Further Experience With Anti-Lock Brake Systems

J.R. Billing and C.P. Lam
Ontario Ministry of Transportation, Ontario, Canada

Sesto Vespa
Transportation Development Centre, Québec, Canada

ABSTRACT

This paper describes an in-service evaluation of antilock brake systems fitted on all axles of B-train double tanker vehicles.

The paper also describes some tests to evaluate the braking efficiency of tractor-semitrailer and A-train and B-train double trailer combinations with various load conditions.

INTRODUCTION

Due to its size, weight, and the wide range of possible payloads, the braking performance of a heavy commercial vehicle can vary substantially in its daily operation [1]. Stopping capability of heavy commercial vehicles has been the subject of investigation among transportation regulatory agencies [2,3].

Assuming that the brake system is maintained in good operating condition, how soon a vehicle can stop when the brake is applied depends, to a large extent, on how well its tires can utilize the available friction from the tire-road interface. An empty vehicle does not require much brake pressure to lock wheels while braking, and the ensuing instability associated with wheel lockup for an articulated vehicle under braking is well understood. Once wheel lockup occurs, the tire side-force capability is greatly reduced, and any significant lateral disturbance may initiate instability. If the front wheels lock, steering control is lost and the vehicle will continue straight ahead or plow out of a turn. If the tractor drive axles lock, the articulated vehicle will fold under the influence of the trailing unit resulting in tractor jackknife. Locking the trailer axles may set off trailer swing. None of these phenomena are desirable for normal highway operation.

During the early 1970s, a number of devices were marketed as anti-jackknife devices to control tractor jackknife and/or trailer swing [4] in competition with antilock brake systems (ABS). However, these devices could only react when instability had already been initiated, and they had only a relatively narrow range of effectiveness. Only the antilock brake system could truly eliminate the cause of instability, by preventing wheel lockup [5]. Reliability and maintenance problems of early ABS designs quickly led to the demise of the lockup prevention and stopping distance requirements introduced in FMVSS 121 in the U.S. in 1975, and further development of ABS in North America was brought to a halt. In contrast, advances in digital technology and microprocessors significantly improved the reliability of ABS, and it is now widely applied on commercial vehicles in Europe, where it is now mandatory on new heavy commercial vehicles manufactured for operation in the countries of the European Economic Community [6].

In 1989, the U.S. National Highway Transport Safety Administration (NHTSA) launched a cooperative project with the trucking industry where 200 tractors were each equipped with one of five different antilock brake systems and operated for two years to study the in-service operation and reliability of these systems [7]. There were two important initial steps in this project. First, the study funded the engineering of the ABS installation and second, all tractors were newly-manufactured with their ABS installed in the factory. A second project was launched in 1990 to study the operation and reliability of 50 ABS-equipped trailers, also over a two-year period. The objectives of these studies were to conduct the necessary research to demonstrate the serviceability and reliability of the systems, promoting acceptance of the technology with industry, and paving the way for legislation of ABS on heavy vehicles [3].

To complement the U.S. research, an in-service evaluation of ABS on B-train double tankers was conducted in Canada for a 12-month period [8]. Test programs were also conducted to study the impact of ABS on the braking performance of various vehicle configurations under different loading conditions [9], and to demonstrate the possible modes of instability of an A-train double trailer combination with all possible combinations of axles equipped with an antilock brake system.

The objectives of all these projects were to promote awareness of ABS technology within the trucking industry, to evaluate its in-service operational characteristics, the operating and maintenance cost and safety, and to demonstrate the impact of ABS on the stopping capability of various vehicle configurations under different loading and road surface conditions.

These initiatives have now resulted in NHTSA publishing its final rule to re-introduce ABS into FMVSS 121 for heavy commercial vehicles [3].

IN-SERVICE EVALUATION OF ABS ON B-TRAIN DOUBLE TANKERS

BACKGROUND

The Canadian ABS technology demonstration project was launched in the winter of 1992, to complement the earlier U.S. evaluations. Its objectives were to determine the operational performance characteristics, reliability, durability, and maintainability of ABS systems, installed on complete B-train vehicles and under actual operating conditions, and to evaluate the impact of ABS on operating cost, safety, and maintenance. The project was developed and funded jointly by Transport Canada's Transportation Development Centre (TDC) and Road Safety and Motor Vehicle Regulation Directorate, and the Ontario Ministry of Transportation (MTO), in cooperation with Shell Canada and Canadian Liquid Air. These companies were developing their own evaluations of ABS at that time, and agreed to share their data by joining the government agencies in the project. A parallel project in the same time period, also sponsored by TDC, evaluated the ABS installation on a log-haul B-train as a by-product of an evaluation of its traction control system [10].

The B-train double tanker as operated by both partners was particularly suited for this evaluation. Each vehicle operated from a fixed base, with each tractor coupled to the same set of trailers. This married pair operation facilitated testing and evaluation as it permitted the use of a smaller fleet of trailers, reduced potential equipment problems due to handling, and reduced variation in vehicle characteristics. If controlled properly, it can provide a valid and direct comparison with similar vehicle units. From the operational point of view, a permanent pair of B-trains eliminated the problem of disparate electrical connectors between tractor and trailers. Finally, the operators were very knowledgeable, had good operating procedures, maintenance and record keeping practices, and were prepared to make their records available for the project.

VEHICLE CONFIGURATION

Shell Canada provided a fleet of six matched pairs of B-train double tankers that deliver fuel to retail outlets from four different bases in Ontario and Quebec. The vehicles were all 8-axle B-trains, similar to that shown in Figure 1, operating at allowable gross weights of 63,500 kg (140,000 lb) for the Ontario vehicles and 59,000 kg (130,000 lb) for the Quebec vehicles. Each trailer has a capacity of roughly 30,000 litres, in four separate compartments that are progressively unloaded at a series of stops during one trip. This results in a diminishing load, with some axles being quite lightly loaded, and others more heavily loaded, at different times during the trip. A wide range of loading conditions can present a challenge to a conventional brake system, and it has been shown that some partial load situations can result in low braking efficiency [1] and increased probability of vehicle instability if a need for a hard brake application arises. The vehicles operate at high speed on highways, but often deliver in urban areas where high numbers of brake applications tends to increase the probability of a hard brake application. Shell Canada elected to provide new Kenworth tractors for the project, equipped with Bosch ABS installed at the factory, and to retro-fit ABS to existing trailer sets. One of each pair of vehicles was equipped with ABS, and the other was left without ABS, as a reference. The tractors were delivered between May and July of 1990 with factory-installed ABS in a 4S/4K configuration, where S stands for a wheel speed sensor and K stands for a brake pressure modulation channel. Speed sensors were installed on both front wheels, and the trailing axle of the drive tandem. The front wheels had individual brake pressure modulation, whereas the drive tandem axles had brake pressure modulation as a pair on each side. The trailer sets were built between 1982 and 1990, and six sets were retro-fitted with ABS between September 1990 and February 1991. The lead trailer used a 6S/4K ABS configuration, with speed sensors installed on each wheel, but with the first two axles controlled as a pair on each side by one brake pressure modulation valve, and the third axle controlled by individual pressure modulation for each wheel. The pup trailer used a 4S/2K ABS configuration for the tandem axle, with the four wheel speeds individually monitored but brake pressure modulation controlled as a pair on each side. Because of the married pair operation, it was not a concern to add a separate fully-powered ABS electrical circuit, using ISO connectors between the tractor and lead trailer and between the two trailers.

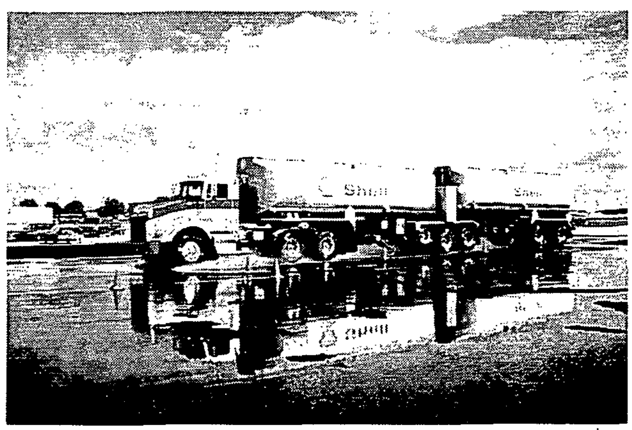

Figure 1. Shell Canada B-train.

Canadian Liquid Air operates a fleet of ABS-equipped 8-axle B-trains hauling liquified nitrogen between its plant in Midale and oil extraction operations in Medicine Hat, Saskatchewan on a continuous, 24-hour-a-day operation, of mostly highway travel that accumulated about 300,000 km per year on each vehicle. The company agreed to provide maintenance information on its fleets to supplement Shell's data.

Canadian Liquid Air selected Freightliner tractors, built between September 1991 and March 1992 with factory-installed Wabco ABS/ATC in a 4S/4M configuration (M stands for a brake pressure modulation channel). The trailers were rebuilt using retro-fitted Wabco ABS in a 6S/3M configuration for the lead trailer and a 4S/2M configuration for the pup trailer.

ABS MONITORING

An electronic data logging system was developed and installed by the Vehicle Monitor Corporation (VMC) of Redmond, WA, U.S.A. to monitor and record real-time operation of each of the ABS-equipped Shell Canada B-trains. This was essentially the same system that was used in the NHTSA study [7]. It consisted of monitoring and data recording equipment installed on the vehicles, a data retrieval system installed at the base from which the vehicles were operated, and data analysis software which allowed analysis of individual events as well as production of summaries of all recorded data.

The on-board monitoring equipment included one data logger for the tractor and another for both trailers. Each data logger could take inputs from six wheel speed sensors, six brake chamber and one treadle valve pressure transducers, six electrical current detectors that detect ABS solenoid circuit activity, one longitudinal accelerometer, one warning light status, and one ignition monitor. The tractor logger monitored the tractor system. The trailer logger monitored both trailers, except for the first (liftable) axle on the lead trailer and the rear axle on the pup trailer.

Continuous data recording was clearly not possible, so the system recorded data only when there was a brake application. The two data loggers were linked to capture data simultaneously when an antilock event was detected, and data from both loggers could be down-loaded from one port on the tractor.

DATA ANALYSIS AND RESULTS

A brake application was deemed to occur whenever the on-board monitoring system detected brake pressure at the treadle valve of the braking system. This could give rise to an ABS event, and these were categorized in terms of severity. A minor ABS event was a brake application that caused Electronic Control Unit (ECU) to activate the "hold" function of the pressure modulating valve with no subsequent ABS activity.

A significant ABS event was a brake application that caused at least one wheel to experience more than 20% wheel slip, so that the ECU activated pressure modulation and the wheel slip was reduced to less than 5%. A major ABS event was a significant ABS event during which four or more solenoid activations were recorded successively on any wheel. These were further divided by vehicle initial speed, below 40 km/h, between 40 and 75 km/h and above 75 km/h, to give three ranges as a measure of severity.

Table 1 summarizes the data retrieved from the on-board ABS monitoring system for the tractors and each trailer separately.

Over the 12-month monitoring period, the tractors logged a total of 10,677 hours of operation, and their antilock brake systems were operational, as indicated by warning light status, for 10,394 hours, resulting in 97.3% system availability. The tractors travelled 328,959 km during which 358,013 brake applications were recorded – an average of 1.09 brake applications per kilometre of travel. Some 29,694 ABS events were recorded, of which 49 were regarded as major and 10 of these occurred at an initial speed over 75 km/h.

Table 1. Summary of operational data.

	Tractor	Lead Trailer	Pup Trailer
Operation (h)	10,677	9,842	9,842
Mileage (km)	328,959	282,042	282,042
Brake Applications	358,013	204,796	204,796
ABS Warning Light on (h)	283	4,631	4,631
ABS Warning Light off (h)	10,394	5,211	5,211
Total ABS Rvents	29,694	24,095	24,095
Significant ABS Events	1,642	497	3,215
Major ABS Events	49	40	148
MajorABS Events < 40 km/h	28	23	37
Major ABS Events 40-75 km/h	11	16	80
Major ABS Events > 75 km/h	10	1	31

For the trailers, the antilock brake system was only operational for 5,211 hours of the total 9,842 hours of operation, giving 52.9% availability. Note that there was only one warning light for the systems on both trailers, so these data may significantly underestimate the actual trailer system availability. The total distance travelled was 282,042 km and there were 204,796 brake applications resulting in an average of 0.73 brake applications per kilometre of travel. A total of 24,095 ABS events were recorded of which 40 and 148 were regarded as major ABS events for the lead and pup trailers respectively. The number of major ABS events that occurred at vehicle speed above 75 km/h were 1 and 31 for the lead and pup trailers respectively.

The lower system unavailability on the trailers was mostly traced to problems with wheel speed sensor adjustments. Since ABS simply reverts to conventional braking in a fail-safe manner when it detects a system malfunction, the problem was left unattended for long stretches of time before maintenance work was done to correct the problem. The monitoring system data also revealed that the lead trailers, which had 50% more speed sensors than the pup trailer, were responsible for more ABS downtime than the pup trailers.

Table 2 summarizes the data from Table 1 by normalizing to 10,000 km and 1,000 hours of operation. Overall, for each 10,000 km of vehicle operation, a total of 1,971 ABS events would occur, of which 9.4 would be major ABS events. By projecting this operational statistic to a vehicle operating a total of 100,000 km per year, the driver would expect to experience approximately 100 major

ABS events, and 20 of those would occur at a speed higher than 75 km/h. The frequency of major ABS events on the pup trailer was 3 to 4 times higher than that of the tractor or the lead trailer. This is a reasonable outcome of the operation which results in the pup trailer being unloaded before the lead trailer.

Table 2. Summary of ABS operation statistics.

Frequency of ABS events	Tractor	Lead Trailer	Pup Trailer	Total
per 10,000 km				
ABS events	903	577	491	1971
Significant events	50	24	131	205
Major events	1.5	1.9	6.0	9.4
per 1000 hr				
ABS events	2775	1660	1414	5849
Significant events	153	68	377	598
Major events	4.6	5.5	17.4	27.5

SYSTEM RELIABILITY

ABS on the tractor was found to have a relatively high availability of 97.3%, while the trailer ABS availability was only 52.9%. However, there was only one warning light for both trailer systems, so the light would be on if only one of the two systems was in warning status. The actual availability of each trailer system would be expected to be higher than 52.9%. The long downtime of ABS on the trailers was due mainly to speed sensors going out of adjustment, without effort at re-adjustment. No ABS hardware component was reported defective during this evaluation period. The present antilock brake system, with the exception of the wheel speed measuring component, demonstrated a high degree of reliability.

SYSTEM MAINTENANCE

As with any other vehicle system equipment, proper maintenance is required to ensure system availability and proper operation. The internal self-test feature of the ABS reports system component failures by storing a special code sequence within the system's ECU and activates a "warning light" placed inside the tractor cab. In this regard, ABS requires minimum effort for troubleshooting. The most frequent maintenance work recorded during the evaluation period that was directly related to ABS was speed sensor adjustments on the trailers followed by replacement of warning light bulbs. Most of the other ABS-related repairs, such as cut wires or inadequate cable routing, were the result of damage due to unrelated maintenance work, or arose from the retro-fit nature of the trailer installation. No problems were experienced with the separate ABS electrical circuit or its connectors, which were mated at all times when the vehicle was driven [10].

A final inspection by the ABS manufacturer at the end of the evaluation indicated that only one pressure modulating valve required replacement from the fleet of four available vehicles at that time. Indeed, the ABS components, with the exception of the speed sensor installation, proved to be remarkably durable and maintenance free.

ABS PERCEPTION BY DRIVERS/OPERATORS

All drivers involved in the project were given an opportunity to familiarize themselves with the capabilities of ABS by driving the prototype installation on the wet low-friction test area at MTO's Commercial Vehicle Test Facility. This initial step gave them confidence in the system and allayed any fears they may have had. Feedback from drivers of ABS-equipped vehicles at the end of the project was generally positive. The drivers developed a high degree of confidence in the performance and reliability of the ABS. They noticed the improved control provided by ABS under hard braking on a slippery road, especially with a partially loaded pup trailer, and they believed that ABS would help them in panic situations. They stated that their driving habits had not been changed by the presence of ABS, and that their attention to the response of the trailers during brake applications had not been reduced.

Most of the operators believed that successful introduction of ABS required an appropriate training program for the operators, drivers, and maintenance staff to become familiar with the technology. ABS service support should be readily available from the ABS supplier. The lack of a service facility would discourage ABS users to properly maintain their systems because of the fail-safe feature that allows the brake system to revert to normal braking. The availability of ABS would eliminate tire flat-spotting and some of the braking system components such as pressure limiting or proportioning valves. None of the operators believed that the additional costs associated with ABS could offset their benefits, provided that the systems were factory installed and that a support facility was readily available. In general, the operators were satisfied with the performance of ABS and would recommend ABS on all new vehicles purchased.

ABS IMPACT ON VEHICLE OPERATION

Tire Wear Tire tread depth measurements were only available from the ABS-equipped and reference tractors. The total tire tread wear rates showed a substantial variation and dispersion within both groups, and there was not a statistically significant difference between the ABS and reference tractor tire tread wear rates. Since the sole function of ABS is to prevent wheel lockup, it would be expected to eliminate tire flat-spotting during severe braking and avoid tire replacement due to premature failure. Due to the infrequent occurrence of emergency braking and the insufficient evaluation time, statistical data were not able to substantiate any savings that could be made by ABS over a conventional brake system.

Brake Wear and Maintenance Brake wear and brake system repairs were determined from the mechanic's maintenance inspection records and the repair invoices sent to the fleet operator from maintenance contractors. At the end of the data collection phase, most of the tractors had logged approximately 250,000 km, and not one, ABS-equipped or reference, required a major braking system repair or replacement part. Some trailers reached that point in their maintenance cycle where they required major braking system maintenance or replacement of parts, but no conclusion could be drawn because the initial condition of the brake system could not be determined. Intermediate measurements of remaining brake lining thickness, recorded by mechanics during periodic maintenance proved to be unreliable. Consequently, no significant difference in brake wear or brake system maintenance between the ABS-equipped and reference vehicles could be established.

Safety Record The duration of the monitoring program simply did not provide enough time to evaluate the safety record of these vehicles because emergency braking for these vehicles were few and far between.

ABS COST IMPACT

Initial Capital Cost In 1992, the cost to equip a tractor with a complete OEM 4S/4K system was approximately $2,000, and the cost to retro-fit ABS on a pair of trailers with 6S/4K and 4S/2K systems was approximately $10,000 (roughly $6,000 for parts and $4,000 for labour). It was estimated that the cost for an OEM-installed system for the trailers would be less, possibly in the $7,000 to $8,000 range. With a 1992 purchase price of $235,000 for a new B-train double tanker with conventional brake system, $10,000 for a complete OEM-installed ABS adds roughly 4% to the purchase price. The current cost of a full B-train ABS installation is now reduced to $3000 to $4000, which reduces the total cost to under 2%.

System Maintenance Cost The individual ABS hardware components proved to be quite reliable and relatively problem free, except for the speed sensors. The self-diagnostic capability of the system detects component failure when the system is first activated, so there is minimal effort necessary for troubleshooting and very little additional cost to regular maintenance. There were relatively few component failures reported in the course of this evaluation period. Repair work related to the ABS equipment, such as cut wires and damaged connecting cables, were all attributed either to equipment handling or damage as a result of other maintenance work, such as for braking and suspension systems. The occurrence of this damage and its associated repair costs will diminish when the drivers and maintenance staff become more familiar with the system. A part of it could also be attributed to the retro-fit installation on the trailer, where wires could be perhaps less well protected than in an OEM factory installation. The only other item reported was the occasional replacement of a burnt-out warning light bulb. The most significant system maintenance cost arose from the wheel speed sensors which required frequent adjustment. This maintenance cost should be greatly reduced when the speed sensors are designed into the axle assembly as an OEM product. In the interim, simple adjustment tools and procedures can reduce the actual maintenance burden [10]. Based on the data collected from this project, the maintenance and repair costs associated with ABS, with the exception of the speed sensor adjustment problem, were estimated at less than 10% of the brake system maintenance cost.

Vehicle Maintenance Cost Due to the inconsistency of collected data and the duration of the monitoring period, no cost savings could be substantiated statistically for either tire wear or brake wear, even though there is a likely saving by avoiding some premature tire replacements due to tire flat-spotting. Similarly, because of insufficient evaluation time, no operating savings could be substantiated related from the safety record where the improved stopping capability and vehicle control from ABS would result in fewer and less severe accidents that could be translated into operating savings in terms of reduced vehicle downtime and insurance premiums.

Overall Cost Impact Table 3 summarizes the impact of ABS on the average B-train double tanker operating costs. Based on an average hourly operating cost of Cdn $62.80, the addition of ABS to a complete B-train unit will increase the average operating cost by approximately $0.46 per hour, or 0.73% of the average operating cost.

Table 3. Average operating cost of a B-train double tanker ($/h).

Cost Elements	Non ABS $	Impact of ABS %	Impact of ABS $	With ABS $	Notes
Maintenance	7.63			$7.69	
Tires	$1.11				Marginal savings
Brakes	$0.63	10%	$0.06		10% due to ABS
Equipment	$9.80			$9.80	Not affected operation
Driver wage/	$34.39			$34.39	Not affected benefit
Others	$0.83			$0.83	Minor insurance saving
Capital investment	$10.15	4%	$0.40	$10.55	4% higher purchase price
Total	$62.80	0.73%	$0.46	$63.26	0.73% higher total cost

OTHER FLEET EXPERIENCE

The maintenance information on Canadian Liquid Air's fleet of four ABS-equipped vehicles, and two similar reference vehicles, indicated that there was a faulty installation on one tractor that required correction after it was put into service, and all ECU's were replaced. Beyond these, no maintenance problems were experienced with the ABS. Wheel speed sensor adjustment was not a problem even though drivers were instructed not to depart on a trip without diagnosing and fixing any ABS warning light instances. Maintenance records also did not reveal any difference in tire or brake wear between ABS and reference vehicles. Although the Canadian Liquid Air and Shell Canada operations were rather different, the maintenance experience was rather similar, except for the wheel speed sensor issue.

CONCLUSIONS

The in-service evaluation demonstrated that current ABS are remarkably reliable, durable, and maintenance-free except with the wheel speed sensor adjustments. Both the operators and drivers were satisfied with the performance of ABS and developed confidence in the improvements they provided under adverse situations. The addition of ABS as an extra option on a complete B-train would increase the average operation cost by less than 1%.

BRAKING EFFICIENCY

BACKGROUND

Braking efficiency is defined here as the ratio of the maximum deceleration attained by a vehicle without exhibiting instability to the peak friction coefficient of the tire-road interface. It is a measure of how effectively the vehicle braking system utilizes the available friction to bring the vehicle from the point of braking to a complete stop. It has been developed as an objective measure of vehicle dynamic performance that could be related to highway safety [11]. Previous study identified that combination vehicles in partial load situations can have a low braking efficiency [1]. This means an increased stopping distance if wheels are not to be locked, or locked wheels and the possibility of tractor jackknife or trailer swing if a more severe brake application is demanded in an attempt at a shorter stopping distance.

A series of full-scale field tests was conducted to study the effect of payload distribution on the braking performance of three vehicle combinations. Straight-line stops were made with a 5-axle tractor semitrailer, an 8-axle A-train, and a 7-axle B-train, with and without ABS, and on both high- and low-friction surfaces.

TEST EQUIPMENT AND PROCEDURES

Test Vehicles All three vehicles were drawn by a 1975 6x4 Freightliner tractor with a 4.42 m (174 in) wheelbase and a 1.84 m (72 in) spread tandem drive axle.

Figure 2 shows the 5-axle tractor-semitrailer. The flatbed "trombone" trailer was stretched to its maximum length of 9.60 m (31.5 ft), and its tandem axle had a 1.22 m (48 in) axle spread. Tests were conducted with the vehicle empty, and loaded in all three possible combinations with concrete blocks placed directly above the tractor drive axles and the trailer axles, as shown in Figure 3. The axle loads represent a partially loaded condition. No attempt was made to load any axle to its maximum legal load capacity. The intention simply was to ensure sufficient difference in axle weight between unloaded and loaded axles that it was possible to select a brake pressure that all unloaded wheels would lock, and no loaded wheels would lock.

Figure 4 shows the 8-axle A-train. It consisted of the same tractor-semitrailer as above, and a second full-trailer made up of a single axle A-dolly and a tandem axle flatbed semitrailer which was 7.41 m (24.25 ft) long with a 5.36 m wheelbase and a 1.52 m spacing between its first liftable axle and second fixed axle. Tests were conducted with the vehicle empty, and loaded progressively from the

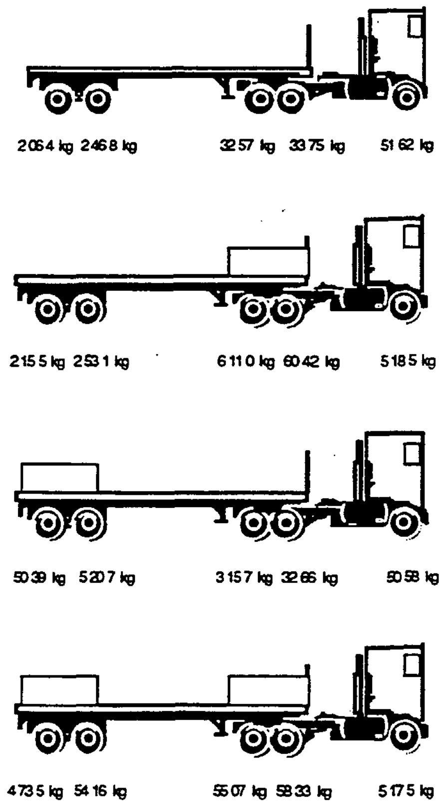

Figure 3. Load distribution and axle loads of the 5-axle tractor-semitrailer.

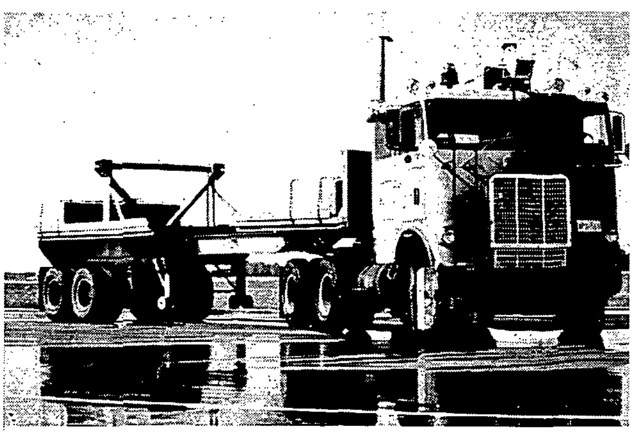

Figure 2. Tractor-semitrailer.

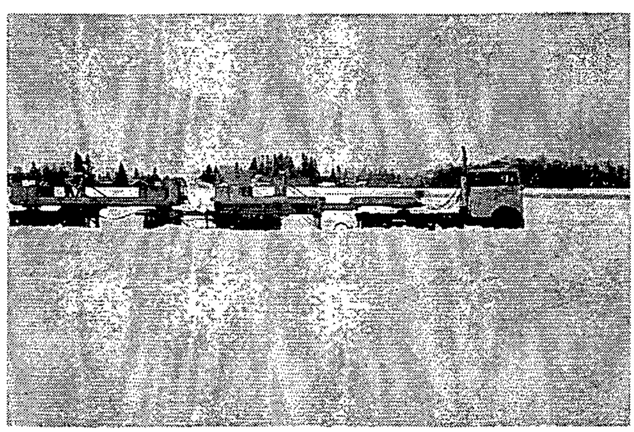

Figure 4. A-train.

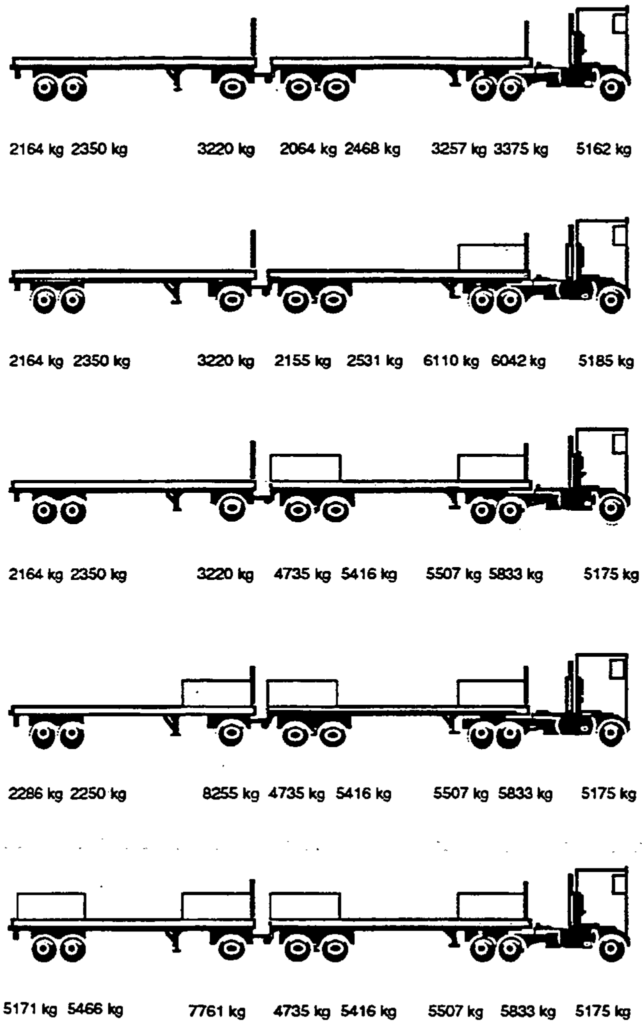

Figure 5. Load distribution and axle loads of the 8-axle A-train.

tractor drive axles to the pup trailer axles in four different configurations with concrete blocks placed directly above the axles as shown in Figure 5.

The 7-axle B-train was comprised of the same vehicle units as the A-train, except for the A-dolly. This was done by switching the pup trailer of the A-train into the lead position, removing detachable portion of deck at the rear of the trailer, and coupling the "trombone" trailer to a fifth wheel mounted on the rear of the trailer under the detachable deck. Figure 6 shows the 7-axle B-train. Tests were conducted with the vehicle empty, and loaded in three of the seven remaining possible combinations with concrete blocks placed directly above the axles, as shown in Figure 7.

Vehicle Preparation The entire vehicle configured as an A-train was sent to a certified commercial vehicle service outlet for brake relining and brake adjustment. A standard brake burnish procedure was carried out on the vehicle to break-in the new brakes before testing.

A pneumatic circuit with a solenoid valve and an adjustable pressure regulator was installed to bypass the treadle valve and facilitate control of air pressure delivered to the brake system. This regulated brake pressure was activated by the driver with a switch located inside the cab.

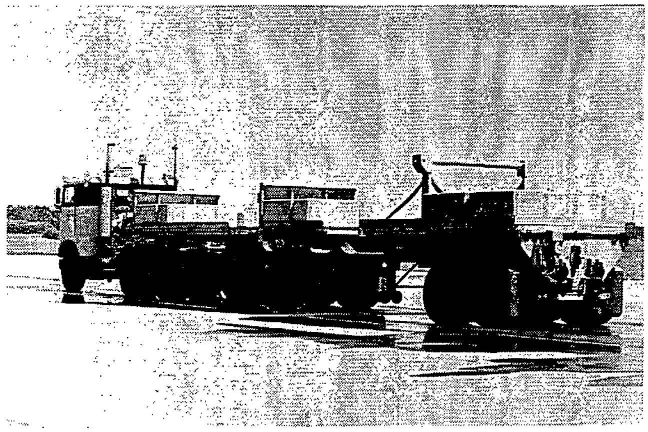

Figure 6. B-train.

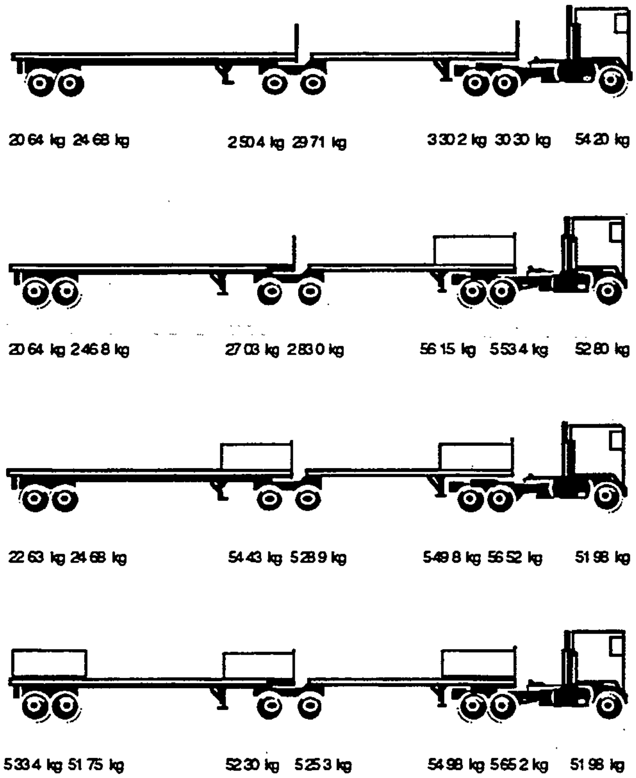

Figure 7. Load distribution and axle loads of the 7-axle B-train.

When the brake switch was in the off position, the vehicle reverted to standard braking by means of the treadle valve.

Bosch ABS was installed by an authorized service outlet on all axles of the tractor, the "trombone" trailer, the A-dolly, and the pup trailer. Each vehicle unit had its own ECU, except the dolly, which was controlled from the ECU on the lead trailer. Each wheel was monitored individually by a speed sensor assembly and had its own brake modulation valve, so the tractor had a 6S/6K ABS configuration. The trailers were both 4S/4K and the A-dolly was 2S/2K. Toggle switches inside the driver's cab could be used to activate ABS or de-activate ABS on each vehicle unit separately, including the A-dolly. It was necessary to re-initialize the system after each change of status.

Instrumentation, Data Capture, and Data Processing The vehicle was equipped with a comprehensive suite of instrumentation to measure both gross vehicle responses and internal brake system parameters. The tractor was equipped with an accelerometer to measure the deceleration of the vehicle in the longitudinal direction. A Humphrey gyro package inside the cab was used to monitor the tractor yaw and pitch responses. Tractor left front wheel steer angle was monitored by a rotary potentiometer. A Nucleus trailing fifth wheel, mounted behind the tractor, was used to monitor the speed and distance travelled. Pressure transducers were installed to monitor brake pressure at the treadle valve and at a number of other wheels on both the tractor and trailers. Thermocouples were installed to monitor the temperature of the brake pads on the left side of the tractor axles, the "trombone" trailer axles, and the lead axle of the pup trailer. The last axle of the "trombone" trailer was strain gauged to measure the vertical and longitudinal force at each wheel. Wheel speed sensors were also installed on the right hand side of the tractor front axle, on both sides of the strain gauged axle and on the pup trailer axles. These data were conditioned and digitized on board the vehicle, and sent by a PCM radio telemetry system to a ground station where they were captured by computer, screened and processed between each test run. This allowed test staff to determine whether the objective of a particular test run had been achieved, and decide whether it should be repeated or the test should move to another condition.

Test Site The entire test program was conducted by MTO staff at its Commercial Vehicle Test Facility at Huron Park in Centralia. It is a former airfield runway re-paved for heavy vehicle testing that includes both high- and low-friction surfaces. The high-friction surface is 150 m long and 50 m wide, with a smooth approach and a typical wet skid number of 66. The low-friction surface is 200 m long, with a sprinkler system to wet the surface and generate a skid number in the 18-24 range.

Peak and sliding friction coefficients for these surfaces were derived by slowly applying the brakes to the trombone trailer until the wheels locked, and examining the loads measured from the axle instrumentation. A number of runs were made at governed speeds from 25 km/h to 62 km/h. Results of the trailer brake test runs indicated that the friction coefficient at the tire-road interface varies with vehicle speed as well as the rate of brake torque application. Generally speaking, the peak coefficient of friction increases as the speed is decreased. On the low-friction surface, the highest peak coefficient of friction measured ranged from 0.55 to 0.6 while that on the high-friction surface was around 0.8.

Straight Line Braking Manoeuvre The driver brought the vehicle to a speed of 62 km/h and entered the test section in a straight line with the speed held constant. When the vehicle reached the test pad, the driver applied the brake and held the steering straight until the vehicle came to a stop. With ABS off, the brake pressure was initially set at a low enough value for each test condition so that no wheels locked. It was increased gradually for each subsequent test run until wheel lockup started to occur. The objective was to determine the highest brake pressure that consistently caused no more than one wheel to lock on any axle or no more than two wheels to lock on any tandem axle. When ABS was activated, full brake pressure was applied in all test runs. In order to minimize the effect of brake temperature on the braking performance of the vehicle, brakes were initially warmed to 80°C before a test, and were allowed to cool below 100°C before the next run.

Parametric Studies The test program examined the effect of all combinations of payload distribution, brake system (conventional or ABS), and road friction (high or low) on the stopping performance of the three vehicle combinations.

TEST RESULTS

Tractor Semitrailer Tables 4 and 5 show the stopping distance and braking efficiency for the 5-axle tractor-semitrailer on the low- and high-friction surface respectively. These data are summarized in Figure 8.

Table 4. Tractor-semitrailer braking on low-friction surface

	Stopping distance (m)		Braking efficiency (%)	
	ABS inactive	ABS active	ABS inactive	ABS active
Empty	93.5	59.6	46	74
Load case 1	113.5	60.7	39	87
Load case 2	75.8	59.0	61	95
Load case 3	82.6	62.3	53	93

Table 5. Tractor-semitrailer braking on high-friction surface

	Stopping distance (m)		Braking efficiency (%)	
	ABS inactive	ABS active	ABS inactive	ABS active
Empty	35.6	27.8	75	92
Load case 1	43.8	30.5	59	85
Load case 2	32.2	29.8	79	91
Load case 3	33.7	31.0	74	84

On the low-friction surface with conventional braking, the "controlled" stopping distance of the tractor-semitrailers ranged from 75.8 m to 113.5 m, a 50% spread among the four load cases, and braking efficiency ranged from 39% to 61%. On the high-friction surface, the stopping distance of the tractor-semitrailers ranged from 32.2 m for to 43.8 m, a spread of 36%, and the braking efficiency ranged from 59% to 79%.

When ABS was activated, the stopping distance was generally much shorter than that without ABS. On the low-friction surface it ranged from 59 m to 62.3 m, a spread of under 6%, and the braking efficiency improved to between 74% and 95%. Although the improvement in stopping distance was not as dramatic as that on the low-friction surface, the stopping distance on the high-friction surface with ABS active was still much shorter than that without ABS, from 27.8 m to 31.0 m, a spread of 12%, and the braking efficiency was improved to between 84% and 92%.

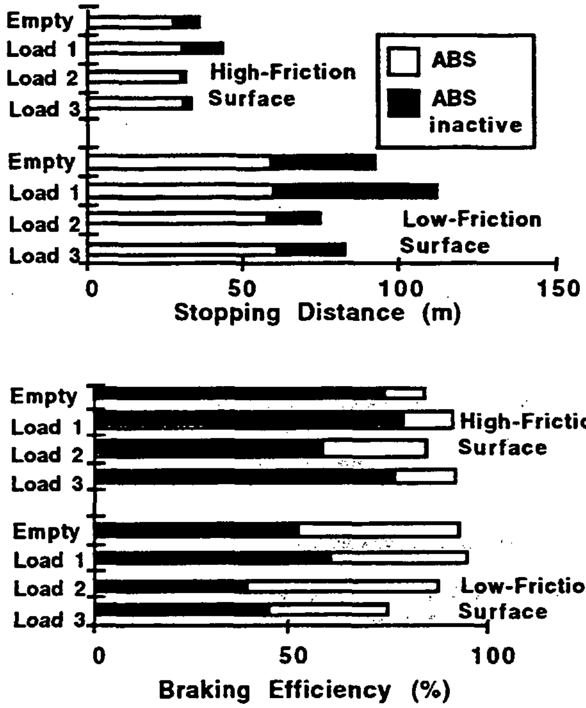

Figure 8. Tractor-semitrailer stopping performance.

It should be noted clearly that this test compares the stopping distance and braking efficiency of the tractor-semitrailer using the full capability of ABS with the same vehicle using a conventional brake system to stop without severe wheel lockup. It is quite possible that the vehicle in the latter case could be stopped in a shorter distance without such a stringent limitation and still stay within a standard 3.75 m (12 ft) lane width. This is not the point. The point is, that once wheels start locking, there is potential for loss of control, and that can result either in trailer swing or tractor jackknife, both potentially very serious instabilities. This potential increases with vehicle speed.

A-train Tables 6 and 7 show similar results for the 8-axle A-train, summarized in Figure 9.

On the low-friction surface with conventional braking, the stopping distance of the A-trains ranged from 76.4 m to 116.2 m for a spread of 52% among the five load cases, and braking efficiency ranged from 28% to 51%. On the high-friction surface, the stopping distance ranged from 37.3 m to 63.8 m for a spread of almost 71%, while the braking efficiency ranged from 38% to 69%.

When ABS was activated, the stopping distances on both surfaces were substantially reduced for each load case. On the low-friction surface, the stopping distance ranged from 55.9 m to 64.3 m for a spread of 15%, and braking efficiency ranged from 84% to 95%. On the high-friction surface, the stopping distance ranged from 30.3 m to 32.7 m for a spread of only 8%, and braking efficiency was improved to between 83% and 87%. Again, the stopping distance with ABS was rather insensitive to loading variation.

Table 6. A-train braking on low-friction surface.

	Stopping distance (m)		Braking efficiency (%)	
	ABS inactive	ABS active	ABS inactive	ABS active
Empty	88.6	3.2	51	84
Load case 1	107.1	64.3	39	88
Load case 2	104.8	61.8	37	86
Load case 3	116.2	56.6	28	92
Load case 4	76.4	55.9	46	95

Table 7. A-train braking on high-friction surface.

	Stopping distance (m)		Braking efficiency (%)	
	ABS inactive	ABS active	ABS active	ABS active
Empty	42.0	30.5	64	87
Load case 1	52.2	30.3	49	87
Load case 2	59.5	31.5	43	83
Load case 3	63.8	31.6	38	83
Load case 4	37.3	32.7	69	83

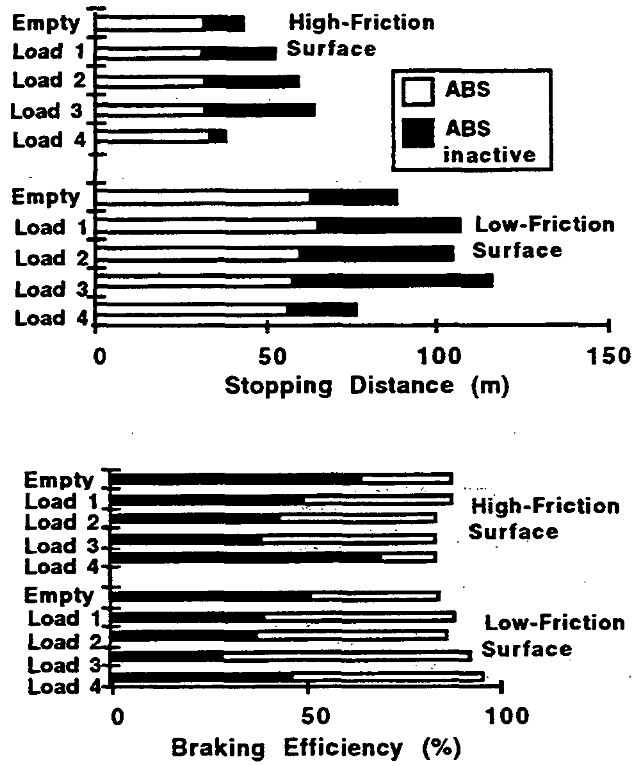

Figure 9. A-train stopping performance.

B-train Tables 8 and 9 show the results for the 7-axle B-train, summarized in Figure 10.

On the low-friction surface with conventional braking, the stopping distance ranged from 91.9 m to 121.0 m for a spread of 32% among the four loading cases, and braking efficiency ranged from 37% to 50%. On the high-friction surface, the stopping distance ranged from 34.2 m to 43.4 m for a spread of 27% among the four load cases, and braking efficiency ranged from 58% to 77%.

Table 8. B-train braking on low-friction surface.

	Stopping distance (m)		Braking efficiency (%)	
	ABS inactive	ABS active	ABS active	ABS active
Empty	91.9	70.7	50	87
Load case 1	121.0	71.8	45	87
Load case 2	112.0	70.5	37	93
Load case 3	97.1	67.4	47	95

Table 9. B-train braking on high-friction surface.

	Stopping distance (m)		Braking efficiency (%)	
	ABS inactive	ABS active	ABS inactive	ABS active
Empty	35.2	29.4	77	89
Load case 1	41.8	30.0	62	87
Load case 2	43.4	30.9	58	80
Load case 3	34.2	31.8	76	83

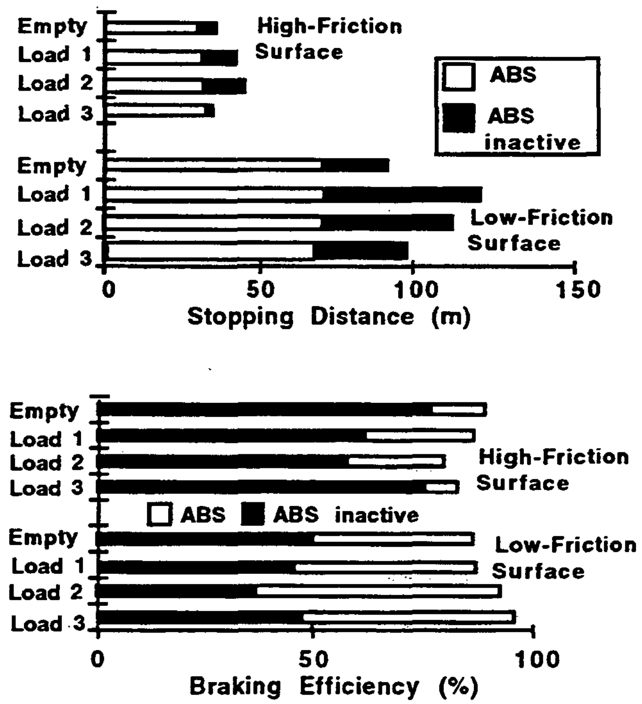

Figure 10. B-train stopping perfromance.

When ABS was activated, the stopping distance ranged from 67.4 m to 71.8 m for a spread of 7%, and braking efficiency improved to between 87% and 95%. On the high-friction surface, the stopping distance ranged from 29.4 m to 31.8 m for a spread of 8%, and braking efficiency ranged between 80% and 89%.

CONCLUSIONS

It was observed that, on a particular surface, the stopping distance with ABS for any load distribution of a particular vehicle was always shorter than the shortest with conventional braking. It was also noticed that, on a given surface, the stopping distance with ABS was rather unaffected by payload distribution. This, combined with the high levels of braking efficiency achieved with ABS, clearly demonstrates that individual wheel control can come close to optimum utilization of road surface friction.

CONCLUSIONS

An in-service evaluation of an antilock brake system fitted to all units of a fleet of B-train double tankers has been conducted. The vehicles were instrumented and the performance of the braking system and the ABS was monitored for a 12-month evaluation period. The availability rate of the antilock brake system on the tractor was 97.3%, while it was only 52.9% on the trailers. Most of the downtime on the trailers was due to wheel speed sensors getting out of adjustment, with this condition being neglected often for long stretches of time. Projecting the operational statistics obtained from this in-service evaluation, a vehicle operating for a total of 100,000 km per year in a similar highway/urban operation would expect to experience roughly 100 major ABS events, and 20 of these would occur at speeds higher than 75 km/h. There was no report of major ABS component repair or replacement that could be attributed to system wear and tear or due to a defective hardware component, and the system hardware demonstrated a remarkably high level of reliability, durability, and maintainability. Apart from the need for frequent speed sensor adjustments on the trailers, and some warning light bulb replacements, the system was almost maintenance-free. Without taking into account the possible savings due to tire and brake wear or safety record, which could not be substantiated due to insufficient monitoring time and quality control of measurement, the addition of a complete ABS as an OEM option on a B-train would increase the average operating cost by no more than $0.46 per hour or 0.73%. The drivers indicated that they developed a high degree of confidence in the performance and reliability of the ABS system and that they noticed the improved vehicle control provided by ABS on a slippery surface, particularly when the pup trailer was partially loaded.

A series of tests were conducted to evaluate the stopping distance and braking efficiency of tractor-semitrailer, A-train, and B-train combinations on high-friction and low-friction surfaces, with and without ABS. The tests without ABS were conducted only up to the point where no more than one wheel per axle, or two wheels per tandem axle, were locking. This is the maximum level of braking that can conservatively assure that the vehicle will stop without loss of control, though more aggressive stops could still be successful. On a given surface, the stopping distance without ABS varied substantially within each vehicle type depending upon the payload distribution. As a result, so did the braking efficiency, from 28% to 79%, depending on the vehicle, payload distribution, and surface. When ABS was active on all axles of the vehicle, the stopping distance was quite consistent for all three vehicles and 8% to 51% less than without ABS, depending upon the vehicle, load, and surface, and the braking efficiency ranged from 74% to 95%. For these tests, the ABS was configured for individual wheel control and the results show that any of these vehicles was able to come close to optimum utilization of roadway friction for any load or road condition. Of course, other ABS configurations might not produce this high level of performance. It is clear from this demonstration test series that ABS provides a significant improvement in both stopping capability and stopping consistency, and can significantly reduce the likelihood of instability while braking.

The evaluation shows that an ABS can operate successfully in-service on a B-train. The system does require maintenance, primarily to maintain speed sensor adjustment, but beyond that it is remarkably reliable. A series of tests shows that ABS improves substantially the braking efficiency of combination vehicles under a wide variation of payload distribution and road surface conditions, and shows the benefit of using ABS on all axles.

REFERENCES

[1] Parker D.J. and Hutchinson B.G., "Large Truck Braking at Signalized Intersections," Report TDS-88-01, Research and Development Branch, Ontario Ministry of Transportation, December 1988.

[2] 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," Interim Report DOT HS 806 739, NHTSA, April 1985.

[3] Federal Register, Friday March 10, 1995.

[4] Snelgrove F.B., Billing A.M. and Choi C., "Performance Evaluation of Several Jackknife Control Devices," Systems Research and Development Branch Report CVOS-TR-80-03, Ontaio Ministry of Transportation and Communications, June 1980.

[5] Leasure W.A. and Williams S.F. Jr., "Antilock Systems for Air-Braked Vehicles," Society of Automotive Engineers, 35th L. Ray Buckendale Lecture, Report SP-789, February 1989.

[6] Nordstrom, O. "Stability, Steerability and Braking Performance of Heavy Duty Vehicles: A Review of Experimental and Theoretical Research and Regulation Proposals by VTI in Sweden," Heavy Vehicle Systems, Special Series, Int. Journal of Vehicle Design, Vol. 1, No. 1, 1993. pp 34-62.

[7] Klusmeyer, L.F. et al "An In-Service Evaluation of the Reliability, Maintainability, and Durability of Antilock Braking Systems (ABS) for Heavy Truck Tractors," Final Report, DOT HS 807 846, NHTSA, March 1992.

[8] Beauchemin-Beaton-Lapointe, "In Service Demonstration of the Maintainability, Serviceability and Operation of B-train Double Equipped with ABS," Report TP11826, Transportation Development Centre, Transport Canada, Montreal, Quebec, May 1995.

[9] Lam C.P., "Impact of an Antilock Brake System on Braking Efficiency of Heavy Commercial Vehicles," Strategic Transportation Research Branch Report CV-95-01, Ontario Ministry of Transportation, Toronto, Ontario, May 1995.

[10] Cox B. "Evaluation of an Antilock Braking System and Automatic Slip Regulation on a Log-Hauling Truck," Technical Report SR-97, Forest Engineering Research Institute of Canada, Vancouver, B.C., February 1994.

[11] Ervin R.D. and Guy Y., "The Influence of Weights and Dimensions on the Stability and Control of Heavy Trucks in Canada - Part 2," CCMTA/RTAC Vehicle Weights and Dimensions Study Technical Report Volume 2, Roads and Transportation Association of Canada, Ottawa, July 1986.