Application of a Heavy Vehicle Brake Condition Monitoring System

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EXECUTIVE SUMMARY

Malfunctioning brakes represent the most common safety violation for commercial vehicles. The objectives of this project were to investigate on-board measurement of a few brake-related parameters in order to monitor the effectiveness of air brakes, and to refine an algorithm for warning drivers and/or informing authorities of impending brake failure. In particular, the feasibility of using air pressure data to determine brake stroke, a vital parameter in determining the effectiveness of the total braking system, was explored.

The Brake Condition Monitoring System (BCMS) (Figure 1), previously known as the Intelligent Brake Warning Device (IBWD), has two operational regimes; both regimes independently assess brake performance through measurement of only a few parameters. The first regime, which was the focus of previous research, incorporates an algorithm that compares actual vehicle deceleration with deceleration that would be expected for that vehicle under ideal conditions of cool, well maintained brakes. The second regime, which was the focus of the present research, contains an algorithm that considers the effect of brake pressure response time (particularly release decay time) to enhance the diagnostic capability. The processing and analysis takes place instantaneously, immediately following brake release.

These techniques, employed simultaneously, form the basis for a robust brake effectiveness evaluation algorithm. The evaluation of trends in deceleration performance in conjunction with analysis of brake pressure decay time (which is proportional to brake stroke but independent of vehicle deceleration and weight) provide for reliable, early detection of brake deterioration.

The importance of brake stroke information was thus highlighted. Because of the characteristics of air brake systems, brake stroke, which is proportional to brake wear, is also related to brake force (for a given application pressure). Because manual measurement of brake stroke is tedious and instrumented measurement can be expensive or problematic, an indirect means of inferring brake stroke during the brake pedal release needed development. To address this problem, a mathematical model of an air brake chamber was created and used to investigate parameter sensitivity. A method capable of indirectly determining brake stroke by examining air pressure data was formulated and its effectiveness was proven through simulation and testing.

Results showed that brake chamber air pressure decay time, even at low application pressures of approximately 100-140 kPa (15-20 psig), was a good predictor of brake stroke. This confirmed that measurable differences in decay time could be used to infer brake adjustment. Using experimental data gathered in the laboratory, code was developed to select candidate "brake release" data segments that provided a reliable indication of brake release.

Algorithm refinement therefore included an important component of air pressure signal analysis, from which brake adjustment, and hence effectiveness, could be inferred.

Future research will pursue prototype development and refinement of the algorithm through extensive field trials. Attention will be focused on uniting the two regimes of the algorithm, and assessing the sensitivity of the BCMS to different vehicle configurations. Incorporation into existing electronic braking system (EBS) architecture will be explored, as will determination of warning threshold.

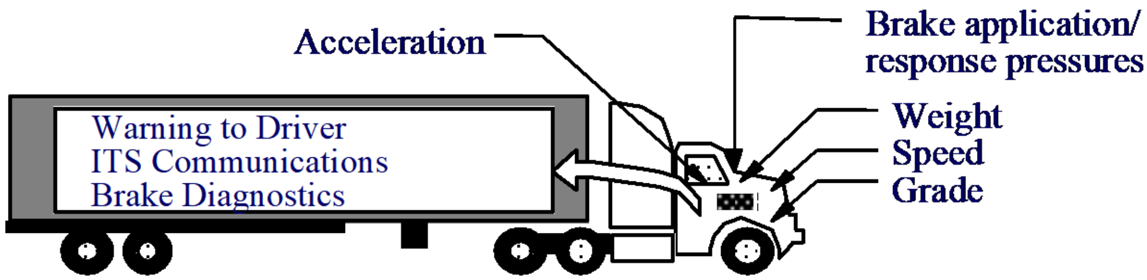

FIGURE 1 Brake Condition Monitoring System Concept.

IDEA PRODUCT

An on-board, brake condition monitoring system (BCMS) for air-brake-equipped commercial vehicles has been developed to improve safety on the nation's roadways. The BCMS is an inexpensive electronic module that mounts in the cab or tractor of a truck or bus and constantly monitors a small number of parameters related to vehicle braking performance. Through an empirically determined algorithm, the BCMS provides real-time information about brake condition to drivers, maintenance personnel, and authorities without the necessity for wheel-to-wheel inspections. Because it tracks trends in actual braking performance, it permits the prediction of potential brake malfunction well in advance of any threat to safety. The BCMS, in its simplest form, requires the addition of only a few inexpensive sensors and systems not already carried on a modern vehicle. It is adaptable to existing vehicles and well suited to complement other on-board safety systems and diagnostics, including anti-lock brake systems (ABS) and electronic braking systems (EBS).

MOTIVATION

Malfunctioning brakes are the leading mechanical cause of commercial vehicle (CV) accidents and constitute the most common safety violation *(1,2)*. Of these brake related safety violations, out-of-adjustment brakes are the most common. During the 1996, 1997, and 1998 International Highway Transportation Safety (IHTS) weeks, 16-24% of total inspections yielded out-of-adjustment brake violations *(3,4,5)*.

Air brake adjustment is maintained either by manual or automatic slack adjusters (ASA). In the case of manual slack adjusters, regular maintenance and adjustment are required to keep braking systems working properly and within legal specifications. ASAs also require regular maintenance, but because they are designed to automatically maintain brake adjustment, they may be overlooked and not regularly maintained, and sometimes result in out-of-adjustment brakes. In 1992, a safety study concerning heavy vehicle airbrake performance reported that in 1520 five-axle vehicle inspections, 15% of ASAs were at or past the legal limit *(6)*. The Federal Highway Administration and Federal Motor Vehicle Safety Standards have required ASAs on all trucks, tractors, buses and trailers with air brakes since 1994 *(7,8)*. From recent IHTS statistics, it is apparent that there are still many vehicles with brakes out of adjustment. Clearly, ASAs are not the final solution to the brake adjustment problem.

In this report results are presented from research on the development of a brake condition monitoring system (BCMS) for vehicles equipped with air brakes. The purpose of the BCMS is to monitor and analyze parameters necessary to determine braking capability and report this information to the interested party. Although identifying a properly adjusted and maintained braking system depends on a number of parameters, a primary indication and necessary parameter in determining the effectiveness of a braking system is brake stroke. Hence an effective way of determining brake stroke on board while the vehicle is operating is vital to the success of the BCMS. Instrumentation on vehicles to directly measure brake stroke is feasible but is potentially costly and impractical. In addition, external conditions encountered by many commercial vehicles are detrimental to the reliability and survival of such instrumentation. This paper presents an alternative method of indirectly determining brake stroke.

BRAKE STROKE

The air brake chamber is the primary device in an air brake system that enables air pressure to actuate brakes (Figure 2) *(9)*. Pressurized air is applied to the chamber, forcing the pushrod outward and thus applying the brakes. Brake stroke, defined as the distance the pushrod moves to apply the brakes under full application of air, increases as brake shoes wear or brake drums expand from increased temperature. The relation between brake stroke and pushrod force for a Type 30 air brake chamber is shown in Figure 3 *(10)*. As brake stroke increases, there is a point at which pushrod force suddenly decreases. If brake stroke increases still further, the pushrod bottoms out in the air chamber and no braking force is available. This is the cause of the sudden decrease in braking force as indicated in Figure 3.

Figure 3 reveals that when brake adjustment is maintained within manufacturer's recommendations, pushrod force, and thus braking force, remains relatively constant. This is desirable in that sufficient braking force is available over a range of brake adjustment; however, this also means that there is not a gradual decline in braking power as adjustment increases through the recommended range. As a result, brake maladjustment may go unnoticed to the operator until it reaches unsafe levels. When brake adjustment is allowed to increase beyond manufacturer's recommendations, the braking force available becomes highly sensitive to brake adjustment and quickly diminishes to zero. The BCMS will detect and warn of such situations.

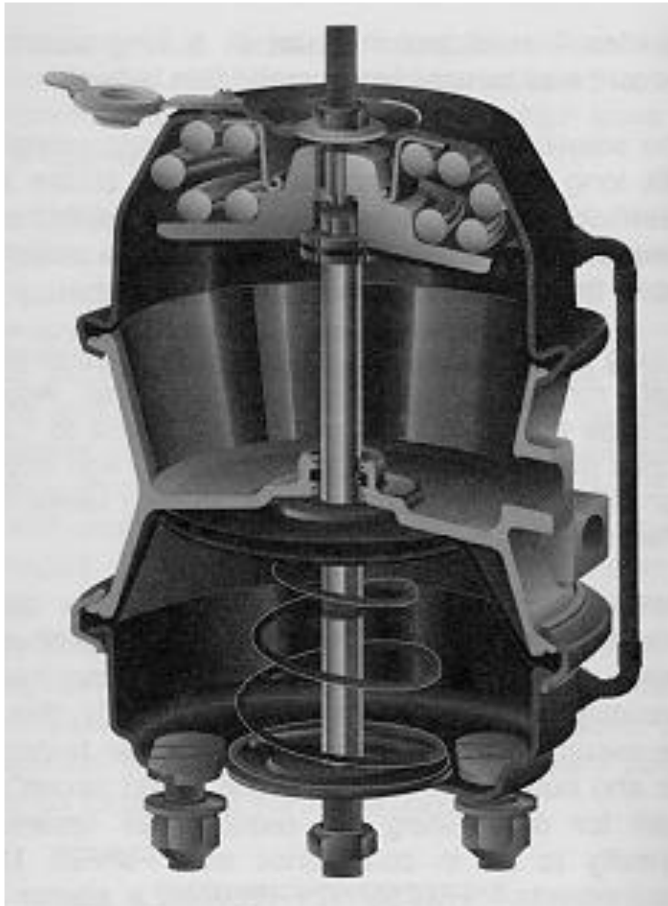

FIGURE 2 MGM Air Brake Chamber [9].

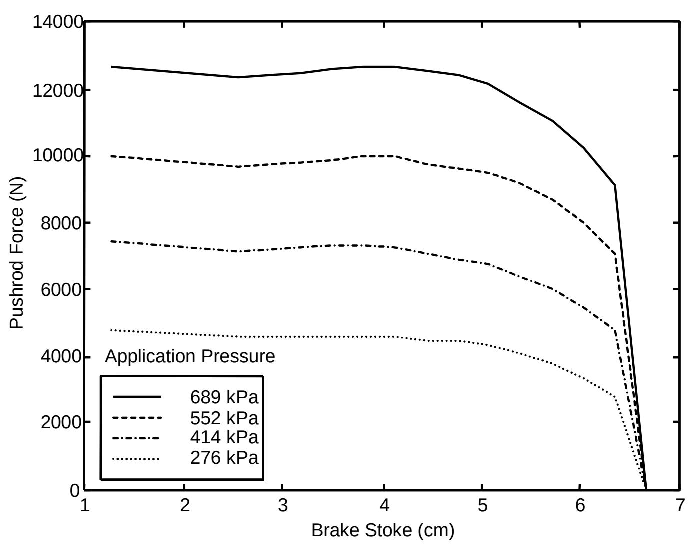

FIGURE 3 Measured Effect of Brake Stroke on Pushrod Force.

CONCEPT AND INNOVATION

The BCMS concept (Figure 1) is unique; it is on-board, it considers the vehicle as a system (rather than considering wheel-to-wheel measurements), and it tracks trend*s* in braking performance rather than attempting to judge performance at a single point in time. The BCMS has two operational regimes; both regimes independently assess brake performance through measurement of only a few parameters. The first regime incorporates an algorithm that compares actual vehicle deceleration with deceleration that would be expected for that vehicle under ideal conditions of cool, well maintained brakes. The second regime contains an algorithm that considers the effect of brake pressure response time (particularly release decay time) to enhance the diagnostic capability. The processing and analysis takes place instantaneously, immediately following brake release.

As brake stroke increases, the volume of air needed to fill the chamber and apply the brake also increases. Therefore, the volume of air used to apply brakes is an indication of brake adjustment. One indirect measure of the volume of air required to fill the chamber is the time required for air pressure to build up in the air brake chamber (air transmission lag time). Previous research has shown that when a pressure-regulating device is used to control and apply air to an axle group, air lag time is indicative of brake adjustment *(11)*. However, when a foot operated treadle valve is used to apply air, as is in actual field operation, this air lag time is highly dependent upon the manner in which the foot pedal is depressed, which varies from one operator to another and from one braking situation to another. This makes lag time an impractical method of determining brake adjustment for a vehicle operating on the road.

Another characteristic closely related to air lag time and also indicative of brake adjustment is the time required for air pressure in the air brake chamber to fall when brakes are released (decay time). In contrast to the dependence of air lag time on brake pedal application, air decay time may not depend on brake pedal release. When brakes are released, they are most often completely released, and hence more independent of driver variation. When brakes are completely released, a relation can be developed to reliably determine brake adjustment from air pressure decay time. The advantage of this is that brake adjustment is determined using already existing instrumentation on present and future CVs.

INVESTIGATION

SYSTEM MODELING

The initial step to determine the relation between air pressure decay and brake adjustment is the development of a mathematical model of the air brake chamber. Due to the rapid process there is insignificant transfer of thermal energy to surroundings and frictional losses are negligible due to short and smooth air passages. Hence, for modeling purposes air flow was assumed to be completely isentropic. The critical pressure ratio for gas discharging through a converging nozzle is given by:

$$P_{crt} / P_{atm} = \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}} \qquad (1)$$

where P_{crt} is the lowest absolute pressure at which critical flow occurs, P_{atm} is the absolute atmospheric pressure (or pressure to which the gas is discharging), and k is the ratio of specific heats for the gas in consideration. For air, with k = 1.4 and P_{atm} = 100 kPa, the critical pressure P_{crt} = 189 kPa. This means that for air pressures greater than 189 kPa, air that is exhausting from the air chamber will be critical, or at the speed of sound. Correspondingly, for pressures less than 189 kPa, air exhausting from the air chamber will be sub-critical, or at less than the speed of sound.

Because air brake systems operate at pressures greater than P_{crt} all the way down to P_{atm}, both cases must be considered and incorporated into the model. For the isentropic discharge of a gas through a converging nozzle, critical and sub-critical equations for the rate of mass exhausted are:

$$\dot{m}_{e\,critical} = A_e\left(\frac{2}{k+1}\right)^{\frac{1}{2(k-1)}}\left(kP_o\rho_o\right)^{1/2} \qquad (2a)$$

$$\dot{m}_{e\,sub-critical} = A_e P_{atm}^{1/k} P_o^{\frac{k-2}{2k}}\left(\frac{2k\rho_o}{k-1}\left[1-\left(\frac{P_{atm}}{P_o}\right)^{\frac{k-1}{k}}\right]\right)^{1/2} \qquad (2b)$$

where $\dot{m}_e$ is the rate at which mass is exhausted (dot denotes derivative with respect to time), P_o and ρ_o are the absolute pressure and density of gas being discharged, respectively, and A_e is the exhaust area.

Pressure and density can be related to each other by:

$$\frac{P_o}{P_{ini}} = \left(\frac{\rho_o}{\rho_{ini}}\right)^k \tag{3}$$

where P_{ini} is the initial absolute pressure and ρ_{ini} is the initial density.

For a finite volume, as in the case of an air brake chamber, the rate at which the mass of gas inside the chamber is changing is equal to the rate at which the mass of gas is exhausting the chamber. Hence:

$$\frac{dm_o}{dt} = \frac{d(\rho_o V)}{dt} = V\frac{d\rho_o}{dt} + \rho_o \frac{dV}{dt} = -\dot{m}_e \tag{4}$$

where m_o is the mass of gas inside the chamber and V is the volume of the chamber.

The simplified physical representation of an air brake chamber shown in Figure 4 and Equations 1 through 4 are the basis for constructing a mathematical model of air pressure decay that occurs inside the air brake chamber when the brake is released. Major features incorporated in the model include inertial effects of the piston and other moving parts, non-linearity of the spring force as brakes are applied, non-linearity of the volume as brake stroke changes, and behavior of the valve used to release pressure from the chamber.

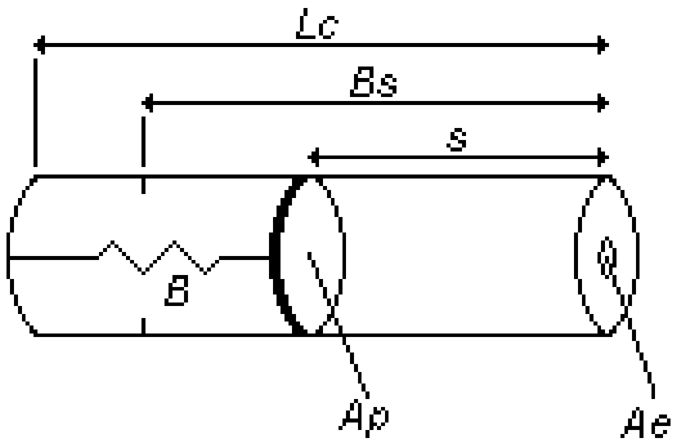

FIGURE 4 Simplified Air Brake Chamber Geometry.

The piston, slack adjuster, s-cam shaft, and brake shoes, represented by mass M_p, are primarily subjected to two forces—that of air pressure and the spring. The resulting governing equation of motion is:

$$M_p \ddot{s} + D_p \dot{s} + B(s) = (P_o - P_{bck})A_p \tag{5}$$

where D_p is the damping in the system, $B(s)$ is the spring force, P_o is the absolute pressure in the chamber, P_{bck} is the absolute pressure behind the piston, A_p is the surface area of the piston, and s is the brake stroke.

The non-linearity of the spring force is introduced into the model because the stiffness of both the return spring and brake components contribute to the overall spring force, $B(s)$, when brakes are applied. Using the pressure regulator shown in the schematic diagram of the laboratory setup (Figure 5), specific pressures were dialed in and the displacement of the pushrod was measured. Figure 6 shows experimental stiffness curves from this data for several brake stroke settings and reveals that indeed the spring force is non-linear.

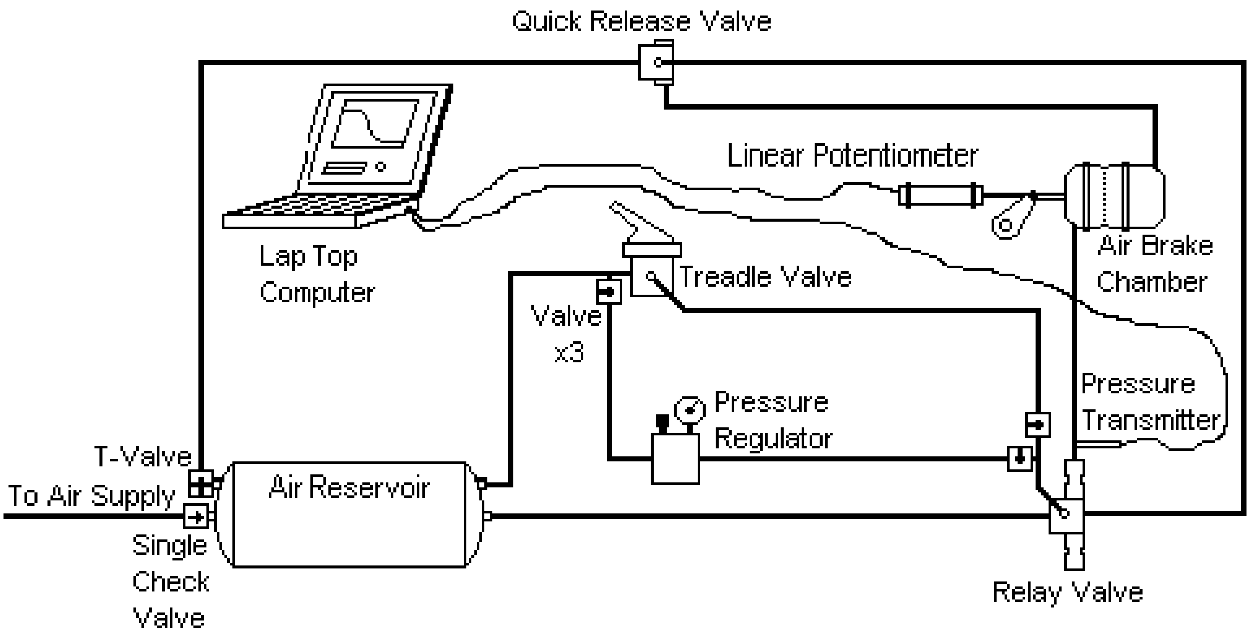

FIGURE 5 Schematic of Laboratory Setup.

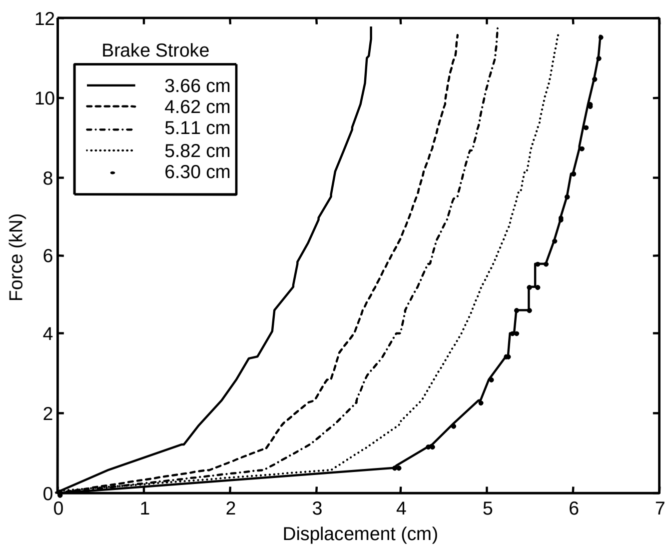

FIGURE 6 Spring Stiffness Curves.

There are two general regions of stiffness. When *s* is small such that the brakes are not applied, the slope is small, representing the stiffness of only the return springs. When *s* is large enough such that the brakes are applied, the slope becomes much larger, representing the addition of the greater stiffness of the brake components as they are compressed. Based on this, the spring force as a function of the brake stroke in the model has been approximated with two linear sections of different slopes.

In the simplified geometry of Figure 4, the chamber is cylindrical and so the volume of the chamber is a linear function of brake stroke. Figure 2 shows that the shape of the chamber is not strictly cylindrical, but rather how the radius of the chamber changes with brake stroke. So, as *s* increases to approximately half of the total length of the chamber the radius steadily increases. As *s* increases further the radius steadily decreases. The more realistic air chamber volume is then piecewise given by:

$$\underset{0\le s\le \frac{1}{2}L_c}{V_1(s)} = \frac{4\pi(r_2-r_1)^2}{3L_c^{\ 2}}s^3 + \frac{2\pi(r_2-r_1)r_1}{L_c}s^2 + \pi r_1^{\ 2}s \qquad (6a)$$

$$\underset{\frac{1}{2}L_c< s\le L_c}{V_2(s)} = \frac{4\pi(r_1-r_2)^2}{3L_c^{\ 2}}\left(s-\tfrac{1}{2}L_c\right)^3 + \frac{2\pi(r_1-r_2)r_2}{L_c}\left(s-\tfrac{1}{2}L_c\right)^2 + \pi r_2^{\ 2}\left(s-\tfrac{1}{2}L_c\right) + V_1(\tfrac{1}{2}L_c) \qquad (6b)$$

where $V_1(s)$ and $V_2(s)$ are the volume of the air brake chamber for appropriate values of s, r_1 is the radius of the chamber at the endpoints, r_2 is the radius of the chamber at the midpoint, and L_c is the length of the chamber.

The valve that releases air pressure from the air chamber is itself activated by the release of air pressure from another signal circuit. Thus, instead of the full exit area, denoted by A_{full}, appearing instantaneously, there is some time required to exhaust air in the signal circuit and thus some time required for the equivalent exit area to go from zero (valve closed) to A_{full} (valve open). This has been incorporated into the model by making the exhaust area, A_e, a function of time, $A_e(t)$. This function consists of a ramp that goes from zero to A_{full} in some finite time and then remains at A_{full} thereafter.

These features and equations were incorporated in the development of the differential equations that govern air pressure inside the air brake chamber as the brake is released. The model consists of a second-order differential equation for the dynamics of the brake stroke and a first-order differential equation for the air pressure. These equations are then solved numerically to yield predicted air pressure decay curves.

EXPERIMENTAL DATA

To verify predictions of the model, it was necessary to collect data from a real air brake system. A partial air brake system was therefore constructed in the laboratory with instrumentation that includes a pressure transmitter to monitor and record air pressure near the relay valve and a linear slide potentiometer to monitor pushrod position. A laptop computer was used for data acquisition (Figure 5).

In order to ensure compatibility between components and in an attempt to make the laboratory setup as realistic as possible, crucial hardware, such as treadle, relay, and quick release valves were taken from a single wrecked commercial vehicle, specifically, a 1988 Western Star truck. The actual foundation brake components, including a hub, spider, brake shoes, drum, and air brake chamber, were purchased new from several truck shops.

Since the focus is air pressure *decay*, the primary concern in creating the partial air brake system was to ensure the realistic release of the air brake. So from the relay valve, which contains the exhaust port where air from the chamber is exhausted to the atmosphere, to the air brake chamber, the original hose used on the truck was used in the laboratory. Literature from brake system manufacturers *(12)* indicate that in future electronic braking systems, pressure sensors will be present within the relay valve/modulator component. Based on this, in addition to this original hose, the pressure transmitter was mounted using a T-joint as close as possible to the relay valve, such that pressure decay could be measured and recorded.

DETERMINING BRAKE STROKE

A least-squares algorithm was used to fit segments of experimental data, corresponding to the free release of the air brake, to the exponential expression:

$$P(t) = P_i e^{-\tau t} \qquad (7)$$

where $P(t)$ is the air pressure, P_i is the initial air pressure, and τ is the time constant. The time constant from this least-squares fit shows correlation to brake adjustment, however, data revealed that this time constant was also dependent upon the application pressure. Application pressure is reflected in the least-squares fit value of P_i and so it was discovered that two parameters were needed, P_i and τ, to determine brake stroke. Figure 7 shows this correlation between time constants, application pressure, and brake adjustment for several brake adjustment settings.

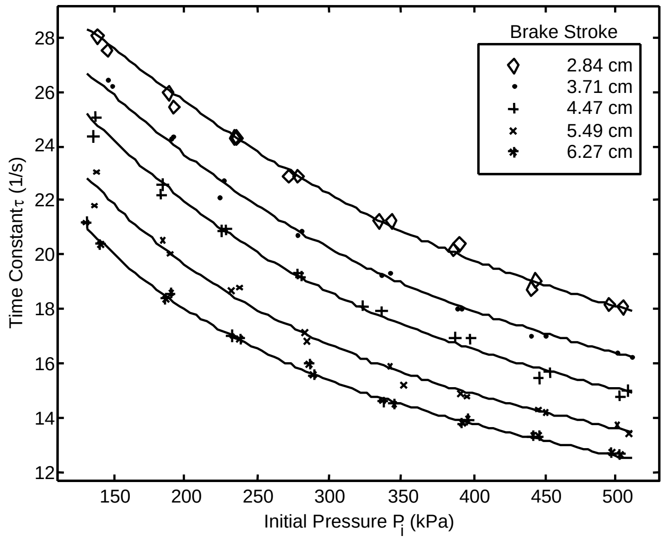

FIGURE 7 Correlation between P_i, τ, and Brake Stroke.

To determine a function of the form $B_s = f\ (P_i\ ,\tau)$, where B_s is brake stroke and P_i and τ are the least-squares fit parameters from Equation 7, a third-order polynomial of the following form was used.

$$B_s = c_1 P_i + c_2 \tau + c_3 P_i \tau + c_4 P_i^2 + c_5 \tau^2 + c_6 P_i^2 \tau + c_7 P_i \tau^2 + c_8 P_i^3 + c_9 \tau^3 + c_{10} \tag{8}$$

TESTING AND VALIDATION

Having established the constants in Equation 8, and so a deterministic equation for brake stroke based on one set of air pressure decay data, the next step was to test this relationship with separate data. Since Equation 8 is concerned only with air pressure decay corresponding to the free release of the air brake, it was necessary to construct an algorithm that was able to select these decaying segments out of arbitrarily collected air pressure data. Brake stroke could then be determined by continuously monitoring air pressure near the relay valve, selecting data corresponding to the free release of the brake, determining the parameters P_i and τ, and computing brake stroke using Equation 8.

Free air pressure decay occurs when the vehicle operator does not interfere with brake release such as might happen by riding the pedal. Segments of data that do not correspond to a free release of air brakes will not be reliable or useful for effectively determining brake adjustment. Criteria were established to identify a free release of air brakes. Testing showed that two criteria were sufficient. First, air pressure must be decreasing as it crossed a threshold level to ensure that it was indeed a decaying segment of data. Second, the data segment must be concave upwards, or its second derivative with respect to time must be positive. This eliminates segments of data where the operator of the foot pedal may have interfered with release of the air brakes. Using numerical differentiation and a low pass filter, segments of data that met both of these criteria were identified and selected.

This algorithm was used to consistently and reliably select segments of data. Figure 8 demonstrates the effectiveness of this selection algorithm as free-decaying segments of data were selected from a ten-second segment of data.

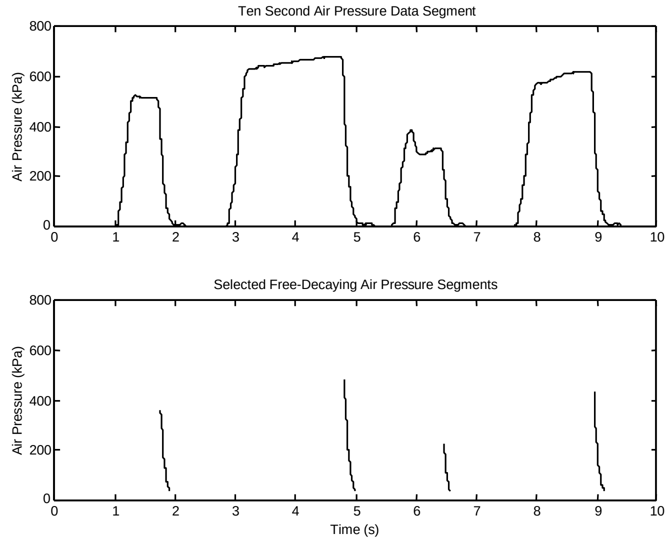

FIGURE 8 Selected Free-Decaying Air Pressure Segment.

RESULTS

In Figure 9, at initial pressures as low as 100 kPa (15 psig), the model indicates significant differences in air pressure decay time for different brake strokes. This is verified by experimental data taken for various brake adjustments and application pressures. Experimental data plotted in Figure 10 reveals that at application pressures as low as 140 kPa (20 psig), air pressure decay times vary significantly with brake adjustment. Both the model and experimental data indicate differences in decay time that are easily detectable with current instrumentation and processing available on CVs. In both cases, as application pressures were increased, these differences in air pressure decay time as brake stroke varied become even more distinguishable.

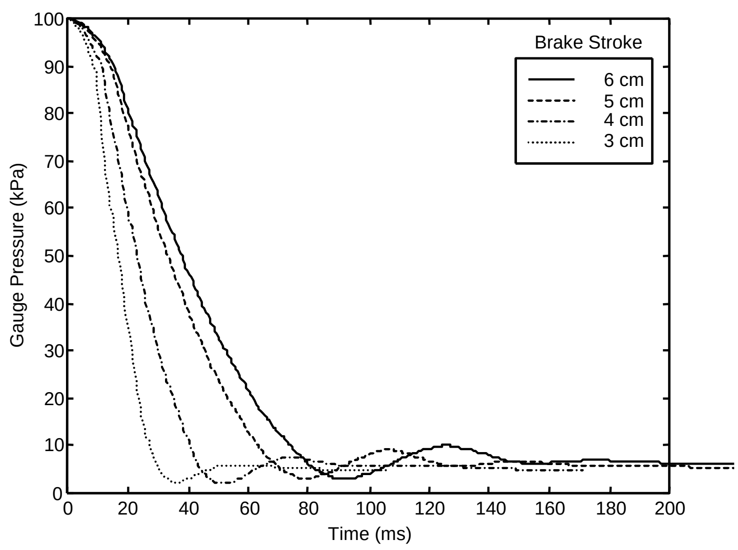

FIGURE 9 Air Pressure Decay from Air Brake Chamber Model.

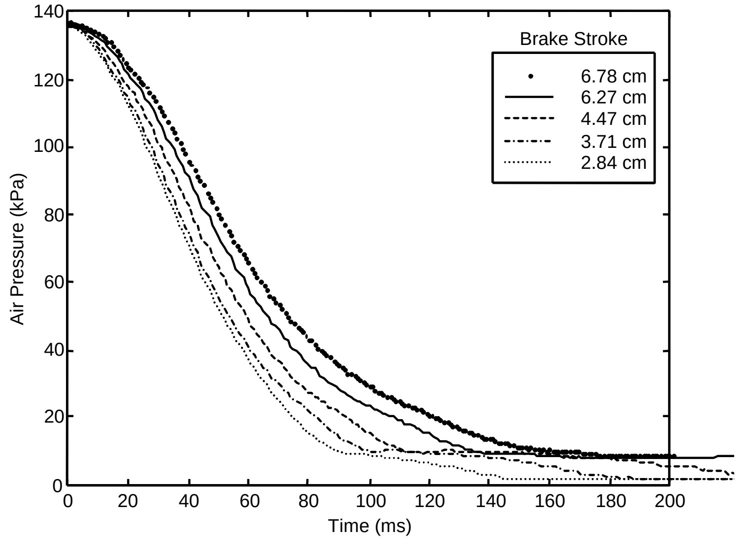

FIGURE 10 Experimental Air Pressure Decay Data.

The effectiveness of this algorithm in determining brake stroke from air pressure data is shown in Figure 11. First, data segments corresponding to the free release of the brake were selected from arbitrarily collected air pressure data. Second, these segments were fitted to the exponential expression of Equation 7 to determine the parameters P_i and τ. Third, these parameters were used to compute brake stroke using Equation 8. Brake stroke as measured with the linear potentiometer is indicated in the legend and brake stroke as determined by these three steps is what is plotted.

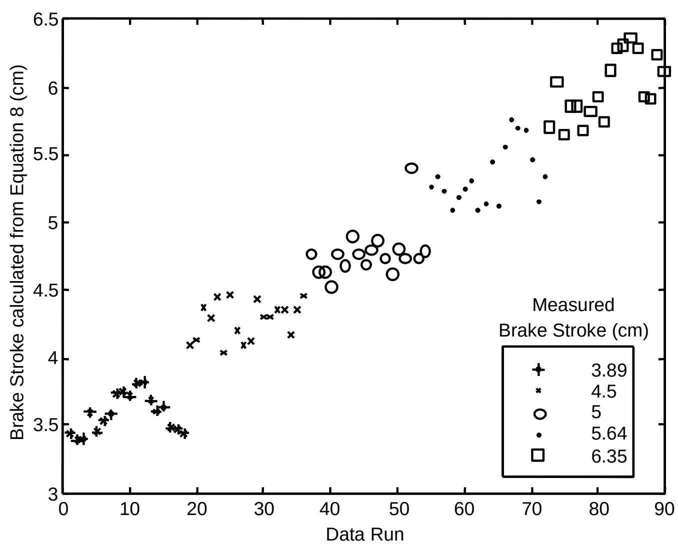

FIGURE 11 Comparison of Measured and Determined Brake Stroke.

BCMS ALGORITHM DEVELOPMENT

The overall objective was to refine the BCMS algorithm previously developed in the first phase of research. It is intended that the BCMS will become an integral part of the entire on-board diagnostic system on a commercial vehicle. At this point, the BCMS contains two major modules: one that deals with monitoring brake adjustment based on air pressure decay data, and another that monitors braking effectiveness based on vehicle deceleration (Figure 12). Together, these modules monitor the overall condition of the braking system and, in conjunction with additional communication systems, make information to interested parties.

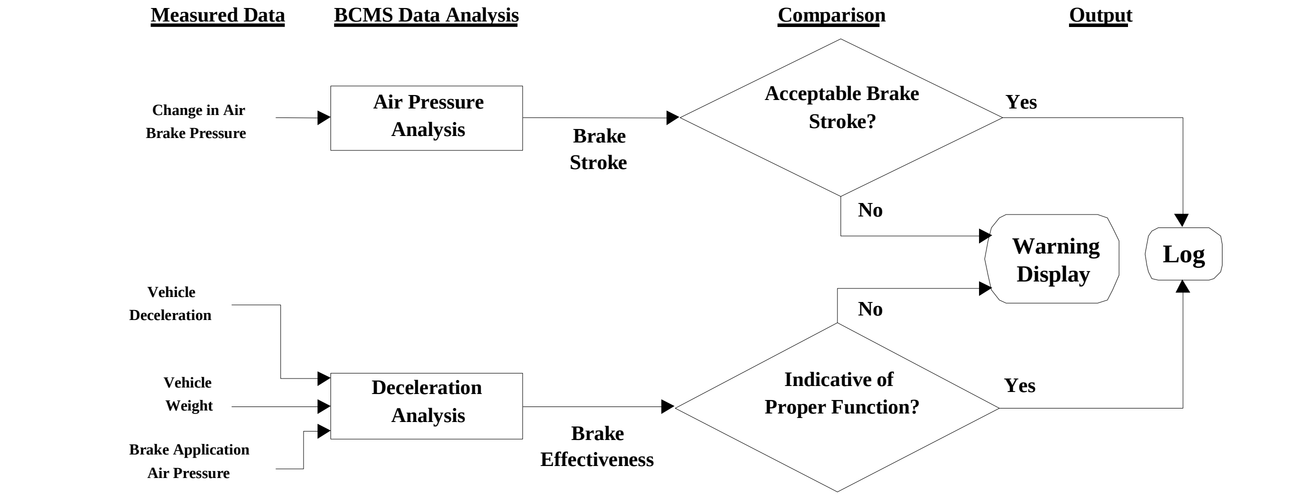

FIGURE 12 BCMS Algorithm Outline.

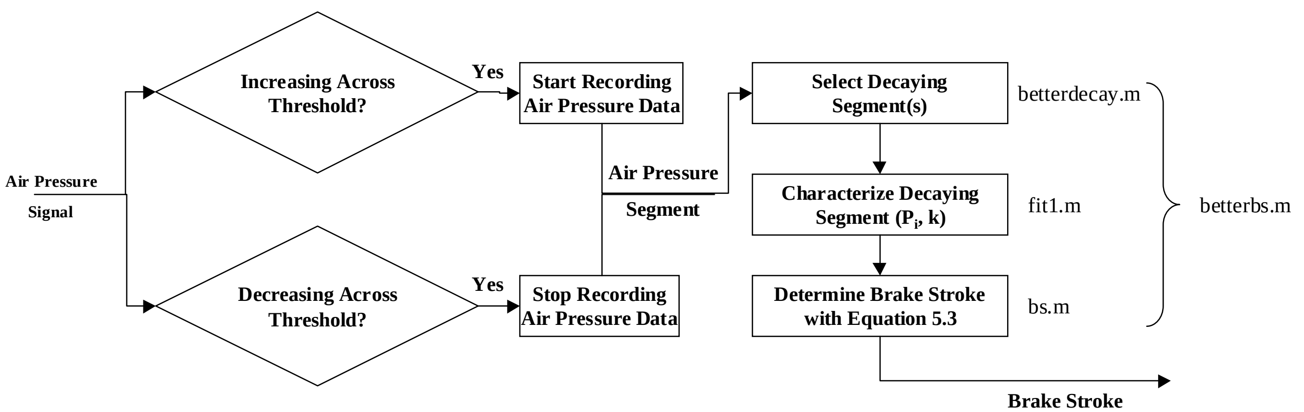

FIGURE 13 Air Pressure Analysis Block Algorithm.

The focus of this phase of research was the Air Pressure Analysis block in Figure 12, which is shown in greater detail in Figure 13. Matlab code files that were developed for various tasks are identified in the figure.

PLANS FOR IMPLEMENTATION

It is envisioned that the BCMS will be installed on future (and some existing) commercial vehicle braking systems. Promising results from present and past research phases suggest a strong opportunity to integrate the BCMS with other emerging ITS technologies, including stationary automated vehicle inspection stations (the BCMS will provide screening of vehicles with brake problems), road-to-vehicle communications (for incorporation of grade severity data), vehicle-to-road communication (for transmission of brake safety status), and electronic safety verification (for improving flow through ports of entry). In addition, the fully developed product will likely be an integral part of EBS, and will complement ABS by providing assurance that the brake system has adequate stopping power at all times.

Discussions are under way with several potential partners about implementation of the BCMS concept. Vehicle, brake component, and sensor manufacturers have shown interest in the further development, production and marketing of the BCMS. Government national laboratories, defense contractors, and trucking industry groups have also expressed interest. The University of Washington has secured a patent on the BCMS, and PACCAR Inc has already demonstrated a commitment by subsidizing extensive full-scale testing during the first phase of the project. The Washington State

Department of Transportation has also provided funding for this research and maintains an interest in the future implementation of the BCMS.

The next phase for the BCMS will likely involve prototype fabrication and field trials. This will require a significant commitment of time and resources, and access to over-the-road truck fleet for verification. It is expected that the concept will require further refinement to assure compatibility with multiple trailers, and integration with ever-changing versions of EBS and on-board diagnostic systems.

CONCLUSIONS

The goal of brake condition monitoring through measurement and interpretation of a small number of parameters has been met; the challenge remains to refine the methods, prove its reliability with operational tests, and assess user acceptability.

The determination and prediction of commercial vehicle brake effectiveness using on-board, real-time, inferential, performance-based techniques shows promise. Throughout the course of both phases of this research, much has been learned about the development and implementation of a BCMS that will perform this function. The challenge of determining brake stroke for air-brake-equipped vehicles in operation, vital to the development of a BCMS, has been addressed. The concept of indirectly determining brake stroke from air pressure data has been explored through modeling and experimental data and has been shown to be an effective method of determining brake stroke. The steps taken to develop this method have been explained and the basic relation necessary to determine brake adjustment from air pressure decay has been established. For the specific brake configuration in our laboratory, numerical values for parameters have been determined and testing results have shown that this method is effective. Finally, an updated algorithm has been proposed and awaits prototype development and field trials.

Because the underlying principles of how air brake components function are the same for most manufacturers, the form of the relation developed for a particular configuration will likely be applicable to all. Because this method of indirectly determining brake stroke does not require additional instrumentation on CVs, it makes the BCMS more attractive to both users and manufacturers, largely for its potential to improve the safety of air-brake-equipped vehicles and ultimately save lives.

However, throughout the course of research, it has been clear that inferential measurement of brake effectiveness is not trivial. The challenge is not only to determine a means to assess brake condition, but to find a reliable, robust method that is compatible with the multiplicity of vehicle configurations and brake componentry.

INVESTIGATOR PROFILES

Dr. Per Reinhall was a Principal Investigator for this program. Dr. Reinhall is a Professor in the Department of Mechanical Engineering at the University of Washington. He received his doctorate in Applied Mechanics from the California Institute of Technology in 1982. Since then he has taught and conducted research in nonlinear dynamics, vibration, and mathematical modeling. Dr. Reinhall has over 20 years of experience applying modern dynamics theory to engineering systems and has written or published over 80 papers and reports on these topics.

Dr. Robert Scheibe shared the role of Principal Investigator with Dr. Reinhall. Dr. Scheibe obtained his doctorate in Mechanical Engineering from the University of Washington in 1996 under the direction of Dr. Reinhall; the first phase of this program was the core of his dissertation research. Dr. Scheibe is an Affiliate Assistant Professor in the UW Department of Mechanical Engineering and a Principal with GT Engineering in Redmond Washington, an engineering consulting firm dedicated to the analysis and prevention of failures and accidents, a field which he has pursued for 20 years. Dr. Scheibe has a background in heavy truck vehicle dynamics and accident analysis, and has personally investigated a number of commercial vehicle accidents involving brake failures.

Mr. Leonard Kandt, a researcher for the project, recently acquired his Master of Science in Mechanical Engineering from the University of Washington under the direction of Drs. Reinhall and Scheibe. He received his Bachelor of Science in Mechanical Engineering from Walla Walla College in 1998. Mr. Kandt was pivotally involved in the development of the analytical model and laboratory analysis crucial to the success of this project. Mr. Kandt is now a Mechanical Engineer with Electro Scientific Industries, Inc. in Escondido, California.

NOTATION AND REFERENCES

NOTATION

$\bullet$: Denotes derivative with respect to time
A_e : Exhaust area
A_{full} : Maximum exhaust area
A_p : Piston area
B : Spring force
B_s : Determined brake stroke
c_1 through c_{10} : Polynomial coefficients determined by least-squares
D_p : Piston damping
f : Denotes function
k : Ratio of specific heats
L_c : Length of air brake chamber
m_e : Air mass exhausted
m_o : Air mass in air brake chamber
M_p : Piston mass
P : Pressure
P_{atm} : Atmospheric pressure
P_{bck} : Pressure back of piston
P_{crt} : Critical flow pressure
P_i : Initial pressure value determined by least-squares
P_{ini} : Initial pressure
P_o : Pressure inside air brake chamber
r_1 : Air brake chamber endpoint radius
r_2 : Air brake chamber midpoint radius
s : Brake stroke
t : Time
V : Air brake chamber volume
V_1 : First piecewise air brake chamber volume
V_2 : Second piecewise air brake chamber volume
ρ_{ini} : Initial density
ρ_o : Density inside air brake chamber
τ : Time constant determined by least-squares

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