealand baseline vehicle. The Australian and Canadian vehicles failed the LSO criterion, and the New Zealand vehicle failed the LTR criterion (see the performance values in bold font).

Table 5.2 Performance of the bulk liquid tankers

Vehicle	**LSO (m)**	**HSO (m)**	**HSTO (m)**	**YDR (-)**	**RA (-)**	**LTR (-)**	**SRT (g)**	**SAR (-)**	**PBM (kNm)**	**PLD (t)**
Target	**≤4.2**	**≤.5**	**≤.6**	**≥.15**	**≤2**	**≤.6**	**≥.35**	-	-	-
Au a-DD^FFF^FFF	**6.31**	0.38	0.25	0.30	1.28	0.35	0.37	8.20	590	47.84
Ca a-DD^FF	**5.53**	0.26	0.14	0.30	1.10	0.33	0.45	5.68	510	25.62
NZ aa-DD_FF-FF	2.76	0.32	0.34	0.24	1.97	**0.64**	0.41	2.78	463	26.63
SEA a-DD	0.95	0.14	0.14	0.30	1.40	0.51	0.38	5.13	552	14.77
UK a-D^fff	3.12	0.26	0.29	0.30	1.50	0.47	0.41	9.37	577	26.45

Figure 5.4 **Performance of the bulk liquid tankers relative to the New Zealand baseline vehicle**



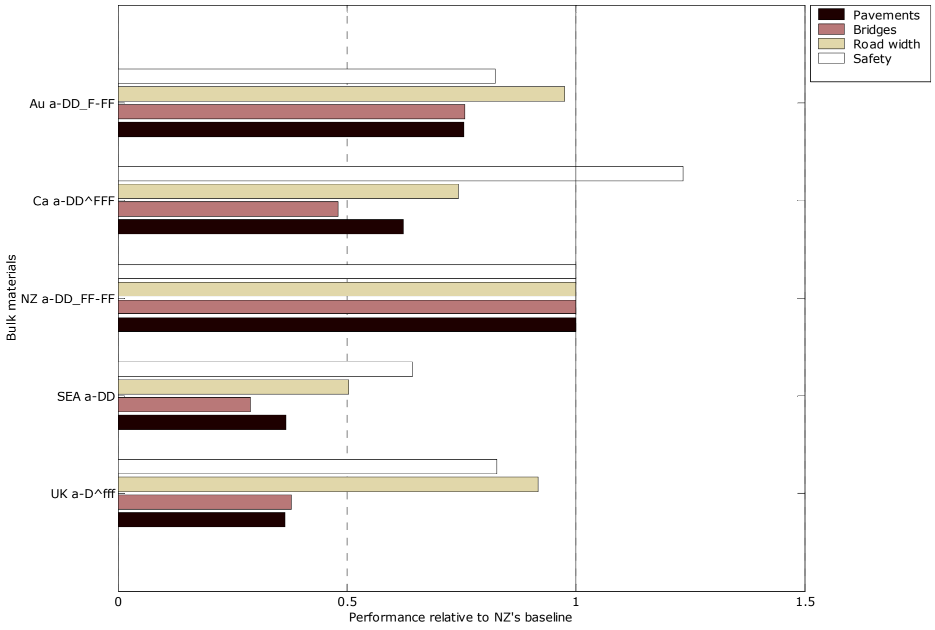
5.4 Bulk materials

Table 5.3 gives the performance results of the bulk material vehicles in terms of the fundamental measures, and figure 5.5 shows these results in terms of the compound measures relative to the New Zealand baseline vehicle. The Australian vehicle failed the RA and LTR criteria.

Table 5.3 Performance of the bulk material vehicles

Vehicle	**LSO (m)**	**HSO (m)**	**HSTO (m)**	**YDR (-)**	**RA (-)**	**LTR (-)**	**SRT (g)**	**SAR (-)**	**PBM (kNm)**	**PLD (t)**
Target	**≤4.2**	**≤.5**	**≤.6**	**≥.15**	**≤2**	**≤.6**	**≥.35**	-	-	-
Au a-DD_F-FF	2.76	0.32	0.39	0.20	**2.06**	**0.64**	0.42	4.81	499	28.58
Ca a-DD^FFF	3.57	0.29	0.27	0.30	1.38	0.44	0.41	6.21	594	30.47
NZ a-DD_FF-FF	2.75	0.32	0.34	0.21	1.93	0.60	0.45	3.73	459	29.28
SEA a-DD	0.95	0.13	0.14	0.30	1.39	0.49	0.38	5.13	552	14.77
UK a-D^fff	2.61	0.26	0.31	0.30	1.63	0.53	0.39	9.37	616	26.87

Figure 5.5 Performance of the bulk material vehicles relative to the New Zealand baseline vehicle



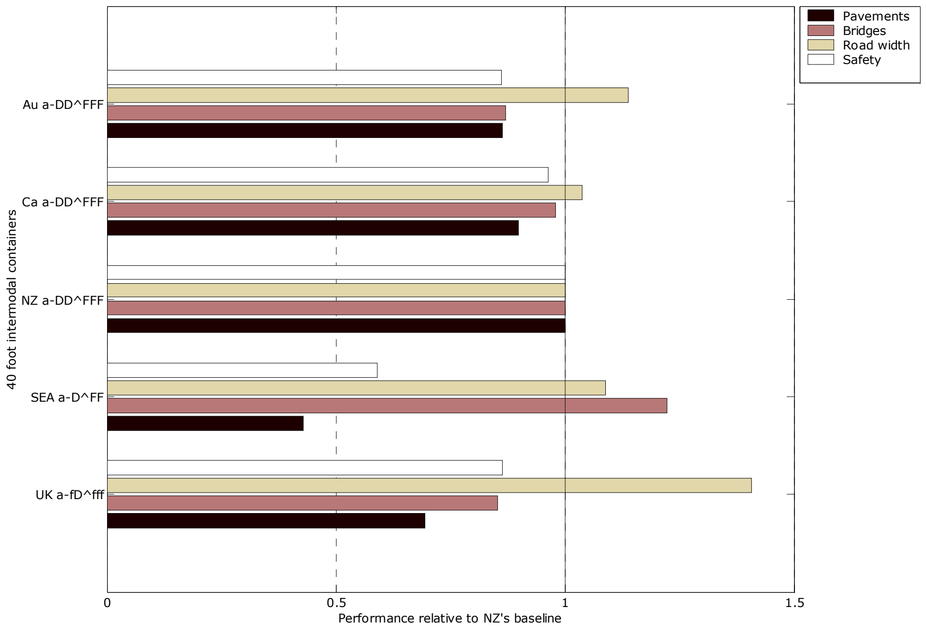
5.5 Intermodal containers

Table 5.4 gives the performance results of the 40 foot intermodal container vehicles in terms of the fundamental measures, and figure 5.4 shows these results in terms of the compound measures relative to the New Zealand baseline vehicle. The Australian vehicle failed the LTR and SRT criteria, the Canadian vehicle failed the SRT criterion, and the Southeast Asian and United Kingdom vehicles failed the LTR and SRT criteria.

Table 5.4 Performance of the 40 foot intermodal container vehicles

Vehicle	**LSO (m)**	**HSO (m)**	**HSTO (m)**	**YDR (-)**	**RA (-)**	**LTR (-)**	**SRT (g)**	**SAR (-)**	**PBM (kNm)**	**PLD (t)**
Target	**≤4.2**	**≤.5**	**≤.6**	**≥.15**	**≤2**	**≤.6**	**≥.35**	**-**	**-**	**-**
Au a-DD^FFF	3.83	0.27	0.27	0.30	1.47	**0.62**	**0.31**	5.28	543	26.38
Ca a-DD^FFF	3.80	0.30	0.30	0.30	1.44	0.57	**0.33**	5.07	522	26.38
NZ a-DD^FFF	3.68	0.24	0.22	0.30	1.42	0.52	0.35	3.82	489	22.08
SEA a-D^FF	3.04	0.28	0.36	0.30	1.61	**0.67**	**0.33**	7.77	437	19.32
UK a-fD^fff	3.19	0.26	0.31	0.30	1.60	**0.65**	**0.33**	6.57	547	26.38

Figure 5.6 Performance of the 40 foot intermodal container vehicles relative to the New Zealand baseline vehicle



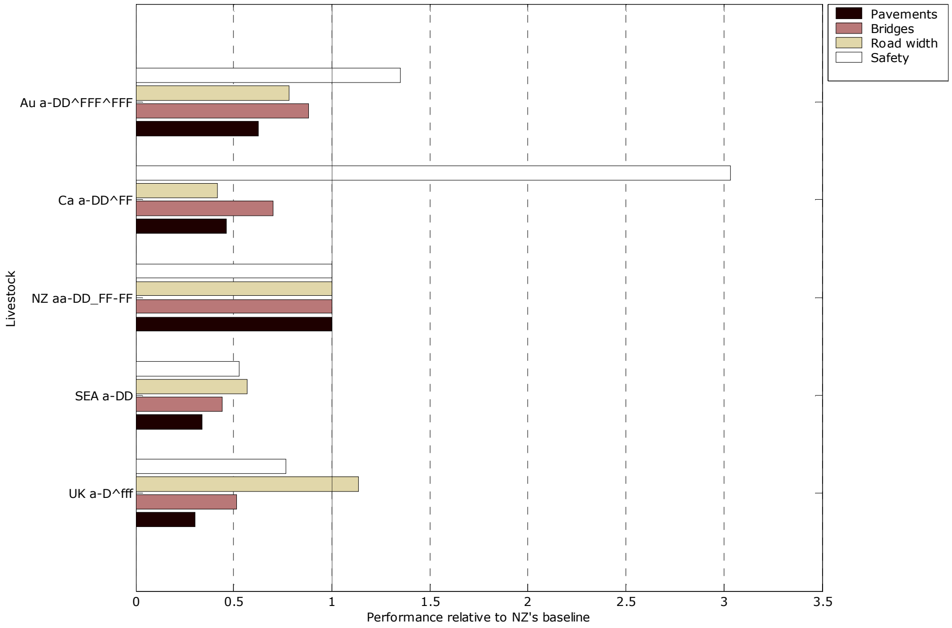
5.6 Livestock

Table 5.5 gives the performance results of the livestock vehicles in terms of the fundamental measures, and figure 5.7 shows these results in terms of the compound measures relative to the New Zealand baseline vehicle. The Australian vehicle failed the LSO and SRT criteria, the Canadian vehicle failed the LSO criterion, and the Southeast Asian and United Kingdom vehicles failed the LTR and SRT criteria.

Table 5.5 Performance of the livestock vehicles

Vehicle	**LSO (m)**	**HSO (m)**	**HSTO (m)**	**YDR (-)**	**RA (-)**	**LTR (-)**	**SRT (g)**	**SAR (-)**	**PBM (kNm)**	**PLD (t)**
Target	**≤4.2**	**≤.5**	**≤.6**	**≥.15**	**≤2**	**≤.6**	**≥.35**	**-**	**-**	**-**
Au a-DD^FFF^FFF	**6.30**	0.45	0.33	0.30	1.44	0.55	**0.27**	8.20	590	46.21
Ca a-DD^FF	**6.03**	0.26	0.11	0.30	1.05	0.30	0.47	5.68	509	23.67
NZ aa-DD_FF-FF	3.43	0.33	0.29	0.30	1.78	0.58	0.35	2.78	460	24.93
SEA a-DD	0.97	0.13	0.15	0.30	1.47	**0.64**	**0.32**	3.88	470	11.77
UK a-D^fff	3.12	0.29	0.36	0.30	1.65	**0.68**	**0.31**	9.37	577	25.37

Figure 5.7 Performance of the livestock vehicles relative to the New Zealand baseline vehicle



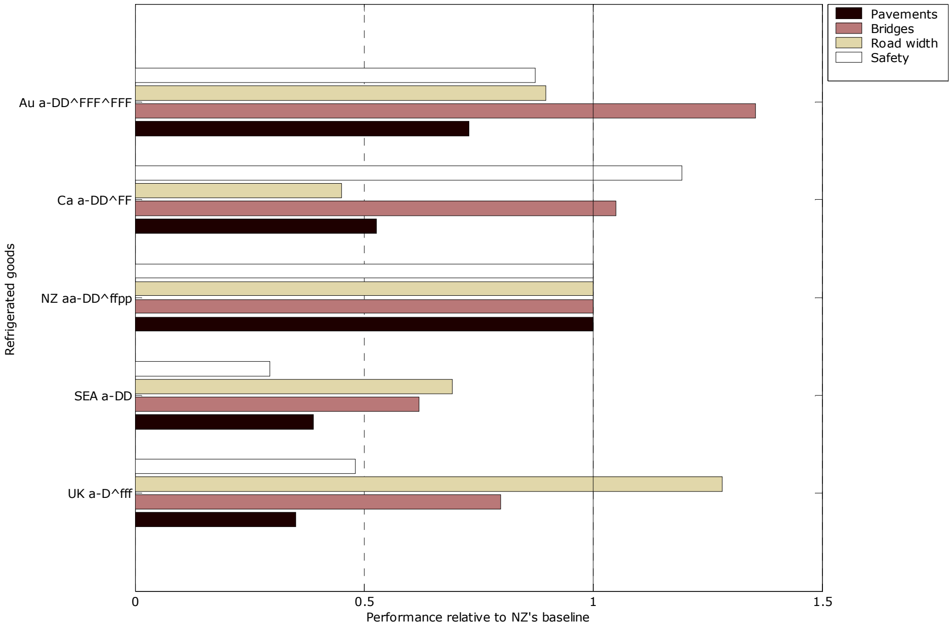
5.7 Refrigerated goods

Table 5.6 gives the performance results of the refrigerated goods vehicles in terms of the fundamental measures, and figure 5.8 shows these results in terms of the compound measures relative to the New Zealand baseline vehicle. The Australian vehicle failed the LSO and SRT criteria, the Canadian vehicle failed the LSO criterion, and the Southeast Asian and United Kingdom vehicles failed the LTR and SRT criteria.

Table 5.6 Performance of the refrigerated goods vehicles

Vehicle	**LSO (m)**	**HSO (m)**	**HSTO (m)**	**YDR (-)**	**RA (-)**	**LTR (-)**	**SRT (g)**	**SAR (-)**	**PBM (kNm)**	**PLD (t)**
Target	**≤4.2**	**≤.5**	**≤.6**	**≥.15**	**≤2**	**≤.6**	**≥.35**	-	-	-
Au a-DD^FFF^FFF	**6.30**	0.43	0.31	0.30	1.40	0.50	**0.29**	8.20	590	46.52
Ca a-DD^FF	**6.12**	0.27	0.13	0.30	1.09	0.35	0.41	5.68	510	23.27
NZ aa-DD^ffpp	3.92	0.30	0.20	0.30	1.16	0.39	0.39	3.35	538	26.03
SEA a-DD	0.97	0.13	0.17	0.30	1.51	**0.66**	**0.32**	4.22	497	12.77
UK a-D^fff	3.12	0.28	0.35	0.30	1.62	**0.63**	**0.33**	9.37	577	25.58

Figure 5.8 Performance of the refrigerated goods vehicles relative to the New Zealand baseline vehicle



5.8 Optimisation of a truck and full trailer

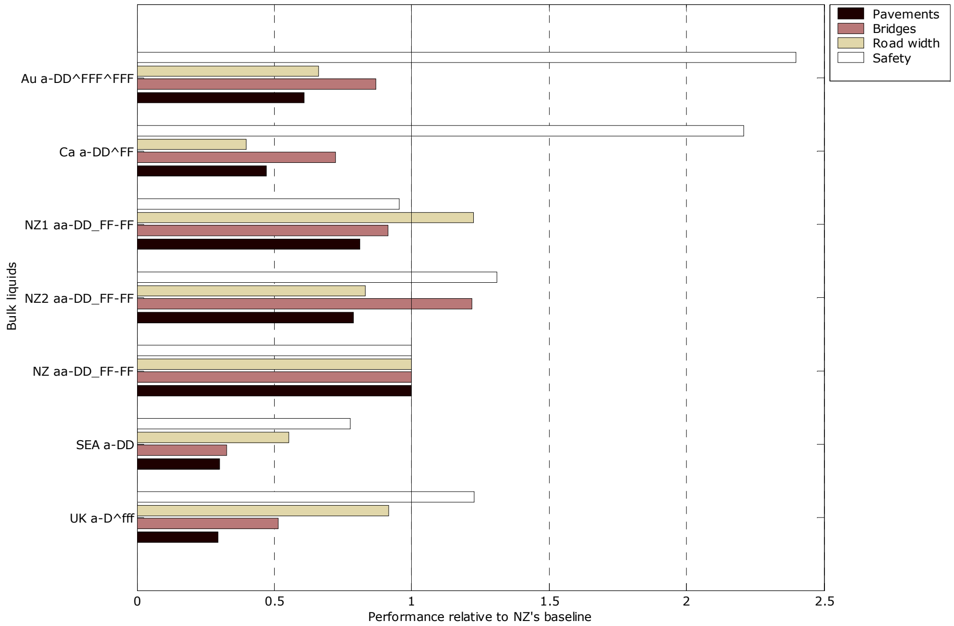
A large number of transport tasks in New Zealand are undertaken by truck and full trailers. This section demonstrates how heavy vehicle optimisation can be achieved. The truck and full trailer used in this example was New Zealand's bulk liquid tanker.

Two variations on New Zealand's bulk liquid tanker were modelled. The first variant (NZ1) had its GCW increased from 44 to 50 tonnes, while the second variant (NZ2) also included increasing its OAL from 20m to 23m and a corresponding increase in tare weight of 1 tonne. Table 5.7 gives the performance results of the New Zealand bulk liquid tanker and its two variants in terms of the fundamental measures, while figure 5.9 shows these results and those of the other tankers in terms of the compound measures relative to New Zealand's baseline vehicle. The New Zealand baseline vehicle and its NZ1 variant failed to meet the LTR criterion; the NZ1 failed the RA criterion, while the NZ2 variant satisfied all the performance criteria.

Table 5.7 Performance of the New Zealand bulk liquid tanker and its two variants

Vehicle	LSO (m)	HSO (m)	HSTO (m)	YDR (-)	RA (-)	LTR (-)	SRT (g)	SAR (-)	PBM (kNm)	PLD (t)
Target	**≤4.2**	**≤.5**	**≤.6**	**≥.15**	**≤2**	**≤.6**	**≥.35**	-	-	-
NZ1 aa-DD_FF-FF	2.77	0.33	0.38	0.24	**2.08**	**0.78**	0.38	4.19	511	32.63
NZ2 aa-DD_FF-FF	3.93	0.35	0.31	0.30	1.71	0.56	0.41	4.19	459	31.63
NZ aa-DD_FF-FF	2.76	0.32	0.34	0.24	1.97	**0.64**	0.41	2.78	463	26.63

Figure 5.9 Performance of the bulk liquid tankers relative to the New Zealand baseline vehicle



6 Discussion

Table 6.1 shows the overall vehicle performance ranking of the transport tasks by country. The country acronyms in bold font indicate that their vehicles failed one or more of the fundamental performance targets. Note that the rankings of the two New Zealand truck and full trailer bulk liquid tanker variants used to demonstrate how heavy vehicle optimisation can be achieved are not included in this table. Instead, their rankings compared with those of other tankers are discussed later in section 6.1.

Table 6.1 Overall vehicle performance ranking of transport tasks by country

Compound measure	Transport task	Vehicle performance ranking by country (descending order)
Pavements	Passenger coach	NZ, Au, UK, Ca, SEA
	Bulk liquids	NZ, Au, Ca, SEA, UK
	Bulk materials	NZ, Au, Ca, SEA, UK
	40 foot intermodal containers	NZ, Ca, Au, UK, SEA
	Livestock	NZ, Au, Ca, SEA, UK
	Refrigerated goods	NZ, Au, Ca, SEA, UK
Bridges	Passenger coach	SEA, NZ, Au, Ca, UK
	Bulk liquids	NZ, Au, Ca, UK, SEA
	Bulk materials	NZ, Au, Ca, UK, SEA
	40 foot intermodal containers	SEA, NZ, Ca, Au, UK
	Livestock	NZ, Au, Ca, UK, SEA
	Refrigerated goods	Au, Ca, NZ, UK, SEA
Road space	Passenger coach	UK, NZ, Au, Ca, SEA
	Bulk liquids	NZ, UK, **Au**, SEA, **Ca**
	Bulk materials	NZ, Au, UK, Ca, SEA
	40 foot intermodal containers	UK, Au, SEA, Ca, NZ
	Livestock	UK, NZ, **Au**, SEA, **Ca**
	Refrigerated goods	Uk, NZ, **Au**, SEA, **Ca**
Safety	Passenger coach	Ca, UK, NZ, Au, SEA
	Bulk liquids	Au, Ca, UK, **NZ**, SEA
	Bulk materials	Ca, NZ, UK, **Au**, SEA
	40 foot intermodal containers	NZ, **Ca, UK, Au, SEA**
	Livestock	Ca, **Au**, NZ, **UK, SEA**
	Refrigerated goods	Ca, NZ, **Au, UK, SEA**

Table 6.2 shows the level of importance that the main vehicle parameters have on the performance outcomes. The qualitative terms of *Low*, *Medium* and *High* express the level of importance that these vehicle parameters have on performance. The positive or negative signs associated with these terms mean that an increase or

decrease in that parameter improves performance. A vehicle's suspension configuration refers to the amount of roll-steer compliance, composite roll stiffness and track width its suspensions have. Where applicable, the vehicle's coupling configuration refers to the type and number of couplings used and their offsets. The following paragraphs describe the relationships between the main vehicle parameters shown in table 6.2 and their effect on the overall vehicle performance shown in table 6.1.

Table 6.2 Importance of the main vehicle parameters on performance

Performance		Axle			Suspension config.	Sprung mass CG height	Coupling config.	Wheel-base length
		Number	Weight	GCW				
Pavements		+ Med	- High	- Low	- Low	- Low	+ Low	+ Low
Bridges	Short	+ Med	- High	- Low	- Low	- Low	+ Low	+ Low
	Medium	+ Med	- Med	- Med	- Low	- Low	+ High	+ High
	Long	+ Med	- Low	- High	- Low	- Low	+ Med	+ Med
Road space		+ Med	- Med	- Med	- Med	- Med	+ High	- High
Safety		+ High	- High	- High	- High	- High	- High	+ High

Pavement performance

Pavement performance is greatly affected by axle weight where lighter axles cause less pavement wear (less SAR) than heavier ones.

New Zealand vehicles caused the least amount of pavement wear and were sufficiently productive to achieve the best pavement wear performance in every transport task. New Zealand vehicles tended to have high numbers of axles with light axle loads.

In contrast, Southeast Asian and United Kingdom vehicles tended to have low numbers of axles with heavy axle loads and were among the worst vehicles in terms of pavement wear performance in each of the transport tasks.

Bridge performance

Bridge performance is also greatly affected by axle weight where lighter axles cause less bridge wear (less PBM raised to the third power) than heavier ones – particularly for short bridges spanning no more than about twice the shortest spacing between axle groups.

On short bridges, single- and double-unit vehicles (eg passenger coaches and tractor semi-trailers) generally cause more bridge wear than the triple-unit vehicles (eg truck and full trailers and B-trains) because of their higher axle weights.

On medium bridges spanning more than about twice the shortest axle spacing between axle groups to about the overall length (OAL) limit, bridge performance is not only affected by axle weight but also by wheelbase length and, where applicable, by axle spread and by the number of couplings and their offsets. The resulting vehicle geometry constrains the axle loads to specific locations throughout a bridge crossing. On medium-span bridges, vehicles with longer wheelbases can distribute their weight over a greater length thus causing less bridge wear than comparable vehicles with shorter wheelbases. On medium-span bridges, vehicles with the same number of axles, overall axle spacing (OAS) and gross combination weight (GCW), and those with more couplings, such as truck and full trailers and B-trains, can distribute their weight more uniformly over their length thus causing less bridge wear than comparable vehicles that distribute their weight non-uniformly.

Of New Zealand's vehicles, the passenger coach caused the least amount of wear to the reference bridge followed by the refrigerated goods B-train, the bulk materials, livestock, and bulk liquids truck and full trailers; with the tractor semi-trailers hauling intermodal containers and refrigerated goods causing the most bridge wear.

Of all the vehicles in each of the transport tasks, those that had the best bridge wear performance were the Southeast Asian passenger coach and intermodal container tractor semi-trailer; the New Zealand bulk liquids, bulk materials, livestock truck and full trailers; and the Australian refrigerated goods B-double.

Although the Southeast Asian passenger coach and intermodal container tractor semi-trailer were the least productive, they caused the least amount of wear to the reference bridge thus they performed the best in their categories. The New Zealand bulk liquids, bulk materials and livestock truck and full trailers caused the least amount of wear to the reference bridge, and they were also among the most productive vehicles thus they performed the best in their categories. Of the bulk material vehicles, the New Zealand truck and full trailer had the highest number of axles and had the longest OAS. Although Australia's refrigerated goods B-double caused the most amount of wear to the reference bridge, it was also the most productive vehicle and performed the best in its category. Of the refrigerated goods vehicles, Australia's vehicle had the highest number of axles and the longest OAS.

Of all the vehicles from each of the transport tasks, Southeast Asian vehicles tended to have low numbers of axles, heavy axle loads, short OAS and the low levels of productivity. With the exception of the Southeast Asian passenger coach and intermodal container vehicle, Southeast Asian vehicles had the worst bridge wear performance in each of the remaining transport tasks. United Kingdom vehicles also tended to have low numbers of axles, heavy axle loads and short OAS which meant that they too were among the worst vehicles in terms of bridge wear performance.

On long bridges spanning more than the OAL limit, it is the sum of the axle weights which is the most important factor. Lighter vehicles with less GCW cause less bridge wear than heavier ones with more GCW.

On long bridges, triple-unit vehicles generally cause more bridge wear than the single- and double-unit vehicles because of their higher GCW.

Road space performance

Vehicle geometry also greatly affects road space performance by constraining axles to specific locations about which pavement and tyre forces and, where applicable, the inter-axle axle and coupling forces influence the tracking behaviour of the vehicle. On low-speed steady-state turns and under certain conditions, the amount of offtracking can be determined entirely by vehicle geometry. Vehicles with shorter wheelbases occupy less road width on low-speed turns (less LSO) than comparable vehicles with longer wheelbases. For vehicles with the same number of axles and OAL, those that have more couplings with longer offsets also occupy less road width on low-speed turns.

On high-speed turns, road space performance is affected not only by vehicle geometry but by the tyre and inertial forces that result from acceleration of the vehicle towards the centre of the turn. On high-speed steady-state turns, the centripetal cornering forces of the tyres must balance the vehicle's centrifugal forces generated through the turn. Reducing the wheelbase length and increasing the amount of cornering stiffness (eg using larger tyres or increasing the number of tyres or axles) and, where applicable, increasing the number of couplings and their offsets, reduces the slip angles of the tyres thus reducing the amount of road width occupied on high-speed turns (less HSO). When an axle undergoes a roll motion relative to the vehicle body, the suspension geometry can cause it to steer. The amount of steering per unit of roll is the roll-steer rate. The roll-steer rate of a vehicle's suspension can greatly affect the amount of occupied road width, particularly on high-speed manoeuvres. The amount of roll-steer can be reduced by having high composite roll stiffness. Suspensions with a high roll-steer rate may also have a high level of composite roll stiffness and so the overall effect on the amount of occupied road width is less severe.

On high-speed path changes, road space performance and safety performance in terms of stability are also affected by the vehicle's geometry, and by the cornering and inertial forces that result from acceleration of the vehicle through a path change. Increasing the wheelbase length and the amount of cornering stiffness reduces the slip angles of the tyres and thus lessens the lateral motions of the vehicle and, where applicable, reduces the lateral motions of the couplings which provide the excitation inputs to successive vehicle units. The lateral motions of the couplings can be reduced further by decreasing their offsets. The reduction of a vehicle's yaw moments of inertia lessens the corresponding inertial forces, which decreases the slip angles of the tyres thereby reducing the lateral motions of the vehicle. In summary, increasing the wheelbase length and the amount of cornering stiffness, reducing the number of couplings and the magnitudes of their offsets, and lessening the yaw moments of inertia all reduce the amount of road width occupied on high-speed path changes (less HSTO), and all improve the stability of the vehicle by reducing the amount of whipping (lower RA) and snaking (more YDR).

The vehicles that had the best road space performance were the United Kingdom passenger coach; the New Zealand bulk liquids and bulk materials truck and full trailers; and the United Kingdom intermodal container, livestock and refrigerated goods tractor semi-trailers.

The United Kingdom passenger coach occupied some of the highest amounts of road width on the prescribed low- and high-speed turns, but the amounts were below the penalty thresholds (ie LSO<2.9m and HSO<0.345m), and as it was one of the most productive it performed the best in its category. Although the New Zealand bulk liquids and bulk materials truck and full trailers occupied some of the highest amounts of road width on the prescribed high-speed turn, the amounts were below the penalty thresholds. These vehicles also occupied some of the lowest amounts of road width on the prescribed low-speed turn, and were among the most productive vehicles and so performed the best in their categories. The United Kingdom short wheelbase intermodal container, livestock and refrigerated goods tractor semi-trailers occupied some of the lowest amounts of road width on the prescribed low- and high-speed turns. These vehicles were also among the most productive and so were the best performers in their categories.

In contrast, the Australian B-double and Canadian tractor semi-trailers were among the longest vehicles and because Canada's vehicles were also the widest, they occupied high amounts of road width on the prescribed low- and high-speed turns. Although they were among the most productive vehicles, their excessive offtracking meant they were among the worst vehicles in terms of road space performance in each of their respective transport tasks. Although the Southeast Asian vehicles were the shortest and occupied the least amounts of road width on the prescribed low- and high-speed turns, they were also the least productive and so were among the worst vehicles in terms of road space performance in each of their categories.

Safety performance

In addition to vehicle geometry and cornering and inertial forces, safety performance in terms of rollover stability on high-speed manoeuvres is affected by the roll moment distribution. Using axles with wider track widths (eg using wider axles, or using wide single tyres instead of duals given the same vertical stiffness), utilising high roll-stiffness suspensions, and increasing the number of axles all improve the rollover stability on high-speed path changes (less LTR) and on high-speed turns (more SRT). In the case of roll-coupled vehicles (eg tractor semi-trailers and B-trains or B-doubles), the roll-stiffness of every axle contributes to the rollover stability of the entire combination. On high-speed path changes, roll-coupled vehicles tend to be more roll stable (less LTR) than comparable vehicles that are not roll coupled. On high-speed steady-state turns, the roll coupling between vehicle units is important in terms of rollover stability if the difference in SRT between the individual vehicle units is large.

The vehicles with the best safety performance were the Canadian passenger coach and Canadian bulk materials, livestock and refrigerated goods tractor semi-trailers; the Australian bulk liquids B-double; and the New Zealand intermodal container tractor semi-trailer.

The Canadian long wheelbase passenger coach had good rollover stability on the prescribed high-speed turn, it occupied one of least amounts of road width and whipped out by the least amount on the prescribed high-speed path change. As it was the most productive coach it performed the best in its category. The Canadian bulk materials, livestock and refrigerated goods tractor semi-trailers were among the most roll stable on high-speed turns and path changes, and they occupied some of the least amounts of road width and whipped out by the least amounts on the prescribed high-speed path change. The Canadian vehicles were configured with 102 inch wide trailer axles which improved rollover stability. Although the Australian bulk liquid B-double was the least roll stable on the prescribed high-speed turn, it was among the best performers on the prescribed high-speed path change. As it was also the most productive it achieved the best overall performance in its category. Although the New Zealand intermodal container tractor semi-trailer was one on the least productive, it was the most roll stable on the prescribed high-speed turn and was the best performer on the prescribed high-speed path change. This performance was sufficient to overcome its lack of productivity and achieved the best overall ranking.

In contrast, Southeast Asian vehicles had some of the highest axle loads, the shortest OAL and the lowest levels of productivity, and were ranked as the worst vehicles in terms of safety performance in every transport task.

All of the vehicles studied had satisfactory resistance to snaking, with the single-unit (passenger coaches and rigid trucks), double-unit (tractor semi-trailers) and B-double vehicles performing particularly well. The truck and full trailers studied also had satisfactory resistance to snaking with their amounts of yaw damping being above the minimum level for acceptable performance. Heavy vehicle configurations that were most likely to have high amounts of snaking included those with simple-trailer and A-dolly vehicle units. Note than any heavy vehicle regardless of configuration can have high amounts of snaking if the load is not correctly distributed. In some jurisdictions including New Zealand and Australia, the mass ratio between the front and rear load-bearing vehicle units is controlled to counteract snaking (LTSA 2002; National Transport Commission 1997).

Reducing either the weight or cg height of the vehicle improves its safety performance by significantly enhancing rollover stability (less LTR and more SRT), and moderately improves its stability (less RA and more YDR). Lessening either the weight or cg height significantly impacts on its road space performance on high-speed manoeuvres when the combined affects of having high amounts of roll steer and low amounts of composite roll stiffness is significant (more HSTO and HSO).

6.1 Optimisation of a truck and full trailer

Section 5.8 demonstrated how changes in vehicle weight and dimensions affected performance and how heavy vehicle optimisation could be achieved. Two variations on New Zealand's bulk liquids baseline truck and full trailer were modelled. Compared with the baseline vehicle, the first variant (NZ1) had more GCW, while the second variant (NZ2) was also longer. The performance of these variants, together with the bulk liquid tankers from the other countries, was compared with the New Zealand baseline vehicle.

Regarding pavement wear performance, New Zealand's baseline vehicle outperformed the NZ1 variant which in turn outperformed the NZ2 variant. Although New Zealand's baseline vehicle was less productive than the two variants, pavement wear for these variants increased more rapidly than their gain in productivity, thus the New Zealand baseline vehicle performed the best of the three. Although both variants caused the same amount of pavement wear, the longer NZ2 variant was slightly heavier in tare weight and was consequently less productive than the NZ1 variant, thus the NZ2 variant was outperformed by the NZ1 variant. All three New Zealand vehicles outperformed the bulk liquid tankers from the other countries in terms of pavement wear performance.

Regarding bridge wear performance, the NZ2 variant outperformed the New Zealand baseline vehicle which in turn outperformed the NZ1 variant. The longer NZ2 variant caused the least amount of wear to the reference bridge and was one of the most productive, making it the best performer of the three New Zealand tankers. Although the New Zealand baseline vehicle was less productive than its variants, it caused one of the least amounts of wear to the reference bridge and so performed second best of the three New Zealand tankers. Although the NZ1 variant was the most productive of all three New Zealand vehicles, it also caused the most amount of wear to the reference bridge and was the worst performer of the three New Zealand tankers. All three New Zealand vehicles outperformed the bulk liquid tankers from the other countries in terms of bridge wear performance.

Regarding road space performance, the NZ1 variant outperformed the New Zealand baseline vehicle which in turn outperformed the NZ2 variant. The NZ1 variant occupied some of the lowest amounts of road width on the prescribed low- and high-speed turns and was the most productive, thus performing the best of the three New Zealand tankers. Although the New Zealand baseline vehicle was less productive than the two variants, it occupied the least amount of road width on the prescribed low- and high-speed turns and so came second to the NZ1 variant. Although the longer NZ2 variant was one of the most productive of the New Zealand tankers, it occupied the most amount of road width of the three on the prescribed low- and high-speed turns, thus performing the worst. All three New Zealand tankers outperformed the bulk liquid vehicles from the other countries in terms of road space performance, except the NZ2 variant which was outperformed by the United Kingdom short tractor semi-trailer. Although the United Kingdom vehicle was less productive than the NZ2 variant (and the other New Zealand tankers for that matter), it occupied less road width on the prescribed low- and high-speed turn and so outperformed the NZ2 variant.

Regarding safety performance, the NZ2 variant outperformed the New Zealand baseline vehicle which in turn outperformed the NZ1 variant. Of the three New Zealand tankers, the longer NZ2 variant occupied the least amount of road width, whipped out the least, and was the most roll stable on the prescribed high-speed path change. It was also one of the most roll stable on the prescribed high-speed turn, and was one of the most productive, so was the best performer of the three. Although the New Zealand baseline vehicle was less productive than the two variants, it occupied one of the least amounts of road width, whipped out by one the least amounts, and was one of the most roll stable on the prescribed high-speed path change It was also one of the most roll stable on the prescribed high-speed turn and overall performed second best of the three New Zealand tankers. Although the NZ1 variant was the most productive of the New Zealand vehicles, it occupied the highest amount of road width, whipped-out the most, and was the least roll stable on the prescribed high-speed path change. It was also the least roll stable on the prescribed high-speed turn and overall performed worst of the three New Zealand tankers. All three New Zealand tankers had satisfactory resistance to snaking.

Regarding safety performance, all three New Zealand tankers were outperformed by the Australian B-double, and the Canadian tractor semi-trailer. However, the Australian and Canadian tankers both exceeded the maximum low-speed offtracking target value and were outperformed by the New Zealand tankers in terms of pavement wear, bridge wear and road space performance. The NZ2 variant was the only New Zealand tanker to outperform the United Kingdom tractor semi-trailer in terms of safety and was also the only New Zealand tanker to satisfy all the safety performance criteria. Given that the increased pavement wear of the NZ2 variant was recoverable by a corresponding increase in road user charges for this vehicle, and that the increased amount of road width occupied by this vehicle was still less than that of other vehicles currently permitted on New Zealand roads, the NZ2 variant was a more optimal truck and full trailer configuration than the alternatives.

7 Conclusions

The performance of typical vehicles used in six transport tasks in New Zealand were benchmarked against vehicles undertaking those same tasks in Australia, Canada, Southeast Asia and in the United Kingdom. The six transport tasks analysed were passenger coach transport, bulk liquids and bulk materials transport, 40 foot ISO intermodal container transport, and livestock and refrigerated goods transport. A demonstration of a more optimal New Zealand truck and full trailer was presented, and ways to optimise other vehicle configurations are discussed later in Section 7.1.

Vehicle performance was assessed in terms of nine fundamental measures and four compound measures. The compound measures quantified four aspects of heavy vehicle performance: pavement wear, bridge wear, road space and safety. Pavement wear performance was determined by the amount of accumulated pavement wear and payload. Bridge wear performance was determined by the amount of accumulated bridge wear when traversing the reference bridge spanning 12.5m and payload. Road space performance was determined by the amount of road width occupied on the prescribed low- and high-speed turns and payload. Safety performance was based on relating the vehicle’s rollover stability and high-speed dynamic stability characteristics to the relative likelihood of being involved in a stability-related crash. The safety performance measure included payload as a measure of vehicle exposure. Payload was also used as a measure of environmental impact where more productive vehicles resulted in fuel and emissions savings and reduced congestion.

The New Zealand vehicles caused the least amount of pavement wear and were sufficiently productive to achieve the best pavement performance in every transport task. The main reason for this is that road tax on heavy vehicles in New Zealand is collected through road user charges which include a component for pavement wear based on the fourth power of the axle loads. This tax has created a situation unique to this country by encouraging operators to fit more axles to carry a given load than is necessary for compliance with the axle group weight limits.

Encouraging operators in New Zealand to fit more axles to reduce pavement wear also contributes to reduced bridge wear, particularly for short bridges. The New Zealand bulk liquids, bulk materials and livestock trucks and full trailers caused the least amounts of wear to the reference bridge and were sufficiently productive to achieve the best bridge wear performance in their respective transport tasks. Regarding bridge wear performance, the New Zealand passenger coach and intermodal container tractor semi-trailer ranked second to the Southeast Asian less productive but also less damaging vehicles. However, the Southeast Asian passenger coach and intermodal container vehicles both caused the highest amounts of pavement wear and were the worst vehicles in each of their respective transport tasks in terms of pavement wear performance. Furthermore, the Southeast Asian passenger coach had the worst road space and safety performance of all the coaches, and the Southeast Asian intermodal container vehicle had the worst safety performance of all the intermodal vehicles and it failed to meet New Zealand’s rollover stability criterion. Regarding bridge wear performance, the New Zealand refrigerated goods tractor semi-trailer ranked third behind the Australian longer and more productive but also more damaging B-double and behind the Canadian longer tractor semi-trailer. However, the Australian and Canadian refrigerated goods vehicles caused more pavement wear and were outperformed by the New Zealand vehicle, along with every other refrigerated goods vehicle, in terms of pavement wear performance. Furthermore, the Australian and Canadian refrigerated goods vehicles both exceeded the maximum low-speed offtracking target value and were outperformed by the New Zealand vehicle in terms of road space performance. Moreover, the Australian refrigerated vehicle failed to meet New Zealand’s rollover stability criterion and was outperformed by the New Zealand vehicle in terms of safety performance.

Because of their high manoeuvrability and adequate levels of productivity, the New Zealand bulk liquids and bulk materials trucks and full trailers achieved the best road space performance. Regarding road space performance, the New Zealand passenger coach ranked second behind the United Kingdom's more productive coach. However, passenger coaches in New Zealand can operate more productively at 13.5m or 14.5m of overall length (OAL) under permit. In that case, the road space performance would be better than that of the United Kingdom passenger coach. Regarding road space performance, the New Zealand livestock truck and full trailer and refrigerated goods tractor semi-trailer ranked second behind the United Kingdom shorter tractor semi-trailers. However, the United Kingdom livestock and refrigerated goods vehicles caused the most amount of pavement wear and were the worst vehicles in each of their respective transport tasks in terms of pavement wear performance. They also caused some of the highest amounts of wear to the reference bridge and were outperformed by the New Zealand vehicles in each of their respective transport tasks in terms of bridge wear performance. Furthermore, the United Kingdom livestock and refrigerated goods vehicles failed to meet New Zealand's rollover stability criterion and also failed to meet the rollover stability criterion on the prescribed high-speed path change. They were outperformed by the New Zealand vehicles in each of their respective transport tasks in terms of safety performance. Regarding road space performance, the New Zealand intermodal container tractor semi-trailer ranked fifth behind those of the United Kingdom, Australia, Southeast Asia and Canada. This was because the intermodal containers on the United Kingdom, Australian and Canadian vehicles weighed 30.4 tonnes (maximum gross container weight) which meant they had 4.22 tonnes more payload than the New Zealand container vehicle, and because the United Kingdom and Southeast Asian vehicles re shorter. However, intermodal container vehicles in New Zealand can operate overweight under permit thus their road space performance would be similar to the Australian tractor semi-trailer.

Regarding safety performance, the New Zealand six-axle intermodal container tractor semi-trailer had the best safety performance even though it was one of the least productive. However, 30.4 tonne intermodal containers in New Zealand can be transported on eight-axle tractor semi-trailers (quad-semis). The safety performance of an eight-axle intermodal container tractor semi-trailer would be similar to the New Zealand refrigerated goods vehicle and would outperform the other intermodal container vehicles. Regarding safety performance, the New Zealand bulk materials truck and full trailer ranked second to the Canadian more productive tractor semi-trailer, while the New Zealand refrigerated goods tractor semi-trailer ranked second to the Canadian refrigerated goods tractor semi-trailer. However, the New Zealand bulk materials vehicle outperformed the Canadian vehicle, and every other bulk materials vehicle for that matter, in terms of pavement wear performance, bridge wear performance and road space performance. Although the Canadian refrigerated goods vehicle outperformed the New Zealand vehicle in terms of safety and bridge wear performance, it was outperformed by the New Zealand vehicle in terms of pavement wear performance, and in terms of road space performance where the Canadian vehicle exceeded the maximum low-speed offtracking target value. The New Zealand passenger coach ranked third behind the Canadian and United Kingdom longer and more productive vehicles. However, passenger coaches in New Zealand can operate more productively at 13.5m or 14.5m OAL under permit thus their safety performance would be similar to the Canadian passenger coach and better than the United Kingdom passenger coach. Regarding safety performance, the New Zealand livestock truck and full trailer ranked third behind the Canadian longer tractor semi-trailer and behind the Australian longer and more productive B-double. However, the Canadian and Australian livestock vehicles caused more pavement and bridge wear and were outperformed by the New Zealand vehicle, along with every other livestock vehicle in that respect. Furthermore, the Canadian and Australian livestock vehicles both exceeded the maximum low-speed offtracking target value and were outperformed by the New Zealand vehicle in terms of road space performance. Regarding safety performance, the New Zealand bulk liquids vehicle ranked fourth behind the Australian longer and more productive B-double, the Canadian longer tractor semi-trailer and the

United Kingdom tractor semi-trailer. Although the New Zealand bulk liquids vehicle failed the rollover stability criterion on the prescribed high-speed path change, it outperformed Australian, Canadian and United Kingdom vehicles, and every other bulk liquids vehicle in terms of pavement, bridge wear and road space performance. The Australian, Canadian and United Kingdom bulk liquids vehicles caused more pavement and bridge wear than the New Zealand vehicle, and the Australian and Canadian bulk liquids vehicles exceeded the maximum low-speed offtracking target value.

A large number of transport tasks in New Zealand are undertaken by truck and full trailers compared with the other countries which tend to use mainly tractor semi-trailers and to a lesser extent B-trains to undertake those same tasks. Truck and full trailers have good low-speed manoeuvrability and thus perform well in terms of road space requirements. With the axle weights used in New Zealand they have a relatively low impact on the pavement and bridge infrastructure and also perform well in this regard. However, their safety performance can be worse than other vehicle configurations if they are not designed well. The New Zealand size and weight regulations do include some requirements aimed at truck and full trailer design for improved safety. Specifically, there is a minimum SRT requirement of 0.35g for all large heavy vehicles, the distance between the rear axis of the truck and the coupling hitch must be less than 40 percent of the truck's wheelbase, and the trailer:truck mass ratio must not be more than 1.5:1.

There are unique road geometry challenges in both low- and high-speed operations in New Zealand. Of particular risk is the frequency of high-speed tight radius curves that challenge drivers and vehicles. Such conditions do not exist at the same level in the benchmark countries. This unique condition argues for rigorous heavy vehicle safety performance evaluation as outlined in this report. As an additional countermeasure, crash avoidance technology such as electronic stability systems and roll stability systems should be considered as a requirement for higher productivity vehicles, including motor coaches.

7.1 Optimisation

The overall performance of passenger coaches in New Zealand can be improved by operating 13.5m or 14.5m coaches under permit. The advantages of longer coaches over the 12.6m coach currently used in New Zealand are as follows:

- Although longer passenger coaches are generally heavier in tare weight than shorter coaches they are also more productive as they can seat more passengers.
- As 12.6m coaches have both good pavement and bridge wear performance, it is possible for longer and more productive coaches to operate without their corresponding axle weight increases impacting significantly on their respective ranking. One benefit of operating longer coaches is that by distributing their weight over a greater span they have less impact on the bridge infrastructure.
- Road space performance of passenger coaches can be improved because even though longer coaches occupy more of the road, the occupied road width is still much less than that used by combination vehicles on the same road network.
- The safety performance of passenger coaches can be improved by operating longer coaches because the increase in productivity results in reduced on-road vehicle exposure; and the increase in overall length (OAL) results in improved stability on high-speed path changes or evasive manoeuvres due to the tyres encountering smaller slip angles.

The overall performance of truck and full trailers in New Zealand can be improved with moderate increases in both gross combination weight (GCW) and OAL limits for the following reasons (eg see sections 5.8 and 6.1):

- As these vehicles have good pavement wear performance, a moderate increase in GCW is possible without it impacting significantly on their respective rankings.
- As these vehicles have good bridge wear performance, increases in both GCW and OAL are possible without impacting significantly on their respective rankings since they distribute their weight more uniformly on bridges than other combination vehicles, and because longer vehicles have less impact on the bridge infrastructure.
- As these vehicles have good road space performance, moderate increases in both GCW and OAL are possible without these increases impacting significantly on their respective rankings.
- The safety performance of these vehicles can be improved with moderate increases in both GCW and OAL as an increase in GCW results in greater productivity and reduced on-road vehicle exposure; an increase in OAL results in improved stability on high-speed path changes or evasive manoeuvres; and moderate increases in both GCW and OAL can be managed so that the rollover stability of these vehicles is no worse or even better than the current vehicle configurations.

An increase in GCW limit for truck and full trailers can be achieved without necessarily increasing their axle group weight limits since these vehicles currently operate with their axle groups weights below the legal maximum.

The overall performance of tractor semi-trailers can be improved with moderate increases of their tri- and quad-axle trailer group weight limits for the following reasons:

- As these vehicles have good pavement wear performance, these weight increases are possible without impacting significantly on their respective rankings. This is because the current weight limits for the tri- and quad-axle groups are less than those reference axle group weights deemed to generate the same amount of pavement wear as one standard axle.
- Although these vehicles do not perform as well as other combination vehicles in terms of bridge wear performance, these weight increases will improve their respective rankings as it is the axle loads on the tractor units, the tandem drive axles in particular, that impact the most on the bridge infrastructure and not their trailer axles.
- As these vehicles do not perform as well as other combination vehicles in terms of road space performance, the best way to improve this is with a moderated increase in productivity through adopting these weight increases.
- The safety performance of these vehicles is generally better than other combination vehicles since they each have only one coupling, and because the fifth wheel provides roll coupling between both vehicle units meaning that every axle contributes to the rollover stability of the combination. These weight increases result in greater productivity and in reduced on-road vehicle exposure thus improving safety.

An increase in the weight limits of tri- and quad-axle trailer groups on tractor semi-trailers also requires a corresponding increase in the GCW limit since many configurations operate their axle groups at full capacity, and because some configurations already operate at the current GCW limit.

For the same vehicle configuration, an increase in weight will mean more pavement wear but this will be recovered by increased road user charges for this vehicle. An increase in New Zealand's GCW limit will require a new weight limit schedule (or bridge formula) to be developed and implemented. The fundamental principle behind any weight limit schedule is to protect the bridge infrastructure from overstress by only allowing longer vehicles more weight. This is because longer vehicles distribute their weight over longer spans which lessen their impact on the bridge infrastructure. However, longer vehicles must also be more manoeuvrable to successfully negotiate the road network. As truck and full trailers are longer and more manoeuvrable than other combination vehicles, an increase in both GCW and OAL limits observe the principles of the weight limit schedule and can be accommodated by linear extrapolation of the current schedule. Conversely, tractor semi-trailers are generally shorter and have relatively poor manoeuvrability compared with other combination vehicles, so if their OAL is maintained at the current limit, increasing the GCW limit alone will contravene the principles of the weight limit schedule and cannot be accommodated by extrapolation of the current schedule in the same way. An increase in weight allowance would be required.

An increase in the OAL limit of heavy vehicles in New Zealand will mean that longer vehicles will inevitably occupy more road space than vehicles at the current length limit. An increase in the OAL limit will also impact on other road users in terms of increased overtaking and intersection clearance times, and increased stacking length at intersections and on right-turning bays. A report by de Pont and Baas (2002) on similar matters states that although no good data is available on the safety impacts of such changes it is reasonable to assume they would be negligible.

Since B-trains have relatively low usage in New Zealand compared with other more popular combination vehicles, their performance was not included as part of this benchmarking study. In general however, the performance of B-trains can be viewed as a trade-off between truck and full trailers and tractor semi-trailers. That is, B-trains generally perform better than tractor semi-trailers but worse than truck and full trailers in terms of road space, and they generally perform better than truck and full trailers but worse than tractor semi-trailers in terms of safety. B-trains in New Zealand have the same OAL limit as truck and full trailers, but they can often distribute their weight more uniformly on bridges than truck and full trailers, thus B-trains generally have slightly less impact on the bridge infrastructure than truck and full trailers. What these comparisons mean in terms of optimisation is that the performance of B-trains can be improved with moderate increases in both GCW and OAL for similar reasons as the truck and full trailers. However, the road space performance criteria will mean that the potential length increase of a B-train is less than that of a truck trailer.

Regarding the types of transport tasks undertaken, those that transport high-density product are safer than those that transport low-density product for the same vehicle and GCW. This result is mainly due to their differences in payload centre of gravity (cg) heights, where high-density products have lower cg heights than low-density products. Payload cg height has a significant impact on safety performance since lower cg heights result in better rollover stability. Therefore vehicles that transport high-density product can operate at heavier weights than those that transport low-density product for the same level of rollover stability, but with improved safety performance because of their greater productivity and reduced levels of on-road exposure. In addition, these more productive vehicles will also have improved road space performance, but these performance improvements will be at the expense of infrastructure performance.

For weight-constrained loads, increasing the allowable vehicle weight limits increases payload capacity, while for volume-constrained loads, increasing the allowable length will improve payload capacity. All of the compound performance measures incorporate payload in the calculation and so that aspect of performance will improve in proportion to the payload increase. However, increasing weight and/or length will also have negative effects on some aspects of performance. For example, increasing weight will worsen pavement performance in proportion to the fourth power of axle loads. Other aspects of performance may improve. For example, increasing weight and length proportionately so that the cg height of the vehicle does not change, should improve the safety performance since longer vehicles have better dynamic stability and because more productive vehicles result in reduced on-road vehicle exposure.

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Appendix A: Bridge formulae

New Zealand

Current limits

$$M = \begin{cases} 3L + 10, & 1.80 \le L < 5.\overline{66} \\ 1.6L + 18, & 5.\overline{66} \le L \le 16.00 \end{cases} \tag{Equation A.1}$$

The actual requirements are represented in tabular form. These equations are a fit to this tabulated data (Sleath and Pearson 2000).

Proposed limits

$$M = \begin{cases} 3L + 10, & 1.80 \le L < 8.\overline{66} \\ 2L + 18, & L \ge 8.\overline{66} \end{cases} \tag{Equation A.2}$$

M is the maximum sum of mass in tonnes and L is the distance in metres between any two or more axles that do not constitute an axle set. The maximum GCW is 44 tonnes unless the bridge formula dictates a lower level (Sleath and Pearson 2000).

Australian PBS Scheme

Access to the PBS Level 1 road network

$$M = \begin{cases} 3L + 12.5, & 2.50 \le L \le 10.00 \\ L + 32.5, & L > 10.00 \end{cases} \tag{Equation A.3}$$

Access to the PBS Level 2 road network

$$M = \begin{cases} 3L + 12.5, & 2.50 \le L \le 11.\overline{33} \\ 1.5L + 29.5, & L > 11.\overline{33} \end{cases} \tag{Equation A.4}$$

Access to the PBS Level 3 and Level 4 road network

$$M = 3L + 12.5, \quad L > 2.50 \tag{Equation A.5}$$

M is the total GCW in tonnes and L is the distance in metres between the extreme axles of any two axle groups (National Transport Commission 2007).

United States of America

Federal bridge formula B

$$M = 500\left(\frac{N}{N-1}L + 12N + 36\right) \qquad \text{(Equation A.6)}$$

M is the overall gross weight in pounds of any group of two or more consecutive axles rounded down to the nearest 500 pounds, L is the distance in feet between the outermost axle centres of any group of two or more consecutive axles and N is the number of axles in the group under consideration.

The Federal gross weight limit is 80,000 pounds unless the bridge formula dictates a lower limit. Additionally, the Federal weight limit on the Interstate system for single axles is 20,000 pounds, and the weight limit for tandem axles closer than 96 inches is 34,000 pounds (Jaykishan 2005).

Proposed TTI-HS20 formula

$$M = \begin{cases} 1000(L+34), & L \le 8 \\ 1000(2L+26), & 8 < L \le 24 \\ 1000(L/2+62), & L > 24 \end{cases} \qquad \text{(Equation A.7)}$$

M is the overall gross weight in pounds of any group of two or more consecutive axles and L is the distance in feet between the outermost axle centres of any group of two or more consecutive axles.

Single and tandem axle (closer than 96 inches) weight limits on the Interstate network of 20,000 pounds and 34,0000 pounds, respectively, are retained but the gross vehicle weight limit of 80,000 pounds is removed (Jaykishan 2005).

Appendix B: Vehicle manoeuvres

Table B.1 Description of the road width and safety manoeuvres and performance measures

Description of manoeuvre	Measures
Constant 393.2m radius turn at 100km/h yielding a constant lateral acceleration of 0.2g at the steer axle to get a measure of HSO, followed by a tightening spiral turn at a steer-wheel angle rate of 0.04 degrees per second to get a measure of SRT (Roads and Transportation Association of Canada 1986).	HSO, SRT
High-speed path-change or evasive manoeuvre. The manoeuvre involves a 1.46m lateral path-change at 88.5km/h with a 2.5 second period yielding a peak lateral acceleration of 0.15g at the steer axle. The manoeuvre has straight entry and exit tangents (Society of Automotive Engineers Incorporated 1993).	RA, LTR, HSTO
High-speed steering pulse manoeuvre. A steering pulse of 3.2 degrees at the road wheel interface at 100km/h applied over a 0.1 second time interval. The manoeuvre has straight entry and exit tangents (National Transport Commission 2007).	YDR
Low-speed swept path manoeuvre. 9.8m radius 90 degree turn relative to the steer axle centre at 8km/h with straight entry and exit tangents (LTSA 2002).	LSO

Note: 1g is the acceleration due to gravity or 9.807m per second squared.

Appendix C: Vehicle properties

Table C.1 Product densities for the given transport tasks

Transport task	Product	Product density (kg/m³)
Bulk liquids	Petrol at 16°C	737[(a)]
Bulk materials	Dry earth	673[(a)]
Intermodal containers	Anonymous	399
Livestock	Generic	299
Refrigerated goods	Processed product	336

Note:

(a) Source accessed 08/07/2009): www.simetric.co.uk/si_materials.htm

Table C.2 Properties of the vehicles studied

Task ID	Country ID	Vehicle ID (TAC sequence)	Load bed height (m)	Load height (m)	Wheel base (m)	Axle group spread (m)	Hitch offset (m)	Axle group weight (t)
PC	Au50	a-Df	1.2	2.4	6.925	1.4	NA	6, 13.75
BL	Au	a-DD^FFF^FFF	1.4 1.4	3.07 3.07	4.25 8.2 9.3	1.35 2.7 2.7	0.34 0.1 0.1	6, 17 22.5 22.5
BM	Au	a-DD_F-FF	1.2 1.2	2.72 2.61	4.34, 4.44 4.6	1.35 1.37	-1.7 0	6 15.5 8 13
IC	Au	a-DD^FFF	1.5	3.86	4.25 8.8	1.4 2.7	0.34	6 17 20.3
LS	Au	a-DD^FFF^FFF	1.4 1.4	4.52 4.52	4.25 8.2 9.3	1.35 2.7 2.7	0.34 0.1 0.1	6 17 22.5 22.5
RG	Au	a-DD^FFF^FFF	1.4 1.4	4.2 4.2	4.25 8.2 9.3	1.35 2.7 2.7	0.34 0.1 0.1	6 17 22.5 22.5
PC	Ca55	a-Df	1.4	2.9	8.08	1.4	NA	7.25 14.425
BL	Ca	a-DD^FF	1.4	2.64	5.31 11.43	1.4 1.35	0.15	5.5 17 24

Task ID	Country ID	Vehicle ID (TAC sequence)	Load bed height (m)	Load height (m)	Wheel base (m)	Axle group spread (m)	Hitch offset (m)	Axle group weight (t)
BM	Ca	a-DD^FFF	1.4	3.06	5.31 7.62	1.4 3.6	0.15	5.5 17 24
IC	Ca	a-DD^FFF	1.5	3.86	5.31 8.077	1.4 3.6	0.15	5.5 17 21.1
LS	Ca	a-DD^FF	0.7	2.85	5.31 12.34	1.4 1.35	0.15	5.5 17 17
RG	Ca	a-DD^FF	1.4	3.12	5.31 12.5	1.4 1.35	0.15	5.5 17 17
PC	NZ50	a-Df	1.2	2.4	6.925	1.4	NA	6 13.75
BL	NZ	aa-DD_FF-FF	1.2 1.12	2.66 2.89	5.055 4.2 4.83	1.78 1.35 1.25 1.25	-2.025	10 12 11 11
BL	NZ1	aa-DD_FF-FF	1.2 1.12	2.66 2.89	5.055 4.2 4.83	1.78 1.35 1.25 1.25	-2.025	10.5 13.5 13 13
BL	NZ2	aa-DD_FF-FF	1.2 1.12	2.66 2.89	6.055 4.2 6.83	1.78 1.35 1.25 1.25	-2.025	10.5 13.5 13 13
BM	NZ	a-DD_FF-FF	1.2 1.12	2.53, 2.68	4.34, 4.74, 4.8	1.35, 1.25, 1.37	-1.7, 0	6, 14, 12, 12
IC	NZ	a-DD^FFF	1.5	3.48	4.25 8.5	1.35 2.7	0.3	6 15 18
LS	NZ	aa-DD_FF-FF	1.2 1.12	3.31 3.23	5.6 3.5 6.45	1.78 1.35 1.35 1.35	-1.8 0	10 12 11 11
RG	NZ	aa-DD^ffpp	1.4	3.6	4.91 9.833	1.78 1.35 4	0.66	9 15 20
RG	NZ	a-DD^FFF^FF	1.4 1.4	3.6 3.6	4.25 6.5 5.25	1.4 2.7 1.35	0.1 -1.35 0	5 12 15 12

Task ID	Country ID	Vehicle ID (TAC sequence)	Load bed height (m)	Load height (m)	Wheel base (m)	Axle group spread (m)	Hitch offset (m)	Axle group weight (t)
PC	SEA44	a-D	1.2	2.4	6.06	NA	NA	7 10.62
BL	SEA	a-DD	1.2	2.96	4.34	1.4	NA	7 17
BM	SEA	a-DD	1.2	2.91	4.34	1.4	NA	7 17
IC	SEA	a-D^FF	1.5	3.23	3.7 7.7	1.25	0.66	6.5 11.5 16
LS	SEA	a-DD	1.2	3.92	4.34	1.4	NA	7 14
RG	SEA	a-DD	1.2	3.82	4.34	1.4	NA	7 15
PC	UK52	a-Df	1.2	2.4	7.335	1.4	NA	6 14.46
BL	UK	a-D^fff	1.4	2.8	3.9 7.7	2.7	0.6	6.5 11.5 22
BM	UK	a-D^fff	1.4	2.98	3.9 6.65	2.7	0.6	6.5 11.5 22
IC	UK	a-fD^fff	1.5	3.86	3.9 7.7	1.4 2.7	0.4	6 16 20.86
LS	UK	a-D^fff	1.4	4	3.9 7.7	2.7	0.6	6.5 11.5 22
RG	UK	a-D^fff	1.4	3.73	3.9 7.7	2.7	0.6	6.5 11.5 22

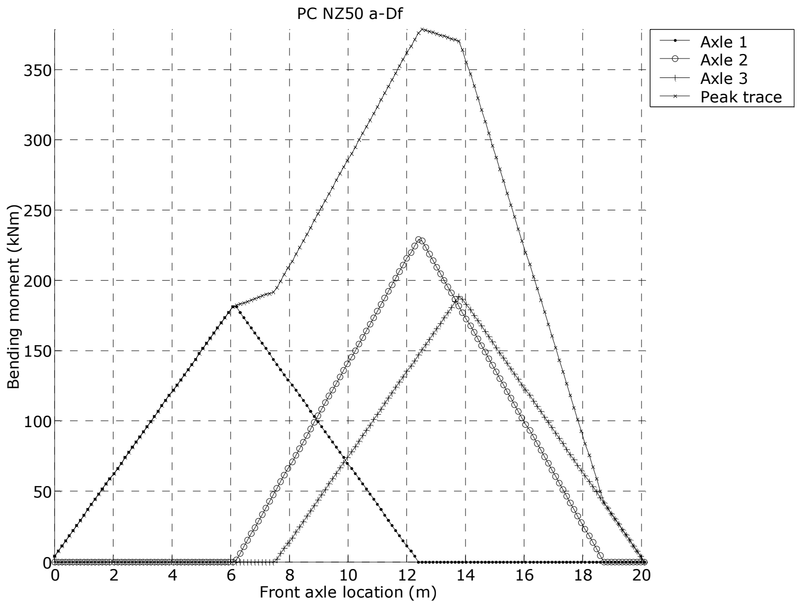
Note:

The coupling offset is its displacement from the centre of its rear axle group. By convention, a positive value indicates a displacement forward of this centre while a negative value denotes a rearward displacement.

The tow-eye and fifth wheel heights were set to 0.56m and 1.32m above the ground respectively.

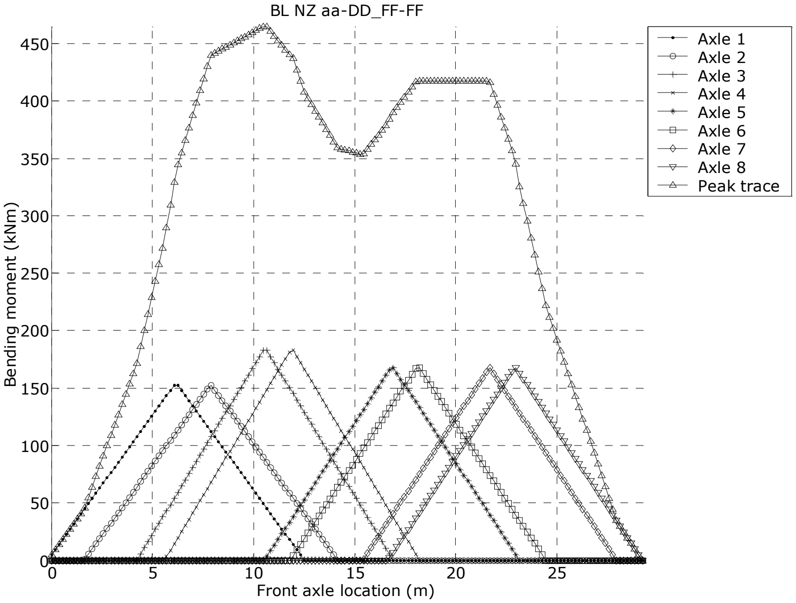
Appendix D: Bending moment figures

Figure D.1 Bending moment versus front axle location of New Zealand's baseline passenger coach as it traverses a simply-supported bridge spanning 12.5m



Span=12.50m, Peak moment=379kNm, Front axle location at peak moment=12.52m

Figure D.2 Bending moment versus front axle location of New Zealand's baseline bulk liquids truck and full trailer as it traverses a simply-supported bridge spanning 12.5m



Span=12.50m, Peak moment=465kNm, Front axle location at peak moment=10.48m

Figure D.3 Bending moment versus front axle location of the New Zealand refrigerated goods B-train as it traverses a simply-supported bridge spanning 12.5m

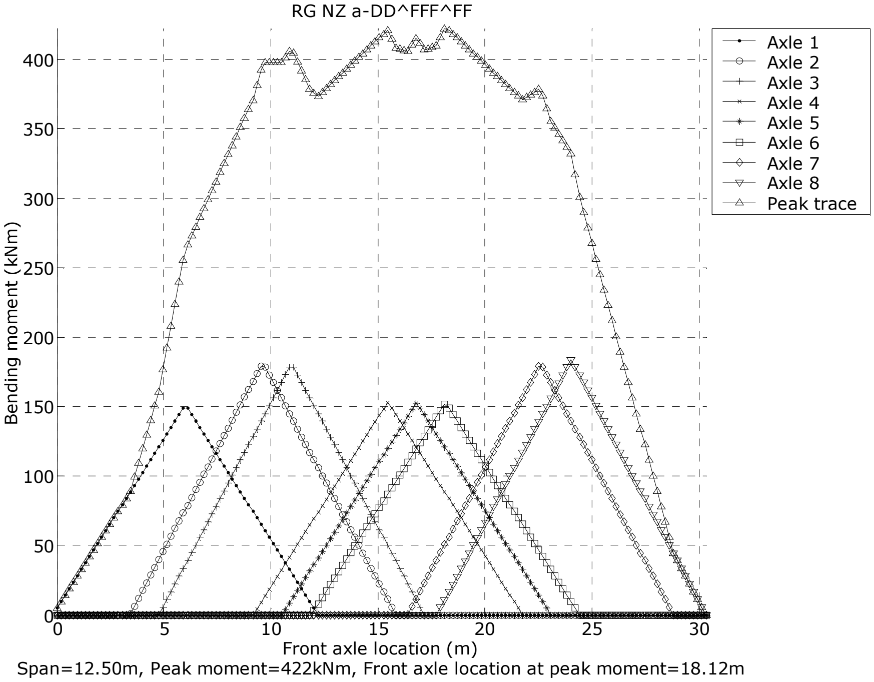


Figure D.4 Bending moment versus front axle location of the New Zealand baseline intermodal container tractor semi-trailer as it traverses a simply-supported bridge spanning 12.5m

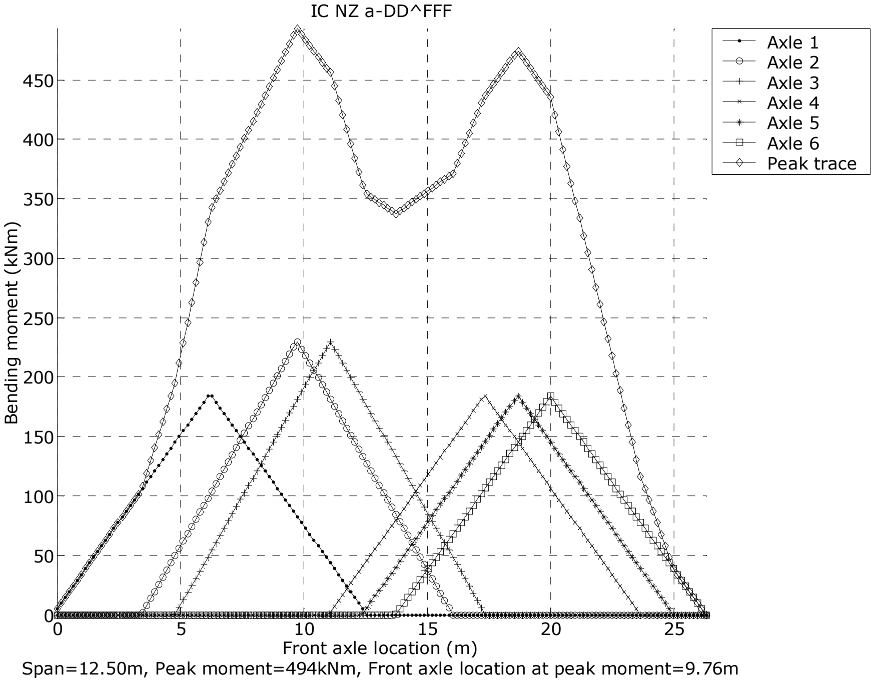
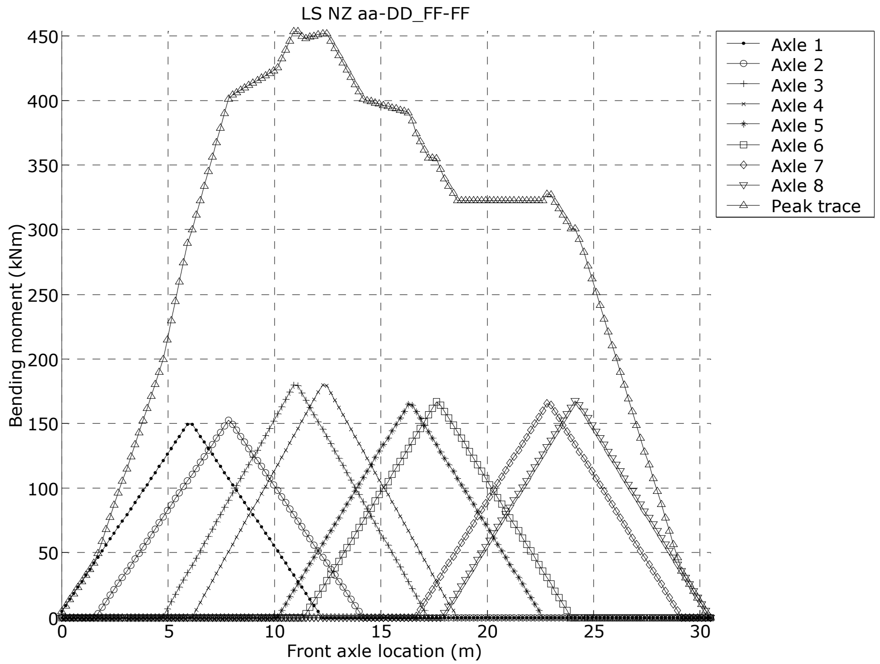
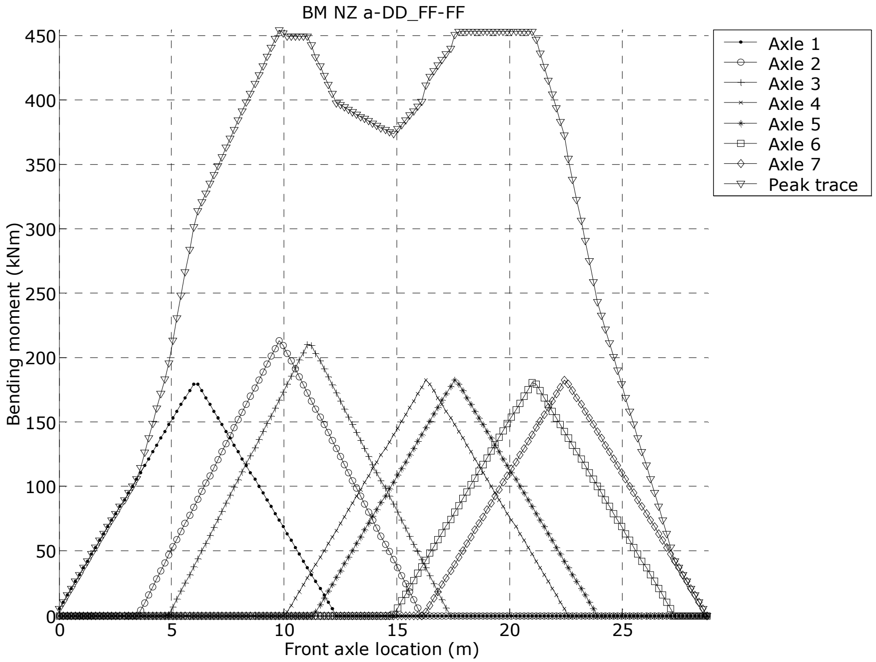


Figure D.5 Bending moment versus front axle location of the New Zealand baseline livestock truck and full trailer as it traverses a simply-supported bridge spanning 12.5m



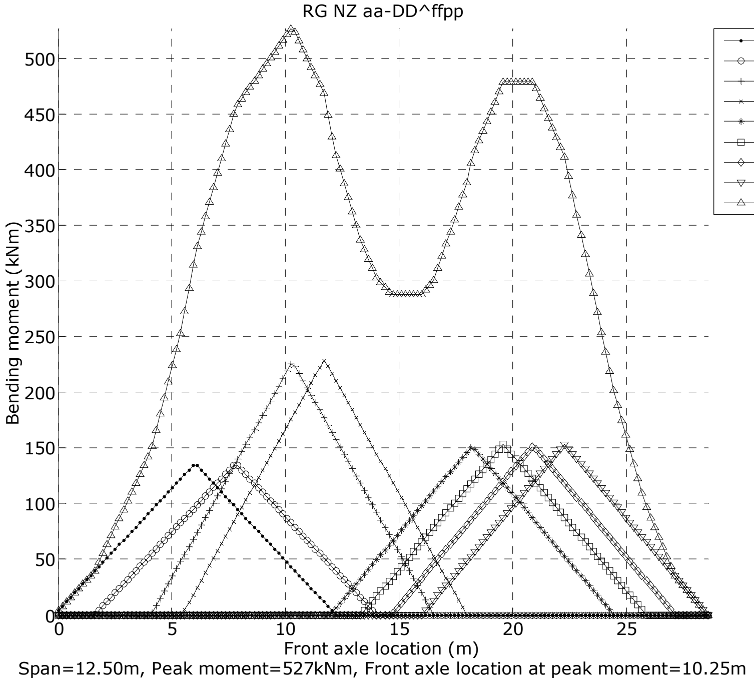
Span=12.50m, Peak moment=454kNm, Front axle location at peak moment=11.12m

Figure D.6 Bending moment versus front axle location of the New Zealand baseline bulk materials truck and full trailer as it traverses a simply-supported bridge spanning 12.5m



Span=12.50m, Peak moment=455kNm, Front axle location at peak moment=9.77m

Figure D.7 Bending moment versus front axle location of the New Zealand baseline refrigerated goods tractor semi-trailer as it traverses a simply-supported bridge spanning 12.5m



Appendix E: Performance measure relationships

Figure E.1 HSO versus LSO of the vehicles studied in this report

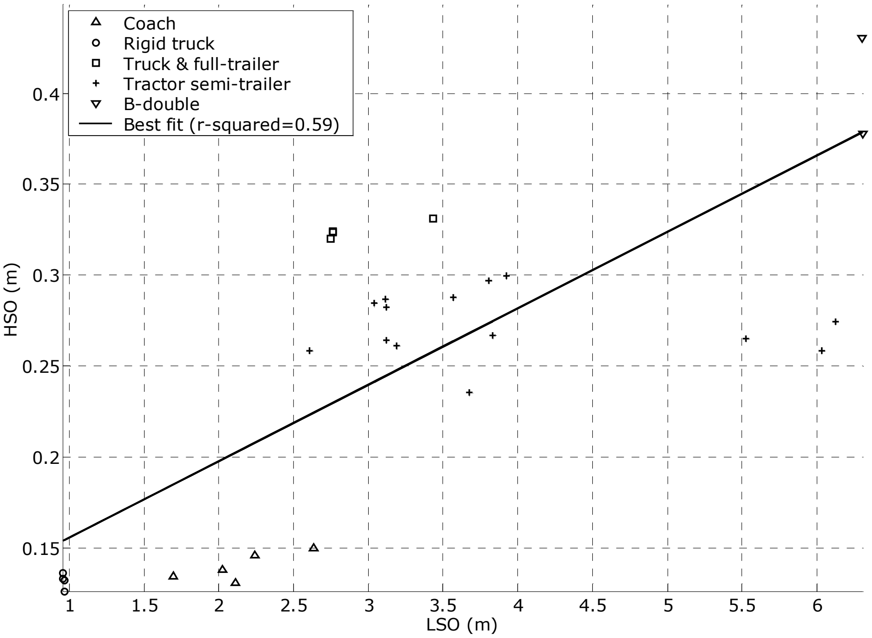


Figure E.2 LTR versus RA of the vehicles studied in this report

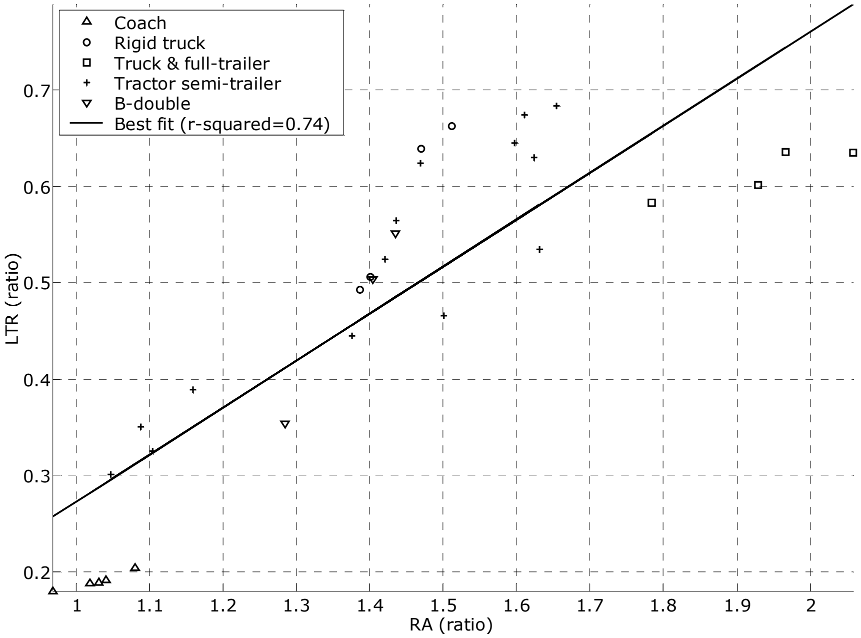


Figure E.3 HSTO versus RA of the vehicles studied in this report

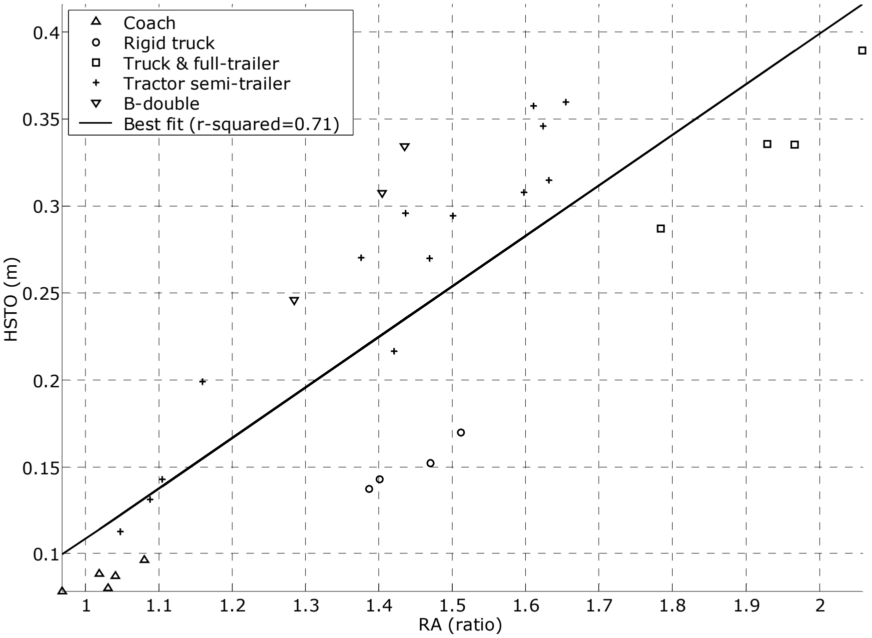


Figure E.4 SRT versus RA/LTR of the vehicles studied in this report