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Development of an Intelligent Air Brake Warning System for Commercial Vehicles

Per G. Reinhall and Robert R. Scheibe
University of Washington

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This investigation was completed as part of the ITS-IDEA Program which is one of three IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in surface transportation. It focuses on products and result for the development and deployment of intelligent transportation systems (ITS), in support of the U.S. Department of Transportation's national ITS program plan. The other two IDEA programs areas are Transit-IDEA, which focuses on products and results for transit practice in support of the Transit Cooperative Research Program (TCRP), and NCHRP-IDEA, which focuses on products and results for highway construction, operation, and maintenance in support of the National Cooperative Highway Research Program (NCHRP). The three IDEA program areas are integrated to achieve the development and testing of nontraditional and innovative concepts, methods and technologies, including conversion technologies from the defense, aerospace, computer, and communication sectors that are new to highway, transit, intelligent, and intermodal surface transportation systems.

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EXECUTIVE SUMMARY

Malfunctioning brakes represent the most common safety violation for commercial vehicles [l]. The objectives of this project were to research on-board measurement of a few brake-related parameters in order to monitor the effectiveness of air brakes, and to develop an algorithm for warning drivers and/or informing authorities of impending brake failure.

The principal parameters that describe braking performance were identified as application pressure, weight, response pressures, temperature, adjustment, and speed. Initial testing quantified and confirmed the importance of these parameters. Multiple regression modeling techniques were developed to predict braking performance without the necessity to measure or monitor brake stroke or temperature. This was done by omitting stroke and temperature as independent variables from the model and "training" the vehicle model at optimum strokes and temperatures. Two models showed promise in preliminary testing and analysis: deceleration and brake lag.

Further analysis after a second phase of full-scale testing under more realistic conditions showed that brake lag could not be reliably determined for a vehicle in service. Further, resolution of brake deterioration from the deceleration model was usually not sufficient at low brake temperatures, However, noticeable performance losses were measured for hot brakes and for certain high pressure tests at cool temperatures. Also, brake decay was explored as another measure of brake performance that would be more easily reconciled under real-time, real-world conditions than brake lag.

Deeper analysis of the statistical modeling techniques produced a simple, universal deceleration model applicable to all vehicle configurations that involved only two parameters: ***pressure*** and ***speed *pressure.*** Cross-validation of models, to investigate the prospects of adjusting one deceleration model for weight and using it to predict performance at another weight, was successful.

Run-to-run variability in measurements, coupled with the nonlinearity of the force versus stroke curve of the brake chamber, has caused the problem of brake assessment to be more probabilistic than deterministic. Unfortunately, cost constraints prevented the collection of the large quantities of data necessary to build or test models with great consistency or accuracy. Nevertheless, modeling of deceleration for various vehicle type and weight configurations was quite promising. Clear trends of diminished brake performance were evident at higher temperatures when adjustment was at or beyond the legal limit, even for the small sample sizes. More data would likely have improved the fit and consistency of models.

An intelligent brake warning device (IBWD) algorithm was developed with three modes: static, training, and operational. In the static mode, brake lag on a stationary vehicle (with cool brakes) will be automatically determined after vehicle start-up and will be compared with the baseline lag for that vehicle. If lag exceeds a pm-determined threshold, a warning will be issued to the driver. The training mode will be used to develop models of deceleration and decay. A vehicle with cool, properly adjusted and maintained brakes will be driven through a series of braking cycles at varying speeds and application pressures. Parameters from a regression model of training data will be automatically stored. In the operational mode, the vehicle will be driven normally; braking cycles will be compared with modeled predictions of optimum performance. A large deviation from the model will result in an immediate warning; a lesser deviation will be averaged with the previous nine data points. If the running average of the last ten runs exceeds a pm-determined threshold, a warning will be issued

Future research will pursue the refinement and extension of the algorithm through more extensive testing and field trials. The concept of brake pressure decay as a real-time indicator of brake condition (and predictor of future performance) will be fully explored; this will involve collecting data at higher sampling rates and testing the model parameters for significance. The static lag model will be thoroughly tested on configurations to assess its sensitivity to different vehicle configurations. Deceleration model refinement will continue with acquisition of larger sample data sets. Minimum sample sixes for training data will be formally determined, and methods for establishing warning thresholds will be explored

IDEA PRODUCT

This IDEA project focuses on developing an on-board, intelligent, brake warning device (IBWD) for air-brake-equipped commercial vehicles. The IBWD, which is low cost, mounts in the cab or tractor of a truck or bus and warns the driver of brake degradation or impending failure from any mechanical cause. The IBWD assesses vehicle brake performance in real time by measuring a relatively small number of on-board parameters. Eventually, the system will also consider environmental information, such as grade severity data, that could be transmitted to the vehicle from fixed stations near steep downgrades via Intelligent Transportation System (ITS) technology.

MOTIVATION

Accident Statistics

Malfunctioning brakes are the leading mechanical cause of commercial vehicle accidents and constitute the most common safety violation [1,2]. Air brakes are used on most tractors and trailers with gross vehicle weight ratings of over 19,000 lb., most single trucks over 31,000 lb., most transit and inter-city buses, and about half of all school buses [3]. Commercial vehicle safety and accident analysis reveals numerous reasons why air brakes are such a problem; these reasons fall primarily into two categories related to the design characteristics of air brake systems. Fist, air brake systems are more sensitive to adjustment condition than hydraulic brakes. Second, air brakes provide less tactile warning of brake degradation to the driver than hydraulic brakes. Because accidents involving heavy trucks and buses have the potential to be severe, a means for detecting such problems is needed. Surprisingly, no system that can warn drivers about a loss of brake effectiveness due to mechanical causes (other than low supply pressure) is currently available.

Data collected by the National Highway Traffic Safety Administration (NHTSA) from 1988 to 1990 show that whereas only 1 percent of registered vehicles are commercial vehicles, they represent 5 percent of total vehicle miles traveled [4]. Furthermore, accidents involving commercial vehicles are estimated to account for approximately 10 percent of fatalities. Data from the Fatal Accident Reporting System (FARS), collected by NHTSA, from 1982 to 1990 show that of the 50,000 fatal accidents involving heavy trucks during that period, only 8400 (17 percent) of the fatalities were heavy truck occupants [5]. The overwhelming majority (69 percent) of fatal injuries were caused to automobile or light truck occupants. Further studies have estimated that 40 percent of all trucks will be involved in a brake related crash during the lifetime of the truck and that in 33 percent of all truck accidents, a brake system problem is a contributing factor [l]. These statistics underscore the importance to the general public of improved commercial vehicle safety.

The only convenient means of determining brake condition is to measure brake chamber adjustment (stroke) on a stationary vehicle, which requires a wheel by wheel inspection by trained personnel. Chamber manufacturers provide specifications for acceptable stroke levels for various chamber sizes. Commercial vehicle enforcement officials nationwide use the Commercial Vehicle Safety Alliance (CVSA) North American Uniform Inspection and Out-of-Service Criteria [6] for determining when to declare vehicles out-of-service (OOS) and hence inoperable. The CVSA guidelines state that a vehicle must be put OOS if at least 20 percent of the vehicle's brakes are defective. One defective brake is defined as either one brake one-quarter inch or more beyond the readjustment point or two brakes less than one-quarter inch beyond the readjustment point. The vehicle must also be declared OOS if a steering axle brake is one-quarter inch or more beyond the adjustment limit, or if brake adjustment on two sides of a steering axle differ by one-half inch or more (because of concerns about steering wheel pull).

A recent survey in five states of approximately 1500 heavy trucks conducted by the National Transportation Safety Board (NTSB) revealed that a disturbing 57 percent of the vehicles surveyed were operating with OOS brakes and that, of those, 44 percent of the OOS violations were caused by out-of-adjustment brakes [2]. The study also showed a positive correlation between the incidence of defective brakes and the following factors: trailer brakes (as opposed to tractor brakes), vehicle age, vehicles in rough service (log trucks, dump trucks), and manual slack adjusters (as opposed to automatic slack adjusters).

Air Brake System Design and Technical Issues

Commercial vehicle air brakes pose a significant safety concern on today's roadways for a number of technical reasons. Ninety percent of heavy truck and bus air brakes currently consist of drum type S-cam foundation brakes, with diaphragm chambers and manual or automatic slack adjusters [3]. A schematic of these components is shown in Figure 1. The diaphragm-type brake is very sensitive to adjustment condition: chamber pressure versus force characteristics are nonlinear, and there is a sudden drop-off in force when the pushrod stroke exceeds the recommended level. Chamber pushrod stroke increases as the brake shoes wear, or as the drums expand at higher temperatures. But when the recommended adjustment level is exceeded, the diaphragm diminishes in effective area as stroke increases, which, along with other kinematic and design-related factors, causes the braking force for a given pressure level to diminish sharply. When pushrod stroke becomes so great that the pushrod bottoms out in the chamber, brake force drops to zero.

Pushrod force versus stroke characteristics were measured during the course of this research for a Type 30 (30-sq.-in.) chamber with a maximum recommended stroke of 2.0 inches. Results are shown in Figure 2. Note that the recommended pushrod stroke adjustment range exists in the flat portion of the curve, thereby ensuring a relatively constant force output for pushrod strokes within that range. The most common brake chamber in use today is the Type 30.

Pushrod stroke limits for typical diaphragm chamber sizes are shown in Table 1. Note that the 24 LS and 30 LS diaphragm "long stroke" chambers have a greater usable stroke range than their standard counterparts. The increased stroke provides additional assurance of maintaining adjustment within the acceptable region, although such chambers are not yet used widely. The IBWD will address many problems associated with commercial vehicle air brakes, some of which are unique to diaphragm-actuated S-cam drum brakes. However, the general approach to the IBWD will also provide an increased margin of safety for less common brake configurations.

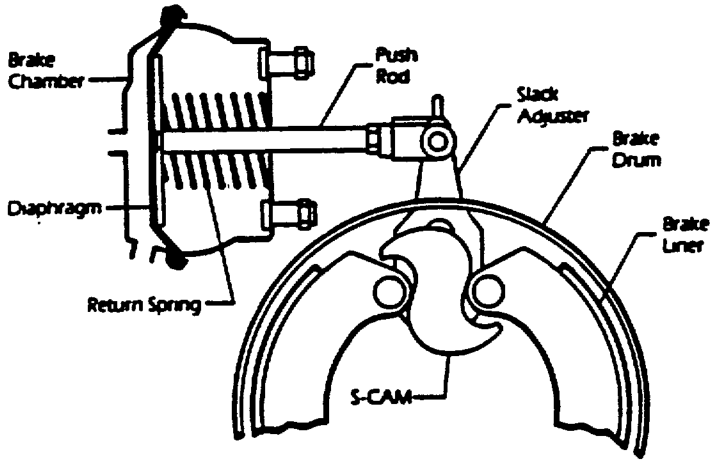

Figure 1. Schematic of air brake components at each wheel [7]

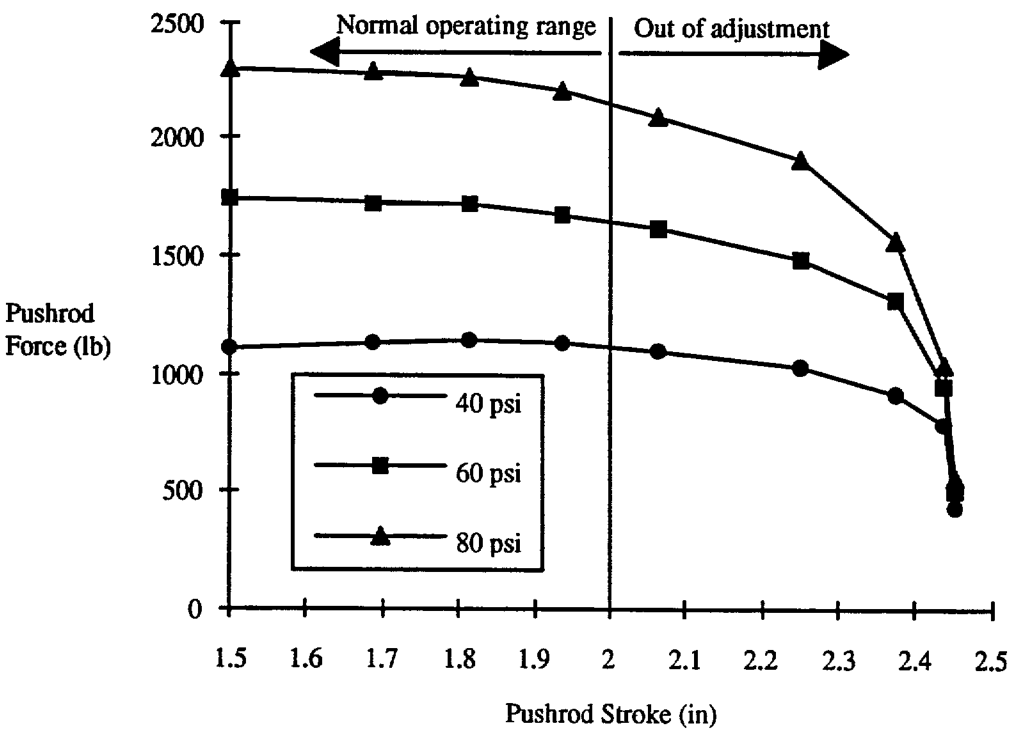

Figure 2. Pushrod force versus stroke characteristics for a Type 30 brake chamber

Table 1. Pushrod stroke limits for various air brake chambers

Chamber Type (diaphragm area, sq. in.)	Stroke When Brake Should Be Adjusted	Max. Possible Stroke
9	1 3/8	1 3/4
12	1 3/8	1 3/4
16	1 3/4	2 1/4
20	1 3/4	2 1/4
24	1 3/4	2 1/4
24 LS	2	2 1/2
30	2	2 1/2
30 LS	2 1/4	3
36	2 1/4	3

The sensitivity of air brake systems to adjustment is compounded by a lack of feedback to the driver. Unlike hydraulic brake systems in which application of the brake pedal acts to pressurize a fluid. The motion of the pedal displaces a fixed volume, so pedal height is proportional to brake adjustment. In contrast, application of an air brake pedal (treadle valve) simply opens a metering valve to divert compressed air from the storage tank(s) to the brake chambers. Hence, only a slight increase in brake pedal travel achieves greater delivered pressure. Because air brake pedal height does not change appreciably with the amount of air used, the driver is insulated from direct energy input to the brakes, and as braking efficiency diminishes (through loss of adjustment, thermal loads, or other factors), very little tactile sensation is transmitted through the treadle valve. In other words, the brake pedal does not necessarily feel "spongy" or low, as in a typical automobile. The only real feedback a driver receives is the sensation of deceleration for a perceived pedal application position. The relatively large mass and low deceleration rates of commercial vehicles exacerbate the difficulty in perceiving brake degradation.

Adjustment sensitivity is further compounded by an increase in the time necessary for all the brakes to reach full operating pressure. As pushrod stroke increases, not only 'does the force level drop, but the brakes take longer to reach the desired application pressure (air transmission lag time). For properly adjusted brakes, it can take over half a second for adequate air pressure to reach the farthest axle of a triple trailer combination; this can add significantly to stopping distance. Tests have shown that application times can increase by about 80 percent when strokes go from the fully adjusted condition to the legal limit [3].

Because of the compounding effects of brake fade and drum expansion, hot brakes experience a significant reduction in braking performance. If only some of the brakes are properly adjusted, then those in adjustment will take a disproportionate share of the load, and may fade prematurely, shifting the load to the other (poorly adjusted) brakes. This further emphasizes the requirement for proper adjustment. One study showed that for a fully adjusted brake operating at 600 ^{o}F, the available brake torque is 85 percent of maximum, and it drops to only 50 percent of maximum when the stroke reaches the upper adjustment limit [7].

An additional factor complicates the understanding of brake performance as measured by pushrod stroke on a stationary vehicle. Pushrod stroke (at a given pressure) has been found to increase beyond the statically determined value when the vehicle is in motion [8]. This phenomenon, called dynamic stroke increase, is believed to be caused by self-energization of the brake mechanism and elastic deformation of the foundation brake components. The dynamic stroke increase has been reported to be approximately 0.1 in. at 85 psi [3].

Recent law now requires the use of automatic slack adjusters on new commercial vehicles, but NTSB studies have shown that automatic slack adjusters are not an entirely effective way of curing brake malfunctions [l]. Although these studies have shown that (on the average) fewer vehicles equipped with automatic slack adjusters are at or near the adjustment limit, some vehicles equipped with certain types of automatic slack adjusters have been found to be no better (and perhaps worse) than equivalent vehicles with manual slack adjusters. Researchers have speculated that this is partially the result of the unreliability of automatic slack adjusters and partially because of an "out of sight, out of mind" mentality. Operators and mechanics may not understand that "automatic" does not mean "maintenance free." Because automatic slack adjusters have not proved to unilaterally provide adequate advances in brake reliability, and because millions of vehicles equipped with manual slack adjusters are still operating and will continue to operate for many years, the need for an intelligent warning system is not expected to wane.

BENEFITS FROM RESEARCH

The most significant benefit from this IDEA product is the improved safety of truck drivers, other vehicle occupants, and pedestrians. Truck drivers will be better informed of rapidly changing brake conditions that may threaten the stopping capacity or stability of their vehicle.

Moreover, on-board diagnostic information about brake condition is made available to maintenance personnel and fleet management. Brake performance data from the IBWD can be downloaded to staff, allowing timely repairs that assure safe operation and minimize costly road calls.

Integration of the IBWD with existing or planned ITS commercial vehicle operation (CVO) technologies, including automatic vehicle identification (AVI), main line vehicle sorting, and automated inspection stations, also promises to further improve highway safety by enhancing safety enforcement. The IBWD will give inspectors a readily accessible, electronic means of evaluating the hidden and most commonly deficient mechanical aspect of commercial vehicle safety without requiring proximity to the passing vehicle. Ironically, brake problems are often discovered incidentally during routine inspections for other, mote obvious violations. Brake inspections are the most labor-intensive task in the typical safety inspection procedure, often requiring approximately 20 minutes out of a typical 30-minute inspection. With the IBWD, brake performance information will be available for electronic transmission to roadside commercial vehicle safety enforcement checkpoints. Hence, enforcement officers will be able to target vehicles that may require detailed inspection.

The IBWD also has the potential to increase the operational efficiency of commercial vehicle operations. One way of improving the flow of interstate trucking and eliminating costly and frustrating delays is through "transparent borders," a concept wherein legal trucks will be able to roll through ports of entry without stopping. Some ITS CVO technologies already exist to accomplish this, including weigh-in-motion (WIM) devices, AVI systems, and electronic credential verification systems, which can verify the legitimacy of various paperwork credentials such as registration and tax payment, However, a recent study of the barriers to realizing the transparent borders concept found that implementation of existing technologies is significantly hampered by a lack of advancement in safety-monitoring technology [9]. States will not allow a vehicle to enter without being able to verify that it is both legal ***and*** safe, and to date, no technology exists to automatically verify safety the way AVI tags can verify credentials. The IBWD represents the first step toward providing this missing link. Although the IBWD specifically addresses only the vehicle brake system, the fundamental concept explored in this research will probably be expandable to encompass other vehicle and driver fitness monitoring functions.

CONCEPT AND INNOVATION

The IBWD concept (Figure 3) consists of an on-board microprocessor that monitors brake air pressures, vehicle weight, speed, deceleration, and roadway environment information such as grade severity. Through an empirically determined algorithm, the IBWD warns the driver of impending loss of brake effectiveness (or provides information to maintenance personnel or authorities) without having to monitor individual brake strokes, temperatures, or mechanical deficiencies. The IBWD is passive so that the driver will not have to calibrate the device or enter any information related to the vehicle, road, or load. Because the IBWD assesses braking performance from the standpoint of the total vehicle system, it is sensitive to brake degradation from ***any*** cause. In its simplest form, the IBWD requires only a few sensors and systems not already carried on a modem vehicle. The concept incorporates ITS communication systems that allows information flow to and from the vehicle. The IBWD is adaptable to existing vehicles and complementary to other on-board safety systems and diagnostics, including anti-lock brake systems (ABS). Although ABS functions to prevent brake lock-up, it does nothing to assure that there is adequate braking power; as such, the IBWD provides a complementary “front end” to ABS.

The IBWD operates in two modes, the first to “train” the algorithm and the second for continuous safety monitoring. In the first mode, the IBWD algorithm creates a model of “ideal” brake performance; to create this ideal, a well-maintained vehicle is driven for a short time with brakes that are cool and properly adjusted. During the second mode, for normal operation, the IBWD continuously monitors performance parameters and makes real-time comparisons with the “ideal” brake performance model that was created during training. The algorithm determines whether measured conditions violate pre-determined rules for the absolute threshold of safety, or whether predictive guidelines indicate that data are displaying an unfavorable trend. An audible or visual go/no-go warning is issued to the driver at the first instant of actual or predicted brake degradation beyond an established threshold. Results of this multi-dimensional analysis are also stored and can made available to vehicle maintenance personnel or authorities through ITS communications.

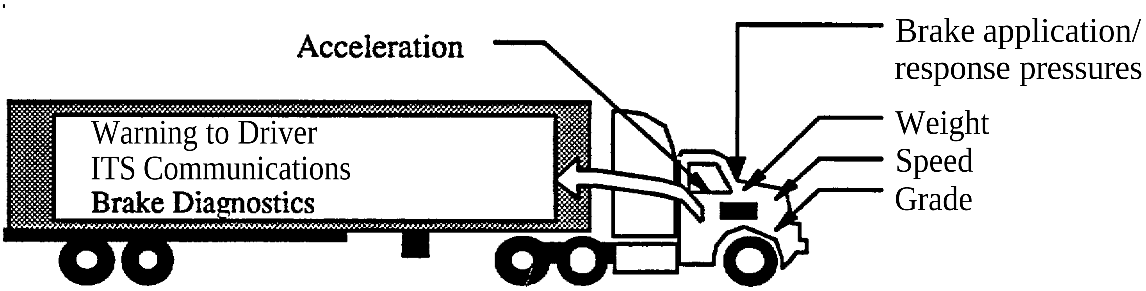

Figure 3. Intelligent brake warning device concept

INVESTIGATION

Research was undertaken to develop a technique to distinguish degraded from properly functioning brakes on air-brake-equipped commercial vehicles. The IBWD concept includes a predictive model of vehicle braking performance for “good” brakes that continuously compares the actual versus predicted braking performance as the vehicle is in service. If significant deviations from predicted performance occur, a warning is issued to the driver and/or cognizant maintenance officials.

Investigation consisted primarily of an empirical study; the complexity, uncertainty, and variability of the data collected during preliminary testing suggested that mechanistic modeling was unlikely to be sufficiently precise to permit definitive predictive models of braking performance to be developed. Even hybrid models, using empirical data from brake system components (e.g., brake chamber performance curves, brake dynamometer test data) in conjunction with first principles were impractical because of the number of variables, and did not offer much promise for accurate on-board sensing of brake effectiveness. Hence, research and algorithmic formulation was focused on experimentation, data collection, and analysis.

Research was conducted at the University of Washington from September 1994 until June 1996. Vehicle testing was performed at the PACCAR Technical Center in Mt. Vernon, Washington, in December 1994 and February 1996. Work was conducted in two phases.

FIRST PHASE

The first phase consisted of the following tasks:

- Detailed review of previous research and background data related to air brake design and perfomance.
- Selection of a minimal set of easily measurable and controllable parameters that characterize brake performance.
- Design of a formal experimental procedure to assess the importance of each parameter.
- Full-scale dynamic testing of a heavy truck on a test track to execute the experimental procedure.
- Qualitative and statistical analysis of empirical data to ascertain the significance and effects of the chosen parameters.
- Statistical modeling of the data to develop initial models that predict braking performance and degradation.

Completion of the first phase, in approximately July 1995, resulted in promising findings that launched the second phase of research.

SECOND PHASE

The second phase of research involved the following tasks:

- Further refinement of predictive models from the first phase.
- Consideration of mechanistic models of vehicle braking, for verification of empirical findings.

- Development of a codable algorithm for the IBWD based upon findings from previous testing and analysis.

- Programming of an IBWD computer and instrumentation interface for real-time, on-board processing of data for determining braking effectiveness.

- Full-scale testing of a heavy truck in several configurations to test the IBWD algorithm, demonstrate the viability of the IBWD concept, and test the sensitivity of the concept to different vehicle configurations.

- Additional data analysis to refine, optimize, and validate the predictive models and to establish brake effectiveness acceptance/rejection criteria.

- Compilation of findings with recommendations for an IBWD algorithm, instrumentation, hardware, and additional research.

EXPERIMENTAL TESTING

Experimental testing was conducted in two sessions at the PACCAR Technical Center. The first session, completed in December 1994, was exploratory; its purpose was to collect adequate data, through a designed experimental process, to allow meaningful investigation of the measurable parameters of greatest importance to vehicle deceleration.

The second session, completed in February 1996, was intended to be confirmatory. It was designed to test the algorithm on several vehicle configurations to verify the first phase results and validate the lBWD concept. It also demonstrated the viability of the concept through use of a programmed laptop PC that provided real-time, on-screen warning of degraded brake condition.

Exploratory Testing

Objectives

Level ground, controlled-stopping maneuvers were conducted on a typical five-axle tractor-trailer at the PACCAR Technical Center to establish basic relationships between brake application pressure, brake adjustment, deceleration, vehicle speed, brake temperature, vehicle weight, and pushrod force. Quantification of the importance of each of the controllable parameters and development of an empirical model describing deceleration were desired. Braking was limited to pre-lockup levels to explore response in the “typical” braking regime, rather than under the maximum deceleration conditions that are more commonly studied. Several static tests were also conducted to characterize chamber force output for a range of pushrod strokes.

Vehicle Data

The test vehicle was a 1993 Kenworth 900 conventional-cab tractor connected to a 40-foot Comet two-axle flatbed semitrailer (Figure 4). The vehicle was chosen to be a typical five-axle tractor-semitrailer, equipped with conventional brake and suspension hardware. Variable loading was accomplished by placing concrete blocks on the trailer.

Both tractor and trailer were equipped with S-cam drum brakes, manual slack adjusters, and diaphragm-type air chambers. Manual slack adjusters were retrofitted to the tractor where automatic slack adjusters had originally been installed. Tandem axle pairs were fitted with 30-sq.-in. combination spring brake chambers; the tractor steering axle was equipped with 20-sq.-in. brake chambers. All brakes were inspected and determined to be adequately burnished and in proper working condition. Although the tractor was equipped with ABS, the ABS was disabled during testing.

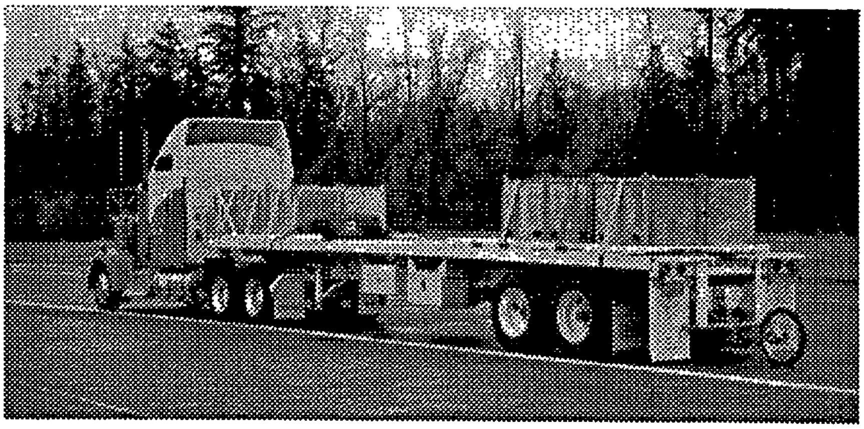

Figure 4. Tractor-semitrailer used for experimental testing

Equipment and Instrumentation

The vehicle was fitted with electronic instrumentation to continuously monitor and record data for the following functions:

- treadle valve (brake application) air pressure
- vehicle speed
- vehicle deceleration
- brake response pressure at each major axle group (three total)
- temperature at four brakes (left and right brake on axles three and five)
- brake chamber pushrod force on the left brake of axle three.

Brake application pressure was administered through a pressure regulating device designed and built by PACCAR Inc, for brake testing. This device allows driver-preset application of a steady brake pressure to all wheels, independent of the treadle valve. It also applies brake pressure to specific axle groups independent of other axles, if desired. Pressure transducers were installed to monitor brake application pressure and right side brake chamber (response) pressures for axles one, three, and five.

Test Matrix and Protocol

A designed experiment was chosen to assure maximum efficiency in determining the effects of each of five controllable factors on deceleration. Those factors were application pressure, vehicle weight, initial brake temperature, brake adjustment level (stroke), and initial speed.

An orthogonal half-fraction factorial test matrix was developed for the test plan (Table 2). The variable levels used for testing represent target values, except for vehicle weight and brake stroke, which were set as shown. Ranges for each variable were chosen to provide the widest variation possible while maintaining a condition of no lockup. Temperature and stroke values were chosen to represent normal and extreme conditions. The stroke levels are shown for tandem axle (Type 30) chambers only; front (Type 20) chambers required proportionally decreased stroke settings.

Table 2. Primary half-fraction test matrix

Runs	Vehicle Weight	Brake Adjust	Brake Temp	Init Speed	Appl Pressure
1-3	48500	1.5	225	20	40
4-6	48500	1.5	225	60	20
7-9	48500	1.5	500	20	20
10-12	48500	1.5	500	60	40
13-15	48500	2.25	225	20	20
16-18	48500	2.25	225	60	40
19-21	48500	2.25	500	20	40
22-24	48500	2.25	500	60	20
25-27	78,000	1.5	225	20	20
28-30	78,000	1.5	225	60	40
31-33	78,000	1.5	500	20	40
34-36	78,000	1.5	500	60	20
37-39	78,000	2.25	225	20	40
40-42	78,000	2.25	225	60	20
43-45	78,000	2.25	500	20	20
46-48	78,000	2.25	500	60	40
49-54	62,900	1.875	360	40	30

Dynamic testing was conducted after vehicle warm-up, and after a number of brake snubs had been performed to stabilize brake temperatures and verify proper operation. All tests were conducted in the same, level portion of the track, in the same direction. Once the driver had reached the desired brake temperatures (by snubbing or coasting), and once the other prescribed test conditions had been satisfied, the vehicle was placed in neutral, and data acquisition equipment was switched on. After coast-down to the target speed, the brakes were activated. The test was completed when the vehicle came to a complete stop.

Preliminary Data Analysis and Modeling

Empirical modeling was undertaken to establish a minimal set of easily measurable parameters that describe braking performance and to understand the relationships between the parameters. An empirical model is useful both because of the complexity of the mechanics of braking and deceleration, and because vehicle response over only a fairly limited range of the controlled variables needed to be modeled.

Analysis of variance (ANOVA) and linear regression modeling techniques were used to assess the significance of each of the five controllable factors and to develop predictive models. From Newton's Second Law,

$$decel = \frac{1}{m}(F_b + F_d) \qquad (1)$$

where ***decel*** is the deceleration of the truck, ***m*** is total vehicle mass, F_b is the braking force on the vehicle, and F_d is the drag force. For this analysis, F_d was assumed to be insignificant in comparison to F_b during braking. Because mass and weight are proportional, weight was used instead of mass for convenience in the analysis. A regression analysis was performed, F_b was assumed to be a function of the following form (three-factor and higher interactions are not shown):

$$F_b = c_0 + c_1 press + c_2 weight + c_3 temp + c_4 stroke + c_5 speed + c_6 press*weight + \ldots + c_{15} stroke*speed \qquad (2)$$

Although this model allowed the five factors of interest to be assessed, it was not practical fro application to predictive modeling for the IBWD. If continuous readings of application pressure, weight, brake temperatures, brake strokes, and speed are readily available, this technique provides a useful and accurate model of deceleration. But until technology enables routine electronic measurements from multiple sensors on trailers, it is likely that information from each brake (temperature and stroke) will not be available. Hence, a variation of this modeling approach was used to develop a method of assessing brake effectiveness without direct measurement of temperature and stroke.

A regression model was created to exclude temperature and stroke as independent variables, but not their effects. In addition, research showed that weight did not significantly influence braking force, hence:

$$F_0 = c_0 + c_1 press + c_2 speed + c_3 press * speed \qquad (3)$$

where F_0 represents the braking force under optimum conditions of temperature and stroke. The model was fit to 19 data points representing temperature and stroke at their lowest levels of 225 ^{o}F and 1.5 in., respectively. Hence, the model represents a prediction of brake force F_0 for cases in which the brakes are in "optimum" (baseline) condition. Brakes in baseline condition should be cool and properly adjusted. Should brake degradation occur for ***any*** reason, deviation from the model will be apparent.

This method relies on collection of a set of "training" data. For training, the vehicle is exercised through a normal working range of the pressures and speeds while maintaining stroke and temperature at their baseline levels. The system must initially collect baseline data on a properly maintained vehicle; the training cycle must be repeated after significant brake modifications or configuration changes. Training sessions will likely be short (half hour or less) and will be part of normal brake servicing routines.

A second measure of brake effectiveness was also considered. Air transmission lag time, which is the response time for pressure buildup at each brake chamber, was determined for each of the three axle groups on the test vehicle (front, tractor tandems, trailer tandems). Lag tune measurement commenced at the instant of pressure buildup at the treadle valve and ended when pressure reached 60 percent of the maximum pressure at each axle group location. Analysis showed that lag times were proportional to brake stroke, as was expected.

Similar statistical analysis and modeling techniques were applied to the prediction of lag time at a particular axle group location. A linear model of the following form was used to predict lag at the tractor tandem axles:

$$lag = c_0 + c_1 press + c_2 speed + c_3 press*speed \qquad (4)$$

The model was fit to data with optimized temperature and stroke levels, so that it would provide a prediction of lag under ideal conditions that could be compared to real-time brake lag data.

Preliminary Results

For the brake force model in Equation 2, all main effects were found to be statistically significant and are shown in order of decreasing significance. Through ANOVA and analysis of predicted sum of squares error, all two-way interactions (e.g., press*weight, temp*stroke) were included in the model to minimize the prediction error. Regression model fit was excellent.

Results showed that knowledge of the chosen five independent variable values was sufficient to predict deceleration response with considerable accuracy. Also, the strong repeatability evident in the collected data validated their usefulness for discerning subtle changes in response, which is essential for prediction of brake degradation.

Because it is inconvenient to obtain direct measurements of temperature and stroke, the model in Equation 3 was developed. Temperature and stroke terms were removed from the model, and the model was fit to data points where temperature and stroke were optimized (at their lowest levels). The model was then used to predict deceleration for all data. For the first 54 test runs, deviations from the predicted "optimum" deceleration conditions were plotted; these deviations (Figure 5) provide a potential measure of brake effectiveness. For example, runs numbered 46-49 show a particularly significant (140 percent) deviation from prediction; they represent a case in which brakes were very hot and stroke was excessively long. The legal maximum stroke limit for the Type 30 brakes on this vehicle is 2.0 in.

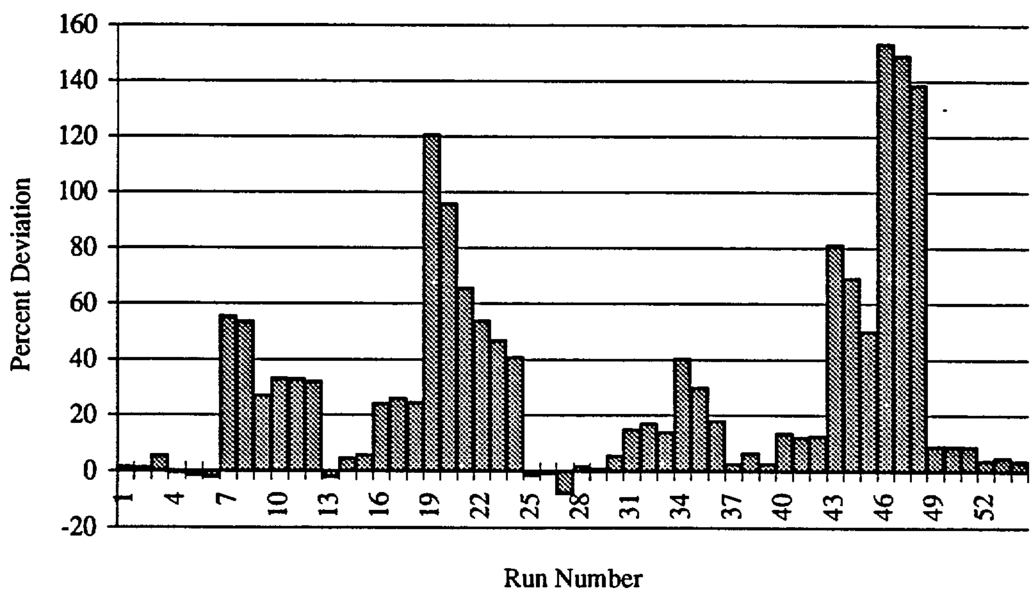

Figure 5. Deviation of measured deceleration from 3-term model (Equation 3)

For the lag prediction model in Equation 4, ANOVA revealed that application pressure was overwhelmingly significant; however, the two-factor interaction was insignificant and hence omitted. As before, a regression model was fit to the data for cases in which temperature and stroke were optimum. The model was used to predict lag for all collected data; a plot of residuals demonstrated that brake lag prediction successfully represented a second, independent means of assessing brake effectiveness.

On the basis of the exploratory testing and analysis, a potential theoretical basis for assessing brake condition was formulated. When both prediction means (deceleration and lag) were employed simultaneously, a more robust brake effectiveness determination was realized. Deceleration prediction residuals were plotted against brake lag prediction residuals, shown in Figure 6. Both models were initially "trained" to fit optimized temperature and stroke data; data points surrounding the origin represent this baseline condition. For different conditions of increased temperature and stroke, data points move outward along varying vectors in the two-dimensional plane, depending upon the level of degradation and/or the sensitivity of the predictor to that degradation.

This technique offers the potential to more reliably determine brake effectiveness because it involves redundant prediction of brake effectiveness by nearly independent measurements and analysis. It also provides the opportunity to distinguish one malady from another. Because temperature and stroke are related (high temperature brake drums expand to yield higher strokes), it may be possible to differentiate purely stroke-related deficiencies from temperature-induced stroke deficiencies by examining time domain data. Even without the benefit of actual temperature or stroke measurement at each wheel, recent pressure versus time histories of brake applications, in conjunction with time

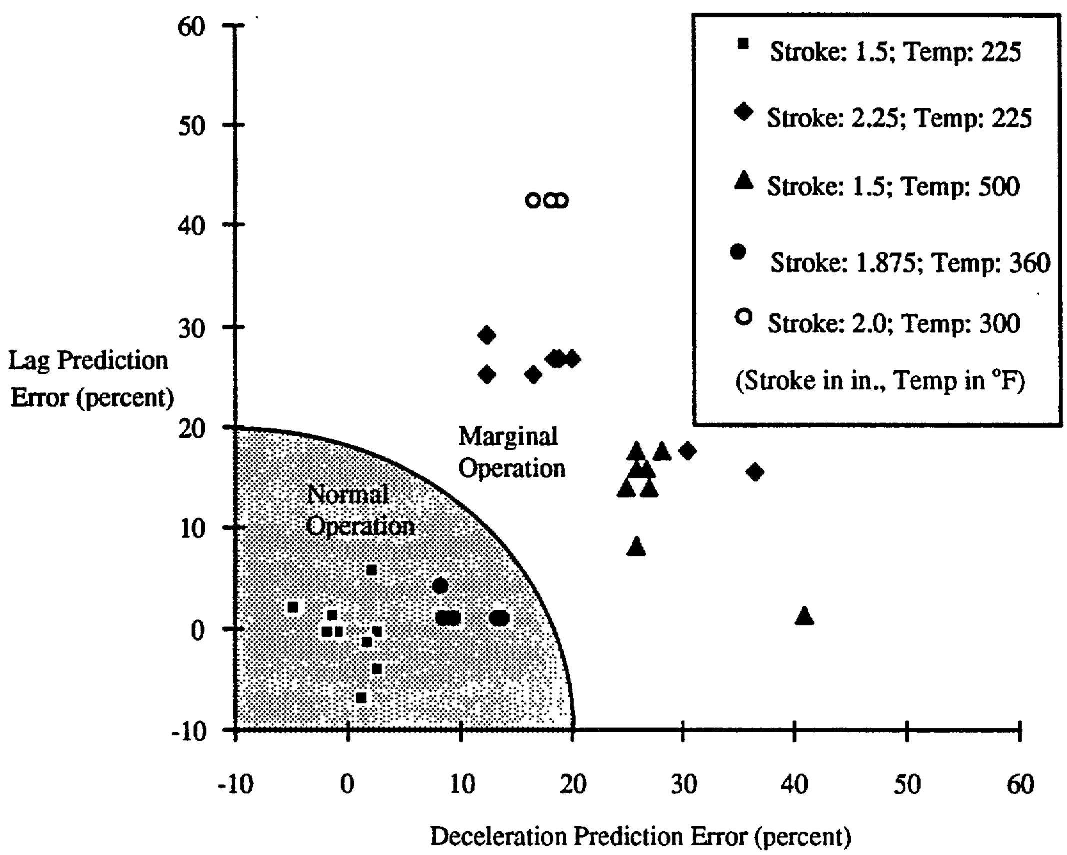

Figure 6. IBWD brake performance regions

histories of the predictors, may show purely stroke-related deficiencies as independent of the frequency or duration of recent brake applications. Temperature-related stroke deficiencies will be more transient. These phenomena will enhance the diagnostic capability of the IBWD.

Confirmatory Test Program

To further validate and evaluate the IBWD concept, a second full-scale test program was conducted at the PACCAR Technical Center in February 1996. This test program was designed to evaluate the on-board brake effectiveness monitoring scheme, developed from previous research, through a realistic test protocol that more closely approached road conditions. The program also sought to demonstrate, through a codified algorithm, that real-time brake monitoring can be conducted with a simple microprocessor attached to only a few sensors.

Objectives

The objectives of the confirmatory test program were as follows:

- Demonstrate that the empirically determined parameters and methods revealed during the first test program and subsequent data analysis are sound for real-world brake effectiveness monitoring.

- Investigate the feasibility of a two-stage evaluative process wherein there is a “training” mode for developing the model of “good” brakes on the vehicle and an “operational” mode for testing the vehicle under actual conditions.

- Develop a computer program capable of real-time processing of on-board vehicle data for rapidly assessing brake effectiveness and, ultimately, for issuing a warning to the driver when appropriate.

- Show that the modeling and algorithmic concepts developed are generalizable and practical, and that the IBWD algorithm can easily be applied to different vehicle configurations.

Vehicle Setup and Instrumentation

All testing was performed with the same Kenworth 900 three-axle tractor that was used in December 1994. A similar Comet 40-foot flatbed semitrailer, of the same age and specifications as the trailer tested in 1994, was used for instrumented test runs. An uninstrumented 48-foot Comet van-type semitrailer (Figure 7) was also tested.

As before, all vehicles were equipped with conventional brake and suspension hardware. Weight on the flatbed trailer was varied by loading concrete blocks. The van trailer load, which was near capacity, was not varied. All vehicles were equipped with S-cam drum brakes, manual slack adjusters, and diaphragm-type air chambers of the same specifications as were used for previous testing. Anti-lock brakes were disabled.

Figure 7. Test vehicle used for 1996 testing, shown with van-type semitrailer

The vehicle was fitted with electronic sensors similar to those used in the 1994 test sequence to continuously monitor and record data. Sensors were used to monitor the following functions:

- treadle valve (brake application) air pressure
- vehicle speed
- vehicle deceleration
- brake response pressure at tandem axle groups (tractor and trailer)
- temperature at four brakes (left and right brake on axles three and five).

There were several differences in vehicle preparation and instrumentation between the 1994 and 1996 test sessions. For the 1996 testing, brake application air pressure was administered through the treadle valve (controlled by the driver's foot), rather than through the treadilator device, to more closely simulate actual driving conditions. No pressure transducer was used at the steer axle, and no pushrod force transducer was installed in 1996 because neither sensor was judged to be important to the IBWD routine.

All sensors were connected to the Megadac 65068 digital data acquisition system used previously. This time, the Megadac was connected via an IEEE 488 General Purpose Interface Bus (GPIB) to an IBM PC 486 laptop computer running National Instruments LabVIEW software. Data were initially collected on optical media in the Megadac and then transferred across the GPIB to the laptop. Hence, the computer functioned both to control the data handling of the Megadac and to process the data for brake effectiveness monitoring. Data collection was initiated when triggered by a preset brake application pressure (of 0.5 psi). After data had been transferred to the PC, processing was accomplished by LabVIEW software that was programmed as described below.

Test Matrix and Protocol

Tests were conducted in a less regimented format than had been undertaken previously. Calibration of the fifth wheel and zeroing of the accelerometer (on level ground) preceded every sequence of tests. Tests were conducted on straight (essentially level) portions of the oval track and were not restricted to a single location, as was the case in 1994. Testing was conducted with three vehicle configurations. The instrumented flatbed trailer was tested both fully and partially laden, and the uninstrumented van trailer was tested in a near-full-load condition.

Data were collected in two modes of operation: "training" and "operational." For the training mode, a vehicle with brakes properly adjusted and cool (under 275 ^{o}F) was decelerated (with the treadle valve), in neutral, at a series of different application air pressures and initial speeds. These tests were designed to establish a baseline for "good" brakes for each of the three vehicle configurations. Application pressure was kept approximately constant (by the driver) over each braking maneuver, or "snub," which lasted approximately three to five seconds. Application air pressure levels were varied from approximately 25 psi to 45 psi, except for the lightly loaded trailer, for which maximum application pressures were limited to 40 psi to avoid lockup. Initial speeds were varied from approximately 30 to 60 mph. Final speeds varied greatly and were not controlled, unlike the December 1994 testing, the vehicle was not brought to a complete stop during each test. The precise level of application air pressure and initial speed was not critical, provided that brake temperatures were maintained below 275 ^{o}F. Nevertheless, an effort was made to vary the combinations of values through their respective ranges. Training cycles varied in length from 20 runs for the van trailer to 49 runs for the fully laden flatbed. The training cycle for the partially loaded flatbed included 30 runs, although training session length for all configurations was somewhat arbitrary.

After completion of the training cycle, a series of tests was conducted on each vehicle configuration in the operational mode. These tests were designed to explore the effects of brakes that had been degraded to various degrees by maladjustment and/or high temperatures, and to assess the sensitivity of the IBWD to these brake deficiencies. For each of the three vehicle configurations, an initial series of at least three brake snubs was run under baseline conditions to provide a validation data set. The baseline validation tests were identical to those made during the training cycle (30 to 60 mph, 30 to 40+ psi, brakes properly adjusted, and temperatures below 275 ^{o}F).

Then brakes were degraded through increased stroke and temperature. Brake snubs were conducted in a series of three tests at each stroke/temperature setting. For the fully laden trailer, brake strokes of 2.0 in. and 2.25 in. (for axles 2 to 5) were tested under normal temperatures (less than 275 ^{o}F) and high temperatures (greater than 500 ^{o}F). For the partially loaded flatbed and for the van trailer, normal and high temperature tests were conducted in the operational mode, but only for a stroke of 2.25 in. For all tests, tractor front axle (axle 1) brakes were left in their properly adjusted (1.325 in. stroke) condition. This was done because axle 1 brakes make only a small contribution to overall braking, and variation of adjustment on that axle was not deemed as important as brake adjustment on the tractor and trailer tandem axles (axles 2 to 5).

Matrices for accomplishing the test objectives are shown in Tables 3 to 5. These tables represent ***targeted*** test conditions, repetitions, and vehicle configurations. Slight variations from plan were required because of experimental control and instrumentation problems. In all, 197 tests were actually executed

Each of the following tables represents a specific trailer type and weight and shows the number of braking snubs for each test condition, whether the tests were in the training or operational mode, the axles that were maladjusted (if any), the degree of maladjustment for the axles affected, and the targeted initial brake temperatures. The most detailed study of brake degradation was conducted for the fully laden flatbed trailer; the partially laden flatbed and the van trailer tests were somewhat abbreviated because of constraints on time and cost.

Table 3. Test matrix for fully laden (78,600 lb) vehicle with flatbed trailer

No. of snubs	Test Mode	Axles Maladjusted	Maladjusted Stroke, in.	Temperature, °F
30-40	Training	none	n/a	< 275
3	Operational	none	n/a	< 275
3	Operational	5	2.25	< 275
3	Operational	4,5	2.25	< 275
3	Operational	2,3,4,5	2.25	< 275
3	Operational	2,3,4,5	2.25	>500
3	Operational	4,5	2.25	>500
3	Operational	5	2.25	>500
3	Operational	none	n/a	>500
3	Operational	none	n/a	< 275
3	Operational	5	2.0	< 275
3	Operational	4,5	2.0	< 275
3	Operational	2,3,4,5	2.0	c 275
3	Operational	2,3,4,5	2.0	>500
3	Operational	4,5	2.0	>500
3	Operational	5	2.0	>500
3	Operational	none	n/a	>500

Table 4. Test matrix for partially laden (47,800 lb) vehicle with flatbed trailer

No. of snubs	Test Mode	Axles Maladjusted	Maladjusted Stroke, in.	Temperature, °F
30-40	Training	none	n/a	< 275
3	Operational	none	n/a	< 275
3	Operational	5	2.25	< 275
3	Operational	4,5	2.25	< 275
3	Operational	4,5	2.25	>500
3	Operational	5	2.25	>500
3	Operational	none	n/a	>500

Table 5. Test matrix for heavily laden (76,040 lb) vehicle with van trailer

No. of snubs	Test Mode	Axles Maladjusted	Maladjusted Stroke, in.	Temperature, °F
20-30	Training	none	n/a	< 275
3	Operational	none	n/a	< 275
3	Operational	5	2.25	< 275
3	Operational	4,5	2.25	< 275
3	Operational	4,5	2.25	>500
3	Operational	5	2.25	>500
3	Operational	none	n/a	>500

COMPUTER INTERFACE

Hardware

To meet test objectives, computer routines were written in National Instruments LabVIEW 3.1 for Microsoft Windows, a graphical programming language for instrumentation and data analysis. Unlike the 1994 tests in which data were stored on the Megadac's optical media and then analyzed in the laboratory, the 1996 tests used the Megadac primarily as a data gathering and signal conditioning device. Data from tests were momentarily stored in the volatile memory of the Megadac during braking maneuvers, then rapidly downloaded across the GPIB to the hard disk of the computer via LabVIEW code. Once on the computer, data were analyzed in LabVIEW, allowing immediate assessment of brake effectiveness.

Several data analysis steps were left as manual operations to provide the flexibility to experiment with different techniques. The resulting need to briefly review graphical data and input several computer commands after each braking maneuver meant that on-screen information (or warning) about brake effectiveness was delayed 20 or 30 seconds. In any commercial manifestation of this concept, all operations handled by the LabVIEW code would be completely automated and programmed into a dedicated microprocessor, allowing instantaneous readings on brake performance.

Software

Several LabVIEW routines were written. One routine (named MEGADRIV) enabled the data to be downloaded across the GPIB to the PC upon completion of each braking maneuver. In practice, this could be done immediately following release of the treadle valve, or for a group of tests, at the end of a series of brake applications. For training cycles, no data would have to be postprocessed until all the training data had been collected, so data downloading would need to occur only once, at the end of the training cycle.

After data had been downloaded, the second LabVIEW code, named TRUCKDAT, was engaged to reduce the data. The TRUCKDAT package (Figure 8) displays a variety of data about each braking maneuver and prompts the user to enter certain information for each test run. A switch on the TRUCKDAT front panel allows the user to choose between the training and operational modes.

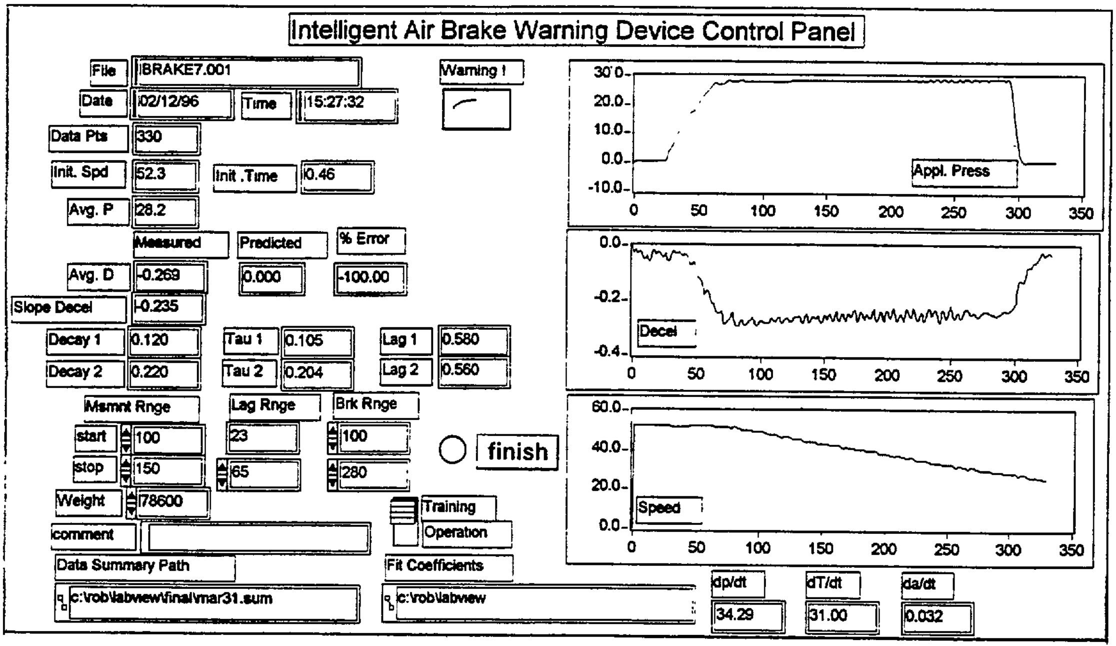

Figure 8. TRUCKDAT front panel, providing primary user interface for IBWD

For this research, vehicle weight was a user-defined entry. Eventually, vehicle weight will be determined on-board, through any of several possible means. The IBWD is intended to be a totally passive device, and none of the inputs currently required of the user will be necessary.

After the training sequence had been completed and each braking run had been analyzed by TRUCKDAT, as described above, the third LabVIEW module was engaged. This code, called MODEL, read in the reduced data set created by TRUCKDAT during the training cycle and created three multiple linear regression models of the data. In the first model, braking force was a dependent variable, thereby allowing a predictive equation for deceleration to be determined. The other two models defined predictive equations for τ_1 and τ_2, decay constants for response pressures at the tractor and trailer tandem axle locations, respectively, which indicate brake adjustment condition. The models created by the MODEL routine represent baseline conditions for "good" brakes for the vehicle configuration being tested. The MODEL routine needed to be run only once for each set of training data.

After predictive model coefficients had been determined by the MODEL routine, the IBWD was "trained" and was ready to monitor vehicle brakes. The TRUCKDAT routine was again activated and the toggle switch on the screen was placed in the operational mode. After user entry of a small amount of information, the screen updated data for the current braking maneuver and showed the actual and predicted values of *decel*, τ_1, and τ_2. If any of the predicted values differed by more than a (user-defined) acceptable tolerance, a red warning light appeared on the screen. Determination of tolerance acceptability will be presented in a later section.

ANALYSIS AND MODELING

Because data collected during the confirmatory test session did not always appear to corroborate findings from the previous tests, more sophisticated techniques were used to further understand and optimize the predictive models. These included automated variable selection techniques such as stepwise forward and backward elimination to choose the optimum subset of independent variables. Also, several optimization techniques were employed to minimize the variance of predicted values by eliminating correlation among the independent variables.

Confirmatory test results also revealed that several additional factors showed promise for indicating brake degradation, including temporal variations in application pressure and acceleration, and the use of brake response pressure decay time as a model response variable.

In addition to the statistical analysis that formed the basis of the predictive model, considerable effort was expended to compare actual (degraded) brake performance with predicted performance. This analysis formed the foundation for the diagnostic capability of the IBWD; "bad" brakes must be distinct from the prediction of "good" brakes for a given set of conditions, and the distinction must be made before brakes are dangerously degraded.

Examination of Data

For the flatbed trailer, a scatter plot showing families of deceleration versus application pressure data for the fully and partially laden vehicle in training and operational modes is shown in Figure 9. During operational tests, data were collected at baseline conditions and under various conditions of maladjusted and/or hot brakes. Brake strokes were 2.25 in. for those cases where brakes were maladjusted. (Operational tests run in the fully laden condition at a 2.0 in. stroke are not shown

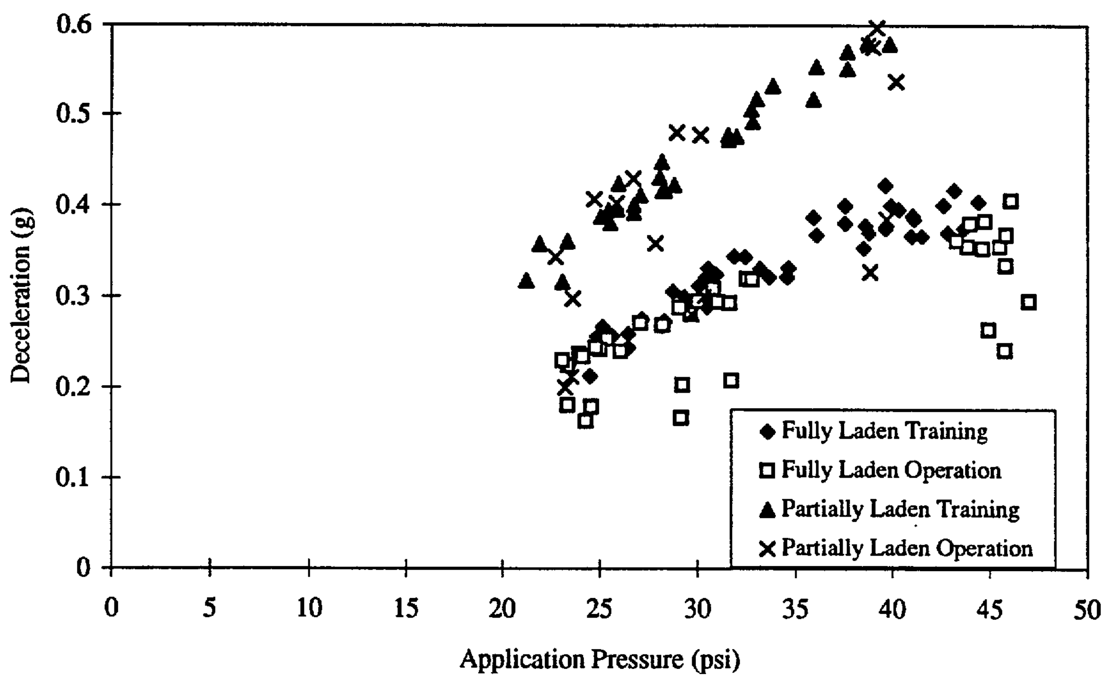

Figure 9. Deceleration versus pressure for fully and partially laden flatbed undergoing operational tests

in Figure 9.) Fairly distinct families of data surround the two weights; for training runs in each weight group, dispersion of deceleration data (at a given pressure) is very low. Within their respective weight families, a number of operational data points deviate significantly from the average training data values.

Because it was not possible from Figure 9 to determine the specific operational test conditions that produced deviations from the training data, detailed subsets of the data are shown in Figures 10 and 11 for the fully laden vehicle with cool and hot brakes, respectively.

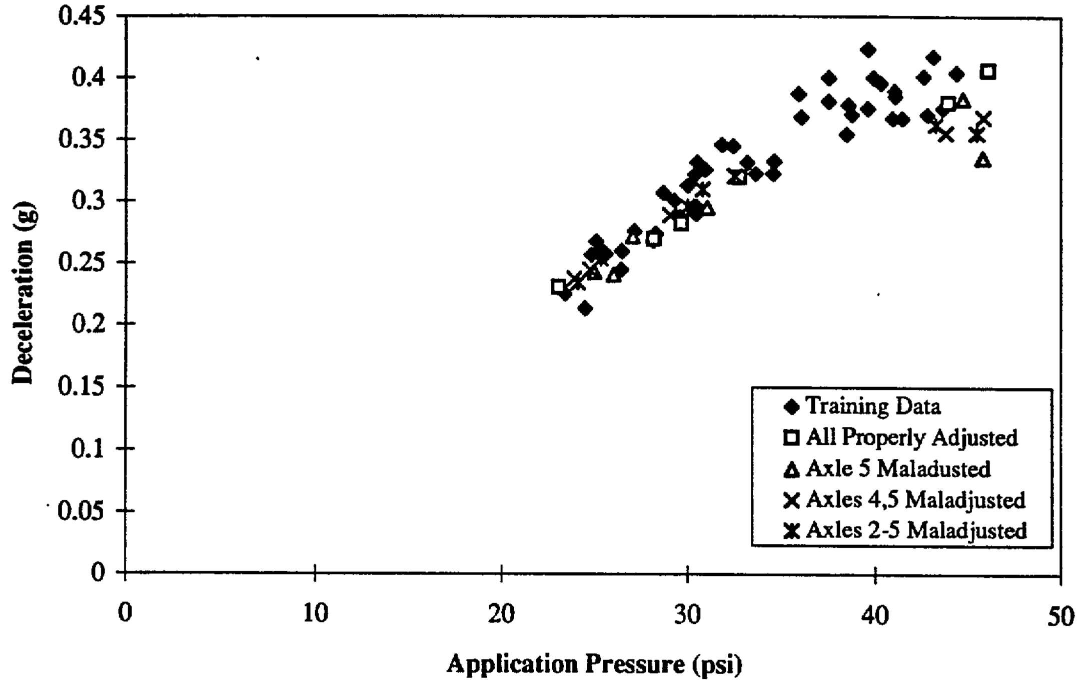

Figure 10. Deceleration versus pressure for fully laden flatbed with cool brakes undergoing operational tests with maladjustment at 2.25 inches

Examination of the data in this manner revealed a number of clear trends concerning the effects of application pressure, brake adjustment, temperature, and vehicle weight on deceleration:

- In general, dispersion of data for both the operational and training runs was more pronounced at higher application pressures. In fact, for the case of cool brakes, there was no perceptible difference between training and operational deceleration values for application pressures below about 35 psi.

- During operational tests, deviation from optimal deceleration (as defined by the training data) was more pronounced for hot brakes than for cool brakes, and was evident at all pressure levels for hot brakes. This was especially obvious for the partially laden flatbed trailer.

- Deceleration tended to decrease with increasing numbers of maladjusted brakes, as would be expected. This observation was more marked for the high temperature tests.

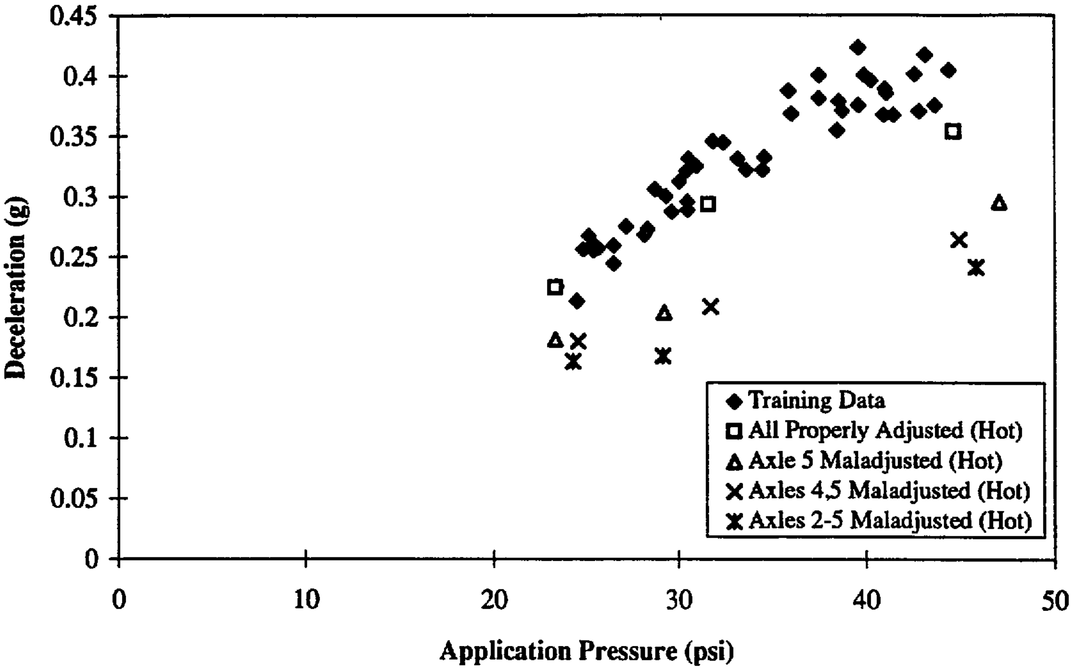

Figure 11. Deceleration versus pressure for fully laden flatbed with hot brakes undergoing operational tests with maladjustment at 2.25 inches

- Maladjustment of 2.25 in. yielded slightly more noticeable deviations from optimal conditions than did 2.0-in. strokes.

- Validation tests in the operational mode (which mirrored training tests) generally overlaid data collected during training runs.

- There was consistency across the three trailer configurations.

On the basis of purely the deceleration and pressure data, there appears to be a good chance of discerning brake efficiency loss, especially for higher pressure and temperature conditions. Data from runs made only at low temperatures and pressures appear to be less useful for predicting brake degradation. Consideration of additional relationships between measured variables, as well as more sophisticated modeling techniques (both of which follow in subsequent sections), will likely enhance the ability to detect brake efficiency loss with on-board sensing of the chosen parameters.

The difficulty in discerning brake degradation at low temperatures underscored the need for on-board brake monitoring. Roadside brake performance monitoring methods are not likely to test brakes at elevated temperatures, where weaknesses in brake performance are more pronounced (and measurable). Only on-board monitoring techniques (with an IBWD) will enable continuous assessment of trends related to temperature, adjustment, and other factors that portend loss of brake efficiency.

Initial research also suggested that application and response pressure relationships (with each other and with time) are of interest in brake diagnostics. Air transmission lag time (brake lag), which is a measure of the time delay in the pneumatic system, was found to be strongly correlated with brake stroke during the initial testing and analysis. However, analysis of the data from the February 1996 tests showed that the less-controlled method of testing used during that sequence made resolution of brake lag more difficult. A time-domain overlay (Figure 12) of application pressure (Pl), response pressure at axle 3 (P2), and response pressure at axle 5 (P3), shows that human application of the treadle valve in the 1996 tests resulted in varying application rates, occasional fluctuations in application as the driver attempted to reach the desired target pressure, and "steady state" pressures that were not steady. Therefore, there was no clear formula for reliably extracting information about brake lag, even though the pressure traces in the 1996 data hinted of corroborative evidence that brake lag increases with stroke and temperature. The human operator, an important element in the second phase of testing, appeared to obfuscate the fragile response pressure timing data Hence, it was concluded that brake lag, although still a potentially important indicator of brake condition, is too difficult to read under operational conditions. A later section details how measurements of brake lag can be used to assess brake adjustment while the vehicle is stationary.

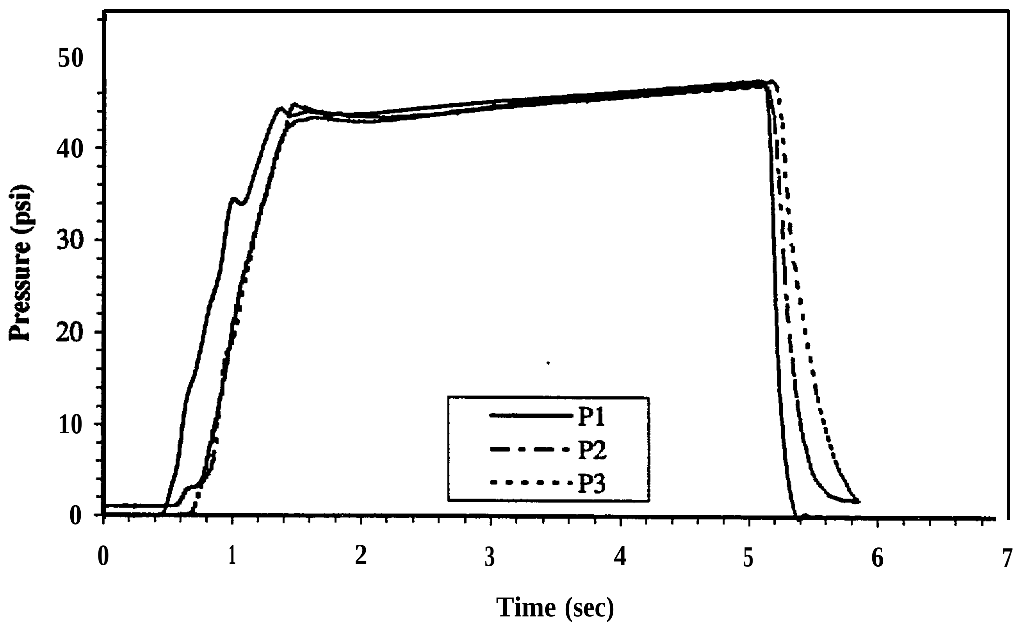

Figure 12. Pressure versus time for training run 14.003, with application pressure of 45 psi, speed of 60 mph, temperatures above 500 °F and brakes properly adjusted

The fundamental concept that transmitted air volume is proportional to brake stroke yields promise that pressure decay time may provide additional diagnostic information. Figure 12, which is typical of the majority of test runs, shows that upon release of the treadle valve, brake pressure exhausts from the air chamber at a smooth and measurable rate. In theory, this decay is exponential, and its decay time constant can be determined. The decay time constant should be proportional to brake stroke, and unlike brake lag, this factor is attractive because it relies upon a free-falling pressure that is unaffected by driver inputs. For the majority of test data, the brake pedal was released quickly, resulting in a smooth pressure decay curve. Hence, in TRUCKDAT, response pressure decay time constants t_1 and t_2 were determined for pressure traces P2 and P3, respectively.

Theoretical analysis confiied that an increase in stroke from 1.5 in. to 2.0 in (which is still within the legal limit for a Type 30 chamber) causes a change in t of 25 percent, which is quite significant. Therefore, there is a high likelihood that brake decay will provide valuable information about brake condition. Unfortunately, the 50 Hz sampling rate used during the subject testing (which was adequate for the exploratory testing) was too low to resolve any meaningful decay data; the brake pressure decay cycle was too rapid. Hence, it was not possible to confirm the usefulness of brake decay data from analysis of the experimental data; further testing with higher sampling rates (on the order of 1000 Hz) will be necessary to achieve the required resolution.

Deceleration Modeling

Following the 1996 test session, multiple regression modeling of vehicle deceleration was again undertaken. The analysis was considerably more sophisticated than what had been done after the 1994 tests. Second and third order models were evaluated, as were models with independent variables not previously considered. Various advanced optimization techniques were employed.

Initially, the model used was the same as presented earlier:

$$decel = \frac{1}{m}(F_0) \tag{5}$$

$$F_0 = c_0 + c_1 press + c_2 speed + c_3 press * speed \tag{6}$$

where F_0 is a measure of optimal braking force under conditions of properly maintained, cool, well adjusted brakes. Training data from three basic vehicle configurations were analyzed; considerable analysis produced the following single model, optimized for all three configurations:

$$decel = \frac{1}{m}(c_0 + c_1 press + c_2 press * speed) \tag{7}$$

Measured deceleration data for each vehicle configuration were plotted with model-predicted deceleration against test runs that had been sorted by ascending application pressure (Figure 13). The Equation 7 model is quite simple; it was chosen because all its parameters were significant across all vehicle configurations, and it provided an excellent fit to the data with no systematic inaccuracies.

Model Cross-Validation

A factor that will be critical in determining the potential success of the IBWD is the flexibility of the system to discern brake maladies for a variety of vehicle configurations (e.g., weights, trailer types) despite having been based on training data collected previously under a single (perhaps different) configuration. Model parameters determined by one configuration were used to predict data collected under another configuration (i.e., model parameters determined by the heavy vehicle were adjusted for weight and used to predict data from the light and van vehicles). Likewise, the van model was used to predict data from the light vehicle, and so forth. Weight adjustment was accomplished by multiplying each parameter by the appropriate ratio of weights.

Results showed that deceleration of the heavy configuration was slightly under-predicted by the light and van models, and deceleration of the light configuration was somewhat over-predicted by the heavy and van models. Deceleration of the van configuration was generally over-predicted by the heavy model and under-predicted by the light model (Figure 14). In all cases, cross-validation predictions were offset from the measured data (or from the native predictor) by a constant.

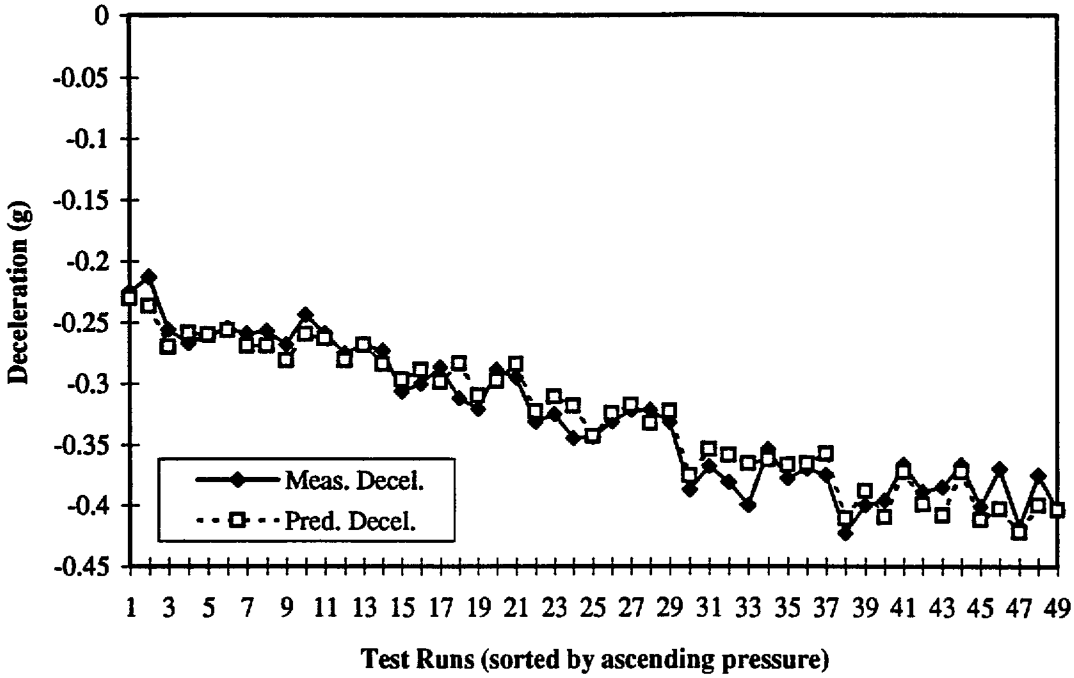

Figure 13. Optimum regression model fit for test runs sorted by ascending application pressure (heavy configuration, N=49, R^2=0.934)

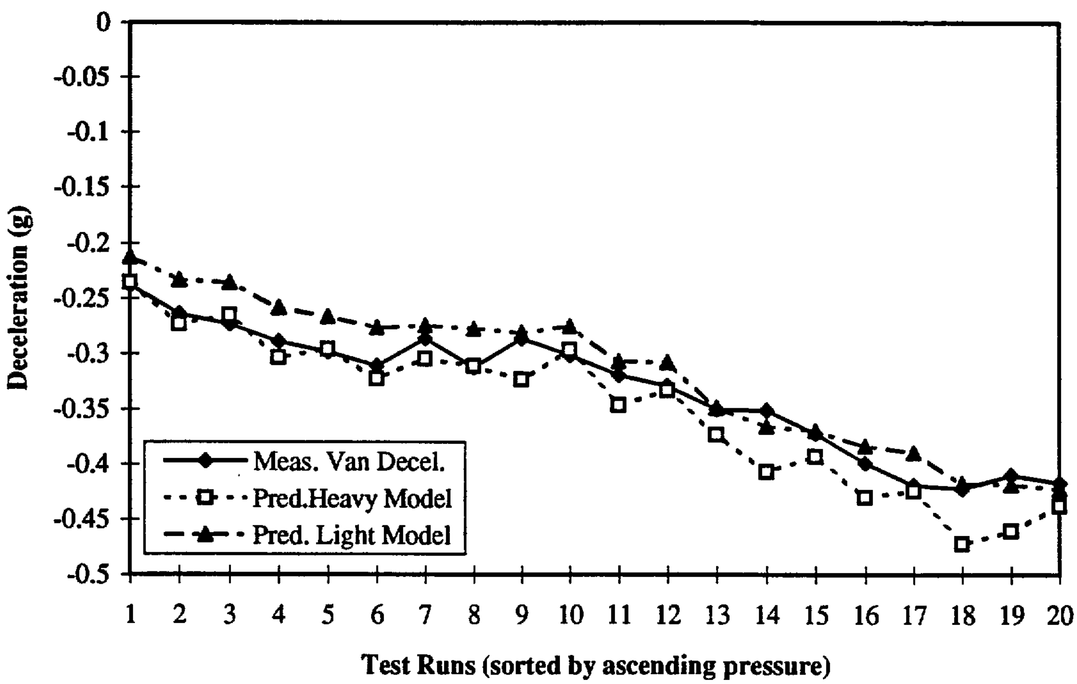

Figure 14. Comparison of measured van-configuration deceleration with predicted deceleration from heavy- and light-configuration models

Modest errors (averaging 5 to 9 percent) in cross-validation predictions occurred between different weights (heavy model predicting light vehicle) and different configurations (heavy model predicting van). There are several possible explanations for this. First, sample sizes for the test sessions were marginal. Test-to-test variations likely caused models to be skewed somewhat toward outlying values; larger sample sizes would assure a more accurate model for each training set, thereby likely improving the cross-validation between configurations. Also, the effect of weight may be more complex than the linear ratio of weights that was used to “translate” the model from one weight to another. Fmally, differences in brake components (e.g., air chambers, brake lining materials, and others) can cause some differences across configurations.

The generality of the model (across different weights and configurations) is very important. Obviously, the IBWD would be impractical if it needed retraining after changes to trailer weight or configuration. Although modest cross-validation errors show promise, future research is likely to considerably improve to the generalization of the IBWD. The majority of the present research did not focus on this issue; rather, effort was concentrated on examining data (for each configuration) to assess the requisite sensitivity of the IBWD to known brake maladies.

COMPARISON OF ACTUAL AND PREDICTED PERFORMANCE

Operational data were compared with predicted performance based on training data to assess the effectiveness of the IBWD models in discerning maladjustment and brake overheating. The lag and decay models, although theoretically feasible, could not be used for this comparison because of limitations previously discussed. Hence, attention is focused below on the comparison of operational deceleration data with performance predicted by training data.

Prediction of deceleration based on the optimum model (Equation 7), with parameters determined by each vehicle configuration, was compared with actual data from each’ respective configuration. For the sake of brevity, only the fully laden vehicle data will be displayed.

Deceleration values from similar operational tests were averaged and compared with model predictions; average percentage deviations from the model were plotted (Figure 15). Two trends were noted. First, large deviations were seen for hot, maladjusted brakes, with a definite trend of increasing deviation from the model with increasing numbers of brakes maladjusted Second (but not apparent from Figure 15), deviation from the model increased for runs with higher application pressures, especially for cool brakes. There was little deviation from the model for cool, maladjusted brakes, even when all four tandem axles were at 2.25 in. unless application pressure was 45 psi.

Deviations from the model showed ranges of about 5 to 8 percent for cool, maladjusted brakes to 40 to 65 percent for hot, maladjusted brakes. Cool, properly adjusted brakes showed about 3 percent deviation, and hot, properly adjusted brakes deviated approximately 8 percent from the model.

When brakes were hot, large deviations from the model for maladjusted brakes as well as proportionality between the degree of deviation and the number of maladjusted brakes, suggest that discernment of degraded brakes is possible. When brakes were cool, total deviations were less than 10 percent unless high (45 psi) application pressures were encountered, and differences between one, two, or four maladjusted axles were negligible. Hence, it will likely be more difficult to discern brake deficiencies in cool brakes based solely on deceleration data.

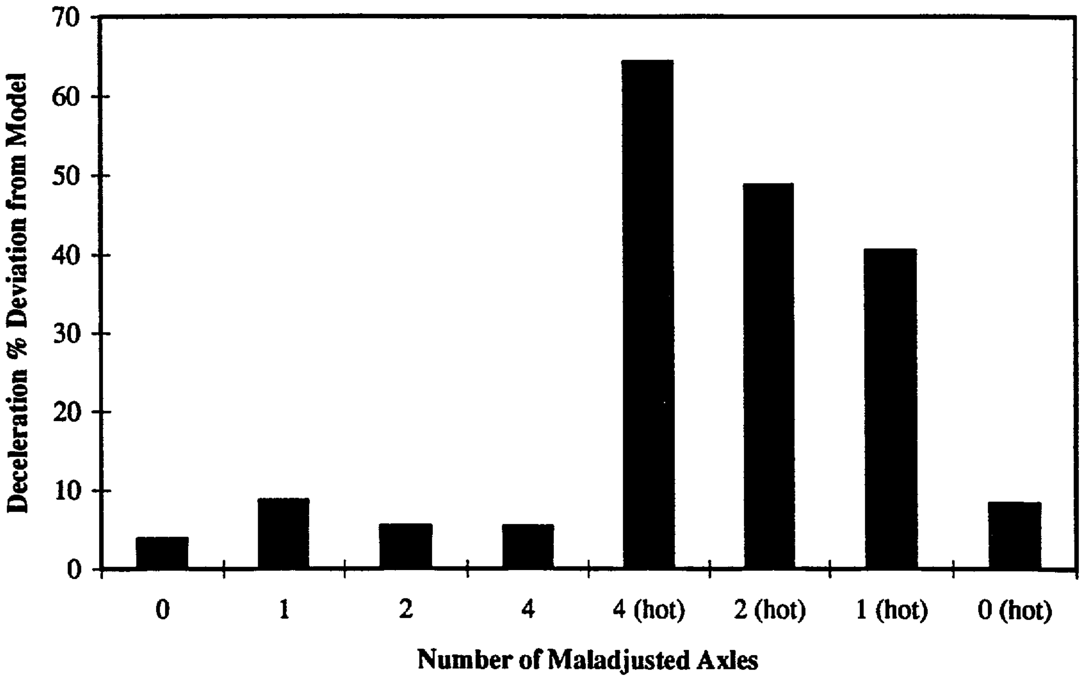

Figure 15. Deviation from model for heavy configuration undergoing operational tests with maladjusted brakes at 2.25 in.; each bar represents an average of either three or six test runs

Operational data were also analyzed for tests with a maladjustment of 2.0 in., which is the legal limit for the brake chambers used on the subject tractor and trailer tandem axles. Several differences between the 2.0-in and 2.25-in. maladjustment cases were noted. First, the 45 psi runs no longer exhibited a trend of greater deviation from the model. Also, although the hot, maladjusted brakes still deviated prominently from the model, stratification for varying numbers of maladjusted axles diminished.

Deceleration data from operational tests for the light configuration were compared with the model created for that configuration. The majority of cool brake tests, regardless of adjustment level, resulted in small negative deviations from the model, a somewhat surprising and seemingly illogical result. This artifact underscores the various uncertainties and measurement errors inherent in this technique. Hot, maladjusted brakes, as before, stood out with 55 to 75 percent deviations from the model. As with the heavy configuration brakes at 2.0 in., there was no obvious trend in any of the data, cool or hot, that would suggest a proportionality between number of axles out of adjustment and the degree of deviation from the model. The one exception to this was that the hot, properly adjusted brakes showed an average deviation of about one third of the deviation of the two cases of hot, maladjusted brakes.

Finally, data from operational tests of the uninstrumented, van-type trailer were compared with a model of deceleration developed for that configuration. As was typical of all configurations, cool brakes deviated very little from the model. There was no obvious sensitivity to application pressure with cool brakes and only a slight trend of increasing deviation for increasing numbers of maladjusted axles. Hot brakes showed significant deviations from optimum conditions, but less stratification by number of maladjusted axles than other configurations. The hot, properly adjusted brakes deviated more from the model than had been the case for other configurations, and as a consequence, they were relatively indistinguishable from hot, maladjusted brakes.

Comparison of real and modeled deceleration resulted in the following significant findings:

- Hot, maladjusted brakes tended to deviate quite significantly from the model in all cases, often showing 40 to 70 percent lower deceleration.

- In most cases, hot, maladjusted brakes exhibited a proportional increase in deviation from the model (or decrease in deceleration) for increasing numbers of maladjusted brakes.

- Cool brakes rarely showed deviations from the model that were greater than 12 percent; in some cases deviations were negative (suggesting the unlikely condition that maladjusted brakes were "better" than the model).

- Cool brakes generally did not show a trend of increasing deviation from the model with increasing numbers of maladjusted brakes; in all cases the variation between adjustment cases was small and likely insignificant.

- Cool brakes at an application pressure of 45 psi (for the heavily laden configuration with 2.25-in. maladjusted stroke levels) showed substantially larger deviations from the model than in tests run at lower pressures.

- Deceleration data from brakes at the legal adjustment limit of 2.0 in. showed less sensitivity to the number of maladjusted axles than was shown by equivalent tests at strokes of 2.25 in. That is, deviations from the model were lower and stratification due to the number of brakes out of adjustment was less prominent.

- A comparison of trends across all three vehicle configurations suggested considerable similarity.

ALGORITHM FORMULATION

The overall objective was to develop an algorithm, based on analytical results and real-world limitations, that would provide commercial vehicle drivers with real-time feedback of brake effectiveness. A basic flowchart showing one possible version of the IBWD is presented in Figure 16.

The IBWD will be contained in a "black box," likely a small, sealed plastic or metal case with a plug-in wire connector containing a circuit board and microprocessor. It will contain a non-volatile memory for storing performance information. The IBWD will be mounted in the cab or engine compartment of the cab or tractor of a truck or bus and will be wired to various sensors on board. The dashboard will have a small lighted display to indicate warning and system status. Warning may also include an audible alarm.

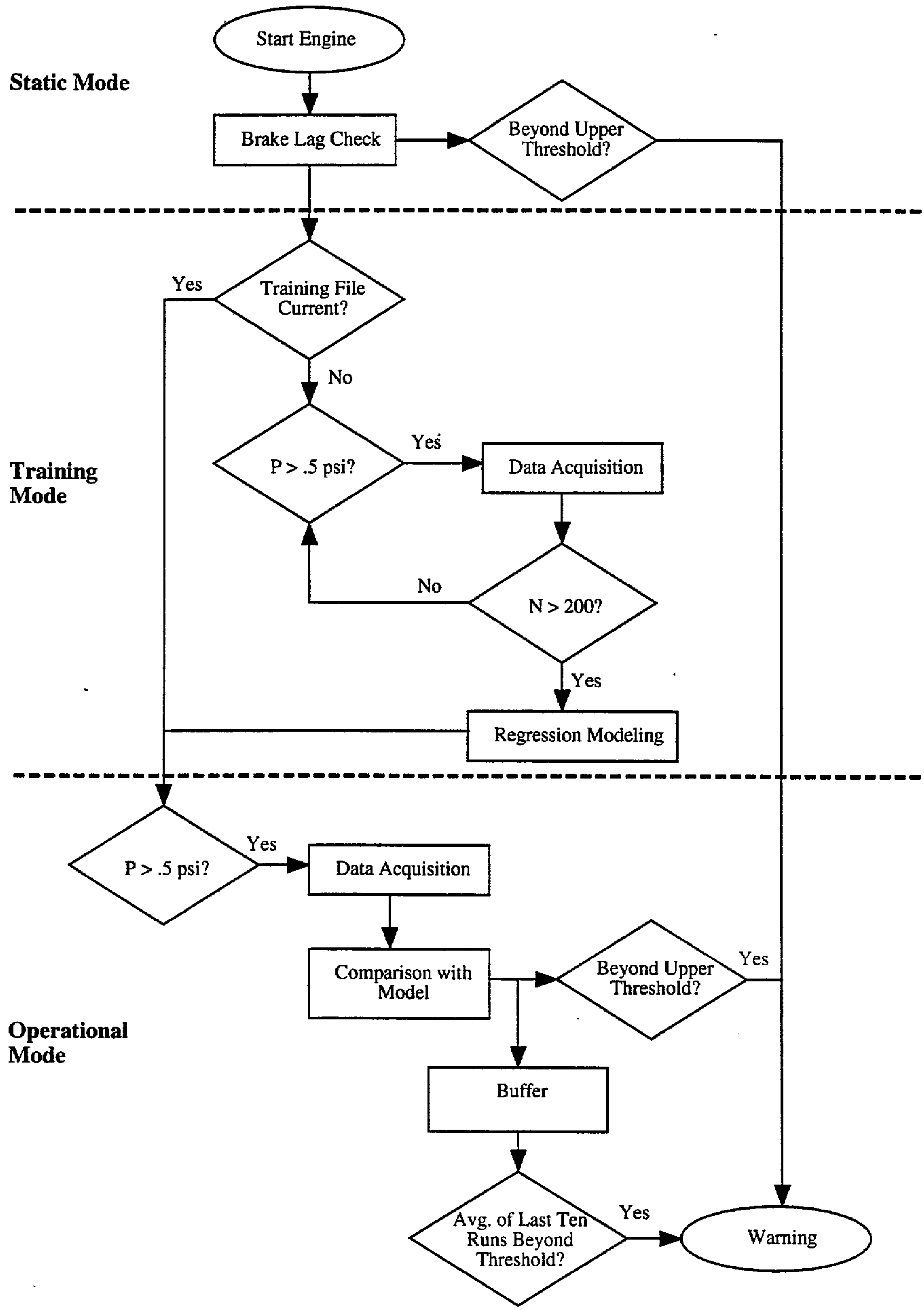

Figure 16. IBWD operational algorithm

The IBWD algorithm requires the following sensor and information inputs:

- deceleration
- application pressure
- response pressures (optional quantity)
- vehicle speed
- weight
- date
- time.

Deceleration will require an accelerometer, likely mounted to a frame rail. Pressures will be monitored with pressure transducers; vehicle speed will be tapped from the electronic speedometer output common on most commercial vehicles; weight will be obtained through any of several possible means; and date and time will be taken from an internal clock on the microprocessor board.

The IBWD algorithm incorporates three modes: static, training, and operational. The static mode involves determination of brake lag. Because findings showed that lag time would likely be too difficult to resolve in service, brake lag will be determined on a stationary vehicle once daily, or perhaps more often if so desired. Although not explicitly shown on the flow chart, baseline lag time will be "learned" by the system through a training session on a stationary vehicle with cool and properly adjusted brakes. Depending on the vehicle, varying numbers of axles will be checked for lag. Not enough research has yet been conducted to determine the "normal" lag for a vehicle combination, or how much that value varies from vehicle to vehicle or between vehicle configurations. Nevertheless, the IBWD will be "taught" the baseline condition for the vehicle. An electropneumatic valve will be programmed to automatically apply the brakes with full pressure soon after vehicle start-up (or at other times, if so desired). That way, brake applications will be regular and predictable so lag can be measured consistently. After each application of the brakes, actual readings will be compared with the ideal target value (which was learned from training); if lag exceeds the threshold by a predetermined amount (yet to be determined), a warning will be issued.

Once the IBWD has sensed that the vehicle is in motion, the algorithm will interrogate system memory to determine whether a current training file is available that contains the deceleration and decay model parameters. If the current training parameters are available, the system will immediately enter the operational mode; otherwise, it will enter the training mode. There will also be a software switch accessible only to service technicians that can set the system in the training mode after significant brake service.

In the training mode, operators will be instructed to drive the vehicle (with properly maintained brakes) at a variety of speeds and to apply the brakes for several seconds at a variety of braking pressures above 20 psi. The driver will be instructed to keep the brakes cool by making brake applications infrequent and short. Brake application pressures greater than 0.5 psi will trigger data acquisition. Braking cycles will be analyzed to determine their suitability for inclusion in the training database. Specifically, a braking cycle will be selected if application pressure reaches a steady threshold of at least 20 psi for at least one second. The braking cycle will be discarded if brake lockup is encountered (as determined by ABS wheel sensors) or if steady pressure is not reached within two seconds of initiation.

As soon as 200 cycles have been collected, a light on the dashboard will signal the driver that training is complete. The collected data will automatically be run through an analytical module similar to the TRUCKDAT routine written in LabVIEW. Appropriate segments of the data will be selected: average application pressure, average deceleration, initial speed, pressure decay time constants, weight, time, and date information will be written to a file for processing. Regression models of deceleration and decay will be created. Regression parameters, representing the optimum braking conditions, will be stored in non-volatile memory for comparison with operational runs. At this point, the system will automatically switch into the operational mode.

Once in the operational mode, the collection and reduction of data will be identical to those of the training mode. Data from each suitable braking cycle will be compared with a prediction from the model. A two-tiered threshold of warning will be instituted. If the measured data point deviates from the model by an amount greater than the "upper threshold," a warning will be issued immediately; if not, deviation from the model for that data point will be stored in memory. A running average of deviations from the most recent 10 runs will be retained. If that average exceeds a "lower threshold," a warning will be issued. In any case, a performance history, much like a flight data recorder, will be kept in memory and available for download by authorities.

Warning of degraded brakes or impending brake failure will hence be obtained through several possible channels. A warning will be issued if

- static brake lag is excessive, indicating excessive stroke
- measured values of deceleration and decay for a single braking cycle are beyond a (high) threshold of acceptable deviation from the model
- the composite average of deceleration and decay for the current braking cycle and the previous nine cycles are beyond a (low) threshold of acceptable deviation from the model.

PLANS FOR IMPLEMENTATION

It is envisioned that the IBWD will be installed on future (and some existing) commercial vehicle braking systems. Our promising results portend an opportunity to integrate the IBWD with other emerging ITS technologies, including stationary automated vehicle inspection stations (the IBWD 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 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 IBWD concept. A sensor manufacturer in Washington has shown interest in producing and marketing the IBWD and will provide strong ties to the trucking industry for field trials. PACCAR Inc has already demonstrated a commitment by subsidizing extensive full-scale testing and is interested in commercialization of the product. Various brake component manufacturers have contacted the authors with an interest in possible collaboration. The Washington State Department of Transportation has provided funding for this research and maintains an interest in the future implementation of the IBWD.

CONCLUSIONS

The determination and prediction of commercial vehicle brake effectiveness using on-board, real-time, inferential, performance-based techniques shows promise. Throughout the course of research, much has been learned about the development and implementation of an IBWD that will perform this function. 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.

If diagnosis of brake condition is to be inferred by measurement of performance criteria (instead of by direct dimensional, thermal, or visual criteria), and if the diagnosis is to be predictive so that there is adequate time for corrective action by the driver, then there must be some measurable change in performance, under normal operating conditions, that can be used as an indicator of current and future brake condition. The dilemma is that diaphragm brake chambers have nonlinear force versus stroke characteristics that tend to produce constant performance output under typical operation until brake adjustment is well beyond the legal limit. Until now, performance-based clues of brake deterioration were difficult to identify and interpret reliably; techniques developed during the course of this research have shown that the IBWD has not one, but several, independent means by which brake effectiveness can be determined and predicted on-board.

Comparison of actual and modeled deceleration is clearly indicative of brake condition when brakes are hot or under high application pressure, especially when adjustment is at or beyond the limit. Significant run-to-run variations in deceleration measurements for similar runs were primarily the result of a small data set; to smooth out trends, more measurements from additional testing will be needed. Nevertheless, observed trends from the deceleration data are supportive of the assertion that brake condition can be discerned early enough (high enough in the nonlinear force decay curve) to permit corrective driver action.

Although brake lag was shown to be a good indicator of brake adjustment, driver control variations made discernment of lag difficult while the vehicle was in service. However, research showed promise that intermittent, on-board, automated lag checks performed on a stationary vehicle provide useful diagnostic information.Stationary, on-board determination of brake lag is a straightforward, inferential measure of brake stroke and is particularly useful when used in conjunction with real-time measurement (and modeling) of deceleration and brake pressure decay time. Release of the treadle valve usually results in exhaustion of air from the brake chamber in an unimpeded fashion; hence, pressure decay time constants can be correlated with stroke for vehicles in service. Theoretical analysis indicates decay time constants are quite sensitive to changes in brake stroke, though testing was unable to confirm this because data sampling rates were not high enough.

A study of visual brake inspections versus roadside performance-based testing described performance-based tests as “objective” but not “predictive” [l0]. The reason stated for this assertion is that performance-based tests (such as dynamometer or stopping distance tests) are specific to a particular vehicle configuration and operating condition and will give no indication of performance at another operating condition. Visual inspections (such as stroke measurement) are more predictive, but are more time consuming.

The IBWD shares the best of all worlds in this regard; it has the advantages of both a visual inspection and a roadside performance check as well as the tremendous benefit of real-time monitoring for tracking trend data. The IBWD is objective in that comparison of measured with a model of ideal braking defines vehicle performance. It is predictive in that the model is flexible and allows assessment of performance for different configurations or weights. The incorporation of static brake lag testing adds an additional predictive element to the equation; measurement of lag is the pneumatic equivalent to visual stroke measurement. Lag is more directly related to stroke than is deceleration; it does not follow the same nonlinear relationship. Fmally, the simultaneous inclusion of decay, somewhat analogous to lag, provides additional real-time predictive capabilities.

INVESTIGATOR PROFILES

The Principal Investigator for this program was Dr. Per Reinhall. Dr. Reinhall is an Associate 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 17 years of experience applying modem dynamics theory to engineering systems and has written or published over 50 papers and reports on these topics.

Dr. Reinhall was assisted by Dr. Robert Scheibe. Dr. Scheibe recently obtained his doctorate in Mechanical Engineering from the University of Washington under the direction of Dr. Reinhall, and for the last 14 years has worked for Failure Analysis Associates, Inc., an engineering consulting firm internationally known for its work in the analysis and prevention of failures and accidents. 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.

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