TRANSPORT ENGINEERING RESEARCH NEW ZEALAND LIMITED

HEAVY VEHICLE STABILITY

VERSUS CRASH RATES

A REPORT PREPARED FOR

THE LAND TRANSPORT SAFETY AUTHORITY

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By

T.H. MUELLER

J.J. DE PONT

P.H. BAAS

Acknowledgments

We are grateful for the help and cooperation from a number of people and organisations where efforts were essential for the success of this project. In particular, we would like to acknowledge the LTSA, Ron McGann for his LATIS navigational skills and general detective work, Doug Latto for his expert heavy vehicle dynamics expertise and Don Hutchinson for his guidance, patience and commitment to improving heavy vehicle safety.

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Executive Summary

This report examines and compares performance measures of the New Zealand Heavy Vehicle Fleet with those involved in crashes classified as rollover or loss of control

Linear regression techniques were used to find relationships between vehicle performance measures calculated by computer simulation and vehicle parameters. Algorithms were developed to assess vehicle performance measures based on simple and easily obtainable vehicle parameters.

The algorithms were then applied to a sample of vehicles obtained from the Road User Charge (RUC) surveys to determine the distribution of these performance measures among the general fleet of combination vehicles and to a second sample obtained from the Commercial Vehicle Inspection Unit (CVIU) crash reports of combination vehicles involved in rollover/loss of control crashes. By comparing the distribution of a performance measure for the crashed vehicles with that for the general fleet we can see whether there is a relationship between the performance measure and the crash rate.

The results clearly indicate that vehicles with lower measures of Static Rollover Threshold (SRT), higher Dynamic Load Transfer Ratios (DLTR) and low Yaw Damping Ratios (YDR) have a higher likelihood of being involved in a rollover crash. Overall, the stability of the New Zealand fleet is good, 85% of the fleet meet the suggested SRT performance target of 0.35 g (Figure 1 below). Furthermore, all of the vehicles included in the survey met or exceeded the suggested High-Speed Transient Off-tracking (HSTO) minimum performance values. However, it is clear that a small percentage of low performing vehicles are contributing disproportionately to the overall number of crashes. With the exception of HSTO, the proportion of vehicles not meeting suggested minimum performance value targets is greater among the crashed vehicles than among the fleet, suggesting a clear correlation between poor performance and crash rate.

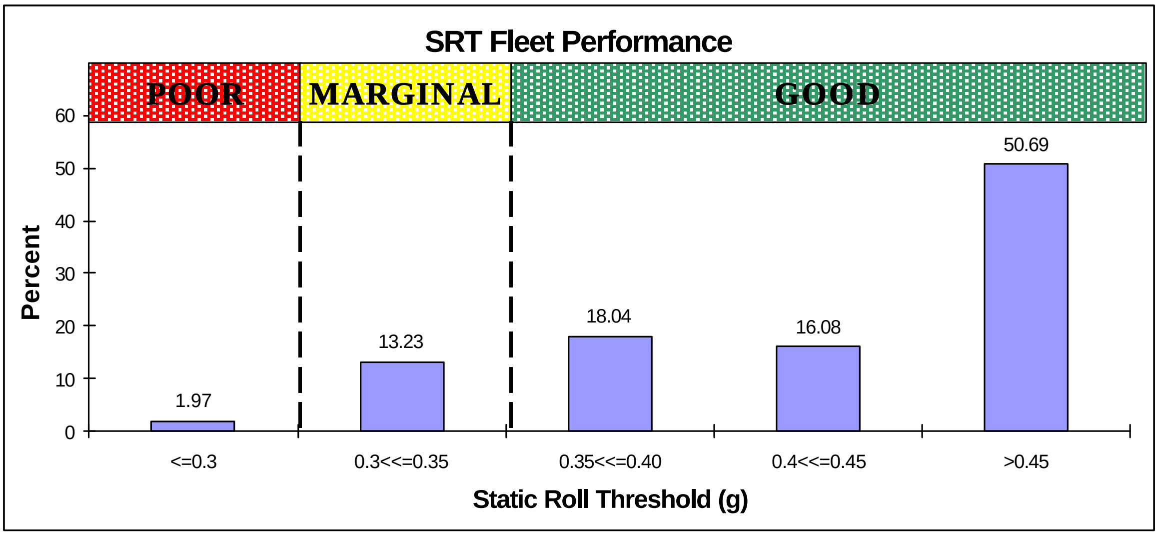

Figure 1. SRT Fleet Performance

From this analysis we see that 15% of the fleet have below minimum target values of SRT and contribute to 40% of the stability related crashes. The results also show that 35% of the fleet do not meet suggested minimum DLTR requirements, contributing to 58% of the stability related crashes. However, only 2% of the fleet fail to meet the suggested minimum performance measure for the Yaw Damping Ratio. Perhaps the most striking result from this profile, is the relationship between SRT and the likelihood of a rollover or instability crash for the poorer performing vehicles. Those vehicles with an SRT of 0.3g or less have more than 3 times the crash rate than the rest of the fleet. Figure 2, below, illustrates this relationship.

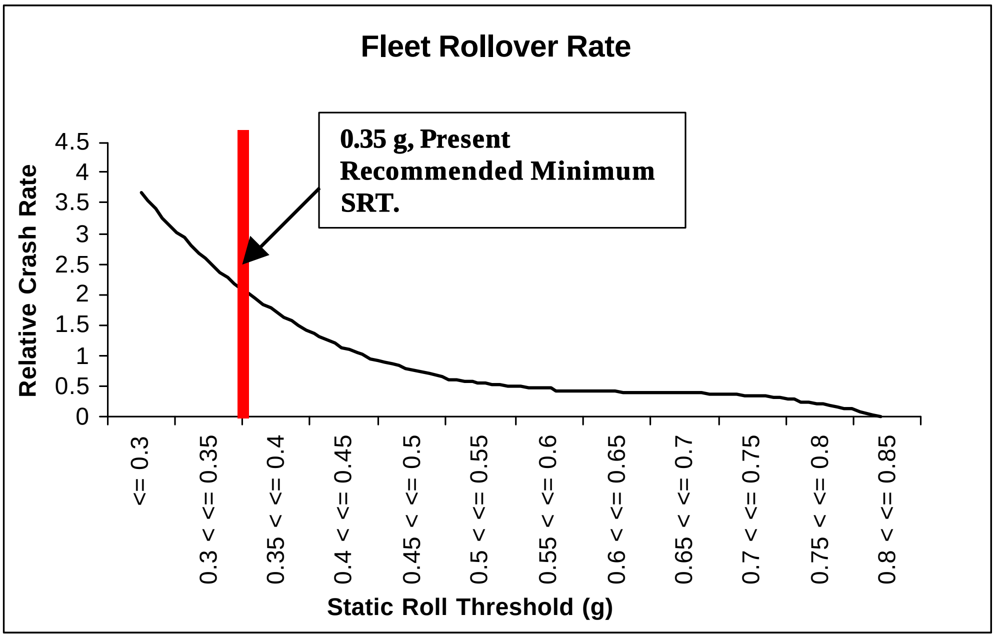

Figure 2. Relative Crash Rate of Fleet, SRT.

Figure 3 below, also suggests a trend that as the High-Speed Transient Off-tracking increases, the crash involvement rate also increases.

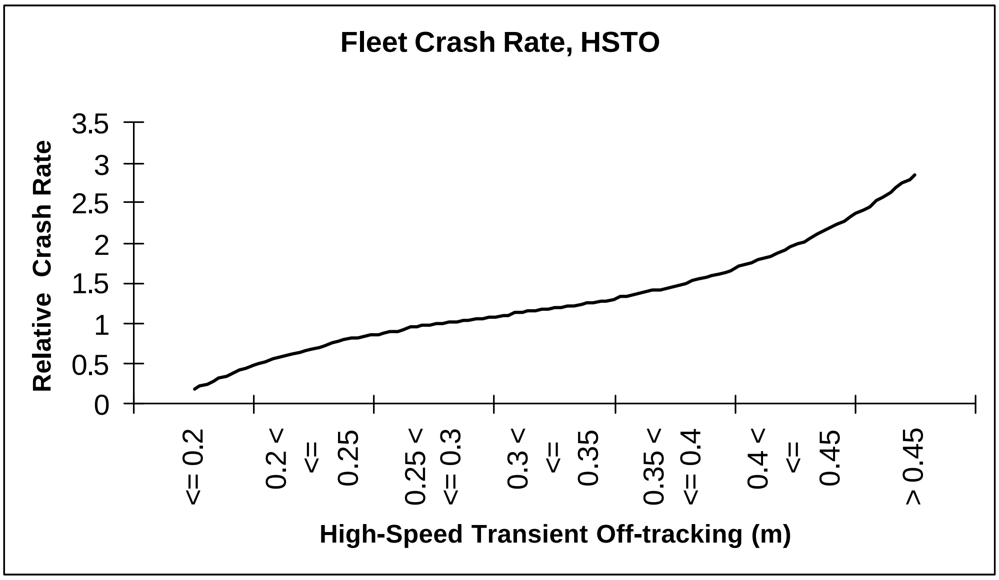

Figure 3. HSTO Relative Crash Involvement Rate.

Similarly the trend for Dynamic Load Transfer Ratio shows an increase in crash rate as DLTR increases, Figure 4 below.

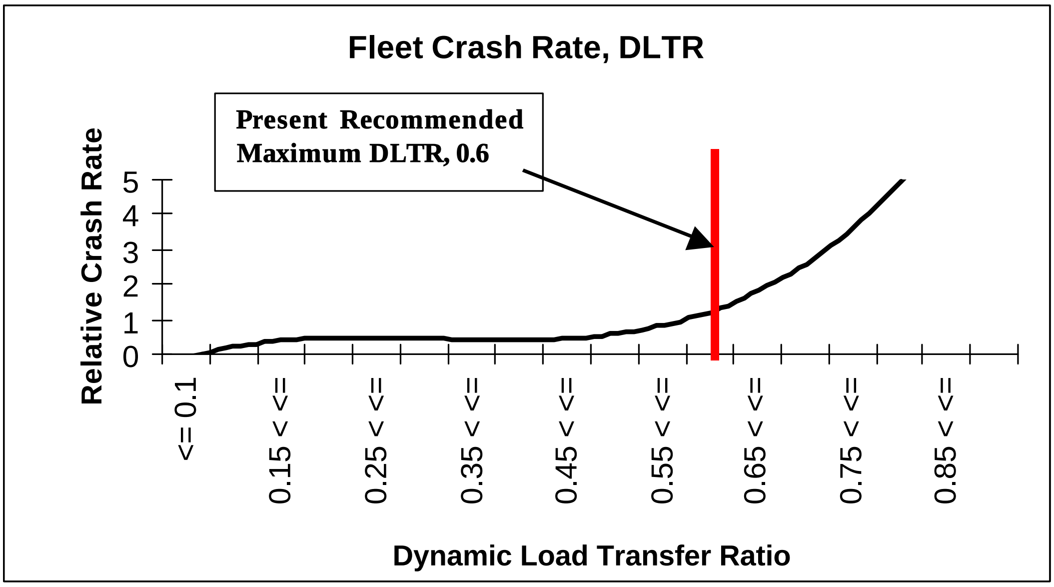

Figure 4. DLTR Relative Crash Involvement Rate

For the 182 vehicles that CVIU reported as having lost control or rolled over, 8 were fatal, 21 involved serious injury, 44 minor injury, 105 property damage only and 4 had no outcome noted. The social and material damage attributable to these crashes totalled $103,155,152 or $39,931,026 per annum. Further analysis indicates that it would be worth spending $22,800 on improving the stability of new combinations and $14,050 to an existing vehicle whose SRT is less than 0.3 g. It would be worth spending $12,700 on new and $7,800 on existing combinations with less than 0.35 g SRT.

The vehicle performance estimates described in this report are useful in describing the overall fleet performance. Caution should be exercised when trying to profile or measure an individual vehicle using these regression formulae alone. The formulae are the result of a statistical profile and it is possible to have vehicles which do not fit the profile. However, the potential exists, based on this report and the methodologies developed to augment the database over time, thus increasing accuracy and predictive usefulness.

1.0 Introduction

The number of crashes involving heavy vehicles (HV) in New Zealand is high compared to Australia, the USA and Europe. During the first 8 months of 1998, 21 percent of the deaths on NZ roads involved a heavy vehicle (LTSA 1998). This figure is an increase from 1997 when 18 percent of the deaths involved a heavy vehicle. On a distance basis trucks have over 3 times the fatal crash involvement rate of other vehicles given that they accumulate 6.2 percent of the total distance travelled on the road (LTSA, 1996). By comparison, in the USA heavy vehicles accumulate 7 percent of the distance travelled (similar to NZ), but are involved in only 8 percent of the fatal crashes and 3 percent of all crashes (Clarke, 1998) .

A particular concern is the high number of HV rollover crashes. A rollover occurred in 190 (29 percent) of the 650 HV crashes the NZ Police Commercial Vehicle Inspection Unit (CVIU) attended from July 1996 to March 1998. This rate (29%) may be higher than the actual rate because CVIU place some priority on attending the more serious crashes. On the other hand, the actual number of rollover crashes will have been higher than this as CVIU are only able to attend a limited number of crashes (Willink, 1998). In the USA in 1995, rollover occurred in 3.4% of the reported large truck crashes. Similarly in the Netherlands, with a much higher population than New Zealand, there is concern about the 100-rollover crashes which occur there every year. Although direct comparison of rollover rates is inappropriate between countries, it does appear as though New Zealand has a higher incidence of rollover crashes than other developed countries.

This report examines the performance measures of three vehicle combinations, B-Trains, Truck-Trailers and Tractor-Semis, from the New Zealand Heavy Vehicle fleet. Comparisons are made with similar vehicles involved in crashes attended by the CVIU, classified as either unstable or a rollover. In addition, relationships are shown between the pertinent stability parameters and crash risk similar to those derived from US data (Clarke, 1998).

Single truck units were omitted from the analysis due to inherent bias in CVIU reporting (Willink, 1998). A-Train combinations were also omitted from this investigation since they represent a very small proportion of the HV fleet (Baas, 1999) and there were no A-train instability or rollover crashes identified in the CVIU reports.

Simplified analytical methods were developed using linear regression techniques to determine the relationships between the performance measures of interest and the vehicle parameters which could be obtained or estimated from both the Ministry of Transport (MOT) Road User Charges (RUC) survey and CVIU databases. This method is similar to that described by Winkler (1993). The regression models were derived using data held at TERNZ. These are the results from a number of years of analysis and testing, using the validated UMTRI computer simulation program, Yaw/Roll (Gillespie, 1982). The methods were then applied to both the RUC and

CVIU databases to obtain distributions of the performance measures for both the general fleet and the crashed vehicles. From these two distributions we can estimate the relative crash risk for different values of the performance measure.

The TERNZ data base does not represent the entire New Zealand Heavy vehicle fleet. The analyses were undertaken for a number of reasons including 44 tonne A-Train certification, mass ratio studies, accident investigations and various other research projects. There is a fair selection of simulated vehicle combination data which includes A-train milk tankers, logging rigs of various size and configurations, as well as general freight B-trains and truck-trailer arrangements, but the distributions of weights and dimensions or configuration numbers are not necessarily representative of the fleet.

It is recognised that having a database specifically designed for this project on which to perform the regression analysis would have been better but it was beyond the time and cost framework of this project to undertake analysis on all the vehicles which were not currently held.

1.1 Performance Measures

The performance measures that were examined in this study include Static Rollover Threshold (SRT), High Speed Transient Off-tracking (HSTO), Dynamic Load Transfer Ratio (DLTR) Rearward Amplification (RA), Yaw Damping Ratio (YDR) and High-speed Steady-state Off-tracking (HSO). A description is provided below in Table 1.

Table 1. Performance Measures

Performance Measure	**Brief Description**
Dynamic Load Transfer Ratio (DLTR)	Indication of nearness to rollover in a highway-speed evasive steering manoeuvre. It measures the transfer of load from one side of the vehicle to the other.
Rearward amplification (RA)	Ratio of lateral acceleration of the rearmost trailer of a combination to that of the prime mover during an evasive steer manoeuvre. Increasing RA reduces safety. RA and DLTR are closely related.
Static Roll Threshold (SRT)	Maximum steady turning lateral acceleration without rollover.
High-Speed Transient Off-tracking (HSTO)	Lateral offset between trajectory of lead and trailing units in a highway-speed evasive manoeuvre. This indicates the amount of additional road space used by the vehicle combination in an avoidance manoeuvre.

Yaw Damping Ratio (YDR)	Rate at which trailer oscillations dampen out. This measure is related to what is commonly known as snaking.
High-Speed Steady State Off-tracking (HSO)	Maximum off-track distance between any axle relative to the first axle of the vehicle. Similar to HSTO but transients are eliminated.

The first three performance measures (DLTR, RA, and SRT) have evolved as being the principal indicators of crash risk. These metrics describe aspects of a vehicle's basic or inherent propensity to roll over when turns or out-of-the-ordinary crash avoidance lane-change manoeuvres are attempted (Clarke, 1993). In an analysis correlating performance measures such as these, Sweatman et al (1993) report that static roll stability is the single most "representative" performance measure. Hence, SRT was the performance measure of greatest interest when classifying the stability of the New Zealand Heavy Vehicle fleet.

1.2 Performance Targets

The performance target values generally used in New Zealand are 0.35 g minimum Static Rollover Threshold, 0.60 maximum for Dynamic Load Transfer Ratio and 0.15 as a desirable minimum level for Yaw Damping Ratio (White, 1996). Values below 0.8 m are also recommended for High-Speed Transient Off-tracking (Baas, 1997).

2.0 Methodology

Three sets of data were used. The first consisted of vehicles in the TERNZ database. The second set was from the New Zealand Ministry of Transport (MOT) 1998 Road User Charges (RUC) roadside survey and the third set was from the New Zealand Police CVIU database. As outlined previously, the TERNZ data were used to develop the methods for estimating the performance measures. The overall distributions of the performance measures for the New Zealand fleet was determined from the RUC data. Once vehicles were identified to be included in the analysis, vehicle specific details (make, model, tare, axle configuration, tyre information and overhang) were obtained through a search of the LAnd Transport Inspection System (LATIS) database and a faxed questionnaire to transport operators. From these parameters the performance measures were estimated. Similarly, the CVIU database and LATIS were used to determine the performance measure values for the crashed vehicles.

2.1 TERNZ Database

All data obtained from the TERNZ database was developed using the UMTRI Yaw/Roll simulation program (Gillespie, 1982). Generally, these vehicles were fully laden though for the mass-ratio studies individual units could be lightly laden or even empty.

Data from more than 50 vehicles, contained within the TERNZ database formed the basis of the regression matrix. Linear regression techniques were applied to ascertain relationships between the performance measures and a range of vehicle parameters. Parameters which were not significant were eliminated and coefficients were determined for those remaining. These coefficients were then used to form a linear equation which was applied to vehicles in the RUC and CVIU databases to calculate the performance measures.

The following vehicle parameters were obtained for each vehicle combination:

- Axle Configuration (S TT, TTT, T T, etc.)
- Tyre Brand, size and type
- Suspension type (air or steel)
- Gross Vehicle Weight for each unit
- Vehicle Tare Weight for each unit
- Wheelbase for each unit
- Forward Distance
- Payload C of G
- Payload Type (load carried)

In undertaking the regression analysis suspension type and tyre information was not used since they were not consistently available for the other databases (RUC and CVIU).

2.2 RUC Survey Data

The RUC survey data consisted of 3159 cases spanning a period between 1 August 1997 through the 23rd of December, 1998. Of those, 2191 cases were not suitable for the purposes of this study (not heavy vehicles, no registration number information, etc.) and so the data set was reduced to 968 suitable vehicle combinations. From 968 cases, only 230 owners were able to be identified through the fax directory, hence a questionnaire was sent by fax to 230 organisations, requesting details about the load height, weight, suspension and tyres of specific vehicles identified in the RUC survey (the questionnaire and covering letter are included in Appendix A).

Out of the 230 organisations contacted, 99 responded, resulting in data for 187 laden vehicle combinations. To bring the total up to approximately 300 combinations, a further 109 were randomly selected and their details obtained from LATIS. These 109 additional vehicles are used to make up the empty vehicles in the fleet. The current RUC survey appears to have not included empty vehicles, while earlier RUC surveys (White, 1996) identified roughly a 30% empty vehicle tally.

Table 2. RUC Survey Results

Combination	Laden	Empty	Total Number
Rigid Truck	43	32	75
A-Train	2	0	2
B-Train	18	31	49
Truck-Trailer	99	30	129
Tractor-Semi	25	16	41
total	187	109	296

Table 2 shows the mix of vehicle configurations in the data. For a number of reasons this distribution is not representative of the proportions of these vehicles in the fleet.

Performance measures were calculated separately for each combination type and for empty and full vehicles. To obtain the distribution for a combination type the full and empty vehicle results were combined in the ratio 0.7:0.3. The distributions for the different combinations were then combined to obtain a fleet distribution using a weighting of 0.34:0.54:0.12 for tractor-semi:truck-trailers:B-trains. These ratios come from fleet profile data by Baas and Arnold (1999) in a study commissioned by the Road Safety Trust.

2.3 CVIU Data

The CVIU Large Bus & Truck Crash database was examined to obtain vehicles which had been involved in a crash involving rollover or loss of control. Incidents from 3August 1996 through 11 February 1999 were used and out of 182 classified as rollover or loss of control, 161 contained enough pertinent information to be analysed in accordance with the parametric analysis developed. Table 3 provides a breakdown of the actual numbers of vehicle combinations analysed.

Table 3. CVIU Vehicle Combinations

Combination	Number
A-Train	0
B-Train	23
Truck-Trailer	101
Tractor-Semi	37
total	**161**

Table 4 lists the injury totals for the 182 crashes attributed to rollover or loss of control. These figures reflect the total incidents recorded for all vehicle combinations, Truck Trailer, B-Train and Tractor-Semi including those not analysed because of a lack of vehicle parameter data.

Table 4. Injury Severity

Injury Severity	Number
Fatal	8
Serious	21
Minor	44
None	105
No Information	4
total	**182**

2.4 Assumptions

In calculating the performance measure estimates for both RUC and CVIU database vehicles, some assumptions had to be made. In making these assumptions the approach was to be conservative and to adhere to legal load requirements and regulations (Baas, 1997; LTSA, 1997), although there is anecdotal evidence that suggests that this is not always the case in practice. Hence, the predictions of performance parameters will tend to be conservative, erring on the side of better performance.

Assumptions when distributing the load and (or) assigning individual vehicle weights ;

1. The load was distributed between all payload carriers (truck-trailer, trailer-trailer, etc.) such that the percentage of payload capacity used is the same for each unit. Essentially, the load is split. An example is provided in Appendix B.
2. Unless otherwise noted in the CVIU report, no load will be made illegal or over dimensioned.
3. If a tare weight was not available then a tare weight is assigned to the vehicle based on a similar vehicle in the vehicle fleet (ie. model, make, number of axles, etc.).
4. Similarly, for wheelbase and forward distance. If data was unavailable (LATIS) then dimensions from similar makes and models were used.
5. The load centre of gravity (CoG) heights had to be estimated. The estimate of CoG height was founded on two criteria, the loading condition of the vehicle and the type of load being carried. These were based on "common loading scenarios" , presented in, *Course on The Mechanics of Heavy-Duty Trucks and Truck Combinations* (UMTRI, 1988, pp 19-38, 19-39). A diagram is

provided in Appendix C of load examples and mass centre height dimensions. Centre of gravity estimates were applied consistently across all loads for both RUC and CVIU data, although load height information was obtained for the RUC vehicles.

6. In calculating tare CoG it was assumed that drive axles weigh 1040 kg, trailer axles weigh 800 kg and steer axles weigh 540 kg. Axles were assumed to have a CoG height of 0.51 m. The tare sprung mass was assumed to have a CoG of 1.1 m for trucks and 1.8 m for trailers. No consideration was given to lowered CoG due to small tyres because tyre data was not consistently available for all databases.
7. The track width, the spacing between the tyres, was chosen to be 2.13 m. There is some vagueness in the literature describing effective track widths. Essentially one of two widths has been used in previous studies. Either the outside edge of a dual set of tyres or the centreline width of the gap between the set of duals. In this analysis, the track width of 2.13 m represents the distance between the centrelines of the outside tyres on the set of duals. A constant value was used in the absence of better information.

3.0 Results & Discussion

An attempt was made to analyse all six of the performance measures listed in Table 1. However, for two of the measures (Rearward Amplification and High-Speed Steady-state Off-tracking), it was not possible to obtain a satisfactory regression fit using the TERNZ database and the vehicle parameters available.
The methodology used to calculate Static Rollover Threshold, the performance measure regression analysis plots and their resulting coefficients are provided in Appendix E.

The figures below represent the overall Heavy Vehicle Fleet profile with regard to the following performance measures; Static Roll Threshold, Dynamic Load Transfer Ratio, High-Speed Transient Off-tracking and Yaw Damping Ratio. All vehicles, B-Trains, Truck-Trailers and Tractor-Semi's are included in an aggregate profile. The results for individual combinations are provided in Appendix D.

3.1 Static Roll Threshold

Below, in Figure 5, we see the fleet SRT distribution. The higher levels of SRT, roughly above 0.8 g, are a result of the empty vehicles in the fleet. The desirable minimum value is 0.35 g and so we see that approximately 15% of the vehicles fall below this.

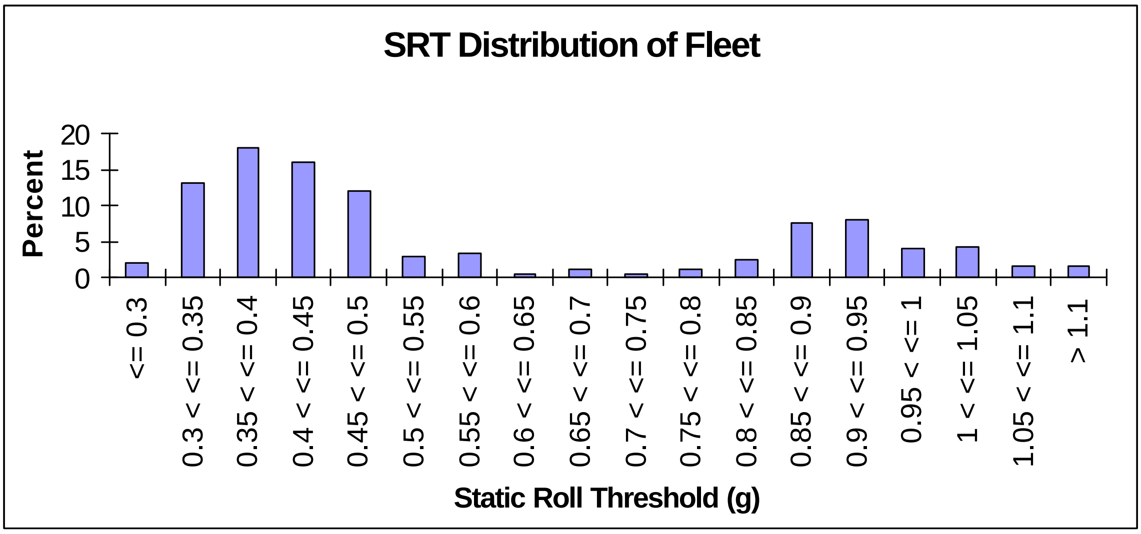

Figure 5. SRT Fleet Distribution.

Figure 6 is a redistributed version of Figure 5. The SRT values are reported in a simplistic form, good, marginal and poor (Baas, 1997). From this we see that about 85 percent of the fleet exhibited good (greater than 0.35 g) Static Roll Threshold performance.

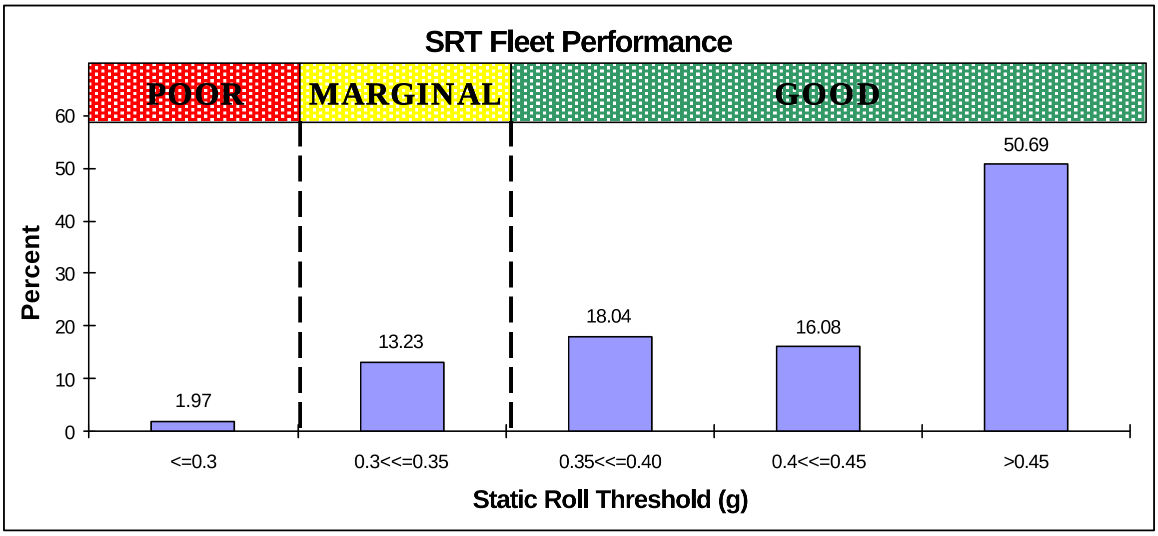

Figure 6. SRT Fleet Performance.

Figure 6 also indicates that 13 percent of the fleet had marginal SRT results (between 0.35 g and 0.30 g) and just under 2 percent of the fleet exhibited poor SRT results (less than 0.30 g).

For the vehicles involved in a crash due to instability or rollover, Figure 7 indicates that roughly 40 percent had Static Roll Thresholds of less than 0.35 g. Out of these, 8 percent had poor SRT's, less than 0.3 g.

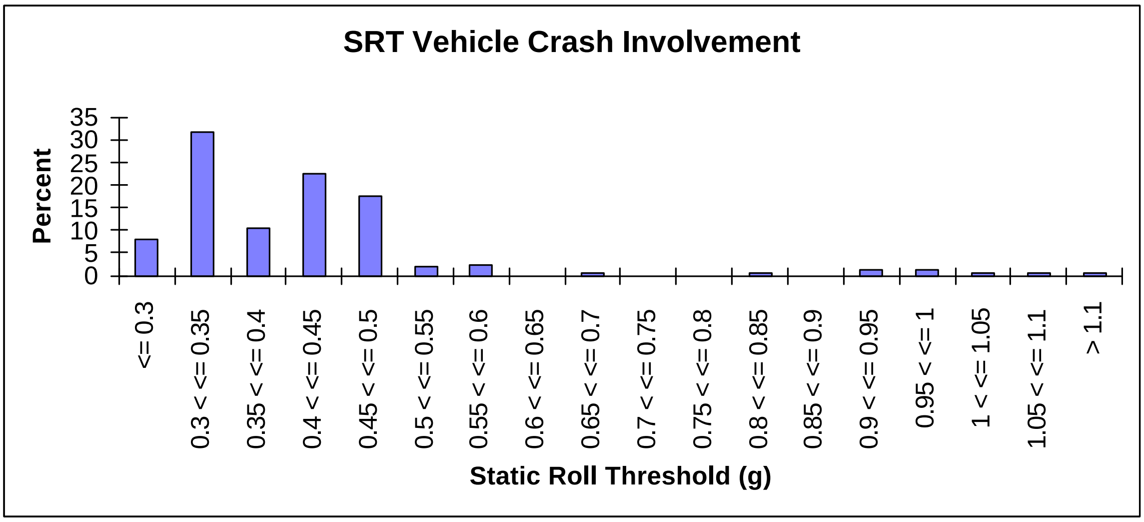

Figure 7. SRT Crash Involvement Distribution.

One of the more significant results highlighted above is that by targeting about 15 percent of the fleet (those vehicles with less than 0.35 g SRT) we focus on 40 percent of the rollover/vehicle instability crashes. Although 0.35 g is the target SRT, more than 50% of the heavy vehicles involved in rollover or loss of control related crashes had an SRT of 0.4 g or less.

Figure 8 reinforces the relationship between instability (low SRT) and the crash involvement rate of heavy vehicles. This figure is obtained by dividing the crash involvement percent (Figure 7) by the fleet percent (Figure 5) to give a relative crash rate. The base line or average crash rate is one. From this we see that vehicles with an SRT of 0.3 g or less have more than 3 times the average rollover crash rate.

The equation for the trend line shown in Figure 8 is;
$y = -63.2\ SRT^3 + 126.8\ SRT^2 - 85\ SRT + 19.4684$. This means that for a given SRT value, we can estimate a relative crash rate (y). The r^2 value for this equation is 0.84.

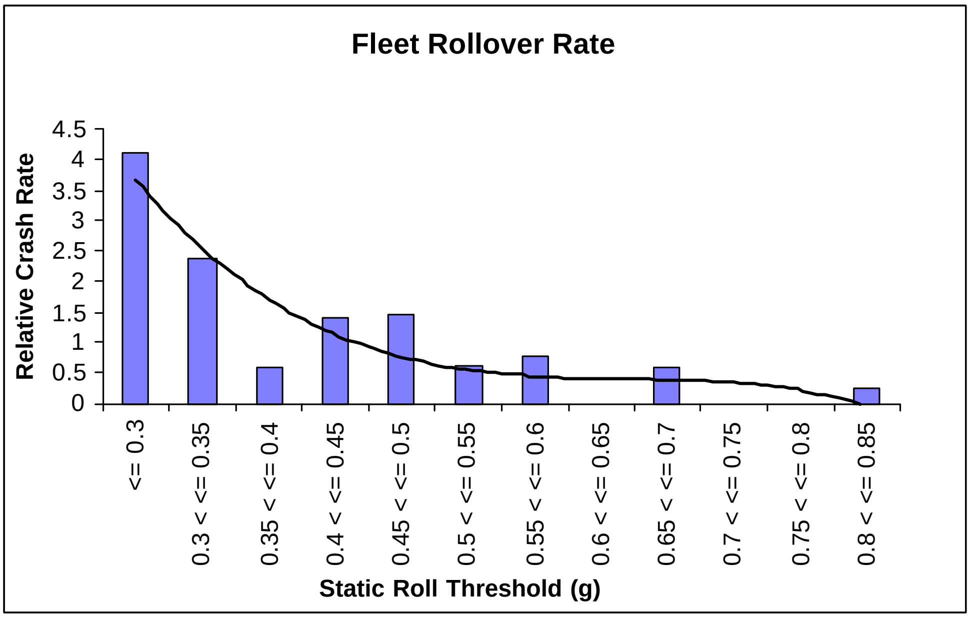

Figure 8. SRT Relative Crash Involvement Rate.

The trend shown in Figure 8, suggests that as the Static Roll Threshold is increased, the crash involvement rate decreases. This matches the USA data reported by Clarke (1998) and shown below in Figure 9. The fatal crash involvement rate for all heavy vehicles and for combination vehicles in New Zealand for 1997 were approximately 3.8 and 7.1 fatal crashes per 100 million kms respectively (Bass, 1999; LTSA, 1998). This compares to approximately 1.8 fatal crashes for all trucks in the US. This would tend to suggest that if SRT versus fatal crashes rate curve were able to be plotted for NZ, the y co-ordinate would be considerably greater than those of the US curve. The shape of the two curves would be similar with lower SRTs having higher crash rates. It was not possible to do this comparison using fatal crash involvement for SRT because the number of fatal crashes in New Zealand is not large enough for statistical analysis.

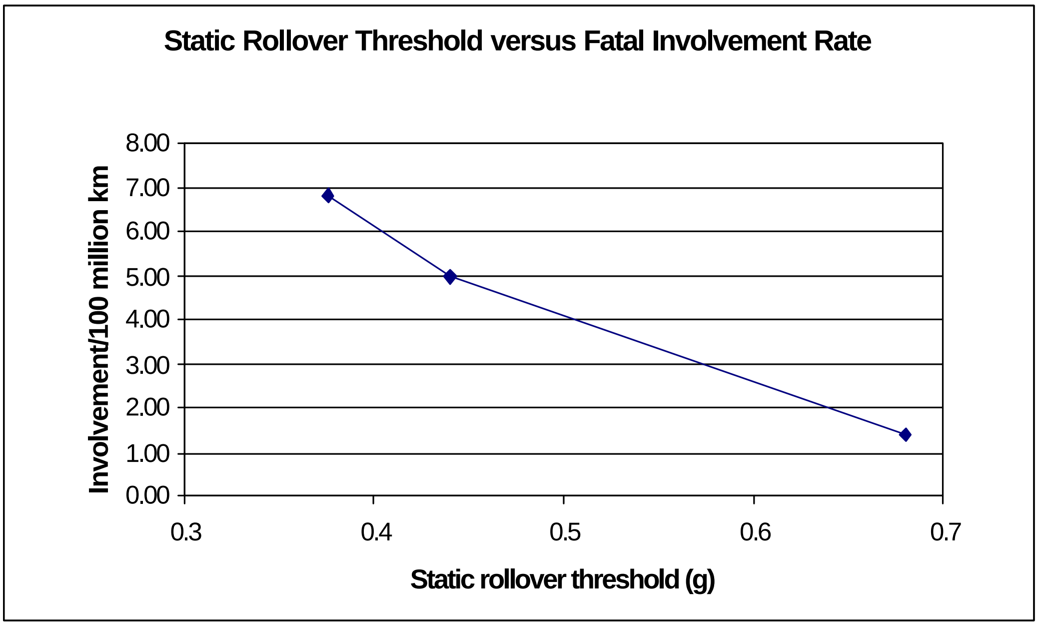

Figure 9. USA Semi Trailer SRT versus Fatal Crash Involvement Rate (Clarke, 1998).

3.2 Dynamic Load Transfer Ratio

From Figure 10 we see that 65% of the fleet have met the target value for DLTR which is less than 0.6. While 35 % of the fleet are above the target DLTR level.

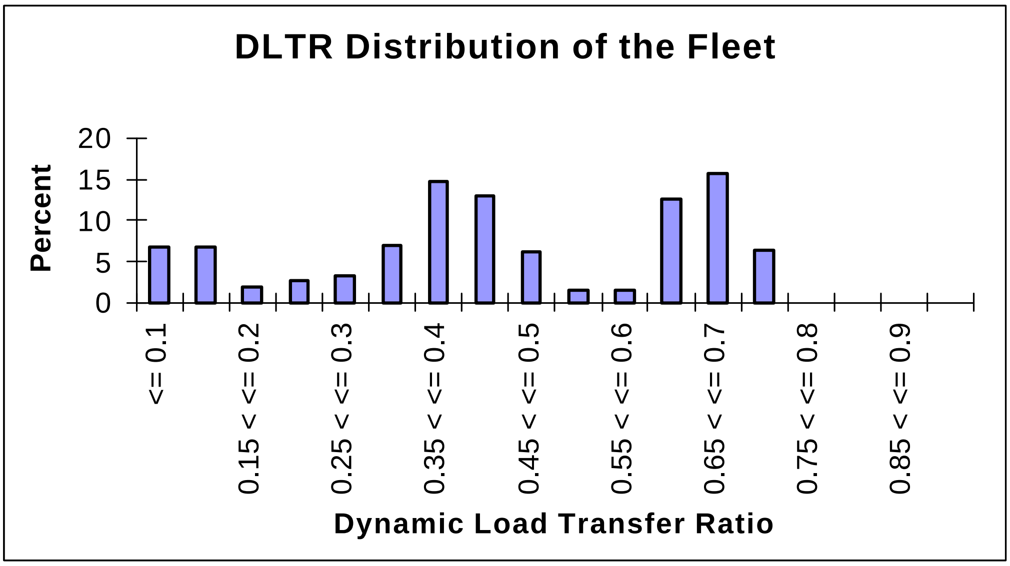

Figure 10. DLTR Fleet Distribution.

Figure 11 shows that 58% of the crash vehicles included in the CVIU data exhibited unacceptable DLTR values.

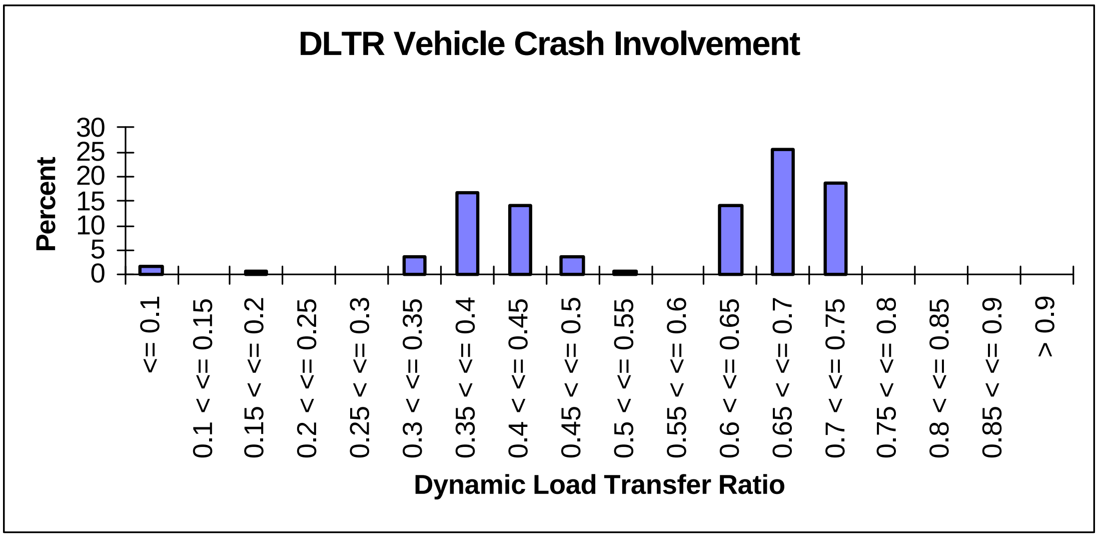

Figure 11. DLTR Crash Involvement Distribution.

The relative rollover rate shown below in Figure 12 confirms what we might expect, that the vehicles which do not meet the DLTR target value of 0.6 have an increasingly larger risk of crash involvement than the vehicles which meet the target. The trend line is described by the equation, $y = 42.4\ DLTR^3 - 45.8\ DLTR^2 + 15.8\ DLTR - 1.27$. The r^2 value for this equation is 0.71.

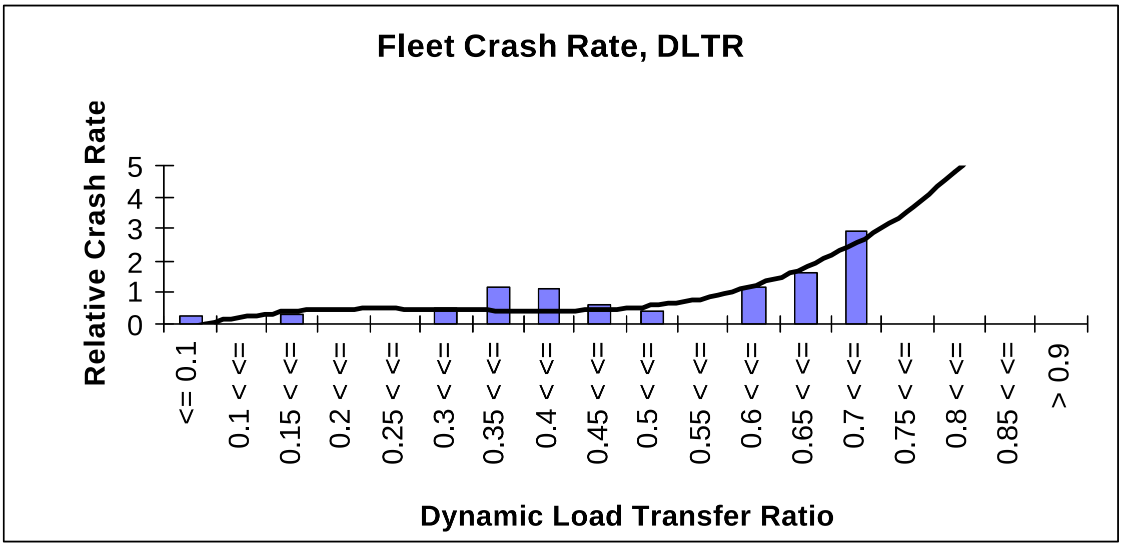

Figure 12. DLTR Relative Crash Involvement Rate.

3.3 High-Speed Transient Off-tracking

Overall, the High-Speed Transient Off-tracking of the fleet is very good. All vehicles surveyed exhibited HSTO values below the maximum target value of 0.8 m. Figure 13 shows the general distribution of the fleet and the majority of vehicles (53%) are below 0.3 m.

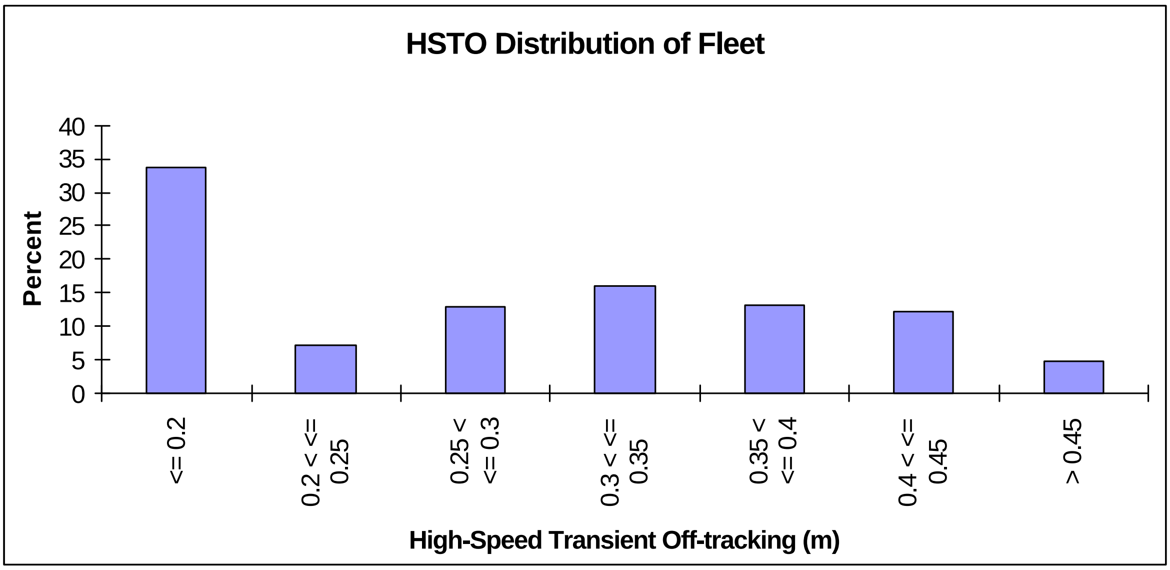

Figure 13. HSTO Fleet Distribution.

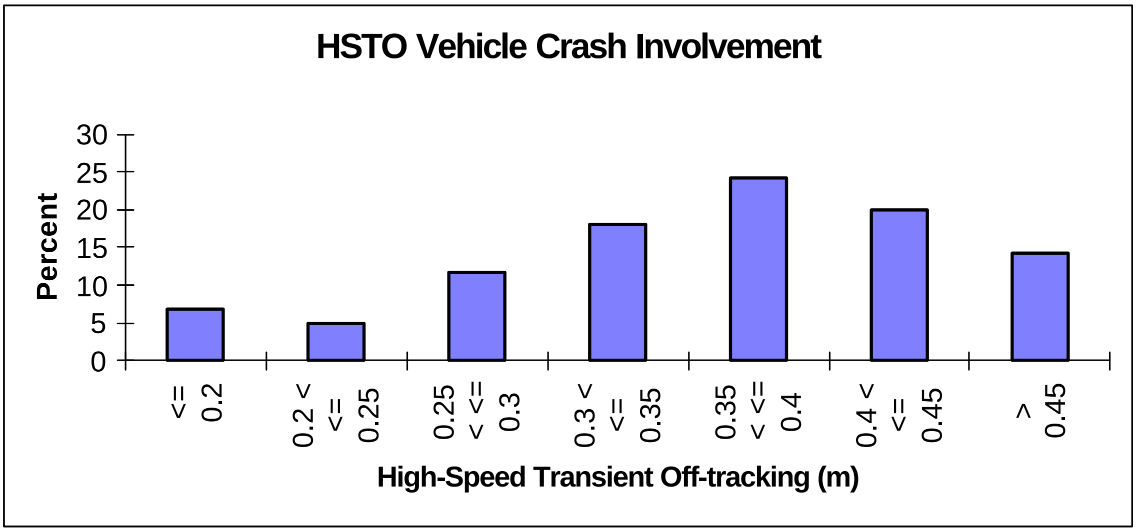

Figure 14. HSTO Crash Involvement Distribution.

The relative crash rate, with respect to HSTO shown in the figure below, illustrates the trend, that as the off-tracking increases then the accident rate increases as well.

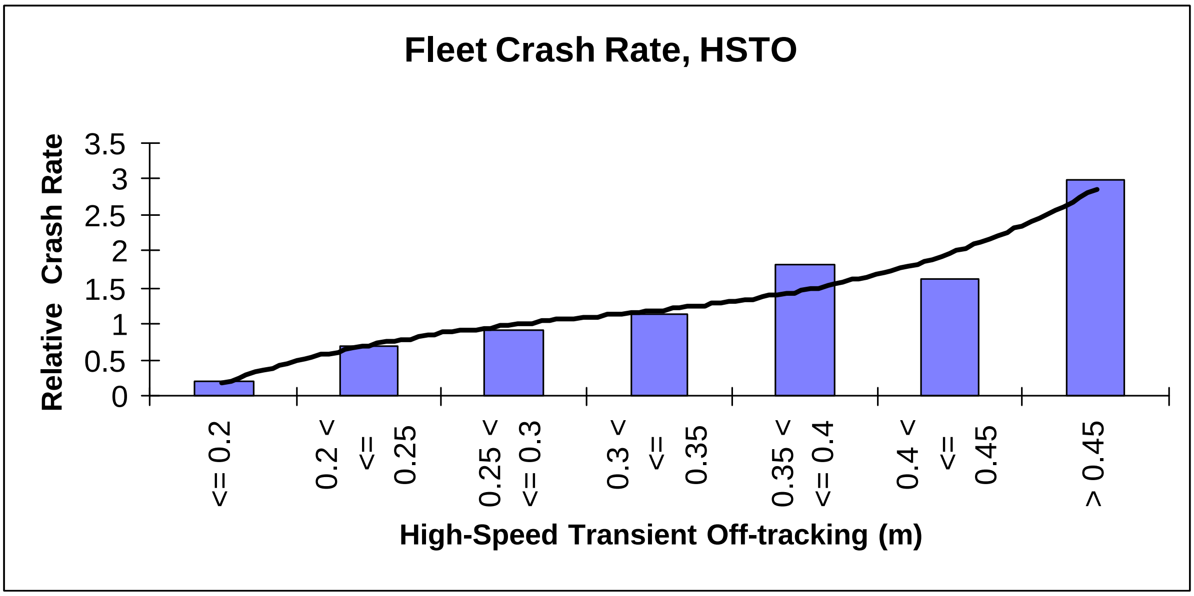

Figure 15. HSTO Relative Crash Involvement Rate.

The equation for the trend line in Figure 15 is,
$y = 206.4\ HSTO^3 - 201.9\ HSTO^2 + 69.822\ HSTO - 7.36$ and the r^2 value is 0.94.

3.4 Yaw Damping Ratio

The minimum target value for yaw damping is 0.15. Overall, the fleet's YDR shown in Figure 16, is good. Less than 2% of the vehicles fail to meet the minimum performance target value of 0.15.

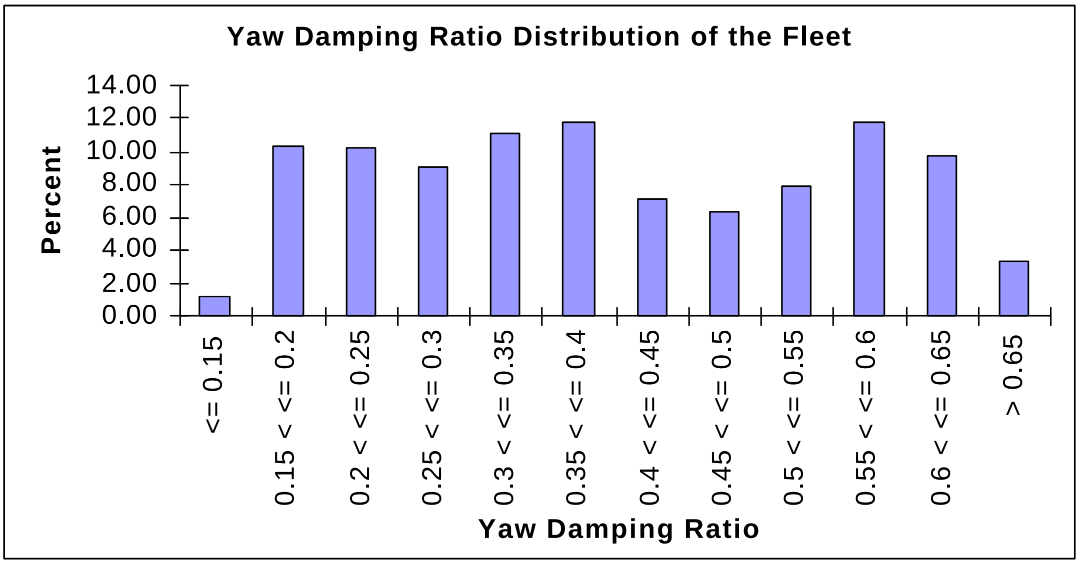

Figure 16. Yaw Damping Ratio Fleet Distribution.

A small proportion (less than 5%) of vehicles involved in rollover and loss of control crashes have under performing YDR's (Figure 17). From Figure 18, we see that those vehicles with YDR below the minimum target value exhibit a relative crash rate 3 ½ times that of the median. However, because of the small number of vehicles in this category there is a high uncertainty on this figure, particularly as the rest of the graph does not show the strong correlation between crash rates and performance measure observed with other measures such as SRT.

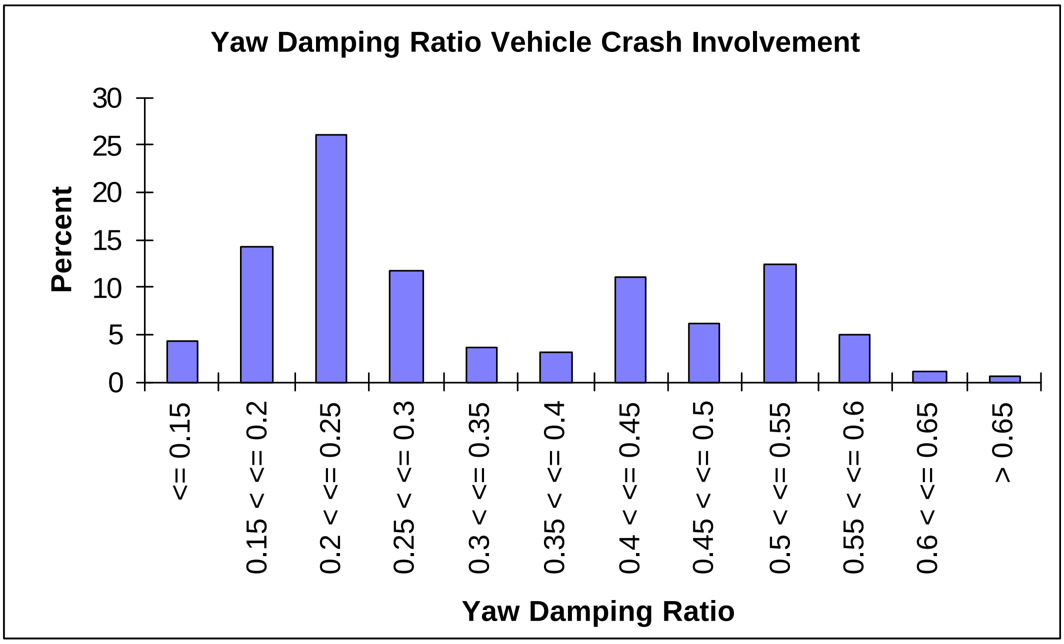

Figure 17. Yaw Damping Crash Involvement Distribution.

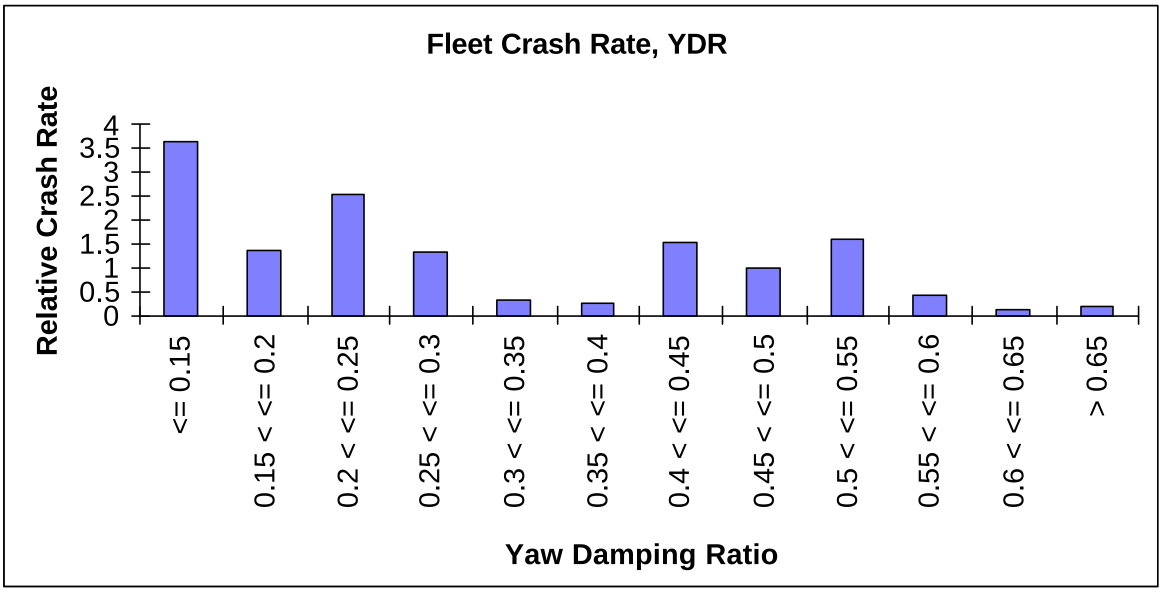

Figure 18. Yaw Damping Ratio Relative Crash Involvement Rate.

3.5 Performance Summary

In all cases except HSTO, the proportion of vehicles not meeting the target performance standard is greater among the crashed vehicles than among the fleet, indicating a clear correlation between poor performance and crash rate. In the case of YDR, the relationship has high uncertainty because only a small number of vehicles do not meet the target.

The performance measures and target values are summarised below in Table 5.

Table 5. Performance Measure Results Summary.

Performance Measure	Target Value	Fleet Performance (Target Value Not Met)	Crash Incidences (Target Value Not Met)
SRT	>= 0.35 g	15%	40%
DLTR	<= 0.6	35%	58%
HSTO	<= 0.8 m	0	0
YDR	>= 0.15	1.2 %	4.7%

3.6 Cost Analysis

Table 6 shows the reported social cost of heavy vehicle crashes based on the TCR database[1].

Table 6. Average Social Cost of TCR reported crashes in June 1998

	Average social cost of reported crashes	Property Damage All veh	Property Damage HVs	HV social cost of reported crashes
Fatal	$2,684,000	$6,700	$31,000	$2,708,300
Serious	$ 434,000	$4,000	$31,000	$461,000
Minor	$ 54,000	$3,500	$31,000	$81,500
PDO	$1,600	$1,600	$21,000	$21,000

An analysis of the TCR and CVIU Large Truck and Bus databases for the 2 years from July 1996 to June 1998 has found that the CVIU attended 66 percent of the fatal reported crashes and 22 percent of the reported injury crashes. Table 7 shows the adjusted social cost per CVIU reported crash. It has been assumed that CVIU also attend 22 percent of the property damage only crashes. This is conservative, as it is likely that they attend a considerably smaller proportion than that.

Table 7. Average Social Cost of CVIU reported crashes in June 1998

	CVIU reporting rate	Average social cost of CVIU reported crashes
Fatal	66%	$4,103,484.85
Serious	22%	$2,095,454.55
Minor	22%	$370,454.55
PDO	22%	$95,454.55

For the period from August 1996 to February 1999 CVIU reported 182 heavy vehicle crashes that involved loss of control or rolled over. Of these, 8 were fatal, 21 involved serious injury, 44 minor injury, 105 property damage only and 4 had no outcome noted (Table 4). Table 8 shows the estimated social cost of loss of control and rollover crashes based on CVIU reporting.

Table 8. Social cost of loss of HV control and rollover crashes.

	Number of CVIU reported crashes	Total social cost	Annual social cost
Fatal	8	$32,827,879	$12,707,566
Serious	21	$44,004,545	$17,034,018
Minor	44	$16,300,000	$6,309,677
PDO	105	$10,022,727	$3,879,765
no info	4		
total	**182**	**$103,155,152**	**$39,931,026**

[1] NZIER – The Social Cost of Road Accidents and Injuries, Table 3-5.

The average social cost of loss of control and rollover crashes of combination vehicles has been estimated as being $39,931,026 p.a. (Table 8, 1996 to 1999). The estimated distance travelled by combination vehicles in 1997 was 661 Million km (Baas, 1999). Consequently, the average social cost associated with rollover and loss of control crashes is $60.40 / 1000km.

Figure 5 indicates that 2 percent of vehicles investigated (on a distance-travelled basis) have an SRT of 0.3 g or less. In Figure 7, we see that 8 percent of the loss of control and rollover related crashes were associated with vehicles having an SRT of 0.3 g or less. If SRT were not a factor in loss of control and rollover crashes then the percentage of vehicles involved in loss of control and rollover crashes would be expected to be 2%. However, since the crash figures are higher (8%) the difference (6%) is the excess in which these poor performing vehicles (SRT of 0.3 g or less) are over represented in the crash statistics. Hence, the additional social cost attributed to these poor performers is $2.4 million p.a..

Similarly, all vehicles with an SRT value under 0.35 g were involved in 40 percent of the rollover and loss of control related crashes but made up only 15 percent of the fleet. This means that 25% or $9.98 million p.a. of the total social cost is associated with the poor performance of those vehicles with SRT of less than 0.35 g.

The total number of heavy vehicle prime movers and trailers in the fleet was 72,680 and 18,714 respectively in 1997 (Baas, 1999). All of the crashes investigated were combination vehicles. Approximately 16 percent of combinations are multi-trailer combinations:– A-trains and B-trains. Allowing for these multi-trailer combinations means that there are approximately 16,133 combination vehicles in the fleet. There are consequently approximately 323 combination vehicles with SRT of less than 0.3, and 2,420 combinations with SRT less than 0.35 on the road at any one point in time. Improving these vehicles would result in a reduction in crash-related costs of $7,420 per vehicle p.a. for the less than 0.3 SRT combinations and $4,125 for the combinations with a SRT of less than 0.35.

To determine present values, it is assumed that a vehicle has a 10 year life, spends ½ of its time unladen or partially laden, and a 10 percent p.a. real discount rate. On this basis it is worth spending $22,800[2] on improving the performance of a new combination that has an SRT of less than 0.3 and $12,700 on a combination with SRT less than 0.35. For existing vehicles, if it is assumed that they are on average ½ way through their life, it would be worth spending $14,050 to improve their stability if their SRT is less than 0.3 and $7,800 on combinations with SRT's less than 0.35

The above analysis assumes the improvements will be through vehicle changes. However operational changes should also be considered. Determining the cost of operational changes is more complex, but the above still provides some order of magnitude for basing an assessment on. It may well be possible to improve vehicle stability at minimal cost through vehicle selection and operational improvements.

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[2] All per vehicle costs rounded to nearest $50.

The above calculations are very conservative. They do not take into account for example:

- Traffic delays due to rollover;
- The probability that the level of under reporting is greater than allowed for above.
- Extreme events such as a major crash with a major loss of life and disruption. Such events have occurred overseas, for example a logging truck –school bus crash in Canada that resulted in 27 lives lost. Already in NZ logs from an overturned logging truck struck a school bus, fortunately with little damage to the bus. If it is assumed that a major crash had a 1 in 100-year chance of occurring and such an event resulted in 15 lives being lost then the social cost of such a crash would be $32.5 million (assuming $2.164 million per fatality). It would be worth spending $1,900 on existing combinations with SRT of less than 0.3 (assuming ½ of their travel is laden) to prevent such an event occurring due to their poor performance. This is in addition to the $14,050 calculated above.

4.0 Performance Measure Prediction

This report illustrates a method for using simple equations to predict pertinent performance measures of heavy vehicle combinations based on vehicle parameters which were relatively easy to obtain. These equations provide a useful and practical tool in determining first-order predictions of vehicle performance measures without the expense of complex and complicated simulations or full scale testing regimes.

The required vehicle parameters have been simplified to a fundamental set which provide meaningful results. Parameter requirements include; tyre track widths, number of axles, wheelbase distances, forward distances, centre of gravity heights, vehicle tare and gross vehicle mass. The parameters used in this analysis are the same parameters used in other studies, namely the USA and Australia (Winkler, 1993; Elischer, 1998). The significance in the relationships between the parameters are similar, which suggests that information obtained in overseas studies founded on the same vehicle parameters are valid in the New Zealand setting.

Although a fairly good representation of combination data was used to determine the regression matrices, it is not all inclusive and the resulting equations are modelled on specific simulation runs. However, these equations are useful provided the user recognises that they have limitations: they are only intended to give approximate predictions of actual vehicle performance characteristics.

5.0 Conclusions

From the analysis undertaken in this report, the following points are highlighted:

- Overall, with respect to Static Roll Threshold, the estimated fleet stability is good.
  - 85% Good
  - 13% Marginal
  - 2% Poor

- Of the crash involved vehicles, 40% had not met the target value for SRT. This would indicate that an impact on roughly 40% of the crashes could be made by targeting a small group of vehicles (15%), those which fail to meet the minimum recommended SRT value of 0.35 g.

- Just under 2% of the fleet exhibit an SRT of less than 0.3 g, yet of the vehicles involved in stability related crashes, 8% had an SRT of less than 0.3 g. As described above, 40% of the crash involved vehicles failed to met SRT target values, compared to only 15% for the fleet.

- In terms of Dynamic Load Transfer Ratio, only 65% of the fleet meet the recommended target value of 0.6 and hence 35% do not. However, of the vehicles involved in stability related crashes, 58% did not meet the DLTR target.

- On the other hand, the estimated High-Speed Transient Off-tracking performance of the fleet is good. All vehicles surveyed were well below the recommended maximum of 0.8 metres. None of the vehicles involved in stability related crashes exhibited values outside the 0.8 m range either. However, there did appear to be a trend of crash rate increasing with increased HSTO.

- Based on this analysis the Yaw Damping Ratio performance of the fleet is good. Less than 2% of the fleet fail to meet the minimum performance target value of 0.15 for yaw damping. Of the vehicles involved in loss of control and stability related crashes, less than 5% had poor yaw damping.

- Combination vehicles involved in rollover or loss of control crashes show a significant stability deficiency, compared with the general fleet.

As described earlier, the two performance measures SRT and DLTR combined with Rearward Amplification are the principal indicators of instability related crash risks.

- Vehicles with lower SRT values have a much higher chance of rolling over or being involved in a loss of control related crash. A vehicle with an SRT of 0.3 g or less has more than 3 times the risk of the average vehicle.

- Similarly, the worst performing DLTR vehicles have roughly 3 times the crash rate of those vehicles which meet the minimum target values.

- The under performing (less than 0.15 YDR) vehicles (2%) carry an associated crash risk of more than 3 ½ times that of the rest of the fleet. There is a high level of uncertainty with this figure due to the small number of vehicles involved.

Cost analysis based on the under performing SRT vehicles (sub 0.35 g) shows:

- Using current vehicle profiles there are approximately 320 vehicle combinations with SRT of less than 0.3 g and 2,420 combinations with SRT less than 0.35 g, on the road at any one point in time.

- Improving vehicle combinations to a minimum 0.35 g SRT would result in a reduction of crash related costs of $7,420 per vehicle p.a. for the less than 0.3 g SRT combinations.

- Similarly, for the vehicle combinations with SRT less than 0.35 g, a savings of $4,125 per vehicle, p.a. could be saved in crash related costs.

- Based on present day values, for a 10 year life of the vehicle, it would be worth spending $22,800 on improving the performance of a new combination that has an SRT of less than 0.3 g.

The vehicle performance estimates described in this report are useful in describing the overall fleet performance. Caution should be exercised when trying to determine the performance of an individual vehicle using these regression formulae alone. The formulae are the result of a statistical profile and it is possible to have vehicles which do not fit the profile. However, the potential exists, based on this report and the methodologies developed to augment the database over time, thus increasing accuracy and predictive usefulness.

6.0 References

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7.0 Appendices

7.1 Appendix A: Fax Survey Information

The following request for information was faxed to 230 transport operators. Fax details were obtained from the *National Fax Directory 1998/99.*

7.1.1 Operator Survey Cover Letter

18 February 1999

Dear xxxxxx

Transport Engineering Research New Zealand Ltd. (TERNZ) is an independent research organisation which undertakes research on issues such as heavy vehicle weights and dimensions, driver fatigue, road friendly suspensions, pavement life and road safety. We work closely with RTF, LTSA and transport companies within the industry. TERNZ is currently undertaking a national survey regarding the New Zealand heavy vehicle fleet. This information is required for a review of heavy vehicle weights and dimensions.

We appreciate how busy people in the industry are, and therefore have selected just a few vehicles (and combinations) with a minimum amount of information required, to participate in the survey. The information you provide will remain confidential to TERNZ. Only the statistical findings will be reported.

TERNZ is particularly interested in the following vehicle(s) and would appreciate you taking a moment filling in the form and faxing it back to us **today**, as there is some urgency regarding the survey, on **09 262 2856**.

Thank you for your cooperation in providing this information.

Kind regards,

Tim Mueller
Engineering Researcher

7.1.2 Operator Survey Information Form

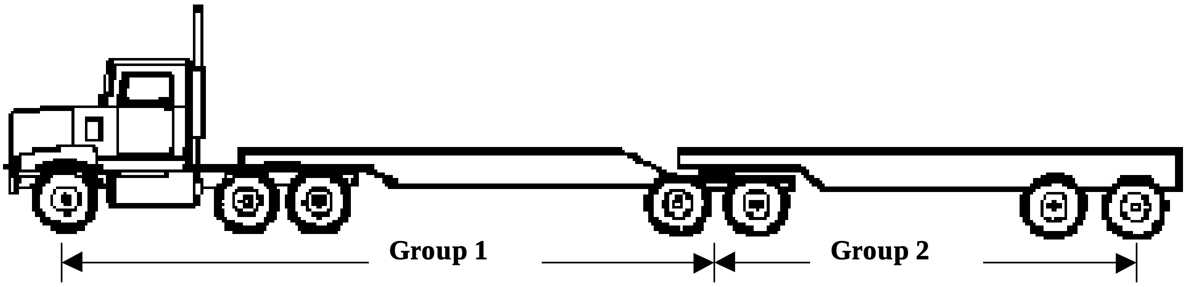
Please Fax the following sheet to: TERNZ 09 262 2856, Today

Heavy Vehicle Operator Information Sheet

	Vehicle
Plate Number	
Suspension Type (circle)	air / steel
Tyres (brand) (circle)	Goodyear / Firestone / Michelin / Dunlop
Type of Operation (circle)	Containers / Logs / Tanker / Curtainsider / Tipper / General Freight other (please specify)______________________________
Load Weight Normally Carried (tick)	10 – 15 tonne ___ 15 – 20 tonne ___ 20 – 25 tonne ___ 25 – 30 tonne ___ + 30 tonne ___
Typical Height to Top of Load (from ground) (tick)	3.5 to 4.2 m ____ 3.0 to 3.5 m ____ Below 3.0 m ___

7.2 Appendix B: Example Calculation of Load Distribution Method

7 Axle B-Train (45,000 Kg) courtesy of Baas (1997).



S	TT	TT	TT
5430 kg	14130 kg	14910 kg	10530 kg

Group 1 includes tractor plus first trailer.
Group 2 includes trailer 2 only.

For this example, Tractor Tare (T_T) =7980 kg, Trailer 1 Tare (T_1) = 7850 kg, Trailer 2 Tare (T_2) = 6280 kg,

Gross Combination Mass (GCM) = 40,000 kg,

P_1 = The payload in $T_{1,}$

P_2 = the payload in $T_{2,}$

<u>For Group 1 we have the following:</u>

$T_T + P_1 + T_1 <= 5430 + 14130 + 0.5(14910)$

$\Rightarrow$ $P_1 <= 5430 + 14130 + 0.5(14910) – 7980 – 7850$

$\therefore$ $P_1 <= 11{,}185$ kg

$\therefore$ The maximum payload to be carried in trailer 1 is 11,185 kg.

<u>For Group 2 we have the following:</u>

$P_2 + T_2 <= 0.5(14910) + 10530$

$\Rightarrow$ $P_2 <= 0.5(14910) + 10530 – 6280$

$\therefore$ $P_2 <= 11{,}705$ kg

$\therefore$ The maximum payload to be carried in trailer 2 is 11,705 kg.

Example Calculation of Load Distribution Method (cont.)

To distribute the payload mass between the two trailers, the maximum payload mass able to be carried by an individual trailer was divided by the total mass able to be carried. From above, we have:

For Trailer 1

$$\text{Percentage of payload} = 11185/(11185+11705) = 0.489 \text{ or } 49\%$$

Hence the percentage of the total payload able to be carried by trailer 1 is roughly 49%. Similarly, for trailer 2 we get the total payload mass able to be carried is roughly 51%.

The amount of payload being carried is simply the GCM minus the tare weights. So, in this example we have:

$$40{,}000 - 7{,}980 - 7{,}850 - 6{,}280 = 17{,}890 \text{ kg.}$$

Now, applying the above percentages to the payload mass being carried we have:

$$\text{Payload in Trailer 1} = 0.489(17890) = 8{,}748 \text{ kg}$$

$$\text{Payload in Trailer 2} = 0.511(17890) = 9{,}145 \text{ kg.}$$

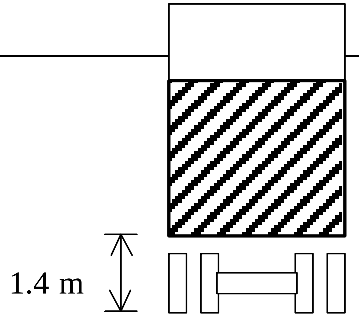
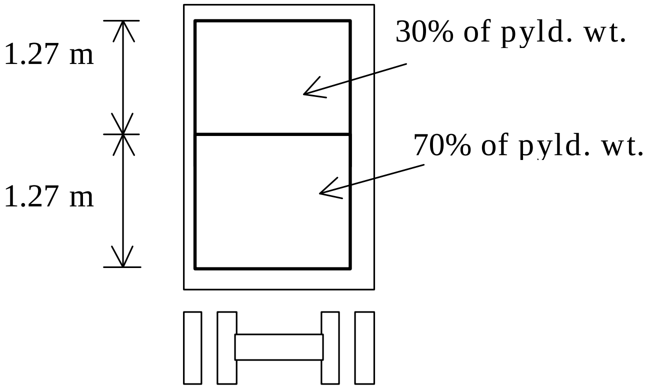
7.3 Appendix C: Load Examples with Mass Centre Height Parameters (UMTRI, 1988)

Payload Centre of Gravity (CoG) heights used in calculating the Static Rollover Threshold values were determined using the following UMTRI chart, Load Examples with Mass Centre Height Parameters (UMTRI, 1988).

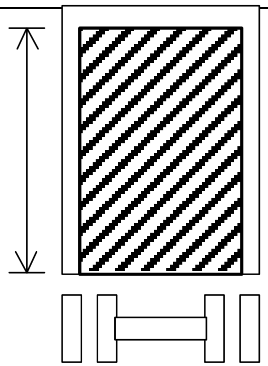
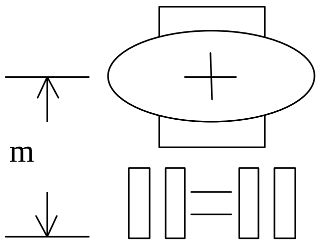
The "Typical LTL Freight Load" case represents what is understood to be typical loading conditions experienced by common carriers hauling "less-than-truckload" (LTL) consolidations of freight. The LTL term is commonly used in the transport industry to refer to transport operations which have collected less-than-truckload quantities of freight from individual shippers and then consolidated the freight such that, ideally, the vehicle is essentially filled to capacity for the major portion of the trip (UMTRI, 1988).

The four examples of loaded vehicles shown in the following chart are seen as covering much of the range of payload CoG heights found in fully-loaded vehicles in service (UMTRI, 1988).

Load Examples with Mass Centre Height Parameters (UMTRI, 1988)

Configuration	**Mass (kg)**		**Mass Centre Height (m)**		
	GVM	Payload	**Payload**	Composite spr. Mass, Trailer & Pyld.	Composite spr. mass, Tractor, Trailer & Pyld.
 Full Gross Medium-Density Freight (545kg / m³)	36,320	23,699	**2.121**	2.032	1.905
Typical LTL Freight Load 	33,142	20,521	**2.413**	2.266	2.085

Load Examples with Mass Centre Height Parameters (cont.)

Configuration	Mass (kg)		Mass Centre Height (m)		
	GVM	Payload	**Payload**	Composite spr. Mass, Trailer & Pyld.	Composite spr. mass, Tractor, Trailer & Pyld.
2.54 m  Full Gross, Full Cube Homogeneous Freight (300 kg / m^3)	36,320	23,699	**2.667**	2.499	2.304
2.25 m  Full Gross Gasoline Tanker	36,320	24,870	**2.250**	2.217	2.062

7.4 Appendix D: Performance Measures by Vehicle Combination

The figures below represent results of the performance measures from each vehicle combination. Both, the overall fleet profile (RUC survey) and crashes attributed to rollover or loss of control (CVIU data) are presented. The fleet vehicles have unladen vehicles factored in as previously described.

7.4.1 B-Trains

SRT Target Value >= 0.35 g.

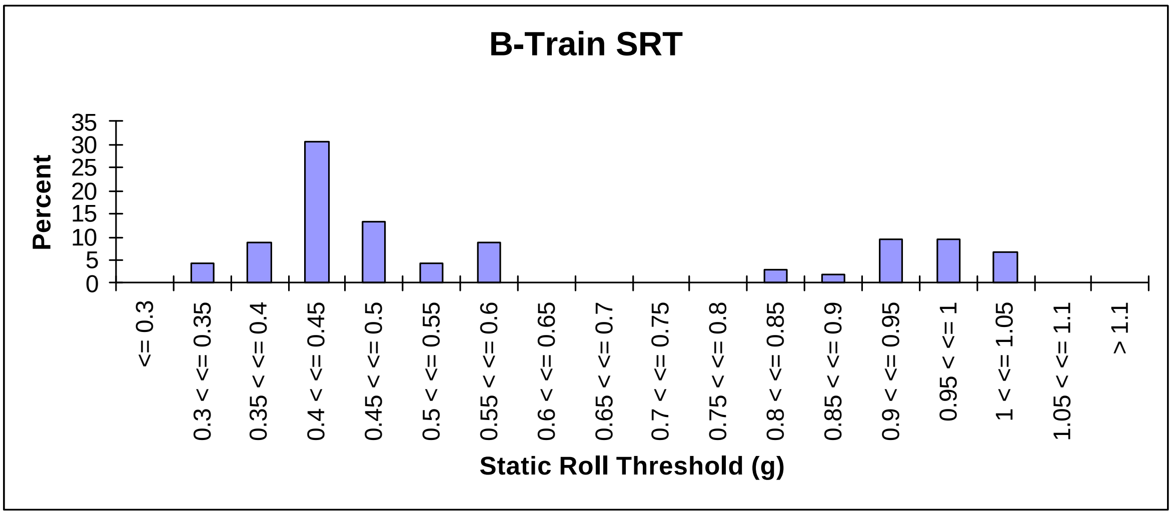


Figure 19. B-Train SRT for the Fleet.

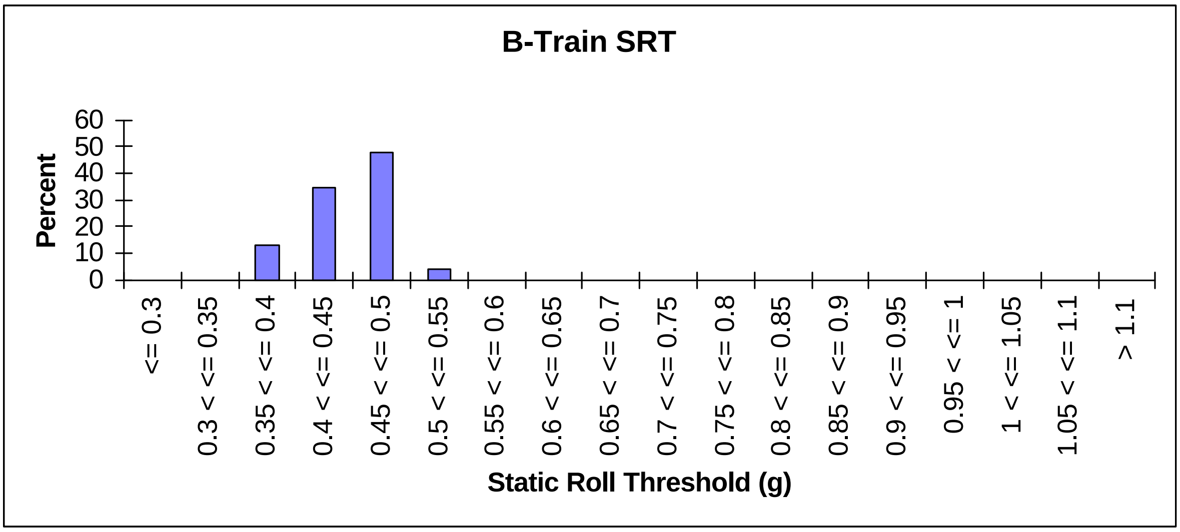


Figure 20. B-Train SRT for Crashed Vehicles.

B-Trains (cont.)

DLTR Target Value <= 0.6.

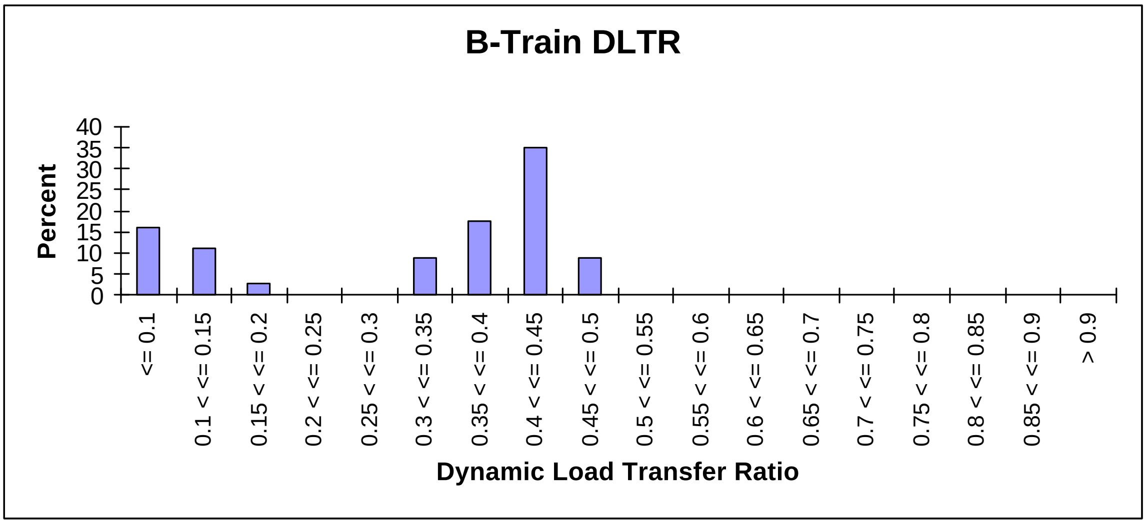


Figure 21. B-Train DLTR for Fleet.

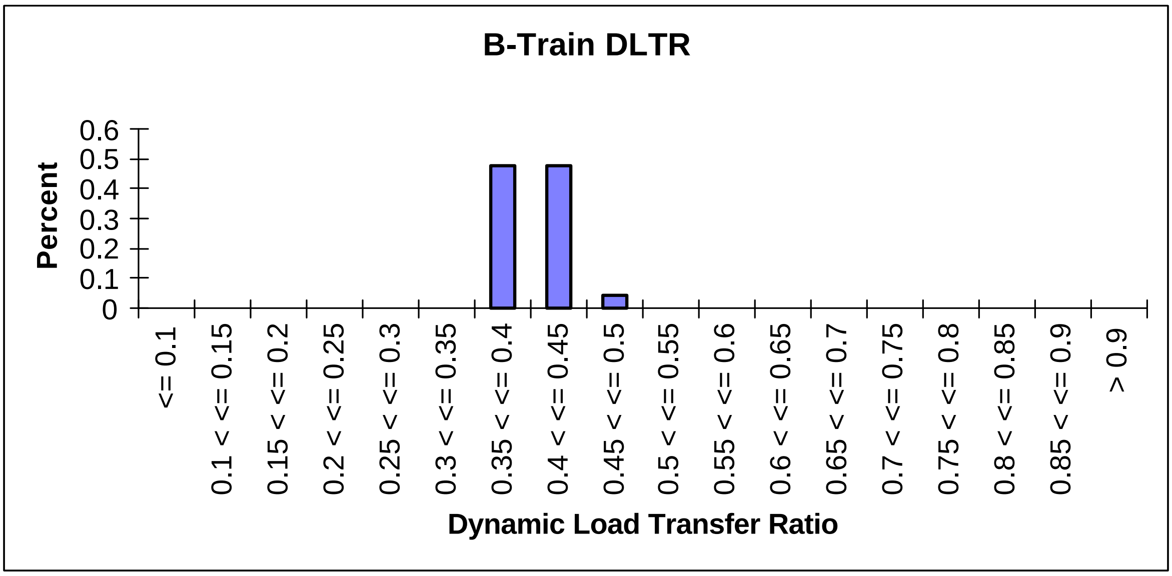


Figure 22. B-Train DLTR for Crashed Vehicles.

B-Trains (cont.)

HSTO Target Value <= 0.8 m.

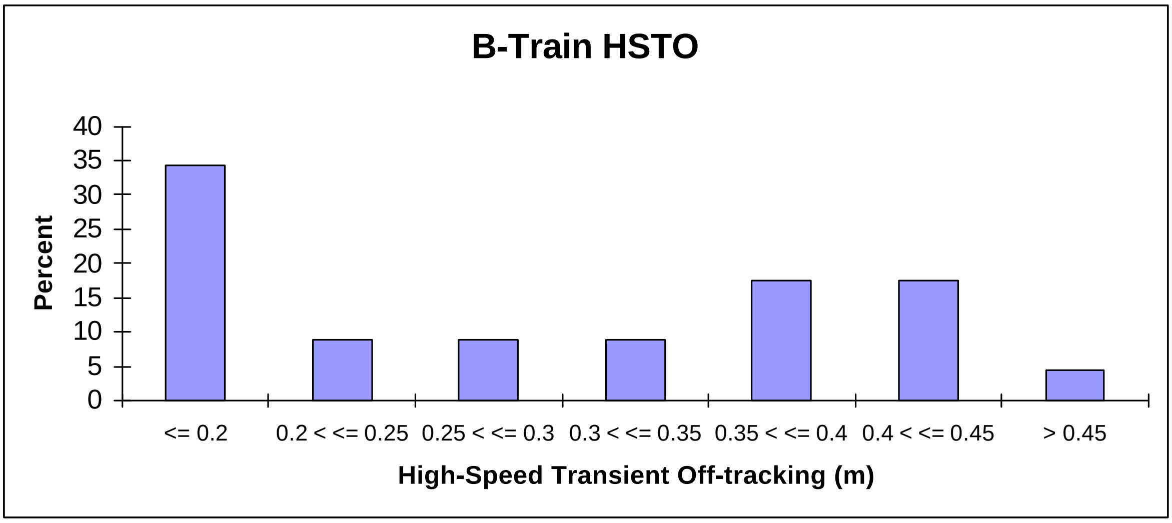


Figure 23. B-Train HSTO for Fleet.

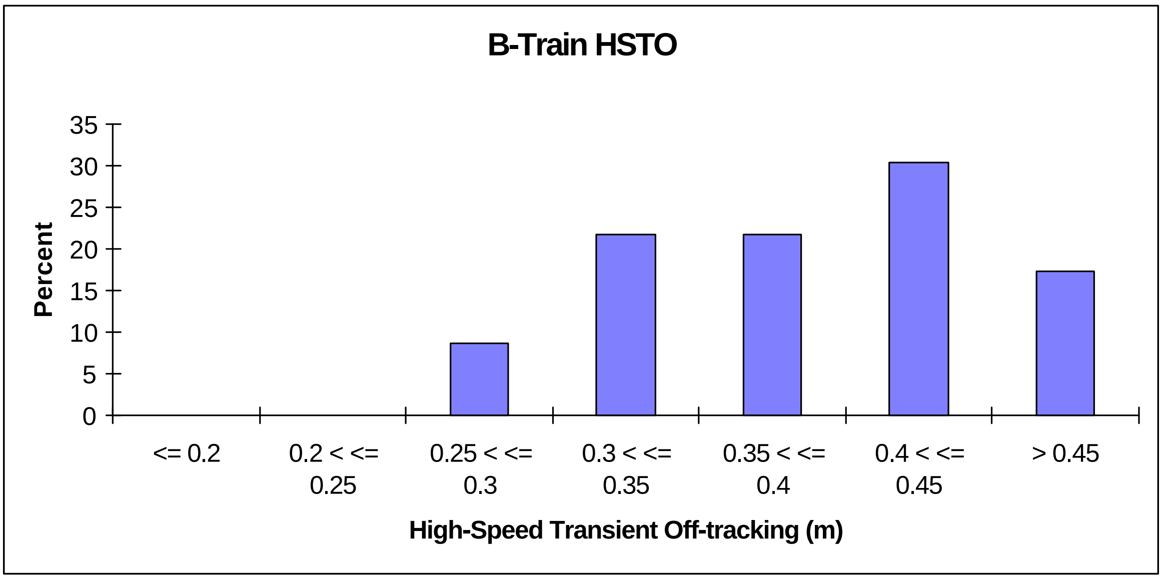


Figure 24. B-Train HSTO for Crashed Vehicles.

B-Trains (cont.)

Yaw Damping Ratio Target Value >= 0.15.

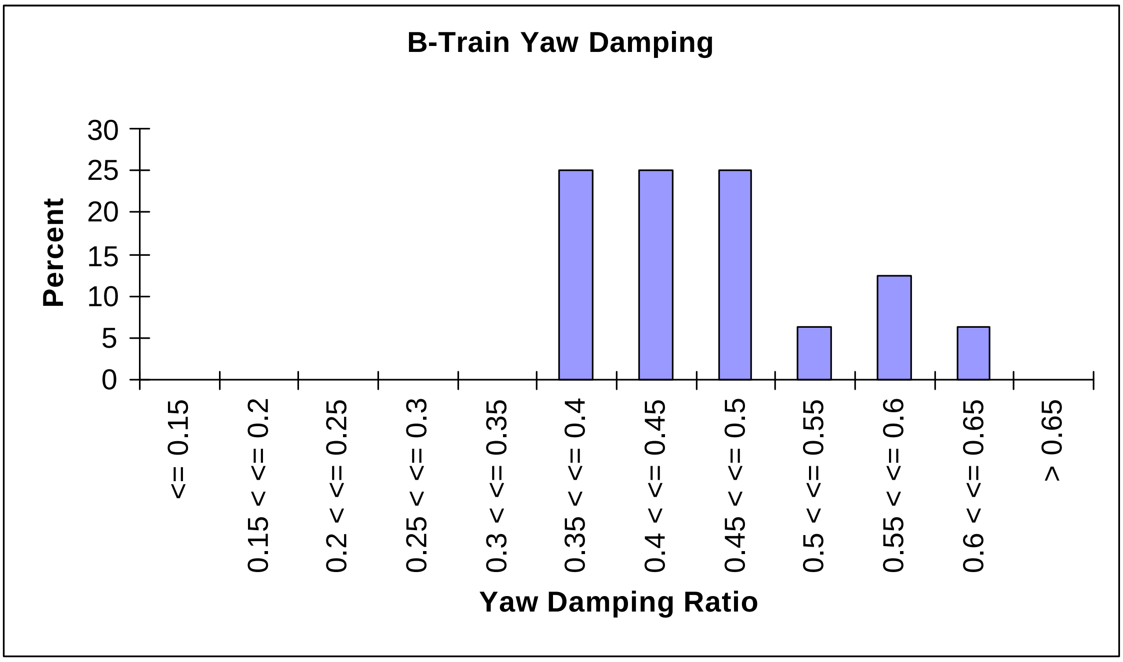


Figure 25. B-Train Yaw Damping for Fleet.

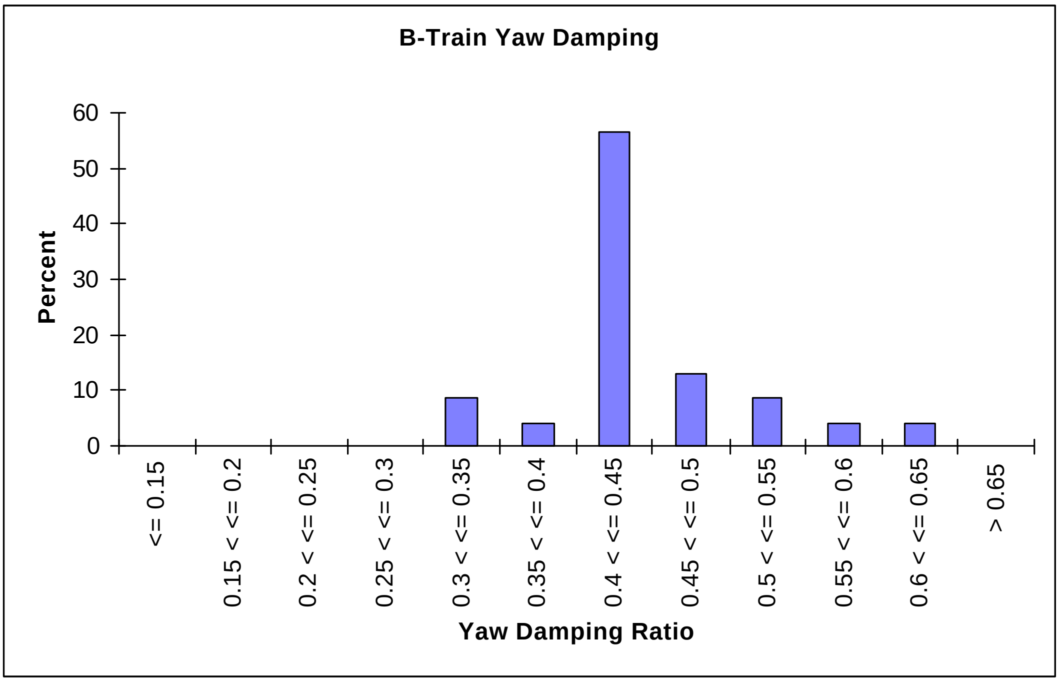


Figure 26. B-Train Yaw Damping for Crashed Vehicles.

7.4.2 Truck-Trailers

SRT Target Value >= 0.35 g.

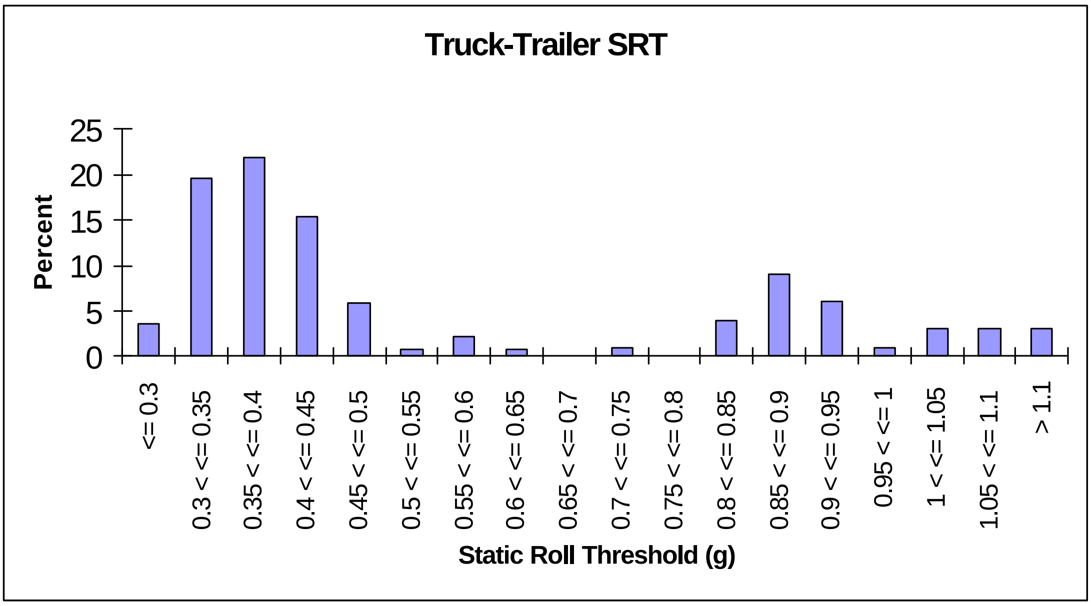


Figure 27. Truck-Trailer SRT for the Fleet.

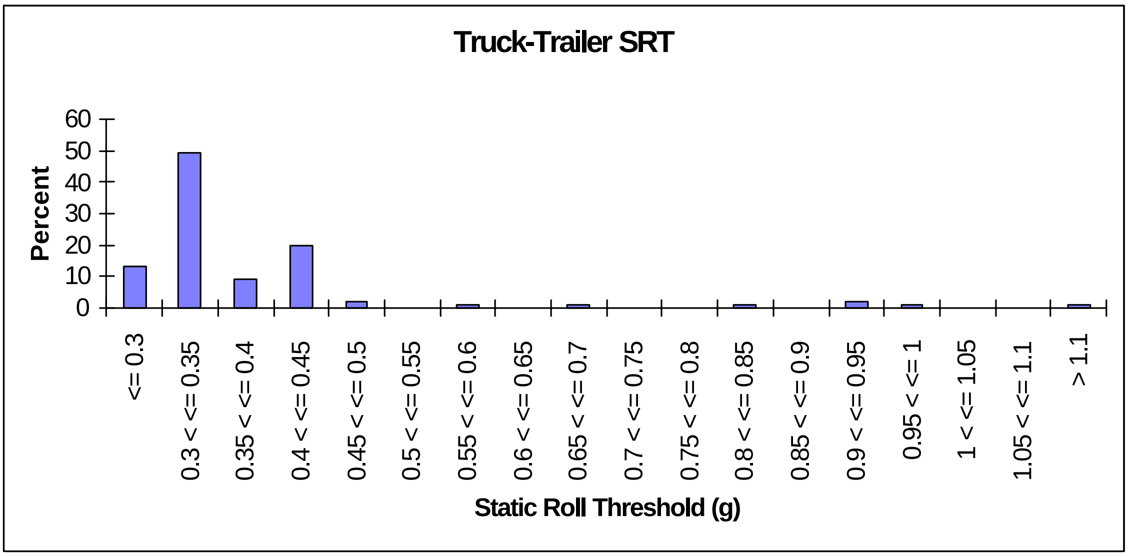


Figure 28. Truck-Trailer SRT for Crashed Vehicles.

Truck-Trailers (cont.)

DLTR Target Value <= 0.6.

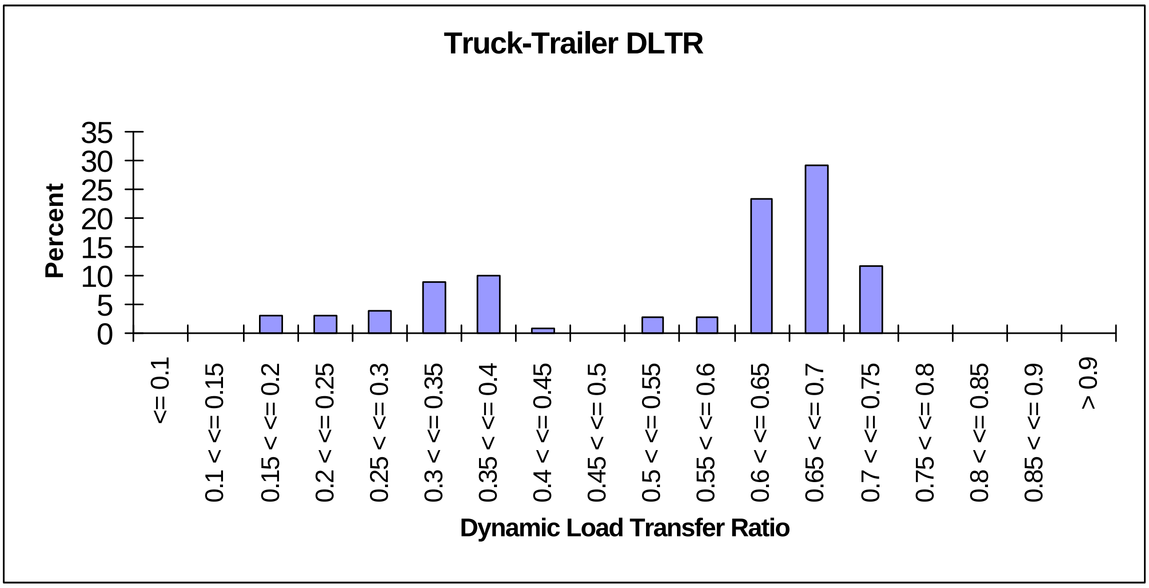


Figure 29. Truck-Trailer DLTR for the Fleet.

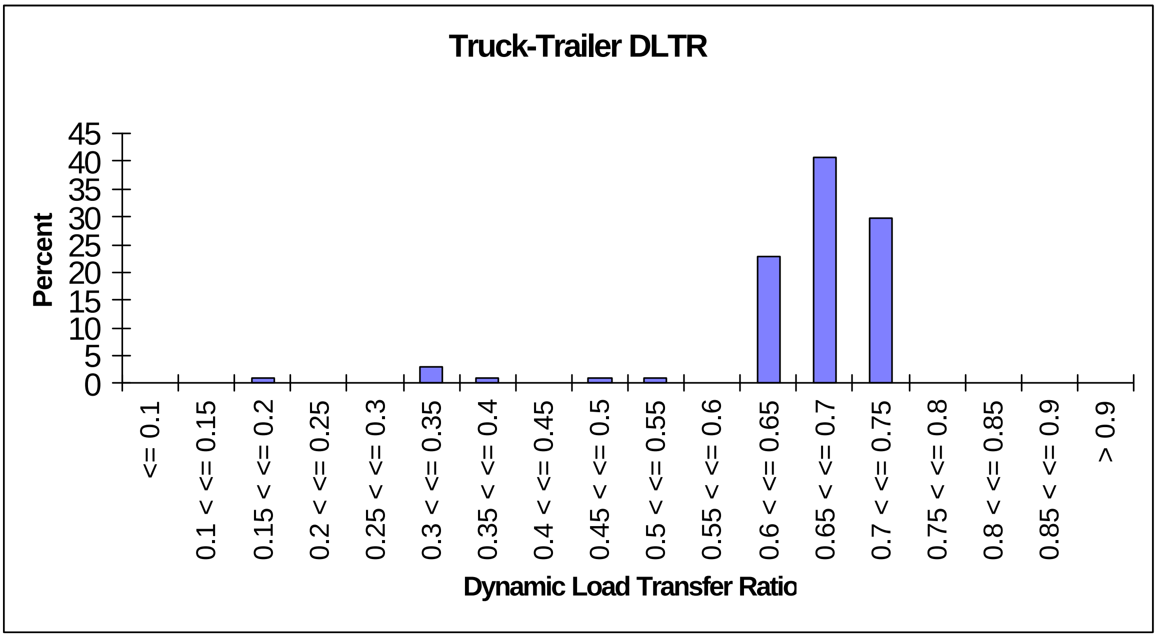


Figure 30. Truck-Trailer DLTR for Crashed Vehicles.

Truck-Trailers (cont.)

HSTO Target Value <= 0.8 m.

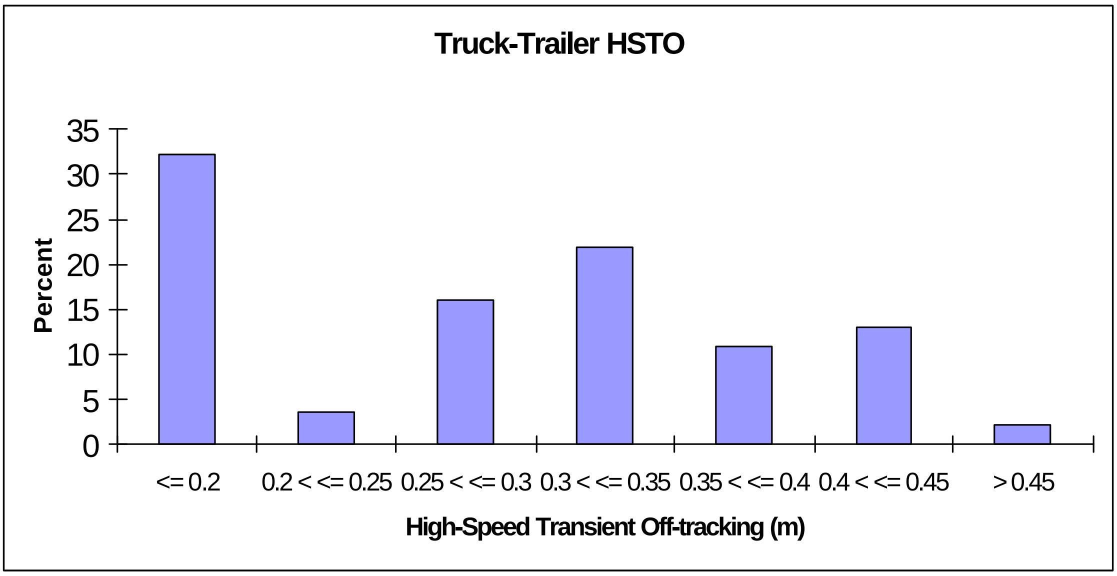


Figure 31. Truck Trailer HSTO for the Fleet.

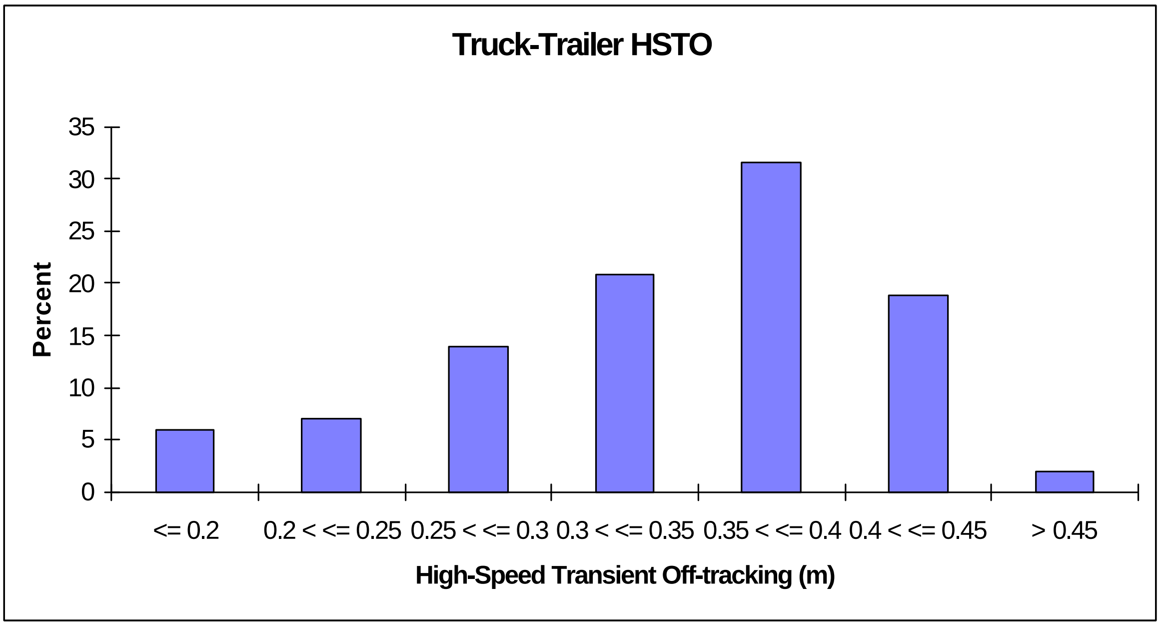


Figure 32. Truck-Trailer HSTO for Crashed Vehicles.

Truck-Trailers (cont)

Yaw Damping Ratio Target Value >= 0.15.

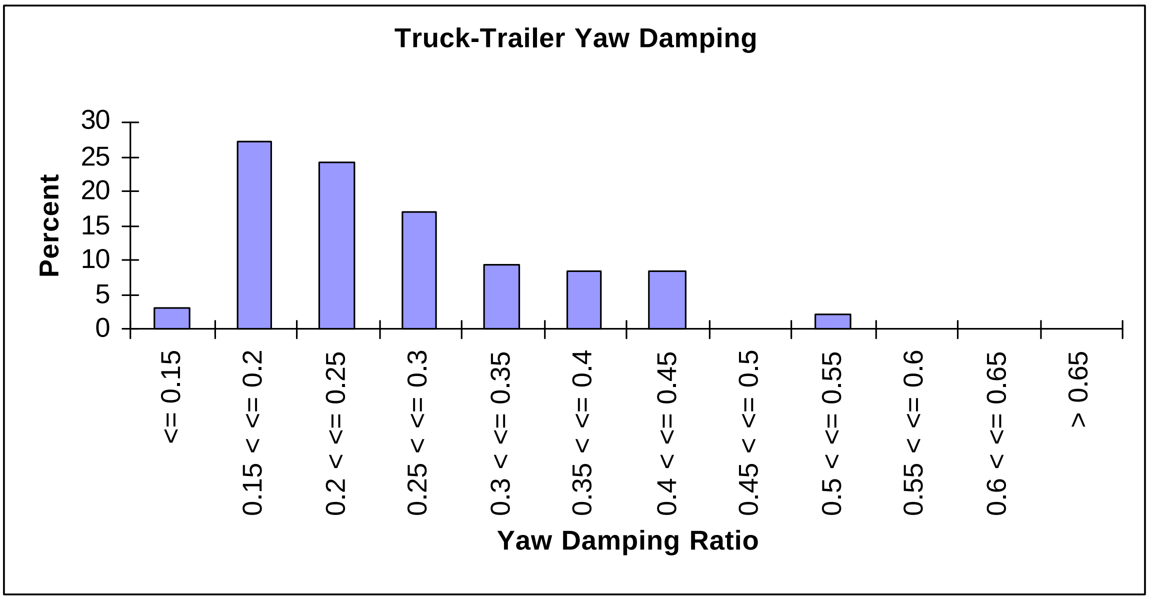


Figure 33. Truck-Trailer Yaw Damping for the Fleet.

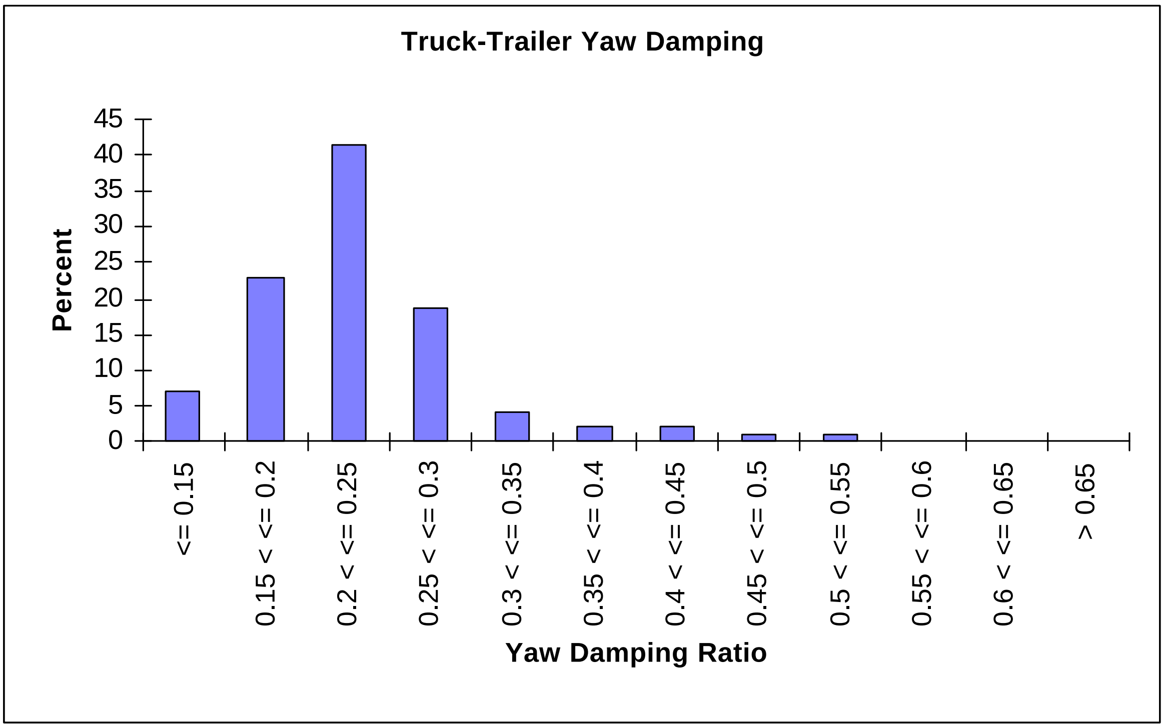


Figure 34. Truck-Trailer Yaw Damping Ratio for Crashed Vehicles.

7.4.3 Tractor-Semi

SRT Target Value >= 0.35 g.

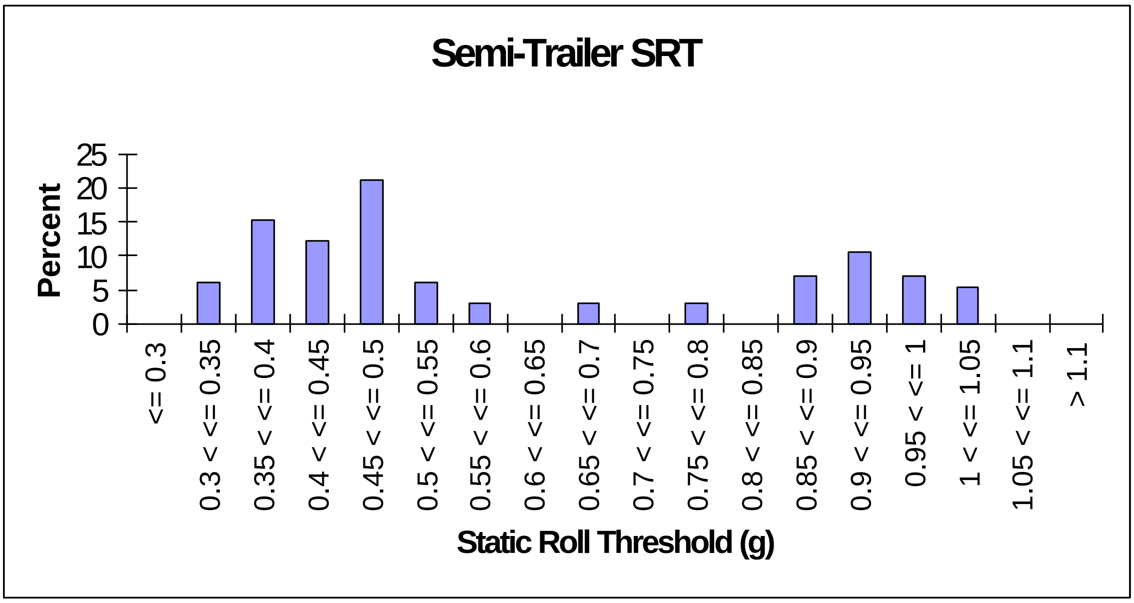


Figure 35. Semi-Trailer SRT for the Fleet.

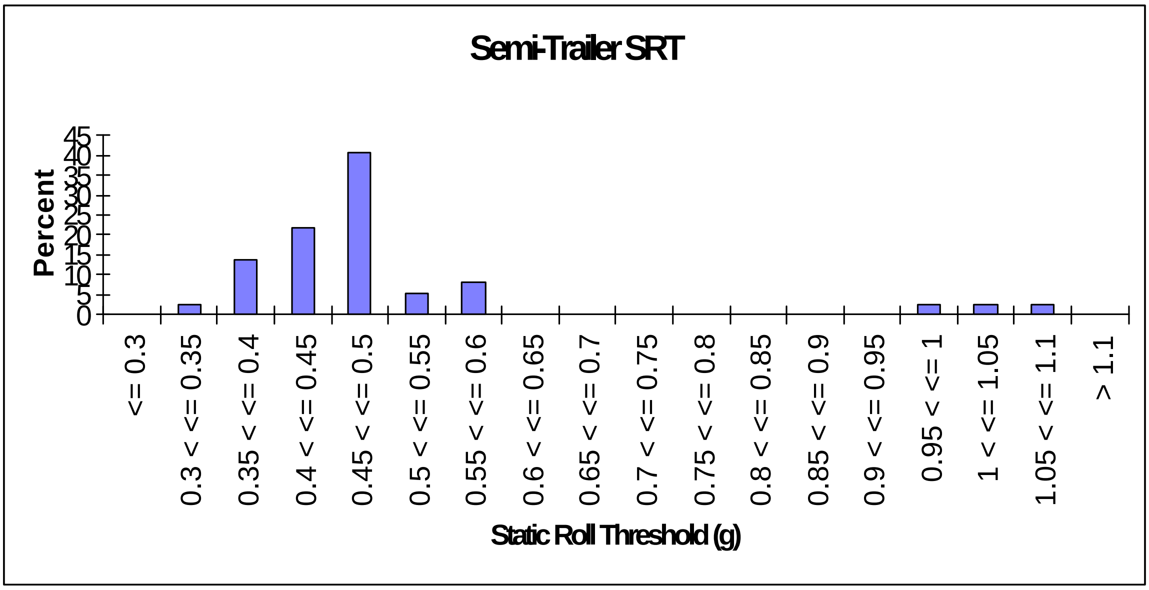


Figure 36. Semi-Trailer SRT for Crashed Vehicles.

Semi-Trailers (cont.)

DLTR Target Value <= 0.6.

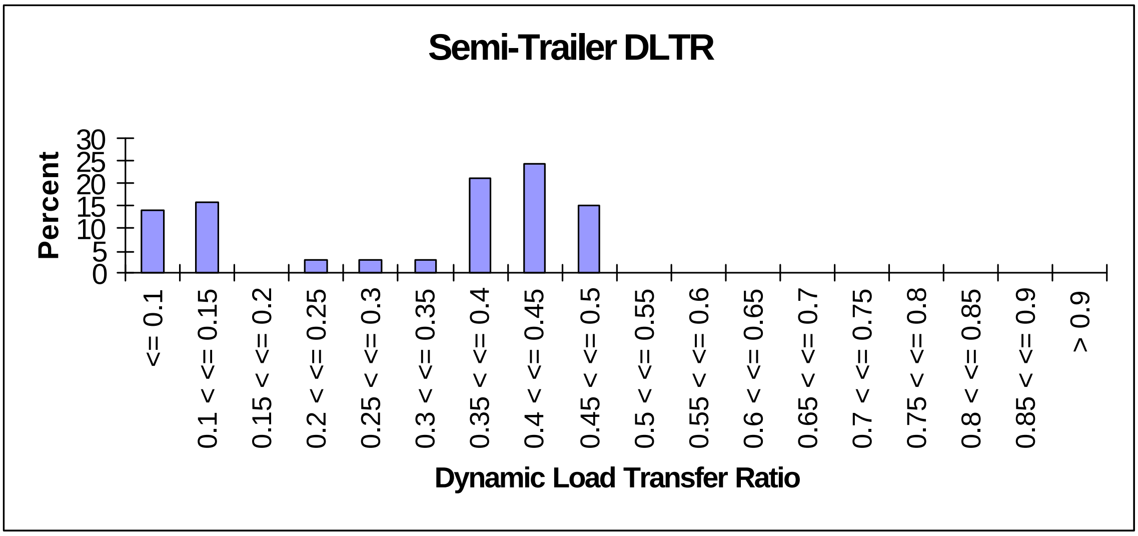


Figure 37. Semi-Trailer DLTR for the Fleet.

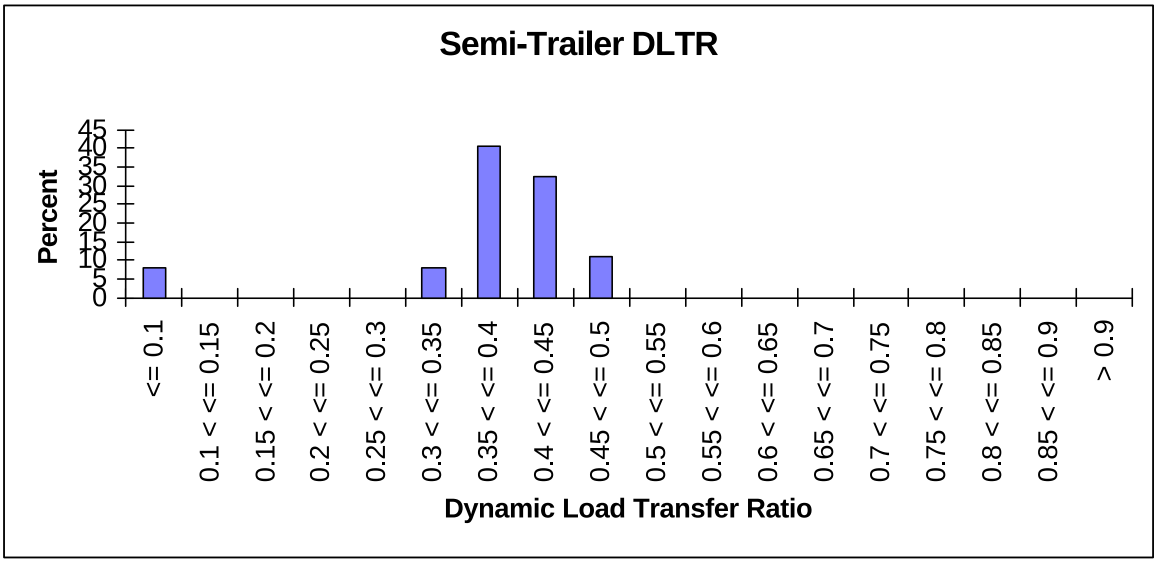


Figure 38. Semi-Trailer DLTR for Crashed Vehicles.

Semi-Trailers (cont.)

HSTO Target Value <= 0.8 m.

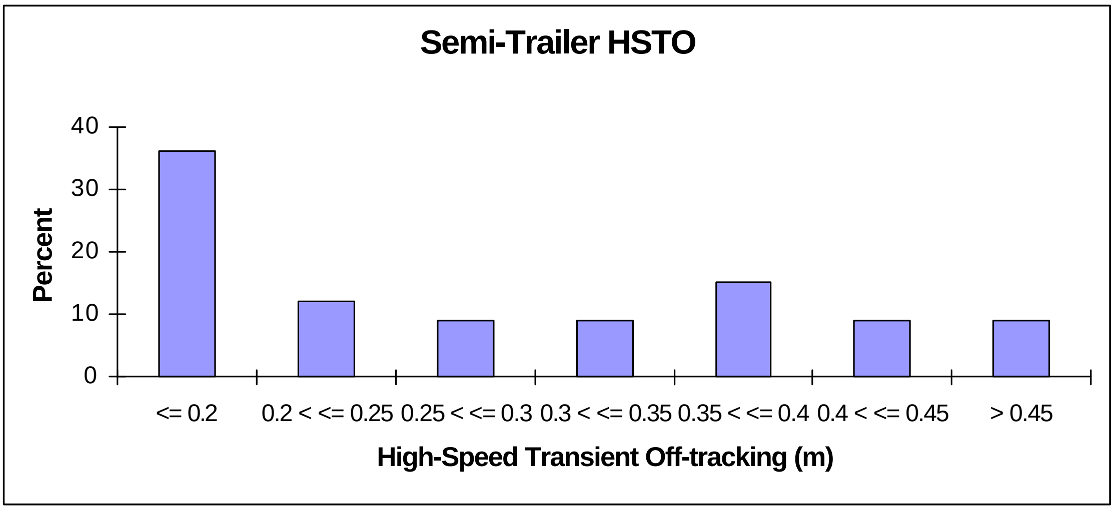


Figure 39. Semi-Trailer HSTO for the Fleet.

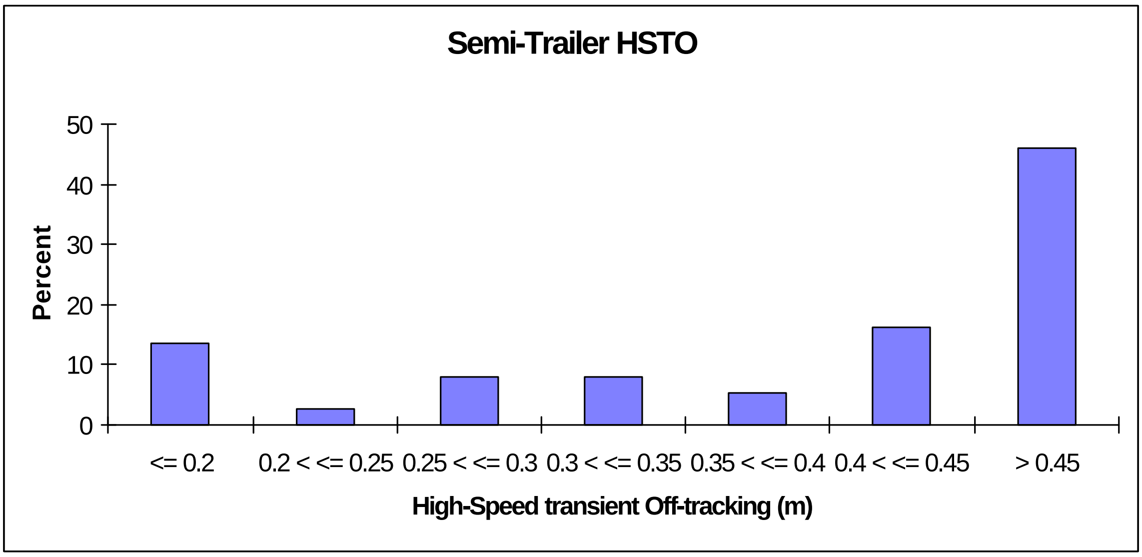


Figure 40. Semi-Trailer HSTO for the Crashed Vehicles.

Semi-Trailers (cont.)

Yaw Damping Ratio Target Value >= 0.15.

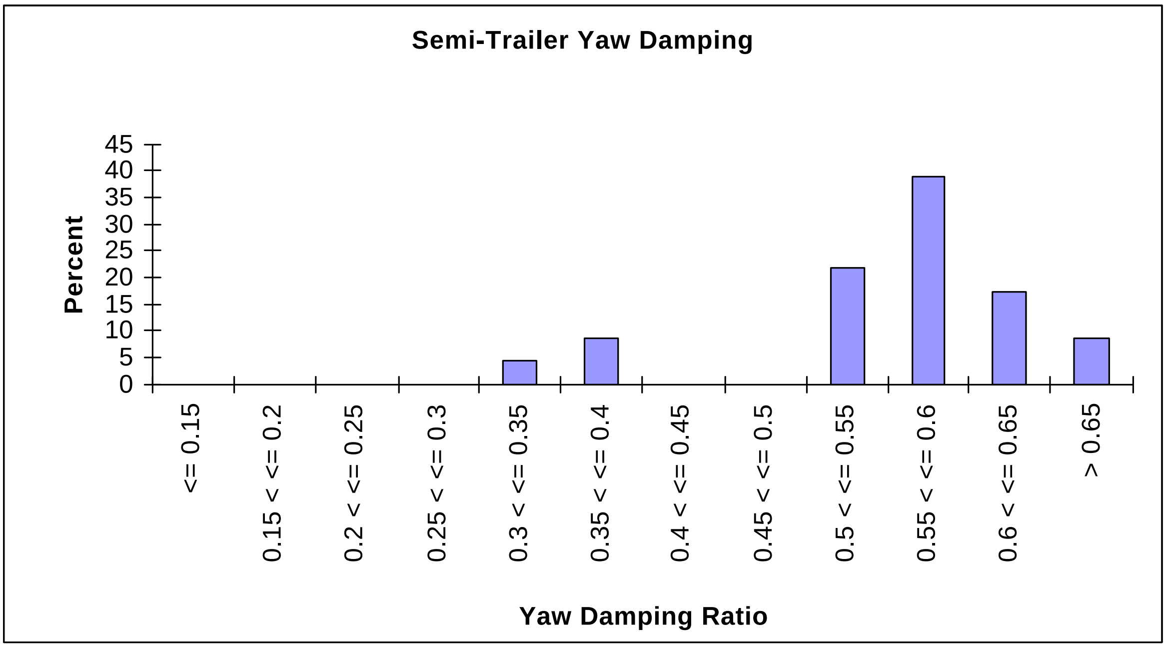


Figure 41. Semi-Trailer Yaw Damping Ratio for the Fleet.

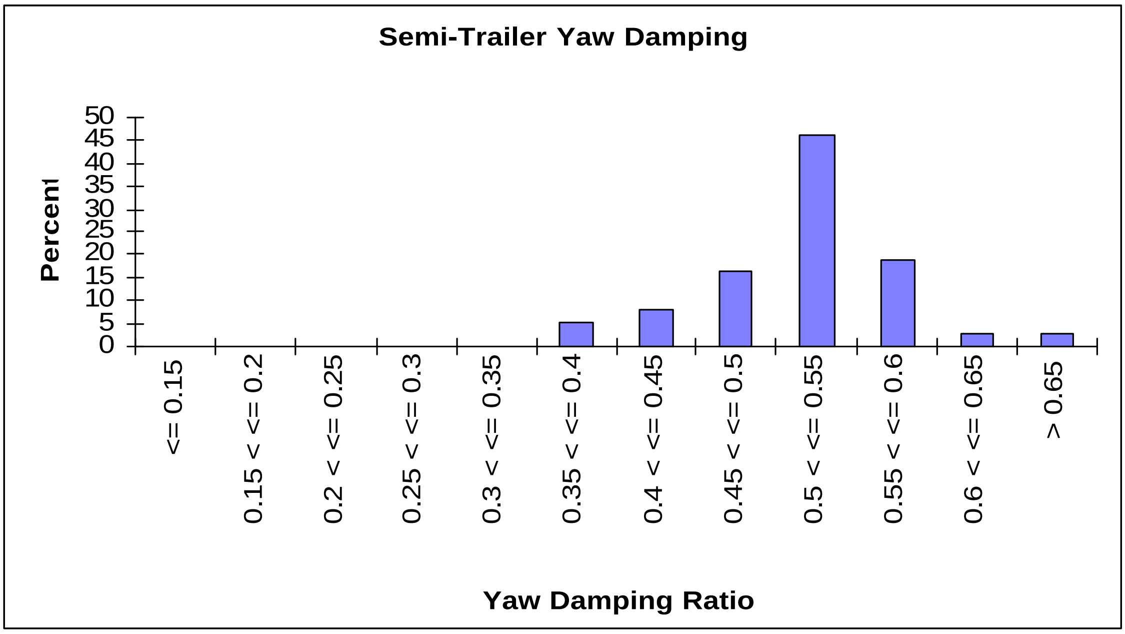


Figure 42. Semi-Trailer Yaw Damping for Crashed Vehicles.

7.5 Appendix E: Regression Analysis and Plots

The calculation of Static Roll Threshold was made using a combination of known information about the vehicle, estimates based on values obtained from UMTRI sources[3,4] and the hybrid formula shown below, based on the Roll Threshold formula developed by Elischer and Prem (1998).

$$SRT = \frac{T}{2HF}$$

where:

T= Track width

H= CoG of Vehicle (tare +payload)

$$F = 1 + \frac{W_P(H_P - H_E)}{H(W_E + W_P)}$$

where:

W_P = Weight of payload

H_P = CoG Height of Payload

H_E = CoG Height of Empty Vehicle

W_E = Weight of Empty Vehicle (tare)

The SRT is calculated for each uncoupled vehicle separately (ie. for a truck and trailer) and the resulting "worst" (lowest) value is recorded as the vehicle's SRT. Roll coupled units (B-Trains and Tractor-Semi's) are calculated as a single unit. Calculated values of SRT are compared to those obtained through previous analysis using Yaw/Roll and shown below in Figure 43.

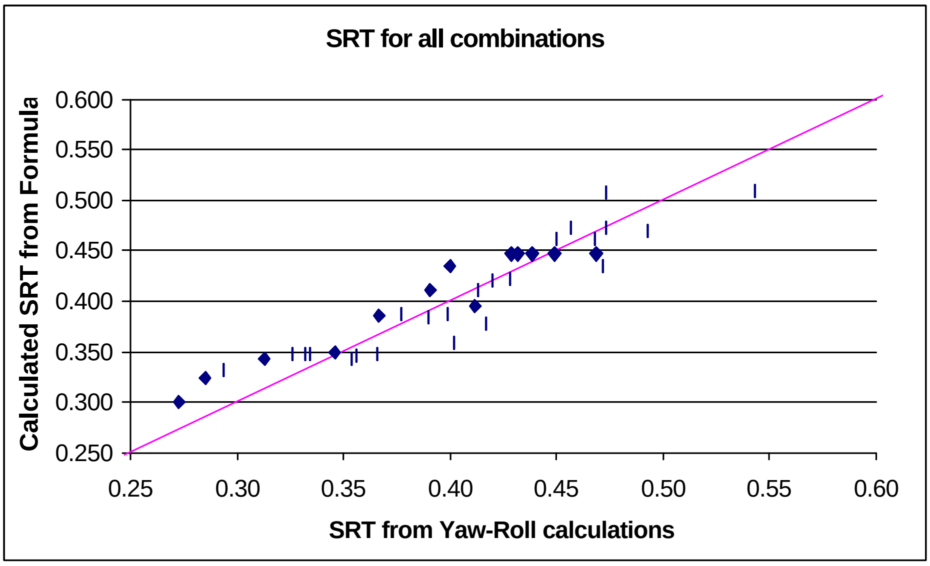


Figure 43. Estimating SRT for all Combinations.

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[3] Winkler et al. –Heavy Vehicle Size and Weight- Test Procedures for Minimum Safety Performance, The University of Michigan Transportation Research Institute, 1992.

[4] University of Michigan Transportation Research Institute, Course on The Mechanics of Heavy-Duty Truck and Truck Combinations, 1988.

Using multi-linear regression analysis, an equation of the form, $y = \sum_i a_i x_i + b$ is determined for the other performance parameters. An Excel "add-in" statistics package, XLSTAT, was used to calculate the regression coefficients. The procedure commenced with a regression using all the independent variables selected and then one by one, eliminated those variables which did not contribute significantly to the model. The level of significance used for this elimination process was 0.05. The plots below show the fit between the data estimated by the regression and Yaw/Roll. The tables contain the "x" variables, their coefficients and Fisher's F value, for each of the performance measures. The r^2 and Fisher's F value are quoted for each regression model. Note, the Fisher's F for each variable is an indication of the relative significance of that variable compared to the others. However, it does depend on the order in which the variables are included in the model. While the regressions presented below show a very good fit, they are not unique and other possible combinations (not necessarily better) can be obtained. The coefficient definitions are provided in Table 13 at the end of this Appendix.

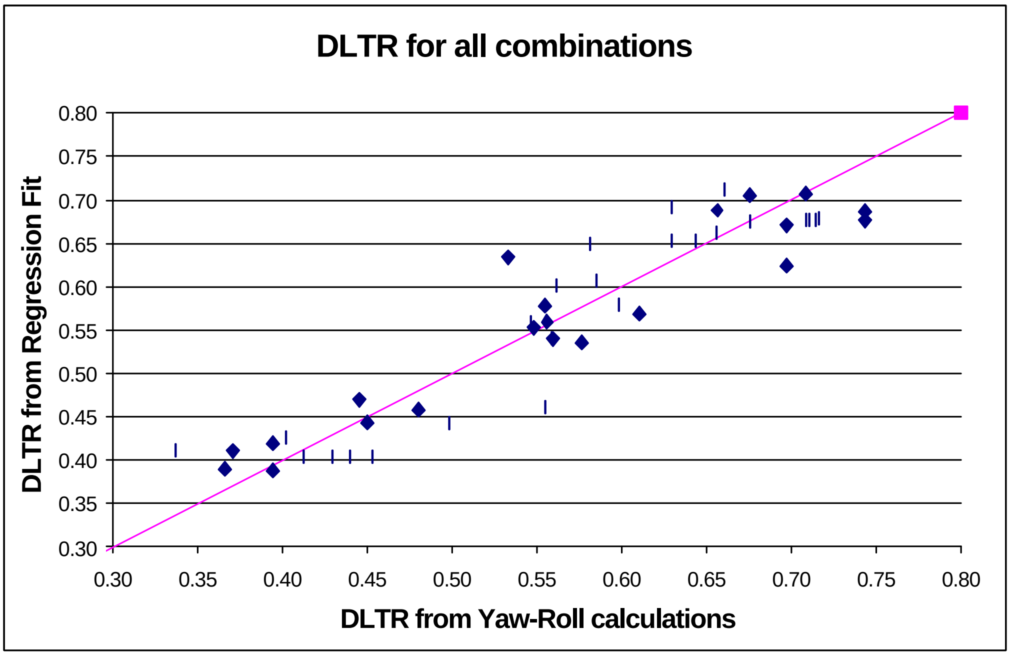

Figure 44. Estimating DLTR for all Combinations.

Table 9. DLTR Equation

Variable	Coefficient	Partial F
No. Un-Coupled Hitches (a_1)	0.212346	247.1399
SRT (a_2)	-0.61215	55.9846
Intercept (b)	0.677937	

The r^2 value for the DLTR regression model is 0.876. The Fisher's F value for the overall model is 152.

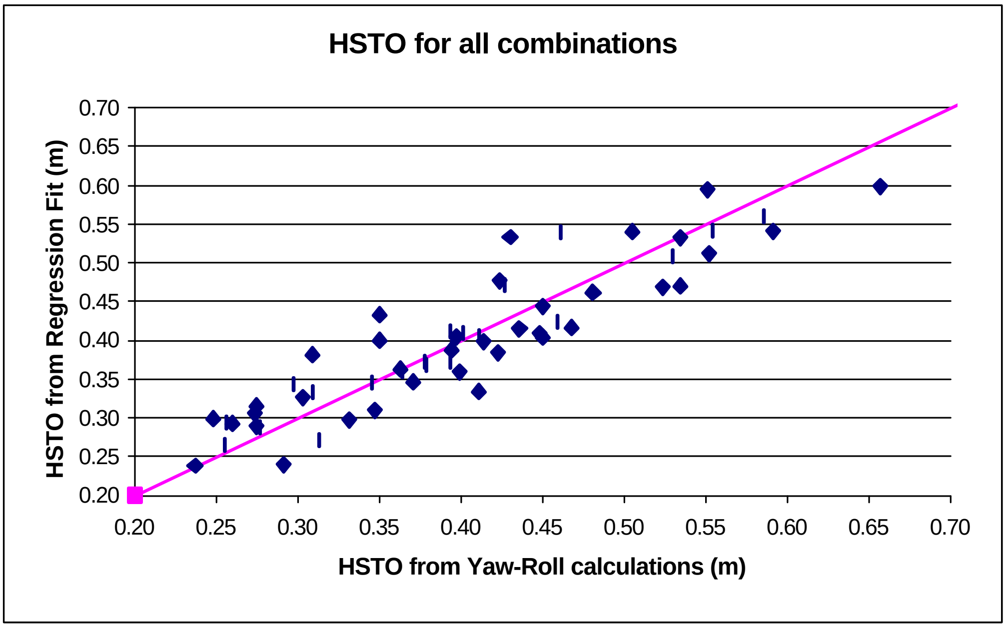

Figure 45. HSTO Estimate for all Combinations.

Two Equations are used to estimate the HSTO, one for truck-trailers and another for B-trains and Semi's. The tables below indicate the variables and their constants.

Table 10. Truck-Trailer HSTO Equation.

Variable	Coefficient	Partial F
Mass Ratio	.124584	115.1364
No. Axles	-0.08659	45.7253
SRT	-0.79549	22.7977
Intercept	0.819786	

The r^2 value for the Truck-trailer HSTO regression model is 0.832 and the Fisher's F value is 61.22.

Table 11. Semi-Trailer & B-Train HSTO Equation.

Variable	Coefficient	Partial F
SRT	-1.140	40.3558
Mass Ratio^2	0.012	24.02724
$\left(\prod_{i=1}^{n} wb_i\right)^{\frac{1}{n}}$	-0.046	13.0255
wb_2	0.136	15.7005
Intercept	0.386	

The r^2 value for Semi-Trailer and B-Train HSTO is 0.878, the Fisher's F value is 23.29.

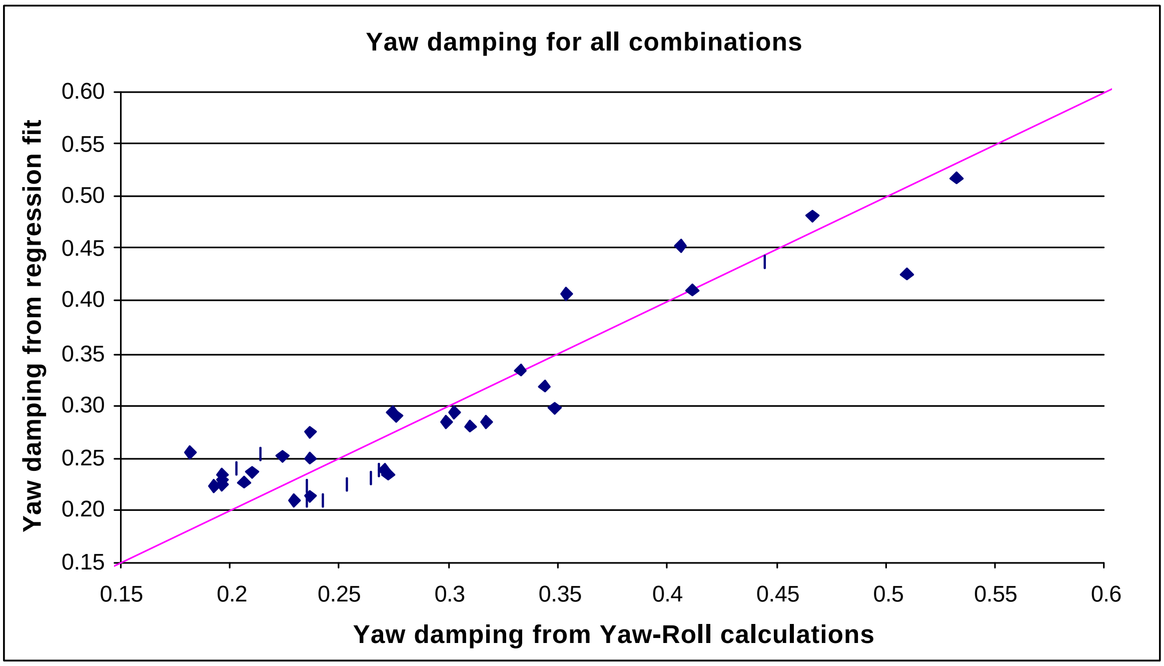

Figure 46. Yaw Damping Estimate For All Combinations.

Table 12. Yaw Damping Ratio Equation.

Variable	Coefficient	Partial F
No. Un-coupled Hitches	-0.0584	140.34
Wb_2	0.077	22.42
Trailer Mass	-4.73E-06	5.93
No. of Roll Coupled Hitches	0.086	5.49
Tyre Ratio	0.124	4.24
No. of Axles on Rear	-0.058	3.95
wb_t	0.035	2.70
Intercept	0.194	

The r^2 value for the Yaw Damping Ratio regression model is 0.870 and the Fisher's F value is 24.30.

Table 13. Parameter Definitions.

Variable	Definition
SRT	Static Roll Threshold, described above
No. of Roll Coupled Hitches	The number of hitch connections that are roll coupled
No. of Uncoupled Hitches	Number of hitches which are not roll coupled
No. Axles on Rear	Total number of axles on the rear unit
Mass Ratio	GVM of last trailer divided by the GVM of the vehicle in front of it
No. of Axles	Total number of axles on the rearmost unit
wb_t	Wheelbase of the tractor or truck
wb_1	Wheelbase of the first trailer unit
wb_2	Wheelbase of the second trailer unit
Front Tyres	Number of tyres on front unit
Rear Tyres	Number of tyres on the rear unit
Tyre Ratio	Rear tyres divided by Front tyres