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# Performance Measures and Crash Rates

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**Abstract**

Performance measures characterise the stability of heavy vehicles using standardised vehicle manoeuvres. In this paper we determine the relative crash rate for different values of the performance measures in the New Zealand Heavy Vehicle fleet. Quantifying the relative crash rates is fundamental to estimating potential benefits and costs associated with countermeasures to improve vehicle stability.

Simple formulae were developed to estimate performance measure values using vehicle parameters that are obtainable from crash reports. Using a database of simulation analysis results and least squares regression, the most significant parameters were identified and best-fit formulae were determined. These formulae were then applied to the set of vehicles in the police crash database, which had been involved in rollover or loss-of-control crashes. For each performance measure a distribution of values was obtained. This analysis was repeated for another set of vehicles randomly selected from the fleet to determine the distribution of the performance measure values for the fleet as a whole. The ratio of these two distributions then gives the relative crash rate by performance measure value.

As an example, the static roll threshold (SRT) results indicated that 15% of the fleet had values below the desired 0.35g target but 40% of the vehicles involved in stability-related crashes were below 0.35g. Similar relationships were found for other performance measures but it should be noted that these other measures are not independent of SRT.

# 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% of the deaths on NZ roads involved a HV (LTSA, 1998). This is an increase from 1997 when 18% of the deaths involved a HV. On a distance basis HV's have over 3 times the fatal crash involvement rate of other vehicles, given that they accumulate 6.2% of the total distance travelled (LTSA, 1996). By comparison, in the USA HV's accumulate 7% of the distance travelled (similar to NZ), but are involved in only 8% of the fatal crashes and 3% of all crashes A particular concern in NZ is the high number of HV rollover crashes.

A performance measure (PM) characterises the behaviour of a vehicle in response to a standardised test, which usually reflects some aspect of vehicle operations. Intuitively we would expect that a vehicle that achieves better PM results relating to vehicle stability would have a lower risk of being involved in a stability-related crash but there appears to be very little published evidence to support this contention and none relating to the New Zealand context. Clarke (1998) shows a graph relating fatal crash rate to one PM (static roll threshold) for the USA but this is based on only three data points. To quantify the benefits associated with any measures introduced to improve vehicle stability the relationship between vehicle performance and crash risk must be known.

This paper considers four stability-related PMs, which are described in Table 1 The desired target values for New Zealand are also shown (White, 1996; Baas, 1997). For each PM the distribution of values for the New Zealand combination HV fleet was determined. Similarly the distribution of those values for the set of HVs involved in stability-related crashes was determined. By comparing the distribution for crashed vehicles with that of the fleet in general the relative crash rate with respect to the PM values can be calculated.

# 2.0 METHODOLOGY

PM values are normally determined by computer simulation using validated software or by physically testing the vehicle. Neither of these methods could practicably be used in this study. Computer simulation requires detailed information of the vehicle parameters, which was not available in either the data on the general fleet or the crashed vehicles. Physical testing could not be undertaken on the crashed vehicles and would be prohibitively expensive to undertake on a representative sample of the whole fleet. Consequently the regression analysis approach used by Winkler (1993) was applied. This derives relatively simple formulae for determining the vehicle's PMs from basic easily obtainable vehicle parameters. These formulae can then be applied to a database of vehicles to obtain the distribution of PM values for that database. Although the formulae may not be very accurate in estimating the PMs for an individual vehicle when applied to a sufficiently large sample of vehicles the resulting overall distribution will be much more accurate.

## 2.1 Simple Formulae for Estimating PM Values

The first stage in the analysis was to derive simple formulae for estimating PM values from vehicle parameters that could easily be obtained or estimated. These parameters were identified and can be categorised as follows:

- configuration - vehicle configuration, axle configuration, tyre configuration
- mass - gross vehicle mass (by unit), tare mass (by unit), payload type
- dimensions - wheelbase (by unit), payload centre of gravity (Cg)

TERNZ holds a database that consists of the results of simulating more than 250 vehicle configurations over the past several years using Yaw-Roll software. These simulations were undertaken for variety of purposes including parameter studies, compliance testing, and crash investigations. In most but not all cases the vehicles were fully laden. Data from more than 50 of these vehicles were used for the regression analysis.

For each PM a likely set of independent variables was selected using the parameters above and combinations of these parameters. Least squares linear regression was then used to find the best-fit relationship between these variables and the PM measure. An iterative process was then used to eliminate, one at a time, those variables which did not contribute significantly (at the 0.05 level) to the model. The final form was a linear equation relating the PM to a set of variables, which were all significant.

## 2.2 Determining the PM Distributions for the Vehicle Fleet

To monitor compliance with the Road User Charges (RUC) regime in New Zealand, the police surveyed 3159 vehicles between 1 August 1997 through 23 December 1998. The survey procedure is designed to obtain a random cross-section of the diesel-powered vehicle fleet and so was felt to be a useful basis for this study. Just over 2000 of the vehicles were not suitable for the purposes of this study (not HV's, no registration information, etc.) leaving 968 vehicles. From these records, 230 owners were identified and contacted requesting further information. Data for 187 laden vehicle combinations were obtained. Further details (tare weight, wheelbases, axle configuration) were obtained from the LAnd Transport Inspection System (LATIS) database. The total number of vehicle combinations in the data set was increased to 296 by adding a further 109 randomly selected vehicles, which were assumed to be empty. This was done because it has been shown that approximately 30% of vehicles are empty (White, 1996b). Table 2 shows the mix of vehicle configurations in the data. Largely because the data set consists of only a small proportion of the total vehicles surveyed the mix of vehicles is not representative of the fleet.

Using the formulae above PMs were calculated for each combination type, split into empty and full vehicles. To obtain the PM 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 vehicle configurations, (tractor semi, truck-trailer and B-train) were then combined using the weighting 0.34: 0.54: 0.12 (Baas, 1999) to obtain a fleet distribution for the PM.

## 2.3 Determining the PM Distributions for Crashed Vehicles

The CVIU attend approximately 25% of heavy vehicle crashes and fill out a report form that is entered into the Large Bus & Truck Crash database. This database was examined for vehicles that had been involved in a crash involving rollover or loss of control. Incidents from 3 August 1996 through 11 February 1999 were used and out of 182 crashes 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. As with the vehicle fleet analysis further vehicle information was obtained from the LATIS database.

### 2.4 Assumptions

In calculating the PM estimates for both RUC and CVIU database vehicles, the following assumptions were made:

1. The load was distributed between the units in the vehicle combination such that the percentage of payload capacity used is the same for each unit.
2. A constant value for track width was used in the absence of better information.
3. If a tare weight was not available then a tare weight was assigned to the vehicle based on a similar vehicle in the fleet (i.e. make, model, number of axles, etc.).
4. Similarly, for wheelbase and forward distance. If data were unavailable then dimensions from similar makes and models were used.
5. Weights and dimensions were assumed to be in compliance with legal requirements.
6. The load Cg heights were estimated from the loading condition of the vehicle and the type of load (UMTRI, 1988). The method of Cg estimation was applied consistently to both RUC and CVIU databases even if better information was available.
7. Calculation of tare Cg assumed that drive axles weigh 1040kg, trailer axles 800kg, and steer axles 540kg. Axles were assumed to have a Cg height of 0.51m. The tare sprung mass was assumed to have a Cg height of 1.1m for trucks and 1.8m for trailers.

These assumptions lead to conservative (better values) estimates of PMs by assuming legal load requirements and regulations (LTSA, 1997) are adhered to. There is evidence to suggest that this is not always the case in practice (Baas, 1997).

## 3.0 ANALYSIS AND RESULTS

### 3.1 Regression Models

Although regression models for the calculation of SRT were developed using variables and parameters proposed by Winkler et al (1992) and UMTRI (1998), it was found that the formula developed by Elischer and Prem (1998) gave equally good results. As this formula is based on a physical model of the vehicle rather than just a statistical one it was used.

Where units were not roll-coupled SRT was calculated for each unit separately. The resulting "worst" (lowest) value was deemed to be the combination's SRT. Roll-coupled units were treated as a single vehicle. Figure 1 shows the formula used and compares the values of SRT calculated using it with those obtained using Yaw/Roll.

For each of the other PMs, an equation of the form, $y=\Sigma\ a_i.x_i + b_i$ was determined using multi-linear regression analysis as outlined in section 2.1. Figure 2 through Figure 4 show the variables used, their coefficients, the $r^2$ statistic for goodness-of-fit and Fisher's F values, together with a plot comparing the values calculated with these formulae with those obtained using Yaw-Roll for each of the PMs. The Fisher's F for each variable is an indication of the relative significance of that variable compared to the others.

### 3.2 Static Roll Threshold (SRT) Results

Applying the simple model for calculating SRT to the sample of vehicles representing the fleet gives the distribution shown in Figure 5. The distribution is bi-modal with the laden vehicles in left group and the empty vehicles in the right. Figure 6 shows the distribution of SRT for the set of vehicles involved in stability-related crashes. For each bin in Figure 6 dividing by the corresponding bin in Figure 5 gives the relative crash rate for that bin. The results of doing this are shown in Figure 7. The trend line shown is a 3rd order polynomial best-fit line generated by the spreadsheet program. If SRT and relative crash rate were unrelated the expected value of all the histogram bins would be unity. However, there is a clear trend showing a strong correlation between low SRT and high relative crash rate.

### 3.3 Dynamic Load Transfer Ratio (DLTR) Results

The analysis steps outlined in the previous section were repeated for DLTR. The resulting relative crash rates are shown in Figure 8. The trend here is similar to that for SRT although mirror imaged because higher DLTR values represent poorer performance. As with SRT the relative crash rate rises steeply once the desired limit is exceeded.

### 3.4 High Speed Transient Off-Tracking (HSTO) Results

The same analysis was undertaken for HSTO. The resulting relative crash rates are shown in Figure 9. In this case none of the vehicles exceeded the target value for the PM. There is a trend for crash rates to rise with increasing HSTO but no sudden rapid increase.

### 3.5 Yaw Damping Ratio (YDR) Results

In respect of YDR the vehicles in the fleet can be separated into two groups; truck-trailers with relatively poor YDR values and tractor semi-trailers and B-trains with relatively good values. Only a very small proportion of vehicles had a YDR value below the target. Although the analysis indicated a high relative crash rate for these vehicles the numbers in this category was too small to be confident of the relationship. For higher YDR values there was no clear trend relating crash rate to YDR.

## 4.0 DISCUSSION & CONCLUSIONS

The results clearly indicate that vehicles with lower SRT, higher DLTR and higher HSTO have a higher likelihood of being involved in a stability-related crash. There is also some indication that a poor value for YDR increases crash risk. These relationships are not fully independent as the regression models for DLTR and HSTO both include SRT as a variable.

The level of the target values for SRT, DLTR and possibly YDR seem reasonable in that the crash rate rises steeply when these PM 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 indicate increased crash risk.

Overall, the stability of the New Zealand fleet is good; 85% of the fleet meet the target SRT, and 65% meet the target DLTR, while nearly all of the vehicles in this survey met the YDR target and all of them exceeded the suggested HSTO minimum performance value.

However, it is also clear that a small percentage of poor-performing vehicles are contributing disproportionately to the crash rate. For example, although only about 15% of the fleet had an SRT value below the target 0.35g, 40% of the vehicles involved in crashes fall into this category. A similar pattern is seen for the other PMs. These results are summarised in Table 4.

In many respects this is a very positive finding because it indicates that improving the performance of the relatively small number of vehicles should have a significant impact of the overall crash rate. The relationships between PM values and relative crash rate developed in this study enable us to quantify this impact and hence to determine the benefits of countermeasures to improve vehicle stability (Baas et al., 2000).

# 5.0 REFERENCES


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# 6.0 TABLES & FIGURES

**Table 1. Performance Measure Description.**

| Performance Measure | Target Value | Brief Description |
|---|---|---|
| Static Roll Threshold (SRT) | ≥ 0.35 g | Maximum steady turning lateral acceleration without rollover. |
| Dynamic Load Transfer Ratio (DLTR) | ≤ 0.60 | Indication of nearness in a highway-speed evasive steering manoeuvre. A measurement of the load transfer from one side of the vehicle to the other. |
| High Speed Transient Off-tracking (HSTO) | ≤ 0.80 m | 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) | ≥ 0.15 | Rate at which trailer oscillations dampen out. The measure is related to what is commonly known as snaking. |

**Table 2. RUC Survey Results.**

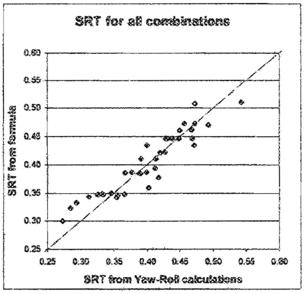
| Combination | Laden | Empty | Total Number |
|---|---|---|---|
| Rigid Truck | 43 | 32 | 75 |
| A-Train | 2 | 0 | 2 |
| B-Train | 18 | 31 | 49 |
| Truck-Trailer | 99 | 30 | 129 |
| Tractor-Semi | 25 | 16 | 41 |
| **total** | **187** | **109** | **296** |

**Table 3. CVIU Vehicle Combinations.**

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

**Table 4. Performance Measure Results Summary.**

| Performance Measure | Target Value | Fleet Performance (Target Value Not Met) | Crashed Vehicles (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% |




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

*where* :

$T = trackwidth$

$H = CoG\ of\ Vehicle\ \ (tare + payload\ )$

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

*and* :

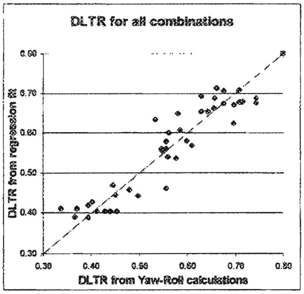
$W_P = Weight\ \ of\ \ payload$

$H_P = CoG\ \ Height\ \ of\ \ payload$

$H_E = CoG\ \ Height\ \ of\ \ Empty\ \ Vehicle$

$W_E = Weight\ \ of\ \ Empty\ \ Vehicle\ \ (tare\ )$

**Figure 1. Estimate of SRT for All Combinations.**

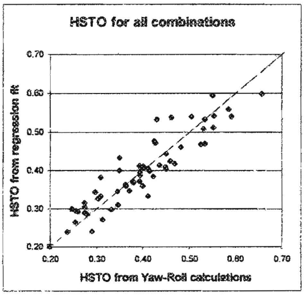



DLTR equation

| Variable | Coefficient | Partial F |
|---|---|---|
| No. of Roll-uncoupled Hitches | 0.212346 | 247.1399 |
| SRT | -0.61215 | 55.9846 |
| Intercept | 0.677937 | |

For the overall model, $r^2$ was 0.876 and Fisher's F was 152.0.

**Figure 2. Estimate of DLTR for All Combinations.**




HSTO equation for truck-trailers

| Variable | Coefficient | Partial F |
|---|---|---|
| Mass Ratio (rear/front) | 0.124584 | 115.1364 |
| No. of Axles | -0.08659 | 45.7253 |
| SRT | -0.79549 | 22.7977 |
| Intercept | 0.819786 | |

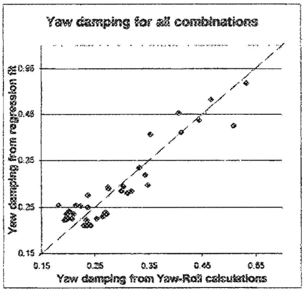
For the model, $r^2$ was 0.832 and Fisher's F was 61.22.

HSTO equation for B-trains and tractor semis

| Variable | Coefficient | Partial F |
|---|---|---|
| SRT | -1.13995 | 40.3558 |
| Mass Ratio$^2$ | 0.012425 | 24.02724 |
| $(\Pi\ \text{wheelbase}_i)^{1/n}$ | 0.136474 | 15.7005 |
| wheelbase 2$^{nd}$ trailer | -0.04601 | 13.0255 |
| Intercept | 0.385553 | |

For the model, $r^2$ was 0.878 and the Fisher's F was 23.29.

**Figure 3. Estimate of HSTO for All Combinations.**




YDR equation

| Variable | Coefficient | Partial F |
|---|---|---|
| No. Uncoupled Hitches | -0.0584 | 140.34 |
| wheelbase 2[nd] trailer | 0.077 | 22.42 |
| Trailer Mass | -4.73E-06 | 5.93 |
| No. Coupled Hitches | 0.086 | 5.49 |
| Tyre Ratio (no rear/no front) | 0.124 | 4.24 |
| No. Axles on Rear | -0.058 | 3.95 |
| wheelbase truck | 0.035 | 2.70 |
| Intercept | 0.194 | |

For the overall model, $r^2$ was 0.870 and Fisher's F was 24.30.

**Figure 4. Estimate of YDR for All Combinations.**

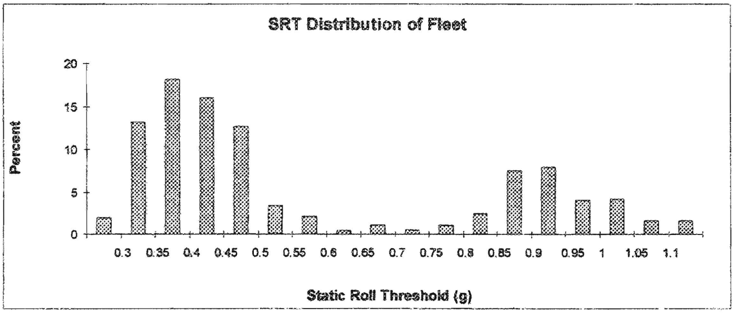



**Figure 5. SRT Distribution of the New Zealand HV Fleet.**

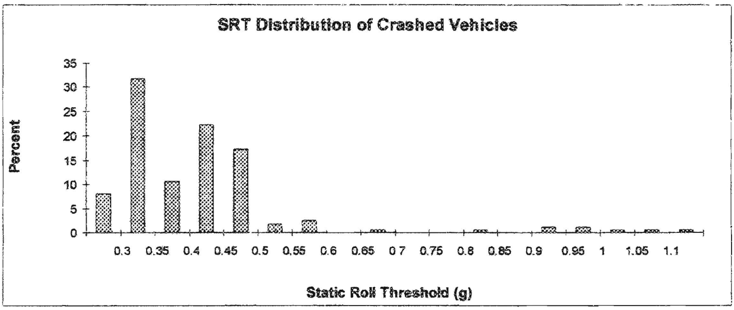



**Figure 6. SRT Distribution for Crashed Vehicles.**

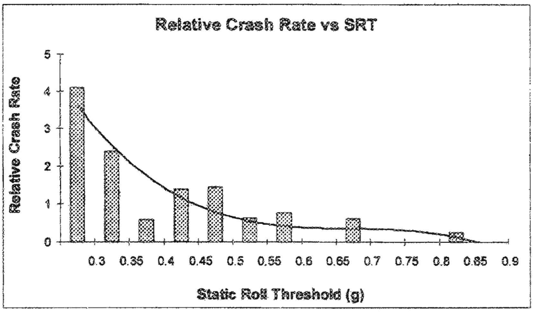



**Figure 7. SRT Relative Crash Involvement Rate.**

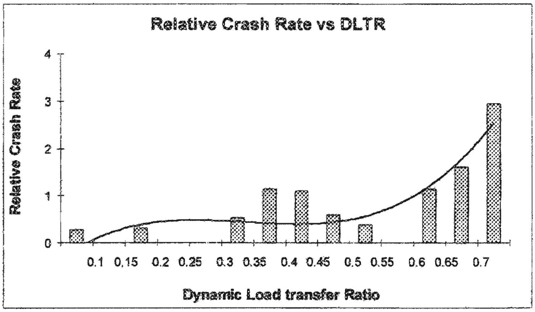



**Figure 8. DLTR Relative Crash Involvement Rate.**

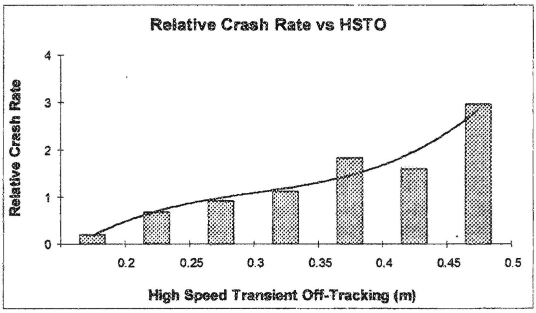



**Figure 9. HSTO Relative Crash Rate.**