SENSITIVITY OF AIR-BRAKED VEHICLES TO MAINTENANCE UNDERSCORES THE NEED FOR RELIABLE LOW-COST CAB-DISPLAY BRAKE FAULT INDICATOR LAMP

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ABSTRACT

A collection of information on the regulation, design, performance, operation and maintenance of air-braked vehicles was reviewed. These data indicate that performance decrements arising from the sensitivity of air-braked vehicles to maintenance has been a safety issue for a considerable period of time. The predominant reason why air-braked vehicles are placed out-of-service at roadside inspections continues to be, predictably, due to maintenance-related braking problems. The ability of drivers to safely maintain control of air-braked vehicles can seriously be restricted when maintenance-related braking problems reduce the braking performance or the limited reserve braking capacity of service (foundation) brakes. Primary safeguards that mainly rely on the vigilance and knowledge of drivers to know whether brake repairs are warranted when daily pre-trip inspections are conducted may be inadequate. There are currently no requirements for a cab-display device to readily alert drivers when the stopping capability of air-braked vehicles has deteriorated to an unsafe level. Comments about the need, feasibility and merits of a low-cost cab-display brake fault indicator lamp for air-braked vehicles are presented.

INTRODUCTION

The sensitivity of air-braked vehicles to maintenance cannot be underscored enough. Regulations require that service (foundation) brakes are checked as part of a duty to perform daily pre-trip inspections on air-braked vehicles. Despite this requirement, maintenance-related braking problems have historically, and moreover, continue to be the number one reason why air-braked vehicles are placed out-of-service by enforcement officials at roadside inspections. Brake-related deficiencies include oil-soaked lining, cracked drums, applied pushrod stroke (with reservoir pressure @ 90-100psi) beyond re-adjustment limits, and excessive component wear (e.g. lining thickness). Left undetected, maintenance-related braking problems can significantly limit the ability of drivers to control the speed or directional stability of air-braked vehicles. This often occurs when air-braked vehicles are descending steep grades or after a hard brake application is made while travelling on wet or slippery road surface. This raises the question - why are so many air-braked vehicles placed out-of-service? Do drivers of air-braked vehicles just simply ignore or inadvertently overlook maintenance-related braking problems when daily pre-trip inspections are performed? Whatever the reason, for the safety of all road users, can reasonable measures be taken to ensure that drivers become acutely aware about brake-related deficiencies before air-braked vehicles are driven?

Societal Cost of Surface Transportation

Transportation of goods has been regarded as vital to the economy and indispensable to society. Despite obvious benefits from surface transportation, there are also costs. A review of the scope and conclusions of major studies to estimate the social cost of motor vehicle use in the United States found little agreement in the distribution and size of transportation costs or whether the use motor vehicles was under-priced. Heavy trucks contribute to the transportation of retail and commercial products. In 1993, for-hire and private heavy trucks delivered 52 percent of U.S. freight shipments. A rise in the volume of goods transported by heavy trucks generally corresponds to an increase in the number of air-braked vehicles that share space on highways with other road users. Between 1990 and 1995, the exposure of single unit and combination heavy trucks (by vehicle miles) surpassed that of passenger cars, taxis, vans, pickup trucks and sport-utility vehicles (21% v. 12%). During that time, there was a modest increase in the number of heavy trucks involved in fatal (mean = 4,496) and injury crashes (mean = 53,600).
According to responses in 1988 to a 19 item questionnaire, Rothe (1991) reported that 72 percent of 145 tractor-trailer truck drivers thought that motorists believed heavy trucks were a threat to passenger vehicles. A poll conducted in Canada in 1996 found that nearly one-half of 1516 respondents (49%) perceived that roads and highways were less safe today than in the past. More than three-quarters of the same respondents (78%) would prefer that government adopt regulations rather than make it voluntary for the trucking industry to improve maintenance standards and practices. Similar sentiments were expressed by 79 percent of 4,000 respondents involved in a 1995 national survey in the United States who characterized government’s involvement in regulating the safety of heavy trucks as very important.

**Heavy Truck Brake Systems**

Air-braked vehicles are equipped with a supply system and control system that generate and deliver pressurized air to activate a series of pneumatic valves that control pressure to the service (foundation) brakes. Three different approaches are generally taken to apply service (foundation) brakes on air-braked vehicles - cam-actuated, wedge-type or disc. The S-shaped cam and wedge serve the same purpose to extend the lining to the inner surface of the brake drum. This differs from the disc brake which uses the force applied by brake pads on each side of a rotating disc to slow the speed of a revolving wheel. Although (as reported by Gohring and von Glasner, 1990) discs brakes exhibit significant advantages to drum brakes, the majority of air-braked vehicles are reportedly (> 90%) equipped with cam-actuated brakes.

**Brake Standards**

[FEDERAL SAFETY STANDARDS have been developed by government to establish mandatory performance and equipment requirements for the manufacture of motor vehicles. Original Equipment Manufacturers (OEM) consider and comply with safety standards during the design and production of new vehicles. This includes brake standards that have been developed and administered by regulators to ensure that air-braked vehicles can stop safely under normal and emergency conditions. The Federal Motor Vehicle Safety Standard 121 (CMVSS in Canada) applies to the manufacture of most heavy trucks, truck-tractors, trailers and buses equipped with air brake systems. The standard contains requirements for equipment and minimum brake retardation forces generated by each brake assembly from dynamometer tests. As a rule, OEM's ensure that newly-manufactured air-braked vehicles will not only meet, but more than exceed minimum braking performance requirements. The braking performance of in-use vehicles that operate within Canada are regulated by each province. This differs from air-braked vehicles involved in interstate commerce in the U.S. that are regulated by the Federal Motor Carrier Safety Regulations (FMCSR). The braking performance and stopping distance test requirements from 32 km/h (20 mph) for in-use vehicles that operate in British Columbia are similar to those contained in Part 393.52 of the FMCSR (Table 1).]

### Table 1

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>Minimum Brake Force (% of GVW)</th>
<th>Minimum Dec. Rate (m/sec²)</th>
<th>Maximum Stop Distance m (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All single unit vehicles over 4,545 kg (except tractors) and combination of 2 vehicles in driveaway or towaway operation</td>
<td>43.5</td>
<td>4.26</td>
<td>10.7 (35')</td>
</tr>
<tr>
<td>All other vehicles and combination of vehicles</td>
<td>43.5</td>
<td>4.26</td>
<td>12.2m (40')</td>
</tr>
</tbody>
</table>

Stopping distance requirements from 97 km/h (60 mph) were re-instated by the U.S. National Highway Traffic Safety Administration (NHTSA) on 10 March 1995. The requirements became effective in the U.S. on 1 March 1997 for truck-tractors and on 1 March 1998 for other single-unit vehicles. A comparison of stopping distance requirements indicate that even with well-maintained service (foundation) brakes that are burnished and fully adjusted, air-braked vehicles require considerably more distance to stop than hydraulically-braked vehicles. Stopping distance requirements for truck-tractors are met while coupled to an unbraked flatbed (control) trailer. The difference between the stopping distance of hydraulically-braked vehicles compared to air-braked vehicles is further increased as the need for brake maintenance arises (Table 2). This was highlighted by Heusser (1991) who reported that
calculated values of deceleration rates of air-braked vehicles could significantly lower (~50%) as a function of brake adjustment.

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>Type of Brake System (FMVSS)</th>
<th>Service (Foundation) Brakes Empty (m)</th>
<th>Service (Foundation) Brakes Loaded (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>Air (121)</td>
<td>85 (280')</td>
<td>85 (280')</td>
</tr>
<tr>
<td>Trucks</td>
<td>Air (121)</td>
<td>102 (335')</td>
<td>94 (310')</td>
</tr>
<tr>
<td>Tractors</td>
<td>Air (121)</td>
<td>102 (335')</td>
<td>108 (355')</td>
</tr>
<tr>
<td>Cars</td>
<td>Hydraulic (135)</td>
<td>70 (230')</td>
<td>70 (230')</td>
</tr>
</tbody>
</table>

VOLUNTARY STANDARDS associated with the performance and maintenance of air-braked vehicles have been developed by industry stakeholders. The Society of Automotive Engineers (SAE), The Maintenance Council (TMC), and the Truck Trailer Manufacturers Association (TTMA) have established standards and recommended practices with respect to the design, specifications, installation, maintenance, and testing of air-braked vehicles and related components (Table 3).

<table>
<thead>
<tr>
<th>Organization</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE</td>
<td>- Standards, Recommended Practices and Information Reports</td>
</tr>
<tr>
<td>TMC</td>
<td>- Recommended Maintenance Practices</td>
</tr>
<tr>
<td></td>
<td>- Recommended Engineering Practices</td>
</tr>
<tr>
<td>TTMA</td>
<td>- Recommended Practices, Technical Bulletins</td>
</tr>
</tbody>
</table>

Brake Performance

Several studies have been conducted to examine the limitations that affect the performance capabilities of air-braked vehicles. Radlinski et al (1982) concluded that a substantial improvement in the braking performance of air-braked vehicles could be achieved if the adjustment of service (foundation) brakes were better maintained. Hargadine and Klein (1983) found that the braking performance of tractor-trailer configurations had deteriorated between 1974 and 1983, and that brake maintenance was still a problem with air-braked vehicles. Radlinski (1987) reported that there was a large gap between the performance of passenger cars and heavy trucks. Flick (1988) found from full scale tests, dynamometer testing, and computer simulation that the stopping distance of an air-braked (5-axle) vehicle could increase by about 50 percent when the service (foundation) brakes were at re-adjustment limits and operating at high temperatures (600°F). A heavy truck safety plan prepared by NHTSA (1991) indicated that research was being pursued to improve the stopping distance and controllability of heavy trucks. Heusser (1991) indicated that a predictive relationship exists between the extension of the applied pushrod stroke of brake chambers (adjustment) and corresponding reduction in the deceleration rate of air-braked vehicles.

Brake Design

Trends in brake design for air-braked vehicles have regularly been reported. Long (1959) reported that the redesign of the S-Cam brake was expected to improve air actuation and reduce friction of cam followers. Long felt that the use of water to cool service (foundation) brakes and a device that could prevent wheels from locking would be obvious advantages in the controllability and safety of commercial vehicles. Koenig and Kreider (1976) postulated that there would be three significant technological changes to air brake system components during the 1980’s - (a) new compressor design to provide higher outputs with improved efficiency, (b) new parking brake to provide comparable performance to spring brakes but with less complexity and improved reliability, and (c) improved braking performance of trucks, truck-tractors and trailers with the adaptation of air disc brakes. McCallum and Tolan (1983) concluded that the S-cam brake still had a lot to offer because it is simple and can be made robust and reliable at a low cost. Oppenheimer (1990) reported that equipping air-braked vehicles with electro-pneumatic braking systems may simplify installation of air brake systems, reduce brake response times, and provide shorter stopping distances. Marwitz et al (1995) predicted that the performance of air-braked vehicles could be further improved with (a) disc brakes...
on all wheels, and (b) the use of electro-pneumatic brake systems. More recently, it was suggested that, however innovative, intelligent transportation system (ITS) technologies should only be pursued after quality and reliability issues have been resolved.

BRAKE DESIGN ISSUES have developed and challenged engineers because of vehicle modification changes that have been made to improve the productivity of air-braked vehicles. This included efforts that were required to maintain traditional levels of braking performance with a downsized 15 X 5/8-inch cam-actuated brake (compared to the standard 16.5 X 7-inch brake) to accommodate lowered frame heights and low profile tires. Other vehicle modifications include, but were not limited, to (a) improved vehicle aerodynamics, (b) lower rolling resistance tires, and (c) fuel efficient diesel engines with less natural retardation. Cost savings expected from modifications that have been made to increase the freight-carrying capacity of Class 8 air-braked vehicles may (in some cases) have been offset by additional costs to maintain service (foundation) brakes. Questions have been raised about whether vehicle modifications have reduced the durability and increased the maintainability of service (foundation) brakes on air-braked vehicles.

Human Factor Issues

Driver error is often regarded as the primary contributing factor to crashes. Evans (1991) reported that road-user characteristics have been identified in multi-disciplinary post-crash investigations as factors in about 95 percent of crashes. Others, however, consider the emphasis placed on driver error as a factor in crashes as a gross oversimplification of the traffic safety problem. Woodson (1998) indicated that operator mistakes (regardless of application) may be encouraged as a function of design rather than merely an act due to carelessness, ignorance or lack of knowledge. Woodson regards human factors engineering as how compatible a product design is with a human’s physical, mental and sensory-motor characteristics, and typical anticipatory and behavioural response expectations.

Wierwille and Peacock (1988) emphasized that no other system is more dependent on its operator than the automobile. This certainly applies to the standard of reasonable care expected of drivers that are not only required to safely operate air-braked vehicles, but also presumed to have the ability to make subjective assessments about whether maintenance-related braking problems exist, then, determine whether repairs are warranted before the vehicle is driven. Unlike drivers of hydraulically-braked vehicles that can become aware of when the “reserve” stroke of actuators (wheel cylinders) has decreased as a function of pedal height, drivers of air-braked vehicles cannot definitively determine whether the service (foundation) brakes are out-of-adjustment by applying the brake pedal. The inability of drivers to determine the eventual out-of-adjustment condition that will develop on air-braked vehicles by depressing the foot-operated brake pedal (more so with those equipped with manual slack adjusters or neglected and inoperative automatic brake adjusters) was explained by Williams and Knipling (1991).

The foot controlled master cylinder of hydraulically-braked vehicles has a fixed displacement. This differs from the foot-operated brake (treadle) valve that simply serves as a metering valve. Compared to a hydraulic brake system, the fixed pedal height of an air-braked vehicle does not change with the amount of pressurized air that is metered through the treadle valve. While the corresponding travel of the foot-operated brake pedal is greater than the treadle valve plunger travel, there is very little change in the movement of the pedal to alert drivers when making a light brake application on an air-braked vehicle if the service (foundation) brakes have become out-of-adjustment or whether another maintenance-related braking condition, that should be addressed without delay, has developed. Since most brake applications that are made by drivers to slow or stop air-braked vehicles (even those heavily laden) are generally light, it is conceivable that a driver of an air-braked vehicle may not become aware when (and to what degree) that a maintenance-related braking problem has reduced his ability to maintain control of the vehicle should an unexpected situation arise that required him to stop in a short distance or have to completely rely on the service (foundation) brakes to safely descend a steep grade.

Thoms (1983) reported that drivers make use of visual information and experience to estimate how much pressure should be applied to the brake pedal to achieve a predetermined deceleration. The plunger travel of the treadle valve is diminutive when the foot-operated brake pedal of an air-braked vehicle is applied. Figure 1 illustrates the non-linear displacement of the treadle valve plunger travel as application pressure rises (E-6 Bendix).
The braking performance of air-braked vehicles is very sensitive and dependent on brake maintenance. Moore (1954) felt that the wide spread between passenger cars and loaded commercial vehicles from the same speed could be narrowed considerably with adequate maintenance, and by the proper selection of engineered components on air-braked vehicles. Tauss (1958) surmised that the brake maintenance in some major fleets was a deplorable situation. Tauss further indicated that newspapers in 1957 were raising the issue of truck safety to the attention of motorists with headlines that read - "Defective Brakes and Deadly Trucks" (Philadelphia Inquirer). Based on a synthesis of information on the braking performance of air-braked vehicles, Radlinski (1987) reported that (a) U.S. air-braked vehicles did not perform as well as cars, (b) performance of air-braked vehicles could degrade significantly from the design-intent level if proper maintenance was not performed, and (c) the brake maintenance situation in the U.S. left something to be desired. The maladjustment of service (foundation) brakes has long been recognized as a problem. The torque output of air-braked vehicles is sensitive to the displacement of the applied pushrod stroke of brake chambers (adjustment). A rise in brake temperatures can further reduce brake torque and increase the stopping distance of air-braked vehicles.

The installation of automatic slack adjusters (ASA) on air-braked vehicles (factory-installed in the U.S. since 20 October 1994) was anticipated to reduce the number of air-braked vehicles found with service (foundation) brakes beyond re-adjustment limits. However, just as brake maintenance can affect the braking performance of air-braked vehicles, so too can brake maintenance directly affect the ability of ASA’s to maintain proper brake adjustment and brake balance. The efficacy of ASA’s can be affected by worn S-cam bushings, loose brake chambers, or inaccurate wheel bearing adjustment. Heusser (1992) revealed that the average pushrod stroke of type 30 brake chambers did not differ greatly between air-braked vehicles that were equipped with automatic slack adjusters (1.62 inch average stroke) and manual slack adjusters (1.68 inch average stroke).

A report by NHTSA (1995) that outlined a new agenda for the 21st century, indicated that 54 percent of defects noted on about 1.6 million air-braked vehicles inspected in 1992 were brake system related. These data indicated that 68 percent of defects involved out-of-adjustment brakes, and, on average nearly 1 of every 10 in-use heavy vehicles is operating with at least one significant non-adjustment-related brake system defect. According to the report, many of these maintenance-related braking problems (e.g. cracked brake drums, chafed or worn air lines, leaking chamber diaphragms) remain undetected simply because drivers were unaware that these latent, potentially hazardous conditions were present.

The stopping capability of air-braked vehicles can also be reduced if the applied pushrod stroke (and corresponding reserve stroke) of brake chambers is forfeited. This may occur from excessive clearance that develops with use or because incorrect repairs were performed that restricted the available pushrod stroke of brake chambers (e.g. worn splines on S-camshaft). No matter how the available pushrod stroke of brake chambers is forfeited, it reduces the reserve braking capacity of air-braked vehicles.

Another undetected maintenance-related braking problem that could significantly degrade the braking performance of air-braked vehicles was discovered in 1997 by the National Transportation Safety Board (NTSB) during the investigation of a truck-car crash. The NTSB attributed the cause of the crash to faulty brake maintenance. A notice was issued to alert the trucking industry that certain dual-systems on air-braked vehicles may have air lines to the foot-operated brake pedal that are reversed, and low-air warning switches that do not function. Despite the best of intentions and actions taken to conduct daily pre-trip inspections or perform periodic inspections, maintenance related braking problems on air-braked vehicles can be overlooked by drivers and trained...
journeyman heavy duty mechanics. A basis for uniformity on the maintenance of service (foundation) brakes for air-braked vehicles has been fulfilled in part by the development of recommended practices.

Faulty Brakes (Enforcement)

Out-of-service criteria for air-braked vehicles was established by the Commercial Vehicle Alliance (CVSA) to assist enforcement officials determine what constitutes an unsafe vehicle-related or driver-related condition. Air-braked vehicles that fail to meet minimum requirements are placed out-of-service until repairs have been performed. CVSA is an association of state, provincial and federal officials responsible for the administration and enforcement of motor carrier safety laws in the United States, Canada and Mexico. The North American uniform out-of-service criteria is the guideline that is used by certified CVSA inspectors to determine whether the service (foundation) brakes on air-braked vehicles are considered defective and should be repaired. Air-braked vehicles are placed out-of-service when 20 percent or more of the service (foundation) brakes are defective or when certain out-of-service conditions on the brakes mounted on the steering axle are found (Table 4).

<table>
<thead>
<tr>
<th>Defective Brake Conditions</th>
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<tbody>
<tr>
<td>• absence of effective braking action</td>
</tr>
<tr>
<td>• missing / broken mechanical components</td>
</tr>
<tr>
<td>• loose brake components</td>
</tr>
<tr>
<td>• audible air leak at brake chamber</td>
</tr>
<tr>
<td>• applied pushrod stroke @ 90-100 psi reservoir pressure beyond re-adjustment limit</td>
</tr>
<tr>
<td>• defective lining (e.g. cracked, oil-soaked, thickness, missing)</td>
</tr>
<tr>
<td>• missing brake on any axle required to have brakes</td>
</tr>
<tr>
<td>• inoperable breakaway braking system (trailer)</td>
</tr>
<tr>
<td>• non-manufactured holes/cracks on spring section of brake chamber</td>
</tr>
<tr>
<td>• external cracks on brake drum</td>
</tr>
<tr>
<td>• portion of drum or rotor (discs) missing or about to dislodge</td>
</tr>
<tr>
<td>• defective air line (e.g. bulge, leak, improper splice, broken, crimped)</td>
</tr>
<tr>
<td>• inoperative or missing defective low pressure warning device</td>
</tr>
<tr>
<td>• unacceptable air loss rate</td>
</tr>
<tr>
<td>• inoperable or missing tractor protection valve</td>
</tr>
<tr>
<td>• insecure air reservoir</td>
</tr>
<tr>
<td>• defective air compressor (e.g. loose, cracked pulley / brackets)</td>
</tr>
</tbody>
</table>

A study was conducted by Fancher et al (1995) to examine 2,146 brake inspections performed by the National Transportation Safety Board. Based on analyses of these data, recommendations were made to change the brake adjustment criteria to reduce the percentage of “false positives” during roadside inspections of air-braked vehicles. This prompted CVSA in 1996 to revise the out-of-service criteria for air-braked vehicles. The change allows the displacement of the applied pushrod stroke of brake chambers (with 90-100psi of reservoir pressure) to extend even further before the service (foundation) brakes are required to be re-adjusted. This essentially permits air-braked vehicles, sensitive and dependent on maintenance, to operate with even less limited reserve braking capacity before pushrods can “bottom-out” in brake chambers. The stroked-out condition of brake chambers is often found when air-braked vehicles are inspected after being involved in downhill runaway events. It remains to be seen whether the change (regarded by some as a liberalized plan) will influence the frequency of crashes that arise because of the sensitivity of air-braked vehicles to maintenance (e.g. maladjusted brakes).

Maintenance-Related Braking Problems

Johnson (1946) reported that brake troubles have been present ever since transport vehicles have been around. Furthermore, that a relatively minor degree of foresight and preventative maintenance could prevent crashes caused by faulty brakes. Johnson concluded that “... the slaughter on our highways ...” could be averted if service (foundation) brakes were maintained. The condition of service (foundation) brakes can be evaluated by reviewing the results of roadside inspections or post-crash inspections of air-braked vehicles.

ROADSIDE INSPECTIONS are conducted in most every jurisdiction in North America. From a review of the Motor Carrier Management Information System, Moses and Savage (1994) suggest that on a rough rule-of-thumb basis, a truck will, on average, be inspected every five years. Data from these inspections have often been reviewed to assess the mechanical fitness of air-braked vehicles. Limpert and Andrews (1987) concluded that as many as 41 percent of heavy vehicles that operate on highways in the U.S. may be unsafe due to defective brakes. The United States General Accounting Office (1980) reported that the out-of-service of air-braked vehicles remained fairly constant (mean 35%) from 1984
to 1989. From roadside inspection results obtained from the Bureau of Motor Carrier Safety for 1966, 1973 and 1983-84, Clarke et al (1991) reported that the proportion of air-braked vehicles that were placed out-of-service for brake-related deficiencies had remained relatively constant (mean = 64.8%). A 17-month study by the NTSB (1992) found that (a) 46 percent of 1,520 air-braked vehicles inspected had maladjusted brakes, (b) 15 percent of automatic slack adjusters were beyond re-adjustment limits, (c) available data do not permit the magnitude of brake-related deficiencies to be readily evaluated, (d) maintenance-related braking problems are associated with more crashes than statistics currently reveal, (e) drivers fail to comprehend the importance of well-maintained service (foundation) brakes, and (f) air-braked vehicles with marginal performance with cool brakes could lose braking effectiveness when brake temperatures rise. From the analysis of inspection data of 1,520 five-axle heavy combination vehicles, Heusser (1992) found that brake-related defects were more likely to be found on older (rather than late) model air-braked vehicles. Seiff (1994) reported that 45 percent of the out-of-service violations recorded by CVSA in 1992 were brake violations. Maintenance-related braking problems were cited as the most frequent violation that resulted in why air-braked vehicles were placed out-of-service in 1995 and 1996.

POST CRASH INSPECTIONS are arranged for some but not all crashes involving air-braked vehicles. This is generally done to determine the condition of the service (foundation) brakes of air-braked vehicles to resolve questions about the circumstances that may have lead to serious crashes. Accident statistics based on police-reported data make it difficult to determine to what extent maintenance-related braking problems contribute to crashes that involve air-braked vehicles. That may be because brake-related deficiencies - similar to driver-related factors like drowsiness - are not always apparent to enforcement officials that attend crash scenes. In-depth investigations have revealed otherwise (Table 5). Jones and Stein (1988) found that 56 percent of 734 large trucks involved in 676 crashes in Washington State had brake defects. Maintenance-related braking problems was a factor associated with a significant number of the 189 heavy truck crashes (> 10,000 pounds) with tow-away damage that were investigated in 1988 by the National Transportation Safety Board. A task force under the direction of the California Highway Patrol (CHP) conducted an analysis of truck-involved and truck at-fault crashes that occurred since truck safety began to deteriorate and crash involvement increased. The task force found that although crashes caused by faulty brakes had steadily declined, brake defects represented a significant proportion (mean = 63%) of the mechanical contributors that were related to truck at-fault fatal and injury crashes that occurred in California between 1978 and 1989.

Table 5

<table>
<thead>
<tr>
<th>Source</th>
<th>Ratio</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Jones &amp; Stein (1988)</td>
<td>56%</td>
<td>Brake defects in 676 tractor-trailer crashes</td>
</tr>
<tr>
<td>- CHP (1991)</td>
<td>63% (mean)</td>
<td>Brake defects related to truck at-fault &amp; injury crashes (1978-89)</td>
</tr>
<tr>
<td>- TIFA (1993)</td>
<td>55%</td>
<td>Brake system identified as vehicle-related factor in fatal truck-involved crash</td>
</tr>
<tr>
<td>Clarke et al (1991)</td>
<td>30-36.4%</td>
<td>Annual number of brake-related crashes</td>
</tr>
</tbody>
</table>

From a review of crashes that occurred because of (a) deficient brakes, (b) downgrade runaways, (c) unable to stop in time, and (d) brake induced instability, Clarke et al (1991) estimated that upward of 30.0 to 36.4 percent of the annual number of crashes involving air-braked combination vehicles could be brake-related. Vehicle-related factors listed in the Trucks Involved in Fatal Accident (TIFA) database were reviewed for 1993. The TIFA dataset includes virtually all the variables from the public version of the Fatal Accident Reporting System (FARS). The combination of FARS accident level variables with the physical detail of the TIFA survey is noted to produce the most detailed account of fatal truck crash data available. An analysis of vehicle-related factors (variable 162) from the 1993 TIFA dataset indicated that the codes for the brake system accounted for over one-half (55%) of the overall number of all “assigned” codes that described a particular component or system on heavy trucks (e.g. brakes, tires, steering). Vaughan (1993) concluded that the role of defects in crashes is grossly underestimated, and that the brake system is by far the largest source of those defects. The findings of an in-depth investigation of a fatal car-truck crash reported by the author (1997) found that maintenance-related braking problems may not always be detected even when a post-
crash inspection of an air-braked vehicle is performed by a certified vehicle inspector. Calculations were performed by Moses and Savage (1997) to determine the upper bound (11%) and mid-range (6%) estimates of crash reduction from roadside inspections due to faulty brakes.

**Brake Improvements**

Pro-active measures have been taken to improve the braking performance and reduce the sensitivity of air-braked vehicles to maintenance. Atkin and Bennet (1964) anticipated steady improvements would be made in the safe operation of air-braked vehicles with the installation of split systems, antilock brake systems and increased use of retarders. A study by Murphy et al (1971) found that significant upgrade in the maximum braking performance of air-braked vehicles could be achieved by (a) better brake balance, (b) faster response times, (c) brake effectiveness that fully utilized the tire-road interface, and (d) advanced brake control systems that would allow rapid brake applications without creating vehicle instability while travelling on slippery surfaces. A test program sponsored by the Insurance Corporation of British Columbia and conducted by MacInnis (1986) to demonstrate the stopping behaviour of bobtail truck-tractors found that the overall brake deceleration substantially improved (almost double) when air pressure to the steer-axle brakes was increased to near maximum. From a series of tests of simulated emergency maneuvers Radlinski and Flick (1987) concluded that most drivers of air-braked combination vehicles with single trailers would be more likely to stop in a shorter distance and not lose control of an air-braked vehicle if truck-tractors were equipped with (as opposed to without) full operational service (foundation) brakes on steering axles.

Additional measures that could be taken to further improve the performance of air-braked vehicles were identified and proposed by Clarke and Radlinski (1991). This included design changes to enhance brake effectiveness, stability and control, and brake balance and compatibility of air-braked vehicles (Table 6). The Maintenance Council has developed a recommended practice (RP 628-1) for brake lining classification. The RP is intended to promote the dissemination of information to compare the performance of aftermarket brake linings on 16.5 X 7-inch brakes which have been tested to the original equipment dynamometer test procedure stipulated in FMVSS 121.

Air disc brakes are noted for providing superior stopping capability. Thompson (1994) predicted that the demand for air disc brakes would escalate for heavy vehicles in the European market. Yet concerns about compatibility and the additional cost of air disc brakes compared to drum brakes has reportedly restricted the wide-spread adaptation of disc brakes on air-braked vehicles in North America. Concerns about compatibility may be addressed with the adoption of a requirement that truck-tractors and other single unit vehicles sold in the U.S. since 1 March 1997 and 1 March 1998 respectively be factory-equipped with antilock brake systems. This may prompt further interest and expand (similar to Europe) the number of air-braked vehicles in North America that, in the future, will be equipped with air disc brakes.

**Table 6**

**Methods Proposed in 1991 to Improve the Braking System Effectiveness, Stability and Compatibility of Air-Braked Vehicles (NHTSA)**

<table>
<thead>
<tr>
<th>Proposed (adopted)</th>
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<tr>
<td>• disc brakes</td>
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<tr>
<td>• higher-friction tires</td>
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<td>• long stroke brake chambers</td>
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<tr>
<td>• automatic slack adjusters (1994)</td>
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<tr>
<td>• antilock brake systems (1997/1998)</td>
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<tr>
<td>• higher capacity steering axle brakes</td>
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<tr>
<td>• stroke indicators on exposed pushrods (1994)</td>
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<tr>
<td>• eliminate use of automatic front-wheel limiting valves</td>
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<td>• stopping distance performance requirements (1995)</td>
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<td>• truck-tractor bobtail proportioning valves</td>
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<tr>
<td>• determine torque rating of aftermarket brake linings</td>
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<tr>
<td>(TMC, 1997)</td>
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<tr>
<td>• performance testing, rating, marking/labeling pneumatic valves</td>
</tr>
<tr>
<td>• compatible tractor / trailer brake timing requirements (1991)</td>
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<td>• supplement use of service (foundation) brakes with retarders</td>
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The introduction of electronically controlled brake systems (EBS) technology has been considered to be the next advancement to further improve the braking performance of air-braked vehicles. Wrede and Decker (1992) predicted that the control and actuation of the service (foundation) brakes on air-braked vehicles would be electronically combined in the form of "brace management". Decker and Wrede (1994) also warned that incompatibility between systems could arise if effort is not taken to standardize the development of brake-by-wire systems. Lindermann et al (1997) regard the outlook...
for electronically controlled brake systems (EBS) as the basis for future safety improvements in the operation of air-braked vehicles. Hecker et al (1997) demonstrated that the control of a solo truck-tractor and laden tractor-trailer combination was considerably improved, even under reduced and varying road surface friction, with the use of an electronic brake system. Electronically controlled brakes (ELB) are apparently factory-installed (standard feature) on air-braked heavy trucks that are manufactured by a European manufacturer.

Finally, manufacturers have made product improvements to the S-cam brake assembly. Some of these changes have eliminated sources of component wear that could result in the forfeiture of available pushrod stroke of air-braked vehicles (e.g., upgraded camshaft bushings). Heavy duty return springs have also been introduced with long-life brake packages to assist automatic slack adjusters properly adjust service (foundation) brakes. Although not required, truck-tractors are often factory-equipped with bobtail proportioning valves to ensure that stopping distance requirements can be achieved. A marketing brochure from a major brake equipment supplier indicated that it is committed to making "... truck brake problems a thing of the past".

Brake Inspections

Compliance measures have been instituted to serve as safeguards to reduce the probability of air-braked vehicles from becoming involved in brake-induced crashes. The primary safeguards to prevent the potential crash involvement of air-braked vehicles are mainly based on subjective assessments of brake system components from visual inspections performed by humans. This action is required to ensure that the condition of air brake systems will allow air-braked vehicles to be safely driven. These safeguards include (a) an obligation in most jurisdictions for truck owners to arrange periodic inspections on air-braked vehicles at least every 12 months, (b) drivers to perform daily pre-trip inspections, and (c) enforcement officials to routinely inspect air-braked vehicles at roadside inspections.

Drivers of air-braked vehicles are required to perform daily pre-trip inspections to satisfy themselves that the vehicle is road-worthy. Part of the inspection includes a visual check of the adjustment and condition of the service (foundation) brakes. Knowledge to perform this duty is acquired from training courses to obtain a higher classification of license or endorsement to drive air-braked vehicles. The inability of drivers to detect defective brake conditions or recognize the importance of maintaining service (foundation) brakes within re-adjustment limits when pre-trip inspections are performed can (usually without their knowledge) significantly reduce their ability to control the speed and direction of air-braked vehicles. Drivers may lapse in their duty to identify maintenance-related braking problems on air-braked vehicles for a variety of reasons, including (a) limited mechanical aptitude, (b) indolence or lack of interest, (c) incorrect assumptions about the actual condition of the brake system, (d) operational demands that compete with available time to perform a thorough check of the brake system, or (e) learning barrier that restricts the ability to fully comprehend technical information about brake systems.

There are multiple other reasons why drivers may not determine whether the service (foundation) brakes are properly adjusted. This includes falsely believing that the adjustment of service (foundation) brakes can be checked by walking around an air-braked vehicle with the (spring) parking brakes applied and observing the extent that exposed pushrods are extended from brake chambers. Alternatively, drivers have been known to believe that the adjustment of service (foundation) brakes on air-braked vehicles can be checked while seated in the comfort of the cab compartment by merely observing the reservoir gauge to determine whether a given amount of pressure drops after the foot-operated brake pedal is fully depressed.

A cursory review of data collected in 1998 during a focused enforcement inspection campaign of construction trucks indicates that drivers of air-braked vehicles (despite having completed daily pre-trip inspections) may not be fully aware of the condition of the service (foundation) brakes, and moreover, the implications that surround the sensitivity of air-braked vehicles to maintenance. Laurie (1938) pointed out that drivers daily reports on the operation of large trucks often provide sufficient advanced warning to notify mechanics about impending failures.

If a maintenance-related braking problem (as depicted in Appendix A) is not identified by a driver, it may continue to be present until the air-braked vehicle is next scheduled for maintenance or a periodic inspection. The problem may still remain undetected if a trained journeyman heavy duty mechanic at a certified inspection facility is not able to detect the defective brake condition, or does not correctly perform the necessary repairs to fully rectify the problem. Should this occur, there is a possibility that the problem may be identified if the air-braked vehicle, by chance, is targeted for a "random"
roadside inspection by enforcement officials. Air-braked vehicles found with maintenance-related braking problems can be placed out-of-service when inspected by certified CVSA inspectors.

Maintenance-related braking problems may be more readily identified with the deployment of performance-based brake inspection testers. A research program sponsored by the Federal Highway Administration was initiated in 1993 to evaluate the merits of using performance-based technologies to inspect air-braked vehicles at roadside inspections. Data collected and analyzed from one year of field tests indicate that performance-based testers, particularly the roller brake dynamometer, showed good correlations with CVSA inspection and appear to be immediately useful as screening devices. Performance-based regulations must be developed, however, before performance-based testers can be used as an enforcement tool. As with other forms of intervention to apprehend unsafe vehicles before crashes occur, there are certain limitations to performance-based testers. These include the understanding that only a chance encounter with enforcement officials will prevent air-braked vehicles with faulty brakes from being stopped, then, subsequently placed out-of-service before potentially becoming involved in brake-induced crashes.

Brake Warnings

Federal Motor Vehicle Safety Standard (FMVSS) 121 requires that air-braked vehicles be equipped with a continuous visible or audible warning in the cab compartment to readily alert drivers when reservoir pressure drops below 60psi (Table 7). The standard also requires that drivers of air-braked vehicles be provided with a gauge that illustrates the amount of pressure in the reservoir system.

<table>
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<th>Table 7</th>
<th>Cab Display Requirements for Air-Braked Vehicles (FMVSS 121)</th>
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<tr>
<td>• gauge(s) to illustrate service reservoir system air pressure</td>
<td></td>
</tr>
<tr>
<td>• audible/visible continuous warning when service reservoir pressure &lt; 60psi (413 kPa)</td>
<td></td>
</tr>
<tr>
<td>• indicator lamp to activate when malfunction affects ABS on power unit</td>
<td></td>
</tr>
<tr>
<td>• indicator lamp to activate when malfunction affects ABS on towed air-braked vehicle (effective on 1 March 2,001)</td>
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Additionally, truck-tractors manufactured on or after 1 March 1997 and each single unit vehicle manufactured on or after 1 March 1998 in the U.S. must be equipped with an indicator lamp (mounted in front or in clear view of drivers) that activates whenever a malfunction affects the generation or transmission of responses or control signals in the antilock brake system. Indicator lamps must remain illuminated whenever malfunctions exist in antilock brake systems while the ignition switch is in the ‘on’ position. After 1 March 2,001, newly-manufactured air-braked vehicles in the U.S. equipped to tow another air-braked vehicle must also be equipped with an electrical circuit that is capable of transmitting malfunction signals from the antilock brake systems of one or more towed vehicles.

There is no current requirement that air-braked vehicles be equipped with a cab-display device to readily alert drivers about maintenance-related braking problems that have degraded the braking performance or reduced the reserve braking capacity of the service (foundation) brakes. These problems are generally the same brake-related deficiencies that historically (and continue to be) discovered when roadside inspections or post-crash inspections are conducted on air-braked vehicles.

Vehicle-Based Warning Devices / Monitoring Systems

Vehicle-based warning devices are usually installed on motor vehicles to provide drivers with an advanced notice about the need to take action. Merker (1966) reported the engineering details of the Sentry Signal Warning System that was developed to provide advantages of both the gauge and warning light. In experiments with drivers to evaluate driver information systems for cars of the future, Green (1996) found that drivers know the brake system is important and would respond as desired to a brake warning. Late model passenger vehicles are equipped with a multitude of warnings lights to both remind drivers (e.g. parking brake applied, service due) or to readily alert drivers about conditions that need immediate attention (e.g. low oil pressure or brake fluid). Some warnings are designed with a safety factor to allow drivers to operate vehicles to the nearest authorized service centre for inspection (e.g. SRS, check engine). Lerner et al prepared definitions to determine when warnings should be issued to prompt the immediate need for drivers to respond to an imminent crash avoidance situation or cautionary crash avoidance situation.

Vehicle-based monitoring systems are being explored to monitor the status of vehicle systems and condition of
drivers. Information generated by vehicle-based monitoring systems may assist drivers make informed decisions about whether action is warranted to circumvent crash involvement. Over 20 years ago, Forman and Lemeshewsky (1975) indicated that although it would be desirable to monitor the status of brakes to avoid the consequences associated with dangerous brake failures, on-board monitoring was limited in scope. One such limitation was the transfer of data between the seven-pin electrical connector (six circuits plus one ground) that supplies power between the tractor and trailer of air-braked vehicles. This can now be accomplished by several possibilities including (but not limited to) communication signal multiplexing, voltage enhancements, radio/telemetry communication linkages, additional electrical circuits, and wiring system upgrades.

An intelligent power and high speed communications link was developed between the tractor and trailer by the Truck Multiplexing (TruckMux™) project using the standard SAE J1067 seven-wire cable and J560 connector. Wissing et al (1998) reported that the TruckMux™ prototype outfitted to a tractor-trailer was capable of handling over 70 million J1939 messages without a single failure. NHTSA (1995) reported that on-board brake system performance monitoring systems offer many potential advantages including providing drivers of air-braked vehicles with advanced notice that brake maintenance or repairs are required. The system approach to design a digital message center that could display warning messages (including maintenance related information about the brake system) to operators of air-braked vehicles was explained by Rodriguez et al (1997).

A tire monitor system (TMS) has been developed (and seemingly became available in April 1998) to provide a cab-display warning to inform drivers of air-braked vehicles when the tire inflation pressure has dropped more than 10 percent of fleet-specified pressure. Sensors mounted within tires (each with their own frequency) use valve stems as antennas to transmit data to the cab compartment. Similarly, new generation [smart] sensors may permit the development of vehicle-based monitoring brake systems that can provide information to drivers about the status of air-brake systems by measuring and monitoring brake torque, temperature, acceleration or the linear angle of applied pushrods.

Depending on the objective, different approaches may be taken to develop vehicle-based brake monitoring systems for air-braked vehicles. Whichever approach is taken, design issues will need to be addressed and challenges resolved. With any type of system that may be entirely relied upon by drivers to make informed decisions, this includes questions that surround the correct interpretation of data, reliability of electronic systems, and human factor issues with regard to providing real-time information to drivers. Additionally, there are questions about the cost-benefit and standardization of advanced systems integrated into air-braked vehicles, that in the future, will likely be equipped with electronically controlled braking systems (EBS). In terms of driver acceptance of vehicle-based monitoring systems, a survey of 152 drivers in Great Britain (1998) found that 89 percent of truck drivers would like a wakefulness monitor that sounds an audible alarm.

**Low-Cost Cab-Display Brake Fault Indicator Lamp**

The concept of a low-cost cab-display brake fault indicator lamp (BFIL) is proposed to address “known” maintenance-related braking problems that arise because of the sensitivity of air-braked vehicles to maintenance. (Appendix B). Unlike the complexities that may accompany the development and installation of more sophisticated vehicle-based monitoring systems that potentially could influence drivers to become complacent and abstain from performing daily checks of air brake systems, a BFIL would be intended to “assist” drivers make informed decisions about whether brake repairs are warranted before air-braked vehicles are placed into service or descend steep grades. Similar to other indicator lamps (e.g. ABS malfunction, check engine) the illumination of the BFIL would be easy to interpret by drivers and the integrity (and collected faults) of a BFIL could be confirmed when periodic inspections were performed. Much like data recorded by electronic engines, decisions could be made by truck owners to determine what information would be captured and stored by a BFIL. The specific details with respect to the design and development of a BFIL are beyond the scope of this paper.

Further research would provide an opportunity to resolve questions about equipping air-braked vehicles with a low-cost cab-display brake fault indicator lamp. For example:

- could the image of the trucking industry be bolstered, and truck safety concerns of road users addressed, by equipping air-braked vehicles with a BFIL?
- is there a strong market demand for the installation of a BFIL in air-braked vehicles?
would the widespread installation of a BFIL in air-braked vehicles be instrumental in reducing the out-of-service rate of air-braked vehicles?

should an initiative to equip air-braked vehicles with a BFIL be industry-driven or regulated?

what role can industry take to standardize the installation of a BFIL in air-braked vehicles?

would enforcement officials have an interest to access data captured by a BFIL?

would a BFIL increase the reliability of service (foundation) brakes by raising the awareness of drivers to conditions that are sensitive to maintenance?

what level of activation error could be tolerated by the integration of a BFIL in air-braked vehicles?

what are the product liability implications should a BFIL malfunction?

DISCUSSION

Clarke et al (1987) reported that with the exception of the steering axle, most air-braked vehicles are capable of generating sufficient brake torque to lock (or nearly lock) all wheels on all road surfaces regardless of loading conditions. This, however, assumes that the service (foundation) brakes are adequately maintained and that someone will be vigilant on a daily basis to ensure that the applied pushrod stroke of each brake chamber is maintained within re-adjustment limits. Even with service (foundation) brakes properly maintained, air-braked vehicles take considerably longer to stop than hydraulically-braked vehicles. This disparity is further aggravated when brake-related maintenance (including adjustment) is overlooked. Continuous intervention is required to preserve the braking capacity of the service (foundation) brakes and compensate for the degradation in the stopping capability of air-braked vehicles as brake components wear. The sensitivity of air-braked vehicles to maintenance has long been recognized as a safety issue. Although several conditions associated with the service (foundation) brakes can be regarded as maintenance-related braking problems (e.g. cracked drums, oil-soaked linings, audible air leaks), the most common problem, by far, remains the excessive applied pushrod stroke of brake chambers (adjustment). Left unresolved, maintenance-related braking problems can seriously affect the ability of drivers to maintain control of air-braked vehicles.

There has been considerable debate about whether there is a causal link between maintenance-related braking problems of air-braked vehicles and crashes. The limited amount of quantitative crash-related data available may explain why a direct link between maintenance-related braking problems and crashes involving air-braked vehicles may not have been definitively established. Despite this finding, serious crashes with tragic outcomes have, and continue, to occur. Perhaps most notably are downhill runaway events that render drivers of air-braked vehicles with little, and in some situations, absolutely no ability to control descent speed. In most instances crash-involved drivers of air brake vehicles (including bus drivers) were not likely acutely cognizant, through knowledge gained from training courses or after performing pre-trip inspections, that a maintenance-related braking problem existed, and moreover, had grossly deteriorated the stopping capability and reserve braking capacity of the service (foundation) brakes.

A false sense of security may be present with respect to safeguards that have been imposed to ensure that maintenance-related braking problems are identified before diminished braking performance leads to the crash involvement of air-braked vehicles. Considerable emphasis is placed (and assumptions made) that someone (usually the driver) will accurately determine whether an air-braked vehicle has a maintenance-related braking problem before it is placed into service. Currently, this can only properly be done through observation or physical action while lying on the ground and crawling around in dim light conditions that exist (regardless of time of day) underneath air-braked vehicles. Visibility restrictions, access constraints, design limitations, and performance that continues to be reliant on maintenance, still require that this same procedure be taken even with air-braked vehicles equipped with stroke indicators and automatic brake adjusters.

The completion of daily pre-trip inspections by drivers does not guarantee that air-braked vehicles will not later (even that same day) be involved in crashes due, partly or entirely, to maintenance-related braking problems. To believe otherwise assumes that drivers of air-braked vehicles are (a) keenly aware about the limited reserve braking capacity of air-braked vehicles compared to hydraulically-braked vehicles, (b) cognizant that maintenance-related braking problems that affect braking performance and reduced braking capacity cannot readily be detected by observing gauges in the cab compartment or with a light brake application, (c) have the mechanical aptitude to know what constitutes a maintenance-related braking problem serious enough to require immediate
attention, or (d) have the authority or wherewithal to make arrangements to resolve maintenance-related braking problems before air-braked vehicles are placed into service. Regardless of the reason why drivers either abstain from inspecting the condition and adjustment of service (foundation) brakes or are unable to detect maintenance-related braking problems, there is unquestionably reason for concern when the most relied upon and dependent safeguard to identify brake faults on air-braked vehicles appears inadequate. The same dependence to identify operational deficiencies of “critical” components to maintain control is not imposed on drivers that drive hydraulically-braked vehicles, nor, operators of other modes of transportation (e.g. air, marine, rail).

Maintenance-related braking problems may also be identified by trained journeyman heavy duty mechanics when air-braked vehicles are next scheduled for routine maintenance, periodic inspections, or by chance encounter with enforcement officials at roadside inspections. This, however, assumes that journeyman heavy duty mechanics will (a) not inadvertently overlook maintenance-related braking problems, (b) always perform proper repairs, and (c) will detect and resolve brake-related deficiencies before air-braked vehicles are involved in brake-induced crashes. In short, visual inspections of the brake systems on air-braked vehicles provides considerable room for interpretation by humans (drivers or mechanics) about whether air-braked vehicles are (or are not) safe to drive. The new millennium is expected to introduce continuous rapid development of low-maintenance air-braked vehicles and more outsourcing of maintenance. Will this assist to resolve or exacerbate safety concerns associated with the sensitivity of air-braked vehicles to maintenance?

Manufacturers have taken steps through design to address the sensitivity of air-braked vehicles to maintenance. Additionally, minimum standards were established to test and license drivers (e.g. CDL endorsements / restrictions) and advancements have been made in the design of brake-related components to address the sensitivity and reliability of air-braked vehicles (e.g. long stroke chambers, automatic brake adjusters). Although it may be premature at this time to know just what effect brake improvements introduced in recent years will have in the future, there continues to be an unacceptable number of air-braked vehicles routinely placed out-of-service at roadside inspections because of maintenance-related braking problems. In terms of a duty of ordinary and reasonable care, Johnson and Eidson (1995) indicated that manufacturers are responsible for (a) the design and production of products, (b) keeping track of advanced discoveries and scientific information associated with the safety of its product, and (c) providing warnings when sound engineering practices cannot effectively eliminate all known hazards.

The only current requirement for air-braked vehicles to be equipped with a continuous audible or visible warning device is to alert drivers when supply (reservoir) system pressure drops below 60psi. Yet it is doubtful that there have been many (certainly fewer than those because of maladjusted brakes) air-braked vehicles involved in serious crashes because of a catastrophic loss of pressure in the supply (reservoir) pressure. Drivers cannot become aware while seated in the cab compartment when the braking performance or reserve braking capacity of air-braked vehicles has been compromised by maintenance-related braking problems. A low-cost cab-display brake fault indicator lamp may be an effective method to prevent costly mistakes that inadvertently and regrettablly can be made because of the inability of drivers (for whatever reason) to detect maintenance-related braking problems on air-braked vehicles before serious crashes occur.

For the safety of all road users, should the duty of care associated with detecting conditions that degrade the braking performance and limit the reserve braking capacity of air-braked vehicles continue to be solely dependent on traditional and conventional means - the ability of drivers to detect maintenance-related braking problems when daily pre-trip inspections are conducted? Or should consideration be given to determine whether advancements in electronic systems may now allow the opportunity for air-braked vehicles to be equipped with a reliable low-cost cab-display brake fault indicator lamp that could in the future (along with inspections of brake components) “assist” drivers become aware of maintenance-related braking problems before air-braked vehicles are placed into service or descend steep grades?

SUMMARY AND CONCLUSIONS

The sensitivity of air-braked vehicles to maintenance has been a safety issue for a long time. Maintenance-related braking problems can significantly diminish braking performance and reduce the limited reserve braking capacity of air-braked vehicles. Left undetected, brake-related deficiencies can further increase the disparity between the distance required for air-braked vehicles compared to hydraulically-braked vehicles to
safely stop. Manufacturers have been instrumental in gains that have been achieved to advance the performance and reliability of air brake systems. Considerable effort has been devoted to optimize the braking performance of air-braked vehicles and address brake maintenance issues. While air brake systems have been improved, maintenance-related braking problems still prevail and the principle reason why air-braked vehicles are placed out-of-service at roadside inspections.

On a day-to-day basis, drivers are the primary safeguard for detecting maintenance-related braking problems on air-braked vehicles. Despite having been trained, drivers as a group are generally limited in their knowledge and understanding about the design limitations, maintenance requirements, and operational demands that affect the braking performance and reserve braking capacity of air-braked vehicles. Drivers of air-braked vehicles may often abstain or inadvertently overlook maintenance-related braking problems when daily pre-trip inspections are conducted, or use inaccurate methods to check the adjustment of service (foundation) brakes on air-braked vehicles.

Similar to driver-related factors, maintenance-related braking problems are not always easily discernible to enforcement officials that attend crashes involving air-braked vehicles. The prevalence of maintenance-related braking problems as a probable cause of crashes involving air-braked vehicles is considered to be under-reported.

Advancements in electronic systems have now made it possible to develop vehicle-based monitoring systems and display messages in the cab compartment of air-braked vehicles. The concept of equipping air-braked vehicles with a low-cost cab-display brake fault indicator lamp (BFIL) may reduce the out-of-service rate of air-braked vehicles inspected at roadside inspections by assisting drivers make informed decisions about whether brake repairs are warranted. A BFIL is not intended to abdicate the duty of drivers to perform daily pre-trip and enroute inspections of air brake systems, but to enhance the safety of air-braked vehicles. Conceptually, this would be done by supplementing information from visual inspections of air brake systems to assist drivers become keenly aware of whether "anticipated" maintenance-related braking problems are present (those historically and routinely discovered at roadside inspections) so that, if necessary, repairs can be arranged before air-braked vehicles are placed into service or descend steep grades.

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The conclusions reached, and opinions expressed, in this paper are solely the responsibility of the author and do not necessarily represent the official policy of the Insurance Corporation of British Columbia.

REFERENCES

Atkin, R.L., Bennett, J.D., Safety Brake Systems for Commercial Vehicles, SAE Paper No. 640076

Canadian Attitudes Toward Trucking Safety on Highways, Angus Reid Group, Inc., October 1996

Case Summaries of 189 Heavy Truck Accident Investigations, National Transportation Safety Board, Report No. PB88-917007, 1988


Decker, H., Wrede, J., Brake-by-Wire: Solutions, Advantages and the Need for Standardization, SAE Paper No. 94C039


*Heavy Vehicle Air-Brake Performance*, National Transportation Safety Board, Report No. PB92-917003, April 1992

*Heavy Truck Safety Plan*, U.S. Department of Transportation May 1991

*Heavy Vehicle Safety Research: A New Agenda for the 21st Century*, June 1995


Heusser, R.B., *Heavy Truck Deceleration Rates as a Function of Brake Adjustment*, SAE Paper No. 910126

Heusser, R.B., *Air Brake Inspections on Five-Axle Combinations*, SAE Paper No. 922443


Laurie, G.W., *Maintenance of a Concentrated Fleet of Large Trucks*, SAE Paper No. 380132


Lindemann, K., *EBS and Tractor Trailer Brake Compatibility*, SAE Paper No. 973283


Murphy, R.W., Limpert, R., Segal, L., *Development of Braking Performance Requirements for Buses, Trucks and Tractor-Trailers*, SAE Paper No. 710046


Radlinski, R.W., Williams, S.F., Machley, I.M., The Importance of Maintaining Air Brake Adjustment, SAE Paper No. 821263

Radlinski, R.W., Braking Performance of Heavy U.S. Vehicles, SAE Paper No. 870492

Radlinski, R.W., Flick, M.A., Benefits of Front Brakes on Heavy Trucks, SAE Paper No. 870493

Radlinski, R.W., NHTSA's Heavy Vehicle Research Program - An Overview, SAE Paper No. 876099

Rodriguez, L., Bertalan, R., Jahns, S., Design Challenges in Developing the PACCAR Digital Message Center, SAE Paper No. 971744


Seiff, H.E., Brake Defects in Roadside Inspections, SAE Paper No. 942290


Status Report on Truck and Truck Driver Safety, California Highway Patrol, January 1991

Tauss, W., Brake Maintenance and Brake Development, SAE Paper No. 580228


Thompson, R.E., Improving Disc Brakes, SAE Paper No. 942301


Vaughan, R.G., Safety Maintenance of Road Vehicles, SAE Paper No. 934267


Wrede, J., Decker, H., Brake by Wire for Commercial Vehicles, SAE Paper No. 922489
Appendix A

PRIMARY SAFEGUARDS TO PREVENT BRAKE-INDUCED CRASHES INVOLVING AIR-BRAKED VEHICLES

Maintenance-Related Braking Problems

- #1 Safeguard
  - Daily Pre-Trip Inspections
    - Undetected
      - Reduced 'Reserve' Braking Capacity

- #2 Safeguard
  - Periodic Inspections
    - Undetected
      - Diminished Braking Performance

- #3 Safeguard
  - ‘Random’ Roadside Inspections
    - Out-of-Service
      - Causal Factors to Brake-Induced Crashes
Appendix B

CONCEPTUAL INTEGRATION OF A RELIABLE LOW-COST CAB-DISPLAY BRAKE FAULT INDICATOR LAMP FOR AIR-BRAKED VEHICLES

Regulated Industry-Driven Enforcement Tool

Concept

Brake Standards Reliable Low-Cost Cab-Display Brake Fault Indicator Lamp

Aftermarket Installations Compliance Measures

Factory-Installed Brake-Related Issues

OEM TRUCK OWNER Periodic Inspections

Brake Supplier Pre-Trip Inspections

Truck Trailer

End-User

Brake Design Duty to Warn Human Factor Issues Chance Encounter

Roadside Inspections

CRASHES

Sensitivity to Maintenance Maintenance Related Braking Problems MDAI Studies

Reduced Braking Capacity Diminished Braking Performance Performance-Based Testers

Post-Crash Inspections

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