Figure - Distribution of New Zealand state highway bridges by span and class

OPTIMISATION OF NEW ZEALAND'S HEAVY VEHICLE FLEET

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Abstract

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. This study benchmarked the typical vehicles used for six transport tasks in New Zealand against the vehicles undertaking those same tasks in Australia, Canada, Southeast Asia, and in the United Kingdom. The benchmarking analysis considered four key aspects of heavy vehicle performance: pavement wear, bridge wear, road width occupancy and safety. Having established the performance of New Zealand vehicles relative to those in other jurisdictions, opportunities for improved performance through size and weight changes were evaluated.

Keywords: Heavy Vehicles, Freight Transport, Passenger Transport, Optimisation, Benchmarking, Performance Standards.

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, to improve safety, to reduce environmental impact and to reduce congestion. To achieve this aim, the study:

- identified six typical road transport tasks and established the typical vehicle configuration used to undertake each of those tasks in New Zealand
- identified the vehicle configurations used to undertake the same tasks in Australia (Au), Canada (Ca), Southeast Asia (SEA), and the United Kingdom (UK)
- developed a set of performance measures that characterise 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 currently prevent the best possible vehicles from being used
- identified new initiatives that could be introduced to produce better performance.

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
- bulk liquids
- bulk materials
- 40 foot ISO intermodal containers
- livestock
- refrigerated goods

Vehicle performance was assessed in terms of nine fundamental measures and four compound measures. The compound measures quantified key four aspects of heavy vehicle performance: pavement wear, bridge wear, road space and safety. All the compound measures were evaluated per unit of payload so that productivity is incorporated in the measures.

Because of space limitation this paper is only a brief summary of the study. A full description is available in the main report (Taramoeroa and de Pont, 2009) which is freely available on-line.

2. Methodology

1. Vehicles

Although there are several shorthand notation schemes in use for describing combination vehicles, none of these is capable of distinguishing the subtleties of the differences between some of the vehicle configurations used. Therefore we have developed a new notation which we call a TAC (tyre, axle, coupling) sequence. This notation uses a letter code for each axle where the letter describes the axle type and the tyre configuration. Between each letter code

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[1] In New Zealand 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. The schedule of charges is based on gross vehicle weight, axle configuration and distance travelled and is intended to reflect the costs imposed by the vehicle on the road transport system.

there is a symbol which describes the type of connection between the axles. The absence of a symbol implies the axles are part of the same group. The letters and symbols used are shown in Table and Table .

Table - Axle and tyre configurations with their designated letter symbols.

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

Table - Connection types and the designated character symbols.

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

Applying this system we can see that the sequence, aa-DD^ffpp, denotes a twin steer 4-axle tractor towing a 4-axle semi-trailer with the rear two axles being self-steering. The drive axles are fitted with dual tyres and all other axles are fitted with single tyres.

For the five jurisdictions considered, the vehicle configurations selected for analysis were as shown in Table and these were matched to the six transport tasks as shown in Table . It should be noted that there are significant differences in the size and weight regulations between the jurisdictions and thus there are corresponding differences in the payload capacities of the same vehicle configuration operating in different jurisdictions. For example, in four of the jurisdictions the typical coach is a 3-axle vehicle with a twin-tyred drive axle and a single-tyred tag axle. However, the passenger capacity varies from 50 in New Zealand and Australia to 55 in Canada because of differences in maximum allowable length and axle loads.

For the freight carrying vehicles, the payload capacities were determined from the weights and dimensions limits applicable in the country being analysed. In Australia and in Europe there are weight concessions for vehicles fitted with road-friendly suspensions. These were assumed to apply. The exception was Southeast Asia where most developing countries in 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 was 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 those of the European Community.

Table - Description of the selected vehicles and their notation.

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

Table - Description of the selected vehicles by country and transport task.

Task description	Country				
	Au	Ca	NZ	SEA	UK
Passenger coach	a-Df	a-Df	a-Df	a-D	a-Df
Bulk liquids	a-DD^FFF^FFF	a-DD^FF	aa-DD_FF-FF[#]	a-DD	a-D^fff
Bulk materials	a-DD_F-FF	a-DD^FFF	a-DD_FF-FF	a-DD	a-D^fff
Intermodal containers	a-DD^FFF	a-DD^FFF	a-DD^FFF	a-D^FF	a-fD^fff
Livestock	a-DD^FFF^FFF	a-DD^FF	aa-DD_FF-FF	a-DD	a-D^fff
Refrigerated goods	a-DD^FFF^FFF	a-DD^FF	aa-DD^ffpp	a-DD	a-D^fff

2. Performance Measures

Particular aspects of a vehicle’s performance can be characterised through the use of standardised performance measures. An issue that then arises is that improving one aspect of performance may cause another aspect to deteriorate. For example, improving a combination vehicle’s low speed manoeuvrability will generally worsen its high speed dynamic performance (Fancher and Winkler, 2007). This creates a problem of how to balance this trade-off and how to rank vehicles where, for example, one has superior low speed performance but inferior high speed performance.

In the analysis we identified three broad categories of vehicle performance that regulators would expect to manage. These are:

- Infrastructure impacts

- Road space requirements
- Safety performance

A fourth important category is environmental impact which was not considered explicitly but is incorporated implicitly to a degree through the productivity factor. Each of the compound measures developed for the other three categories includes payload so that higher productivity produces a better score. Thus, implicitly, vehicles with lower environmental impacts achieve a better ranking.

Within each category there are one or more aspects of vehicle performance, which can be characterised using performance measures that will contribute to the overall category rating. Category ratings were developed by combining the relevant performance measures.

Infrastructure Impacts

The main infrastructure impacts are pavement wear and bridge wear. Pavement wear was quantified in terms of **standard axle repetitions (SAR)** which represent the amount of accumulated pavement wear. The number of SAR applied by an axle or axle group is determined by the weight of the axle or group divided by a reference weight for that axle configuration raised to a power. The pavement design guide used in Australia and New Zealand (Austroads, 2004) specifies reference weights for the common axle group and tyre configurations and uses a fourth power to calculate the equivalent number of standard axle loadings for a given axle weight. The fourth power relationship has its origins in the AASHO road test undertaken 50 years ago in the USA (Highway Research Board, 1961). Although there has been some debate over the validity of a fourth power relationship for New Zealand pavements (Arnold et al 2005), it is still the basis for current pavement design and management practice in New Zealand and so we have used it for this analysis. The total SAR of a vehicle is the sum of the individual SAR produced by each of its axle groups. The measure of pavement impact used was:

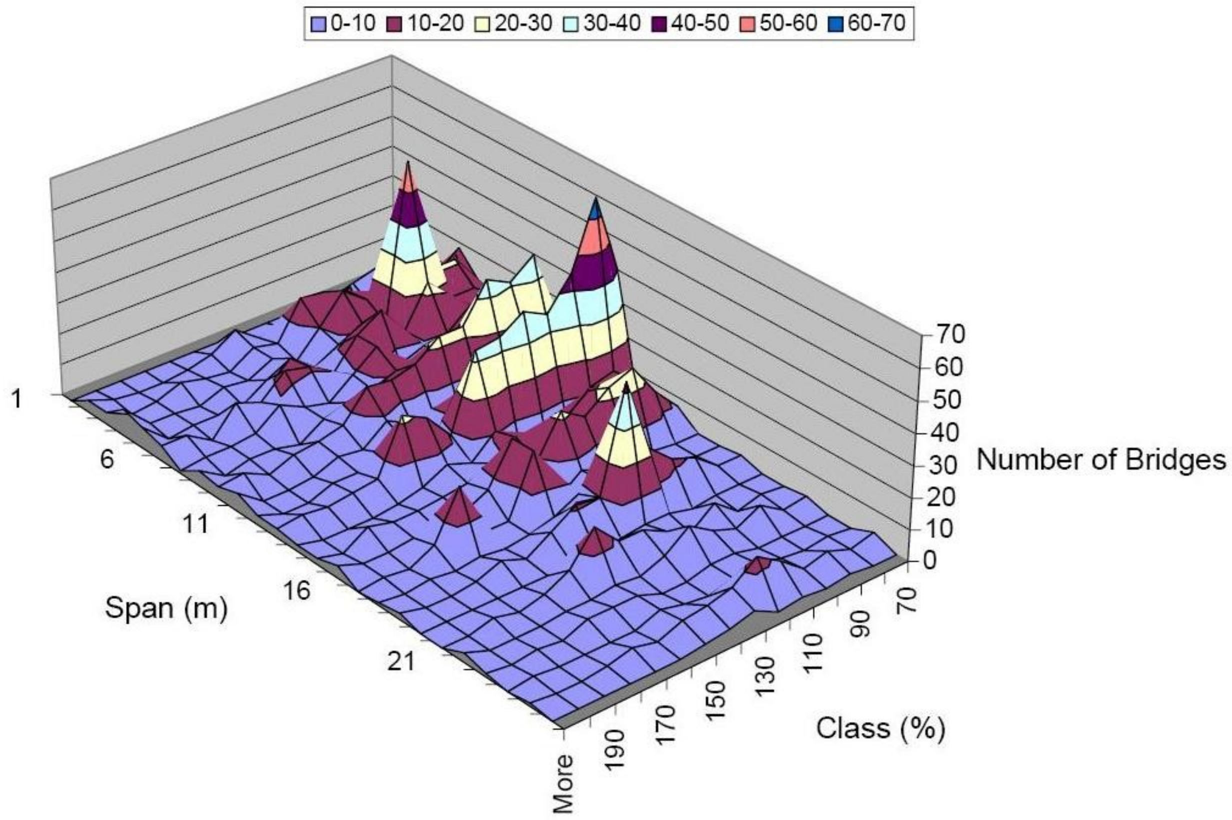
Pavement Impact= PayloadSAR

Based on experimental data and fracture mechanics principles, the 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 can be represented by the **peak bending moment (PBM)**. In this study, bridge wear is quantified in terms of the magnitude of the PBM raised to the third power.

Bridge Impact=PayloadPBM3

Lower values indicate better performance in terms of reducing the wear caused to the bridge infrastructure. Roberts and Heywood (2001) present an inventory of 2358 state highway bridges in New Zealand by span and class. These bridges can be characterised as follows:

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



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

In comparing the different vehicles and freight tasks, pavement and bridge impacts were considered separately. No attempt was made to combine the measures.

Road Space Requirements

There are two aspects to road space requirements. During low speed turns the path of the rear of the vehicle will track inboard of the path of the steer axle and that of the front of the vehicle. This offtracking is determined primarily by the vehicle geometry. This behaviour can be characterised using a performance measure called low speed offtracking (LSO). Several variations of LSO have been used in different studies. In this study we have used the following definition.

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. The LSO manoeuvre used is that defined in Schedule 8 of New Zealand's Vehicle Dimensions and Mass Rule 41001. This manoeuvre 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). It consists of a 9.8m radius 90° turn undertaken at 8km/h.

In high speed turns, the lateral accelerations generate lateral forces in the outward direction. These are balanced by forces in the opposite direction at the road-tyre interface. For the tyres to generate lateral forces requires a slip angle and thus the rear of the vehicle tracks outboard of the steer axle. The performance measure used to characterise this behaviour is **high-speed offtracking (HSO)** which is defined as 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 manoeuvre used for measured HSO in this study was that specified in the Roads and Transportation Association of Canada (1986) vehicle weights and dimensions study. This consists of a 393.2m radius turn undertaken at 100km/h.

In both cases the total road width required is the vehicle width plus the offtracking. To give an overall road space requirement indicator these two performance measures were combined as follows:

Road Space Impact=PayloadVehicle Width+LSO2.9x(Vehicle Width+HSO0.345))2

The subscript on the performance measures indicate that any vehicle with a score lower than that value is given the score for that value. That is LSO$_{2.9}$ means that any vehicle with an LSO value of less than 2.9m is given a score of 2.9m. The reason for this is that we assume that at the level of performance the vehicle will comfortably fit on the network and there will be no further gains from additional reduction in LSO. The reason for raising the score by a power is to increase the penalty for poor performance. Using a linear relationship did not provide sufficient "disincentive" for vehicles that would not fit on the existing network. Second power produces a relationship that seems reasonable.

SafetyPerformance

There are a number of performance measures that have been used to characterise the safety of vehicles. Some of the most important are:

Static roll threshold (SRT) is used to determine a vehicle's roll over stability during steady speed cornering. 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. 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.

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.

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.

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.

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.

The overall safety performance measure developed for this study is given by

Safety Impact=SRT32 .Payload(LTR x RA x HSTO)13

The three measures in the denominator all relate to the vehicle's performance during an evasive manoeuvre. The $^{1}/_{3}$ power was introduced so that the influence of this aspect of performance did not dominate the score. SRT appears in the numerator because increasing SRT implies better performance while for the other measures increasing value implies poorer performance. The exponent of $^{3}/_{2}$ applied to the SRT was selected so that, for the vehicles analysed, the graph of the inverse of the safety impact score versus SRT had approximately the same shape as the graph of relative crash rate versus SRT found by de Pont et al (2000). Yaw damping was not included in the measure because all of the vehicles in the study had acceptable YDR values (>15%) and de Pont et al (2000) found no clear relationship between YDR and crash rate for vehicles with this level of YDR.

3. Results

The study compared 30 vehicle-freight task combinations using nine specific performance measures and four category measures. It is not possible to present the full scope of the findings within this paper so we will limit ourselves to a selection of interesting results. For more detail the reader is referred to the technical report (Taramoeroa and de Pont, 2009).

With respect to pavement impacts, the New Zealand vehicles were the best performing for all freight tasks. This is not surprising because New Zealand has a weight-distance based road user charging regime in which pavement wear costs are allocated using the same fourth power relationship as was used to calculate the pavement impact rating in this study. An effect of the road user charging system is that it encourages operators to select vehicle configuration with more axles than are strictly needed to meet the weight regulations.

Interestingly Australia was in second place for pavement impacts for five of the six freight categories. For three of these freight categories this was due to the use of B-trains which are very productive and use tridem axle groups which are relatively road friendly. For bulk materials the Australian truck and dog trailer was better than the semi-trailers and rigid trucks used in the other jurisdictions while the passenger coach was better because of the lower axle load limits.

In terms of bridge impacts, the New Zealand vehicles again scored well being the best performers for three of the freight tasks and in second place for a further two. To some extent this is a reflection of the bridge formula in the New Zealand Vehicle Dimensions and Mass Rule. By international standards, the axle weight limits are relatively low and the axle spacings required relatively large.

For both the pavement impact and bridge impact measures the UK and South East Asia ranked poorly. The reason for this is that they allow relatively high axle loads but use relatively short vehicles with relatively low gross combination weights.

These characteristics are more advantageous when considering the road space requirements and the UK vehicles achieved the highest rank for four of the six freight tasks as well as second place in a fifth task. Interestingly the New Zealand vehicles achieved the top ranking in the other two freight tasks and were second for a further three freight tasks. The reason for this is that New Zealand uses truck and dog trailers extensively and these have good manoeuvrability together with reasonable payload capacity.

With regard to safety impact the Canadian vehicles achieve the best performance with the top ranking in four of the freight tasks and second ranking in the other two. The reason for this is that the Canadians use tractor semi-trailer combinations extensively which have very good safety performance. The UK also uses semi-trailers widely but their vehicles are shorter than the Canadian ones and thus tend to be less stable because the payload centre of gravity is higher. The New Zealand vehicles achieved one first place ranking, two second places, two third places and one fourth place. If the safety rankings for all freight tasks are summed, the Canadian vehicles are best with a score of 8 (four firsts and two seconds), New Zealand vehicles score 15, Australian vehicles 18, UK vehicles 19, and South East Asian vehicles 30.

4. Optimisation of Vehicle Configurations

The measures developed in this study provide a basis for identifying more optimal vehicle configurations. For example, if we consider the transport of bulk liquids. In New Zealand the typical vehicle configuration used for this task is a 4-axle truck and 4-axle dog trailer combination operating at 20m overall length and 44-tonne gross combination weight. In the international comparison, using the four compound performance measures, this vehicle ranked first for pavement impacts, bridge impacts and road space requirements but only fourth for safety.

There have been proposals from various industry sectors to increase the allowable gross combination weights. Typically these would allow this vehicle to operate at 50-tonne. If we increase the gross combination weight to 50-tonne without changing the vehicle's dimensions we find that the road space impact measure improves because the road space requirements are unchanged and the vehicle carries more payload. However, the other three measures all deteriorate. That is, the decline in performance is greater than the productivity gain and so the combined effect is negative. The decline in the two infrastructure impact measures is not too serious for two reasons. First, the vehicle is best performer internationally in this regard and retains the number one ranking after the weight increase. Second, in New Zealand the cost of infrastructure wear is recovered directly from the road users using the same pavement impact model. Thus the truck operator will incur higher road user charges for the additional weight and thus will not use the weight capacity if it is not profitable to do so. However, the decline in safety performance is more serious. The vehicle already has a low international ranking in this regard.

However, if we increase the vehicle's length in conjunction with the weight increase we can improve its safety. For example, if we consider a 23m long vehicle operating at 50 tonne. In this we need to allow extra tare weight for the extra length and so the productivity gain is not quite as high. This vehicle achieves a gain in safety performance and a gain in bridge impact performance but loses road space performance and pavement wear performance. However, it retains its number one ranking internationally for both these aspects while improving its safety ranking and thus is a better vehicle than the original.

The previous discussion has shown how the composite performance measure can be used to develop better vehicle configurations for a given freight task. This is not a true optimisation because we have no means of comparing the relative importance of the different aspects of performance. For example, increasing vehicle length will generally increase the road space requirements (worsen the road space impact measure) but reduce the bridge impacts (improve the bridge impact measure). Where does the balance lie?

To overcome this we need to scale the measures to a common basis and common units. The most obvious unit is economic cost. However, this is not a trivial task. The infrastructure impact measures are probably the simplest to address. The annual cost of pavement and bridge maintenance is known and, in New Zealand, has been allocated to the various road user groups in order to calculate the schedule of road user charges. Thus we can estimate a dollar cost per SAR and per PBM[3]. Determining the cost of road space requirements and allocating them to road users is more complicated. Although it can be argued that the road space that must be provided is determined by the requirements of the worst performing legal vehicle and that any vehicles with lesser road space requirements impose no additional cost this is too simplistic. Heavy vehicles with higher road space requirements are more likely to cause damage to kerbing, pavement edges and roadside furniture which incurs costs. However, this is difficult to quantify and this has not been done. Safety is even more difficult to cost. In New Zealand, government agencies use a social cost of crashes (Ministry of Transport, 2009) to undertake cost-benefit analyses of road safety interventions. This value (currently $3.53M for a fatality) is determined by public survey and represents the amount the public is “willing- to-pay” to prevent a crash. However, these values are much lower than the economic benefits the public “willing-to-accept” for an additional crash. In practice, it is rare that any measure is introduced that can be shown to decrease safety even if there were substantial benefits. To assign a dollar value to the safety impact measure we first need to determine the effect of the safety impact score on crash rates which is very difficult and then we need to apply the costs associated with the crashes in a non-linear way so that the effect of an increase in crash rate is not just the opposite of the effect of a reduction in crash rate.

These issues have not yet been resolved.

5. Conclusions

This study has developed heuristic composite performance measures for comparing categories of performance of different vehicles. These measures were applied to the typical vehicles used for each of six transport tasks in five jurisdictions. This enabled us to compare the performance of New Zealand vehicles with those used for the same freight task elsewhere.

In most respects the New Zealand vehicles performed very well compared to their international counterparts. The main aspect of performance where they were not so strong was safety, although on an overall ranking they were in second place.

The composite performance measures provide a mechanism for developing vehicle configurations with better performance and hence moving closer to the optimal vehicle for the task. However, for true optimisation it is necessary to scale the composite performance measures and convert them to a common unit of measure so that the trade-offs between them can be reasonably compared. Significant further work is required to achieve this.

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