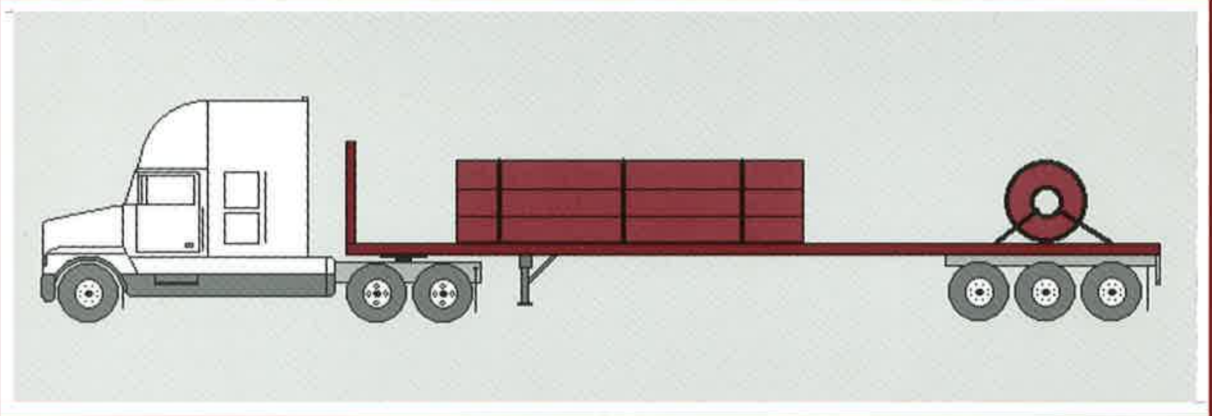
CCMTA Load Security Research Project

Report # 20

PERFORMANCE LIMITS OF HEAVY TRUCKS



CCMTA • CCATM

CANADIAN COUNCIL OF MOTOR TRANSPORT ADMINISTRATORS
CONSEIL CANADIEN DES ADMINISTRATEURS EN TRANSPORT MOTORISÉ

CCMTA Load Security Research Project

Report # 20

PERFORMANCE LIMITS
OF HEAVY TRUCKS

Prepared for

Canadian Council of Motor Transport Administrators
Load Security Research Management Committee

By

J.R. Billing
31 La Peer Blvd.
Agincourt, Ontario
M1W 2H3

October 1998

Disclaimer

This report is one of a series commissioned by the sponsors of the ***CCMTA Load Security Research Project***. Readers are cautioned on the use of the data and the conclusions drawn from this particular aspect of the research program as this report is only one of a series related to this multi-faceted issue. The report and the results are not intended to be used in any way as a basis for establishing civil liability.

The material presented in this text was carefully researched and presented. However, no warranty expressed or implied is made on the accuracy of the contents or their extraction from reference to publications; nor shall the fact of distribution constitute responsibility by CCMTA or any of the sponsors, researchers or contributors for omissions, errors or possible misrepresentation that may result from use or interpretation of the material contained herein.

ISBN 0-921795-50-5

Canadian Council of Motor Transport Administrators
2323 St. Laurent Blvd.
Ottawa, Ontario
K1G 4J8

Telephone: (613) 736-1003
Fax: (613) 736-1395

E-mail: ccmta-secretariat@ccmta.ca
Internet Web site: www.ccmta.ca

North American Cargo Securement Standard

CCMTA is serving to coordinate the development of a revised North American Cargo Securement Standard. To this end the research results in this report are being reviewed and discussed by interested stakeholders throughout North America.

Those readers interested in participating in the development of the North American Cargo Securement Standard through 1998 are invited to visit the project Web site at www.ab.org/ccmta/ccmta.html to secure additional project information.

Table of Contents

Abstract

The North American Cargo Securement standard will be based on objective criteria that are derived from the performance limits of heavy trucks within the highway system, up to but not including a crash. The following performance criteria have been proposed:

- 0.8 g braking deceleration;
- 0.5 g longitudinal acceleration;
- 0.5 g lateral acceleration; and
- 0.2 g vertical acceleration.

This report summarizes data from the literature on which these are based, and provides some insights into some of the choices made.

Executive Summary

A lack of understanding of the technical basis for existing regulations on cargo securement meant it was not possible to resolve differences between them to revise a cargo securement standard for Canada's National Safety Code. This process identified a number of research needs, which have been addressed through the North American Load Security Research Project. The issue of vehicle performance criteria was not pursued in the research project, as it was considered part of the standard development process. This report examines various sources of data that can help identify vehicle performance criteria for the proposed North American Cargo Securement standard.

Most of the data on braking performance of heavy trucks is reported as stopping distance from speed, which yields only an average deceleration, commonly in the range 0.45-0.55 g. In a hard stop, the peak deceleration occurs just before the vehicle comes to a stop, may be sustained for several seconds, and may be 30-40% higher than the average deceleration. This means sustained peak decelerations over 0.7 g are possible. The stopping capability of most vehicles on the highway probably does not approach their full capability. However, a series of regulatory and maintenance measures now under way should result in a steady improvement in heavy truck braking efficiency. Trucks have been able to achieve a peak deceleration over 0.7 g for a number of years now, and their stopping capability clearly now exceeds the current 0.6 g requirement. If braking systems will offer better performance and greater reliability, the proposed deceleration criterion of 0.8 g seems prudent.

Longitudinal acceleration and braking in reverse are both much less severe than braking, and this is reflected in the proposed performance criterion of 0.5 g.

Lateral acceleration arises from driving at high speed on a curve or ramp. Many loaded trucks roll over below 0.5 g. Few drivers would knowingly enter a curve at this lateral acceleration, and those who did so would likely be unable to follow the curve.

The vertical acceleration environment differs from longitudinal and lateral directions. The 0.2 g criterion here is chosen to ensure that cargo is secured, and to increase friction between cargo and deck to as great an extent as possible.

Road and rail shock and vibration environments are really quite similar. The rail environment has significant longitudinal and lateral shock and vibration in the 2-6 Hz range, that is absent on the road. However, the rail environment is also missing the severe quasi-steady braking and lateral accelerations that can occur on the highway.

The proposed performance criteria for securement of cargo on heavy trucks operating to their limits within the highway system, and short of a crash, appear reasonable and prudent based on data available in the literature. They are also closely in accordance with recent recommendations or practice from a number of other countries.

1/ Introduction

Heavy truck cargo securement is a matter of public safety, subject to a body of industry practice and government regulation. Regulations are broadly similar across North America's many jurisdictions, but there are also some significant differences. When the Canadian Council of Motor Transport Administrators (CCMTA) came to revise a cargo securement standard for Canada's National Safety Code [1], a lack of understanding of the technical basis for existing regulations made it impossible to resolve differences between them, and a number of research needs were identified [2]. Ontario Ministry of Transportation prepared a draft proposal for this research that was widely circulated for review through governments and industry. The proposal was revised and became the work statement for the North American Load Security Research Project [3]. It had three objectives :

- To determine how parts of cargo securement systems contribute to the overall capacity of those systems;
- To demonstrate the adequacy of parts, and the overall capacity, of cargo securement systems; and
- To develop principles, based on sound engineering analysis, that could contribute to an international standard for cargo securement for heavy trucks.

The goal was to supplement existing practice with the research findings, and to develop uniform North America-wide standards for cargo securement and inspection.

The original [2] work raised questions about the validity of the assumptions of existing regulations [1]. However, these related to the performance of vehicles within the highway system, a subject which is already rather well covered by an extensive literature. Reviewing this literature to set the performance criteria was considered a role for the standard development process rather than a research task [3]. Now that the research has been completed [4], and performance criteria have been proposed for the standard, it is necessary to document the process more fully so that basis for the proposed performance criteria is widely understood.

2/ Performance Limits of Heavy Trucks

The acceleration of an object falling freely due to gravity is 9.81 m/s/s (32.2 ft/s/s). This means that the velocity of the object increases by 9.81 m/s (32.2 ft/s) for every second it falls. Accelerations are commonly reported as a proportion of the acceleration due to gravity, in units of g. For example, an acceleration of 0.6 g is 0.6x9.81=5.89 m/s/s (0.6x32.2=19.32 ft/s/s).

2.1/ Braking

The mechanics of braking a heavy truck are surprisingly complex. It is necessary to understand some fundamentals of tires and braking systems to interpret heavy truck stopping data.

2.1.1/ Tires

Tire braking traction depends upon a number of parameters, which include tread pattern, tread depth and rubber compound, operational parameters like vehicle speed, wheel longitudinal slip and wheel load, and road surface and interface conditions.

Figure 1 illustrates tire braking traction as a function of slip, which is the percentage difference between vehicle speed and wheel speed. A perfectly rolling wheel has zero slip, and a locked non-rolling wheel has 100% slip. A rolling undriven wheel usually has quite small rolling resistance, so its slip is close to zero. As the brake is applied, slip increases. Figure 1 shows that braking traction rises to a peak with slip in the range of 15-20%, then diminishes somewhat as slip increases to 100%, when the wheel locks. Optimum braking is achieved at the peak of the braking-slip curve, the technique of threshold braking, which is quite difficult, as the wheel locks very rapidly as soon as the slip passes beyond the peak of the curve.

Figure 2 envelopes data from a number of tires to illustrate generic tire properties.[5]. It shows that peak and slide braking traction both tend to diminish as speed increases. This means that vehicle deceleration tends to increase as speed diminishes during a stop, and reaches a maximum just before the vehicle actually comes to a stop. Figure 3 envelopes the same data, and shows that peak and slide braking traction tend to decrease as wheel load is increased, so deceleration is reduced for the same vehicle as its weight increases.

Finally, braking traction tends to increase as a tire wears initially, reaches a plateau, then diminishes increasingly rapidly over about the last one-third or so of useable tread depth [6].

2.1.2/ Braking Systems

When the driver starts braking, the pneumatic system sends a signal to the valves controlling pressure in the brake chambers. There is some time delay for this signal to travel, with the signal taking longer to reach the more distant than closer valves. There is also some small pressure loss to the more distant valves.

Brake adjustment is a significant factor in the ability of a brake to develop torque. A brake develops maximum torque when it is tightly adjusted, around 38 mm (1.5 in) stroke. Torque diminishes relatively slowly as stroke increases, up to the typical adjustment limit of 50 mm (2 in) for the most common chamber, then drops off sharply at longer stroke.

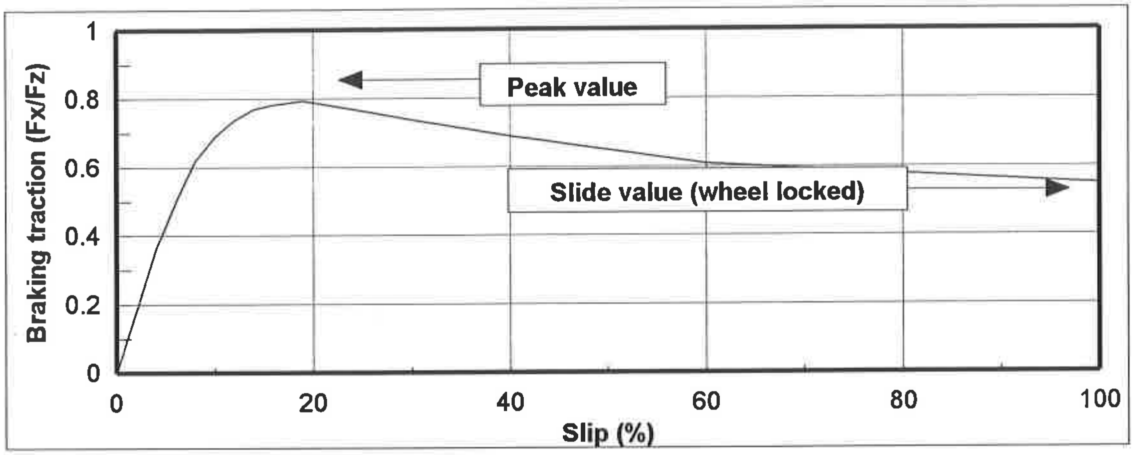


Figure 1/ Characteristic relationship of truck tire braking traction to slip

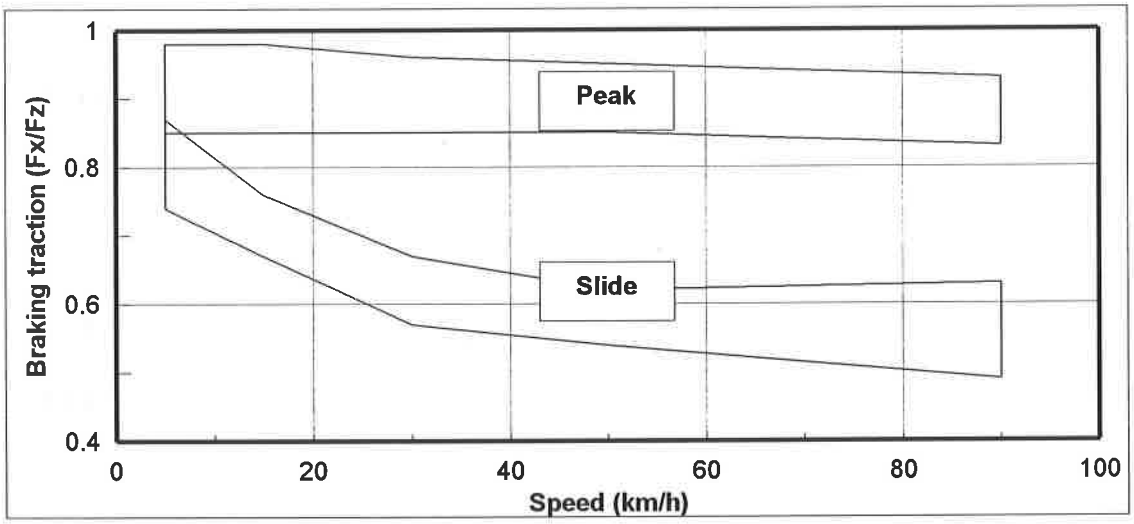


Figure 2/ Envelopes of peak and slide tire braking traction with speed

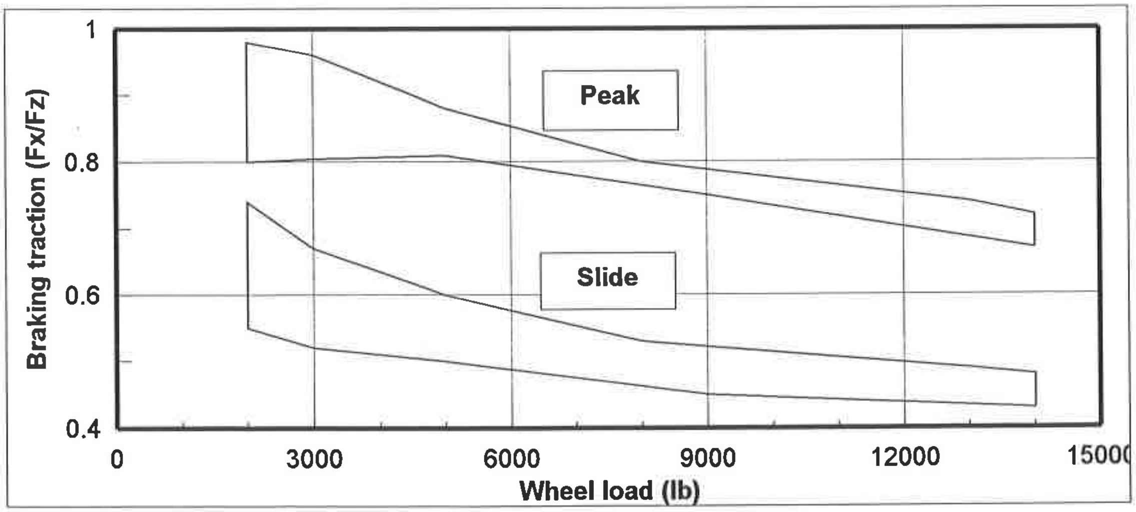


Figure 3/ Envelopes of peak and slide tire braking traction with wheel load

Brake temperature also has a significant effect on torque. As a brake warms, its torque increases significantly, peaking in a temperature range of about 65-149°C (150-300°F). Beyond this, thermal expansion of the drum effectively increases the stroke, and torque begins to drop off. Much higher temperatures, up to 260-315°C (500-600°F) can develop during stop-and-go urban freeway traffic, or in long mountain descents, which can result in significant fade for even well-adjusted brakes.

A driver has a single control, the treadle valve, that applies multiple brakes on a heavy truck, from four on a two axle vehicle up to 16 on an 8-axle vehicle. With training and practice, a driver can accomplish threshold braking of a vehicle with a small number of axles provided they are all loaded compatibly to the brake torque, and the road surface is uniform. This can produce a stop with each wheel around the peak of the braking-slip curve. However, as the number of wheels increases, or the load varies significantly between wheels, or the road surface deviates from uniform friction, this becomes increasingly difficult. The wheels loaded the least, or those on a lower friction surface, will tend to lock. If the driver brakes so that these wheels are at the peak of their braking-slip curve, the other wheels will be significantly under-braked, and the stopping capability of the vehicle will be reduced. An anti-lock brake system (ABS) resolves all these problems. The ABS is interposed between the driver and the brakes, and controls the brake pressure on wheels, axles or groups of axles to maintain braking near the peak of the braking-slip curve when braking is so severe that any wheel would be inclined to lock. ABS does nothing when the braking is so moderate that no wheel approaches lock. Essentially, with ABS, the driver uses the treadle to set a stopping objective, and ABS provides the controls to achieve that objective as efficiently as possible. ABS can ensure, in a severe stop, that each wheel, axle or group of axles is providing close to its maximum possible contribution to braking the entire vehicle, almost regardless of wheel load or road surface condition. Because ABS prevents wheels from locking prematurely, it also ensures that the vehicle is fully controllable during the stop. There are various means of implementing ABS, but even the least efficient of these for a whole vehicle is usually at least as efficient as a driver in the best conditions, and may be much more efficient in adverse conditions.

Brake torque is usually limited. Heavy truck brake systems are designed and rated to stop fully loaded vehicles, so can easily lock lightly loaded wheels. However, there may not be enough torque to lock a heavily loaded wheel at all on a high friction surface. The stopping distance of a heavily loaded vehicle will exceed that of the same vehicle empty or lightly loaded with its wheels locked if the braking system does not have enough capacity to reach that slip which results in a braking traction equal to that at slide, or 100% slip. However, the lightly loaded vehicle will always be able to stop shorter, to the extent that slip can be controlled to approach the peak braking traction.

2.1.3/ Braking Performance

The next step is to look at actual data. Ontario Ministry of Transportation (MTO) conducted a series of tests to compare the braking efficiency of various vehicle configurations with various load distributions with and without ABS [7]. This paper only reports stopping distances, but an unpublished report [8], and some actual data, provide more insights. The portion of the test of interest was conducted using an MTO test vehicle, a 5-axle tractor-semitrailer, equipped with an anti-lock brake system (ABS) configured for individual wheel control. This could provide braking close to the peak of the braking traction-slip curve at each wheel, regardless of variations in load, brake, tire or road friction characteristics between wheel locations. The brakes were equipped with automatic slack adjusters, which were initially checked for proper adjustment. The entire vehicle had been subjected to an SAE brake burnish cycle to condition the brake system. Thermo-couples were installed in each brake lining, and tests were conducted with all lining temperatures in the range 65-121°C (150-250°F), to maximize brake torque. The tires were about one third worn, so were in the range of higher traction. The tests were conducted on a wet high-friction surface. The vehicle and test conditions were therefore set up to be as reasonably close to ideal as possible, other than the surface condition. Figure 4 shows traces of treadle valve pressure, vehicle speed and deceleration against time for a sample full stop from a speed of 61.2 km/h (37.8 mi/h) with the vehicle unladen. The driver simply stamped hard on the treadle, depressed it fully, and kept his foot there until the truck came to stop. The deceleration rose with the build up of brake pressure to the peak of the braking traction-slip curve, after which the ABS cut in and modulated brake pressures to keep the slip at each wheel around that peak. As speed dropped, the tire traction characteristic took over, and deceleration increased moderately to reach 0.745 g shortly before the vehicle came to a stop. The peak is relatively well sustained, not momentary. The oscillations at the end occurred after the truck was stopped, and are due to the truck pitching. The average deceleration for this stop, derived from the stopping distance of 27.7 m (91 ft), was 0.53 g. The peak deceleration therefore was 1.40 times the average deceleration. This test series, for three vehicle configurations in three or four load conditions each, with ABS, resulted in peak decelerations in the range 0.64-0.75 g and stopping distances in the range 27.8-31.8 m (91-104 ft), which correspond to average decelerations of 0.46-0.53 g. The average ratio of peak deceleration to average deceleration was 1.42 for all these stops. The wet skid number for the test surface was about 65-70, and the dry skid number was about 85-90. It is expected that deceleration would increase roughly in proportion to the skid number, and stopping distances would decrease inversely proportional to the skid number.

A further series of tests were conducted later on the dry high-friction surface, stopping the same vehicle empty and half-loaded from speeds of 60 and 80 k/h (35 and 50 mi/h), with ABS [9]. These resulted in average decelerations from 0.57 to 0.67 g, so peak decelerations would be over 0.9 g.

There is a voluminous literature on all aspects of the braking performance of heavy trucks. NHTSA has conducted many extensive and consistent braking tests. One of these used 19 air-braked vehicles, stopping from 32 and 97 km/h (20 and 60 mi/h) on low- and high-friction surfaces, empty and loaded, with a variety of parameters being examined [10]. Loaded tractor-semitrailers stopped in 68.6-91.4 m (225-300 ft) from

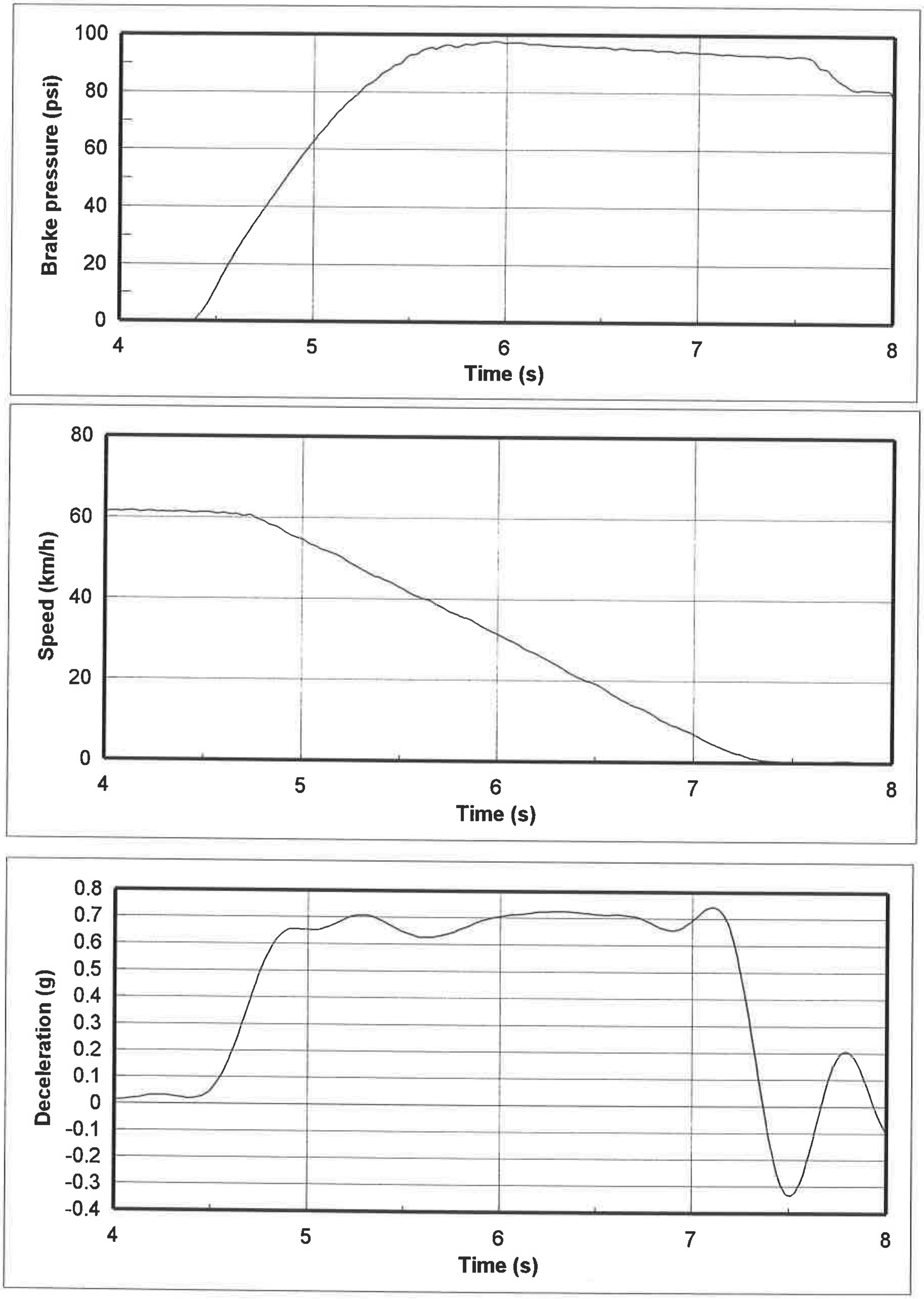


Figure 4/ Typical Stop from 61.2 km/h, with ABS, wet high-friction surface

97 km/h (60 mi/h) on a surface with an ASTM E501 skid number of 81, which corresponds to 0.40-0.53 g average deceleration. The same vehicles, empty, stopped in 91.4-129 m (300-425 ft), which corresponds to only 0.28-0.40 g. However, these latter tests were performed with manual threshold braking, not ABS. MTO work shows threshold braking efficiency of a tractor-semitrailer is in the range 59-79%, depending on load, whereas with ABS it improves to 84-92% [7].

Even more detailed and comprehensive tests were conducted for 13 hydraulically braked vehicles without ABS [11]. Tests were conducted using maximum braking when loaded to the gross vehicle weight rating, or best effort threshold braking when empty. Stopping distances from 97 km/h (60 mi/h) ranged from about 67-137 m (220-450 ft), equivalent to average decelerations of 0.27-0.55 g.

Some later tests [12], under the same conditions as above [11], show loaded stopping distances in the range 68.6-82.3 m (225-270 ft), equivalent to average decelerations of 0.44-0.53 g, with or without ABS. The empty stopping distances without ABS were 79-97 m (260-320 ft), equivalent to average decelerations of 0.38-0.46 g. Of more significance are consistent empty stopping distances of 68.6 m (225 ft) with ABS, for an average deceleration of 0.53 g.

NHTSA also conducted a comparison of braking performance of a European and U.S tractor-semitrailer [13]. Neither had ABS, but the European vehicle had load-sensitive proportioning valves to control brake pressure on both tractor and trailer tandem axles. The stopping distances under threshold braking were similar for the two vehicles when loaded. The European vehicle stopped 30% shorter than the U.S. vehicle when empty, in 56.4 m (185 ft) from 97 km/h (60 mi/h), equivalent to an average deceleration of 0.65 g. It stopped 12% shorter when half loaded. This performance should be consistently achievable if the vehicle had ABS. One of the reasons for the difference is that European vehicles make full use of the braking capability offered by the front axle, whereas U.S. vehicles historically have been significantly under-braked on the front axle, if there were brakes, and if there was no front axle limiting valve.

Tests of a straight truck equipped with ABS showed that it had a much better than typical balance of front-to rear braking, so achieved a high braking efficiency when empty [14]. Stopping distances were 54.6-62.5 m (179-205 ft) from 97 km/h (60 mi/h), equivalent to average decelerations of 0.59-0.67 g.

A series of identical tests at nine different test sites produced average bobtail stopping distances for three different tractors with ABS of 62.8-66.4 m (206-218 ft) from 97 km/h (60 mi/h), equivalent to average decelerations of 0.55-0.58 g [15]. Stopping distances with an unbraked trailer loaded so that the tractor drive tandems were at half their rated load resulted in stopping distances of 77.7-85.3 m (255-280 ft) from 97 km/h (60 mi/h), equivalent to average decelerations of 0.43-0.47 g. This stopping distance would clearly have been reduced if the trailer had been braked. The ASTM E1337 peak friction coefficients for the surfaces ranged from 0.87 to 1.00, yet there was no apparent correlation of reduced stopping distance to increased surface friction.

One of the few sources [16] to report decelerations directly gives average decelerations for a loaded tractor-semitrailer from 0.53-0.61 g, depending on the method of measurement used. The test conditions and methods of analysis are not clearly explained, but it is noted that the vehicle was under-braked on the front axle.

The largest collection of actual brake application data occurred during the NHTSA ABS demonstration program [17]. About 85% of all brake applications for the 200 tractors monitored over two years occurred during normal driving, and resulted in decelerations under 0.19 g. Only about 0.11% of all brake applications resulted in decelerations over 0.4 g. Only three of 17 major ABS incidents occurred on dry roads, with reported decelerations of 0.32, 0.38 and 0.57 g, all from maximum pressure brake applications. The decelerations reported are presumed to be peak values, though this is not stated.

Shock and vibration data were gathered to assess the highway environment for intermodal operations [18]. These data show maximum peak-to-peak longitudinal accelerations of 0.85 g on interstate and primary highways, and 1.30 g on urban roads, with peak values of about 0.45 g and 0.64 g, respectively. The longitudinal shock and vibration environment therefore seems less severe than the quasi-steady deceleration of an emergency stop.

The vast majority of sources, those cited here, and most others, only report stopping distance from speed, which only allows the average deceleration to be obtained. These sources provide a wide range of results, depending on the vehicle, test objectives and test procedures. The data summarized above shows that average decelerations over 0.50 g have been achievable with empty or lightly loaded vehicles for many years now. The deceleration from a typical 68.6 m (225 ft) stopping distance from 97 km/h (60 mi/h) is around 0.53 g. Using the ratio of peak to average deceleration derived from the MTO tests described above, the peak deceleration would be expected to be about 0.53x1.42=0.75 g. It is also clear that higher decelerations are now possible. An average deceleration of 0.6 g with the same ratio results in a peak deceleration of 0.60x1.42=0.85 g. A reduced ratio of 1.25 still results in a peak deceleration of 0.60x1.25=0.75 g. It is concluded that sustained peak decelerations above 0.70 g, and even perhaps above 0.8 g, are now quite possible.

Such high peak decelerations are probably not likely to be achieved by a majority of vehicles on the highway at this time. The data reported above were virtually all obtained from tests conducted with carefully prepared vehicles whose braking systems were as close to ideal as possible. This may not be typical of the real world. When a driver is called upon to make an emergency stop, it happens with the brake, load and road conditions at that time. A significant number of trucks have some brakes out of adjustment [19], which reduces their braking capability [16]. The brake linings may well not be warmed to provide optimum friction, which can have a dramatic effect on stopping capability [20, 21]. Even ABS's are not all the same, and most production systems will probably be less efficient than the individual wheel control of the MTO test vehicle [7].

Regulatory and technical developments are not fundamentally increasing brake torque or tire-road friction. However, regulatory measures like required front brakes, no front axle limiting valve, tractor and trailer ABS, long-stroke brake chambers, automatic slack adjusters, and slack adjustment indicators are steadily making the braking system of the whole vehicle more reliable. Many of these measures are relatively recent, and have not been in force long enough to propagate through truck fleets. Their impact will be more immediate on tractors than trailers, because of the much longer life of trailers. New technologies, like electronic braking systems, will follow. The focus on the high incidence of brakes out of adjustment during roadside inspections [19] also now seems to be having an effect. Continued market penetration of recent technical improvements, and improved maintenance of braking systems, together should gradually make truck stopping capability more consistent and reliable. A gradual increase in the braking efficiency, and the ability of a vehicle to use all the roadway friction and tire traction available, should increase the average deceleration capability of the fleet. Some vehicles are already able to achieve a sustained peak deceleration over 0.70 g. It is likely that this number should gradually increase. It appears prudent to recognize not just the current situation, but the increasing capability of braking systems, in selecting a value for design of cargo securement systems. The only other recent source to discuss this issue followed essentially this same line of argument [22].

It is clear that the maximum deceleration of vehicles loaded close to their maximum allowable gross weight may not exceed 0.6 g by much. This is somewhat less than that of empty and lightly loaded vehicles, which may reach 0.70 g or more, as noted above. 0.8 g was proposed as the longitudinal deceleration performance criterion for design of cargo securement systems, and, in the interest of simplicity, it was proposed that this apply to all vehicles, whatever their weight.

If the proposed criterion of 0.8 g is considered to be too onerous for some heavily loaded vehicles, it is conceptually possible to set a longitudinal deceleration criterion based on the weight of the vehicle. This should probably not be less than 0.6 g for a fully loaded vehicle, and when the arguments about the likely improvement in braking efficiency are considered, may need to be 0.7 g. The gap between 0.6 or 0.7 g and 0.8 g seems so narrow that it does not warrant anything more than a demarcation between "lightly loaded", which would use 0.8 g, and "heavily loaded", which would use the lower value. It does not seem possible to choose either a single payload or gross weight number for all vehicles, as there are trucks with two axles operating at legal weights of 4,600 kg (10,000 lb), up to trucks with eleven axles operating up to about 72,600 kg (160,000 lb). Vehicle configurations and allowable weights vary so widely across North America, it does not seem easy to choose numbers even by the number of axles. It might be logical to choose the axle load where a typical brake in typical adjustment would just not be able to lock on a dry road. But not all brakes are "typical", and axles may not be uniformly loaded through a vehicle, especially on double trailer combinations. Alternatively, the demarcation could be something like "half loaded", by vehicle or trailer. However, this is not always easy to assess. The absence of a simple way to separate "lightly loaded" and "heavily loaded" vehicles that applies across all classes of vehicle leads back to the conclusion that a single criterion should be used.

3.2/ Longitudinal Acceleration

Trucks are typically designed to start on a 12% grade, so need a longitudinal acceleration from a stop of at least 0.12 g [22]. A higher acceleration is needed actually to start and keep rolling up such a grade. Higher acceleration is possible for empty or lightly loaded trucks, with momentary higher peaks during gear shifts. A recent test conducted by MTO, where the 465 hp tractor was towing an empty semitrailer, achieved a momentary longitudinal acceleration of 0.25 g.

An emergency stop while reversing would appear at first sight to be as severe as a stop while travelling forward. However, driving in reverse is limited to a very low speed, and the truck will stop during the time it takes the pneumatic system to develop full pressure, essentially regardless of weight. The maximum deceleration in reverse is, therefore, much less than that from a high speed travelling forward, when the pneumatic system does have time to develop full pressure. The largest longitudinal acceleration probably occurs when a vehicle backs into a dock. This is momentary, as the dock quickly stops the vehicle from a very low speed. If cargo is dislodged, it would only slide a very short distance before it stops.

The maximum deceleration due to braking is thus considerably more severe than longitudinal acceleration. A performance criterion of 0.5 g should cover the quasi-steady acceleration, as well as the shock and vibration environment discussed above [18].

3.3/ Lateral Acceleration

The lateral acceleration that occurs while driving a curve or ramp is proportional to the square of the vehicle's speed, and inversely proportional to the curve radius. Thus, for a given ramp, if the speed is doubled, the lateral acceleration increases by a factor of four. If the vehicle drives two curves at the same speed, one with half the radius of the other, then the lateral acceleration on the curve of smaller radius will be double that on the other. In reality, curves and ramps are often banked, which introduces small corrections to these general statements.

Many ramps are posted with yellow advisory speed signs, intended to ensure that vehicles are driven with an adequate margin of safety against skidding on a wet and slippery road. The typical lateral acceleration while driving a curve or ramp at the posted advisory speed is in the range 0.05-0.17 g. Loaded vehicles with a high cargo centre of gravity roll over at a lateral acceleration above about 0.30-0.35 g. Lightly loaded vehicles, or heavily loaded vehicles with a lower cargo centre of gravity, may not roll over even for a lateral acceleration above 0.50 g, and the theoretical rollover threshold for a very low cargo centre of gravity as arises, for instance, with steel plate, could be as high as 0.75 g [4].

There is little published data on actual truck lateral accelerations on ramps. One source finds a mean lateral acceleration of 0.15 g with a standard deviation of 0.05 g, but some trucks were observed at lateral accelerations above 0.30 g, and as high as 0.40 g [23]. These published data almost certainly only reflect "normal driving". Even those trucks in the high end of the range were probably being driven to that limit because their drivers knew that the traffic, road and vehicle conditions were suitable.

If a truck has a high rollover threshold, the lateral acceleration limit is the tire lateral traction limit, which can be as high as 0.9 [4]. A driver of a straight truck or tractor would lose control of the vehicle well before this point, but it is theoretically achievable during trailer swing. However, if a tractor is centred in a lane, it takes only few degrees of trailer articulation angle before the wheels of the trailer run off the road or strike the curb. This acceleration may be rather large, but is being excluded from the performance criteria as it is considered a crash condition, albeit usually a mild crash.

The highest practical lateral acceleration probably occurs when a driver approaches a curve or ramp without adequate awareness of what lies ahead, enters it considerably over-speed, realizes the situation, and steers sharply to try and follow the curve. If this does not result in a rollover, it is almost certain that the driver would have great difficulty following the curve, and might be likely to run off the road.

Data measured on the highway shows peak lateral accelerations up to 1.5 g [18]. However, the bulk of this occurs in the range 15-25 Hz, which is identified as trailer body lateral vibration modes [18]. If this vibration is of any consequence for cargo shift, and there is no evidence it is, the net effect over a long period should essentially be zero, as acceleration to one side will be very close to acceleration to the other side.

As a consequence of this discussion, a lateral acceleration performance criterion of 1.0 g is too high [22]. For practical purposes, if most trucks would either roll over or be driven off the road at 0.5 g, there is really no need for any higher criterion.

3.4/ Vertical Acceleration

Vertical acceleration occurs as vehicles drive over undulations in the road, and at discrete deviations from the planar surface, such as expansion joints, cracks, potholes, patches, accreted ice in the winter, grade crossings, and so on. It is evident that incremental vertical acceleration well over 1 g is possible, simply by observing the response of lightly loaded vehicles to moderate and severe roadway input.

Vertical acceleration due to the designed vertical curvature of the roadway is insignificant. Vertical accelerations due to roadway roughness can be quite large, with peaks up to about 2.8 g on interstate and primary roads, and over 8 g on urban roads, for a loaded container on a tractor-semitrailer [18]. This is primarily heave and pitch of the trailer, in the frequency range 2-5 Hz. The same conclusion was reached from measurements of 2.44 (8 ft) logs carried transversely on a semitrailer, where vertical accelerations on the deck and a log at the top of the load both exceeded 1 g [24]. However, more detailed examination likened the load to a sponge, absorbing the vibration, so that the top logs were not, in fact, momentarily airborne [25]. Nevertheless, the vibration would appear to be reducing the force momentarily between logs, which effectively can reduce friction if they are simultaneously subjected to a lateral acceleration.

The effect of longitudinal or lateral acceleration is to tend to cause the cargo to shift on the deck. However, when vertical acceleration is imparted to the deck, and it carries the cargo up with it, it is possible that cargo and deck could separate on the downward part of the cycle, so effectively the cargo hops.

The conclusion is, that while momentary high accelerations and cargo hop may occur, they are not evidently a concern for strength of the cargo securement system. An alternative approach was therefore followed. Friction between cargo and deck has been identified as the principal factor preventing cargo shift [4]. Tiedowns that bear down on the cargo and increase the apparent weight of the cargo effectively increase the coefficient of friction. For cargo secured using the general rule that tiedown aggregate working load limit should equal half the weight of the cargo [29], tiedowns tensioned to 20% of their working load limit provide an apparent additional weight equivalent to 0.4 g. This is a typical initial tension possible with many tiedown systems. Turning this around, a requirement to secure for a vertical acceleration of 0.2 g means that cargo that is not contained must be tied down, and that the tiedowns should be tensioned to 20% of their working load limit. It would be possible to delete the 0.2 g requirement if the latter requirement was spelled out directly in the standard.

Cargo that is simply contained in a box without being secured needs a different requirement. This should be a sinusoidal vertical acceleration with a frequency typical of body heave, which is in the range 2-5 Hz. The frequency and acceleration can be combined into a requirement for a minimum distance for the article below the top of the box, so that the article cannot jump out of the box. The acceleration should perhaps be of the order of 8-10 g for a single rigid article [18], somewhat less than that for a loose bulk load composed of many articles in contact with each other [25]. This approach results in a requirement for the cargo to be in the range 15-50 cm (6-20 in) below the top of the box, depending on the assumptions made.

3/ Comparison of Road and Rail Environments

The truck manoeuvres discussed here derive from quasi-steady manoeuvres of braking and turning, which may be sustained for several seconds, and from roadway roughness, which is both momentary and continuous. The railroad loads that correspond to the highway quasi-steady manoeuvres are much less severe than on highway, because railroad trains brake much more sedately, and curve at more moderate lateral accelerations, than heavy trucks. The real issue for railroad freight, and freight damage, arises from the continuous and apparently rather severe shock and vibration environment. A comprehensive test program documents rather thoroughly both the highway environment and a variety of inter-modal environments [26].

The highway and railroad shock and vibration environments were found to be rather similar in many respects. However, the railroad environment does exhibit high levels of longitudinal shock and vibration, due to back and forth movement of cars within the train in the 2-6 Hz frequency range. This results in a series of small movements of cargo, the net effect would be expected to be almost zero, because the essentially sinusoidal nature of the shock and vibration results in nearly equal forward and rearward accelerations. In this situation, it is in fact easier and more effective to place cargo loose on friction mats and let it float around, as on average, even on a cross-continent trip, it is likely to end up almost where it started. This also avoids the possibility that the securement system could damage the cargo, always a concern to both shipper, carrier and recipient. In contrast, high braking decelerations are possible on the highway, which may be able to overcome any coefficient of friction in the presence of vibration, even in the absence of contaminants in the interface. These high decelerations are not balanced by corresponding longitudinal accelerations. It is well known that the net effect of acceleration and braking on loose cargo in a level vehicle is to move the cargo to the front of the vehicle.

In the lateral direction, there is also relatively high shock and vibration in the same 2-6 Hz frequency range, likely due also to train action. This also is dealt with by the same remedy. In this instance, quasi-steady lateral accelerations on the highway would also tend to balance out to left and right, as during a trip most vehicles will turn left nearly as often as they turn right. The very occasional extreme event would almost certainly not be included in this, and it is known that if cargo is free to move laterally within the vehicle, it can significantly deteriorate the roll threshold of the vehicle..

The data suggest that AAR measures to protect cargo against damage should be effective on the highway, too [27]. However, the quasi-steady events of emergency braking and high-speed turn, that can cause significant cargo movement, are absent from the railroad environment. Nevertheless, many of the AAR-approved securement methods would appear to meet the proposed requirements for the highway [27].

4/ Other Performance Criteria for Cargo Securement

There are a number of sources that have adopted or proposed performance criteria for cargo securement. These are summarized in Table 1. The six European sources were obtained from one summary [28], and have not been examined individually.

The proposed longitudinal and lateral acceleration criteria agree well with recent recommendations from Europe [28], Australia [30] and New Zealand [31], and are more liberal than a recent North American recommendation [22]. There are few vertical acceleration recommendations, but again the proposal agrees with those that have been made.

Table 1/ Summary of Performance Criteria

Source	Deceleration	Rearward Deceleration	Lateral	Vertical
FHWA [29]	0.6 g	0.6 g	0.6 g	None
R273 [28]	1.0 g	0.5 g	0.5 g	None
VDI 2702 [28]	0.8 g	0.5 g	0.5 g	None
Schneidersmann [28]	0.8 g	0.5 g	0.5 g	None
NF R 18-150 [28]	1.0 g	0.5 g	0.5 g	None
Spanset [28]	0.8 g	0.5 g	0.5 g	None
UTAC [28]	0.8 g	None	0.35 g	0.2 g
Gillespie [22]	0.75 g	None	1.0 g	None
Australia [30]	0.8 g	0.5 g	0.5 g	0.2 g
New Zealand [31]	1.0 g	0.5 g	0.5 g	'Appropriate consideration'
Proposed standard	0.8 g	0.5 g	0.5 g	0.2 g

5/ Conclusions

This report examines various sources of data that can help identify performance criteria for the proposed North American Cargo Securement standard.

Most of the data on braking performance of heavy trucks is reported as the stopping distance, which provides only an average deceleration. Values equivalent to an average deceleration in the range 0.45-0.55 g are commonly found. However, a detailed examination of any hard stop shows that the highest deceleration occurs just before the vehicle comes to a stop, may be sustained for several seconds, and may be 30-40% higher than the average deceleration. The stopping capability of most vehicles on the highway probably does not approach their full capability. However, a series of regulatory and maintenance measures that are under way should result in a steady improvement in braking efficiency of heavy trucks. Trucks have been able to achieve peak decelerations over 0.7 g for a number of years now, and their stopping capability clearly now exceeds the current 0.6 g requirement. If their braking systems will be able to offer better performance and greater reliability, the proposed braking deceleration of 0.8 g seems prudent.

Longitudinal acceleration and braking in reverse are both much less severe than braking deceleration, which is reflected in the proposed performance criterion of 0.5 g.

Lateral acceleration arises from driving at high speed on a curve or ramp. Many loaded trucks would roll over below 0.5 g. Few drivers would knowingly enter a curve at this lateral acceleration, and it is expected that those who did so would be unable to follow the curve.

The vertical acceleration environment differs from the longitudinal and lateral directions. The 0.2 g criterion here is chosen to ensure that cargo is secured, and to increase friction between cargo and deck to as great an extent as possible.

Road and rail shock and vibration environments are really quite similar. The rail environment has significant longitudinal and lateral shock and vibration in the 2-6 Hz range, that is absent on the road. However, the rail environment is also missing the severe quasi-steady braking and lateral accelerations that can occur on the highway.

The performance criteria proposed for securement of cargo on heavy trucks operating to their limits within the highway system, and short of a crash, appear reasonable and prudent based on data available in the literature. They are also closely in accordance with recent recommendations or practice from a number of other countries.

References

[1] National Safety Code for Motor Carriers, Standard 10, "Security of Loads Standards", Canadian Council of Motor Transport Administrators, 1988, ISBN 0-921795-01-7.

[2] "New Challenges, New Opportunities, New Requirements for Motor Carrier Load Securement", Report of Task Force on Load Security to CCMTA Standing Committee on Compliance and Regulatory Affairs, November 1992.

[3] Billing J.R., Mercer W.R.J. and Cann W., "A Proposal for Research to Provide a Technical Basis for a Revised National Standard on Load Security for Heavy Trucks", Transportation Technology and Energy Branch, Ontario Ministry of Transportation, Report CV-93-02, November 1993.

[4] Billing J.R. and Couture J., "North American Load Security Research Project Summary Report", North American Load Security Research Project Report 18, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[5] Ervin R.D., Winkler C.B., Bernard J.E. and Gupta R.K., "Effects of Tire Properties ion Truck and Bus Handling", University of Michigan Transportation Research Institute, NHTSA Report DOT HS-802141, December 1976.

[6] Mercer W.R.J., "Comparison of Lateral and Longitudinal Traction Characteristics of Three Heavy Truck Tires", Report CV-85-02, Transportation Technology and Energy Branch, Ontario Ministry of Transportation, December 1985.

[7] Billing J.R. and Lam C.P., "Further Experience with Anti-Lock Brake Systems", Proceedings of Fourth International Symposium on Vehicle Weights and Dimensions, Ann Arbor, Michigan, June 1995.

[8] Lam C.P., "Impact of an Antilock Brake System on the Stopping Capability of Heavy Commercial Vehicles", Unpublished report, Ontario Ministry of Transportation, 1994.

[9] Stephenson W.R., "Test to Determine Peak Vehicle Deceleration", Internal memorandum, Ontario Ministry of Transportation, 6 June 1996.

[10] Radlinski R.W. and Williams S.F., "NHTSA Heavy Duty Vehicle Brake Research Program Report No. 1 -- Stopping Capability of Air Braked Vehicles, Volume 1 -- Technical Report", NHTSA Report DOT HS 807738, April 1985.

[11] Kirkbride R.L. and Radlinski R.W., "NHTSA Heavy Duty Vehicle Brake Research Program Report No. 4 -- Stopping Capability of Hydraulically Braked Vehicles", Appendices, five volumes, NHTSA Reports DOT HS 806861 to 806864, October 1985.

[12] Flick M., "NHTSA Heavy Duty Vehicle Brake Research Program Report No. 9 -- Stopping Distances of 1988 Heavy Vehicles", NHTSA Report DOT HS 807531, February 1990.

[13] Flick M. and Radlinski R.W., "NHTSA Heavy Duty Vehicle Brake Research Program Report No. 8 -- Comparison of the Braking Performance of a U.S. and a European Combination Vehicle", NHTSA Report DOT HS 807345, July 1988.

[14] Radlinski R.W. and Bell S., "NHTSA Heavy Duty Vehicle Brake Research Program Report No. 6 -- Performance Evaluation of a Production Antilock System Installed in a Two Axle Straight Truck", NHTSA Report DOT HS 807046, August 1986.

[15] Kempf R.C., "MVMA/NHTSA/SAE Heavy Truck Round Robin Brake Test", SAE paper 922484, November 1992.

[16] Heusser R.B., "Heavy Truck Deceleration Rates as a Function of Brake Adjustment", SAE paper 910126, 1991.

[17] Klusmeyer L.F., Gray A.W., Bishop J.S., Van Schoiack M., Woods J.M. and Mahmoud W.M., "An In-service Evaluation of the Reliability, Maintainability and Durability of Antilock Braking Systems (ABS) for Heavy Truck Tractors", National Highway Traffic Safety Administration, U.S. Department of Transportation, Report DOT HS 807846, March 1992.

[18] Blackman J.H., "A Technical Summary of the Intermodal Environment Study: Phase III, Interstate, Primary Highway and Urban Street Truck Transport, and Lift-on/Lift-off Intermodal Ramp Operations", Report DP 3-90, Association of American Railroads, Freight Claim and Damage Prevention Division, October 1990.

[19] "Heavy Vehicle Airbrake Performance", National Transportation Safety Board, Report NTSB/SS-92/01, PB92-917003, April 1992.

[20] Radlinski R.W., Williams S.F. and Machey J.W., "The Importance of Maintaining Air Brake Adjustment", SAE paper 821263, November 1982.

[21] Flick M.A., "The Effect of Brake Adjustment on Braking Performance", NHTSA Report DOT HS 807287, April 1988.

[22] Gillespie T.D., "Engineering Analysis of Cargo Restraint on Commercial Highway Trucks", University of Michigan Transportation Research Institute, Report UMTRI-87-28, August 1987.

[23] Harwood D.W., Mason J.M., Glauz W.D., Kulakowski B. and Fitzpatrick K., "Truck Characteristics for Use in Highway Design and Operation", Volume 1, Federal Highway Administration Report FHWA-RD-89-226, August 1990.

[24] Franklin G.S., "Testing of Methods to Secure 8' Wood on a Tractor-Trailer Haul Unit", Forest Engineering Research Institute of Canada, Montreal, Report TR-60, January 1985.

[25] Franklin G.S., "Load Security on Tractor-Trailer Haul Units with 8-foot, 16-foot and Tree-length Wood", Forest Engineering Research Institute of Canada, Montreal, Report SR-55, November 1988.

[26] Feltaugh T.E., Blackman J.H. and Arguello V., "A Technical Summary of the Intermodal Environment Study Incorporating Phase I, Phase II and Phase III", Report DP 3-91, Association of American Railroads, Freight Claim and Damage Prevention Division, April 1991.

[27] "Intermodal Loading Guide for Products in Closed Trailers and Containers", Cicrcular No. 43-C, Pamphlet No. 45, BOE Pamphlet No. 6C, Association of American Railroads, Washington D.C., 1995.

[28] Paureau J. and Jacqmin M., "Arrimage de produits sidérurgiques sur véhicules routiers", Cahiers de notes documentaires, No. 143, 2^e trimestre 1991.

[29] Federal Motor Carrier Safety Regulations, "Protection Against Falling or Shifting cargo", 49 CFR 393.100, Federal Highway Administration, U.S. Department of Transportation.

[30] "Load Restraint Guide", Federal Office of Road Safety, Department of Transport, Australian Government Publishing Service, Canberra, Australia, 1994.

[31] "The Truck Loading Code", Land Transport Safety Authority, Wellington, New Zealand, 1985.

North American Load Security Research Project Reports

[1] Billing J.R., W.R.J. Mercer and W. Cann, "A Proposal for Research to Provide a Technical Basis for a Revised National Standard on Load Security for Heavy Trucks", Transportation Technology and Energy Branch, Ontario Ministry of Transportation, Report CV-93-02, November 1993.

[2] Rakheja S., P. Sauvé and D. Juras, "Experimental Evaluation of Friction Coefficients of Typical Loads and Trailer Decks under Vertical Vibration", North American Load Security Research Project, Report 2, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[3] Heidersdorf E. and E. Hay, "Slippage Tests with Anti-skid Mats", North American Load Security Research Project, Report 3, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[4] Hay E., W. Williams and E. Heidersdorf, "Dressed Lumber Tiedown Tests", North American Load Security Research Project, Report 4, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[5] Mercer W.R.J. and J.R. Billing, "Effect of Cargo and Tiedown Characteristics on Equalization of Tension in the Spans of Tiedowns", North American Load Security Research Project, Report 5, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[6] Mercer W.R.J. and J.R. Billing, "Effect of Binder Type and Chain Length on Tension in Chain Tiedowns", North American Load Security Research Project, Report 6, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[7] Billing J.R. and C.P. Lam, "Friction Coefficients between Typical Cargo and Truck Decks", North American Load Security Research Project, Report 7, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[8] Mercer W.R.J. and J.R. Billing, "Load Capacity of Nailed Wood Blocking", North American Load Security Research Project, Report 8, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[9] Billing J.R. and C.P. Lam, "Effect of Cargo Movement on Tension in Tiedowns", North American Load Security Research Project, Report 9, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1998.

[10] Billing J.R. and D.K.W. Leung, "Evaluation of the Strength and Failure Modes of Heavy Truck Cargo Anchor Points", North American Load Security Research Project, Report 10, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[11] Mercer W.R.J. and J.R. Billing, "Tests on Methods of Securement for Thick Metal Plate", North American Load Security Research Project, Report 11, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[12] Mercer W.R.J. and J.R. Billing, "Tests on Methods of Securement for Large Boulders", North American Load Security Research Project, Report 12, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[13] Mercer W.R.J. and J.R. Billing, "Bending Strength of Trailer Stakes", North American Load Security Research Project, Report 13, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1998.

[14] Mercer W.R.J. and J.R. Billing, "Effect of Tiedowns on Wood Blocks Used as Dunnage", North American Load Security Research Project, Report 14, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1998.

[15] Billing J.R. and C.P. Lam, "Tests on Methods of Securement for Metal Coils", North American Load Security Research Project, Report 15, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

[16] Mercer W.R.J. and J.R. Billing, "Tests on Methods of Securement for ISO Containers", North American Load Security Research Project, Report 16, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1998.

[17] Leung D.K.W. and J.R. Billing, "Analysis of Heavy Truck Cargo Anchor Points", North American Load Security Research Project, Report 17, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1998.

[18] Billing J.R. and J. Couture, "North American Load Security Research Project Summary Report", North American Load Security Research Project, Report 18, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

---

[19] Grandbois J., "Assessing a Securement Method for the Transportation of Heavy Machinery Using a Combination of Highway Vehicles", North American Load Security Research Project, Report 19, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1997.

---

[20] Billing J.R., "Performance Limits of Heavy Trucks", North American Load Security Research Project, Report 20, Canadian Council of Motor Transport Administrators, Ottawa, Ontario, 1998.