

# **Engineering Assessment of Current and Future Vehicle Technologies**

**FMVSS No. 121; Air Brake Systems**

**Final Report**

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## Executive Summary

Federal Motor Vehicle Safety Standard (FMVSS) No. 121, Air brake systems, contains requirements for the performance and design of air brake systems on trucks, buses, and trailers. Its purpose is to ensure the safe braking performance of these vehicles under normal and emergency conditions. NHTSA asked that the technology review focus on three specific areas: electronic brake actuation or electronically-controlled braking systems (ECBS), air reservoir capacity, and brake performance measurement.

In the United States, market demand for ECBS is small and unlikely to grow substantially in the next three years. Nevertheless, manufacturers are aware of the advantages offered by ECBS and would welcome clarification of the standards regarding ECBS. The industry is uncertain as to what extent the current rule allows ECBS. ECBS is not necessary to meet any current needs for stopping distance or stability, but the industry would eventually like to move to ECBS for the shorter stopping distances and other efficiencies it offers. One contact said that ECBS is unlikely to be deployed in North America in less than two years, but another believes ECBS will be inevitable in eight to ten years to meet the demand for yet shorter stopping distances. United Nations Economic Commission for Europe Regulation 13 (ECE R13) has failure tests regarding magnetic or electrical interference, tractor trailer incompatibility, and power supply failure, but it does not cover all failure modes. Evaluating the possible failure modes of an ECBS using traditional performance standards is difficult; a new philosophical approach to ensuring fault-tolerant braking systems may be required.

Modern systems on trucks, notably tire inflation systems and air suspension systems are placing additional demands on the air supply. Pressure protection valves protect the brake air supply from a catastrophic failure in a non-braking system, but a slow leak can prematurely wear the air compressor. Both ECE R13 and Society of Automotive Engineers (SAE) Recommended Practice J1609 take a performance-requirements approach to sizing air reservoirs.

Existing onboard brake monitoring systems can assess stroke, lining thickness, and general failures. Component tests for the linings are available, as are low speed on-vehicle performance-based brake tests (PBBT).

This report was produced by Battelle, the University of Michigan Transportation Research Institute (UMTRI), and the Transportation Research Center, Inc., who were contracted by the National Highway Traffic Safety Administration (NHTSA) to provide support for the Regulatory Review Plan. This program systematically reviews all FMVSS on a regularly scheduled basis. This report describes an engineering assessment of FMVSS 121. Other aspects of the review, including the target safety problem assessment and a listing of other societal factors, are being performed separately by NHTSA. The standard for motorcycle brake systems, No. 122, and the two standards relating to hydraulic brake systems, FMVSS Nos. 105 and 135, have been assessed under earlier tasks on this contract. [1, 2]

## Introduction

The National Highway Traffic Safety Administration (NHTSA) has implemented a Regulatory Review Plan to systematically examine each of the Federal Motor Vehicle Safety Standards (FMVSS), 49 CFR 571. This review examines all factors that are relevant to the standards, including demographics, societal values, crash statistics, and vehicle mix in the national fleet. An important element of the review is an engineering assessment of new developments in technology that may influence the standard. The purpose of the technology assessment is to determine whether there have been changes that have significantly altered the vehicle systems affected by the standard, thereby necessitating its enhancement. It also will yield information on the capabilities of the newly available technologies, or technologies in development, to meet a higher level of safety performance.

NHTSA has contracted with a team composed of Battelle, the University of Michigan Transportation Research Institute (UMTRI), Transportation Research Center Inc., and Smithers Scientific Services to support the technology component of the regulatory review. This team examines the standards individually on a schedule established by NHTSA. The current report addresses FMVSS 121, air brake systems.

The team follows a common work plan for each assessment, adapting the plan for the nature of the standards and the scope of the review. At the outset of each review, members of the contractor team meet via teleconference with the NHTSA Contracting Officer's Technical Representative (COTR) and regulatory, compliance, and other engineers responsible for the standard to establish the scope for the assessment of the particular standard. The scope for this search is documented in the first section of this report. The team then gathers information from published literature and private contacts within the industry. The information is summarized and categorized. Subject matter experts are consulted to assess the relevance and expected significance of each technology. The result is summarized in Section II of this report. If requested by NHTSA, the assessment may include engineering analysis. Such analysis was not requested for the present standard. The final section of the report reiterates the major conclusions of the assessment and the possible implications of the developing technologies on the safety standard.

### I. Scope of the Search

The scope-setting conference call for this assessment was held on June 27, 2007. The participants were:

- NHTSA: Hyun Peck, Bruce Spinney, Matt Lehmer, Tim Johnson, Jeff Woods, George Soodoo, Dick Hoover, and Barbara Faigin.
- Battelle: Doug Pape, Steve Shaffer, Patrick Esber, and Dave Walters.
- TRC: Randy Landes

Air braking is a field of active research by the industry and by NHTSA. Many topics were discussed during the conference call, but the major topic for this assessment was to be electronic brake actuation. Considerations on reservoir capacity and possible test procedures for brake linings were to be included as well.

## A. Systems for Assessment

Table I summarizes the systems affected by the standard.

**Table I. Systems Affected by FMVSS 121**

Purpose of the standard	The safety goal of the standard is to insure safe braking performance under normal and emergency conditions.
Systems affected	Service, emergency, and parking brakes. ABS or ECBS. Air system (air compressor, reservoirs, towing vehicle protection systems, pressure gages, and warning signals).
Indirectly affected subsystems	Traction control, stability- and control-enhancement systems
Other relevant standards	<p>As called out in the standard:            ASTM E1136 standard reference test tire;            ASTM Method E 1337-90 standard test method for peak tire/pavement braking coefficient using standard tire            ASTM Method E-274-70 pavement friction measurement</p> <p>In addition there are numerous SAE, ISO, EU and other national standards in existence and currently under development relating to vehicle braking performance, the braking system and braking system components for air braked vehicles.</p> <p>These include:            ECE R13 “Braking on Vehicles of Categories M, N, and O”            ECE R90 “Uniform Provisions Concerning the Approval of Replacement Brake Lining Assemblies and Drum Brake Linings for Power-Driven Vehicles and Their Trailers”            TMC RP628 “Aftermarket Brake Lining Classification”            SAE RP J1609 “Air Reservoir Capacity Performance Guide—Commercial Vehicles”            SAE RP J1911 “Test Procedure for Air Reservoir Capacity—Highway Type Vehicles”            SAE RP J1802 “Brake Block Effectiveness Rating”</p>

Table II details the scope of the search for FMVSS 121. A notice of proposed rulemaking regarding stopping distances is pending [3]; stopping distance was a part of the search only to the extent that it was incidental to these three topic areas.

**Table II. Scope of the Search for FMVSS 121**

1. Actuation	Review existing, in-development, and proposed brake actuation systems such as pneumatic (2P), pneumatic/electronic (1P1E) and fully electronically actuated brakes (2E). Highlight areas where the existing standards may be insufficient or problematic in terms of system requirement (S5), test conditions (S6) and/or test procedures (i.e., TP-121V-05).
2. Reservoir Capacity	Review existing and foreseeable trends that will affect demand on the reservoir or affect its available size.
3. Sensing for application and on-board performance measurement	Review existing and proposed sensing systems for brake application (ECBS) and diagnostics, where brake application is directly affected by the output from such sensors, and warnings can be communicated as a result of diagnostics. Also review current and future brake performance assessment systems for replacement linings or other components for use on in-service vehicles.

## B. Methodology

Table III lists specific questions that were to be answered.

**Table III. Questions to be Answered during the Search**

<b>ECBS and other non-conventional actuation systems</b>
Are there current production vehicles or announced plans for future vehicles with complete brake-by-wires systems (2E), without any pneumatic control backup?
Are brake manufacturers delivering or planning to deliver electronically controlled air brakes for use on trucks or buses in the North American market?
How does ECE R13 accommodate partial or full electronic actuation?
What is the prevalence of electronic control or (a lower-priority) “air over hydraulic” control on heavy vehicles being imported to the United States?
<b>Reservoir Capacity</b>
Do non-braking systems that require compressed air (such as tire pressure monitoring systems or air suspensions) or braking systems that do not ordinarily use air (such as regenerative braking) affect the requirements on the reservoir capacity?
What technologies might help develop performance-based standards for air consumption or reservoir volume?
<b>Performance Measurement</b>
What technology exists for on-board measurement of brake performance, and how might these affect the standard? Examples include: brake stroke indicators, on-board sensors (decelerometers in combination with ECBS- or ABS-system based pressure transducers) and instrumented anchor pins.
What technologies or test procedures are available to characterize aftermarket brake linings, and perhaps methods to assess them on in-service vehicles?

The task leader at Battelle was Dr. Steven Shaffer, who was assisted by Patrick Esber, Dave Walters, and Douglas Pape. UMTRI's contribution was led by Dr. Timothy Gordon with assistance from Christopher Winkler. Randy Landes was responsible for the input by TRC.

### **C. Sources**

In pursuing this technology assessment, the Battelle team reviewed the relevant technical and fleet-focused literature. Members of the Battelle team interviewed engineers at all major suppliers of air brake systems and almost all manufacturers of Class 8 tractors. Some of these individuals are on Society of Automotive Engineers (SAE) committees responsible for systems being assessed; others are involved in the development of European standards such as ECE R13. The team also contacted manufacturers of hybrid drive systems, suppliers of onboard sensing devices, semitrailer manufacturers, and bus manufacturers. Both North American and European engineers were contacted to provide information and perspectives from both jurisdictions. Air brake veterans Duane Perrin and Dick Radlinski gave valuable insights. Federal Motor Carrier Safety Administration (FMCSA) staff were consulted for their knowledge of on-board brake performance testers or lining tests.

## **II. Search Results and Engineering Assessment**

The three subsections below address engineering trends and relevant standards for the three topic areas of the search—electronically controlled braking systems, air reservoir capacity, and evaluation of brake components.

### **A. Electronically Controlled Braking Systems**

When the foot treadle is displaced in a traditional air brake system, a pneumatic control signal is sent to each of the proportional relay valves on the vehicle or combination vehicle. The air pressure supplied to the chambers is “proportional” to the pressure of the pneumatic control signal. The relay valves, also known as distribution valves, allow compressed air from the reservoirs to flow to the air chambers (typically two per axle or four per tandem axle set), which in turn actuates the brakes. In an Electronically Controlled Braking System (ECBS), an electrical signal replaces the pneumatic control signal that is sent to the relay valves.

ECBS offers advantages of decreased stopping distance and advanced technologies that are enabled by the electronics. Stopping distances could be shortened by ECBS in two ways. First, an electrical signal travels faster than a pneumatic signal. The benefit would increase as the length of the vehicle increased, and particularly for multiple trailers. In addition, ECBS allows for better monitoring and control of brake proportioning and tractor-trailer balancing. This could be effective for shortening stopping distances, as the brake forces could be maximized in proportion to the limit of slip, and adjusted for tractor and trailer balancing. ECBS typically also provides roll and yaw stability control by the automatic application of individual brakes to control the vehicle's trajectory. Pneumatic ABS can provide a degree of proportioning and balancing, and all three major suppliers of air brakes in North America are currently offering various stability systems with pneumatic ABS. An advantage inherent to ECBS is manufacturing and maintenance; wires are simpler to install than air hoses, and wires are not subject to air leaks.

Nomenclature for pneumatic and electronic brake configurations was defined in Figures 2 and 3 of a report to NHTSA in 1998 [25]. “0E-2P” referred to two independent circuits on a tractor. A “1E-2P” system would have an electronic control for one or both of the pneumatic circuits. In a “2E-0P” system, there were two independent electronic control circuits, which may or may not be independent in their control of the actuators. When used informally, these terms can mean different things to different people. The difference lies in what component is being duplicated—the control line or supply line.

## 1. The market for Electronically Controlled Braking Systems

### Key Points:

- There is little market pull for ECBS in the United States.
- In Europe, ECBS is the dominant system for large trucks.

Very few vehicles with ECBS are being manufactured or imported into the United States. Freightliner has offered a 2E2P ECBS since 1995, but few are buying it. In contrast, a large percentage of tractors currently being manufactured for use in Europe are equipped with ECBS. ECBS is dominant in Western European countries; pneumatic ABS remains the more popular choice in Eastern Europe.

Engineers in North America are aware of the potential advantages of ECBS. [4] They aver that it is not cost-effective in the North American environment, though the details of the reasons for this differ. Many contacts indicated that ECBS is not cost effective under the current 121 wording because electronic controls would need to be added to the required double pneumatic controls, and the extra level of redundancy is not cost effective. There is, however, more than one school of thought as to what the current wording of 121 requires<sup>1</sup>.

A more fundamental reason why ECBS is not common in North America is that this market is unwilling to incur any unneeded cost. This unwillingness is closely linked to the traditional conservatism of the North American market. Established technology is reliable, while new technology is considered less reliable and down-time for a vehicle is a costly expense. Current stopping distance requirements can be met with ABS, electronic stability controls can be incorporated with ABS, and, as is discussed in Section C below, even rudimentary diagnostics can be built into ABS. Whereas tractor manufacturers were looking forward to developing ECBS when the market, standards, regulations, and cost were right, the trailer manufacturers

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<sup>1</sup> Most engineers contacted hold that 121 requires a 2P system and any electronic control would need to be added on top of that. The requirement of having an emergency system that will stop the vehicle if there is “a single failure in the service brake system of a part designed to contain compressed air or brake fluid” (FMVSS 121, S5.7.1) dictates that on the supply side there will always be 2P. Others say that a more careful reading of the standard merely requires a backup control system but does not require that the backup be pneumatic. By this view, a 1E1P system, having one electronic and one pneumatic control line, would be acceptable under FMVSS 121. At least two have noticed that the definition S4, “Air brake system means a system that uses air as a medium for transmitting pressure or force from the driver control to the service brake. . .” excludes systems with purely electronic control. By the Scope in S1, then, a system with only wires coming from the brake pedal would not be covered at all by FMVSS 121. The industry representatives doubt that any manufacturer would actually make such an argument, though there is at least one interpretation letter consistent with that reading [5].

seemed much less interested in pursuing ECBS. Manufacturers would require a minimum of two years to develop and test an ECBS system before releasing it in North America. One posited that ECBS would become necessary in eight to ten years with foreseeable market trends and likely future reductions in stopping distance requirements.

The contacts were aware of air-over-hydraulic systems and agreed that they were mostly on mid-size imports. None believed them to represent a substantial market share. The primary benefit to an air-over-hydraulic system is a slight savings in space.

In Europe ECBS is on approximately 80% of large trucks, and it is becoming common on mid-size trucks. This greater demand for ECBS is a result of ECE R13 requiring shorter stopping distances than FMVSS 121 (see Table IV).

**Table IV. Required Stopping Distances for a Loaded Tractor from 60 mph**

Standard	Distance
Current FMVSS 121	355 ft
Proposed FMVSS 121	249-284 ft
ECE R13	196 ft*
* This distance is for an N <sub>3</sub> vehicle (used for the carriage of goods having a maximum mass exceeding 12 tonnes category) with the engine connected.	

In Europe, proportioning is often used to help achieve the shorter stopping distances. While proportioning can be accomplished by a pneumatic system, it requires expensive valves, and European manufacturers have found that by spending incrementally more money to get ECBS, they can enable proportioning and the other benefits of ECBS. A factor that facilitated the insertion of ECBS in Europe was that tractors and trailers there are not custom-made as they are in North America. It is more like the system for passenger cars; there are choices between several models or options of vehicles. In this market environment, ECBS could be offered on luxury models. All of the heavy-duty, medium-duty, and light-duty trucks offered by one European manufacturer are equipped with 1E2P systems. At the customer's request, the medium-duty and light-duty trucks can be downgraded to conventional air brake systems. One European bus manufacturer sells only 1E2P ECBS systems. Newer disc brake systems from some manufacturers (which are 75% of production in one case) are exclusively ECBS. The upcoming European requirement of electronic stability protection (ESP) will push even more manufacturers to ECBS because manufacturers will not want to develop ESP for ABS, which is a declining market.

## 2. Regulatory Considerations for Electronically Controlled Braking Systems

### Key Points:

- Electronic control systems are not well suited to generic performance tests.
- ECE R13 has been tailored to allow ECBS and addresses certain ECBS failures.
- Electronically controlled, pneumatic brake systems are being developed for railroads.

Electronic controls are naturally subject to different failure modes than are pneumatic controls, so they must be tested in different ways. Moreover, the components of ECBS, with their integrated circuits and software, are packaged in a fundamentally different way than are pneumatic components. It is impossible for a regulator to anticipate all of the failure modes before suppliers design the systems. One expert noted that even possible failures in the logic of ABS are not covered in the current FMVSS No. 121. The previous engineering assessment of hydraulic brake systems [2] extensively discussed the implications of fault-tolerant braking systems on pages 14 and 15. NHTSA has long been aware that a different approach is necessary for testing these systems<sup>2</sup>. The following paragraphs describe how testing electronic braking controls has been addressed in two prior situations.

The major regulation involving ECBS is ECE R13 [6], the European standard that regulates the braking of most tractors, trailers, and buses. Work was started in 1989 to incorporate ECBS into ECE R13, and by 1996 ECBS regulations were incorporated. This updating of ECE R13 focused on concerns that were unique to ECBS.

Electromagnetic interference is addressed in paragraph 5.1.1.4 of R13: “The effectiveness of the braking systems, including the electric control line, shall not be adversely affected by magnetic or electrical fields.” Compatibility with older tractors and trailers equipped only with pneumatic control is addressed in paragraphs 5.1.3-5.1.3.8: “A power-driven vehicle equipped according to paragraph 5.1.3.1.3 shall recognize that the coupling of a trailer equipped according to paragraph 5.1.3.1.1 is not compatible. When such vehicles are electrically connected via the electric control line of the towing vehicle, the driver shall be warned by the red optical warning signal specified in paragraph 5.2.1.29.1.1 and when the system is energized, the brakes on the towing vehicle shall be automatically applied.” (5.1.3.1.3 refers to a tractor or trailer that has only electronic control and 5.1.3.1.1 refers to a tractor or trailer that has only pneumatic control) Common practice in Europe is to maintain matched tractor-trailer pairs, so such a drastic result (applying the tractor brakes) is better tolerated than it would be in the United States. Paragraph 5.2.1.9 deals with the possibility that a malfunction would apply the brakes against the driver’s wishes: “Malfunctions of the electric control transmission shall not apply the brakes contrary to the driver’s intentions.” ECE R13 also discusses various failures involving the supply of electricity to the control system, such as failure of the alternator or main supply battery, in paragraphs 5.2.1.27-5.2.1.27.10: “In the event of a failure of the energy source of the electric control transmission, starting from the nominal value of the energy level, the full control range of the service braking system shall be guaranteed after twenty consecutive full stroke actuations of the service braking control.” Paragraph 5.1.3.1.3 and footnote 4 anticipate pure 2E systems: “Until uniform technical standards have been agreed, which ensure compatibility and safety, connections between power-driven vehicles and trailers conforming to paragraph 5.1.3.1.3 shall not be permitted.”

ECE R13 Annex 18 addresses the special safety requirements of complex electronic vehicle control systems, such as ECBS (the complex electronic vehicle control system is referred to as “The System”). Annex 18 “does not specify the performance criteria for ‘The System’ but covers the methodology applied to the design process and the information which must be

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<sup>2</sup> A 2000 news article quoted then-NHTSA engineer Duane Perrin, “We’ve dealt with simple failure testing, such as how brakes work if an air line hose connection breaks. With electronics, however, you can’t get inside a chip and unhook a hose.” [7]

disclosed to the technical service, for type approval purposes. This information shall show that “The System” respects, under normal and fault conditions, all the appropriate performance requirements specified elsewhere in this Regulation.”, Annex 18 paragraph 1. The manufacturer must provide the following information about their system:

- Description of the functions of “The System” including all of the input and output variables and how the output variables are controlled.
- System layout and schematic, including signal flow and priorities.
- Safety Concept of the manufacturer, which describes how the control system will continue to function even if there are failures within the system.

Furthermore, “as the means of establishing the normal operational levels, verification of the performance of the vehicle system under non-fault conditions shall be conducted against the manufacturer's basic benchmark specification unless this is subject to a specified performance test as part of the approval procedure of this or another Regulation.”, Annex 18 paragraph 4.1.1. The safety concept is “checked under the influence of a failure in any individual unit by applying corresponding output signals to electrical units or mechanical elements in order to simulate the effects of internal faults within the unit.”, Annex 18 paragraph 4.1.2. After all of the requirements for the control system have been met, the control system is given type certification.

Braking regulations for passenger cars have been harmonized with FMVSS 135 in document ECE R13 H. Heavy vehicle manufacturers would welcome the efficiencies of harmonizing FMVSS 121 with ECE R13.

Emerging markets in China and India will be using ABS for at least the next ten years. Brazil, in contrast, is just now contemplating the move to ABS. This will prompt manufacturers to continue making both ABS and ECBS systems regardless of any harmonization.

The Federal Railroad Administration released a Notice of Proposed Rulemaking (NPRM) for electronically controlled pneumatic (ECP) brake systems. Air brakes work differently on trains than they do on trucks and buses. The air supply and brake control are a single line on a train. The NPRM [8] explains how ECP will be implemented: In a conventional braking system, the locomotive engineer uses the main reservoir to charge the brake pipe—a 1-1/4-inch-diameter pipe—that runs the length of the train and is connected between cars with hoses. Braking occurs through a reduction of air pressure in the brake pipe, which signals the valves on each car to direct compressed air from the reservoir on each car to its respective brake cylinder for an application of brakes. ECP brake technology requires equipping locomotives and cars with special valves and equipment that are unique to the operation of ECP brakes. Instead of using reductions and increases of the brake pipe pressure to convey application and release signals to each car in the train, ECP brake technology uses electronic signals, resulting in an almost instantaneous application and release of brakes on each car in the entire train. Each car connects to the locomotive via special connectors with a two-conductor wire. ECP brake systems are not functionally compatible with conventional pneumatic air brake systems, but the NPRM notes that manufacturers have developed three methods of achieving interoperability where trains have a mixture of conventional and ECP cars. The proposed rule changes a number of testing requirements so they are compatible with practices that will be necessary for efficient implementation of ECP.

## **B. Reservoir Capacity**

Reservoirs store air that has been pressurized by the compressor, and they deliver the air on demand to the brakes and auxiliary systems. FMVSS 121 requires that the volume of all reservoirs for trucks and buses be 12 times the combined volume of all service brake chambers (S5.1.2.1) and 8 times for trailers (S5.2.1.1). When the air reservoirs are depleted below 85 psi for a bus or 100 psi for a truck, an air compressor is required to cut in and refill the reservoirs (S5.1.1.1).

Several OEMs noted the high demand on space where the air reservoirs are located and expressed a desire to reduce the reservoir volume if possible. Some modern systems place new demands on the air supply, while others reduce the need for air, at least on occasion. ECE R13's requirements for reservoir capacity are based on performance, not strictly a volume, as is SAE Recommend Practice J1609. [9]

### **1. Additional Demands on Reservoir Air**

The incorporation of new technology into heavy duty trucks has increased the demands on compressed air. Three technologies increase the demand for air.

- ABS
- Tire inflation systems
- Active air suspension systems

Anti-lock brakes increase demands on compressed air by continuously actuating and releasing the brakes. A little air is vented every time the ABS cycles. Non-braking demands include tire inflation systems, often included with tire pressure monitoring systems, and air suspension systems. Even if the tire inflation system and air suspension systems are functioning correctly they will still be drawing compressed air from the air reservoirs to keep the tires or air suspension bags inflated.

Engineers give air brakes priority over non-braking systems. The air braking system is protected from a catastrophic failure in the auxiliary systems by a pressure-protection valve, which closes when the pressure drops below typically 80 psi. A small continuous leak in an auxiliary system is actually the greater concern. This small leak causes the air compressor to run more. The heavier demands on the air compressor will eventually cause its seals to become worn. This would decrease the air compressor's efficiency, causing it to run yet more in a cycle leading to failure of the compressor if the problem is left unchecked.

### **2. Factors That Could Decrease the Required Reservoir Capacity**

There are three factors that can decrease the demand for air from the reservoir. They are:

- Retarders
- Regenerative brakes
- Higher reservoir pressures

Non-air brakes include retarders such as engine brakes and transmission brakes, are well established in the heavy vehicle industry. Retarders, like regenerative brakes, extend the life of the friction material and, at least within the span of a few brake applications, decrease the need for brake air. Regenerative brakes, rather new in light vehicles, are beginning to appear in mid-size and heavy vehicles. In vehicles equipped with regenerative braking, during a braking application the vehicle's kinetic energy drives a generator or pump which stores energy in batteries, ultracapacitors, or hydraulic tanks. Ultracapacitors store energy by using plates and a separator to polarize an electrolytic solution. This solution stores the energy until it is ready to be discharged. [10] Eaton offers the option of either batteries or hydraulic tanks to store the recovered energy. The Eaton vehicles equipped with hydraulic systems come in two types: one where the hydraulic drivetrain assists the conventional drivetrain and one where the hydraulic drivetrain completely replaces the conventional drivetrain. [11] A Scania concept bus is making use of ultracapacitors to store the energy regained from regenerative braking. [12] When the energy storage device is at maximum capacity, the regenerative braking can no longer assist the service brakes. Manufacturers who install regenerative braking are reportedly not making any changes to the design of the primary air brakes.

Charging a reservoir to a higher pressure allows its size to be reduced while maintaining its functional capacity. In the United States, trucks operate at a maximum air pressure of 130-135 psi (896-931 kPa); however, European trucks operate at a maximum air pressure of 140-150 psi (965-1000 kPa).

### **3. Performance Standards for Reservoir Capacity**

FMVSS No. 121 is a design standard for reservoir sizing, with its factors of 12 times chamber capacity for tractors and 8 times for trailers. Existing performance standards that are less restrictive with respect to design are:

- SAE J1609 and the accompanying test procedure SAE J1911
- ECE R13, Annex 7 and Annex 13

SAE J1609, observes that "A vehicle's air reservoir capacity is quantified by its ability to provide a brake application pressure which is adequate to stop the vehicle within emergency brake stopping distances specified in Table II of FMVSS 121, after seven full brake applications with the air compressor disabled." The recommended practice provides for the eighth application: "The brake actuator pressures measured during the eighth brake application shall not be less than 310.05 kPa (45 psi)." SAE J1911 provides a test procedure to assist with checking the vehicle's compliance with the above requirements. [13]

ECE R13 does not explicitly require that the system use air reservoirs. ECE R13 uses tests similar to SAE J1609 for power-driven vehicles in Annex 7 paragraph 1.2.1: "The energy storage devices (energy accumulators) of power-driven vehicles shall be such that after eight, full-stroke actuations of the service braking system control, the pressure remaining in the energy storage device(s) shall be not less than the pressure required to obtain the specified secondary braking performance." The rule for trailers is in Annex 7 paragraph 1.3.1: "The energy storage devices (energy accumulators) with which trailers are equipped shall be such that, after eight full-stroke actuations of the towing vehicle's service braking system, the energy level supplied to the operating members using the energy does not fall below a level equivalent to one-half of the

figure obtained at the first brake application and without actuating either the automatic or the parking braking system of the trailer.” ECE R13 has additional requirements for vehicles using ABS in Annex 13 paragraphs 6.1-6.1.4. After cutting off the supply to the energy accumulators, the brakes are to be applied and held for 15 seconds after which they are to be actuated four times. On the fifth application the braking force should not be less than 22.5 percent of the maximum stationary wheel load<sup>3</sup>. In addition, the fifth brake application should not cause an automatic application of any braking system not being under the control of the anti-lock system.<sup>3</sup>

One contact noted that the Brake Release Time requirement, S5.3.4 of FMVSS 121, is outdated for vehicles with ABS. The release path for air from ABS is different from the driver’s releasing the treadle.

## **C. Component Evaluation**

Onboard measurement of brake performance, performance based brake testing, and replacement lining tests each evaluate a different aspect of in-service brake performance. On-board measurement of brake performance uses various sensors to monitor brake component functionality, performance based brake testing evaluates the effectiveness of individual brakes and of the brake system as a whole, and replacement lining tests seek to ensure the quality of replacement linings.

### **1. On-Board Measurement of Brake Performance**

Three means of assessing brake performance onboard operating vehicles are in use today:

- Wheel speed sensors (ABS)
- Stroke sensors
- Lining condition sensors

Wheel speed is already monitored through the ABS. By comparing the chamber pressure to the deceleration, the system determines how effectively the brakes are working. There are ABS systems on the market today that indirectly sense brake force by measuring wheel speed differences. They determine when a brake is not providing as much torque as the other brakes, automatically balance the torque on axle ends, or even infer tire pressure.

Stroke sensors can detect problems with drum brakes by measuring the travel of the push rod. Three different types of problems can be detected: over-stroke, under-stroke, and unresponsive brakes. Over-stroking causes a reduction in the force used to actuate the brakes. Over-stroking occurs when the gap between the brake drum and brake lining has increased beyond normal levels or when cam-shaft busings are worn. The increase in gap distance can be caused by the brake linings being worn down (and the brake adjusters not compensating for the wear), or the thermal expansion of the drum. Under-stroking means the brake is not releasing entirely. This can cause overheating and possibly fires in the brakes. The ultimate failure detected by stroke sensors is the push rod not moving when the brakes are applied. Non-responsive (inoperative) brakes could be detected in a pre-trip inspection.

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<sup>3</sup> Meeting this requirement is demonstrated on two types of performance-based testers (PBBT), a roller dynamometer or a flat-plate brake tester.

Brake lining sensors are used to alert the driver when the brake linings are beginning to be worn down. The drivers are alerted by a gauge similar to a fuel gauge that shows the percent of brake linings left. Currently, manufacturers of these products are working to combine the stroke sensors and brake lining sensors into one system that would alert the driver if there were problems with either. In the future, manufacturers plan to make all of these systems available for both tractors and trailers.

Stroke sensors, lining sensors, and ABS sensors are complementary and they measure different quantities. Manufacturers are currently working to incorporate data loggers into these systems and in the next step these sensors can be made to broadcast the quality of brakes to a driver, the fleet, or an inspector. Where to transmit the information is a matter of philosophy. A general consensus is that the driver should not be burdened with more non-emergency information. The information may be transmitted electronically via the fleet's wireless dispatching system, or it may be made available for a mechanic to download through the J1587 bus. A conscientious fleet would repair wearing brakes or send a message to a driver at the next scheduled stop in urgent cases. Transmitting the information to inspectors would alert them to which vehicles and which brakes need to be physically inspected. This could be done in a manner similar to how electronic credentialing is already handled on a voluntary basis in some corridors. [14]

The FMCSA web site has more information on both stroke and lining sensors and contact information for manufacturers. [15]

Anchor pin strain sensors and brake shoe thermocouples have been used in research [16] but are not feasible for general use. Anchor pin strain sensors use strain gauges to measure the shear stresses applied to the anchor pins. By comparing the shear stresses in the anchor pins to the rotational speed of the associated wheel and the deceleration of the truck, brake deficiencies in individual wheels can be detected. Thermocouples located in the brake shoes could theoretically detect problems with the brakes by monitoring differences between the temperatures in each brake. Variations in initial brake temperatures, slow response time and general inaccuracies make brake shoe thermocouples not feasible for development into a consumer system unless improvements are made.

While ECBS can be used as an on-board brake performance indicator, at this time the industry's focus is not on developing new systems for checking the performance of brake systems. This is demonstrated by the demand for the systems currently available. Transit buses are the only heavy vehicles that use a large number of stroke sensors or brake lining sensors. In discussions with OEMs the general response has been that the sensors are good but not cost effective. Legislation was recently introduced in the House to provide tax incentives for advanced safety systems, including brake stroke monitors and stability systems, on commercial vehicles. [17] An OEM also mentioned that he would like to seek stroke sensor that could measure smaller changes of only 0.1 inch.

## **2. Performance Based Brake Testing**

There are two means by which FMVSS 121 assesses air-braked vehicle performance: minimum stopping distance requirements, and dynamometer tests. The former accounts for brake material effectiveness, brake timing, and stability, and is conducted using the vehicle as a whole. The

latter assesses performance of only the brake material and brake hardware, isolated from any effects of the pneumatic plumbing. Both of these tests are conducted from an initial high speed (typically 60 mph for the stopping distance tests and 50 mph for the inertial dynamometer tests). Once a vehicle is in service, however, there is no practical means to verify that the stopping performance of a replacement brake lining, or other replacement parts, can still meet the original safety standard. The Federal Motor Carrier Safety Regulations (FMCSR), 49 CFR 393.52, contain provisions for lower speed stopping distance and deceleration tests, but the logistics of conducting a 20-mph stopping tests on a vehicle effectively prohibit this method from being used.

Recent changes to FMCSR 393.52 have introduced an alternative method for assessing an in-service vehicle's braking performance, without the need to run an actual stopping test. The alternative method makes use of a performance based brake tester (PBBT). PBBTs can take the form of an instrumented roller dynamometer or a flat plate. These devices measure the brake force at each individual wheel-end, which can then be compared to various standards. Examples include calculating the braking "efficiency" by dividing the brake force by the wheel load, left-to-right balance across an axle, or brake force as a function of applied air pressure. The total vehicle braking efficiency can be obtained by the summing the brake forces and dividing by the current vehicle weight. Alternatively, the gross vehicle weight rating (GVWR) can be used in the calculation.

If a low-speed or static test were included in the new-vehicle standard FMVSS 121, it would provide reference values for checking both the quality of vehicle maintenance and the effectiveness of replacement brake components of in-service vehicles. While a low speed test is not a substitute for a full vehicle stopping test from highway speeds, it is the only practical means by which the brake performance of an in-service vehicle can be assessed. Infrastructure for PBBTs exists in Europe and elsewhere in the world, and many new vehicles are equipped by the OEM with quick-disconnect couplings to allow pressure transducers to be used during PBBT tests. Pressure ports are provided which enable monitoring of the applied air pressure as well as that for each brake chamber supplied by a single distribution valve. Factory installed quick-disconnect pressure couplings facilitates on-board brake performance measurements, and enables vehicles to undergo braking safety checks without having to conduct an on-road stopping test.

### **3. Tests for Replacement Linings**

The brake lining tests in FMVSS 121 ensure adequate performance for new vehicles. However, the performance properties of replacement linings are crucial to ensuring the continued effectiveness of a vehicle's brakes. There is a consensus among industry representatives that there is currently no comprehensive means for truck operators to assess replacement linings, vis a vis their vehicle's original linings. Therefore, unless the exact OEM linings are used as a replacement, the vehicle operator has no assurance that the vehicle's original braking performance would be maintained. Several contacts and comments in the docket on the pending NPRM [18] noted that good quality replacement linings are essential for maintaining safe brake performance. Ideally, a test for replacement brake linings would include three parts: a cold effectiveness test (to simulate normal operation), a fade and recovery test, and a static "breakaway" test (done on a dynamometer at very slow speed to simulate the parking brake).

The following standards for replacement linings are discussed:

- FMVSS 121 (Though a new vehicle test, elements of 121 partially meet the needs for replacement lining tests.)
- ECE R90 requires that replacements be as good as originals.
- TMC RP628 is a single test under limited conditions.
- APTA BT-RP-002-05 is a more thorough test for transit buses.
- SAE RP J1802 is a test that is no longer widely used.

The dynamometer tests in FMVSS 121 (S5.4, S6.2) test for cold effectiveness and fade and recovery, but they do not technically apply to replacement linings. In Europe ECE R90 regulates the use of replacement braking linings. In the United States there are recommended practices and voluntary tests, such as RP 628 and APTA BT-RP-002-05.

ECE R90 [19] dictates that any replacement linings “shall satisfy the relevant braking prescriptions of Regulation No. 13 including the 09 series of amendments” (ECE R90 paragraph 5.1.a), “display performance characteristics similar to that of the original brake lining assembly or original drum brake lining it is intended to replace” (Paragraph 5.1.b) and “shall not contain asbestos” (Paragraph 5.1.d). In Europe each lining must be certified on each brake for which the lining is being sold, to require this in the US might be too big a burden to place on the manufacturer.

TMC’s RP 628 [20] lists the torque values recorded at 40 psi for the dynamometer test FMVSS No. 121, S5.4.1, for the linings that have been successfully tested. Linings that are not listed were not tested or failed the test. More than one expert expressed an opinion that RP 628 does not provide adequate guidance for an operator to select the correct replacement lining.

The American Public Transportation Association considered adopting RP628, but it did not meet their needs. Rather, APTA created their own recommended practice APTA BT-RP-002-05 [21]. This recommended practice advocates that the brake torques be recorded for 20 psi, 40 psi, and 80 psi and the fade rating also be recorded according to the FMVSS 121 dynamometer tests for three different samples (paragraph S5.4.1 and S5.4.2). In addition, an independent lab is to conduct an audit test on one sample at regular intervals to ensure that quality standards are maintained over time. This recommended practice is voluntary, but APTA believes it will become a de facto mandatory standard because the great majority of buses are public transit buses and the individual transit authorities will eventually require that replacement brakes be APTA certified. The first lining under APTA BT-RP-002-05 has just been certified, but the first audit test has yet to be done.

SAE Recommended Practice J1802 [22] tests brake linings for both hot and cold effectiveness. SAE J1802 makes use of a “standard brake” the brake linings are tested on. This allows the performance data of the material to be found and compared regardless of what size and type brake is used. This standard was issued in 1993 and is no longer widely used. Sensitivity to the geometry of the test setup was identified as a key reason for differing results from different test facilities. [23]

An overview of several of the preceding standards and recommended practices has been published. [24]

### III. Conclusions

ECBS is the dominant system in Europe, having roughly 80% of the market share of heavy-duty vehicles and buses. This is due to updates in ECE R13 which accommodate ECBS and the shorter stopping distances required by ECE R13. Also, unlike in the United States, tractors and trailers in Europe tend to stay connected together, so compatibility is a much smaller concern there. Few manufacturers in the United States offer ECBS. The industry is extremely sensitive to costs and slow to adopt new equipment. Another obstacle to deployment is uncertainties as to what redundancy would be needed in pneumatic and electrical systems to make ECBS acceptable under FMVSS 121. The costs of duplicating both pneumatic and electronic systems and uncertainty has led the market to use advanced ABS and sophisticated valves to accomplish some of what can be done with ECBS to decrease stopping distances and improve performance.

The fundamental approach to motor vehicle compliance in the United States is self certification by the manufacturers, while vehicles in Europe must receive type certification. ECE R13's standards for ECBS, while not necessarily exhaustive, are more suited to evaluating an electronic control system than are performance-based tests common in the FMVSS. An observation made in the report on the hydraulic braking standards [2] applies equally well to air brakes: Modification of [Federal Motor Vehicle Safety Standards] may become appropriate due to emerging brake technologies. Primary among the issues involved is the increasing dominance and complexity of the electronic computer/software elements of the brake system and their integration with other computer/software systems on the vehicle. As a result, issues of fail-safe and partial failure performance, once concerned with rather simple, purely mechanical and hydraulic systems, are becoming highly complex. In the short term, additions to the standards for individual new systems may suffice. In the longer term, a new philosophical approach to ensuring fault-tolerant braking systems may be required.

New systems, such as ABS, tire inflation systems, and air suspension systems, have increased the demands on the brake air. The extra demand is a greater concern for the compressor than for the reservoirs. Non-friction braking systems (retarders, which are well established, and regenerative brakes, which are new but rapidly growing) reduce the short-term demands on reservoir air, but manufacturers are not altering the design of foundation brakes because of their presence. Higher reservoir pressures in Europe have allowed smaller reservoir volumes while maintaining adequate performance. ECE R13 has a performance standard for reservoir capacity, as does an SAE recommended practice.

Stroke sensors, lining sensors, and ABS wheel speed sensors are complementary and when used together they can give an effective picture of brake performance on an in-service vehicle. Information from these three systems could be pooled and broadcasted in an effort to keep fleets safe and up to date on their maintenance. However, the cost has kept these performance measures from widespread use. Another way to measure in-service brake performance would be a performance based brake tester. A possible way for this to be accomplished would be for FMVSS 121 to include a PBBT test so that the results of that test could be compared to the results from an in-service vehicle. This is currently done for type approval in Europe.

There are no mandatory requirements for replacement linings in the United States. In Europe, ECE R90 mandates that replacement linings meet all of the requirements of the original linings, and replacement linings must be certified to every brake for which they are sold. In the United

States, two recommended practices provide performance test data: RP 628 and APTA BT-RP-002-05. RP 628's tests are under limited conditions that many feel are inadequate. The new APTA BT-RP-002-05 provides torque values at 20 psi, 40 psi and 80 psi and the fade rating. Both are based on the FMVSS 121 dynamometer tests.

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