Executive Summary

Introduction

Based on a series of tests using performance-based brake testers (PBBTs), this report presents the results, conclusions and recommendations concerning the suitability of PBBTs to enforce prospective in-service commercial motor vehicle brake performance regulations.

A PBBT is a device that can assess the braking capabilities of a vehicle in its current condition. It measures either individual wheel brake forces, overall vehicle braking performance, or both. A PBBT is of benefit to both the law enforcement and the motor carrier communities because it can consistently provide an objective measure of the current braking performance of a vehicle. It does so irrespective of the brake type (disk or drum), the energy supply (air, hydraulic, electric, or spring), or the application method (s-cam, wedge, piston, spring, or lever and cable).

Several PBBTs were evaluated during a round robin[1] test series in order to assess their functional performance and potential for use in law enforcement. In addition, factors influencing the relationship between a vehicle's on-road stopping performance and that predicted by the PBBT were investigated. The tests were conducted in July of 1998 at the Vehicle Research and Test Center (VRTC) of the National Highway Traffic Safety Administration (NHTSA), United States Department of Transportation (USDOT). The project was sponsored by the USDOT, Office of Motor Carriers (OMC), now the Federal Motor Carrier Safety Administration (FMCSA).

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[1] The term "round robin" describes a series of tests in which a single "standard" is used to evaluate the consistency of various test apparatus. In the round robin presented in this report, the "standard", a specific configuration of brake forces and wheel loads on a heavy-duty vehicle, was used to evaluate the candidate PBBTs and their operating protocols.

Background

Functional performance specifications for PBBTs have been developed and published for comment in the Federal Register[2].

For brake systems, current commercial vehicle safety enforcement is based on the results of a visual inspection designed to identify defective components. This technique cannot provide a measure of actual braking performance. New performance-based regulations are currently under consideration to permit the use of PBBT results for enforcement. A vehicle could be placed out of service (OOS) if it is found to have inadequate braking capability, or a citation could be issued if an individual brake is found to be weak.

For the use of recommended performance-based regulations, it is important that a vehicle's individual brakes or overall braking capability be judged accurately by a PBBT and consistently between different PBBTs. The purpose of the round robin was to evaluate the ability of the current generation of PBBTs to measure brake forces (BFs) and wheel loads (WLs) accurately and consistently, and to verify that these measurements could be used as an alternative to stopping distance tests or on-road deceleration tests.

Overview of the Test Plan

For the round robin, two types of commercial vehicles, with different braking and loading configurations, were instrumented: a combination three-axle tractor, two-axle semi-trailer (3-S2), and a two-axle straight truck. Each vehicle was tested fully laden and unladen. Both vehicles were set up with target low brake force to wheel load ratios (BF/WL) on selected wheels, keeping the braking capability of the vehicle consistent with the

[2] "Development of Functional Specifications for Performance-Based Brake Testers Used To Inspect Commercial Motor Vehicles", FHWA-1998-3611-1, Federal Register, Vol. 63, No. 108 (June 1998).

performance-based regulation under consideration at the time by the OMCS[3] (i.e. the ratio of the total brake force to the gross vehicle weight (BF_{TOT}/GVW) = 0.4).

The eight PBBTs tested were three portable roller dynamometers (RD), two in-ground RDs, two flat plate brake testers (FP), and one portable breakaway torque tester (BTT). The testing program had two parts. In the first part of the testing program, the following evaluations were performed on weakly-braked vehicles:

1) The accuracy and applicability of BF measurements: For the accuracy, the PBBT-measured BFs per wheel were compared to the BFs measured using a calibrated torque wheel. For the applicability, the PBBT-measured total BFs (BF_{TOT}) were compared to BFs computed from the 32.2 km/hr (20 mph) on-road stops.
2) The accuracy and applicability of WL measurements: For the accuracy, sets of cement blocks of known weight were placed on the PBBT weighing mechanisms and the PBBT results were compared to the known weights. For the applicability, the PBBT-measured axle loads were compared to axles loads obtained using traditional in-ground or portable certified scales.
3) The applicability of the equivalent deceleration predicted using the PBBT measurements ($decel_{EQ} = BF_{TOT}$/GVW) for the vehicle: The PBBT results were compared to decelerations achieved during 32.2 km/hr (20 mph) road stops.
4) The repeatability of PBBT measurements (BFs, WLs and $decel_{EQ}$): PBBT results from three replicates were compared.

In the second part of the testing program, the brake forces of the two-axle truck were restored to their fully adjusted values and the vehicle load was changed. The brake forces were sufficient to lock the wheels in a high demand or panic stop. The following evaluations were performed on the strongly-braked 2-axle vehicle:

1) The applicability of the equivalent deceleration ($decel_{EQ}$): The equivalent deceleration predicted using the PBBT measurements was compared with the deceleration obtained during 32.2 km/hr (20 mph) road stops.

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[3] S. J. Shaffer and P. A. Gaydos, "Development, Evaluation and Application of Performance-Based Brake Testing Technologies", FHWA/MC-98/048 (April 1998). The executive summary is accessible at: http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/8mn01!.pdf

2) The repeatability of the BFs measurements: PBBT-reported BFs from three replicates were compared.
3) The effect of wet test surfaces on the PBBT-reported BFs was evaluated by comparing the maximum BFs reported under both wet and dry conditions.

Results

Part I: Vehicles with Weak Brakes

Brake Forces - Accuracy and Applicability of PBBT Results versus Reference BFs

The brake force reported by the PBBTs per wheel was compared to the brake force measured using a calibrated torque wheel. The torque wheel data were reduced to a single value using three different methods. Using the best match of the methods, agreement within the 2.5 percent accuracy requirement of the performance specifications was found for all of the RDs and for the BTT. However, for the HEKA FP, the BF data discrepancies were sometimes very large and appeared to be related to both the acquisition and the handling of dynamic data from the stop on the plates. As such, further demonstration of the HEKA accuracy in reporting BFs would be required. For the Hunter FP, the discrepancy in BF values were less than 10 percent, and appeared to be due solely to differences between the algorithm Hunter used and that used for the torque wheel data. Since the deceleration predicted by Hunter was subsequently found to match the on-road deceleration very well, the difference in BF was considered resolvable and not a potential safety concern.

The PBBT-measured BFs showed different degrees of applicability when compared to the BFs deduced from the 32.2 km/hr (20 mph) road stops. The Hunter test, which is conducted at 16 km/hr (10 mph), appeared most applicable. For the RDs, their applicability may have been affected by a sensitivity of brake torque output to speed. In general, slightly higher BFs were measured in the RD tests, in which the wheel is rotated at less than 2 km/hr (1.2 mph), compared with that deduced from the 32.2 km/hr (20 mph) on-road stopping test. Although the deviations were only on the order of ten percent, further investigation of the

development of a scaling factor may be required to accurately predict on-road deceleration. The BTT also showed good applicability for the on-road stop in three of the four vehicle conditions. The applicability for the unladen 2-axle, however, may have been influenced by the higher measurable BF for the strong wheels using the BTT than that available due to traction with the ground during the on-road stop. As such, an upper limit cut-off (similar to the use of scaling factors for the RDs) would be required in such cases for improved accuracy in predicting on-road stopping performance.

Vehicle Weights - Accuracy and Applicability of PBBT Results versus Reference WLs

The weights reported by the PBBTs were found to be well within the 2.5 percent accuracy requirement during calibration tests using concrete blocks of known weight.

The reporting of axle loads from vehicles indicated that the loads obtained during the brake test were not always representative of those of the vehicle when flat on the ground. As such, for some PBBTs, the applicability of the weight measurements will require additional considerations for use in enforcement. The reporting of vehicle weight (total of axle loads) by PBBTs matched the reference values for 4 of the 8 PBBTs for the two-axle straight truck in both the laden and unladen conditions. For the 3-S2, the reported total vehicle weights adequately matched the reference value for only 2 of the 8 PBBTs (the Hunter FP and in-ground RAI RD) in both loading conditions. For the HEKA FP, RDs and the BTT, the differences in the axle-load measurements were due to load transfer between axles as the vehicle was braked into position on the PBBT. This load transfer was most significant with the particular vehicle characteristics (e.g. the 4-spring suspension and tandem axles) of the 3-S2. These effects were also more visible on the portable PBBTs because of the elevated test platforms. Improvement can be expected with implementation of different ramp configurations for these portable PBBTs. It was concluded from the axle load tests that special considerations or test procedures will be required for some vehicles.

Equivalent Decelerations - Comparison of PBBT results with Vehicle Deceleration

Using the equivalent deceleration (BF_{TOT}/WL_{TOT}, or BF_{TOT}/GVW) as the measure, 6 of the 8 PBBTs accurately predicted the vehicle's stopping capability for the laden and unladen 2-

axle vehicle. For the laden 3-S2, 2 of 8 PBBTs accurately predicted the vehicle's stopping capability. For the unladen 3-S2, one of the 8 PBBTs accurately predicted the vehicle's stopping capability. Brake force measurements were accurate. The inaccurate predictions of deceleration stemmed primarily from weight measurements as some PBBTs reported high axle loads. Other factors included the coefficient of friction (COF) between the test surface and the tire being different from the COF between the road and the tire or early test termination by the PBBT control mechanism or computer. Recommendations for correction were made at the time of the round robin, and these were being addressed by the PBBT manufacturers at the time of this report. Future work will focus on the resolution of these issues.

Repeatability

The ability of PBBTs to assess the overall vehicle stopping performance within an acceptable range of repeatability (ARR) was very good. Approximately 93 percent of all measurements, including BFs and WLs, were within the ARR.

Part II: Vehicles with Fully Adjusted, Strong Brakes

The ability of the PBBTs to measure the full braking capability of a strongly-braked vehicle was assessed. The traction which exists between the tires and the test surface (or the road) limits the maximum BF achieved by the vehicle either during a PBBT test or during a stopping test on the road. As such, variations reported between PBBTs in these tests were primarily a reflection of the different test surfaces used. PBBTs with higher traction between the test surface and the tire than that between the road and the tire tended to show a higher $decel_{EQ}$ than measured during the on-road stop, and vice-versa. No safety concern exists providing the differences in traction can be documented and accounted for. A summary of the findings of Part II follows:

- Most PBBTs predicted at least the on-road deceleration, which was approximately 0.6g[4] for the vehicle tested.
- The FPs showed higher variability testing the strongly-braked vehicle than the weakly-braked vehicles. This was likely due to variability in driver performance and possible wheel skidding[5].
- The VIS RD measured low BFs compared to the other PBBTs, apparently as a result of either premature test termination or a low traction roller surface.
- The BTT results were unaffected by either the vehicle's loading conditions or the presence of water on the test surface.
- For the VIS and standard HEI RDs, the presence of water on the test surface reduced the traction between the tire and the rollers, and greatly affected BF measurements.

Conclusions

The round robin was the first of its kind and constituted a significant milestone in the FMCSA's program to permit the use of PBBTs as a tool for law enforcement.

- Under most test conditions, the accuracy and repeatability of most of the participating PBBTs, regardless of the principle of operation, were acceptable for meeting the functional specifications, and therefore for use in law enforcement.
- The Hunter FP and the RAI in-ground RD showed the most immediate potential for use in law enforcement on weakly-braked vehicles based on repeatability and accuracy results when compared to measured vehicle decelerations in a 32.2 km/hr (20 mph) road stop.
- Where needed, factors or modifications to obtain acceptable PBBT performance for use in enforcement fell into one of two categories:
    1) Modifications consistent with the PBBT functional specifications that had been developed for eligibility for funding through the Motor Carrier Safety

[4] "g" represents the acceleration due to gravity.

[5] It should be noted that Hunter considers a test in which the vehicle is skidding to be invalid.

Assistance Program (MCSAP).

2) Procedural modifications to improve the applicability of the PBBT results to on-road stopping results.

- Weight measurements were found to be affected by specific characteristics of the vehicles or by the elevation and ramp configurations of the portable PBBTs.
- Consideration should be given to additional criteria for judging brake effectiveness in cases where weights are unavailable or cannot be measured in a representative manner due to vehicle configuration. For example, when wheel lock up occurs, if the traction between the tire and the test surface is at least equal to 0.6 (as required in the PBBT functional specifications), the braking capability of the wheel would be considered adequate, regardless of the weight measurements. When the brakes are too weak to lock up the wheels, the weight measurements are critical, and alternative procedures and/or criteria would be required.
- The PBBT-measured BFs were in good agreement with the BFs measured with the torque wheel. Deviations were attributed to one of two causes:
  - The algorithm used by PBBT manufacturers to acquire and manipulate the raw data and report a single BF value.
  - In the case of the flat plate testers, the effect of dynamic loading.
- The roller dynamometers, as a class, reported slightly higher BFs for weakly-braked vehicle on dry pavement than the corresponding reference values derived from road stops. It was suspected that this was a result of either geometry of the wheel/roller contact patch or changes in brake torque output as a function of speed: the portable RDs operate at less than 2 km/hr (1.2 mph), while the road stops were performed at 32.2 km/hr (20 mph). Additional data are required in this area.
- Finally, the following recommendations were made to the PBBT manufacturers to assist them in meeting the functional specifications:
  - Alter the test surface to meet minimum COF requirements.
  - Standardize test protocols, including data analysis and reporting procedures.
  - Develop appropriate calibration procedures.
- Some PBBTs showed that their BF results were unaffected by the condition of the test

surfaces. Although the COF in wet conditions is not part of the proposed PBBT functional specifications at this time, PBBTs for which BF measurements were affected by the test surface conditions should address this problem.

Remaining Challenges

Remaining challenges for use of PBBTs in law enforcement include:

- Establishing appropriate test termination, data reduction and reporting algorithms for the PBBTs such that consistent results are obtained from machine to machine for a given vehicle.
- Developing standard test procedures for each type of PBBT.
- Developing training requirements for inspectors to use PBBTs for enforcement, including calibration and operating protocols.
- Establishing a list of special considerations for certain vehicle configurations (e.g. axle load or BF measurement applicability limitations). When applicable, modified testing procedures should be implemented.
- Developing regulations for individual brake pass/fail evaluation that are independent of WL, when WL measurements are either unavailable or significantly altered by the vehicle configuration.
- Establishing a policy or procedure for compliance testing, including documentation of calibration requirements necessary to meet potential legal challenges.

For a fundamental understanding of the relationship between PBBT testing and vehicle on-road performance, the following challenges are posed:

- Characterizing and understanding the sensitivity of brake force to velocity, static versus dynamic testing, wheel contact geometry or COF limitations as they are needed to establish the correlation between PBBT measurements and 32.2 km/hr (20 mph) road stops.