

COMPATIBILITY OF HEAVY VEHICLE BRAKE SYSTEMS

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In New Zealand large heavy combination vehicles must comply with the New Zealand Heavy Vehicle Brake Code (NZHVBC). The code, which is based on UN/ECE Regulation No. 13, sets out requirements for these combination vehicles when they are operated in a fully laden condition, but not when they are operated in a partially laden or unladen condition. Therefore brake compatibility is not ensured when a vehicle in the combination is not fully laden.

The Ministry of Transport, in conjunction with Land Transport New Zealand, is proposing changes to the law on heavy-vehicle brakes. One proposed change is that combination vehicles must have balanced brake performance under all load conditions.

This raises the obvious question as to what will happen when one vehicle in the combination has been fitted with a brake system that complies with new requirements while another vehicle in the combination has a brake system that only meets the old requirements. To investigate the impact on performance of mixing brake systems a series of braking tests was undertaken. A rigid truck and full trailer combination with EBS brakes was modified so that the brakes could be operated in either EBS mode or NZHVBC mode and both vehicles were extensively instrumented. Full brake application stopping tests were undertaken from speeds of 30 km/h and 50 km/h. From these speeds all possible 16 combinations of brake (EBS or NZHVBC) and load (laden or unladen) configuration were tested.

Interestingly the best stopping distance performance was achieved by the NZHVBC brake systems but the improved directional stability of the EBS systems would allow drivers to use full brake application with confidence in circumstances where they would not do so with NZHVBC brakes.

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1 INTRODUCTION

Large combination heavy vehicles (GCM between 39 and 44 tonnes) in New Zealand are currently required to comply with the New Zealand Heavy Vehicle Brake Code (NZHVBC). This code, which is based on the UN/ECE Regulation No. 13, specifies a band of braking efficiency that must be achieved by vehicles when they laden to their Brake Code Mass. As the brakes on each axle group of each vehicle must fit within this band of performance a degree of compatibility between vehicles in laden combinations is assured. However, the NZHVBC does not specify any performance requirements for the unladen vehicles and hence compatibility is not guaranteed when any or all of the vehicles are not fully laden.

A New Zealand Land Transport Rule concerning heavy vehicle braking is currently under development. The purpose of Land Transport Rules is to clarify, consolidate and update existing regulations. A draft of this Rule was released for public consultation in June 2004. A number of changes from existing brake requirements have been proposed in the Rule. The main changes proposed are:

- For imported vehicles, compliance with a recognised overseas braking standard such as UN/ECE Regulation No. 13.
- For locally manufactured or modified vehicles intended for use in combination vehicles, compliance with technical requirements similar to those in UN/ECE Regulation No 13, which are now included within the Rule (covering both the laden and unladen conditions), to cover all heavy vehicles, not just those between 39 and 44 tonnes.
- brake system performance is required to be balanced across all vehicle combinations and at all load conditions to ensure that directional stability can be maintained. In practice this requires vehicle brake systems to incorporate load-sensing valves (LSVs) or an anti-lock braking system (ABS).

None of the new requirements are proposed to be retrospective so existing vehicles could continue to operate with their current brake systems unmodified. However, this raises the obvious question as to what will happen when one vehicle in the combination has been fitted with a brake system that complies with new requirements while the other has a brake system that only meets the old requirements.

The draft Rule addressed this issue by proposing that trailers fitted with brakes that meet the new requirements should only be towed by vehicles that also meet the new requirements, and trailers fitted with brakes that meet the old requirements may only be towed by prime movers whose brakes also meet the old requirements. That is, there should be no mixing of newer and older brake technologies within a combination.

This proposal caused some concern within the industry because it is common practice to replace individual vehicles at different times. This spreads the capital requirements over time and accommodates the fact that the average life of prime movers and trailers is not the same. It was felt that, although mixing brake technologies within a combination was likely to produce a level of performance that is inferior to having the new technology on all the vehicles in the combination, the brake performance may be comparable with having old technology brake systems on all vehicles in the combination. Thus there may be no reduction in safety in allowing the mixing of brake technologies. The primary purpose of the tests described in this paper was to test this hypothesis.

Some testing of brake compatibility has recently been undertaken in the United States (Radlinski, 2003) but this compared EBS systems with their current requirements which include mandatory ABS so the performance differences between the systems in these are less than would be expected in New Zealand.

2 METHODOLOGY

A dairy tanker combination consisting of a 4-axle truck coupled to a 4-axle dog trailer was configured so that the brake system on each vehicle could be switched between operating as a standard NZHVBC compliant system or a modern EBS system. The combination vehicle was extensively instrumented and a series of hard stopping tests were undertaken at two speeds and with various combinations of load and brake configuration. The basic vehicle parameters are shown in Table 1.

Table 1. Vehicle parameters

	Wheelbase	Unladen weight	Laden weight
Truck	5.055 m	12,220 kg	21,000 kg
Trailer	4.830 m	5,240 kg	23,000 kg

The brakes on the two vehicles were able to be switched independently of each other. In the planning stages of the project there was some debate as to which brake systems to compare. One option was to compare the standard NZHVBC system with a LSV system, as the LSV system will be the minimum requirement under the proposed Rule. However, the decision was made to compare the standard NZHVBC system with the latest technology EBS systems as this represents the largest possible difference between systems and hence the greatest chance of incompatibility. If the incompatibility between the EBS and NZHVBC systems does not lead to unacceptable brake performance, it is reasonable to expect that more similar systems would be unlikely to have unacceptable performance.

The combination vehicle was instrumented with pressure transducers on the brake control line and on the brakes of each of the axle groups, yaw rate transducers on each vehicle, an accelerometer on the truck to measure deceleration, and strain gauges on the drawbar to enable assessment of the tensile and compressive forces between the vehicles during braking. In addition the brake light signal was monitored to identify the timing of the brake application and a Tapley brake tester was used to measure deceleration and to provide a cross-check on the accelerometer results. The data were logged on a laptop computer using an 16-bit data

acquisition card at a sampling rate of 300 Hz. Data acquisition was triggered manually from in the cab of the truck. Water-based paint marks were applied to each tyre so that wheel lock-up would be visually obvious.

The tests were undertaken in July 2005. Full brake application stopping tests were undertaken from 30 km/h and 50 km/h. All 16 combinations of brake configuration and vehicle load condition were assessed. With tests conducted at two speeds this gave a total of 32 test runs. Video recordings were made from front-on and side-on to record jack-knife or trailer swing and wheel lock-up. In addition to the hard braking tests, the vehicle was subjected to roller brake testing to characterise the brake system performance and confirm compliance with the NZHVBC.

3 ANALYSIS AND RESULTS

Although it was not raining at the time of the tests, the road surface was wet. This reduced the available road-tyre friction and hence facilitated skidding. Any difference in the directional stability of the braking systems would become more apparent in these conditions and so this was seen as a positive characteristic. During the day the road surface began to dry out and water was applied to the surface to maintain this wet condition. Although the road friction was not measured or controlled, it was sufficiently low that in all tests where an unladen vehicle was fitted with NZHVBC brakes, wheel lock-up was observed on that vehicle.

Table 2 and Table 3 below show the peak decelerations as measured by the Tapley brake tester for each of the 32 tests. In general, the peak deceleration in the 50 km/h tests is greater than that in the 30 km/h tests.

Table 2. Deceleration in g's from 30 km/h.

Load Configuration Truck/Trailer	Brake Configuration Truck/Trailer			
	NZHVBC/NZHVBC	NZHVBC/EBS	EBS/NZHVBC	EBS/EBS
Empty/Empty	0.63	0.61	0.59	0.58
Empty/Full	0.56	0.59	0.61	0.56
Full/Empty	0.57	0.58	0.57	0.56
Full/Full	0.65	0.53	0.62	0.53

Table 3. Deceleration in g's from 50 km/h.

Load Configuration Truck/Trailer	Brake Configuration Truck/Trailer			
	NZHVBC/NZHVBC	NZHVBC/EBS	EBS/NZHVBC	EBS/EBS
Empty/Empty	0.75	0.69	0.57	0.62
Empty/Full	0.65	0.60	0.72	0.63
Full/Empty	0.64	0.60	0.65	0.61
Full/Full	0.68	0.63	0.69	0.59

Some aspects of the results are somewhat surprising. In general, higher decelerations were achieved when the EBS system was switched off. However, this raw measure does not consider

the level of directional stability achieved during braking. Furthermore the mixed brake systems do not appear to have any adverse impact in terms of stopping distance. Note, however, that the full EBS system was more consistent across all load conditions. In all cases the decelerations achieved exceeded the minimum requirement for New Zealand vehicles (0.5g deceleration).

The raw accelerometer signals had significant high frequency content and were somewhat difficult to interpret. However, integrating the signal to determine speed eliminated this difficulty as illustrated in Figure 1. Because this accelerometer used (Crossbow CXL01LF1) is DC-coupled it is straightforward to determine the offset for each test and correct for it. Vehicle pitch will introduce a small error into the acceleration signal which will lead to an under-estimate of the acceleration. However, because the test involved full brake application this error is small (<3%) and consistent from test to test. The signals have been synchronised so that in each case, activation of brake pedal control occurred at a time of one second. As can be seen there were small differences in the initial speed which were unavoidable with a human driver.

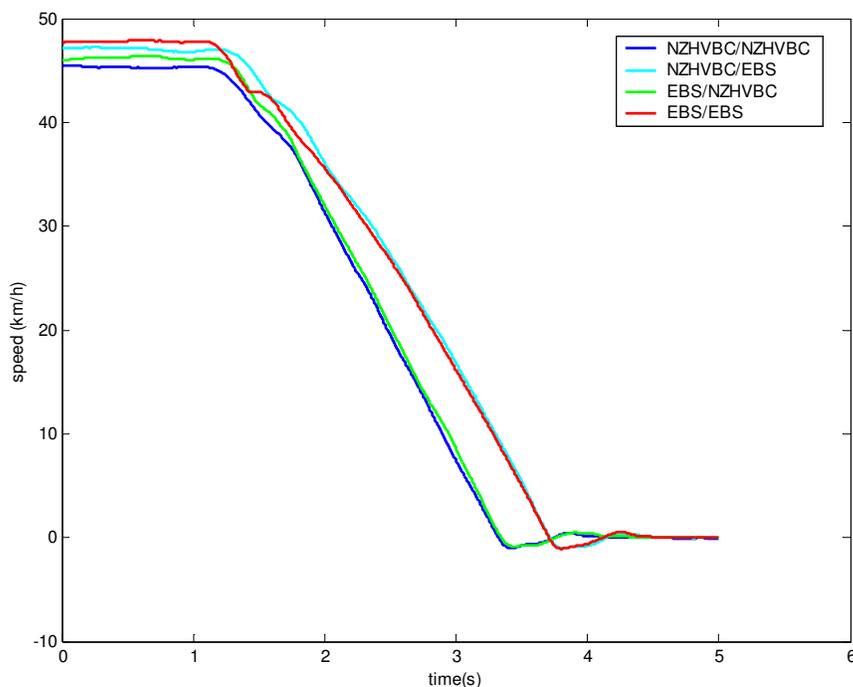


Figure 1. Change in speed of laden truck and trailer during braking from 50 km/h.

Figure 2-Figure 4 show examples of the signals recorded from some of the other transducers during the same set of tests (fully laden combination stopping from 50 km/h). The brake pressure signals clearly illustrate the effect of the EBS system. The relatively large magnitude of the brake pressure modulations when the EBS system is operating and the relatively low frequency of the oscillations means that the average brake force applied by the EBS systems was considerably lower than that applied when the EBS systems were inactive. This explains why higher decelerations were achieved when the EBS systems were switched off.

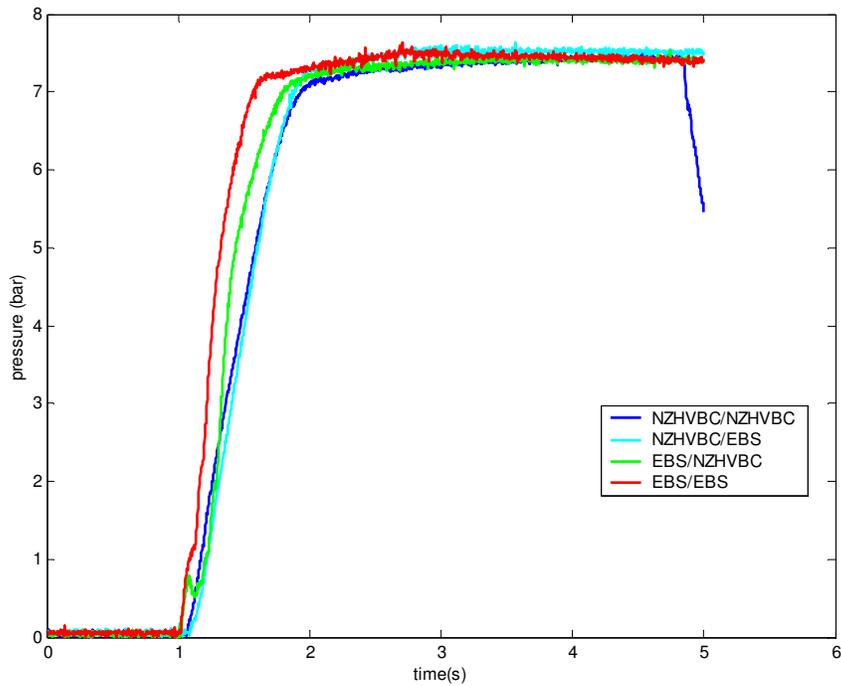


Figure 2. Coupling head pressure for laden truck and trailer stopping from 50 km/h.

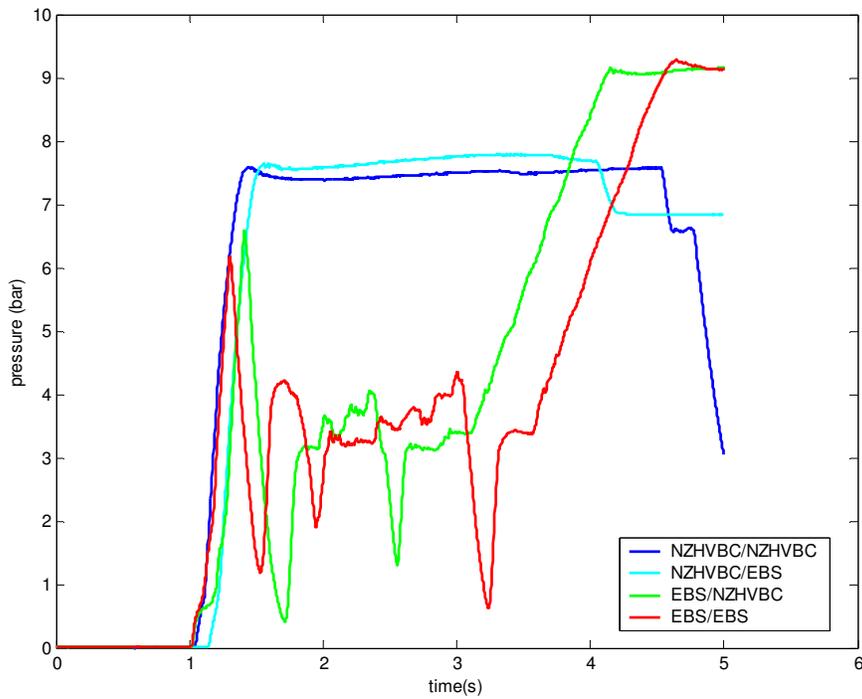


Figure 3. Truck rear axle brake pressure for laden truck and trailer stopping from 50 km/h.

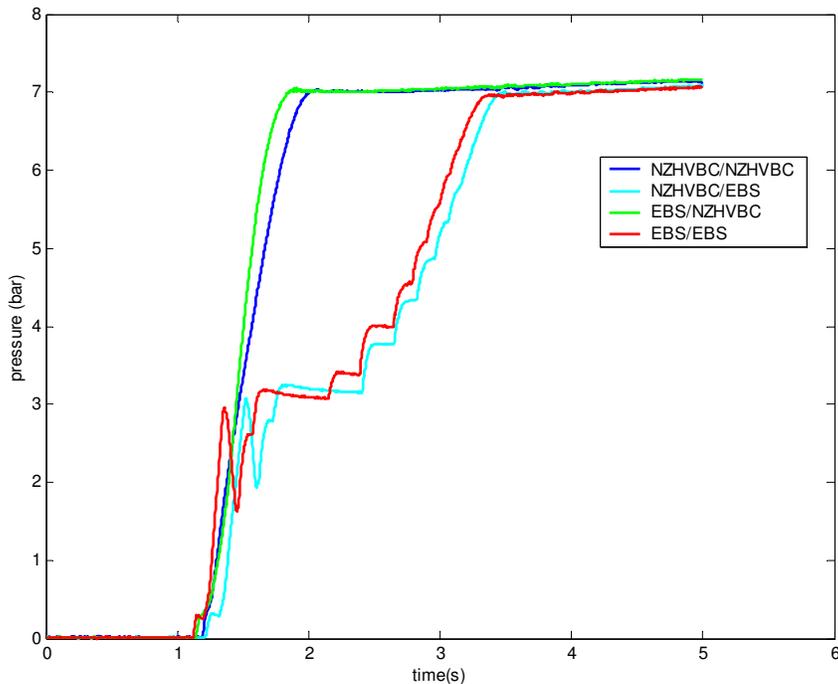


Figure 4. Trailer front axle brake pressure for laden truck and trailer stopping from 50 km/h.

The examples so far have shown the results of the tests with the fully laden truck and fully laden trailer stopping from 50 km/h. These tests were repeated at 30 km/h and at both speeds for the empty truck and empty trailer, empty truck and laden trailer and laden truck and empty trailer.

Comparing the speed change and stopping distance results for the three other load configurations with those for the fully laden case we make the following observations:

- In general, the NZHVBC brakes generated more braking force than the EBS systems resulting in more rapid changes in speed and shorter stopping distances under the test conditions. To some degree this is offset by the shorter response time of the EBS systems but not totally. Note that if the road surface had been more slippery this would not necessarily be the case because the EBS systems would utilise more of the available friction while the NZHVBC systems would lock the wheels and cause the vehicle to slide.
- With a human driver there were inevitably small variations in the speed at which the braking was initiated. Because stopping distance is proportional to speed squared, these variations have a significant impact on stopping distance.
- When we synchronised the speed change and stopping distance signals at a fixed speed during the braking event (25 km/h for the 30 km/h stops and 40 km/h for the 50 km/h stops) we found that, in general, the shortest stopping distances were generated by the full NZHVBC system and the longest stopping distances were generated by the full EBS system. The two mixed brake systems are usually in between. There were some exceptions to this but the differences are small. This method of synchronisation does include the faster response time of the EBS systems and thus understates their performance somewhat. Some conventional methods of determining stopping distance also do not include brake system response time and similarly under-estimate the performance of EBS systems.

Considering the coupling head pressure signals:

- For all load configurations and test speeds, the coupling head pressure rises were similar when the truck was operating with NZHVBC brakes. This is very much as expected.
- For all the 30 km/h tests, the full EBS brake configuration gave very similar results with a significantly more rapid rise in coupling head pressure than the NZHVBC-braked truck. However, it should be noted that when both the truck and the trailer have EBS, the braking process is controlled by the EBS and the control line pressure at the coupling head would only become important if the EBS failed.
- For the tests when the EBS truck was coupled to the NZHVBC trailer, the initial coupling pressure rise was identical to the full EBS system but when the pressure reached approximately 1 bar there was a pause and a slight pressure drop before the pressure again rises rapidly. The duration of this hesitation in pressure rise varies from test to test from being almost imperceptible through to maximum of about 0.2 seconds.
- A similar hesitation in coupling pressure rise occurred for the full EBS configuration during the 50 km/h tests. It is not clear what was causing this effect.

When we look at the brake pressure signal for each of the axles we find that:

- For the front axles of the truck, the initial pressure rise parallels the coupling head pressure rise so that in the cases where there was a hesitation in the coupling pressure rise there was also a hesitation of similar duration in the front axle brake pressure.
- Where the truck was fitted with EBS brakes, once the front axle brake pressure reached its peak there was an immediate reduction in pressure followed by a rise. These oscillations continued with decreasing magnitude. The size of the initial oscillations was quite large, in some cases more than 80% of the original peak. The period of the oscillations was about 0.5 seconds which for the 30km/h stops was a significant proportion of the total braking time.
- For the cases where the truck was operating with NZHVBC brakes, the front axle brake pressures rose in proportion to the coupling head pressures with the peak pressure about 70% of the coupling pressure.
- The truck rear axle brake pressures behaved similarly to the front axles but with some variations in the magnitudes.
- Where the truck was operating with EBS brakes the average rear axle pressure underlying the oscillations was substantially lower when the truck was unladen compared to when it was laden. The period of the oscillations appeared to be slightly greater than that of the front axles. The magnitude of the change was exactly as expected. The EBS system reacts to the axle load and rear truck axles are considerably less loaded when the vehicle is unladen. The difference on the steer axles is much less.
- When the truck was fully laden, for both the front and the rear truck axles, the average brake pressure with EBS was lower than with NZHVBC brakes. This suggests that the EBS algorithm considers the vehicle to be over-braked with NZHVBC brakes for the road surface friction available. However, the large size of the initial brake pressure modulations under EBS and the relatively long cycle time meant that the EBS system had longer stopping distances than the NZHVBC brakes.
- With the trailer brakes the response of the front and rear axles to the change in load was more similar. In both cases, when the EBS system was operating, the unladen trailer axles

had an average brake pressure that was about one quarter of the average pressure when the vehicle was laden. The NZHVBC brake system gives full brake pressure on all axles regardless of load. The brake pressures of the NZHVBC systems were significantly higher (about 75%) than the average brake pressures of the EBS when the vehicle was laden.

- In most, though not all, of the tests the magnitudes of the modulations in brake pressure generated by the EBS system on the front trailer axles were smaller than observed on the truck. The pressure modulations on the rear axle brakes were similar in magnitude to those on the truck. The period of the modulations was also similar to those on the truck brakes.

When a wheel locks-up it ceases to have directional control and only provides a frictional force in the direction it is sliding. If only one axle (or axle group) on a vehicle locks up it will have a tendency to slide towards the front (in the direction of travel). Thus on a 2-axle vehicle if the rear wheels lock up the vehicle will tend to spin while if the front wheels lock up it will tend to hold its line. These principles also apply to combination vehicles but the situation is more complicated. With a truck and trailer combination if the rear axles of the truck lock up, the rear of the truck will tend to slide out sideways and because of the coupling the trailer will follow it. This phenomenon is called "jack-knifing". If the rear axles of the trailer lock-up first the rear of the trailer will slide out to one side. This is called "trailer swing". With a full trailer like the test vehicle there is also a possible instability if the front axles of the trailer lock up first. In this case there is a tendency for the trailer dolly to slide out sideways and the rest of the trailer must necessarily follow. We will call this form of trailer swing "dolly swing". EBS (and ABS) brakes aim to avoid these problems by monitoring the wheel rotation speed during braking and modulating the brake pressure to eliminate wheel lock-up.

Each wheel set on the combination vehicle was marked with a radial stripe of water-based paint. Thus wheel lock-up on any axle group was clearly visible on the video record. One of the video camera operators recorded an end-on view of the vehicle after braking was completed for each test where there was an obvious misalignment of the vehicle units (i.e. where jack-knifing, trailer swing or dolly swing had occurred). These video records were reviewed and assessed in a "semi-blind" manner. The records were identified by test run number and so while the author was aware of the test speed he could not identify the load or brake configuration when making the assessment. Still images were extracted from the video and an example is shown in Figure 5.

The results of this video review are:

- No 30 km/h stopping tests were recorded as having significant misalignment of the vehicle units. For these tests the stopping distances were so short that, presumably, any instability did not have time to develop.
- No tests where both the truck and the trailer were fully laden were recorded as having significant misalignment of the vehicle units. The NZHVBC is designed to ensure brake compatibility in the fully laden state. Hence we would expect the brake systems to be reasonably compatible when the vehicle is fully laden.
- No tests where both the truck and the trailer were operating EBS brakes were recorded as having significant misalignment of the vehicle units. Thus the full EBS system on both vehicle units was effective in ensuring stability during braking under all load configurations.

- With both the truck and the trailer unladen and NZHVBC brakes on both vehicles both the truck and trailer axles locked up. After the stop the rear of the trailer was about 0.5 m out of line with the truck. It was not clear whether this was the result of jack-knife or trailer swing. With NZHVBC brakes on the truck and EBS brakes on the trailer, the truck wheels locked up and some jack-knifing occurred. After the stop the vehicle units were out of line by about 0.3 m. With EBS brakes on the truck and NZHVBC brakes on the trailer, the trailer wheels locked up and trailer swing occurred resulting in a misalignment of about 0.3 m.
- With the truck unladen and the trailer laden and NZHVBC brakes on both units, the truck wheels locked up and there was some jack-knifing with a final offset of approximately 0.3 m. In the case where the truck was operated with NZHVBC brakes and the trailer with EBS brakes there was also some jack-knifing but the final offset was less, while for the case where the truck was operated with EBS brakes and the trailer with NZHVBC brakes there appeared to be a very small amount of trailer swing.
- With the laden truck and empty trailer and NZHVBC brakes on both units, the trailer wheels locked up and there was some trailer swing with a final offset of approximately 0.5 m. In the case where the truck was operated with NZHVBC brakes and the trailer with EBS brakes there appeared to be some jack-knifing with the final offset being about 1 m, while for the case where the truck was operated with EBS brakes and the trailer with NZHVBC brakes there was substantial trailer and dolly swing with the final offset at least 1 m.



Figure 5. Full truck and empty trailer with EBS/NZHVBC brake system from 50 km/h.

4 CONCLUSIONS

The key findings from the tests were:

- Under the test conditions, directional stability was not an issue in any of the 30km/h tests or in any of the 50 km/h tests where both vehicles were fully laden or any tests where both vehicles had the EBS brakes operating.
- There was a loss of directional stability in the 50km/h tests where one or both vehicles were empty and one or both vehicles were operating with the EBS off. In general the directional instability appeared to be associated with the empty vehicle that was operating without EBS.

- The greatest loss of directional stability occurred for the cases where an empty NZHVBC-braked trailer was being towed by a laden truck. The reverse case of an empty NZHVBC-braked truck towing and laden trailer also exhibited some instability but this did not appear to be as severe. For some freight tasks it may be possible to avoid the first situation by distributing the load so that freight is gradually unloaded from both the truck and the trailer.
- Under the test conditions the NZHVBC combination generated higher decelerations and shorter stopping distances than the full EBS. To some extent this is offset by the faster response time of the EBS which reduces the lag between brake pedal actuation and brake application. However, even when the lag is taken into account the NZHVBC brakes achieved a more rapid stop.
- Based on the characteristics of the EBS response it is likely that under different test conditions such as lower road friction or higher speeds the EBS brakes would outperform the NZHVBC brakes with respect to deceleration and stopping distance.
- The stopping distance and deceleration performance of the vehicles with mixed brake systems (i.e. one vehicle with EBS brakes and the other with NZHVBC brakes) was generally between that of the full NZHVBC combination and the full EBS combination.
- Both brake systems comfortably met the deceleration requirements specified in legislation.

The main conclusions therefore are:

- The use of EBS brake systems substantially enhances the directional stability of heavy vehicles under heavy braking although in some circumstances at the expense of a small increase in stopping distance.
- NZHVBC combinations perform well when fully laden but when unladen experience significant wheel lock-up under heavy braking and there is some loss of directional stability.
- Mixing NZHVBC brake systems with EBS brake systems in a combination vehicle results in brake performance in between that of all NZHVBC brakes and all EBS brakes.
- It would appear that allowing combination vehicles with mixed brake systems should have no negative impact on safety. If allowing greater flexibility in mixing brake types in a vehicle combination results in a faster uptake of the new brake technologies then this should have a positive effect on safety.
- In allowing the mixing of the technologies there would be further safety gains by ensuring that NZHVBC vehicles always have some load on them to reduce over-braking.

REFERENCES

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