

FEDERAL BRIDGE FORMULA: HOW IT INFLUENCES VEHICLE DYNAMIC BEHAVIOR

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Abstract

There is interest in improving road transport efficiency through increased truck size and weight thereby enhancing vehicle productivity, reducing road wear, fuel consumption and associated pollutants. Larger trucks have proven to be an effective means of achieving these goals however concern exists over how increases in size and weight will influence vehicle stability and safety.

To prevent over stressing of bridge structures all heavy vehicles must comply with the U.S. Federal Bridge Formula. The formula tends to influence vehicle design by prescribing the number of axles, inter-axle spacing and axle weights for a given maximum gross vehicle weight. As the gross vehicle weight increases the bridge formula tends to lengthen the vehicle thereby increasing the cubic cargo capacity which is a desirable productivity attribute. These size and weight changes prescribed by the bridge formula affect the dynamic behavior of commercial vehicles. This paper investigates how vehicle dynamic performance of trucks is influenced by the Federal Bridge Formula as maximum gross vehicle weight is increased. The study is based on truck tractor double-trailer combinations currently in use on the Interstate and state highway systems within the U.S.

This study uses vehicle simulation analysis of existing vehicle combinations designed to operate in states which have different maximum allowable gross vehicle weight regulations. This provides a range of practical vehicles designed for different gross weights governed by the Federal Bridge Formula. The dynamic performance of the vehicles is analyzed using heavy vehicle performance measures specifically designed for commercial vehicles. In addition, the brake capacity of the vehicles is calculated to determine how the Federal Bridge Formula influences vehicle brake capacity as gross vehicle weight increases.

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1. INTRODUCTION

Forces associated with domestic and global competition, a need to reduce transport related fuel consumption and associated gaseous pollutants have rekindled interest in larger trucks as a transport efficiency strategy. Increasing truck size and weight is seen as a means to achieve significant efficiency gains particularly with long vehicle combinations (LCV). An analysis of a progressive LCV program in Alberta Canada (1, 2) found that for a given freight task, LCVs reduced truck distance traveled by 44%, fuel use and pollutants by 32%, road wear by 40% and shipping costs by 29% (compared to conventional tractor semi-trailers performing the same task). The Federal Bridge Formula in part governs the design of heavy trucks by prescribing acceptable axle weights and spacing between axles, combination vehicle unit length and overall vehicle length for a given gross vehicle weight. These are important vehicle design factors known to be associated with vehicle stability and control performance. The objective of this paper is to explore how the vehicle dynamics of large truck tractor double trailer combinations currently in use on the Interstate and State Highway Systems, is influenced by Federal Bridge Formula as gross vehicle weight increases.

2. LEGISLATIVE HISTORY AND THE BRIDGE FORMULA

The US federal bridge formula was developed to protect the Interstate bridge inventory from damage due to excessive truck weights. Federal-Aid Highway Legislation of 1956 (3) applied 8,200-kg (18,000-lb) single-axle load limits, 14,500-kg (32,000-lb) tandem axle load limits and 33,300-kg (73,280-lb) gross vehicle weight limits on the Interstate system. This legislation allowed trucks of higher weight limits to operate on the interstate system within states where higher limits were legal prior to July 1, 1956. In 1967 Congress increased the single axle weights to 9,100 kg (20,000-lb) and tandem axle weights to 15,500-kg (34,000-lb). In response to the Arab oil embargo of 1973-74, the Federal-Aid Highway Amendment of 1974 (4) reduced the maximum speed limits to 90-km/h (55-mph) and increased the overall gross vehicle weight limit to 36,400-kg (80,000-lb) as a quid pro quo for the slower speed limits. The Amendment also adopted the Federal Bridge Formula but capped the maximum gross vehicle weight at 36,400-kg (80,000-lb) for all states except those that had been “grandfathered” by the 1956 Federal-Aid Highway Legislation.

Using the “grandfather” exemption many western states have issued special permits for vehicles carrying divisible loads well in excess of 36,400 kg (80,000-lb) provided they comply with the Federal Bridge Formula. This practice is well entrenched having existed for over 30 years. In

1982 the Surface Transportation Assistance Act (STAA) required states to permit double trailer combinations with each trailer measuring up to 7.86m (28.5-ft) long to operate on the Interstate system at gross vehicle weights up to 36,400-kg (80,000-lb). The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) defined longer combination vehicles as “any combination of truck tractor and two or more trailers or semi-trailers which operates on the Interstate System at a gross weight greater than 36,400-kg (80,000-lb) and imposed a freeze on the use of Longer Combination Vehicles (LCV), limiting such vehicles to the weights, dimensions, and routes that were allowed at the time ISTEA was passed.

From this review of size and weight regulation history we find significant variation in size and weight limits among states. This provides an opportunity to examine the vehicle dynamic performance of various vehicle combinations designed to meet the US Federal Bridge Formula.

In most States, the Bridge Formula is capped at a fixed value, but the magnitude of the cap varies among the States. The remaining uncapped states allow the bridge formula to be used to the practical limit. Table 1 contains a listing of all of the States reviewed showing the capped gross vehicle weight (GVW) limits as well as identifying the uncapped States (*in italics*).

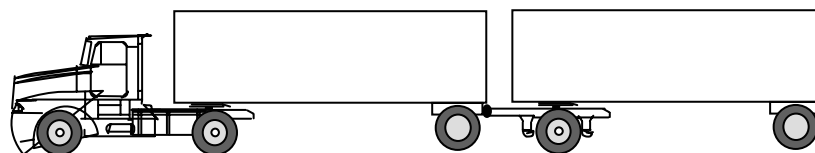
Table 1: Capped Bridge Formula Values and Uncapped States (*italics*)

State	Capped Bridge Limits Max GVW (lbs)	Capped Bridge Limits Max GVW (kg)
Colorado	110,000	50,000
Idaho	105,000	47,700
Kansas	110,000	50,000
Montana	131,000	59,500
North Dakota	105,000	47,700
Nebraska	94,000 109,250*	42,700 49,700*
Nevada	129,000	58,600
Oklahoma	90,000	40,900
Oregon	105,500	48,000
<i>South Dakota</i>	<i>uncapped</i>	<i>uncapped</i>
<i>Utah</i>	<i>uncapped</i>	<i>uncapped</i>
Washington	105,500	48,000
Wyoming	117,000**	53,200**

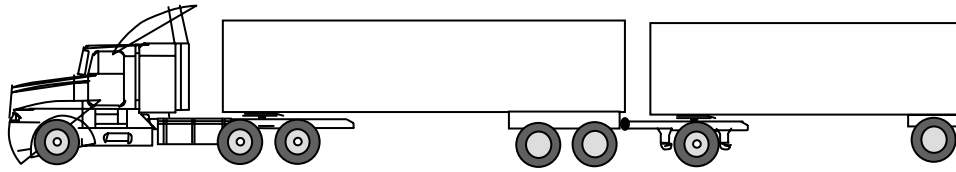
Legislative documents use Imperial units, SI units are rounded conversions

* Agricultural product exemption

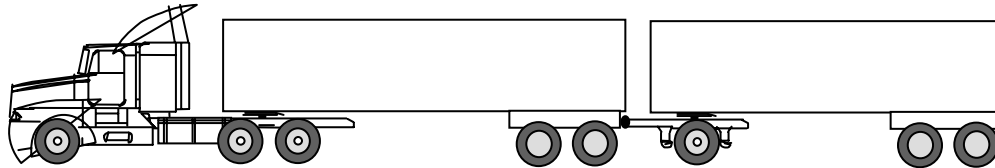
** uncapped on non-Interstate roads



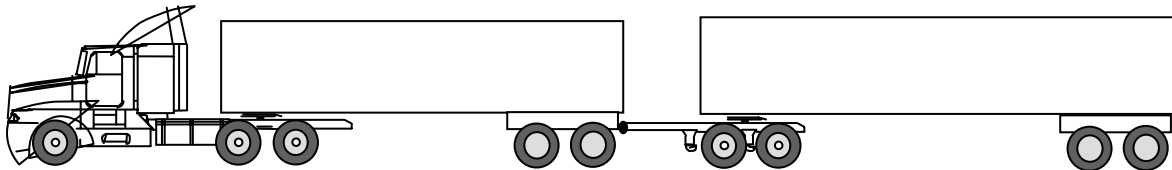
**Figure 1. STAA Double GVW 36,364-kg (80,000-lb)
(Over all vehicle length 22.5m)**



**Figure 2. Seven Axle Rock Mountain Double GVW 51,364-kg (113,000-lb)
(Over all vehicle length 29.1m)**



**Figure 3. Eight Axle Double Rocky Mountain Double GVW 53,182-kg (117,000-lb)
(Over all vehicle length 29.1m)**



**Figure 4. Nine Axle Turnpike Double GVW 58,636-kg (129,000-lb)
(Over all vehicle length 32.2m)**

For the analysis, representative bulk commodity and van trailer vehicles from the various states in Table 1 were selected to determine their vehicle dynamic performance. The bulk commodity used for the analysis was coal with a fixed product density. The second vehicle group consisted of van type longer vehicle combinations shown in Figures 1-4. The van trailers were modeled assuming the product occupied full cubic capacity which required assumptions of variable product density. These two distinct load scenarios represent the extremes of transport load types thereby providing a comparative reference. For the bulk commodity vehicles examined, the vehicle dimensions and axle spacing were optimized to comply with the maximum allowable GVW based on the Federal Bridge Formula. The van trailers also complied with the bridge formula.

The Federal Bridge Formula is as follows:

$$W = 500 \left[\frac{LN}{N-1} + 12N + 36 \right]$$

W = maximum weight (GVW) in pounds that can be carried on a group of two or more axles.

L = distance in feet between the outer axles of any two or more consecutive axles.

N = the number of axles being considered.

3. SIMULATIONS

Vehicle stability characteristics were evaluated by computer simulation (UMTRI Yaw/Roll Model) using identical procedures from the “Comprehensive Truck Size and Weight Study” (5,6) and the Western state Scenarios Study (7). A sizable effort was made to fully understand the priorities and constraints unique to the Western States that would influence vehicle design particularly with respect to the bridge formula. In addition, the vehicles currently operating were examined in detail so that the simulations properly reflect the basic vehicle design.

3.1 Performance Measures:

The following performance measures were calculated each of the vehicles using the UMTRI Yaw/Roll Model:

- Static Rollover Threshold (SRT)
- Rearward Amplification (RA)
- Load Transfer Ratio (LTR)
- High Speed Transient Offtracking (HSTO)
- High Speed Offtracking (HSO)

3.2 Assumptions

All vehicles were assumed to have the same hitch properties, suspension, tire and unsprung mass properties. This allows for a comparison of the relative vehicle behavior without the influence of such variables.

3.3 Tire descriptions

Tires on the steer axle were assumed to be 11R22.5 and all other tires were assumed as 295/80R22.5. In all cases, the tire vertical stiffness was taken as 788 kN/m. In addition, the peak friction between the tires and the road was assumed as 0.8, a typical value for a dry asphalt road.

3.4 Trailer Payload Description

Each payload for the van trailers was comprised of two homogeneous cuboids of equal size, one on top of the other. The bottom cuboid was assumed to constitute 70 % of the payload. The bulk coal hopper trailer cross section is shown in Figure 5 with dimensions shown in Table 2. The density of coal payload for the bulk hopper trailers was taken as 881 kh/m^3 . From this it was possible to determine the moments of inertia and centers of gravity for the payloads.

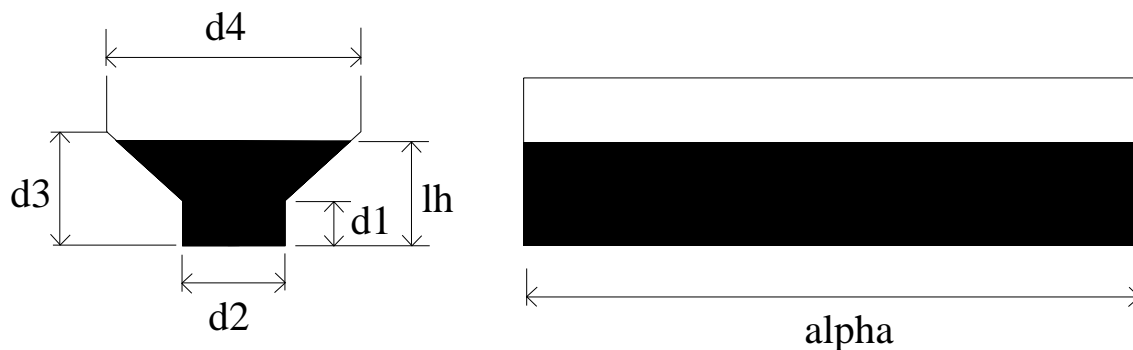


Figure 5. Hopper Cross Sectional Profile (not to scale)

Table 2: Dimensions of Hoppers

Dimension	Value (metres)
d1	0.305
d2	1.219
d3	2.134
d4	2.438

4. RESULTS

4.1 Static Rollover Threshold

Static rollover threshold (SRT) is an important vehicle performance measure because it influences overall vehicle stability under transient and quasi-static conditions, such as, emergency lane changes as well as the more common relatively constant lateral acceleration condition that occurs when negotiating well designed roadway curves. Higher values indicate better performance.

Rollover threshold simulation results of the comparative vehicles are shown in Figure 6. For the weight range examined, there is a slight increase in the center of mass height for the bulk hopper trailers as a function of increased (GVW) and no apparent change for the van trailers. The difference between the SRT performance of bulk hopper and van trailers is attributed to the analysis method used for product density definition. The bulk carrier used coal at a constant density while the van trailers used composite cube-out loading method (Section 3.4) which optimizes density for each van trailer examined. These two different approaches to density definition add value to the analysis, as they address the two prevailing loading philosophies.

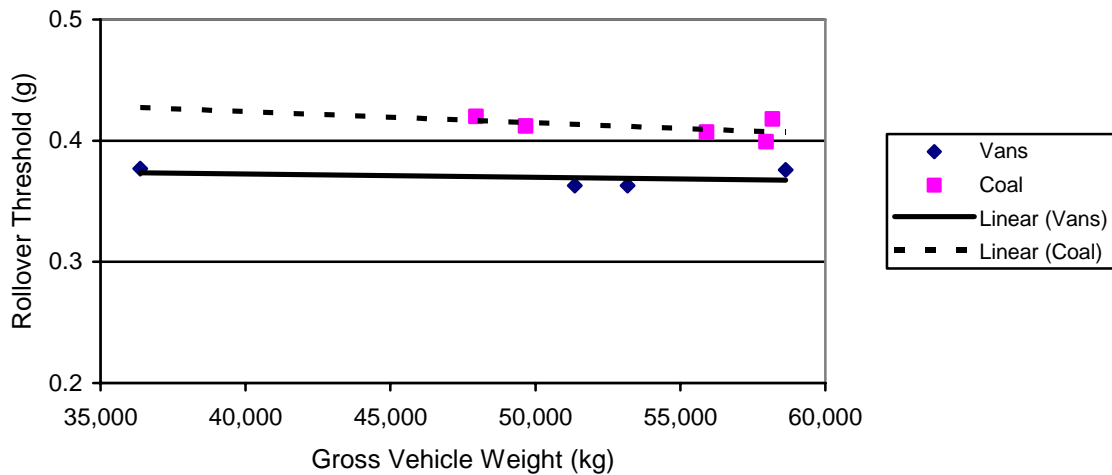


Figure 6. Influence of Maximum GVW on Static Rollover Threshold
(For Varying GVW Conditions Tied to the Bridge Formula)

4.2 Rearward Amplification

Rearward amplification of lateral acceleration gives insight into the dynamic characteristics of the vehicle. When articulated vehicles undergo rapid lateral manoeuvres such as would occur in

an emergency lane change, the lateral acceleration experienced at the tractor is amplified by the following trailers. Lower values indicate better performance.

Figure 7 simulation results show that for the range of gross vehicle weights examined, rearward amplification diminished by 40.5% as gross vehicle weight increased from 36,400-kg to 58,600-kg. This effect is attributed to changes in overall vehicle length, box length and total payload length as prescribed by the Federal Bridge Formula. The beneficial effect is seen in both the van and bulk trailer vehicles. The reduction in rearward amplification as GVW increases suggests that the influence of increased axle spacing and vehicle length as directed by bridge formula has greater influence on dynamic response than increased vehicle mass.

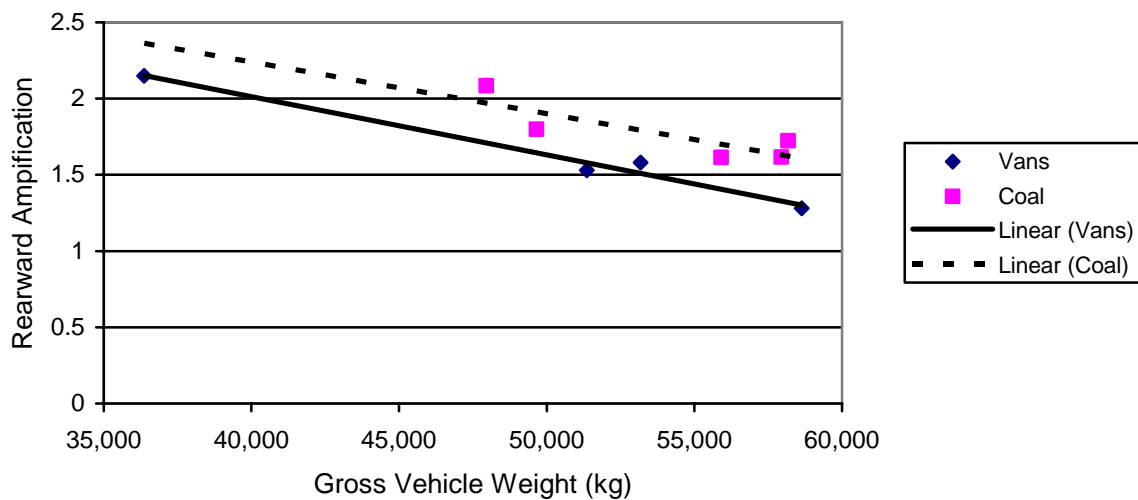


Figure 7. Influence of GVW on Rearward Amplification
(For Varying GVW Conditions Tied to the Bridge Formula)

4.3 Load Transfer Ratio

Load Transfer Ratio (LTR) is defined as the proportion of load on one side of a vehicle unit transferred to the other side of the vehicle in a transient manoeuvre. LTR is a vital measure of rollover stability and is particularly relevant to high speed operations. Lower values represent better performance. In jurisdictions that employ performance measures, it is broadly accepted that the recommended LTR limit for acceptable vehicle behavior is 0.6.

Figure 8 simulation results show that doubles designed for lighter load conditions 36,400-kg (80,000-lb) and 51,400-kg (113,000-lb) failed to meet the performance requirement of 0.6 while the heavier vehicles were in the acceptable performance range. Load Transfer Ratio decreased by 43.0% as gross vehicle weight increased from 36,400-kg to 58,600-kg. This improvement in vehicle performance is attributed to the influence of the Federal Bridge Formula.

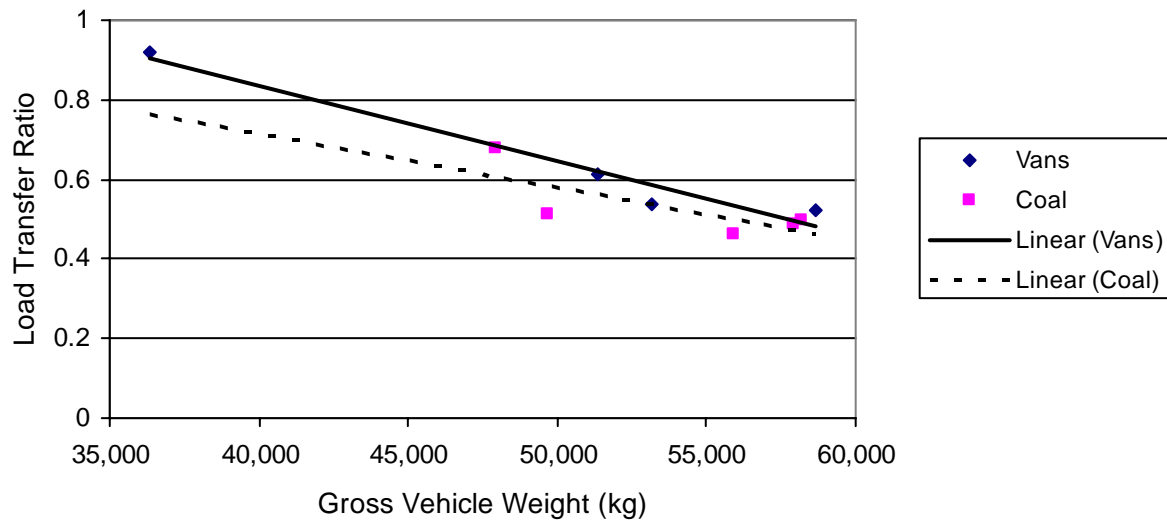


Figure 8. Influence of GVW on Load Transfer Ratio
(For Varying GVW Conditions Tied to the Bridge Formula)

4.4 High Speed Transient Offtracking

High Speed Transient Offtracking is a measure of lateral excursion by the rear of the vehicle with reference to the path taken by the front of the vehicle during a dynamic manoeuvre. This expresses the amount of additional road space used by the vehicle combination in an avoidance manoeuvre. The generally accepted limit recommended for this measure is 0.8-m. Lower values represent better performance.

As shown in Figure 9, high speed transient offtracking diminishes significantly as vehicle mass increases as prescribed by the Federal Bridge Formula. The performance of all of the vehicles simulated was within acceptable limits. As the van trailer vehicle mass was increased from 36,400-kg to 58,600-kg, high speed transient offtracking diminished by 55.9%. The bulk coal transport vehicles had significantly less improvement as vehicle mass increased.

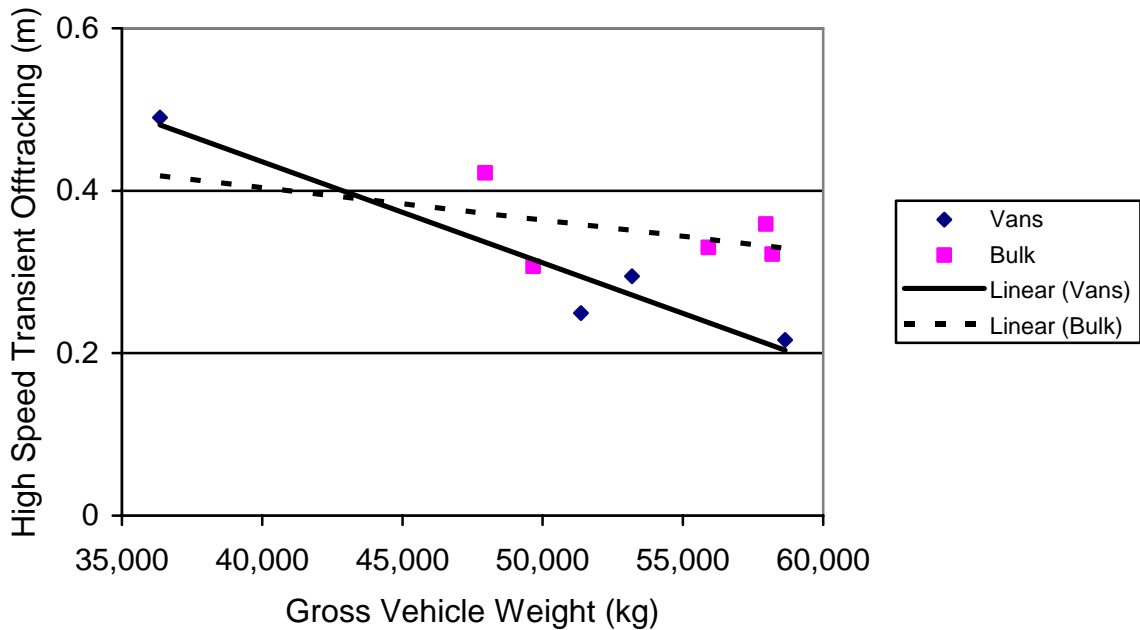


Figure 9. Influence of GVW on High Speed Transient Offtracking
(For Varying GVW Conditions Tied to the Bridge Formula)

4.5 High-Speed Offtracking

High-speed offtracking is defined as the extent to which the rearmost vehicle tires track outboard of the hauling unit tires in a steady turn at highway speed. High speed offtracking relates closely to road width requirements for the travel of combination vehicles. The generally accepted limit recommended for this measure is 0.46-m. Lower numbers represent better performance.

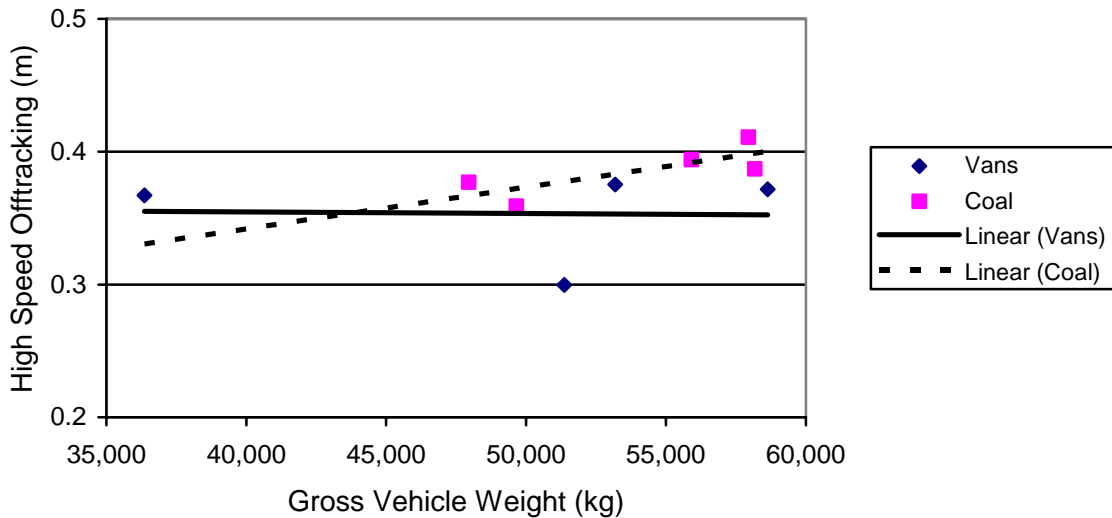


Figure 10. Influence of GVW on High Speed Offtracking
(For Varying GVW Conditions Tied to the Bridge Formula)

The simulation results contained in Figure 10 illustrate, for the van trailers examined, there is little change in high speed offtracking as vehicle mass increases when the vehicle design is constrained by the Federal Bridge Formula. In contrast however, the high speed offtracking for bulk coal transport vehicles increased with vehicle mass but remained within acceptable limits.

4.6 Influence of Increased GVW on Brake Performance

It is a requirement that the heavy truck manufacturing industry comply with Federal Motor Vehicle Safety Standards (FMVSS). In particular, FMVSS 121 establishes requirements for braking systems on vehicles equipped with air brake systems to ensure safe braking performance under normal and emergency conditions. FMVSS 121 regulations specify maximum stopping distances for pneumatically braked heavy vehicles.

Axles that are added to any truck or trailer are rated for load carrying capacity which is referred to the Gross Axle Weight Rating (GAWR). The brakes fitted to the axle are sized to be in compliance with FMVSS-121 brake performance requirements relative to the particular GAWR of the axle. A typical weight ratings for trailers axles is 9,000-kg (20,000-lbs) per axle. Typical GAWR for tractor steer axles is 5,500-kg (12,000-lb). Drive axles are rated at 9,000-kg (20,000-lbs) per axle or higher. Using pre-rated axles and brakes allow manufacturers to assemble vehicle units with sufficient brake capacity for a given vehicle design.

Increases in vehicle weight that are governed by the Federal Bridge Formula result in longer vehicles with additional axles. Standard axles with brake systems that are sized for the gross axle weight rating (GAWR) are used by manufactures. For example, a tandem axle group comprised of two 9,100-kg (20,000-lb) axles will have braking capacity sufficient to manage 18,000-kg (40,000-lb). However, size and weight regulations limit the tandem axle group to 15,500-kg (34,000-lb) which means the tandem axle group has more braking capacity than required. Table 3 shows the gross vehicle weight (GVW) for each configuration, the corresponding brake capacity expressed in terms of vertical axle load and percent surplus brake capacity available for the vehicle configuration.

Table 3: Surplus Brake Capacity by Vehicle Mass

Regulated GVW (lb)	Regulated GVW (kg)	# Axles	Total GAWR Brake capacity (kg)	% Surplus Brake capacity
80,000	36,364	5	41,500	14.1
113,000	51,364	7	59,500	15.8
117,000	53,182	8	68,500	28.8
129,000	58,636	9	77,500	32.2

GAWR assumptions: Steer axle 5,500 kg
 Drive axle 9,000 kg
 Trailer axle 9,000 kg

Figure 11 shows that surplus brake capacity trend increases when vehicles are designed for increased payload in accordance with the Federal Bridge Formula. Because the increase is directly tied to the number of axles, the additional braking capacity increases in a stepwise manner. For the van trailers examined, the surplus brake capacity more than doubled as the

vehicle mass was increased from 36,400-kg to 58,600-kg. The merits of surplus brake capacity include shorter stopping distance when vehicles are operated under heavily loaded conditions (assuming there is sufficient friction between the road and tire), better brake wear and increased overheating resistance.

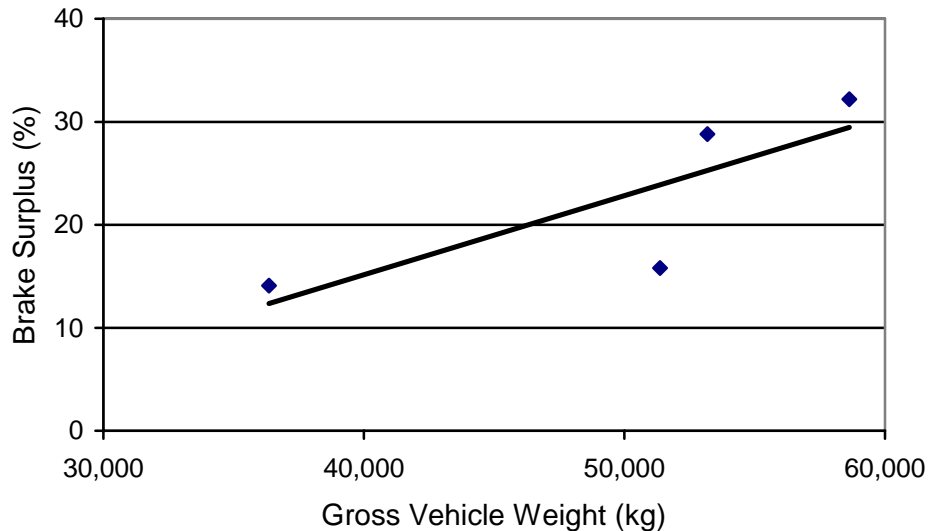


Figure 11. Influence of GVW on Brake Surplus Capacity
(For Varying GVW Conditions Tied to the Bridge Formula)

5. CONCLUSIONS

The analysis of the vehicles examined in this study show that the Federal Bridge Formula has a significant effect on vehicle performance. Of the performance measures examined, the bridge formula had less influence on static rollover threshold and high speed offtracking. These are non dynamic measures evaluated under steady state conditions.

The influence of the Federal Bridge Formula on vehicle performance was most apparent for rearward amplification, load transfer ratio and high speed transient offtracking. These measures are evaluated under dynamic conditions (lane change manoeuvres). As the mass of the vehicle is increased and the geometry and number of axles changed to comply with the bridge formula, the dynamic performance of the vehicles examined improved. Similarly as the mass of the vehicles increased, the available brake capacity increased at a rate greater than the gross vehicle weight which results in greater surplus brake capacity.

Performance benefits were found for a bulk commodity constant density payload (coal) as well as variable density payloads optimized to occupy van trailer cubic capacity. From the analysis of the vehicle sets examined during this study, it is concluded that in general, as vehicle mass increases in compliance with the Federal Bridge Formula the resulting vehicle dynamic performance and brake capacity show beneficial trends.

6. REFERENCES

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