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## **USE OF ENGINEERING PERFORMANCE IN EVALUATING SIZE AND WEIGHT LIMITS**

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### **ABSTRACT**

The Transportation Studies Division of the Federal Highways Administration (FHWA) is carrying out a Comprehensive Truck Size and Weight (TS&W) Study and has developed methodologies and tools for evaluating the effects of size and weight policies on vehicle safety, pavements, bridges, roadway geometry, traffic operations, truck costs, logistics, truck travel, mode share, enforcement, environment, energy conservation, permits and pricing mechanisms.

Studies of the influence of a range of TS&W policy scenarios on a wide range of productivity, safety, infrastructure, economic, industrial and community outcomes have been carried out. To provide specific input on the implications of certain changes in size and weight limits with respect to heavy vehicle safety performance, Roaduser Research was commissioned to provide a computer-based analysis of vehicle performance under current and potential future size-and-weight scenarios.

The engineering performance of current and potential future US heavy vehicle configurations has been quantified using computer simulation models. The following performance attributes were evaluated:

- steady-state roll stability
  - rearward amplification
  - load transfer ratio
  - friction utilization
  - low-speed offtracking
  - high-speed offtracking
  - transient high-speed offtracking.
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The FHWA Transport Studies Division's Engineering Performance Database was the result of the computer simulation of 1,600 heavy vehicle options conducted by Roaduser Research. These heavy vehicle options are characterised by vehicle configuration, Gross Vehicle Weight (GVW), body type, length dimensions, width and the density of the freight carried. In total, the Database contains some 9000 engineering performance numerics.

Analysis was carried out to assist the evaluation of the safety implications of replacement vehicle configurations and appropriate GVW limits for those configurations. This included the development of robust performance standards

The Database was systematically explored with regard to the ranges and distributions of performance numerics and the sensitivities of performance numerics to the independent variables contained in the Database, and simple statistical analyses were carried out.

Correlation analysis provided extremely useful information with regard to how vehicle performance measures relate to each other, particularly stability measures. This type of analysis has not been carried out before, and the large size of the Database meant that completely new knowledge and understanding of vehicle performance relationships, particularly with regard to setting performance standards, was generated.

Comprehensive analysis of the Database and appropriate performance criteria was carried out, including (i) consideration of existing relationships between vehicle performance and accident risk (ii) consideration of the performance capabilities of vehicle configurations which are currently operating with apparent success and (iii) previously-proposed performance criteria.



## **INTRODUCTION**

Heavy truck size and weight policies have a profound effect on truck design and affect pavement wear, bridge stress, road geometrics, and vehicle stability and control. In Canada, New Zealand and Australia, a move towards a performance-based approach to size and weight regulatory policy has proven to be an effective means of achieving goals of improved safety, increased truck productivity and improved management of the highway infrastructure wear. This regulatory approach has not been attempted in the United States and is being considered in the FHWA Comprehensive Truck Size and Weight Study

Highway safety is the over-riding concern in the review of size and weight limits. Any changes in limits (which would assist productivity and competitiveness) must not degrade safety. There is, however, no agreed absolute safety performance standard applicable to individual vehicles.

Performance based measures need to be identified that consider (i) improving the safety performance of trucks using US highways, (ii) the performance of the current fleet (iii) the relationship between accident risk and performance attributes (iv) what is practical to measure and (v) how these measures would effect the current fleet. Such performance measures cover certain key aspects of heavy vehicle stability and control and generally relate to the engineering performance capabilities of trucks. To the extent that they are able to meet the rather demanding requirements listed above, they are termed robust performance measures.

Roaduser Research has carried out extensive analysis of the engineering performance of a comprehensive selection of current and potential future US truck configurations, including a wide range of the following variables: Gross Vehicle Weight (GVW), body type, vehicle width,

trailer length and freight density. The resulting FHWA Engineering Performance Database, based on simulation of vehicle dynamics, is the most extensive database of its type ever assembled. Analysis of this Database has provided a significantly enhanced basis for recommending appropriate performance measures for US trucks.

The following key aspects of the potential use of engineering performance measures to evaluate US size and weight options are discussed in this paper:

- statistical analysis of the FHWA Engineering Performance Database
- correlations that exist between various performance attributes
- the performance of the current fleet, particularly in relation to the performance standard of commonly-used vehicle configurations
- what is known about the relationship between accident risk and performance measures
- previously-proposed performance standards and the conditions under which they were evaluated
- the practicality of measuring various performance attributes, particularly with regard to testing for compliance and enforcement of regulations.

## **ANALYSIS OF ENGINEERING PERFORMANCE DATABASE**

### **Characteristics Of Database**

The FHWA Transport Studies Division's Engineering Performance Database was the result of the computer simulation of 1,600 heavy vehicle options conducted by Roaduser Research. These heavy vehicle options are characterised by vehicle configuration, Gross Vehicle Weight (GVW), body type, length dimensions, width and the density of the freight carried. The prime purpose of the Database was to provide a means of evaluating size and weight regulatory options and its scope is therefore relatively broad.

The Database was not intended to represent the operation of the current US fleet; while the scope of the variables in the Database may be broad enough to attempt this, the Database contains no specific information on the relative incidence of various configurations, body types, dimensions, weights and freight densities in US highway transportation operations. The Database does reflect the range of engineering performance, and sensitivities to key variables, associated with heavy vehicles permitted under current US size and weight limits and under options for future changes to size and weight limits.

The Database contains numerics representative of each vehicle option's performance quality with respect to the following safety-related attributes of engineering performance:

- steady-state roll stability
- rearward amplification
- load transfer ratio
- transient high-speed offtracking.
- high-speed friction utilization
- high-speed offtracking
- low-speed offtracking
- low-speed friction utilisation.

In total, the Database contains some 9000 engineering performance numerics.

## Distributions Of Performance Measures

In order to systematically explore the Database with regard to the ranges and distributions of performance numerics and the sensitivities of performance numerics to the independent variables contained in the Database, simple statistical analyses were carried out.

It should be noted that the Database contains results which have been averaged over all freight densities and these numerics were excluded from the statistical analysis.

Initially, charts were constructed displaying the frequency distributions of all performance numerics (e.g. static roll stability, load transfer ratio etc) for all vehicle configurations in the Database. Examples of these distributions are shown in [Figure 1](#) (a,b & c). Figure 1 shows the key performance numeric distributions for the 3-S2 tractor-trailer configuration. It was found that the distributions of performance numerics resembled normal distributions in some cases, but in many cases were skewed or bi-modal in appearance.

## CORRELATIONS BETWEEN PERFORMANCE MEASURES

It was expected that, for a particular vehicle configuration, there would be some degree of correlation between the various performance numerics. For example, a relatively high static roll stability may be associated with a relatively low load transfer ratio, at least within a particular vehicle configuration. In terms of developing robust performance measures such correlations are of great significance because (i) the number of performance attributes requiring specification may be reduced and (ii) potential conflicts between performance criteria in different attributes may be avoided.

Because the Database reflects, as reasonably as possible, the range and key variables of trucks operating under current and potential future limits, it is considered to be highly suitable for this purpose.

The correlation analysis provided extremely useful information with regard to how vehicle performance measures relate to each other, particularly stability measures. This type of analysis has not been carried out before, and the large size of the Database meant that completely new knowledge and understanding of vehicle performance relationships, particularly with regard to setting performance standards, was generated.

Relationships were sought for all relevant combinations of performance measures, resulting in the investigation of 29 possible relationships. Of the twenty nine combinations, the following four combinations have the highest correlation:

- Load Transfer Ratio vs Static Roll Stability<sup>n</sup>
- (Rearward Amplification/Static Roll Stability) vs Load Transfer Ratio
- High-speed Dynamic Offtracking vs Static Roll Stability
- High-speed Offtracking vs Static Roll Stability

It is interesting to note that static roll stability features in all these correlations and is the single most “representative” performance measure.

[Figure 3 \(a,b,c & d\)](#) shows examples of the relationships found between performance measures. It is important to note that these relationships are unique to each vehicle configuration.

It was found that, for all vehicle configurations, the strongest correlation was either between (i) static roll stability and load transfer ratio or (ii) rearward amplification divided by static roll stability versus load transfer ratio.

It was found that LTR vs SR<sup>n</sup> provides a higher correlation for certain configurations (straight trucks and truck-trailers), RA/SRS vs LTR provides a higher correlation for certain other configurations (tractor-trailers and A-doubles) and there is little difference between the power of the two relationships for some configurations.

## **DOMINANT PERFORMANCE CHARACTERISTICS OF CURRENT FLEET**

The United States heavy vehicle fleet consists of the following five basic vehicle classes:

- Single unit straight trucks
- Tractor-semi-trailers
- Truck-trailer combinations
- Double-trailer combinations
- Triple-trailer combinations

Within each class there may be up to 10 different axle configurations. However, the most dominant vehicle in the fleet is the 3-S2 tractor-semi-trailer. There are approximately 953,000 3-S2 units in the fleet which cover 83% of the annual Vehicle Miles Travelled (VMT) for vehicles with 5 axles or more (1).

It would appear that the tractor-semi-trailer vehicle class is best represented by a 3-S2 with a 48ft van trailer, a GVW of 80,000 lb and a width of 2.6m (102"). This vehicle has the largest number of units and VMT of the entire fleet.

The truck-trailer combinations are best represented by a 3-2 (F) tanker operating at a GVW of 80,000lb. This vehicle has the largest number of units and VMT in its class. It is also dominated by low centre-of-gravity (COG) body types.

The double-trailer class appears to best represented by a 2-S1-2 (A) double van operating at a GVW of 80,000 lb. This vehicle has the largest number of units in its class and the third largest VMT of the entire fleet. Two 28ft van trailers dominate this configuration.

The performance of the three vehicles which dominate the main classes in the United States truck fleet are summarised in Table 1. These performance measures apply to the worst-case COG height situation for a given GVW, when the density of the commodity carried is such that it fills the available load space to maximum height, as well as producing the maximum vehicle weight; this is termed the Gross-Out/Cube-Out freight density condition. Note that, in the case of the truck-trailer class, low-COG vehicles dominate and the 3-2 (F) has been represented by a tank vehicle.

**TABLE 1. PERFORMANCE OF KEY VEHICLE CLASS REPRESENTATIVES (at Gross-Out/Cube-Out Freight Density)**

Vehicle Config'n	GVW	Body Type	Performance Attribute							
			SR (g)	RA	LTR	HSDOT (ft)	HSOT (ft)	LSOT (ft)	HSFU	LSFU
3-S2	80,000 lb	Van	0.32	1.29	0.57	0.82	1.05	16.1	-0.15	0.35
3- 2 (F)	80,000 lb	Tank	0.45	1.90	0.77	1.56	1.15	8.8	-0.18	0.34
2-S1-2 (A)	80,000 lb	Van	0.33	2.16	1.0	2.46	1.50	12.6	-0.16	0.23

By far the dominant single example of heavy vehicle engineering performance using US highways is the 3-S2 48 ft 102 inch van tractor-trailer, with a GVW limit of 80,000 lb. Its key safety performance characteristics in the Gross-Out/Cube-Out condition are:

- static roll stability of 0.32 g
- load transfer ratio of 0.57

and Table 2 illustrates the manner in which these performance characteristics vary with freight density. It is apparent that engineering performance is sensitive to freight density and improves significantly for loads with densities, which differ from the Gross-Out/Cube-Out condition, which is very much “worst-case”. The actual distribution of load density conditions in the use of the US highway system by 3-S2 vehicles is not known.

**TABLE 2. VARIATION OF 3-S2 PERFORMANCE WITH FREIGHT DENSITY**

Freight Density (lb/cu. ft)	Performance Attribute	
	SR (g)	LTR
Gross-Out/Cube-Out (13.3)	0.32	0.57
20	0.40	0.41
40	0.52	0.28

While its presence is much less than that of the 3-S2 van, the dominant single example of combination vehicle engineering performance on limited-access facilities is the 2-S1-2 (A) van double 28 ft 102 inch trailer combination, with a GVW limit of 80,000 lb. Its key safety performance characteristics in the Gross-Out/Cube-Out condition are:

- static roll stability of 0.33 g
- load transfer ratio of 1.0.

and Table 3 illustrates the manner in which these performance characteristics vary with freight density. It is again apparent that engineering performance is sensitive to freight density and improves significantly for loads with densities, which differ from the Gross-Out/Cube-Out condition, which is very much “worst-case”.

**TABLE 3. VARIATION OF 2-S1-2 (A) PERFORMANCE WITH FREIGHT DENSITY**

Freight Density (lb/cu. ft)	Performance Attribute	
	SR (g)	LTR
Gross-Out/Cube-Out (11.0)	0.33	1.00
13	0.36	0.998
20	0.44	0.76
40	0.53	0.56

It is apparent that usage of US highways by vehicles with SR in the range 0.32 - 0.52, and LTR in the range 0.28 - 0.57 is extremely common, although the actual incidences of various levels of performance within these ranges is not known; it is known that these levels of SR and LTR are highly correlated. The main difference between the general access 3-S2 van and the limited access 2-S1-2 (A) van is in LTR, where the double has LTR in the range 0.56 - 1.00.

## ACCIDENT RISK RELATIONSHIPS

Relatively little is known about the relationship between performance attributes and accident risk. However some work has been conducted in this area by University of Michigan Transportation Research Institute (UMTRI) (2). The relationships determined by UMTRI apply to the following two vehicle configurations:

- 3-S2 tractor-trailer vans
- 2-S1-2 (A) double trailer combinations

In the case of the 3-S2 tractor-trailer van, accident risk in fatal accidents has been related to static roll stability as is shown in [Figure 4](#). In the case of the 2-S1-2 (A) double trailer combination, accident risk in fatal accidents has been related to rearward amplification. [Figure 5](#) shows this relationship.

The relationship for the 3-S2 vehicle shows that the accident risk is sensitive to SR, although the reason for the slight decrease in accident risk at the lowest SR levels is not known.

The relationship for the 2-S1-2 (A) vehicle (Figure 5) shows that the accident risk does not increase until the rearward amplification is above 2.3. Thus the accident risk relationship implies that LTR levels well above the often quoted level of 0.6, and even beyond the scope of the standard lane-change manoeuvre may be needed to generate a substantial increase in accident risk on limited access facilities. This indicates that, for the 2-S1-2 (A) vehicle configuration, high accident risk is associated with very poor dynamic stability.

The available accident risk relationships therefore indicate that:

- for the very common 3-S2 vans on general access facilities, accident risk increases steadily as the SR reduces from approximately 0.6 g (typical of higher-density loads and lighter GVWs) to approximately 0.35 g (typical of lighter-density loads and higher GVWs); concurrently, the LTR of these vehicles changes from approximately 0.2 to approximately 0.6
- for 2-S1-2 (A) double vans found on limited-access facilities, accident risk is dependent on whether the LTR is “above” or below approximately 1.0; concurrently, the SR of these vehicles lies above or below 0.33 g
- the LTR-related difference in accident risk for 2-S1-2 (A) double vans found on limited-access facilities may be accentuated at higher speeds.

While these relationships provide an incomplete picture of accident risks related to engineering performance, they are consistent with the following basic tenets:

- accident risks of all heavy vehicle configurations are sensitive to variations in SR
- for configurations with LTR in excess of approximately 0.6, and particularly those with LTR of 1.0 or “above”, accident risks are sensitive to incremental LTR.

## **TOWARDS DYNAMIC PERFORMANCE CRITERIA**

Previously recommended dynamic performance criteria have tended to be based on considerations of encouragement of the better-performing examples of a limited number of current vehicle configurations. Suggested criteria have encompassed Static Roll Stability, Rearward Amplification, Load Transfer Ratio, High-speed Dynamic Offtracking and High-speed Offtracking.

Statistical analysis of the Database has shown that Static Roll Stability is the single most powerful numeric. It is not necessary to control all of the three numerics Static Roll Stability, Rearward Amplification and Load Transfer Ratio. Some degree of control of High-speed Dynamic Offtracking and High-speed Offtracking is available through control of Static Roll

Stability. However, in order to take advantage of these relationships in setting performance standards, it is necessary to consider different static roll stability requirements for different vehicle configurations **adding to the complexity of vehicle assessment policy.**

Such complex procedures can be avoided if the load transfer measure can be used. This study has established a configuration specific relationship between the combined measures of static roll threshold, rearward amplification and load transfer ratio. It is possible then possible to infer load transfer ratio from field-test data. This may be sufficient to allow roll over threshold and load transfer ratio to be used as the primary vehicle performance measures.

## **PREVIOUSLY-SUGGESTED PERFORMANCE STANDARDS**

### **RTAC Standards**

The vehicle weights and dimensions study conducted by the Roads and Transportation Association of Canada (RTAC) (6) was the first study to recommend performance standards for heavy vehicles. In this study, simulations were carried out for a range of vehicle configurations under two conditions of centre-of-gravity height: (i) for a fixed freight density of  $545 \text{ kg/m}^3$  ( $34 \text{ lb/ft}^3$ ) and (ii) for a fixed high-COG location. Considering only the vehicle configurations involved in the current FHWA study, the static roll stability in the former case ranged from 0.35 g to 0.54 g, and in the latter case ranged from 0.31g to 0.37 g.

The set of performance standards that evolved from the RTAC study are:

- load transfer ratio < 0.6
- static roll stability > 0.4 g (recommended by study but not enforced nationally)
- rearward amplification < 2.0
- low speed offtracking < 19.7 ft (6.00 m)
- high speed offtracking < 1.5 ft (0.46 m)
- high speed dynamic offtracking < 2.62 ft (0.8 m)

The performance standards recommended by RTAC were targeted slightly above the average performance of the vehicles investigated. However, vehicles were simulated with a freight density of  $545 \text{ kg/m}^3$  ( $34 \text{ lb/ft}^3$ ). This freight density is well above the worst-case Gross-Out/Cube-Out condition used in the FHWA study and results in vehicles performing considerably better than vehicles loaded in a Gross-Out/Cube-Out loading condition. The RTAC standards therefore were based on non-stringent loading conditions.

With regard to static roll stability in particular, it is apparent that the recommended standard of 0.4 g is well above the performance range of the RTAC high-COG vehicles and is more applicable to the fixed freight density case of  $545 \text{ kg/m}^3$  ( $34 \text{ lb/ft}^3$ ).

This may be illustrated by considering the 3-S2 with a 48ft van trailer and a GVW of 80,000 lb, as analysed in the current FHWA study. If this vehicle is simulated with a freight density of  $545 \text{ kg/m}^3$  ( $34 \text{ lb/ft}^3$ ), the static roll stability becomes 0.48 g and the load transfer ratio becomes 0.32. These results are considerably better than both the results at Gross-Out/Cube-Out in the present study and the minimum required RTAC standards.

### **UMTRI Recommendations**

UMTRI has carried out a number of studies of heavy vehicle engineering performance (7,8,9) and has recommended certain performance standards. A common theme of these performance standards has been their use in improving size and weight regulations, in the design-development process proceeding from size and weight rules to productive and new truck



designs and in the design and regulation of vehicles weighing more than 80,000 lb. It has been explicitly recognised (eg. 7) that this new performance-based approach would result in a new breed of vehicles designed and configured to have engineering performance exceeding that of current trucks.

With regard to the key measures being considered in this report, UMTRI's recommendations are as follows. In 1989/1990, the judgement-based example target performance level of 0.38 g was proposed for static roll stability (for fully-laden vehicles with the COG of the payload at the center of the cargo container) (7,8). Subsequently, work was carried out to arrive at test procedures for minimum safety performance standards applicable to overweight and over-length vehicles (9). The minimum desired level of static roll stability chosen was 0.35 g, noting that a rigorous approach to choosing this value was not carried out, and no cost/benefit analysis was carried out. Accompanying the 0.35g performance level was a specification of the loading condition for vehicle stability evaluation; this protocol allowed for the alternatives of (i) general freight of a specified minimum density, (ii) LTL packaged freight, (iii) known and uniform density freight and (iv) tankers.

UMTRI proposals for dynamic stability were less well-defined and concentrated on rearward amplification rather than load transfer ratio. The chosen rearward amplification performance target for LCVs was 2.0, and this was specifically chosen to reflect the performance of the 3-S2-2 Western Double with 28 ft trailers (8). According to the FHWA Engineering Performance Database, this vehicle has rearward amplification of 2.05 and load transfer ratio of 0.95 at Gross-Out/Cube-Out.

To summarise UMTRI's proposals in the key areas of static and dynamic stability, the following recommendations have been made for vehicles exceeding current limits (80,000 lb) and having engineering performance generically-superior to that of current trucks:

- static roll stability of 0.35 - 0.37 g, evaluated under specific loading conditions with regard to COG height
- obstacle avoidance capability equivalent to a load transfer ratio of 0.95.

UMTRI work quoted in a TRB report (8) indicates increased fatal accident involvement for doubles on interstates and rural primaries when rearward amplification exceeds a value of 1.6, and the FHWA Engineering Performance Database equates this to a load transfer ratio of 0.75.

## **Recommended Criteria**

Consideration of the available information on accident risks related to engineering performance indicates that there are safety benefits in improving static roll stability levels present in current trucks and in requiring "new" classes of vehicle exceeding current limits to meet higher performance standards than are generally evident in current vehicles.

## **Vehicles Within Envelope of Current Vehicle Configurations and 80,000 lb Cap**

With regard to current vehicles, any change involving the application of minimum performance standards, and reducing the incidence of the lower-performing vehicles, is likely to improve safety. From an accident risk point of view, there is no "natural" level at which to set such a performance standard, although it could be expected that diminishing returns would occur for very high minimum standards (for example, static roll stability above 0.4 g).

In order to arrive at the optimum level for such a standard, it would be necessary to consider the distribution of operating conditions and performance in current vehicle configurations and effects on VMT as well as the costs of imposing such a standard. In the absence of such

information, a practical starting point is the minimum performance inherent in the most commonly-used multi-axle vehicle configuration: the 3-S2 van. The static roll stability of this vehicle at maximum weight and at the Gross-Out/Cube-Out COG height condition is currently 0.32 g; it should be noted that this value increased from 0.28 g when semi-trailer width increased from 96 in to 102 in, and therefore a significant improvement in the safety performance of this vehicle has already occurred. It should also be noted that several current configurations within the 80,000 lb envelope perform well below the 3-S2 van.

The recommended minimum standard for size and weight decisions affecting current vehicle configurations is therefore: minimum steady-state roll stability of 0.32 g evaluated at maximum weight and at the Gross-Out/Cube-Out COG height condition.

The appropriate requirement for obstacle avoidance capability is more difficult to define because the relevant accident risk relationships are less well established. There appears to be some evidence that accident risks begin to increase for load transfer ratio values above 0.75 and are significantly higher “above” 1.0 and the most common example of doubles combination ( 2-S1-2 (A) van) has LTR of 1.0, while UMTRI’s benchmark doubles combination has an LTR of 0.95. In order to introduce some degree of conservatism in lieu of any definitive accident risk relationship, it is suggested that the minimum standard for obstacle avoidance capability for size and weight decisions affecting vehicles with weights up to 80,000 lb should be an LTR of 0.8.

The application of these standards in size and weight decisions will improve safety provided that they are accompanied by the requirement that changes in regulations are only permitted if the current vehicle configuration and GVW equate to performance below the above standards. The implication is that current configurations which are above these standards would not be permitted to reduce performance below current levels.

### **Vehicles with Weights in Excess of 80,000 lb**

When considering changes in size and weight regulations which involve GVWs in excess of the current limit of 80,000 lb, it is recommended that higher performance standards should apply. There is already a trend to higher static roll stability performance as GVW increases and this should be encouraged and reinforced.

In recommending these performance standards, account has been taken of the potential for technological improvements, for example in suspensions and tires, which will bring about performance levels higher than those in the FHWA Engineering Performance Database. It is highly desirable that any major change in vehicle configurations (such as conversion from 3-S2 to 3-S3) should also involve the use of an improved level of performance-related technology from the very outset.

The concept of increasing performance standards with increasing GVW also has great potential for long-term improvement in safety performance because there is an in-built incentive for the transportation industry to improve vehicle performance.

Taking into account the current performance of all vehicle configurations across a wide GVW range and the potential for improve vehicle technology, it is recommended that the trend of increasing performance values shown in Table 5 should be adopted. For intermediate GVWs falling between the values in Table 5, interpolation should be used. All measures are evaluated at maximum weight and at the Gross-Out/Cube-Out COG height condition.

**TABLE 5. RECOMMENDED REGIME OF MINIMUM PERFORMANCE VALUES VS GVW**

GVW (1000's lb)	STATIC ROLL STABILITY (g)	LOAD TRANSFER RATIO
up to 80	0.32	0.8
90	0.33	0.75
100	0.34	0.7
110	0.35	0.65
120	0.36	0.6
130	0.37	0.6
140	0.38	0.6

## CONCLUSIONS

This paper presents a methodology for the systematic development of a set of Robust Performance Standards for the United States heavy vehicle fleet. The main findings and significance of this analysis are summarised below:

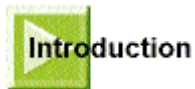
1. It was found that the distributions of the performance numerics resembled normal distributions in some cases, but in many cases were skewed or bi-modal in appearance.
2. Key performance measures are highly correlated. Powerful vehicle-configuration-specific relationships were developed which relate Load Transfer Ratio to Static Roll Stability and (Rearward Amplification/Static Roll Stability) to Load Transfer Ratio. The lowest correlation coefficient for these relationships was 0.87 and the highest was 0.999.
3. Relatively little is known about the relationships between performance attributes and accident risk.
4. Through data available for the common 3-S2, it is known that accident risk is related to Static Roll Stability, and this is believed to apply to all vehicle configurations.
5. In the case of 2-S1-2 (A) double combinations, high accident risk is related with very poor dynamic stability, as expressed by Load Transfer Ratio.
6. Using Load Transfer Ratio in place of Rearward Amplification would greatly simplify the procedures by allowing for a the same criterion to be applied to all vehicle types. Given that computer simulation has become the preferred method of vehicle assessment, the use of this configuration-independent performance measure would far out weight the limitations imposed through the inability to obtain the performance measure through field-testing.
7. Previously-proposed performance standards appear to be based on non-stringent loading conditions and these standards are therefore less conservative than may appear.
8. Minimum performance criteria for Static Roll Stability and Load Transfer Ratio have been proposed for discussion. In addition to wider use of the 3-S3 configuration, the implementation of such performance standards would also allow several new vehicle configurations with good inherent dynamic performance , such as the 3-S3-S2 B-train, to be encouraged and to be introduced with a high standard of vehicle design and technology.

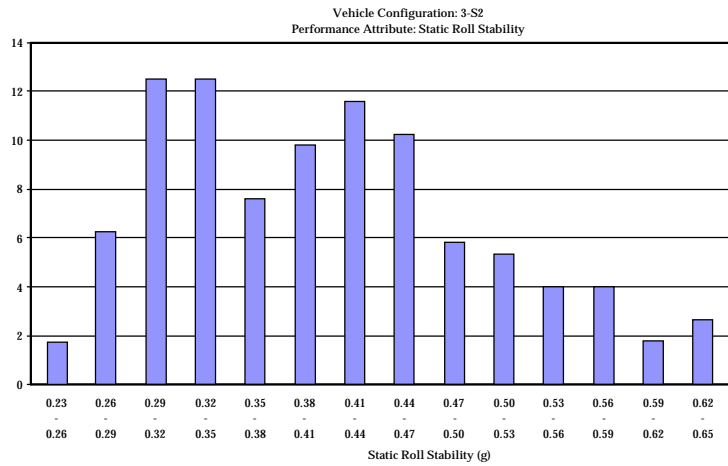




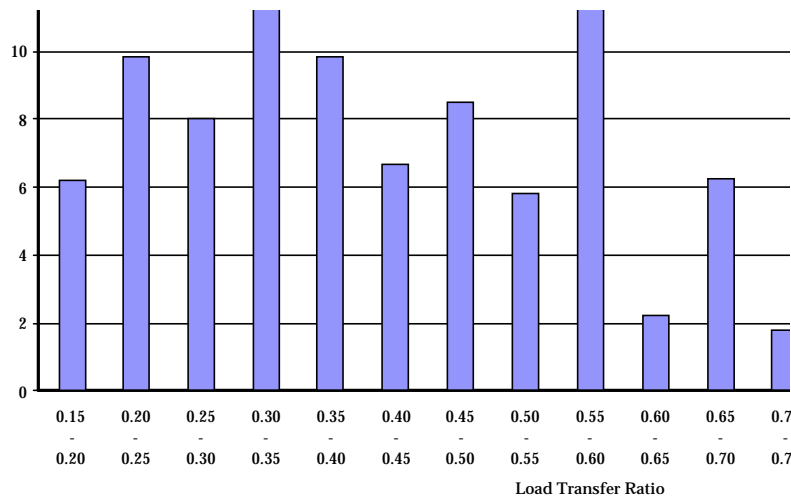
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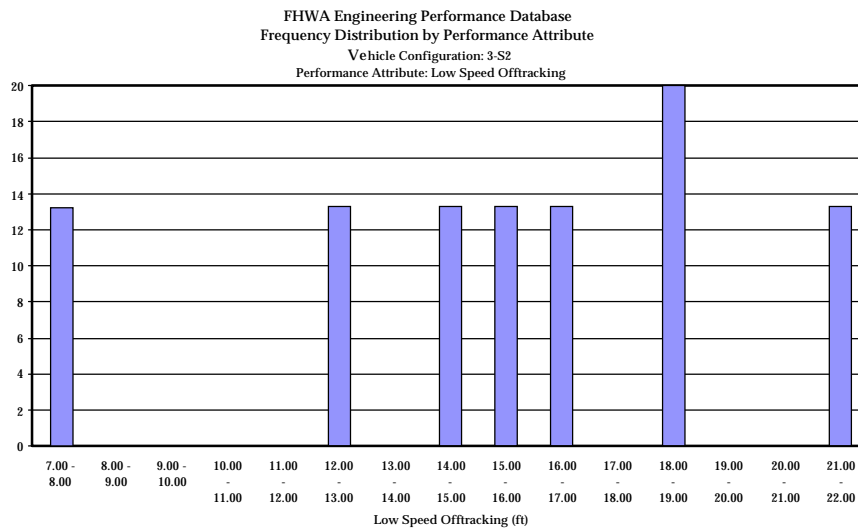




**Fig 1 (a). Performance distribution for 3S-2 vehicle configuration - static roll stability**



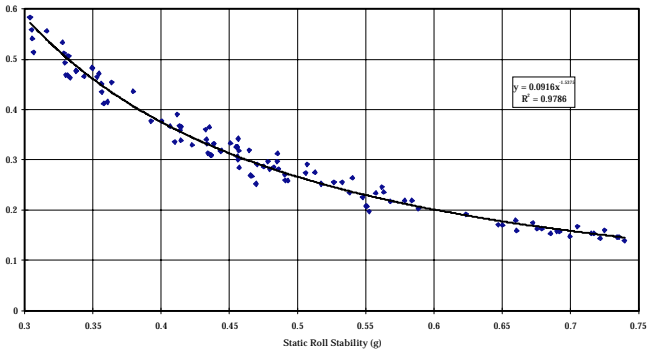
**Fig 1 (b). Performance distribution for 3S-2 vehicle configuration - load transfer ratio**



**Fig 1 (c). Performance distribution for 3S-2 vehicle configuration - low-speed offtracking**

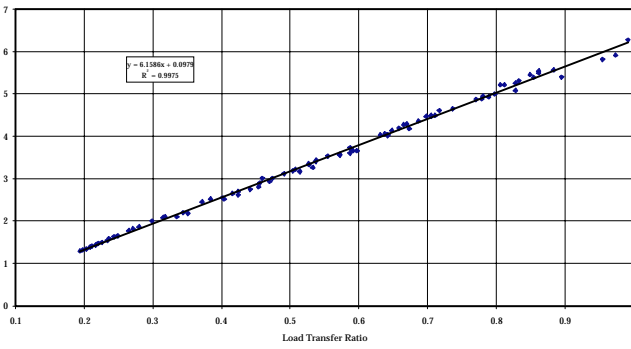


FHWA Engineering Performance Database  
Load Transfer Ratio vs Static Roll Stability  
Vehicle Configuration: 3S2-S2



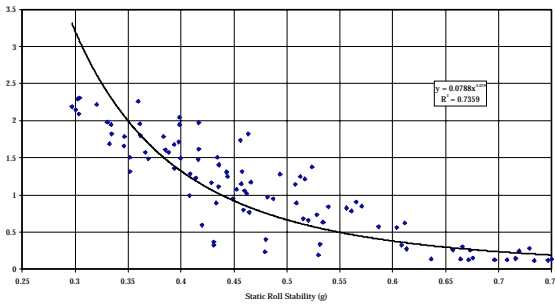
(a). Load transfer ratio vs static roll stability

FHWA Engineering Performance Database  
Rearward Amplification/Rear Unit Static Roll Stability vs Load Transfer Ratio  
Vehicle Configuration: 3S2-2 (RMD)



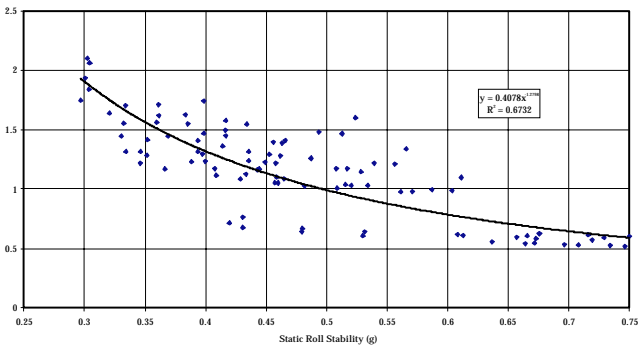
(b). Rearward amplification/static roll stability vs load transfer ratio

FHWA Engineering Performance Database  
High Speed Dynamic Offtracking vs Static Roll Stability  
Vehicle Configuration: 3S2-2 (RMD)

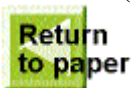


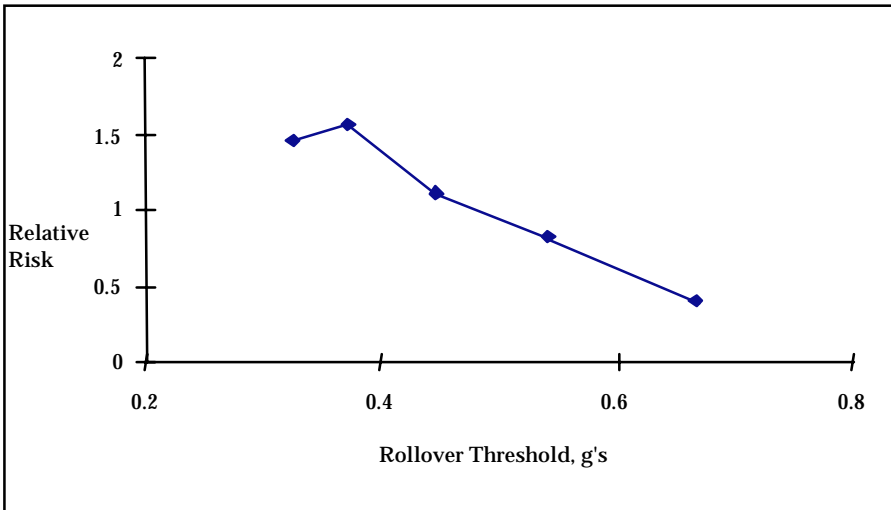
(c) High-speed dynamic offtracking vs static roll stability

FHWA Engineering Performance Database  
High Speed Offtracking vs Static Roll Stability  
Vehicle Configuration: 3S2-2 (RMD)



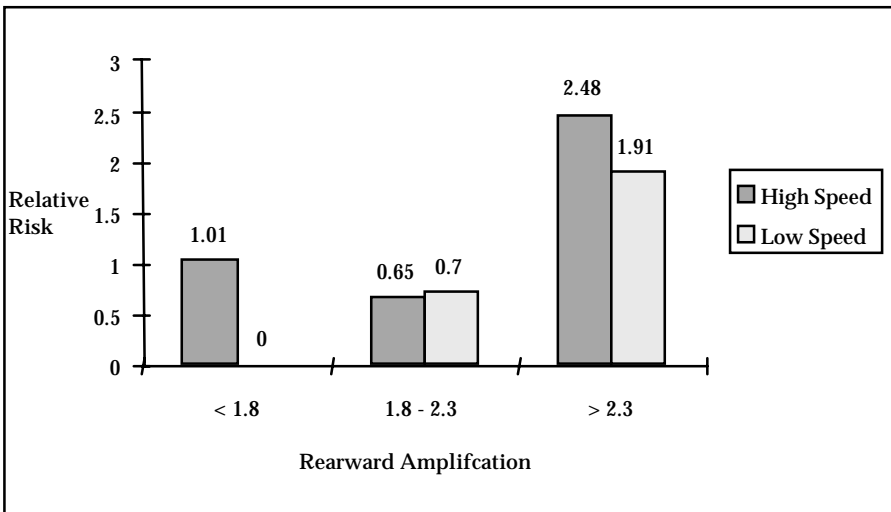
(d) High-speed offtracking versus static roll stability





**Figure 4. Relative risk of fatal accident involvement of 5-axle van tractor-trailers by rollover threshold**





**Figure 5. Relative risk of single-vehicle fatal accident involvement for 5-axle double trailer combinations by rearward amplification**

