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NHTSA Light Vehicle ABS Performance Test Development

DISCLAIMER

The testing performed in this study was for methodology development. The vehicles tested were new vehicles leased from local automobile dealerships or vehicles owned by the National Highway Traffic Safety Administration.

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16. Abstract

The goal of the research presented in this report is to develop suitable minimum performance criteria for the safe operation of antilock brake systems (ABS). The National Highway Traffic Safety Administration (NHTSA) has evaluated vehicles using the European regulation for minimum ABS stopping performance (ECE R13-H) several times in the past. These past evaluations have raised concerns about the methods used to determine adhesion utilization. In addition, to meet U.S. standards of objectivity, quantitative values must replace several qualitative statements that appear in ECE R13-H (e.g., replace "reasonable time" with "one second"). This report presents the results of the study conducted to address these issues.

Testing was conducted on contemporary examples from several major U.S.-market new vehicle categories. The categories of vehicles tested included compact passenger car, full-size passenger car, minivan, standard pickup truck, and mid-size sport utility vehicle. Issues pertaining to adhesion utilization were examined to ensure that the addition of ABS to a vehicle does not excessively affect a vehicle's ability to stop. Functionality tests subjected each ABS to a wide range of conditions commonly encountered in regular driving, helping to quantify the stability and existing performance criteria addressed in this report.

Based on the collected data, the goal to develop test methods that can yield meaningful and repeatable adhesion utilization data for ABS-equipped light vehicles was met with mixed results. Since the peak coefficient of adhesion (peak friction coefficient or PFC) constantly increases as the vehicle decelerates, a passenger vehicle will underestimate available adhesion when a constant brake pedal force is used, and will therefore produce incorrect adhesion utilization results. However, alternative methods that assessed the effect of ABS on vehicle stopping performance were successful. The results also provide a framework for understanding the parameters that should be considered during the development of future ABS performance standards.

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For the convenience of visually impaired readers, descriptions of the figures found in this document have been included to satisfy Section 508 of the Americans With Disabilities Act (ADA). These descriptions are for the benefit of visually impaired readers using text-to-speech software. These descriptions can be found in **Appendix F**.

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EXECUTIVE SUMMARY

The goal of the research presented in this report is to develop suitable minimum performance criteria for the safe operation of antilock brake systems (ABS). The National Highway Traffic Safety Administration (NHTSA) has evaluated vehicles using the European regulation for minimum ABS stopping performance (ECE R13-H) several times in the past. These past evaluations have raised concerns about two areas of ECE R13-H. The first included clarifying why difficulties had previously been encountered with the adhesion utilization procedures. Second, quantitative values were needed to replace qualitative statements that appear in the performance requirements for ABS functionality (e.g., replace "reasonable time" with "one second").

The ECE's ABS adhesion utilization test method is difficult to use and produces incorrect results. Since the peak coefficient of adhesion (peak friction coefficient or PFC) constantly increases as the vehicle decelerates, a passenger vehicle will underestimate available adhesion when a constant brake pedal force is used. Single-axle testing and several other procedural factors also contribute to the underestimation of available adhesion. Since the total amount of available adhesion cannot be accurately quantified, subsequent adhesion utilization results are unreliable, even when they are under 100 percent. As such, the ECE's single-axle test method is not recommended for determining ABS adhesion utilization.

The ASTM E1337 method for determining PFC was used to produce an estimate of the total available adhesion; however, the data revealed that this method could not accurately estimate available adhesion. The Standard Radial Test Tire (SRTT) is used to compare the frictional properties of different surfaces to one another, and/or to compare the same surface to itself as it changes over time. Friction is unique to a given tire-surface combination and varies significantly with speed, and to a lesser extent with tire load and surface temperature. The measured friction results did show large differences between the vehicle and traction trailer's rubber compound, making the SRTT ill-suited for predicting vehicle stopping performance. Added to that, a decelerating vehicle's tires are exposed to constantly decreasing speeds and at least two tire loads (front and rear), both of which effect the PFC measurement. All told, the ASTM E1337 method is not recommended for calculating ABS adhesion utilization. For these and the many reasons contained herein, it is recommended that adhesion utilization not be included in any form for the evaluation of ABS performance.

The alternate method for evaluating ABS performance involved comparing a vehicle's ABS-on deceleration with the ABS-off deceleration, using both axles simultaneously. For the five vehicles examined, the majority of ABS decelerations were quicker than the comparable deceleration of the foundation brake system alone, indicating that ABS used more of the available adhesion. However, this method cannot fairly be called adhesion utilization because the total amount of available adhesion is never established. To its credit, this method does philosophically comply with the intent of setting a minimum value for ABS adhesion utilization, which is to ascertain that stopping ability is not excessively sacrificed to maintain stability and maneuverability.

A functionally similar alternative to comparing decelerations would be to compare stopping distances. Since formulae for stopping distance already exist in FMVSS 135, the most logical

solution for setting minimum performance criteria for ABS stopping performance would consist of subjecting ABS-equipped vehicles to the existing stopping distance requirements found there. Subjecting all vehicles to the same braking performance requirements is reasonable and fair because all vehicles sacrifice stopping performance for stability whether they have ABS or not, although they accomplish this in different ways. For standard brake systems, front brake bias gives up a portion of the rear axle's brake performance to minimize yawing forces, while ABS manages brake line pressure to allow all four tires to generate near-maximum force. It is recommended, however, that consideration be given to improving the stopping distance requirements. The current test vehicles all weighed less than 2500 kg GVWR and were not challenged in any way by the existing requirements, with or without ABS. It is also recommended that the maximum pedal force be limited to no more than 500 N for ABS performance testing. Using forces greater than this to achieve maximum braking performance will exclude a portion of the driving population from being able to fully benefit from their vehicle's brake system.

The tests performed in this study found that ABS stopping performance on low coefficient of friction surfaces was always superior to the non-ABS stop, made under identical conditions and without wheel lockup. This was expected since ABS can manage wheel slip at all four wheels independently, something a driver is incapable of doing. However, the amount of time spent finding the best non-ABS deceleration without wheel lockup proved burdensome. It is the authors' recommendation that a shorter approach be taken, perhaps that of comparing the peak ABS deceleration to the no-ABS deceleration where all four wheels are locked, which is the most probable outcome for drivers braking in an emergency on a surface where the nominal PFC is 0.25 (e.g., on ice).

The ECE R13-H ABS functionality tests themselves are suitable as minimum performance criteria in their present form, with two exceptions. The first is that the top speed for vehicle testing should be lowered from 120 km/h to 90 km/h for safety reasons. The second relates to the split-coefficient test, which relies on the single-axle test method to determine available adhesion. Since the single-axle test method and the search for available adhesion both produce unreliable results, an alternative test method is provided in this report. The objective performance requirements for these ABS functionality tests were determined during the current research. Recommended values are presented near the end of this report.

1.0 INTRODUCTION

During the early to mid 1980's, efforts were made to harmonize passenger car braking regulations in order to promote free trade among countries. Development of this rule progressed through a number of evaluations of the proposed test sequence, as issues relative to the procedure and requirements were raised and periodically addressed. In May of 1985, a Notice of Proposed Rulemaking was issued proposing FMVSS 135 as a harmonized standard to the European ECE R13-H (13-H) [1]. Revisions pursuant to two subsequent Supplemental Notices of Proposed Rulemaking eventually resulted in its enactment, effective March 6, 1995. At that time, standards for Antilock Brake System (ABS) performance were evolving but underdeveloped and therefore not included. An Advance Notice of Proposed Rulemaking released July 12, 1996, deferred a mandate requiring ABS for light vehicles, citing minimal changes in overall traffic fatalities, no reduction in insurance claims, and an increasing trend (at that time) for manufacturers to voluntarily equip their light vehicles with ABS in response to market demand.

Collateral factors that supported this deferral were a number of ambiguities contained in Annex 6 of 13-H, the section that applies to ABS, that were not suitable to the compliance testing methods used in the United States. Additional complications surrounded the method for determining the peak coefficient of adhesion (a.k.a. peak coefficient of friction). Annex 6 uses the test vehicle to obtain this information, and in certain instances the use of these ABS-equipped vehicles would yield adhesion utilization values (a.k.a. braking efficiencies) that were above 100 percent. These and other issues were left unresolved as a result of the 1996 ANPRM. This study therefore takes up the matter of developing a set of minimum performance criteria for ABS through a reevaluation of the existing European rule (found in Annex 6) followed by suggested modifications.

2.0 BACKGROUND AND OBJECTIVES

2.1. ABS Fundamentals

ABS assists drivers attempting to slow down or stop by preventing wheel lockup. ABS automatically controls the longitudinal slip of one or more wheels using wheel speed sensors to detect the wheels' angular velocities and accelerations. The ABS control unit uses this information to gauge vehicle velocity, recognize impending wheel lock, and modulate brake pressure as necessary. It estimates the maximum amount of braking force that can be applied for a given surface based on how quickly a wheel spins up and spins down when ABS is actively controlling the vehicle's braking. These changes in rotational velocity are influenced by brake line pressure and the peak and slide coefficients of friction between the road and tire.

Although antilock brake systems may shorten stopping distances on many surfaces, particularly low coefficient of friction ones, their primary purpose is to improve vehicle stability and control during braking. By sensing wheel speed, preventing wheel lockup, and controlling wheel slip, the braking force in the direction of motion is kept near its maximum while a substantial portion of the side force capability of the tire is maintained. This enables a driver to maintain steering ability during an extreme braking event while directional stability is preserved.

2.2. ECE R13-H Annex 6

In Europe and other countries around the world, compliance with brake safety standards is based on type approval. Type approval is the confirmation that production samples of a design will meet specified performance standards. Manufacturers submit product specifications to governmental authorities, which then require third party approval - testing, certification and a production conformity assessment by an independent body. Each Member State is required to appoint an Approval Authority to issue the approvals and a Technical Service to carry out the testing to the EC Directives (whole vehicle) and ECE Regulations (vehicle components and sub-systems) [2].

In the U.S., vehicle safety standards are required to be objective so that manufacturers can self-certify that their vehicles are in compliance. Any adoption of a type-approval based rule, such as the ABS requirements found in ECE R13-H Annex 6, requires that empirical values be applied as necessary, in support of the rule's general intent, such that automotive manufacturers may self-certify their vehicles' compliance with existing North American standards.

ECE R13-H Annex 6 contains 3 basic sections: energy consumption, adhesion utilization, and ABS functionality tests. Of particular interest are the adhesion utilization and functionality tests. The adhesion utilization section has several steps, the first of which uses single-axle braking (with ABS off), combined with static measurements and rigid-body assumptions, to individually estimate the peak coefficient of adhesion of each axle, K_f and K_r, as seen on the next page.

Equation 2.1 Front Axle Friction Coefficient on a Rear Drive Car

$$K_f = \frac{Z_m pg - 0.015F_2}{F_1 + \frac{h}{E} Z_m pg} = \frac{\text{front braking force} - \text{rear drag}}{\text{dynamic weight on front wheels}}$$

Equation 2.2 Front Axle Friction Coefficient on a Front Drive Car

$$K_f = \frac{Z_m pg - 0.01F_2}{F_1 + \frac{h}{E} Z_m pg} = \frac{\text{front braking force} - \text{rear drag}}{\text{dynamic weight on front wheels}}$$

Equation 2.3 Rear Axle Friction Coefficient on a Rear Drive Car

$$K_r = \frac{Z_m pg - 0.01F_1}{F_2 - \frac{h}{E} Z_m pg} = \frac{\text{rear braking force} - \text{front drag}}{\text{dynamic weight on rear wheels}}$$

Equation 2.4 Rear Axle Friction Coefficient on a Front Drive Car

$$K_r = \frac{Z_m pg - 0.015F_1}{F_2 - \frac{h}{E} Z_m pg} = \frac{\text{rear braking force} - \text{front drag}}{\text{dynamic weight on rear wheels}}$$

Where

Z_m is the mean braking rate (of 3 runs within 5 percent of that axle's quickest decel time)
p is the mass of the vehicle
g is acceleration due to gravity
F_1 is the static normal force over the front axle
F_2 is the static normal force over the rear axle
h is the height of the center of gravity
E is the wheelbase of the vehicle

and $\frac{h}{E} Z_m pg$ is the dynamic weight transferred between axles during braking

Single axle vehicle decelerations are completed at incremental brake line pressures until lockup is achieved. Multiple runs are then completed at slightly less than this lockup pressure to obtain Z_m, which is specific to the axle being tested. The static forces and dimensions from Equations 2.1 – 2.4 are shown in the following figure.

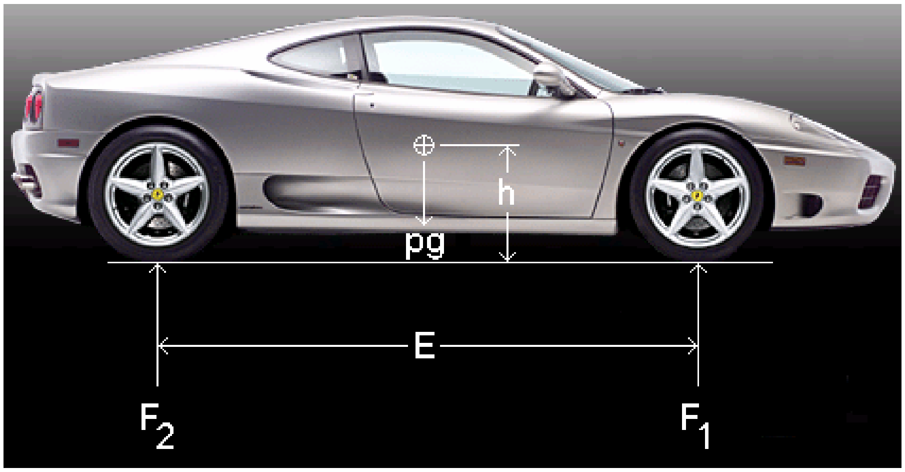


Figure 2.1 Force and Dimension Variables From Equations 2.1 - 2.4

After these friction coefficients are derived, they are placed into Equation 2.7, found below, along with the ABS "on" deceleration rate with both axles operative (Z_{AL}). Other values included in Equation 2.7 are the estimates of the dynamic normal force at each axle with ABS active, calculated using Equations 2.5 and 2.6.

Equation 2.5 Normal Force on the Front Axle With ABS On

$$F_{fdyn} = F_f + \frac{h}{E} * Z_{AL} * p * g$$

Equation 2.6 Normal Force on the Rear Axle With ABS On

$$F_{rdyn} = F_r - \frac{h}{E} * Z_{AL} * p * g$$

Equation 2.7 Effective Peak Coefficient of Adhesion

$$K_M = \frac{K_f * F_{fdyn} + K_r * F_{rdyn}}{p * g}$$

Where

F_f is the static normal force over the front axle (identical to F_1 in Equations 2.1-2.4)

F_r is the static normal force over the rear axle (identical to F_2 in Equations 2.1-2.4)

Z_{AL} is the mean braking rate (of 3 runs within 5 percent of the quickest decel time)

$\frac{h}{E} * Z_{AL} * p * g$ is the dynamic weight transferred between axles during ABS braking

All other variables have the same definition as the previous set of equations. The quantity derived, K_M, is interpreted here as the effective peak coefficient of adhesion for the vehicle. The final step is to divide the ABS deceleration rate by the overall peak coefficient of adhesion for the vehicle to arrive at the utilization of adhesion (ε).

Equation 2.8 Adhesion Utilization

$$\varepsilon = \frac{Z_{AL}}{K_M}$$

The intent of the adhesion utilization section is to ensure that the addition of ABS to a vehicle does not excessively affect a vehicle's ability to stop. This is laid out in Section 5.2.1 of Annex 6, which reads, "The utilization of adhesion by the anti-lock system takes into account the actual increase in braking distance beyond the theoretical minimum." (See **Appendix A** for full details of Annex 6.) The rule indicates that ABS must use at least 75 percent of the available adhesion. This value probably originates from an earlier understanding of what ABS does: it releases brake line pressure to prevent wheel lockup, and with reduced pressure comes decreased brake torque and increased stopping distances. The rule also allows for utilizations up to 110 percent before the tests must be repeated (Annex 6, Appendix 2, Section 1.3).

The ABS functionality tests are straight-line stopping events designed to subject an ABS to road conditions experienced during normal driving. The intent of these tests is twofold. One is to ensure that vehicle stability is not affected in situations where ABS is actively controlling the amount of tire slip. The other is meant to ensure that available adhesion is utilized even when it is changing or unequally distributed among the wheels.

The first functional test, found in Section 5.3.1 of Annex 6, examines how a sudden brake application affects wheel lock on the high- and low-coefficient surfaces, at two speeds and two loading conditions. For this type of test, all four wheels of the vehicle are on the same coefficient surface when braking is initiated. The second functional test is the high-to-low coefficient transition, again examining instances of wheel lock as the vehicle passes onto a slipperier surface while braking. The third test, found in section 5.3.3, is the low-to-high coefficient transition and is meant to ensure that the vehicle's braking rate increases as traction improves. The final test is the split-mu, where one side of the vehicle is on a high-coefficient surface while the other half is on a low-coefficient one. This test replicates the situation where a vehicle has partially departed the road while the driver brings it to a stop.

These ABS functionality tests are type-approval based and, as mentioned earlier, need empirical values added to certain parts before they can be used for compliance testing. Some examples include "…the deceleration of the vehicle must rise to the appropriate high value within a reasonable time…" (Section 5.3.3) and " … brief periods of wheel-locking shall be allowed…" (Section 5.3.6). There are a few provisions in this regulation that appear impractical, such as placing the transmission in neutral before stopping or aggressively braking from 120 km/h (~75 mph) on a slippery surface. Testing that replicates normal road conditions is apropos, but testing in a manner dissimilar to how the vehicle will be driven in the hands of the consumer seems inconsistent. A complete list of issues and problems encountered during ABS testing using the ECE method can be found in **Appendix B**, the majority of them being addressed during the course of this report

2.3. Objectives

NHTSA has evaluated vehicles using the European ABS regulation several times in the past, which revealed numerous issues with it. The resulting body of knowledge guided the development of the current test plan. The test plan was divided into two tasks, the first to address adhesion utilization related issues and the second to address the performance standards.

Task 1 used the ECE method for comparative data and focused on exploring alternative methods of measuring braking efficiency. The goal of the work was to develop a test procedure that yields meaningful and repeatable adhesion utilization data for ABS-equipped light vehicles. Special interest was given to provide some explanations as to why earlier ECE testing, on occasion, produced ABS adhesion utilization (braking efficiencies) over 100 percent.

Task 2 was devoted to defining existing performance criteria, investigating alternative performance tests, and to providing a framework for understanding the efficacy of testing a “brake and steer” maneuver representative of “real-world” driving.

All testing described in this report was conducted at NHTSA’s Vehicle Research and Test Center (VRTC) located at the Transportation Research Center (TRC) Inc. in East Liberty, Ohio.

3.0 METHODOLOGY

3.1. Test Vehicles and Preparation

Testing was conducted on one example from each of several major U.S.-market new vehicle categories. The categories of vehicles tested included compact passenger car, full-size passenger car, minivan, standard pickup truck, and mid-size sport utility vehicle. These five vehicles are all model year 2000 vehicles that were leased to VRTC for two years as test vehicles for the Light Vehicle ABS Performance Test Development Study. Each came equipped with ABS (the Toyota Corolla's ABS was an option) and all had automatic transmissions. A list of the vehicles tested is shown below in **Table 3.1**. Additional information can be found in **Appendix C**.

Table 3.1 Vehicles Selected for Preliminary Study

Vehicle Category	Vehicle	ABS Supplier	Curb Weight	Brake Type Front/Rear
Compact Car	2000 Toyota Corolla	Lucas & Sumitomo Brake Inc. (LSB)	2403 lbs	Disc/Drum
Full-Size Car	2000 Le Sabre Custom	Bosch 5.3	3567 lbs	Disc/Disc
SUV	2000 Honda CRV 4WD SE	Nisshinbo	3254 lbs	Disc/Drum
Minivan	2000 Toyota Sienna CE	LSB	3880 lbs	Disc/Drum
Pickup Truck	2000 GMC Sonoma SLS	TRW EBC-325	3268 lbs	Disc/Drum

Since VRTC leased these vehicles when they were new and their respective mileages were very low, no brake system components were replaced. The OEM tires that the vehicles were fitted with were in excellent condition for similar reasons. A burnish was conducted to make certain the pads and shoes were in full contact when used. Four extra OEM-style tires were purchased for use on the skid trailer (as called for in the test plan). These tires were mounted on the test vehicles and driven for a 200-mile scrub-in period, the approximate distance driven during a burnish procedure, before being delivered for use in surface monitoring. The vehicles were tested with the driver and instrumentation on board (see details below). Prior to testing, each vehicle was fueled and weighed, tire pressures were checked, tread depth measured, air cylinder filled, and the fifth wheel calibrated.

3.2. Instrumentation and Data Collection

All vehicles were similarly instrumented for testing with sensors, a data acquisition system, and auxiliary equipment.

3.2.1. Sensors and Sensor Locations

A multi-axis inertial sensing system was employed to measure three-axis linear accelerations and angular rates. The system package was placed at the center of gravity of each vehicle (as measured with driver) to minimize roll, pitch, and yaw effects. The package does not provide inertial stabilization of its accelerometers; however, the longitudinal accelerations were corrected for vehicle pitch angle during data analysis.

A string-type rotary potentiometer was used to measure handwheel position. It was connected to the handwheel shaft such that the string wrapped (and unwrapped) around the shaft as the wheel was turned to the left or right. String potentiometers were also installed parallel to each shock absorber to measure suspension deflection.

An ultrasonic distance measurement system was used to collect front and rear vertical displacements for the purpose of calculating vehicle pitch angle. One ultrasonic ranging module was mounted on each bumper of the vehicle. To improve sensor stability in regard to torsional deflection of vehicle bodies, the modules were positioned at the center of each vehicle's bumper.

Brake pedal force was measured with a load cell transducer attached to the face of the vehicle's brake pedal. A one-inch diameter air cylinder (shown below) was used to actuate the brakes via a trigger mounted to the steering wheel, and was attached to the other side of the load cell.

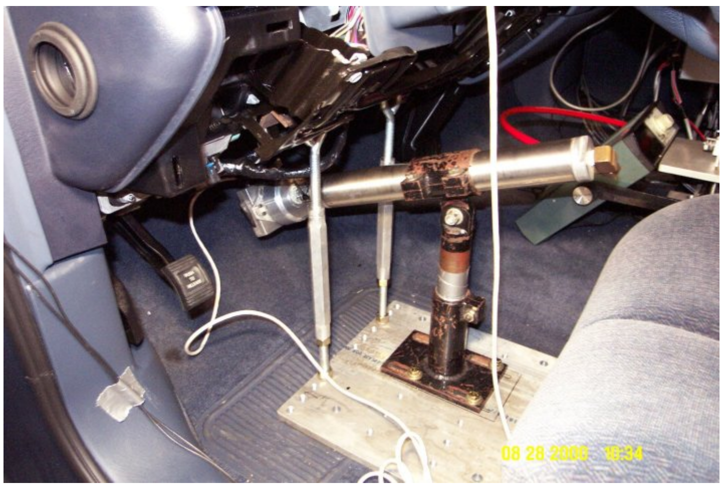


Figure 3.1 Pneumatic Brake Ram

In-line fluid pressure transducers were connected between the hard and flexible brake lines of each wheel of the test vehicle. In-line transducers were also placed in the brake lines leading from the master cylinder to the ABS controller. The outputs of the pressure transducers were primarily used to identify instances of ABS activation at a given wheel.

Individual brake temperatures were measured with plug-type thermocouples, installed according to FMVSS 135 Section 6.4.1 (based on SAE J79), and displayed inside the vehicle.

Vehicle speed was measured with a Labeco fifth wheel centrally located on the rear bumper with outputs to the data acquisition system, and to a dashboard display unit. Individual wheel speeds were initially measured by tapping into the wheel speed sensors (WSS) of the vehicles antilock brake system. These taps were of a 1:1 gain so as not to drain current away from the ABS and cause a malfunction. Wheel tachometers were necessary on the rear of the GMC Sonoma (an indirectly controlled system) and then adopted on the remaining vehicles for ease of setup and for detecting wheel lock quicker.

An infrared brake trigger sensor was positioned on the front bumper and used with the Task 2 functionality tests. A reflective plate that was placed on the ground was used to automatically trigger the brake's air ram while the driver focused on controlling the maneuver. Vehicle speed at the transition was recorded using a second reflective plate.

A single-axis torque wheel measurement system was employed for certain portions of the adhesion utilization testing to measure torque at each road wheel. The system is composed of a sensor, which measures the torque, vehicle-specific adapter plates to attach the sensor between the wheel and the brake, and digital FM telemetry for transmitting the torque signal. Chassis-mounted modules received the data and passed it on to the data acquisition system. The adapter plates and torque transducer can be seen below. Additional sensor information can be found in **Appendix D**.

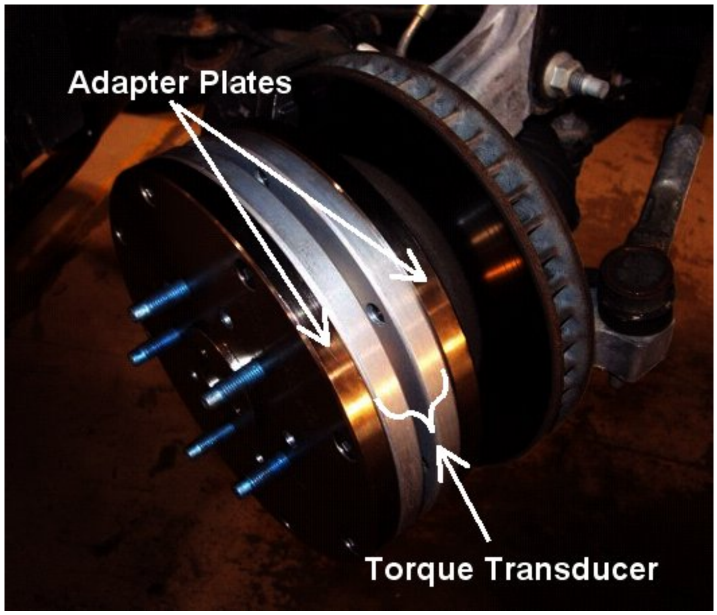


Figure 3.2 Torque Wheel Assembly

3.2.2. Data Acquisition and Processing

Ruggedized industrial computers, each equipped with a 650-MHz Pentium III microprocessor, collected data during test maneuvers. The computers employed the DAS-64 data acquisition software developed by the VRTC. Analog Devices Inc. 3B series signal conditioners were employed to condition data signals from all transducers listed in **Appendix D**. Measurement Computing Corp. PCI-DAS6402/16 boards digitized analog signals at a collective rate of 200 kHz. Final sample rates were set at 200 Hz, well above the 40-Hz minimum required by regulation. Data recording was triggered manually prior to applying the vehicle's brakes.

Signal conditioning performed by the 3B signal conditioners consisted of amplification and filtering. Amplifier gains were selected to maximize the signal-to-noise ratio of the digitized data. Filtering was performed using a two-pole low-pass Butterworth filter with the nominal cutoff frequency of 15 Hz, selected to prevent aliasing.

Data was processed using a phaseless 12-pole, 2-pass Butterworth filter at frequencies ranging between 2 and 15 Hz depending on the source of the data.

3.2.3. Skid Measurement System

An important part of Task 1 was to compare the peak friction coefficients (PFC) of OEM style tires with those generated with the ASTM E1136 tire, or Standard Radial Test Tire (SRTT), both according to the ASTM E1337 method. This was accomplished using TRC's Skid Measurement System, pictured in the figure below, which consists of an instrumented full-sized pickup truck and a K. J. Law (now DynaTest) traction trailer that is towed behind the truck. The traction trailer is equipped with water application nozzles and electronically controlled brakes that can be applied for various durations depending on the test. The traction trailer's axles are instrumented with load cells to measure the horizontal braking and normal forces in real time, which are then sent to the truck for data logging. From this, peak and slide coefficients of friction can be gathered for most tire-paved surface combinations, wet or dry.

Figure 3.3 TRC's Skid Measurement System

3.3. Test Surfaces and Course Descriptions

Task 1 adhesion utilization testing was conducted on the high coefficient of friction surface of TRC's Vehicle Dynamics Area (VDA), a 50-acre paved asphalt rectangle with a 1 percent grade running north to south, and on the low coefficient basalt tiles, a 60×1000 foot stretch of ½-inch thick tiles covered with a thin layer of water. These two surfaces had nominal PFC numbers of 0.9 and 0.2, respectively. The basalt tiles are shown below without water.

Figure 3.4 Basalt Tiles

Task 2 functionality testing was conducted on several different surfaces on the VDA. Two concrete profile surfaces were used to investigate the response of ABS to bumps. A Jennite coated asphalt surface, wetted to lower the coefficient of adhesion, and the surrounding wetted asphalt were also used. These two surfaces had nominal PFC numbers of 0.4 and 0.85, respectively. Transition tests, like those found in ECE Sections 5.3.2 and 5.3.3, used both surfaces during the same test. For example, on the high-to-low coefficient transition the driver would apply the brakes while on the asphalt, just before the vehicle passed onto the Jennite. The split-mu test of Section 5.3.4 had one side of the vehicle on asphalt and the other half on Jennite, as seen below.

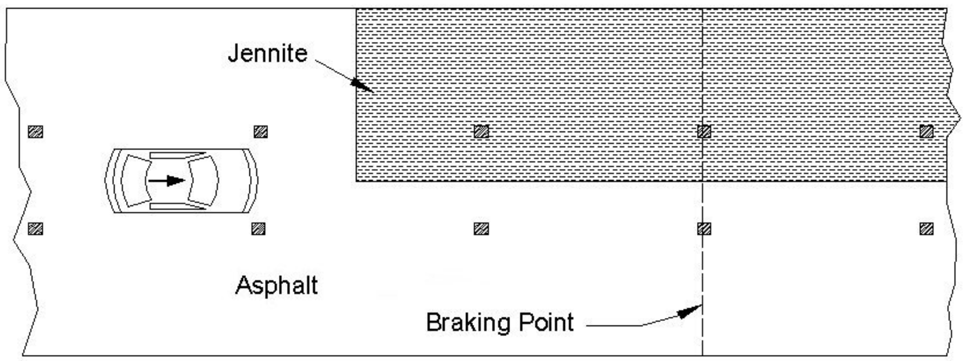


Figure 3.5 Layout of the Split-Mu Test

Tests added to the ECE functionality tests examined in Task 2 were ones meant to replicate those that might be encountered during normal driving. Test vehicles were aggressively braked over two different concrete profile surfaces, each with a different style of bump. One was comparable to a speed bump; the other one was a one-inch drop-off. Each maneuver would be described as a high-low-high, meaning braking was initiated on a high coefficient of friction surface, momentarily went low (read: no tire contact), then returned to high. These tests only subjected one axle at a time to this condition. Another possible type of high-low-high test is for both axles to simultaneously pass over a low coefficient surface (a 20-foot long wet, polished steel plate), a situation sometimes found in construction zones or as an ice patch beneath an overpass. This test could not be performed during this test program due to the lack of a suitable test surface.

Another test of interest was braking in a curve. To see how much lateral force ABS would preserve while braking and turning, a curve resembling an interstate off-ramp was marked on the Jennite surface. The lane was 15 feet wide and it had an inside radius of 50 feet, with a planned entrance speed of 40 km/h with the surface wetted.

3.4. <u>Experimental Design</u>

Task 1 adhesion utilization tests were largely based on the ECE methods. Included were two loading conditions, lightly loaded vehicle weight (LLVW) and gross vehicle weight rating (GVWR), three axle conditions (front only stops, rear only, and both), ABS on and off, and two different surfaces, asphalt and basalt. The single-axle test condition with functioning ABS was not explored. After these treatment combinations were completed, torque wheels were employed to gather additional vehicle data about the nature of braking forces during a stop.

The test plan for Task 1 also called for skid trailer measurements to be simultaneously collected in order to compare the PFC estimate from the ASTM method with the ECE method. This part of the study comprised a 2×2×3×6 factorial design, with PFC as the dependent measure. The four independent variables were surface type (dry asphalt/wet basalt tile), load (1033 lbs. and GVWR), speed (20, 40, and 64.4 km/h) and tire (5 OEM tires from each vehicle and the SRTT). Each treatment combination consisted of at least 10 runs (in compliance with ASTM E1337). Surface temperature was eventually added to this model because of its significant influence on PFC.

The Task 2 portion of the test plan was more exploratory in nature, therefore less defined. The majority of testing followed Annex 6 Section 5.3 et seq., with the addition of the previously described braking events (over bumps and in a curve). A small 2×1 test was conducted to see how to characterize the response of ABS at different transition speeds, since there was a question regarding the necessity of conducting the transition tests at 120 km/h versus a safer 90 km/h (bearing in mind the unrealistic nature of driving 120 km/h on ice).

3.5. Procedure

The routine prior to testing included fueling each vehicle to capacity and setting tire pressures to the manufacturer's specifications. The vehicles were then weighed with the fifth wheel in the down position. After the fifth wheel was calibrated on a measured 1000-foot section of track, the driver conducted a series of stops in order to raise the brake temperatures above 65ºC (149ºF). Once testing commenced, the driver monitored an in-car display to verify that brake temperatures remained between 65ºC (149ºF) and 100ºC (212ºF) before each test run. The brakes were not adjusted during the course of the experiment.

Testing was conducted during daylight hours on non-rainy days. The ambient temperature range for testing was set between 1.7°C (35°F) and 40°C (104°F). The lower limit was necessary because the basalt tile portion of the facility cannot be used when ambient temperatures fall below 35°F.

For Task 1, the vehicles were tested at LLVW and GVWR on asphalt and basalt. A precision air regulator supplied air to the brake ram piston. Sensitivity was very good as brake line pressures could be adjusted in 5-10 psi increments. The brake line pressure was increased after each stop that failed to lock a wheel and continued until the point where wheel lock was detected during the stop. The pressure was then reduced to the previous setting and 6 to 10 stops were performed in an attempt to gather 3 that would end up within 5 percent of the shortest deceleration time.

Surface temperatures and skid numbers were initially measured using TRC's Skid Measurement System. The original test plan called for PFC measurements while the vehicles were being tested. However, as testing progressed it became obvious that skid support and vehicle testing could not always be coordinated. This situation required the collection of surface temperature data so that skid support could mimic similar testing conditions at a later time. (This was possible because the asphalt area that was provided for ABS testing saw little to no traffic outside the ABS test program, so wear was not an issue, and basalt has proven itself to be a very consistent surface.) The focused attention on temperature precipitated an on-the-fly statistical analysis, which found significant PFC variations (based on temperature) that were unique to each tire. Thereafter, surface temperatures were recorded in detail.

For Task 2, the vehicles were again tested at LLVW and GVWR, on asphalt, Jennite, basalt, and concrete. The precision air regulator still supplied air to the brake ram piston, although its high accuracy was not needed for these tests. The ECE's "Additional Checks" called for "the full force" to be "suddenly" applied, which meant setting the air pressure to produce 500 N or 1000 N of pedal force depending on the load (GVWR maxed at 500 N, LLVW at 1000 N).

A noted problem with the ECE is the recurrent use of ambiguous wording. Since "suddenly" was undefined, a review of available brake pedal force data from a "panic stop" study [3] revealed that a force of 90 lbs. (400 N) in 0.1 sec. was the quickest ramp rate produced by any subject. Supplying the brake ram with 50-100 psi of air pressure produced ramp rates between 98-116 lbs. (436-516 N) per 0.1 sec., which was sufficiently sudden enough. Another benefit of using the brake ram was having highly uniform brake pedal force input.

The use of SunX plates to automatically trigger brake events and record vehicle speed at the time of transition was added to Task 2. These plates reflected infrared light back to a sensor located on the bumper, whose signal was used to activate the brake ram. Depending on the test, a target maneuver speed was selected based either on the ECE or on safety considerations. For example, when performing the Low-to-High Transition of Section 5.3.3, the maneuver speed was "approximately 50 km/h" at the transition. After a trial run, if the vehicle was slower than the maneuver speed, testers would move the SunX closer to the transition to delay the onset of braking. The plate would be moved back if the vehicle speed exceeded the maneuver speed.

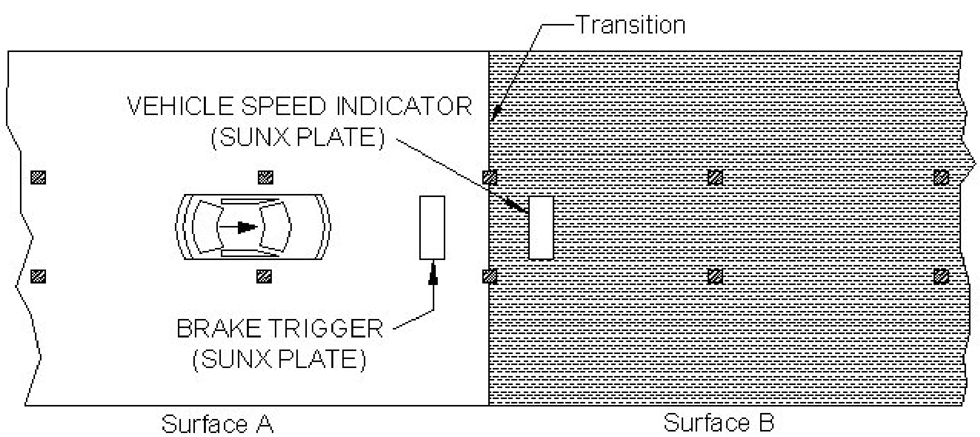


Figure 3.6 Adjusting Maneuver Speed With an Automatic Brake Trigger

Vehicle speed at the time of transition was assessed in two different ways, both based on graphed data output. The first way was used for the transition style tests, where the second SunX plate was positioned in such a way that as the front wheels first came into contact with the second surface, the reflective plate would be under the sensor on the front bumper. The software recorded this second plate's signal as an impulse, which was then graphed alongside the fifth wheel output (see Figure 3.7 on the next page).

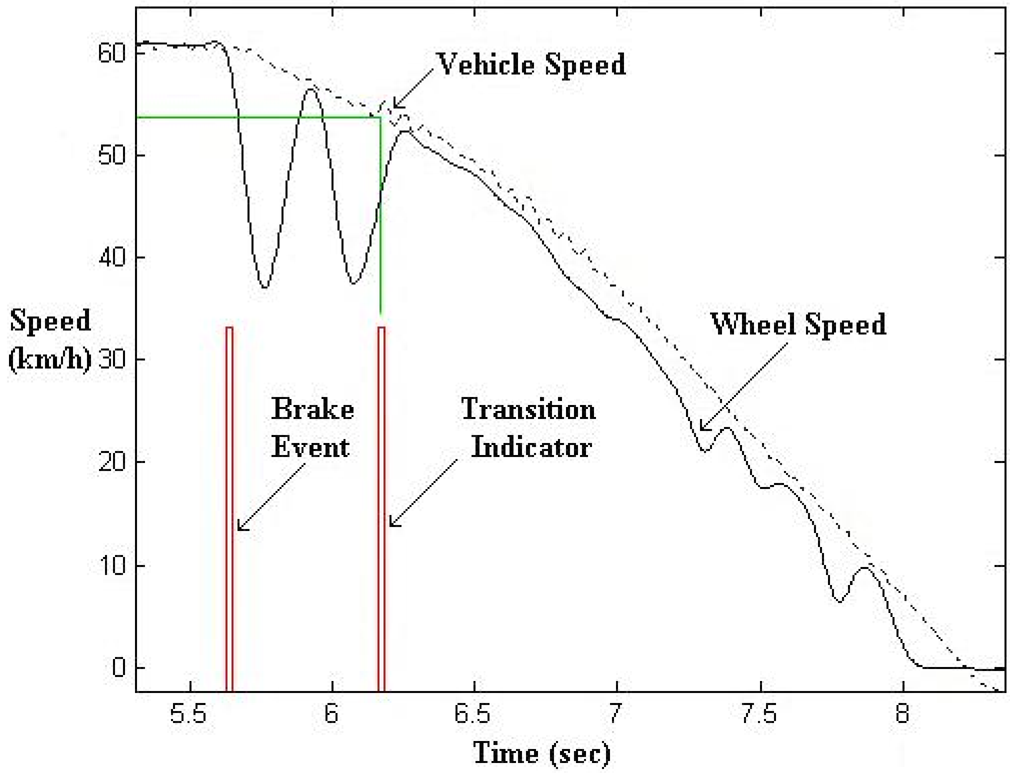


Figure 3.7 Vehicle Speed During Low-to-High Transition Test

The second method, used for the brake over bump tests, relied on the first sizeable drop in front wheel speed to indicate where the tire was momentarily airborne (i.e.: had reached the perturbation), which was then mapped to the fifth wheel output.

4.0 RESULTS AND DISCUSSION

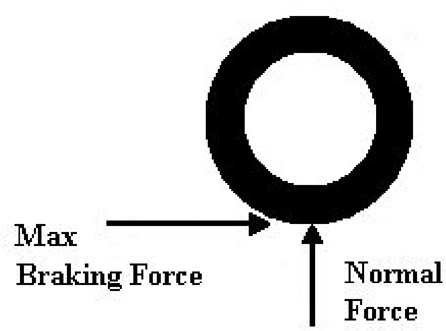
The results of this study are more readily understood with additional comments, so the Results and Discussion sections are combined here for that reason. This framework is split into two portions, one that examines the measurement of adhesion utilization and the other that addresses ABS performance and vehicle stability. It provides the reader with an understanding of how the various aspects of the experiment eventually lead to the conclusions contained herein.

The basics of coefficient of adhesion are initially set forth, supported by related graphs. Following this are the vehicle results derived from the ECE procedure. Weaknesses with this procedure, and how they influenced the adhesion utilization numbers, are covered. Alternative methods of determining adhesion utilization are included, with comparisons made between the existing methods.

The ABS performance tests were again drawn from the ECE as a baseline, supplemented with tests meant to replicate braking events commonly encountered in normal driving. Efforts were made to reduce unnecessary and repetitive procedures, as well as to increase safety for testers.

4.1. Adhesion Utilization Measurements - Task 1

To understand the nature of adhesion utilization, one must understand what coefficient of adhesion is, and the mechanics of what a tire does when the brakes are applied. The terms "coefficient of adhesion" and "coefficient of friction" are synonymous and can be used interchangeably. The coefficient of adhesion (k) is defined in the ECE (Section 1.1.1 of Annex 6 - Appendix 2) as the maximum braking forces without locking the wheels divided by the dynamic load on the braked axle. A simplifying assumption will be made here that maximum braking forces occur when both wheels produce their maximum braking force individually. One such wheel is shown in Figure 4.1. With this assumption, the ECE's definition of k can also be described as the peak friction coefficient, or PFC, between the tire and the road. It is important to keep in mind that the coefficient of friction is not a property of just the surface, or just the tire, but of the interaction between the two materials. Whenever either of the materials is changed, such as switching from concrete to asphalt or changing the rubber compound (replacing the vehicle tires with non-OEM tires), the coefficient of friction will also change.



$$k = \frac{\text{Max Braking Force}}{\text{Normal Force}}$$

Figure 4.1 Coefficient of Friction (k)

As for tire mechanics during braking, when brakes are applied the tire is actually rolling slower than the ground underneath it is passing by. This is longitudinal slip, or percent slip, which is defined as the ratio of the longitudinal slip velocity to the spin velocity of the straight free-rolling tire, expressed as a percentage. Each tire has an optimum value of percent slip that will generate the most force and therefore the highest coefficient of friction (a.k.a. PFC), as the previous equation shows. This optimum slip percent is between 10 and 20 percent for dry asphalt, and typically less on wet, slippery surfaces. It is generally understood that surface properties (macrotexture, material, temperature, conditioning, etc.), tire properties (compound, inflation pressure, tread depth, load, temperature, etc.), and environmental conditions (which affect the nature of the interaction between the two materials) have a direct impact on PFC. The speed at which a tire travels across a surface also has a significant influence on the PFC. The following figure shows the force vs. percent-slip curve of one of the test vehicle's tires on dry asphalt at 40 km/h with a 1035-lb. load, collected with a traction trailer. The longitudinally directed force reached a peak of 910 lbs. at 15 percent slip, which means the PFC for this particular run was 910 lbs/1035 lbs, or 0.879.

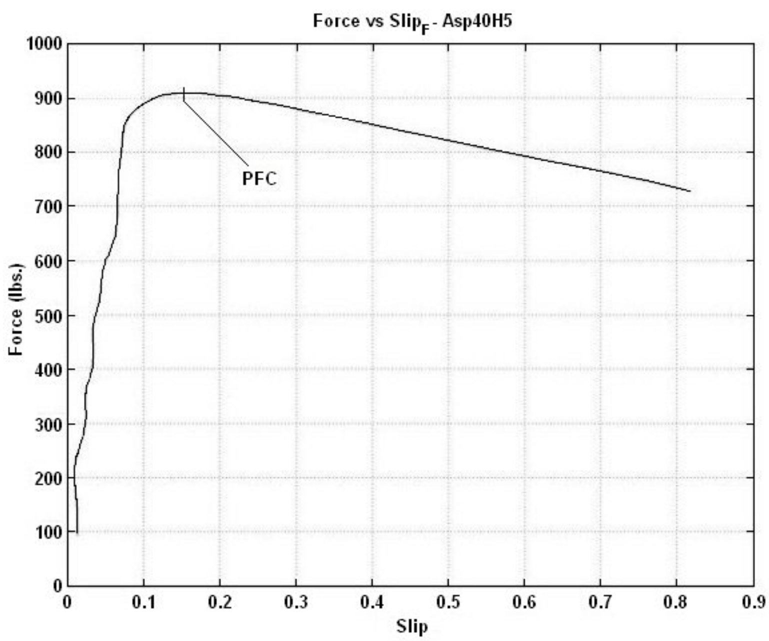


Figure 4.2 Example of a Force vs. Slip Curve

The ECE's adhesion utilization method estimates the PFC at each axle by finding the maximum vehicle deceleration for each axle. As described earlier, air pressure in the brake ram was incrementally increased with a precision air regulator to the point of wheel lockup. Prior to lockup, wheel slip was monitored graphically so that the testers would know how much more air pressure was needed for the subsequent run. Two such graphs can be seen in Figure 4.3. The image on the left is characteristic of an asphalt stop, while the image on the right is a stop from the basalt tiles. On the high coefficient asphalt, wheel slip was easiest to recognize by the separation between the decreasing slopes of the braked wheel's measured wheel speed, and the unbraked fifth wheel, which monitored vehicle speed. As previously noted, the braked wheels are spinning slower than the vehicle is actually traveling.

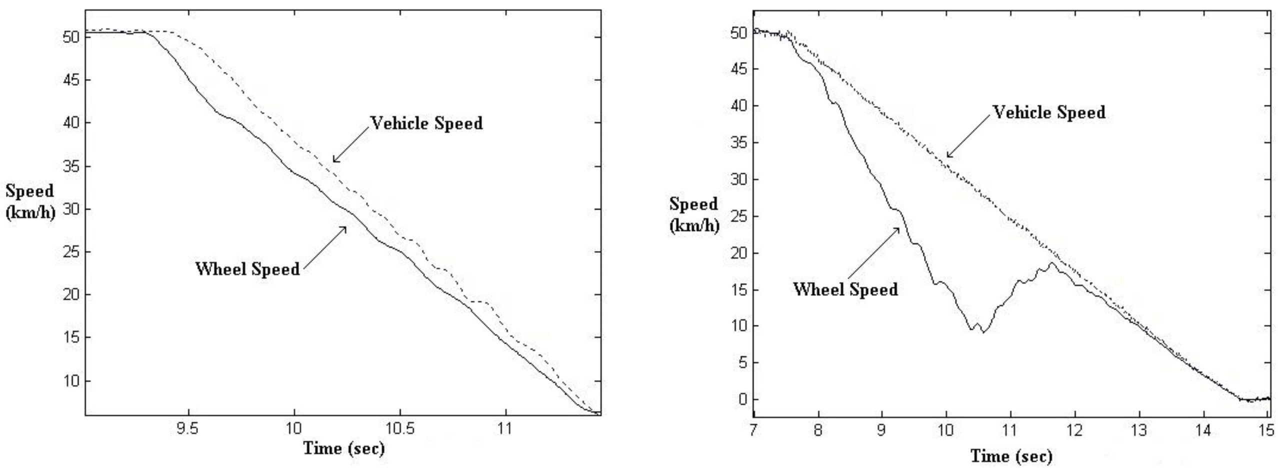


Figure 4.3 Graphed Wheel Speed Illustrating Slip

The large amount of separation seen in the basalt tile image was typical of a basalt test where tires were on the verge of 100 percent slip. Any increase in brake ram air pressure, no matter how small, would instantly lock that wheel. Basalt tests enjoyed a higher degree of predictability because the air pressure was regulated so low that the brake ram had less gain. Asphalt tests demanded more finesse. The following figure shows an example of what testers would see when a wheel locked up (reached 100 percent slip). The wheel speed of the locked wheel would drop almost vertically to zero. For all ECE adhesion utilization testing, wheel lock was not permitted between 40 and 20 km/h.

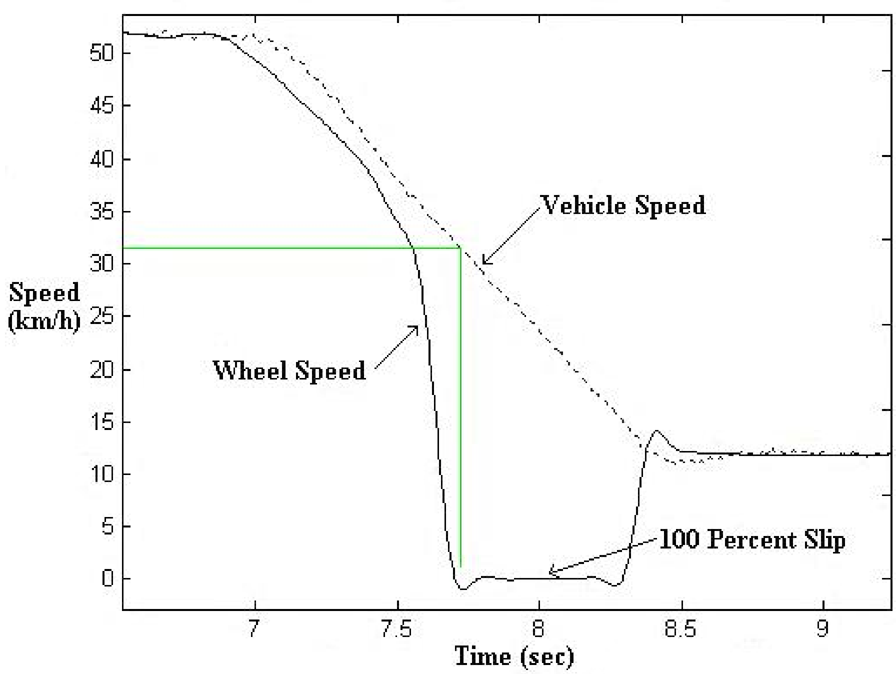


Figure 4.4 Failed Single Axle Test: Wheel Locked at 32 km/h

It is important to note that the time it takes for a wheel to go from optimal slip to 100 percent slip is very small. Once the maximum braking force allowed by the tire and surface is exceeded, lockup is virtually instantaneous (0.1 sec.) as the previous graph shows. Monitoring the graphical output from each stop allowed testers to determine the brake ram air pressure that would utilize the most available adhesion, at least for the tire that approached lockup first. The ECE method's search for the maximum deceleration ends when increasing pedal force causes one or both wheels to lock up. Using data taken from the quickest decelerations without wheel lockup between 40 and 20 km/h, an estimate of the PFC can then be calculated.

4.1.1. ECE by the Numbers

The desire to find the coefficient of adhesion, or PFC, is based largely on its use in determining adhesion utilization under the current ECE rule. The ECE procedure attempts to quantify the available adhesion first, then verifies that ABS uses between 75 and 110 percent of that value. This is accomplished by comparing the vehicle's ABS "on" deceleration rate with the calculated coefficient of adhesion obtained during the single-axle, ABS "off" decelerations. Consider that a car with ideal brakes (100 percent efficient) should be capable of generating a 0.8-g stop with a 0.8 coefficient of adhesion between the surface and tire. By definition, if all four tires were to reach their peak braking force simultaneously, that vehicle would exhibit 100 percent braking efficiency (perfect adhesion utilized) at that instant. Such an event would not occur naturally except by *extreme* chance; front brake bias and unequal loading of tires are the primary reasons why. Decreasing vehicle speed would further limit this rarity to a fraction of a second if it did occur. Data that supports these points are provided in upcoming sections. The values for peak coefficient of adhesion generated using the ECE procedures can be found in the following table.

Table 4.1 Adhesion Utilization Values Derived Using the ECE Test Method

Vehicle	Surface	Load	K_f	K_r	K_M	ε
Buick LeSabre	Asphalt	LLVW	1.033	0.888	0.997	0.903
	Asphalt	GVWR	0.947	0.645	0.855	1.083
	Basalt Tile	LLVW	0.248	0.205	0.233	1.164
	Basalt Tile	GVWR	0.247	0.203	0.228	1.015
GMC Sonoma	Asphalt	LLVW	0.868	0.816	0.856	1.033
	Asphalt	GVWR	1.024	0.462	0.820	0.974
	Basalt Tile	LLVW	0.249	Bad Data	Cannot Derive	Cannot Derive
	Basalt Tile	GVWR	0.231	0.239	0.235	0.855
Honda CRV	Asphalt	LLVW	0.908	0.731	0.866	1.029
	Asphalt	GVWR	0.935	0.535	0.819	1.077
	Basalt Tile	LLVW	0.255	0.503	0.353	0.704
	Basalt Tile	GVWR	0.258	0.508	0.372	0.669
Toyota Corolla	Asphalt	LLVW	0.892	0.651	0.834	1.062
	Asphalt	GVWR	0.902	No Lock	Cannot Derive	Cannot Derive
	Basalt Tile	LLVW	0.235	0.283	0.252	1.041
	Basalt Tile	GVWR	0.227	0.221	0.224	1.062
Toyota Sienna	Asphalt	LLVW	0.965	0.612	0.880	1.065
	Asphalt	GVWR	No Lock	No Lock	Cannot Derive	Cannot Derive
	Basalt Tile	LLVW	0.239	0.243	0.240	0.910
	Basalt Tile	GVWR	0.245	0.233	0.239	1.057

As can be seen in 11 places in Table 4.1, ABS adhesion utilization (ε) was above 100 percent using the ECE methods and equations. Overall, 14 conditions were in the (ECE's) acceptable range, 2 were under (75 percent), 1 over (110 percent), 2 with insufficient braking torque to finish the calculations, and 1 had data problems. K_M values always fell between K_f and K_r, and K_r was lower than K_f 70 percent of the time. The wide variations seen in ε and the differences in K_f and K_r can for the most part be explained. Such explanations are warranted given that these variations are at the heart of the adhesion utilization test method's problems.

4.1.2. Factors That Adversely Affect the ECE's Measurement of Adhesion Utilization

As stated previously, the ECE's adhesion utilization calculations rely on single-axle, ABS-off vehicle decelerations, static measurements, and rigid-body assumptions to individually estimate the peak coefficients of adhesion at each axle, K_f and K_r. These coefficients are then used to compute K_M, which effectively makes it the peak coefficient of adhesion for the vehicle. K_M can also be thought of as a measure of the total available adhesion. This method is meant to provide a means for understanding how quickly the vehicle could decelerate with both axles working.

There are a number of factors that marginalize the ECE adhesion utilization values. They can be loosely grouped into two sections, the first of which deals with using a vehicle to find available adhesion, and the second of which deals with the ECE's adhesion utilization procedures. With one exception, all of these factors contribute to the underestimation of available adhesion (K_M), which will lead to artificially higher adhesion utilization percentages from ABS, sometimes over 100 percent (recall that adhesion utilization, Equation 2.8, has K_M in the denominator). These factors are examined next.

4.1.2.1. Vehicle Factors

The vehicle-related issues that contribute to the underestimation of available adhesion are all related to the loss of optimal wheel slip at all four wheels during a stop. With suboptimal wheel slip, braking forces never reach their full potential and the vehicle decelerates at a slower rate. Examining one wheel initially will provide the basis for understanding these losses.

As previously mentioned, vehicle speed has a significant influence on the measured PFC. It is well-documented that PFC increases with decreasing vehicle speed. The next section, which contains the PFC analysis of the test vehicles' tires, also shows this strong trend. These upcoming measurements were collected with the traction trailer traveling at a constant speed. Since PFC constantly increases as the vehicle decelerates, a passenger vehicle will underestimate available adhesion when a constant brake pedal force is used, as the next paragraph explains.

During the adhesion utilization testing, the vehicle's brakes are applied (at an initial speed of 50 km/h) with just enough pedal force so that the limiting wheel is on the verge of lockup. The "limiting wheel" is defined here as the wheel that reaches the upper limit of tire traction first, thus ending the test sequence. It is also the wheel to initially examine when considering suboptimum slip. As the vehicle slows down and the PFC increases, this tire *could* take more brake torque. However, this does not happen because Section 1.1.3 in Appendix 2 holds "During each test, a constant input force shall be maintained…" Therefore, this single tire example shows in part why test vehicles underestimate the maximum amount of available adhesion:

additional brake force *could* have been generated by this tire but was not. Since deceleration is used to eventually estimate K_M, this loss of brake force leads to slower decelerations and a lower estimate of available adhesion. Extending this premise to the full vehicle demonstrates that brake force losses are contributed by all four tires. This effect obviously applies to both axles as they are tested individually as well.

Two additional factors that limit a vehicle's usefulness in determining the maximum available adhesion are front brake bias and unequal normal forces acting on each of the four tires. These factors act together during a stop, producing a vehicle with 4 wheels rotating at 4 different velocities. The following table shows the average wheel slip percentages (averaged between 40 km/h and 20 km/h) for the lightly loaded Corolla; the data comes from its quickest two-axle ABS-off stop.

Table 4.2 Average Wheel Slip Percentages From a Two-Axle Stop

	Left Side % Slip	Right Side % Slip
Front Axle	7.74	9.95
Rear Axle	6.72	6.89

As the above numbers show, on average the right front wheel was rotating slower than the other ones. This is because brake line pressure on all cars is front biased, and because the left side of the car had more weight over the tire (driver and steering column). If both wheels on the front axle are getting similar brake line pressure, then the lighter wheel will approach its peak percent of slip before the other. Looking at it from the perspective of adhesion utilization (and ignoring losses due to increasing PFC), testing on this vehicle would end when the right front wheel locked up, but clearly the other three tires were nowhere near their respective peak percent of slip, therefore they would not have been producing the maximum amount of retarding force, and the estimate for the total amount of available adhesion would be falsely low.

The ECE eliminates the discrepancies caused by front brake bias by looking at the relative brake-force contributions of each axle separately (single-axle testing), but does nothing to regulate side-to-side variability produced by load differences. Single-axle testing also introduces additional slip related losses due to weight transfer issues that are addressed in the next subsection.

One final vehicle-related issue that affects the adhesion utilization results is due to the *over*-estimation of available adhesion for four-wheel drive equipped vehicles. The Honda CRV employs a four-wheel drive system that automatically transfers drive torque front to back if the front wheels begin to slip. Although the four wheels do not receive equal amounts of torque, the wheels share a physical connection via the automatic transmission. The ECE's single axle testing does not call for disconnecting the driveshaft of the unbraked axle, and it is the resulting parasitic losses from the CRV's transmission/transfer case and unbraked axle that produced quicker decelerations than the rear axle brakes could have accomplished by themselves. The K_r values on the basalt surface were not only higher than the values for K_f, they were higher than physically possible. Wet basalt tiles have a nominal PFC between 0.2 and 0.3, yet the ECE procedure estimated the CRV rear axle K_r to be 0.508 GVWR and 0.503 LLVW. These large K_r numbers lead to the over-estimation of available adhesion (K_M) and are responsible for the low adhesion utilization numbers (ε) found in Table 4.1. This is another reason to question the value of single-axle compliance testing, given that a substantial portion of new vehicles sold in the United States are equipped with four-wheel drive. Parasitic losses would affect asphalt adhesion utilization values as well, but to a lesser extent because they are small in comparison to the overall asphalt braking forces.

4.1.2.2. Procedural Factors

The procedure-related issues found in the ECE that contribute to the underestimation of available adhesion relate to the loss of optimal wheel slip and the use of inappropriate decelerations. The deceleration-based inaccuracies are for the most part mathematical. The slip related losses due to weight transfer have their origins in the equations for K_f and K_r, found in Section 2.2. They contemplate an ideal state where weight is transferred from the rear axle to the front axle during a stop. As realistic as this may sound, the amount of load transferred during a two-axle stop cannot be replicated with the single-axle procedure set forth in the ECE, as the following analysis shows.

The amount of load transferred while braking on a level surface is determined exclusively by the amount of vehicle deceleration. A vehicle's deceleration is based on the brake force contributions from both axles. During hard braking, front brake line pressure is significantly higher than in the rear due to the proportioning valve. This means that the front brakes contribute more to the vehicle's deceleration than the rear brakes do, and are therefore responsible for the majority of the deceleration-based load transfer. The equations used to calculate K_f and K_r, Equations 2.1 – 2.4, have a component in their denominators for the amount of load transferred during a stop, based on deceleration. This component, which is based on the assumption that a vehicle behaves like a rigid-body during braking, is shown below.

Equation 4.1 Dynamic Load Transferred During Deceleration

$$Load\ Transferred = \frac{h}{E} Z_m pg$$

Examining only this portion of the data revealed large differences between the amount of weight released during rear axle testing versus the amount the front axle tests indicated were received (a legitimate concern since the rigid-body assumption predicts that any weight transferred off the rear axle goes onto the front axle). These differences ranged between 1034 N and 1887 N (232.5 lbs. and 424.2 lbs.) for asphalt and between 6 N and 218 N (1.3 lbs. and 49 lbs.) on the basalt tiles (ignoring the CRV's flawed data). No direct relationship between the magnitude of differences in load transfer and ε was found to exist, suggesting that some combination of factors contributed to the prevalence of low K_r values (a certain source for high adhesion utilization values). These will be addressed in turn.

The manner in which load is transferred is affected by the moments about each braked axle. Single-axle braking eliminates the braking torque that is normally produced by the unbraked axle during two-axle braking. Braking forces oppose the forward motion of the vehicle but do so at the four tire-road contact patches. When only the rear axle is used to stop the vehicle (for example), these braking forces, combined with anti-lift suspension geometry, produce a moment about the rear axle that causes the rear of the vehicle to squat down. This squatting effect is always present at the rear axle whenever the rear brakes are used but it is not noticeable to the naked eye when both axles are in use, primarily because the quicker, two-axle deceleration transfers a portion of the rear load to the front axle (thus taking advantage of the higher brake line pressures). All test vehicles exhibited varying degrees of rear-axle squat during the rear axle only tests.

To ascertain how single-axle testing affected physical load transfer (as opposed to the calculated amount), the suspension travel data was analyzed. This provided an initial estimate for the change in the amount of weight over each axle, based on a force versus suspension-displacement model. (It is definitely an "estimate" because only a portion of the load transfer is directed through the strut assemblies; load will transfer through all suspension hard points.) The modeling process involved placing each test vehicle on a car scale and incrementally applying sandbags over the front axle while measuring the change in suspension travel (using string potentiometers). This simulated the front suspension "dive" normally experienced during hard braking. Using a floor jack to incrementally raise the rear end of the vehicle simulated rear "lift". When the vehicles were actually tested, the suspension displacement was mapped to a regressed curve fitted to the data, and that "weight" was used in the estimation of load transfer.

Figure 4.5 Test Vehicle's Front Suspension at Maximum Compression

The data in the following table were derived from the regression curve fitted to the force versus suspension-displacement data from one of the test vehicles. The data used for this table are from the quickest deceleration for each axle condition, with ABS off. As these tables show, the proportion of weight transferred through the strut assemblies was not the same between the three different types of stops.

Table 4.3 Comparison of Estimated Weight Distribution During Braking (in Percent)

Sonoma at LLVW on Asphalt			
Axle =>	Both	Front only	Rear only
LF	37.1	37.3	29.3
RF	36.0	36.2	27.2
LR	14.1	13.8	21.6
RR	12.8	12.7	21.9
Z (g)	0.889	0.660	0.299

Sonoma at GVWR on Asphalt			
Axle =>	Both	Front only	Rear only
LF	28.1	28.9	26.1
RF	26.1	26.8	25.4
LR	22.1	21.4	23.4
RR	23.7	22.9	25.1
Z (g)	0.821	0.634	0.228

The shaded numbers in the previous table seem to indicate that single-axle testing places more weight over the tested axle than would normally be there (compared to a similarly loaded two-axle stop). However, the numbers are slightly misleading in the case of the front suspension.

The suspension displacements from the front axle only condition and both axles together are almost identical, but the quicker deceleration of the two-axle condition would have transferred the greater load. The front axle only condition lacked the rear-axle, anti-lift moment, so most of the deceleration based load transfer moved through the struts (suspension dive) rather than longitudinally through the suspension hard points.

As for the rear-axle only condition, a greater load was present than would normally be there during a two-axle stop. This is clear from the lightly loaded Sonoma data. Though less pronounced when the Sonoma was fully loaded, this data was included to show that this effect is present despite 1000 lbs. of sandbags in the bed. This provided some proof that the rear-axle, operating alone, did not produce sufficient deceleration to transfer the appropriate amount of load and thereby counteract the rear-axle moment.

The next step was to examine how increased weight over the rear axle affected vehicle performance. The rear brakes receive a small but consistent portion of available master cylinder pressure. Any increase in the load over the rear wheels requires an increase in brake force so that the tire's percent slip will remain near its peak. When tire load exceeds the rear brake force, which is limited by brake line pressure, the rear tires will no longer operate at their optimum percent slip. To validate this premise, the percent wheel slip (averaged from 40 km/h to 20 km/h) was examined on another test vehicle. The data in Table 4.4 were taken from the quickest deceleration for each axle condition, with ABS off, and includes the data from Table 4.2 in the left-most column. Wheel slip numbers for the unbraked axle's wheels were one percent or less, not relevant to this discussion and therefore left blank.

Table 4.4 Comparison of Average Percent Wheel Slip During Braking

Corolla at LLVW on Asphalt			
Axle =>	Both	Front only	Rear only
LF	7.7	9.7	
RF	10.0	10.8	
LR	6.7		5.7
RR	6.9		5.3
Z (g)	0.80	0.65	0.25

Corolla at GVWR on Asphalt			
Axle =>	Both	Front only	Rear only
LF	7.7	6.8	
RF	11.1	11.3	
LR	7.8		2.8
RR	7.2		2.8
Z (g)	0.88	0.65	0.18

The data shows that wheel slip increased for the lightly loaded, front axle only condition, suggesting that less weight had transferred to the front axle due to the slower deceleration. The rear axle only condition saw a modest loss of slip. Conversely, the heavily loaded, rear axle data reveals substantial losses in percent wheel slip, which is the crux of the single-axle testing problems. With the appropriate amount of weight transferred to the front axle during a two-axle stop, the brake line pressure going to the rear axle is sufficiently high to allow the rear wheels to generate an effective percent slip. In the rear axle only test, the combination of increased weight over that axle and insufficient brake line pressure resulting from front brake bias produced decelerations so low that K_r could not realistically be calculated. It should also be noted that only 300 lbs. were needed to bring this vehicle to GVWR, so the drop in performance between loading conditions was due more to the lack of deceleration-based load transfer than to large increases in vehicle mass.

Overall, the single-axle tests showed that only two vehicles were capable of locking one rear wheel on asphalt in the lightly loaded condition, and none in the heavily loaded condition. When lack of brake torque prevents a wheel from locking, there are direct implications on how much adhesion was used by the vehicle itself. The ECE procedures provide no insight as to how lack of brake torque in the single-axle tests should be accounted for.[1] Insufficient brake force will lead to slower decelerations, and in the case of the ECE testing, a low estimate for the coefficient of adhesion at each axle (as shown by the K_r values in Table 4.1).

The questionable results produced from the single-axle test procedures were compounded by two other contributing sources of error: ending the deceleration testing at the first instance of wheel lockup and the averaging of the top 3 decelerations used to calculate K_f and K_r. These procedural factors can be found in Appendix 2 of Annex 6. Both situations result in a slower overall deceleration, which in turn lowers the estimate for K_M and inflates adhesion utilization. Another possible source of error comes from the use of different speed ranges set for the timed decelerations. These are touched on briefly below.

The ECE test method attempts to find a maximum ABS-off deceleration rate for each axle in order to eventually estimate K_M. But this "maximum" deceleration is determined by a specified cutoff point (when one or both of the axle's tires reach 100 percent slip), which is not necessarily the actual maximum. If both wheels reach their peak percent of slip simultaneously, then that run would likely produce a quick ABS-off deceleration. On the other hand, if one wheel reaches its peak before the other and then locks up, there is nothing currently in the ECE methodology for discovering if the maximum deceleration was found. Premature wheel lockup such as this is a certain source of error for the calculation of adhesion utilization because it would lower the estimate of K_f and/or K_r, leading to a low estimate of K_M and a higher adhesion utilization value.

No explanation of how a vehicle is to be loaded exists in Annex 6 of the ECE. During the course of this experiment, vehicles tested at GVWR were loaded proportionally to the individual GAWR's but not necessarily equally from side-to-side. Differences were kept to a minimum whenever possible but space considerations on fully loaded vehicles could impose weight discrepancies as high as 100 lbs. (one sandbag's worth). Vehicles tested at LLVW did not get additional weight, so the left side of the car could be up to 130 lbs. more than the right side.

Regardless of the vehicle's loading condition (LLVW or GVWR), the unequal loading of two wheels on the same axle will influence premature lockup at the "least heavy" wheel. This is purely a mathematical observation, but assuming brake line pressure to each side of the same axle is nearly identical, and assuming that the two tires of the same axle will have nearly identical PFC's with the pavement for the duration of the stop, then placing more weight over one tire would allow it to generate greater braking force before locking up. The "lighter" of the two wheels will lockup early, thus ending the test and underestimating K_i for that axle.

[1] Section 5.2.5 of Annex 6 does allow for tests to be omitted when the specified pedal force fails to cycle the ABS. If tires never reach optimum slip, they certainly do not approach 100 percent slip, so ABS will never intercede. Technically speaking, ABS will then use the same amount of adhesion as the foundation brakes (100 percent efficient) but this is not perfect adhesion utilization. ABS adhesion utilization in this instance is meaningless and it is appropriate to omit such testing.

Mandating that side-to-side weight distributions be within a certain tolerance would minimize this source of error.

Setting theory aside, the matter of premature lockup remains a factor regardless of its source. As a proportion of the overall number of single-axle stops, the test runs that had at least one wheel locking up between 40 km/h and 20 km/h were by far in the minority. But this is an artifact of the ECE procedure which only asks for the highest deceleration rate preceding wheel lockup, so no higher brake line pressures were sought out to see if deceleration rates might improve as the second wheel approached lockup. Once the rejection criteria of “no wheel lockups between 40-20 km/h” was removed, the data revealed that some previously discarded tests had deceleration rates superior to the best rate recorded for that vehicle under similar conditions. Table 4.5 summarizes the comparison made between the best “non-locked” deceleration rate and the best deceleration rate for that vehicle. The best “non-locked” deceleration rate is distinguishable from the average of three within 1.05 of the best deceleration as was done in the ECE. The rear wheel data was omitted because of the lack of rear wheel lockups.

Table 4.5 Was Vehicle Deceleration Quicker With One Front Wheel Locked?

Vehicle	Surface	Load	Quicker Decel?	How much?
Corolla	asphalt	LLVW	no	—
	asphalt	GVWR	no	—
	basalt	LLVW	yes	12.6%
	basalt	GVWR	no (close)	—
CRV	asphalt	LLVW	no	—
	asphalt	GVWR	no	—
	basalt	LLVW	yes	7.1%
	basalt	GVWR	same	—
LeSabre	asphalt	LLVW	no (close)	—
	asphalt	GVWR	no	—
	basalt	LLVW	no	—
	basalt	GVWR	yes	2.0%
Sienna	asphalt	LLVW	yes	4.3%
	asphalt	GVWR	no lock	—
	basalt	LLVW	yes	3.0%
	basalt	GVWR	yes	1.4%
Sonoma	asphalt	LLVW	yes	5.5%
	asphalt	GVWR	no	—
	basalt	LLVW	yes	0.9%
	basalt	GVWR	no	—

This front axle data demonstrates that maximum deceleration may occur with one wheel locked. The majority of improved decelerations were on the basalt tile surface because the braking forces on asphalt are comparatively much higher. The longer a wheel is locked, the more stopping performance is lost. However, if a wheel locks very late in the 40-20 km/h speed range, it would be disqualified under the ECE method but could actually be an extremely quick deceleration, as was probably the case in the two asphalt conditions shown above. This lead to a change in thought about why a single-axle test run should be rejected: as long as the vehicle continues to stop in its original direction of travel, accept the quickest deceleration regardless of whether a wheel locked or not.

Another of the procedural aspects in the ECE that lowers deceleration is the averaging of the three shortest brake snub times within 1.05 of the best time in order to calculate K_f and K_r. The surest way to estimate PFC (literally *the peak* friction coefficient) is to use only the best time from the accumulated runs. The quickest stop was achieved because the traction was available, so averaging slower decelerations with the peak one will indisputably produce lower overall coefficients (the K_M term) and therefore higher adhesion utilizations.[2]

Another procedural factor that could potentially affect deceleration related to how the ABS-on deceleration range (45-15 km/h) was different than the ABS-off range (40-20 km/h), and what effect that might have on the adhesion utilization calculations. Data from all of the vehicles' ABS-on decelerations (from 45-15 km/h) were processed in a separate routine to compare how the vehicle's deceleration from 40-20 km/h measured up to the deceleration from 45-15 km/h for each individual stop. Deceleration differences ranged from 7.5 percent quicker to 4.8 percent slower. Of the 20 basic adhesion utilization conditions examined (5 vehicles × 2 loads × 2 surfaces), 8 revealed consistently slower deceleration rates and 1 was quicker; the remaining conditions had no recognizable pattern. Because these deceleration times are the basis of the Z_{AL} calculation, using the slower values would have resulted in lower adhesion utilization for that vehicle had the 40-20 km/h range for ABS deceleration been in effect.

From the factors previously discussed, it seems clear that the total amount of available adhesion cannot be accurately quantified. Both vehicle-related issues (associated with the loss of optimal wheel slip at all four wheels during a stop) and procedural-related issues (associated with single-axle load transfer and the encumbrances of choosing the peak deceleration) are responsible for this outcome. This lack of precision renders subsequent adhesion utilization results unreliable for all vehicles (even when they are under 100 percent). The inability of the ECE procedure to accurately quantify available adhesion is the most likely reason why vehicles in previous studies have, on occasion, produced adhesion utilization values over 100 percent. ABS has not used more adhesion than is available when $\varepsilon > 100$ percent, it just used more than the foundation brakes did.

This report documents that the majority of these contemporary vehicles had $\varepsilon > 100$ percent using the ECE method. The combination of an over-performing ABS with any deficiencies in estimating available adhesion will definitely produce higher adhesion utilization percentages for ABS. ABS does in fact provide better decelerations in many instances because it manages wheel slip at the limiting wheel, thereby allowing the other tires to approach their optimum percent slip. It is because of this that ABS uses more adhesion than the foundation brakes.

With all things considered, these observations were deemed sufficient to cast serious doubt on the efficacy of the ECE procedure. The next step in the research involved two alternative

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[2] Averaging Z_{AL}, the numerator of ε, has the opposite effect of lowering the adhesion utilization values. In this case, however, it is appropriate to average the ABS deceleration rate. The purpose of ABS adhesion utilization is to examine the typical or average response of ABS to a given peak level of coefficient of adhesion.

methods for measuring the coefficient of adhesion directly, thus skipping the need for finding K_f and K_r altogether.

4.1.3. Alternative Adhesion Utilization Method - Using Traction Trailer Results for K_M

Since the test plan was designed to examine suspected weaknesses with the ECE method, two alternative methods for finding the peak coefficient of adhesion were concurrently investigated. The two methods used a traction trailer to provide surrogate values for K_M (the effective peak coefficient of adhesion for the vehicle), one using an OEM tire and the other an SRTT (both to ASTM E1337). A third method for examining adhesion utilization was also investigated, and will be discussed shortly.

Previous evaluations of the ECE had left the impression that the adhesion utilization procedure produced K values that were artificially low, which was why certain vehicles had adhesion utilization (braking efficiencies) over 100 percent. It was assumed at the onset of data collection that providing different values for K, such as those from the traction trailer, would show this when compared directly to the ECE method. This proved to be only partially correct.

Early in testing it was clear that PFC varied with given test conditions. The results of a statistical analysis (ANOVA for unequal cell sizes, using Proc GLM in SAS) showed that speed, tire type, weight, and surface temperature, as well as many of their interactions had strong effects on PFC. The omega-squared index [4] was used to compare the relative magnitude of these effects. Accordingly, test speed and the type of tires were shown to have the strongest effects on PFC.

The three different test speeds selected for the traction trailer (20, 40 and 64 km/h) were based on ASTM E1337's 40 mph (64.4 km/h) test speed and the ECE's speed range for single axle snubs (40–20 km/h). As can be seen in the following tables, as speed increases PFC decreases. Weight was based in part on the E1337's weight of 1033 lbs. (4595 N), and in part on a preliminary estimate of the vehicles' gross dynamic weight over one of the front tires. This estimate was derived using the force versus suspension-displacement curve described in the previous section. The dynamic weights used for the Buick LeSabre, Toyota Sienna, GMC Sonoma, and Honda CRV were 6895 N, 6677 N, 5583 N, and 5809 N (1550, 1501, 1255 and 1306 lbs.) respectively. The Corolla was the lightest car and used the 1033 lbs. (4595 N) from the E1337 procedure as its dynamic heavily loaded weight, and 822 lbs. (3656 N) as its lower weight (which is the weight of the traction trailer completely empty.

Table 4.6 Measureable Effects Influencing Asphalt PFC

Measured Effects	Levels	Mean PFC	S.D.	n	F – ratio	P – value Type III
Speed	20 km/h	1.063	0.05	270	427.75	<0.0001
	40 km/h	1.026	0.047	270		
	64 km/h	0.997	0.045	270		
Tire	SRTT	1.001	0.049	300	153.29	<0.0001
	Buick	1.027	0.053	150		
	Sienna	1.002	0.046	90		
	Sonoma	1.050	0.037	90		
	CRV	1.081	0.031	90		
	Corolla	1.074	0.035	90		
Weight	1033 lbs.	1.031	0.055	510	16.34	<0.0001
	dyn GVWR	1.023	0.053	300		
Surface Temperature ºF	50's	1.024	0.044	30	32.73	<0.0001
	60's	1.030	0.043	90		
	70's	1.003	0.038	90		
	80's	1.045	0.071	135		
	90's	1.025	0.058	195		
	100's	1.017	0.041	150		
	110's	1.044	0.052	105		
	120's	1.071	0.028	15		
Weight*Temp	–	–	–	–	76.41	<0.0001
Weight*Tire	–	–	–	–	25.71	<0.0001
Tire*Temp	–	–	–	–	72.83	<0.0001
Speed*Temp	–	–	–	–	5.12	<0.0001

Table 4.7 Measureable Effects Influencing Basalt PFC

Measured Effects	Levels	Mean PFC	S.D.	n	F – ratio	P – value Type III
Speed	20 km/h	0.322	0.035	310	452.32	<0.0001
	40 km/h	0.272	0.031	310		
	64 km/h	0.232	0.032	310		
Tire	SRTT	0.258	0.047	390	89.02	<0.0001
	Buick	0.299	0.046	180		
	Sienna	0.295	0.045	90		
	Sonoma	0.297	0.040	90		
	CRV	0.264	0.046	90		
	Corolla	0.270	0.052	90		
Weight	1033 lbs.	0.271	0.051	615	14.32	0.0002
	dyn GVWR	0.283	0.045	315		
Surface Temperature ºF	50's	0.278	0.050	75	18.65	<0.0001
	60's	0.271	0.049	285		
	70's	0.284	0.048	375		
	80's	0.261	0.050	180		
	90's	0.298	0.037	15		
Weight*Temp	–	–	–	–	36.19	<0.0001
Weight*Tire	–	–	–	–	22.79	<0.0001
Tire*Temp	–	–	–	–	8.68	<0.0001
Speed*Temp	–	–	–	–	2.10	0.0332

The data reflects the strong effect speed had on peak coefficient of friction. No matter what tire was used, the loading condition, or the temperature of the surface tested on, the PFC increased with decreasing speed. In fact, this was true for sliding friction too. Torque plots from both surfaces showed that torque steadily increased with decreasing speed. Data from the basalt surface is shown below.

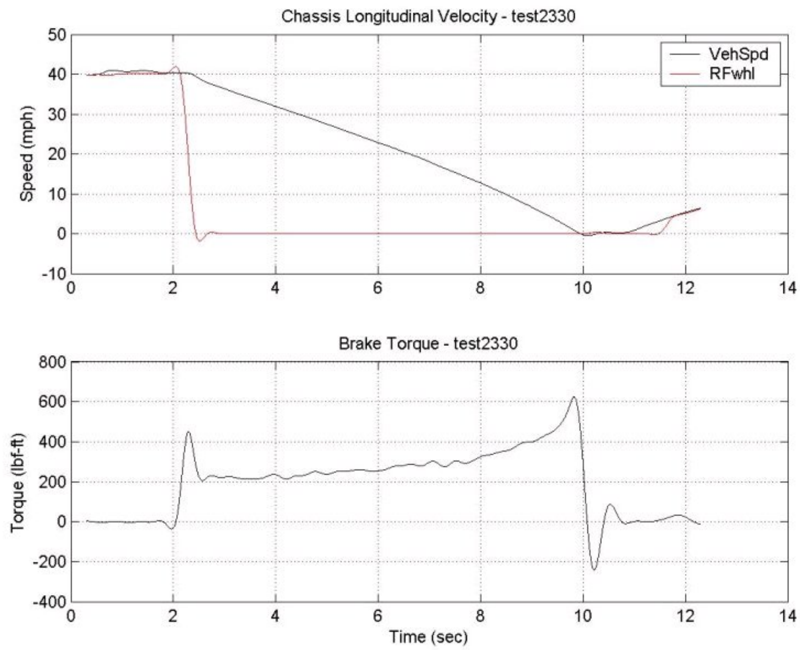

Figure 4.6 Plot of Decreasing Vehicle Speed While Wheel Torque Increases

Locked skids on asphalt show a sharper increase in torque followed shortly by a steady decrease, most likely due to the tire rubber melting. Both of these findings are important when considering the ECE methodology for determining adhesion utilization, with the first step being "find PFC". Given that PFC changes with vehicle speed, the most one can say about PFC is that it will fall between two values, based on the starting and ending speeds of the brake test. The changing slide coefficient is not as pressing because that just affects how fast a locking wheel will spin back up when ABS is managing slip. The ECE calls for a peak-to-slide ratio between 1 and 2 on the low coefficient surface but it is doubtful that it envisioned maintaining this ratio throughout the range of speeds a vehicle is subject to during brake testing.

The second biggest influence on PFC was the type of tire used. On asphalt, only the Sienna's tire provided PFC numbers similar to the SRTT. All of the other OEM tires' PFC's were significantly higher than the SRTT. The CRV and Corolla's tires' PFC's were not significantly different from each other. On basalt, all the tires were much closer in overall performance. The SRTT once again offered the lowest overall PFC of the group. The CRV tire was not significantly different from the SRTT or the Corolla tire, though the Corolla was significantly different from the SRTT. The three remaining OEM tires all offered similar PFC numbers on the basalt surface, all greater than the other three.

Surface temperature and amount of weight on the tire both had significant impacts on recorded PFC numbers, but no discernable patterns or trends were obvious. This may be a result of the analysis having unequal sample sizes, including some open cells. The unequal number of runs is a consequence of surface temperature changing throughout the day and over the course of three months of testing; not all tires saw all temperature ranges. Adding to this was the volume of data originally set forth in the experimental design. Once PFC patterns became evident, adjustments were made to reduce the number of data points while preserving the quality of the PFC estimate.

Interpreting the main effect of weight was problematic in that it represented the maximum weight that a vehicle would place over its front wheel during a two-axle stop while loaded to GVWR (estimated using the same data from the force versus suspension-displacement model). There was some evidence in the data to suggest that a critically loaded tire had a lower PFC, but tighter experimental control would be needed to experimentally prove this.

The point that should be made here is that when using a numerical value with the term "coefficient of adhesion", be aware that this number is not fixed. The ASTM E1337 method is in agreement with this, where it clearly states that peak friction is unique to each test run, and "does not necessarily represent a maximum or fixed value" (Section 1.1 of that standard). Even when speed, load, and surface temperature do not vary (ASTM method) there is still variability in the ten PFC numbers collected from the individual runs. PFC changes continuously during all types of driving, including decelerations, and is therefore only partially predictable. The previous statistical analysis answers the question of whether PFC numbers generated with a traction trailer using ASTM E1337 and the SRTT can be used in place of the estimates derived from the ECE equations, and the answer is "no". If the ECE's K_M estimates were low and produced high adhesion utilization percentages, the traction trailer using the SRTT will not work either. The SRTT tire produces lower PFC numbers as compared to the OEM tires, and the speed at which data is collected is much faster than the timed snub test speeds (coefficient of adhesion decreases with increasing speed). Using these lower PFC numbers as a surrogate for K_M will produce adhesion utilization numbers that are higher than expected.

The next table shows how the use of surrogate PFC numbers (for K_M) generated using the skid truck affected adhesion utilization numbers. The table brings the K_M and ε numbers found in Table 4.1 (found using the ECE method) alongside the K_M value from the SRTT (gathered at the ASTM speed of 40 mph (64 km/h)), the K_M value from the OEM tires themselves (again at 40 mph to show the tire effect by itself), and the K_M value representative of what the OEM tires may have experienced during the brake snub (shown as 40–20 km/h in the right-hand column). The resulting adhesion utilizations (braking efficiencies) are shown to the right of their respective K_M source. The columns are shaded for grouping purposes.

Table 4.8 How Surrogate PFC Numbers Affect Adhesion Utilization

Vehicle	Condition	K_M from ECE	ε	K_M – SRTT 64 km/h	ε	K_M – OEM 64 km/h	ε	K_M – OEM 40-20 km/h	ε
Corolla	light asph	0.834	1.062	0.967	0.916	1.044	0.849	1.100	0.806
	hvy asph	no rear lock	no data	0.920	1.018	1.033	0.906	1.083	0.865
	light basalt	0.252	1.041	0.215	1.223	0.205	1.282	0.285	0.923
	hvy basalt	0.224	1.062	0.221	1.080	0.225	1.061	0.311	0.768
CRV	light asph	0.866	1.029	0.967	0.922	1.055	0.845	1.095	0.815
	hvy asph	0.819	1.077	0.920	0.959	1.054	0.837	1.095	0.805
	light basalt	0.353	0.704	0.215	1.157	0.221	1.125	0.280	0.889
	hvy basalt	0.372	0.669	0.221	1.127	0.222	1.122	0.292	0.852
LeSabre	light asph	0.997	0.903	0.967	0.931	1.021	0.882	1.059	0.850
	hvy asph	0.855	1.083	0.920	1.007	0.984	0.942	1.030	0.900
	light basalt	0.233	1.164	0.215	1.259	0.258	1.049	0.321	0.844
	hvy basalt	0.228	1.015	0.221	1.048	0.257	0.902	0.320	0.725
Sienna	light asph	0.880	1.065	0.967	0.969	0.998	0.939	1.036	0.904
	hvy asph	no cycle	no cycle	0.920	no cycle	0.963	no cycle	0.991	no cycle
	light basalt	0.240	0.910	0.215	1.019	0.252	0.869	0.334	0.656
	hvy basalt	0.239	1.057	0.221	1.144	0.242	1.045	0.305	0.829
Sonoma	light asph	0.856	1.033	0.967	0.915	1.045	0.846	1.081	0.819
	hvy asph	0.820	0.974	0.920	0.868	1.002	0.797	1.044	0.765
	light basalt	bad data	bad data	0.215	1.002	0.267	0.807	0.320	0.673
	hvy basalt	0.235	0.855	0.221	0.908	0.255	0.787	0.311	0.646

Note that the surrogate PFC values used in the table for the "light" asphalt and "light" basalt are the values from the corresponding OEM tire used at the E1337 method's specified weight of 1033 lbs. (except in the case of the Corolla, which used 1033 lbs. for the "heavy" conditions and 822 lbs. for the "light"). They are not to be confused with the dynamic stopping weight over the front tires of the lightly loaded vehicle, which is what the ECE method attempts to approximate and does use. Also keep in mind that the K_M values for the OEM 40-20 km/h are the average of two separate sets of test values. The traction trailer maintains a constant speed when it collects data (per the ASTM method), and the distinct values of "40 km/h" and "20 km/h" represent the beginning and ending speeds of the vehicle in a timed deceleration. Although the test vehicle might only be exposed to these coefficients of adhesion once during a stop, it is assumed here that the average coefficient of adhesion between the vehicle's front axle and the pavement during the snub and the calculated average of these two traction trailer data sets will not be significantly different, statistically speaking.

The surrogate K_M values obtained from the ASTM method are both higher and lower than the values from the ECE method. This was expected because the SRTT has absolutely nothing to do with how the test vehicles actually performed. Substituting the OEM tire for the SRTT while maintaining the 64.4 km/h test speed improved the numbers for K_M and brought most adhesion utilization percentages below their previous amount. The Corolla and CRV's basalt data showed a decreasing trend in K_M. Using the averaged PFC data from the OEM 40-20 km/h runs, the data best suited as a surrogate for K_M, produced still higher K_M values and reduced adhesion utilization percentages for all but the CRV on the low coefficient basalt surface, due to the parasitic losses from the 4-wheel drive design as previously discussed (Section 4.1.2.1). Decreasing K_M brought the adhesion utilization (ε) numbers for those two basalt tests above the 75 percent threshold for rejection.

After looking at the OEM 40-20 km/h numbers, there might be the inclination to take them at face value. They certainly are more persuasive than the ECE numbers, primarily because none are over 100 percent. However, there are problems with evaluating adhesion utilization in this manner. The validity of any adhesion utilization approach depends entirely on the accuracy of the estimate of available adhesion. In this particular situation, the process of estimating available friction did not account for the different loads that the axles (and therefore tires) were exposed to during a stop (assuming that side-to-side differences could have been minimized).

The amount of load placed over the tire while it is in the traction trailer influences the amount of measurable friction it develops when inflation pressure is held constant. When load and inflation pressure are optimally situated, the contact area is at its maximum. When load is less than this ideal load, the contact area is reduced and the tire has reduced capability to apply braking forces. When tire load exceeds this ideal load, the contact area is relatively unchanged but the stresses across the contact area become distorted, resulting in a loss of applicable braking forces and therefore measurable PFC. The loss in PFC is typically 0.01 for a 10 percent increase in load when the tire is near its rated load [5].

The data collected for the OEM 40-20 km/h runs only used two different loads. One was the 1033 lb. load used in the ASTM E1337 method, which was used for the lightly loaded vehicle condition (except the Corolla). The other was an estimate, based on suspension travel measured at the strut, of the front tire load during a stop when the vehicle was loaded to GVWR. These loads, and the PFC numbers derived using them, were used to directly estimate the available adhesion (K_M) between 40 and 20 km/h. As the next table shows, these loads do not accurately reflect the front and rear tire loads from both vehicle-loading conditions. The calculated numbers below were derived using Equation 4.1 and the Z_{AL} deceleration rate (two axle) from the ECE testing (Sienna at GVWR was estimated). The asphalt figures were used because the higher deceleration rates produced the biggest differences between front and rear tire loads.

Table 4.9 Differences in Tire Load on an Asphalt Surface

Vehicle	Condition	"g"	Calculated Front Tire Load (lbs.)	Calculated Rear Tire Load (lbs.)	Load Used For OEM 40-20 Estimate (lbs.)
Corolla	light asph	0.89	1125	354	822
	hvy asph	0.94	1240	397	1033
CRV	light asph	0.89	1424	433	1033
	hvy asph	0.88	1486	615	1306
LeSabre	light asph	0.9	1508	496	1033
	hvy asph	0.93	1635	709	1550
Sienna	light asph	0.94	1708	542	1033
	hvy asph	0.94	1821	790	1501
Sonoma	light asph	0.88	1569	482	1033
	hvy asph	0.8	1644	936	1255

These sizeable differences in tire load will change the measured PFC, but to what degree is unknown because this study focused primarily on brakes and not on tires. However, the principal problem with this method is that the majority of calculated rear-tire loads were well below the lower design capacity of the traction trailer (822 lbs. empty). One commercially available tire tester has a lower limit of 400 lbs. and an upper limit of 2000 lbs., but even this range would be insufficient to measure the gamut of tires loads that light vehicles up to 3500 kg GVWR would exhibit. Until a more suitable tire tester becomes available, finding available adhesion with a towed trailer will continue to suffer from inaccuracies and therefore should not be widely adopted within this class of vehicles.

Having already developed surrogate numbers for K_M using representative tire loads, the following tables highlight some of the other concerns with calculating adhesion utilization using approximate PFC's. These concerns revolve around the interactions of vehicle weight, measured tire friction, and percent wheel slip.

Table 4.10 Data of ABS Deceleration Rates on Basalt and Surrogate ε Ratios

Vehicle	Test Wt.	LLVW "g"	K_M 40-20	ε
Corolla	2956 lbs.	0.263	0.285	0.923
CRV	3709 lbs.	0.249	0.280	0.889
LeSabre	4150 lbs.	0.271	0.321	0.844
Sienna	4500 lbs.	0.219	0.334	0.656
Sonoma	4100 lbs.	0.216	0.320	0.673

Test Wt.	GVWR "g"	K_M 40-20	ε
3273 lbs.	0.239	0.311	0.768
4164 lbs.	0.249	0.292	0.852
4818 lbs.	0.232	0.320	0.725
5224 lbs.	0.253	0.305	0.829
5160 lbs.	0.201	0.311	0.646

This first table contains data from the basalt surface, sorted by vehicle name, and includes the vehicle weight as tested, the ABS "on" deceleration rate (Z_{AL}) collected during the ECE testing, and the optimized K_M and associated adhesion utilization values found in Table 4.8.

Consider first the LeSabre in its two loading conditions. The brakes on that vehicle have the same capacity to do work regardless of how the vehicle is loaded; this is fixed by the brake's design. If the surrogate traction trailer numbers are to be believed, then the LeSabre's tires were impervious to the 500 lb. increase in load (0.321 PFC at LLVW versus 0.320 PFC at GVWR). With these facts as such, one is left with an identical vehicle and tire combination that decelerated 0.039 g slower when it was 668 lbs. heavier, thus lowering its "braking efficiency" below the proposed acceptable threshold (of 75 percent adhesion utilization). Did the heavier version have more kinetic energy to dissipate? Certainly. Did it utilize less adhesion during the process? The above data derived from the traction trailer PFC's indicates yes, but in reality it is impossible to tell without examining percent wheel slip.

The heavily loaded Corolla and Sonoma elicit a similar question. The traction trailer found that both tires had a PFC of 0.311 on basalt; the heavily loaded Sonoma weighs almost 1900 lbs. more. What portion of the Sonoma's deceleration can be attributed to the weight difference and what portion might be due to lack of adhesion utilization? Neither the ECE method nor the traction trailer data can determine this.

Next consider the numbers from the LeSabre loaded to LLVW and the CRV loaded to GVWR. The vehicles are approximately the same weight (LeSabre is 14 lbs. lighter), the LeSabre produced a slightly better stop than the CRV (by 0.022 g) on tires with a higher PFC than the CRV's tire (which could explain most of the improved deceleration rate), yet the CRV had better adhesion utilization because of its lower tire-surface PFC. As this example shows, using traction trailer PFC numbers allows a vehicle equipped with "lesser tires" to improve its adhesion utilization numbers. This makes it difficult to consider a rule that is easier to pass with a minor decrease in the quality of part, tires in this case. A review of the corresponding asphalt data, arranged in the next table, also shows that the lowest surrogate K_M values produced the highest adhesion utilization values.

Table 4.11 Data of ABS Deceleration Rates on Asphalt and Surrogate ε Ratios

Vehicle	Test Wt.	LLVW "g"	K_M 40-20	ε
Sienna	4500	0.937	1.036	0.904
LeSabre	4150	0.900	1.059	0.850
Sonoma	4100	0.885	1.081	0.819
CRV	3709	0.892	1.095	0.815
Corolla	2956	0.886	1.100	0.806

Vehicle	Test Wt.	GVWR "g"	K_M 40-20	ε
LeSabre	4818	0.927	1.030	0.900
Corolla	3273	0.936	1.083	0.865
CRV	4164	0.882	1.095	0.805
Sonoma	5160	0.799	1.044	0.765
Sienna	5224	no cycle	0.991	no cycle

With the data sorted by adhesion utilization, one can see that vehicle weight does not appear to have a consistent effect on deceleration rate in either of the two loading conditions. One might argue that K_M increased with decreasing vehicle weight as seen in the LLVW data, but such a position has little foundation. It is far from clear what relationship exists between vehicle test weight at LLVW and the E1337 tire load of 1033 lbs., the latter of which was used to derive the LLVW K_M values with the traction trailer. Even if that relationship could be established, the vehicles' test weight at GVWR and corresponding K_M values were derived using different data and do not follow that trend.

There appears to be a trend in the LLVW data between K_M and ε. This observation describes the mathematical relationship between ε, deceleration and K_M: as higher K_M values are placed into the denominator of the adhesion utilization equation, adhesion utilization will decrease. The GVWR data follows this trend except for the Sonoma, which had a much slower deceleration rate as compared to the other vehicles. The uncertainties associated with this particular data set from the traction trailer reinforce the need for developing a better estimate of the total available adhesion, K_M.

To wrap up this section, the ECE analysis supports the view that those methods produce coefficient of adhesion numbers that are artificially low, and that this has an unmistakable impact on adhesion utilization percentages. However, this latest section shows that one cannot just conjure up PFC numbers using a method unrelated to vehicle braking and suggest a vehicle's brake performance can be accurately assessed using it. Care must be taken when developing an estimate for the total available adhesion to ensure accurate adhesion utilization results.

As it was implemented, this surrogate K_M method is a modest improvement over the ECE method. However, inaccuracies resulting from the inappropriate loading of tires while measuring tire PFC's would not instill complete confidence in the ensuing adhesion utilization results. The next section expands upon a deceleration-based test method that captures many of the ECE's strengths and includes a slight change in perspective about adhesion utilization.

4.1.4. Alternative Adhesion Utilization Method – ABS Effectiveness Factor

There are 6 primary factors that determine how well a vehicle will stop, presented here in no particular order:

1. The kinetic energy in the system, based on the mass and speed of the vehicle.
2. The design capacity of the brake system to convert kinetic energy into heat.
3. How quickly the system reaches its maximum rate of energy conversion.
4. The peak coefficients of friction between the tires and surface.
5. How well the brake system manages these 4 individual PFC's.
6. The potential energy in the system, based on the grade of the test surface.

The basic design of the ECE procedure is clever in that it controls for most of these factors. By setting the speed range for the timed decelerations at 40-20 km/h, the portion of variability associated with vehicle speed (number1, above) is eliminated. Recording the time it takes for the vehicle to complete this brake snub produces the "g" force generated by the vehicle's brakes, which takes into account the mass of the vehicle (the rest of number 1), the design capacity of the brake system (number 2), and the part of number 5 related to front brake bias. As long as testing is conducted in the same direction and location (not explicit in the ECE procedure), influences due to surface grade are normalized. Number 3 above is influenced by the gain provided by the brake system. However, any differences arising between vehicles are sidestepped by applying the brakes before the timed deceleration begins so that the vehicle settles into quasi steady-state behavior, as called for in the ECE procedures. Therefore, the timed deceleration test is preferable to a stopping distance measurement because it eliminates the variability associated with number 3 above. Testing deceleration or stopping distance in the same direction will normalize small losses due to the drive train, aerodynamic drag, and the tires' rolling resistance. This leaves PFC (number 4) largely unaccounted for. As noted in an earlier section, the increasing friction coefficient as a vehicle slows and constant brake pedal force only makes it possible to accurately estimate PFC at the start of the brake snub.

Essentially the layout of the ECE test method is to first approximate the available adhesion for the entire vehicle with ABS disabled (K_M) by determining the contribution to deceleration that each axle makes and adding them together. ABS is then enabled and timed decelerations are averaged so that "adhesion utilization" can be determined. However, the "adhesion utilization" percentage used to describe ABS performance is not based on all available adhesion (the PFC's for all four tires throughout the deceleration range), but as a percentage of what that vehicle's foundation brakes could use. Therefore, the actual ECE process could more appropriately be described as a comparison between the adhesion utilization achieved by the foundation brakes and the adhesion utilization achieved by ABS, using deceleration as the metric of comparison. This of course is not adhesion utilization, but something more along the lines of "ABS effectiveness".

A quote from Section 2.2 of this report is worth repeating: "The intent of the adhesion utilization section is to ensure that the addition of ABS to a vehicle does not excessively affect a vehicle's ability to stop. This is laid out in Section 5.2.1 of Annex 6, which reads, 'The utilization of adhesion by the anti-lock system takes into account the actual increase in braking distance beyond the theoretical minimum.'" However, it is this search for the "theoretical minimum" that drives the ECE towards finding the "peak" coefficient of adhesion. Reality suggests that it is not necessary to find a PFC, or quantify all available adhesion, in order to compare two different deceleration rates from the same vehicle on the same surface (which is what the ECE essentially does). Dividing the 2-axle ABS-on decelerations with the best 2-axle ABS-off deceleration will reveal in short order whether ABS adversely affected the foundation brakes' stopping ability. This ratio, defined here as the "ABS Effectiveness Factor," will be denoted by the upper case epsilon (E).

Equation 4.2 ABS Effectiveness Factor

$$\mathrm{E} = \frac{Average\ ABS\ Adhesion\ Utilization}{Foundation\ Brakes'\ Adhesion\ Utilization} = \frac{\dfrac{Average\ of\ 3\ Quickest\ \text{"}ABS\ on\text{"}\ Decels}{Total\ Available\ Adhesion}}{\dfrac{Max\ \text{"}ABS\ off\text{"}\ Decel}{Total\ Available\ Adhesion}}$$

The method used to derive the E values consisted of averaging the three best ABS decelerations (not necessarily within 1.05 of the quickest time) and dividing that number by the best deceleration (without wheel lockup) achieved by the vehicle with both axles functioning and ABS disconnected. The ECE's ε values found in Table 4.12 are taken directly from Table 4.1. The two columns provided for E represent the two different ABS-deceleration speed ranges previously mentioned, the ECE's 45-15 km/h and the reprocessed speed range of 40-20 km/h. The subsequent discussions are in reference to the data found in the 40-20 km/h column.

Table 4.12 Comparison of ECE "Adhesion Utilization" With ABS Effectiveness Factor

Vehicle	Condition	ECE ε	45-15 km/h E	40-20 km/h E
Corolla	light asph	1.062	0.919	1.005
	hvy asph	no data	1.063	1.059
	light basalt	1.041	1.061	1.062
	hvy basalt	1.062	1.154	1.146
CRV	light asph	1.029	0.993	0.987
	hvy asph	1.077	1.037	1.025
	light basalt	0.704	1.074	1.057
	hvy basalt	0.669	1.240	1.203
LeSabre	light asph	0.903	1.001	0.989
	hvy asph	1.083	1.085	1.065
	light basalt	1.164	1.461	1.464
	hvy basalt	1.015	1.216	1.202
Sienna	light asph	1.065	1.033	1.026
	hvy asph	no cycle		
	light basalt	0.910	1.031	1.031
	hvy basalt	1.057	1.118	1.125
Sonoma	light asph	1.033	0.979	0.990
	hvy asph	0.974	0.973	0.961
	light basalt	bad data	1.128	1.121
	hvy basalt	0.855	1.315	1.279

There were 6 conditions on asphalt where the ECE method had adhesion utilization values in excess of 1; in each instance the E method produced numbers lower than ε (although not all fell below 1.00). The data also shows that just 4 in 19 times did the non-ABS snub produce a higher deceleration then the ABS snub (i.e. E was less than 1), and these were all on asphalt. There is at least one point that could be made here, and that is that ABS tends to utilize more adhesion than the tests that cease after the first wheel locks up. If this "best non-locked deceleration rate" cutoff point was lifted and brake line pressures were allowed to increase, the asphalt decelerations would "self-regulate" (based on the material already provided in this report) and produce some improvement in the decelerations, thus decreasing the numeric ratio of E.

The asphalt E data show a reduction in the frequency and magnitudes of numbers exceeding 1.00 as compared to the ε numbers from the ECE (despite the first locked wheel cutoff point). There is the added benefit that whenever E > 1.00, the sole interpretation is that ABS improved upon the foundation brakes' deceleration. When E < 1.00 the opposite is true. How much ABS should be allowed to reduce the foundation brake's deceleration rate, if this test method were to be implemented, is a matter for future research. The reason for this is that this round of testing ended at the first instance of wheel lock per the ECE's guidelines, so the quickest ABS-off deceleration rates were not necessarily measured.

The final point to come from the E analysis is in regards to basalt. The 10 basalt surface test conditions account for the majority of high E values (top 7 and every one within the highest 12), all of which are over 1.00. This clearly shows that ABS will outperform low coefficient of friction tests that cease after the first wheel locks up. However, extensive testing on the basalt surface left experimenters with the impression that stopping performance improved as more wheels were locked up. Recognizing that the replacement test for the low-coefficient adhesion utilization test needed to challenge existing ABS designs, this phenomenon was investigated more thoroughly.

4.1.5. Low Coefficient Adhesion Utilization Method – ABS Effectiveness Factor Variant

The method used to derive the E values defined the denominator as the best deceleration (without wheel lockup) achieved by the vehicle with both axles functioning and ABS disconnected. As with all of the "no wheels locked" testing, this is a lengthy process of adjusting brake pedal pressure and gathering deceleration data. This process is also predisposed to inaccuracies associated with the loss of optimal wheel slip described earlier in Section 4.1.2.1. These losses were credited as the source of superior ABS stopping performance on the basalt surface. When used on the basalt tiles, this method has the same fundamental problem as adhesion utilization: without using the quickest deceleration possible, available adhesion is underestimated and ABS appears to provide superior braking performance.

In an attempt to reduce these slip-related losses, it was decided to measure the stopping performance of the vehicles with all 4 wheels locked up to see whether a superior deceleration could be achieved. The original presumption was that the force vs. percent slip curves of basalt would be similar in shape to the ones generated on asphalt, as depicted in Figure 4.2. A sudden brake application with ABS off causes all 4 wheels to instantly lock up, placing the minimum braking performance of the vehicle at a fairly high level, as the next figure helps to demonstrate.

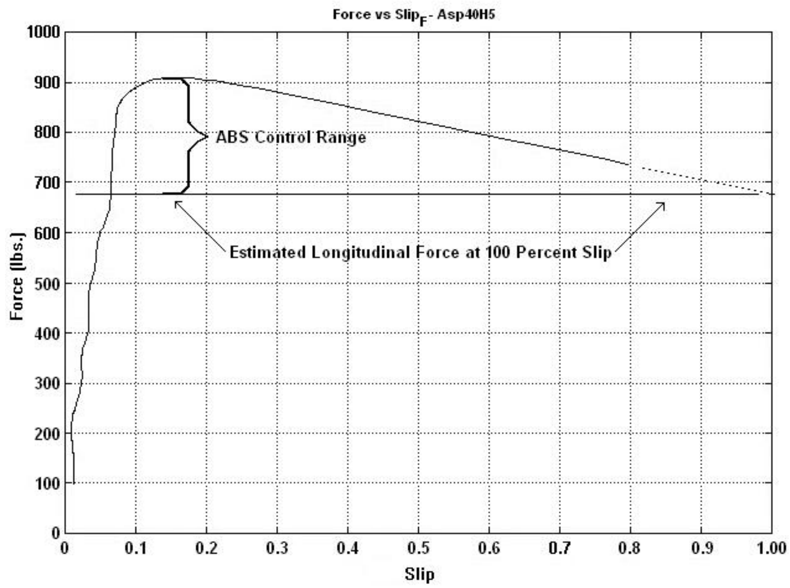

Figure 4.7 Example of the Force Generated by a Tire at 100 Percent Slip

This relabeled data from Figure 4.2 approximates the amount of force generated by the fully locked Corolla tire (about 680 lbs.) on this particular test. With a maximum force of 910 lbs, the 680 lb. estimate suggests that the locked wheel would have exerted nearly 75 percent of the maximum force. It was hypothesized that all 4 wheels generating this high percentage of force simultaneously, as well as throughout the deceleration range (40-20 km/h) as available friction increased, would provide superior deceleration when compared to the same vehicle decelerating with no wheels locked using a constant brake pedal force.

If this ratio of sliding force to peak force were maintained throughout the deceleration range, then the sliding vehicle would have utilized roughly 75 percent of the available adhesion. The reciprocal of the slide-to-peak ratio is the more frequently used peak-to-slide ratio, therefore 75 percent adhesion utilization is loosely equivalent to a peak-to-slide ratio of 1.33. The data in the next table compares the E values derived using the best "4 wheels locked" deceleration with the previously calculated E values (best non-locked deceleration rate).

Table 4.13 Comparison of E Values Derived Using Different ABS-Off Decel Rates

Vehicle	Condition	ABS On (g)	ABS Off (g) 4 Wheels Locked	Difference (g)	40-20 km/h E 4 Wheels Locked	40-20 km/h E Table 4.12 Values
Corolla	light basalt	0.2466	0.3178	-0.0712	0.776	1.062
	hvy basalt	0.2370	0.2299	0.0071	1.031	1.146
CRV	light basalt	0.2344	0.3060	-0.0716	0.766	1.057
	hvy basalt	0.2308	0.2748	-0.0440	0.840	1.203
LeSabre	light basalt	0.2531	0.2561	-0.0030	0.988	1.464
	hvy basalt	0.2261	0.1873	0.0388	1.207	1.202
Sienna	light basalt	0.2191	0.2684	-0.0493	0.816	1.031
	hvy basalt	0.2437	0.2138	0.0299	1.140	1.125
Sonoma	light basalt	0.2142	0.2211	-0.0069	0.969	1.121
	hvy basalt	0.1951	0.2279	-0.0328	0.856	1.279

The E values that are less than 1 indicate where ABS performance was less than the equivalent 4-wheels-locked skid. The data show that 8 out of 10 times the vehicle deceleration was superior when all 4 wheels were locked up as opposed to no wheels locked. Although a 4-wheels-locked skid may not necessarily be the quickest ABS-off deceleration, insights emerge here about ABS testing on low coefficient surfaces, raising several questions as to the nature of ABS performance testing on these types of surfaces.

What does this data say about adhesion utilization when all 4 wheels are locked? Without ever finding the total available adhesion, the above numbers show that the majority of the 4-wheels-locked skids used more adhesion than ABS did (7 times out of 10). Knowing that an ABS rule must provide a minimum level of acceptable performance for the low coefficient surface, it really just becomes a matter of selecting one that is easy to find and protects stopping ability while stability is being maintained.

A practical and relevant question that should then be asked is: What kind of braking performance will the majority of drivers achieve with a surface-tire PFC around 0.3 (that of wet basalt) using a vehicle not equipped with ABS? The answer is a 4-wheel locked skid. Therefore, as a possible starting point for a rule, consider setting the 4-wheels-locked sliding deceleration as the minimum deceleration for the vehicle when ABS is active to insure that there is no loss in stopping performance when vehicles are equipped with ABS. This satisfies the intent of the rule, the threshold is easily found, and it also appears that such a requirement will challenge some portion of existing ABS systems. This method of testing has the added benefit of improved safety, since the sliding vehicles have no yawing tendencies, and low wear on the tires.

Returning to the presumption that the force vs. slip curves of various low coefficient surfaces are similar, then proposing that the quickest deceleration for a 4-wheels-locked skid be the minimum deceleration rate when ABS is operating would insure approximately 75 percent adhesion utilization (Fig. 4.7) and force ABS to control wheel slip within the narrow range (labeled) to match the sliding deceleration of the vehicle. However the Table 4.13 results showed that the majority of vehicles would have failed this test, so further analysis was required.

To further explore this method of testing, skid data was collected on 3 types of wet surfaces (basalt, Jennite, and concrete), with the realization that basalt tiles may not be a widely available test surface. The TRC traction trailer was used, traveling at 40 mph with a 1033 lb. load atop two Corolla test tires. Ten force vs. slip curves were generated from the data collected on each of these 3 surfaces. The following figure shows the two most common types of curves from the basalt surface.

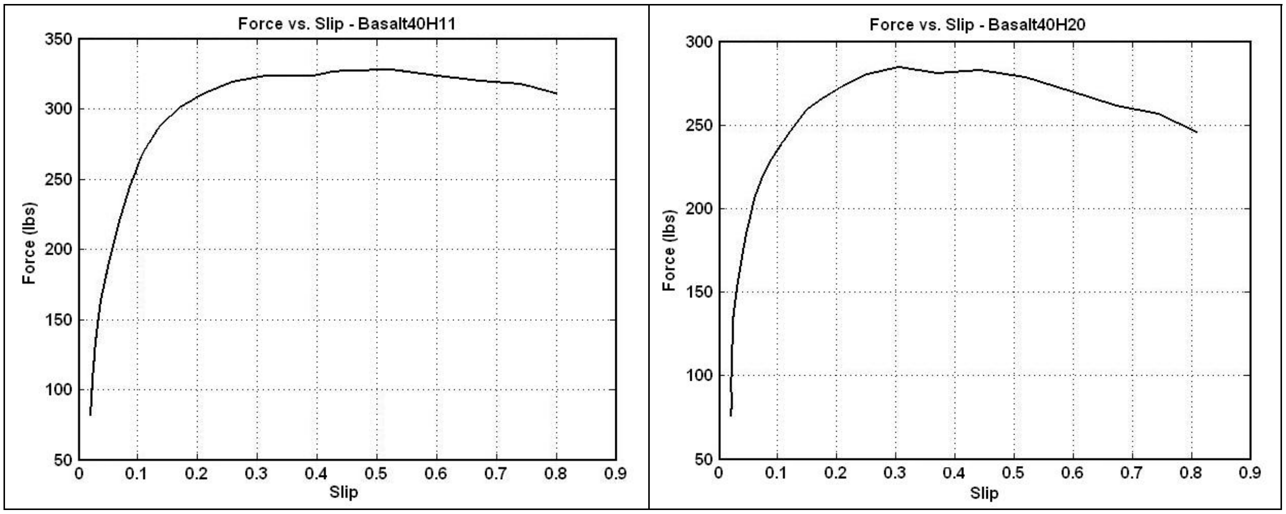

Figure 4.8 Examples of Force vs. Slip on Basalt

The above two curves demonstrate why ABS could only outperform the quickest 4-wheels-locked skid deceleration 3 out of 10 times on basalt. The adhesion utilization of the fully locked wheel in the left graph is approximately 90 percent, while the right side is around 80 percent. These graphs confirm the experimenters' opinion that stopping performance improved when more wheels were locked up. They also show that force vs. slip curves are not similar. Typical wet Jennite and wetted concrete curves can be seen in the next figure.

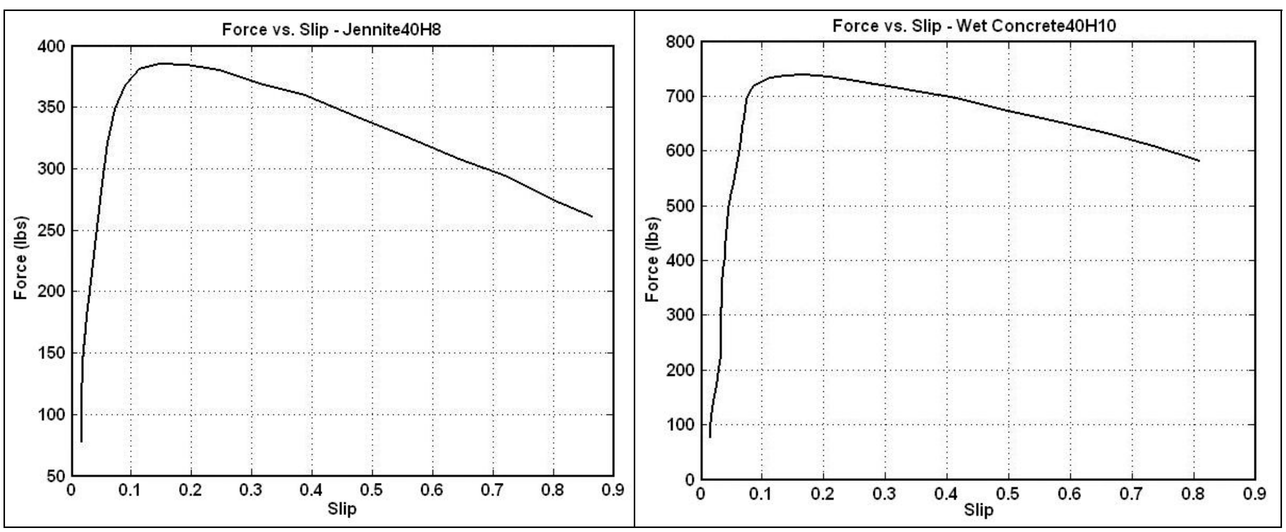

Figure 4.9 Examples of Force vs. Slip on Wet Jennite and Wet Concrete

The plotted Jennite data on the left indicates that this would not be the surface of choice for a 4-wheels-locked skid type of test because the sliding force would be around 50 percent the peak force, or approximately 50 adhesion utilization. For Jennite, it is likely that the best non-locked deceleration rate would be superior to the best 4-wheels-locked skid deceleration rate, but this would need to be confirmed. Wetted concrete, on the right, shows a more conventionally shaped peak-to-slide relationship. An examination of the skid data compiled using the traction trailer and Corolla tire is summarized in the following table.

Table 4.14 Comparison of Low Coefficient of Friction Surfaces

Surface	Basalt	Jennite	Wet Concrete
Average Peak	30.7	42.6	82.2
Peak St. Dev.	2.5	2.1	3.4
Average Skid	25.0	19.4	55.3
Skid St. Dev.	1.4	1.2	2.3
Avg. Peak to Slide Ratio	1.231	2.202	1.488
Peak to Slide Ratio St. Dev.	0.097	0.097	0.072
Adhesion Utilization of Locked Skid	0.812	0.454	0.672

Looking just at PFC, the test tires experienced the least amount of friction from the basalt tiles. The Jennite had a higher average PFC than the basalt, but it had the lowest average sliding friction coefficient. This corresponded to the highest average peak-to-slide ratio of the three low-coefficient surfaces. Inverting this highest ratio will yield an approximate adhesion utilization value of less than 50 percent. Doing the same for the basalt tiles yields an approximate adhesion utilization value greater than 80 percent, with wetted concrete utilizing approximately two-thirds of the available adhesion. Based on this data, if the proposed minimum ABS deceleration rate is to be at least equal to the best deceleration rate of a 4-wheel-locked skid, then the desired level of adhesion utilization will determine which testing surface to select.

For this reason, it appears that wetted concrete would be the more realistic surface for such a test but for the potential wear the tires would most likely sustain at this level of friction. A viable alternative would be to multiply the sliding deceleration by a normalization factor, giving the surfaces approximately the same level of stringency. (These normalization factors are derived from the "Adhesion Utilization of Locked Skid" data shown above.) Multiplying the deceleration of the basalt tests by 0.85 and those from the Jennite by 1.5 should place the actual ABS adhesion utilization in the 65 – 70 percent adhesion utilization range. No matter what method is ultimately chosen, a low coefficient test should be an established part of any ABS performance rule.

4.1.6. FMVSS 135 Adhesion Utilization Method – Stopping Distance

To provide an additional perspective on adhesion utilization, a moment will be taken here to translate stopping distance requirements (found in FMVSS 135 [10]) into adhesion utilization percentages. Equations are provided for calculating the maximum allowable stopping distance on asphalt, based on test speed and the type of test. If one assumes a constant rate of deceleration in a straight line, an equivalent "g" force can be associated with the given stopping distance. The following table provides this data.

Table 4.15 Converting FMVSS Stopping Distances Into Percent Adhesion Utilization

FMVSS 135 Test	Maximum Test Speed	Stopping Distance	Average "g"	Adhesion Utilization for 0.9 PFC Average	Adhesion Utilization for 1.0 PFC Average
Cold Effectiveness	100 km/h	70 meters	0.562	62.4	56.2
High Speed	160 km/h	187.5 meters	0.537	59.7	53.7
Engine Off	100 km/h	70 meters	0.562	62.4	56.2
ABS Failed	100 km/h	85 meters	0.463	51.4	46.3

The test surfaces specified for the 135 tests above are all required to have a PFC of at least 0.9. Section 6.2.1 provides that surface friction is to be measured using the ASTM E1337-90 method. Without revisiting the entire tire-PFC analysis, the reader is reminded that the SRTT is a crude tool for predicting brake performance. It is well documented that PFC increases with decreasing vehicle speed, regardless of the type of tire used. Examination of the individual OEM tire data reveals that the differences between 64.4 km/h (40 mph) and 20 km/h (lower end of ECE snub) ranged from 0.043 to 0.083 PFC. The closest OEM tire to 0.9 PFC at 64.4 km/h was 0.92, which increased to almost 0.99 at 20 km/h. It is possible that the average PFC from 100 km/h to zero would be around 0.95 for this tire. The point being made here is that the adhesion utilization columns in the above table contain approximations of the overall PFC, simply because there is no way to know for certain the total amount of available adhesion. The two numbers (0.9 and 1.0) are representative of the PFC numbers for the tires and test conditions used in this study, and were arbitrarily selected. Dividing the "g" column by the hypothetical "average PFC" generates the corresponding adhesion utilization numbers; multiplying them by 100 converts them to percent adhesion utilized.

If these approximations are agreeable, then one can say that the FMVSS 135 stopping distances equate to about 55 percent adhesion utilized. That would mean that the ECE's position that ABS must use 75 percent of the available adhesion is significantly more stringent, but easily achievable (on asphalt) as the data in Table 4.11 shows. All of the test vehicles seem capable of making a 0.8-g stop or better on asphalt, regardless of loading condition. However, this data cannot speak for the entire class of light vehicles since the test vehicles weighed less than 2500 kg GVWR.

In and of itself, the level of adhesion utilization is not the issue when considering the ECE procedures. It is the method of evaluating brake performance using adhesion utilization, which carries with it the burden of trying to find the total available adhesion first. The most practical and simple solution to replace the ECE's high-coefficient, ABS adhesion utilization method is to subject all light vehicles to the same stopping distance requirements as currently set forth in the 135 standard.

4.1.7. Some Closing Thoughts on Adhesion Utilization

The earlier conclusion that the SRTT and traction trailer are not recommended to serve as a surrogate to K_M, or the above statement that it is a crude tool for predicting brake performance, should not be construed to mean that it does not produce useful data, just that this data has a very specific application. Standards for measurement, such as a 1-kg mass or a ruler, are used to compare different things to each other. The Standard Radial Test Tire (SRTT) is no different; it is used to compare the frictional properties of multiple different surfaces to one another, and/or to compare the same surface to itself as it changes (over time, to moisture, with changes in temperature, etc.). ASTM explains the limited purview of the E1337 test method in the paragraph on bias (Section 14.2 of that standard), which is in agreement with this standpoint.

As far as vehicle braking is concerned, the standard for measurement is the test surface itself. If multiple vehicles are to be compared to one another, using either stopping distance or deceleration rate, then only one test surface can be used if the comparison is to remain impartial, and testing *must* be conducted under similar environmental conditions so that frictional properties do not change. Both stopping distance and deceleration rate are extremely sensitive to changes in frictional properties. Consider the increase in stopping distance that is common to wetted pavements as evidence of this.

Testing on two asphalt surfaces at separate test facilities is another issue worth discussing. If the same test vehicle is tested on both surfaces, one yielding a PFC of 0.90 with the vehicle's tires and the other 1.00, expect approximately a 10 percent decrease in stopping distance and a 10 percent increase in deceleration rate when testing on the 1.00 surface (surface-tire combination to be accurate), assuming the vehicle's brake system can develop sufficient brake torque to capitalize on the improvement in available friction.

A moment should be taken here to explicitly distinguish between PFC and K_M and what impact each has on brake testing. The peak friction coefficient (PFC), as defined in FMVSS 135 S4, is a theoretical number that is described in the following equation:

Equation 4.3 Textbook Definition of Peak Coefficient of Friction

$$PFC = \frac{Maximum\ \ Braking\ \ Force}{Normal\ \ Force}$$

However, the term PFC as it is used in the literature (see FMVSS 135 S6.2.1) is actually an average value that comes from the ASTM E1337 test method. A single tire on one surface is used to individually collect a minimum of 8 "PFC" estimates that are then used to develop this mean, as well as a standard deviation (Section 12.3 of E1337). A standard deviation recognizes that there is a distribution about that mean. The theoretical peak would be nearer the maximum value obtained from these 8 measurements and could be described as such. The theoretical peak might also be described as being greater than the 3rd standard deviation above the mean. Whatever the definition, better estimates of total available adhesion would be available if a more precise definition of PFC was used, and collected at several different speeds and tire loads (equal to those used during testing).

It is worth emphasizing that the theoretical PFC does not necessarily relate well to real world vehicle braking. Theoretical PFC occurs when two perfectly uniform surfaces are in contact with and moving in opposite directions from one another at a constant speed. Tire to pavement contact is anything but uniform. The tire's contact patch during braking is in a continuous state of deformation. This deformation is the source of frictional force, with frictional force increasing from the front to the rear of the contact patch. Vertical load is not uniformly distributed across the contact patch either, so all friction measurements that come from a traction trailer are the summation of forces exerted by the contact patch divided by the overall vertical load.

The term K_M, as used in the ECE, is an attempt to describe the vehicle's response to the test surface. K_M was interpreted at the onset of this report as the effective peak coefficient of adhesion for the vehicle. K_M can also be thought of as the average of the 4 individual tire-surface friction coefficients, as each of them is averaged across the speed range from 40-20 km/h. As has been shown in this report, K_M is not necessarily equal to the total available adhesion, although it was designed for that purpose.

Lastly, an important safety consideration to keep in mind is that prior to assessing a vehicle's braking performance, one qualifying condition must be met: there must be enough brake torque to be able to lock all four wheels at once on the test surface (or cycle ABS at all four wheels). Any brake system incapable of reaching the optimum slip percent on all the wheels, at some realistic level of pedal force, should be rejected. This may seem peculiar but it really is the focal point of why braking performance is measured, namely safety. If a vehicle's brake system can lock all four wheels simultaneously, then at least that system is capable of using all of the available adhesion (whatever that number may be).

To qualify this position, it should be added that a minimum deceleration rate be achievable if the wheels do not lock or cycle (recognizing that heavily loaded vehicles are less likely to approach peak frictional force on the higher PFC's common to dry asphalt or concrete). This should be the case only for an adhesion utilization test methodology, since stopping distance contains an intrinsic minimum deceleration rate.

Annex 6 of the ECE sidesteps the issue of insufficient brake torque in Section 5.2.5 ("omit laden tests if 500N doesn't produce cycling" and "omit unladen test if 1000N doesn't produce cycling"). By not including a minimum deceleration rate for the vehicle, this compliance test for ABS adhesion utilization could be met by lowering the gain of the system; if the wheels never approach peak slip, there is no opportunity for the ABS to cycle and the vehicle would pass ipso facto (using the ECE method).

For the lightly loaded, high coefficient of adhesion surface test, the ECE's approach of doubling pedal force in order to obtain ABS cycling is going in a direction that is not beneficial. It makes sense if trying to get the system to cycle is the only goal, but it glosses over the fact that there isn't enough torque to use what adhesion is available and it ignores human factors issues. Just because a brake system is capable of generating high-g stops, it is a marginal feature if a subset of the driving population cannot deliver the necessary pedal force to reach that optimum performance level. Research has shown that the 5^{th} percentile female is capable of delivering approximately 445 N with the right foot [6]. The amount of pedal travel displaced at 445 N should also take into consideration the maximum range of extension for the 5^{th} percentile female's leg. Earlier brake research sponsored by NHTSA, which investigated driver response to brake gain, identified an optimized range of pedal force versus deceleration values [7]. The line of minimum gain – maximum pedal force data places 445 N at almost a 1.0-g deceleration rate.

Now it is not realistic to expect all vehicles to deliver 1.0 g in a timed brake snub, and even less realistic to suggest that drivers would be comfortable operating a vehicle at that extreme. Nevertheless, any braking regulation that places a minimum level of performance on a vehicle's brakes (be it stopping distance, deceleration rate, or adhesion utilization) should include a specification that brake pedal forces not exceed a set maximum, such as 445 N, or the 500 N limit that is used in the FMVSS 135 stopping distance tests for non-ABS equipped vehicles.

4.2. ABS Functionality Tests - Task 2

Under the National Traffic and Motor Vehicle Safety Act, manufacturers conduct their own testing or analysis and must certify that their vehicles comply with applicable safety standards. The Safety Act requires that safety standards be objective in order that a manufacturer can self-certify that each model of vehicle is in compliance.

The ECE's ABS functionality tests have gaps in the required objectivity to complete compliance testing, primarily because they were written as type-approval rules. These tests are straight-line stopping events designed to test vehicle stability over sudden changes in the level of surface friction, adhesion utilization under these same conditions, and any trade-offs that exist between stability and adhesion utilization. The tests, as described in Sections 2.2 and 3.3 of this report, can be found in Sections 5.3.1 - 5.3.4 of Annex 6 (See Appendix A of this report for complete details), with additional performance criteria set forth in Sections 5.3.3 and 5.3.5 – 5.3.7.

The portions of the ECE ABS functionality tests that need rewording to satisfy objective compliance testing are underlined in the following selected provisions from Annex 6:

5.3.1. The wheels directly controlled by an anti-lock system must not lock when the full force is <u>suddenly</u> applied on the control device… "Suddenly" is used again in 5.3.4.

As discussed in Section 3.5 of this report, an ABS literature review prior to testing revealed that human subjects in a NHTSA study could reach "panic stop" application rates equal to 90 lbs. (400 N) of brake pedal pressure in 0.1 seconds [3]. Another study [8] assessed the initial pedal force application rate recorded during testing in order to place each stop into one of four classes. The "Class A" performance from this study was over 445 N (over 100 lbs.) at 0.1 seconds. In the current study, air ram ramp rates between 98-116 lbs. (436-516 N) per 0.1 seconds were observed, which is at the upper end of human performance.

5.3.3. When a vehicle passes from a low-adhesion surface (K_L) to a high-adhesion surface (K_H) where $K_H \geq 0.5$ and $K_H/K_L \geq 2$, with the full force applied on the control device, <u>the deceleration of the vehicle must rise to the appropriate high value within a reasonable time</u> and the vehicle must not deviate from its initial course.

During the design stage of this experiment, a proposed metric for evaluating ABS response was 86.5 percent of the average maximum deceleration, which represented two time constants for the steady state output of a dynamic first order system. However, this metric is unnecessarily burdensome because finding a maximum deceleration is quite similar to using the vehicle to find PFC; the large amount of variability decreases confidence in the estimate. Instead, consider the time it takes for the brake line pressure to rebuild, or to rebuild and dump again, after transitioning to the higher coefficient surface. Such a method would guarantee that the braking force has reached the peak frictional force and that the wheel is teetering on lockup. As explained in this report, that would be at or near the vehicle's peak ability to decelerate (using ABS) and the method is very easy to determine graphically. It is only a matter of measuring the time it takes for the pressure to reach its first peak from transition, or from transition to trough, as Figure 4.10 shows.

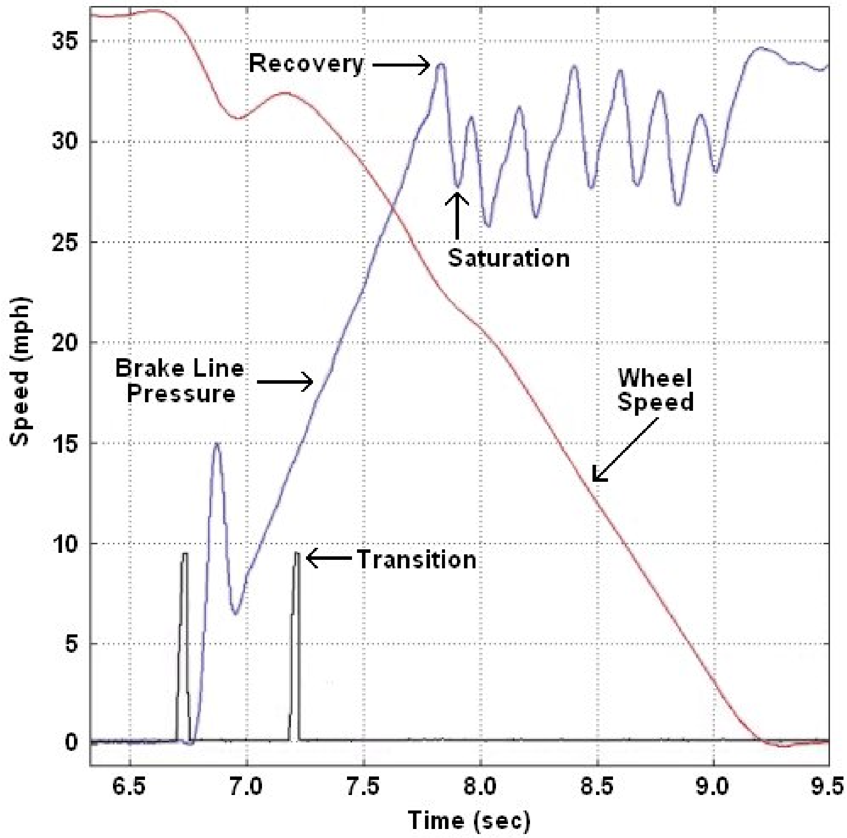

Figure 4.10 Wheel Speed and Brake Line Pressure During Low-to-High Coefficient Test

There is an assumption being made here that the maximum recommended pedal force of 500 N would produce ABS cycling on the higher coefficient of friction surface. Since water used on the lower friction surface wetted the adjacent high coefficient surface, ABS continued to cycle on each of the test vehicles until they came to a complete stop.

5.3.6. However, in the tests provided in paragraphs 5.3.1., 5.3.2., 5.3.3., 5.3.4. and 5.3.5. of this annex, brief periods of wheel-locking shall be allowed. Furthermore, wheel-locking is permitted when the vehicle speed is less than 15 km/h; likewise, locking of indirectly controlled wheels is permitted at any speed, but stability and steerability must not be affected and the vehicle must not exceed a yaw angle of 15° or deviate from a 3.5 m wide lane;

In an attempt to define the word "brief", the proposed metric of 0.10 seconds was examined in the current study. The spirit of why wheel lock should be as short as possible is to reduce yawing forces and thereby enhance vehicle stability. Furthermore, 0.10 seconds is consistent with the FMVSS 135 passenger car brake system regulations, where it specifies no wheel lockup for more than 0.10 seconds at speeds greater than 15 km/h (9.3 mph). The current research demonstrates that incidents of wheel lockup are highly dependent on speed, as the next figure helps to illustrate.

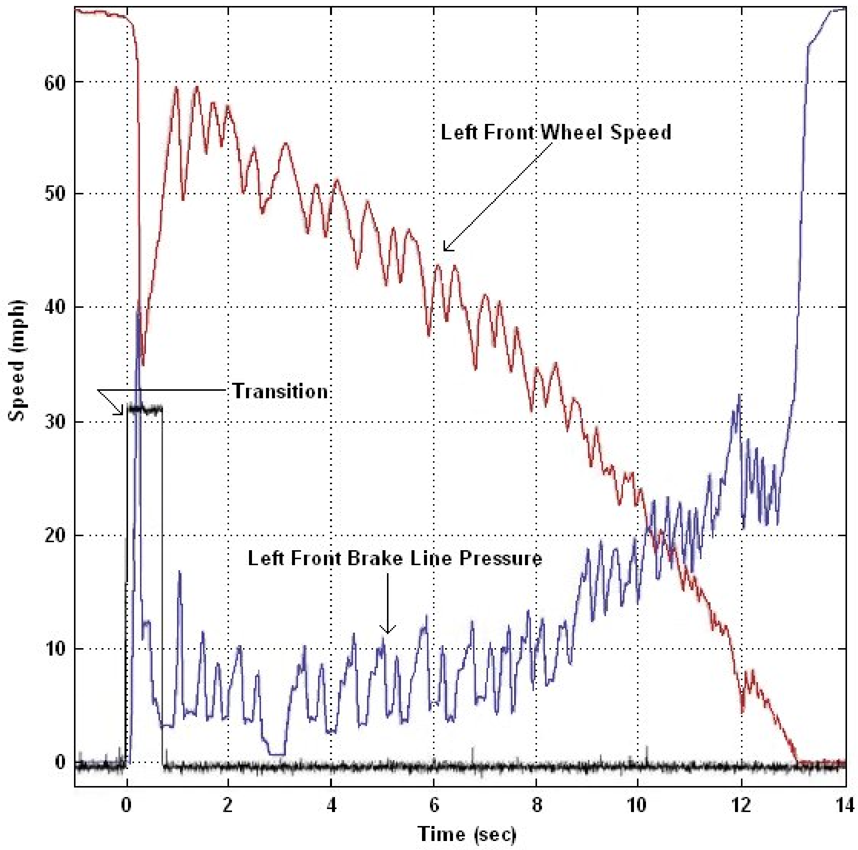

Figure 4.11 Plot of Wheel Speed and Brake Line Pressure

This data plot from one of the test vehicles shows the left front wheel speed (upper line) and left front brake line pressure (middle line) during a stop where the coefficient of friction was low. To register an occurrence of wheel lockup, the wheel speed has to go to 0 mph, but in the example above, the wheel speed drops from an initial speed of 65 mph down to approximately 35 mph before enough brake line pressure is released to allow the wheel to resume rolling.

What this graph basically shows is that the faster the vehicle's wheels are spinning, the more time ABS has to respond and avoid measurable wheel lockup. This drop in wheel speed is less severe when testing is done on a higher coefficient of friction, since the wheel decelerates slower and recovers quicker (due to the higher forces placed on the tire). The point being made here is that recording instances of wheel lockup on tests 5.3.1 and 5.3.2 at the recommended high speed of 120 km/h (~75 mph) will not produce any useful information and place the driver and vehicle at unnecessary risk, especially for the low coefficient of friction condition because of hydroplaning (shown in the following figure). Should verification that ABS modulates brake line pressure at higher vehicle speeds be preferred, consideration should be given to reducing the test speed or using a hardware-in-the-loop simulation.

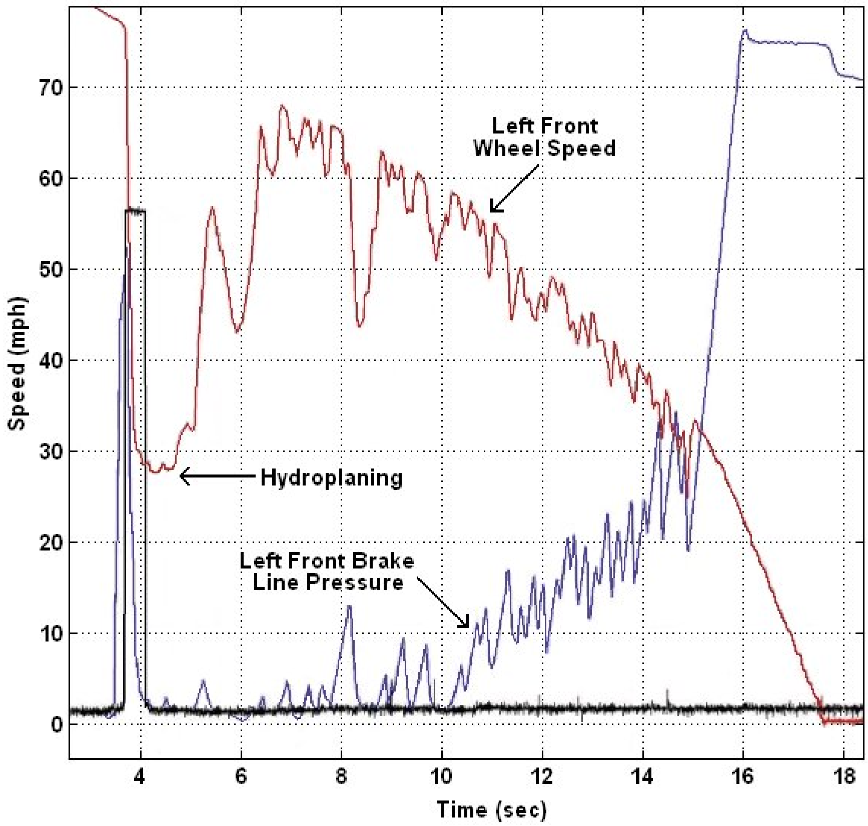

Figure 4.12 Plot Illustrating Hydroplaning During Low Coefficient Test Condition

This data plot is similar to the previous one, again showing the left front wheel speed (upper line) and left front brake line pressure (middle line). This braking event was conducted at the high speed, low coefficient of friction treatment combination required by the ECE regulation. The arrow points to a large 50 mph drop in wheel speed where the hydroplaning takes place, evident because the wheel speed did not recover for more than a second after the brake line pressure went to zero. Also noteworthy is the sharp increase in pressure after 15 seconds, due to the fact that the test vehicle ran off the end of the 1000-foot long basalt tiles and onto the emergency run-off asphalt.

Further comments to 5.3.6 relate to the next underlined phrase, "stability and steerability." The phraseology should reflect that none of the tests should cause instability above 15 km/h, including those that test ABS stopping performance. Instability is already objectively defined as exceeding "a yaw angle of 15 degrees" and deviating "from a 3.5 m wide lane." In addition, "steerability" appears to be redundant since minimizing instances of wheel lockup would insure wheel rotation, thus preserving a portion of the tire's lateral force, which maintains "steerability."

Despite these noted ambiguities, the functionality tests provide a solid foundation for testing ABS. The tests are described next along with the results and recommended changes to one of the procedures.

The test found in Section 5.3.1 uses a sudden brake application to verify that wheel lock does not occur on the high- and low-coefficient surfaces, at two speeds and two loading conditions. For this type of test, all four wheels of the vehicle are on the same coefficient surface.

Table 4.16 Results from Test 5.3.1 of Annex 6

	Surface	Loading	56 mph High Speed	25 mph Low Speed	Low Speed Lock Duration (in seconds)		
			lockups/tests	lockups/tests	Average	Min	Max
Toyota Corolla	Jennite	Light	0/2	1/3	0.015	0.015	0.015
	Jennite	Heavy	0/3	1/4	0.025	0.025	0.025
	Asphalt	Light	0/5	0/4	0	0	0
	Asphalt	Heavy	0/3	0/4	0	0	0
Honda CRV	Jennite	Light	0/4	1/2	0.035	0.035	0.035
	Jennite	Heavy	0/5	3/3	0.042	0.015	0.075
	Asphalt	Light	0/1	2/2	0.035	0.025	0.045
	Asphalt	Heavy	0/5	4/5	0.024	0.005	0.045
Buick LeSabre	Jennite	Light	0/5	N/A	N/A	N/A	N/A
	Jennite	Heavy	0/7	4/7	0.016	0.01	0.03
	Asphalt	Light	N/A	0/4	0	0	0
	Asphalt	Heavy	0/5	0/5	0	0	0
Toyota Sienna	Jennite	Light	0/3	2/3	0.05	0.03	0.07
	Jennite	Heavy	N/A	N/A	N/A	N/A	N/A
	Asphalt	Light	0/4	0/3	0	0	0
	Asphalt	Heavy	N/A	N/A	N/A	N/A	N/A
GMC Sonoma	Jennite	Light	0/5	N/A	N/A	N/A	N/A
	Jennite	Heavy	N/A	N/A	N/A	N/A	N/A
	Asphalt	Light	0/3	2/3	0.03	0.025	0.035
	Asphalt	Heavy	0/4	3/4	0.033	0.03	0.04

Knowing that the layout of the Jennite test area would limit the maximum attainable test speed, preliminary testing was conducted to determine if any differences in occurrences of wheel lock were apparent between tests conducted at 120 km/h (~75 mph) and those done at 90 km/h (56 mph). Since no wheels locked in either case, the tests from Section 5.3.1 were conducted on the Jennite at the lower high speed of 90 km/h, which are the results seen above. Instances of wheel lock were recorded whenever any of the four wheel's speed channels registered less than 1 mph. The Sonoma's Jennite tests were dropped due to resurfacing. The Sienna's heavy tests on asphalt where dropped per Section 5.2.5 (insufficient brake torque at 500 N), with the heavy Jennite being inadvertently dropped when this rule was overextended.

As expected, there were no instances of wheel lock recorded for the high-speed test. There were several recorded wheel lockups at the lower test speed, none of which were longer than the 0.10-second time limit previously mentioned. In the case of the Sonoma, the instances of wheel lock were not the rear wheels, which were indirectly controlled and are allowed to lock any time per the ECE regulation. All the other vehicles had four directly controlled wheels.

The second functional test, found in Section 5.3.2, is the high-to-low coefficient transition, where the use of a sudden brake application again examined instances of wheel lock as the vehicle passed onto a slipperier surface (Jennite) while braking. This type of test is conducted at two speeds and two loading conditions.

Table 4.17 Results from Test 5.3.2 of Annex 6

			56 mph High Speed	High Speed Average Lock (in seconds)	25 mph Low Speed	Low Speed Lock Duration (in seconds)		
			lock/tests		lock/tests	Avg	Min	Max
Toyota Corolla	Jennite	Light	0/3	–	1/1	0.085	0.085	0.085
	Jennite	Heavy	0/5	–	7/7	0.147	0.13	0.18
Honda CRV	Jennite	Light	0/6	–	5/5	0.043	0.005	0.085
	Jennite	Heavy	0/5	–	3/3	0.063	0.005	0.13
Buick LeSabre	Jennite	Light	5/7	0.042	7/8	0.037	0.005	0.055
	Jennite	Heavy	0/6	–	6/6	0.036	0.03	0.06
Toyota Sienna	Jennite	Light	0/2	–	6/7	0.079	0.03	0.16
	Jennite	Heavy	N/A	N/A	N/A	N/A	N/A	N/A
GMC Sonoma	Jennite	Light	2/7	0.078	6/6	0.128	0.11	0.145
	Jennite	Heavy	N/A	N/A	N/A	N/A	N/A	N/A

The high-speed tests of Section 5.3.2 were conducted at the lower 90 km/h (56 mph) velocity. The criteria for wheel lockup remained the same as the previous test, as did the reasons for not collecting data for the heavy Sienna and heavy Sonoma conditions.

As with the previous results, occurrences of low-speed lockups far outnumbered the high-speed ones. In fact, nearly all of the low-speed tests had some amount of lockup. This marked increase in the number and frequency of wheel lockups relates directly to the amount of brake line pressure while on the Jennite (nominal 0.4-0.5 PFC). The tests of 5.3.1 were sudden brake applications when the vehicle had all four wheels on Jennite, so the pressure was building when the ABS took over. For the high-to-low transition here in 5.3.2, the pressure was at its maximum for the higher coefficient of friction asphalt (nominal 0.85 slightly wetted to 1.00 dry) before crossing onto the lower coefficient Jennite. The ABS assumed control (at this higher pressure) when it recognized a decrease in the coefficient of friction and dumped brake line pressure in response.

The distinct increase in lockups under these conditions is not cause for concern. Vehicles often brake over transient low PFC's, such as bumps or painted lines, during real-world driving. In situations such as this, it is important that pressure not be inadvertently dumped, which would mean giving up valuable stopping distance. Graphical analysis of ABS stops consistently showed that ABS reacts after wheel speed drops. It is not unreasonable that ABS be given time to verify that the coefficient of friction has definitely decreased and not just encountered a momentary low. Even with these considerations only two out of eight vehicle treatment combinations had averages exceeding the 0.10-second criterion. For these reasons, caution is given here regarding any attempt to reduce the occurrence of lockup, through regulation, under the conditions of this particular test.

The third test, found in section 5.3.3, is the low-to-high coefficient transition and is meant to ensure that the vehicle's braking rate increases as traction improves. A sudden brake application while all four wheels of the vehicle are still on the Jennite surface initiates ABS cycling. This test is conducted at two loading conditions, while the speed is such that vehicle is traveling 50 km/h as it passes onto the asphalt surface.

Table 4.18 Results from Test 5.3.3 of Annex 6

Vehicle (Load)	Pressure Recovery Time (sec)	Pressure Saturation Time (sec)	Vehicle (Load)	Pressure Recovery Time (sec)	Pressure Saturation Time (sec)
CRV (Light)	0.285	0.345	CRV (Heavy)	0.405	0.465
CRV (Light)	0.37	0.44	CRV (Heavy)	0.18	0.24
CRV (Light)	0.67	0.745	CRV (Heavy)	0.24	0.29
CRV (Light)	0.865	0.925	CRV (Heavy)	0.28	0.355
Corolla (Light)	0.63	0.705	Corolla (Heavy)	0.795	0.875
Corolla (Light)	0.6	0.675	Corolla (Heavy)	0.74	0.81
Corolla (Light)	0.815	0.89	Corolla (Heavy)	0.875	0.95
Corolla (Light)	0.62	0.695	Corolla (Heavy)	0.96	1.03
			Corolla (Heavy)	0.745	0.82
LeSabre (Light)	0.195	0.275	LeSabre (Heavy)	0.59	0.665
LeSabre (Light)	0.095	0.17	LeSabre (Heavy)	0.55	0.62
LeSabre (Light)	0.225	0.31	LeSabre (Heavy)	0.67	0.735
			LeSabre (Heavy)	0.565	0.64
Sienna (Light)	0.79	0.865			
Sienna (Light)	1.11	1.22			
Sienna (Light)	1.28	1.36			
Sienna (Light)	1.25	1.34			
Sonoma (Light)	0.57	0.74			
Sonoma (Light)	0.47	0.635			
Sonoma (Light)	0.495	0.61			
Sonoma (Light)	0.42	0.515			
Sonoma (Light)	0.505	0.665			
Sonoma (Light)	0.555	0.65			
Sonoma (Light)	0.425	0.58			
Sonoma (Light)	0.385	0.47			

The data are separated into vehicle-by-load treatment combinations and sorted according to test number (not shown). The lightly loaded CRV was the only condition that demonstrated consistently longer pressure recovery times as testing progressed. The most probable explanation is that water from the Jennite was finding its way onto the asphalt and thus lowering the friction coefficient. The "Pressure Recovery Time" and "Pressure Saturation Time" columns refer to the time it takes for the brake line pressure to rebuild (pressure recovery) and to rebuild and dump again (pressure saturation), after transitioning to the higher coefficient surface. These points are depicted in Figure 4.10 and labeled accordingly. The pressure data used were selected exclusively from the front axle since it is the front axle that provides the majority of a two-axle light vehicle's stopping ability. Left- to right-side differences were generally small. The heavily loaded Sienna and Sonoma data were not collected, as previously mentioned.

Overall, the data show that 4 of the 5 vehicles could reach the limits of friction on the high coefficient surface in less than 1 second, regardless of the loading condition. This assessment is based on the second column, the "Pressure Saturation Time" point. This data was selected because it is the longer of the two time intervals and leaves little doubt that ABS is fully managing slip at that wheel. The fourth run of the heavily loaded Corolla had a time of 1.03 seconds, and 3 of the 4 lightly loaded Sienna runs were over the 1-second mark. The Sienna's ABS was sluggish when compared to the other systems, but each of these vehicle's decelerations could be described as having reached "an appropriate high value within a reasonable time".

Some of the variability within treatment condition can be attributed to what ABS was doing when the vehicle transitioned to the asphalt surface. Basically, times will be slightly longer when ABS is dumping pressure at the transition as compared to when it is building pressure. Differences between vehicles are not necessarily a direct comparison of the ABS's ability because of the many other factors that influence brake performance (vehicle mass, tire size and inflation pressure, engine vacuum, pedal pressure, etc.). Despite these differences, a minimum level of performance must be set in order to be objective. Towards that end, one second appears to be an appropriate value for the time it takes ABS to rebuild and dump pressure, thus resuming full slip management on the high coefficient surface.

The final test found in Annex 6, Section 5.3.4, is often referred to as the split-coefficient or split-mu test because one half of the vehicle experiences a high coefficient of friction while the other side has a lower coefficient. This test replicates the situation where a car has partially departed the road while the driver brings it to a stop. The split-coefficient test is one of the few tests available that simultaneously evaluates deceleration rate and vehicle stability. This is important because vehicle stability comes at the expense of a vehicle's deceleration rate, regardless of whether the vehicle has ABS or not. The following figure depicts the split-coefficient test.

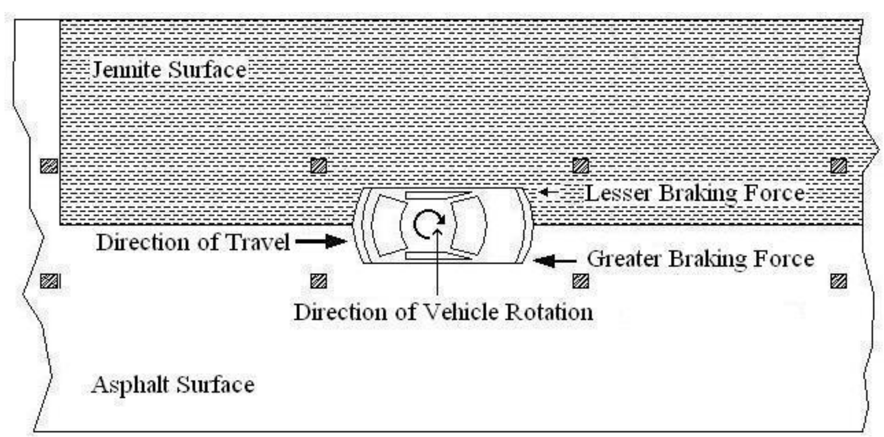

Figure 4.13 Simplification of Braking Forces and Resulting Moment of Vehicle

Vehicles stopping in a split-coefficient situation have a tendency to rotate, as shown in the figure. The greater the difference in the two coefficients of friction, the greater the moment about the vehicle's center of gravity is, assuming the brakes are operating at their respective peaks.

The ECE's split-coefficient test uses a sudden brake application at 50 km/h to verify that the directly controlled wheels do not lock, with the same qualifications as those in Sections 5.3.1 and 5.3.2. Section 5.3.5 requires that laden vehicles decelerate at the rate provided in Appendix 3 to Annex 6. Section 5.3.7 requires that handwheel input be less than 120 degrees in the first 2 seconds and less than 240 degrees overall to maintain the vehicle in the lane. Each of these 3 requirements is addressed in order below.

The results of this test revealed no instances of wheel lockup, due to two previously mentioned factors. The first factor was observed in the tests of 5.3.1, where the pressure was building when ABS assumed slip management. The other factor has to do with the slightly higher test speed of 50 km/h (31 mph). The 25 mph tests in 5.3.1 had several instances of wheel lockup, but all of them except for one were under 0.05 seconds in duration. The 6 mph increase in test speed provided the extra speed "cushion" needed to eliminate wheel lockup. These results would suggest that all 5 vehicles passed this condition of the split-coefficient test.

Analysis of the deceleration requirements of Section 5.3.5 is the most intricate one for the split-coefficient test. It is defined in the rule as:

Equation 4.4 Minimum Deceleraton Rate as Defined by the ECE

$$Z_{MALS} \geq 0.75\left(\frac{4K_L + K_H}{5}\right) \text{ and } Z_{MALS} \geq K_L$$

where Z_{MALS} is the vehicle's ABS-on deceleration rate for the split-coefficient test. K_L and K_H are the low and high coefficients of adhesion, respectively, measured using the ECE's single-axle method. What is most noticeable about this equation is its low deceleration requirement, expecting the vehicle to use just one-fifth of the available high-coefficient friction. This deceleration is further reduced by taking 75 percent of the calculated friction ratio, possibly following in line with the 75 percent adhesion utilization from earlier in the regulation. The rule also states that vehicle deceleration must at least meet the low coefficient of friction ($Z_{MALS} \geq K_L$).

The table on the next page contains the split-coefficient deceleration rates (converted into g units) as set forth in the ECE. These deceleration rates were calculated using the previous equation, using various combinations of low and high coefficient of friction surfaces. The first column contains the numbers for the "high" coefficient surface (K_H), ranging from 0.50 to 1.10. The remaining columns contain the numbers for the "low" coefficient surface (K_L), ranging from 0.20 to 0.55. Section 5.3.4 requires that the PFC of K_H must be at least twice that of K_L. It is because of this prerequisite that many of the cells have no deceleration rates in them. The lightly shaded cells are the deceleration rates that, when calculated using 75 percent of the "four-fifths the low/one-fifth the high" equation, produced deceleration rates below the "$Z_{MALS} \geq K_L$" minimum threshold. Therefore the correct deceleration rates for these cells would be K_L.

Table 4.19 Split-Coefficient Test Deceleration Rates (g) Using the ECE Equation

High Side (K_H)	Low Side (K_L)							
	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
0.50	0.195	0.225						
0.55	0.203	0.233						
0.60	0.210	0.240	0.270					
0.65	0.218	0.248	0.278					
0.70	0.225	0.255	0.285	0.315				
0.75	0.233	0.263	0.293	0.323				
0.80	0.240	0.270	0.300	0.330	0.360			
0.85	0.248	0.278	0.308	0.338	0.368			
0.90	0.255	0.285	0.315	0.345	0.375	0.405		
0.95	0.263	0.293	0.323	0.353	0.383	0.413		
1.00	0.270	0.300	0.330	0.360	0.390	0.420	0.450	
1.05	0.278	0.308	0.338	0.368	0.398	0.428	0.458	
1.10	0.285	0.315	0.345	0.375	0.405	0.435	0.465	0.495

So for obvious reasons, if vehicles were actually designed to meet just the minimum level of deceleration (the 29 cells shaded above), the two sides of the vehicle would decelerate equally and no yaw would ever be induced. There are 62 cells in the above table with decelerations (in g), 45 of which are within 10 percent of the K_L deceleration minimum. These levels of deceleration are extremely low. Improvement is obviously needed.

Fortunately, most vehicles provide a greater deceleration rate than the minimum. In the process of selecting an equation representative of contemporary ABS functionality, tables identical to the one above were developed (found in **Appendix E**). The first change was a modified version of the ECE that preserved the "four-fifths the low/one-fifth the high" calculation but removed the 0.75 from the equation. The next equation looked at a deceleration based on "two-thirds the low/one-third the high" without a 0.75 reduction. The remaining two equations also excluded the 0.75 reduction, using ratios based on "three-fifths the low/two-fifths the high" and "one-half the low/one-half the high". The average PFC's during testing for the Jennite and wetted asphalt were 0.35 and 0.85 respectively, using the ASTM E1337 method. The table below provides a range of decelerations (in g) based on these equations and PFC numbers.

Table 4.20 Existing and Alternative Split-Coefficient Decelerations (g)

Equation	ECE	Modified ECE	2/3L – 1/3H	3/5L – 2/5H	1/2L – 1/2H
Deceleration (g)	0.338	0.450	0.517	0.550	0.600

Now it has been demonstrated thus far that the friction characteristics of the SRTT are slightly lower than those of the test vehicle's tires. Therefore, the following table of test data will not definitively point out the best equation because the decelerations achieved by the vehicles are slightly quicker than decelerations that would have been achieved if the vehicle's tires produced PFC numbers similar to the SRTT. Also keep in mind that using traction trailer PFC numbers to estimate vehicle deceleration will have the same problems as those associated with using surrogate traction trailer number for estimating adhesion utilization. A new set of suggested test methodology and performance requirements for the split-coefficient test will follow the handwheel angle analysis.

Table 4.21 Vehicle Deceleration Rates for the Split-Coefficient Test

Vehicle	Load	Test #	Deceleration (g)	Speed Range (mph)
LeSabre	LLVW	2424	0.5855	50-0
		2427	0.5758	50-0
LeSabre	GVWR	2421	0.5797	50-0
		2419	0.5701	50-0
		2418	0.568	50-0
Sonoma	LLVW	2095	0.6122	50-0
		2098	0.5608	50-0
		2096	0.5563	50-0
		2097	0.4786	50-0
Sienna	LLVW	2224	0.5344	50-0
		2225	0.5231	50-0
		2222	0.5173	50-0
		2223	0.5036	50-0
		2221	0.4799	50-0
Corolla	GVWR	2285	0.5535	50-0
		2286	0.5409	50-0
		2282	0.536	50-0
		2283	0.5006	50-0
		2284	0.4923	50-0
CRV	LLVW	2017	0.5646	52-0
		2015	0.5351	49-0
		2016	0.4898	49-0
CRV	GVWR	2360	0.6732	45-0
		2365	0.5144	45-0
		2361	0.5096	45-0

The majority of the deceleration rates fall in between the modified ECE equation's deceleration and the 2/3L – 1/3H equation, supporting the position that a more aggressive deceleration rate can be mandated. However, when comparing the test data to the range of decelerations afforded by these modified equations, it is important to take into account that the measured decelerations only apply when the PFC's are 0.35 and 0.85. There is no way of knowing, short of further testing, how a broader range of differing PFC's will effect vehicle deceleration. All of the vehicle tests shown above easily pass the ECE's requirement for deceleration. Note that the CRV tests did not have clean speed ranges, which has a mild impact on the results.

The last requirement for Section 5.3.4, found in Section 5.3.7, examines the driver's handwheel input. A moment should be taken here to briefly explain the ABS build strategy during a split-coefficient stop. When brake pedal force is rapidly increased during a split-coefficient stop, brake line pressure at all wheels increases until the "low" side (of the front axle) begins to slip, at which point the ABS will intervene. The ABS then searches for a higher threshold on the "high" side, rapidly introducing yaw into the vehicle. The short delay before reaching maximum pressure on the high side gives the driver some reaction time to initiate corrective steering so that stability and lane position can be maintained. Examining a graph of handwheel angle and vehicle speed reveals several noteworthy items that need to be considered.

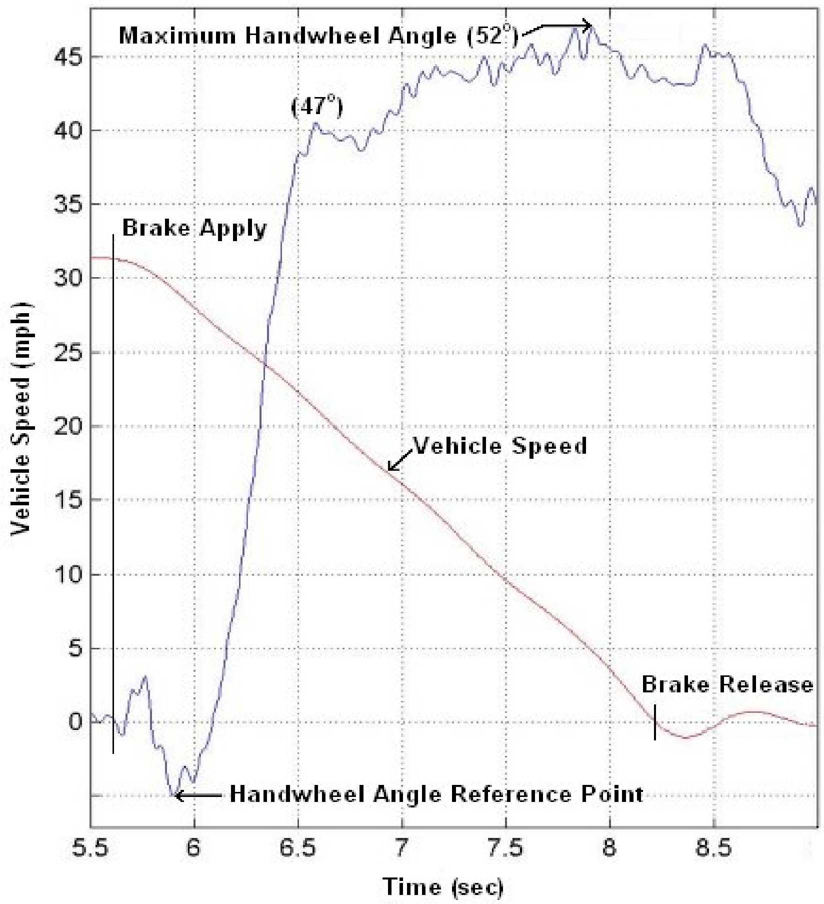

Figure 4.14 Handwheel Angle During a Split-Coefficient Stop

To begin with, each vehicle has a signature handwheel response to a split-coefficient stop, but there are common characteristics (based on the tested vehicles). From the point of brake application, the handwheel angle typically reaches a low value (in a direction opposite the counter steer), labeled above as the "Handwheel Angle Reference Point", in response to the initial yaw forces. The driver then begins to correct for vehicle yaw between 0.25 – 0.5 seconds after the brake is applied. What follows is a rapid linear change in handwheel angle (lasting approximately 1 second), followed by a gradual and smaller final change in handwheel angle. The amount of steering input needed to create these two slopes depends on the steering gain, suspension geometry, the yaw characteristics of the vehicle, the ABS "build" strategy, and the difference between the two PFC's that act through the tires. The first slope can be characterized as the vehicle's response to the ABS's pressure buildup on the high coefficient, while the second slope is in response to the increasing frictional forces attributable to decreasing vehicle speed.

Another item to consider is that power steering allows manufacturers to design vehicles with higher steering gains. Any one of the test vehicles exhibiting 240 degrees of overall steering input would almost certainly have been unstable (well in excess of 15 degrees of vehicle yaw) and potentially would have left a 3.5-meter wide lane. There is also the fact that the ECE regulations are written such that a split-coefficient test could be conducted with a low PFC of 0.2 and a high PFC of 1.10. Large differences in side-to-side forces would produce greater amounts of yaw, perhaps requiring 120 degrees of handwheel input within 2 seconds for a power assisted steering unit. In addition to the handwheel inputs, the length of time needed to complete a stop depends on the coefficients of friction. A vehicle attempting to stop on a split-coefficient surface with a low side of 0.55 PFC and a high of 1.10 (meeting the $K_H/K_L \geq 2$ requirement of Section 5.3.4) could do so in less than 2 seconds from 50 km/h (31 mph). How the ECE decided that "handwheel input be less than 120 degrees in the first 2 seconds and less than 240 degrees overall" is not clear. What is clear is that the current research cannot fairly assess whether these handwheel-angle/stability requirements are lenient or not because of the wide range of vehicles and surfaces under which testing can occur.

Table 4.22 Vehicle Handwheel Angle Results for the Split-Coefficient Test

Vehicle	Load	Test #	Max. Handwheel Angle (degrees)	Time to Max (sec)
LeSabre	Light	2424	66	1.14
		2425	54	1.55
		2426	35	1.99
		2427	48	1.32
LeSabre	Heavy	2418	33	1.46
		2419	46	1.42
		2420	42	1.22
		2421	71	3.93
Sienna	Light	2221	14	1.6
		2222	12	1.5
		2223	12	1.4
		2224	16	1.7
		2225	10	1.4
Sonoma	Light	2095	58	2.1
		2096	52	2.0
		2097	47	2.1
		2098	52	2.3

The table above contains the handwheel angle results from the current study. The Corolla and CRV, being the last two vehicles tested, were not instrumented due to time constraints and the observation that none of the five vehicles had approached 90 degrees of handwheel input for this test. The maximum handwheel angle was measured from the "Handwheel Angle Reference Point" (shown in Figure 4.11) to the maximum amount of handwheel displacement input prior to the vehicle stopping. The ECE does not define where this measurement should begin. Time is measured from the moment the brakes are applied to the point of maximum handwheel displacement input prior to the vehicle stopping. The most logical method for defining vehicle stability will limit the maximum vehicle yaw angle and place lane restrictions on each test, much like Section 5.3.6 describes. All of the test vehicles were observed to have minimal yaw angle response.

With this suggestion in mind, the final recommendations for the split-coefficient test emerge. Steerability should be assessed by monitoring instances of wheel lockup. In place of extensive testing of handwheel angles and numerous combinations of PFC's, vehicle stability can be quickly and easily verified by observing lane position (3.5 meters wide) and integrating yaw rate for total yaw angle (15 degrees).

Instead of using the traction trailer or the ECE's single-axle method to determine PFC, consider basing the split-coefficient deceleration on a ratio of two decelerations from that vehicle, one from each of the surfaces used in the split-coefficient test. For each surface, test each vehicle with all four wheels exposed to the same surface and ABS enabled. Collect 8-10 usable runs in the same speed range as the final split-coefficient test (50 km/h – 0), find the average deceleration for each run and then average these averages together to understand how quickly that vehicle tends to decelerate on each surface. From there, using an as-yet-to-be-determined equation, vehicle deceleration can be verified. Vehicles should be tested in both lightly loaded and heavily loaded conditions.

4.2.1. Supplemental Tests Conducted During this Experiment

To assess the range of performance improvements afforded by ABS, the study also examined the test vehicles in a number of different braking maneuvers, ones that emphasized events representative of real-world driving. Three tests were initially chosen, two transition tests and one brake-in-a-curve maneuver. A fourth test was investigated using vehicles from a different program and was based on the fishhook maneuver (for a full description see [9]). The details of the first three tests are given below.

The first transition test was conducted on TRC's Special Profile Road Lane H, which is a 1-inch deep by 4-inch wide metal channel set in concrete. It is situated such that both wheels of the same axle pass over it simultaneously. The brake apply point (SunX) was located 25 feet away from the first channel and entry speed varied by vehicle so that the vehicle would be traveling at 40 mph when it passed over the first channel. Pedal force was again provided by the air ram and set so that 500 N would be suddenly applied when the vehicle passed over the SunX plate.

The second transition test was conducted on TRC's Special Profile Road Lane K, which is an asphalt surface with an asphalt speed bump on it, approximately 3 inches high and 8 inches wide. The remaining test parameters are identical to the previous transition test. Each vehicle was subjected to these two tests in both the lightly loaded and heavily loaded conditions.

The third test, conducted on the Jennite surface, was a lane following exercise while braking in a curve. The curve itself had an inside radius of 50 feet and the lane was 15 feet wide. The entrance speed was 25 mph and 500 N of brake pedal force were applied as soon as all 4 tires were on the Jennite surface.

All four of the tests provided a slightly different look at ABS performance, but none of them provided data that was markedly superior to the ECE functionality tests already in use. The first transition test from Lane H failed to cause ABS to cycle on any of the vehicles. From a practical design standpoint, the second transition test was a combination of the tests in Section 5.3.2 and 5.3.3, the "high-to-low" coefficient test and the "low-to-high" pressure recovery test, respectively. In other words, it was a “high-low-high” test (one axle at a time). Speed bump data were difficult to interpret objectively, and the admonition given in the analysis of 5.3.2, about not attempting to strictly regulate instances of wheel lockup under these conditions, continues to hold. For this particular case, minimizing instances of wheel lockup over a momentary “low” coefficient will cause unnecessary pressure dumps and greatly increased stopping distances.

The Jennite curve was designed to create a brake event similar to a slippery interstate off-ramp. Although it sounded like a good idea and was innovative, it too had problems that kept it from producing meaningful and repeatable results. The primary offender was the surface itself. The idea was to get the ABS to cycle at a low speed to reduce the risk to the driver. Wet Jennite is a surface well suited for this, but surface conditioning is key and Jennite has a tendency to polish with use, which reduces the coefficient of friction. Now for the straight-line tests of the ECE, this was not an issue because the response of ABS to a low coefficient surface was all that was asked for. However, using the constant entrance speed of 25 mph going into a curve with dropping friction characteristics produced problematic lane following results. The curve itself was very slick to begin with, and as it polished up during repeated testing the ability of the vehicles to develop lateral acceleration dropped off significantly. Another problem with Jennite is that keeping the surface highly polished to reduce variability eventually has the opposite effect because the surface wears off and the asphalt underneath the Jennite gradually becomes exposed.

Testing on a wetted-asphalt turn would provide the low surface variability needed. However, testing at 25 mph would produce very short tests due to the higher coefficient of friction, and increasing test speed would also increase the risk of rollover for certain vehicles, with the ABS tending to cycle more on the inside half of the vehicle, an element similar to a split-coefficient test. Testing on the low coefficient basalt tiles was not practical since they are narrow and designed for straight-line testing.

Controlling driver input variability is another factor that would make this test difficult to use. The potential exists that a vehicle might pass or fail depending on who drove it. Another consideration unfavorable to testing brakes in a curve is the difficulty with making a test that is equally stringent. Vehicle factors that influence maneuverability, such as the wheelbase, track, center of gravity height, and suspension compliance, would complicate the brake analysis if braking and maneuvering are combined. Electronic stability control would also have a role in determining the outcome of such a test if it was equipped. Designing a test for consistent steering input and lateral acceleration adds another layer of complexity unrelated to braking and would likely involve the installation of outriggers to prevent rollover.

A brake-in-a-curve maneuver could be helpful in one situation: failed mode for an ABS with electronic brake force distribution (EBD). The control module manages front and rear bias with this type of ABS. If the computer were to fail, pressure might be equalized front to rear (depending on design), and a lightly loaded vehicle would almost certainly become unstable while braking in a curve because the rear wheels would lockup first. However, ABS failed mode bias can be checked while testing in a straight line using brake line pressure transducers at each wheel, so again there is no urgent need to test brakes in a curve for light vehicles.

The final maneuver, the fishhook, was originally designed to challenge ABS by causing the vehicle to roll back and forth and expose the tires to changing levels of frictional force, alternating side-to-side. On the dry asphalt, though, the vehicle usually came to a stop (from 45 mph) before the second handwheel input was completed. A split-coefficient test that alternated the high and low coefficient sides would challenge an ABS similarly while providing cleaner brake results by removing vehicle maneuverability factors. When one examines braking while maneuvering, it is important to remember that as long as the wheels continue rolling, some portion of the lateral force on the tire will be preserved. This is more than a non-ABS vehicle could safely and consistently provide during extreme braking and is the only benefit that should be considered in the final analysis. Both the brake-in-a-curve and the fishhook tests are ones better suited to testing stability control than brake compliance.

5.0 CONCLUSIONS

The ECE's ABS adhesion utilization test method has proven to be difficult to use and it produces questionable results. Adhesion utilization cannot be determined until the total amount of available adhesion is calculated, and this is difficult because it is an ideal quantity. Available adhesion is the sum of the peak braking forces acting on each tire, which changes continuously with the speed of the vehicle and tire load. PFC is specific to a tire-surface combination and varies significantly with surface temperature, tread depth, and other factors that occur when a vehicle is stopping. This is not to say that an estimate of adhesion utilization cannot be found; what it does say is that it is not very practical.

From a methodological standpoint, single-axle testing produces low deceleration values because of unrealistic load transfer and several other factors. Since deceleration is the basis for estimating the total amount of available adhesion, these inaccuracies show up in the resulting adhesion utilization numbers. There is no conceivable fix for the single-axle test method and an alternative method of determining ABS efficiency should be considered. Using the ASTM E1337 method as an alternate means for quantifying the total available adhesion has been examined; however, this method only produces PFC values for one particular speed, which is not the same as total available adhesion. This method is well suited for comparing two different surfaces to one another, or one surface to itself over time (wear), but its tire (SRTT), constant test velocity (40 mph), and weight (1033 lbs.) really have nothing to do with the friction experienced by tires on a decelerating vehicle. These factors combine to produce a low estimate of available adhesion, so it too may not be sufficiently accurate. Testing with both axles operational provides the best data, of these three methods, for determining ABS adhesion utilization. Two-axle testing will still produce inaccuracies, but these can be minimized if decelerations are collected past the point of first wheel lock for the ABS-off condition.

This leads to the practical issues involved with attempting to adopt the ECE adhesion utilization procedures. Even if adhesion utilization was easy to calculate and fairly accurate, suggesting that light vehicles use 75 percent of the available adhesion would mean decelerating on dry asphalt ("average" 1.00 PFC) at approximately 0.75 g. This rate, though plausible, is at least 25 percent more demanding than the decelerations required by some of the FMVSS 135 stopping distance equations (assuming constant deceleration) for vehicles not equipped with ABS.

The ABS adhesion utilization testing on basalt also produced questionable results. The tests performed in this study found that ABS stopping performance on low coefficient of friction surfaces was always superior to the non-ABS stop, made under identical conditions and without wheel lockup. This was expected since ABS can manage wheel slip at all four wheels independently, something a driver is incapable of doing. However, the amount of time spent finding the best non-ABS deceleration without wheel lockup proved burdensome. It is the authors' recommendation that a shorter approach be taken, perhaps that of comparing the peak ABS deceleration to the no-ABS deceleration where all four wheels are locked, which is the most probable outcome for drivers braking in an emergency on a surface where the nominal PFC is 0.25 (e.g., on ice).

For these and the many other reasons found in this report, the authors believe that adhesion utilization will not provide a sufficiently accurate estimate of the efficiency of ABS and should not be included in FMVSS 135 brake standard. If the goal is to ascertain that ABS does not adversely affect stopping distances, this report has set out two possible methods. The first of these was a comparison between the ABS-on and ABS-off decelerations, using the ABS-failed mode to estimate the foundation brakes' performance. This method will work on all types of surfaces, assuming that a vehicle's ABS-off mode has brake bias comparable to a non-ABS equipped vehicle. However, further testing is required to fully develop a range of expected and acceptable values for E, the ABS Effectiveness Factor.

The second method, by far the easiest, would be to subject ABS-equipped vehicles to braking distance standards similar to those already in FMVSS 135. If ABS can release brake line pressure and still bring the vehicle to a stable stop within the distance specified for non-ABS equipped vehicles on high-coefficient of friction surfaces, then there should not be any concern about its ability to utilize available adhesion. As noted earlier in this report, 75 percent adhesion utilization is probably attainable for all vehicles under 2500 kg GVWR on a high coefficient of friction surface (and should be attainable at 500 N pedal force or less). If stopping distance is the agreed upon compliance test method, it is recommended that consideration be given to improving the stopping distance requirements. The current test vehicles all weighed less than 2500 kg GVWR and were not challenged in any way by the existing requirements, with or without ABS. Another recommendation is that any high coefficient of friction testing be conducted within a range of surface temperatures, and not just ambient temperature.

The stopping distance recommendation given above could be complemented with a low-coefficient of friction test that compares the ABS deceleration rate with a four-wheel locked skid's deceleration rate, as previously mentioned. Additional testing would help in further understanding what method provides superior stops, and to develop a tolerance for ABS as necessary, since preserving maneuverability is a useful benefit. Using these methods in place of the "adhesion utilization" performance standards has the added benefit of being able to support newer methods of vehicle braking, such as electro-mechanical or regenerative, without modification. Maximum pedal force should not exceed 500 N for the stopping distance tests and the basalt skid test.

The ABS functionality tests contained in the ECE are suitable to the FMVSS 135 compliance tests with the addition of the following objective performance criteria. The term "suddenly" used in these tests should be defined as a brake pedal force application rate equal to or greater than 400 N in 0.1 seconds. The high initial speed for Sections 5.3.1 and 5.3.2, which reads $V = 0.8\ V_{max} \leq 120$ km/h, should be rewritten to just say $V = 90$ km/h. The low-to-high transition test of Section 5.3.3 should be rewritten to reflect a pressure recovery theme, such that one second after transitioning to the high coefficient of friction surface the ABS will have fully rebuilt brake line pressure and partially released it, indicating where the new peak deceleration was reached. The split-coefficient test found in Section 5.3.4 should be rewritten in accordance with the suggestions found at the end of Section 4.2 in this report, with the understanding that additional testing will be necessary before an equation for deceleration can be fairly established.

The final sections of the ECE functionality tests, 5.3.5-5.3.7, modify the previous four tests. Section 5.3.5 specifies a deceleration rate for laden vehicles on the split-coefficient surface. This should be rewritten to include all vehicles and at both loading conditions, with the deceleration rate yet to be determined as was just mentioned. Section 5.3.6, which modifies Sections 5.3.1-5.3.4, allows for brief periods of wheel lock, which should be defined as 0.1 seconds for all tests except the low speed (40 km/h/25 mph) test of Section 5.3.2, which should be more (perhaps 0.15-0.2 seconds). Section 5.3.6 also provides parameters for stability and steerability that should apply to all vehicles, regardless of the type of ABS used, and to all the tests. It should be reworded to only include "Vehicles must not exceed a yaw angle of 15 degrees or deviate from a 3.5 meter wide lane." Section 5.3.7 contains the maximum handwheel angle permitted for the split-coefficient test, which should be dropped as discussed earlier in the report. The last sentence in this section describes the manner in which a vehicle should be driven over the split-coefficient surface, and should be included with Section 5.3.4.

5.1. <u>Additional Comments</u>

One question that arose during testing was whether an ABS-disabling switch, which would be very useful on roads with a deformable surface, such as gravel or snow, should be permitted. However, a problem exists with getting drivers to restore ABS functionality so that it is available when needed. Two possible solutions are contemplated here.

An ABS-equipped vehicle attempting to slowly negotiate a downhill road paved with gravel runs the risk of not being able to slow down if ABS were to intervene (as the wheels began to slip). There is little doubt that if the slope was steep enough, a vehicle in this situation would continue to accelerate as long as the vehicle continued downhill, despite having the brakes activated.

The first proposed solution is to consider the introduction of a control mode switch integrated with the gear selector, whereby the ABS algorithms would change based on what position the gear selector was in. Changing the algorithm would allow the front wheels to lock whenever the vehicle was placed in low 1 (on an automatic transmission) or first gear, and possibly second (for a manual transmission), which is consistent with allowing wheel lock below 15 km/h. Deactivating ABS in this manner would provide the driver with additional braking force on deformable surfaces (the ability to lock the front wheels), and ABS would automatically be reactivated as soon as the driver attempted to resume faster driving speeds.

The second proposed solution could potentially be used with the above idea or by itself. It contemplates a software solution to the downhill scenario whereby the front wheels would lock up if the brakes are applied, ABS intervenes, and the vehicle's speed continues to increase while brake pedal displacement remains constant (at near-maximum displacement) or increases.

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7.0 APPENDICES

Appendix A. ECE R13-H Annex 6

Annex 6

TEST REQUIREMENTS FOR VEHICLES FITTED WITH
ANTI-LOCK SYSTEMS

1. GENERAL

1.1. This annex defines the required braking performance for road vehicles fitted with anti-lock systems.

1.2. The anti-lock systems known at present comprise a sensor or sensors, a controller or controllers and a modulator or modulators. Any device of a different design which may be introduced in the future, or where an anti-lock braking function is integrated into another system, shall be deemed to be an anti-lock braking system within the meaning of this annex and annex 5 to this Regulation, if it provides performance equal to that prescribed by this annex.

2. DEFINITIONS

2.1. An "anti-lock system" is a part of a service braking system which automatically controls the degree of slip, in the direction of rotation of the wheel(s), on one or more wheels of the vehicle during braking.

2.2. "Sensor" means a component designed to identify and transmit to the controller the conditions of rotation of the wheel(s) or the dynamic conditions of the vehicle.

2.3. "Controller" means a component designed to evaluate the data transmitted by the sensor(s) and to transmit a signal to the modulator.

2.4. "Modulator" means a component designed to vary the braking force(s) in accordance with the signal received from the controller.

2.5. "Directly controlled wheel" means a wheel whose braking force is modulated according to data provided at least by its own sensor. 1/

2.6. "Indirectly controlled wheel" means a wheel whose braking force is modulated according to data provided by the sensor(s) of other wheel(s). 1/

2.7. "Full cycling" means that the anti-lock system is repeatedly modulating the brake force to prevent the directly controlled wheels from locking. Brake applications where modulation only occurs once during the stop shall not be considered to meet this definition.

3. TYPES OF ANTI-LOCK SYSTEMS

3.1. A vehicle is deemed to be equipped with an anti-lock system within the meaning of paragraph 1. of annex 5 to this Regulation, if one of the following systems is fitted:

3.1.1. Category 1 anti-lock system

A vehicle equipped with a category 1 anti-lock system shall meet all the requirements of this annex.

3.1.2. Category 2 anti-lock system

A vehicle equipped with a category 2 anti-lock system shall meet all the requirements of this annex, except those of paragraph 5.3.5.

3.1.3. Category 3 anti-lock system

A vehicle equipped with a category 3 anti-lock system shall meet all the requirements of this annex, except those of paragraphs 5.3.4. and 5.3.5. On such vehicles, any individual axle which does not include at least one directly controlled wheel must fulfil the conditions of adhesion utilization and the wheel-locking sequence of annex 5 to this Regulation, instead of the adhesion utilization requirements prescribed in paragraph 5.2. of this annex. However, if the relative positions of the adhesion utilization curves do not meet the requirements of paragraph 3.1. of annex 5 to this Regulation, a check shall be made to ensure that the wheels on at least one of the rear axles do not lock before those of the front axle or axles under the conditions prescribed in paragraph 3.1. of annex 5 to this Regulation, with regard to the braking rate and the load respectively. These requirements may be checked on high- and low-adhesion road surfaces (about 0.8 and 0.3 maximum) by modulating the service braking control force.

4. GENERAL REQUIREMENTS

4.1. Any electrical failure or sensor anomaly that affects the system with respect to the functional and performance requirements in this annex, including those in the supply of electricity, the external wiring to the controller(s), the controller(s) 2/ and the modulator(s) shall be signalled to the driver by a specific optical warning signal. The yellow warning signal specified in paragraph 5.2.21.1.2. of this Regulation shall be used for this purpose.

4.1.1. The warning signal shall light up when the anti-lock system is energized and with the vehicle stationary it shall be verified that none of the above-mentioned defects are present before extinguishing the signal.

4.1.2. The static sensor check may verify that a sensor was not functioning the last time that the vehicle was at a speed greater than 10 km/h. 3/ Also during this verification phase, the electrically controlled pneumatic modulator valve(s) shall cycle at least once.

4.1.3. The above-mentioned optical warning signal must be visible even in daylight and it must be easy for the driver to check that it is in working order.

4.2. In the event of a single electrical functional failure which only affects the anti-lock function, as indicated by the above-mentioned yellow warning signal, the subsequent service braking performance must not be less than 80 per cent of the prescribed performance according to the Type-O test with the engine disconnected. This corresponds to a stopping distance of $0.1 v + 0.0075 v^2$ (m) and a mean fully developed deceleration of 5.15 m/s^2.

4.3. The operation of the anti-lock system must not be adversely affected by magnetic or electrical fields. 4/ (This shall be demonstrated by compliance with Regulation No. 10, 02 series of amendments).

4.4. A manual device may not be provided to disconnect or change the control mode 5/ of the anti-lock system.

5. SPECIAL PROVISIONS

5.1. Energy consumption

Vehicles equipped with anti-lock systems must maintain their performance when the service braking control device is fully applied for long periods. Compliance with this requirement shall be verified by means of the following tests:

5.1.1. Test procedure

5.1.1.1. The initial energy level in the energy storage device(s) shall be that specified by the manufacturer. This level shall be at least such as to ensure the efficiency prescribed for service braking when the vehicle is laden. The energy storage device(s) for pneumatic auxiliary equipment must be isolated.

5.1.1.2. From an initial speed of not less than 50 km/h, on a surface with a coefficient of adhesion of 0.3 6/ or less, the brakes of the laden vehicle shall be fully applied for a time t, during which time the energy consumed by the indirectly controlled wheels shall be taken into consideration and all directly controlled wheels must remain under control of the anti-lock system.

5.1.1.3. The vehicle's engine shall then be stopped or the supply to the energy transmission storage device(s) cut off.

5.1.1.4. The service braking control shall then be fully actuated four times in succession with the vehicle stationary.

5.1.1.5. When the brakes are applied for the fifth time, it must be possible to brake the vehicle with at least the performance prescribed for secondary braking of the laden vehicle.

5.1.2. Additional requirements

5.1.2.1. The coefficient of adhesion of the road surface shall be measured with the vehicle under test, by the method described in paragraph 1.1. of appendix 2 to this annex.

5.1.2.2. The braking test shall be conducted with the engine disconnected and idling, and with the vehicle laden.

5.1.2.3. The braking time t shall be determined by the formula:

$$t = \frac{v_{max}}{7}$$

(but not less than 15 seconds)

where t is expressed in seconds and v_{max} represents the maximum design speed of the vehicle expressed in km/h, with an upper limit of 160 km/h.

5.1.2.4. If the time t cannot be completed in a single braking phase, further phases may be used, up to a maximum of four in all.

5.1.2.5. If the test is conducted in several phases, no fresh energy shall be supplied between the phases of the test. From the second phase, the energy consumption corresponding to the initial brake application may be taken into account, by subtracting one full brake application from the four full applications prescribed in paragraph 5.1.1.4. (and 5.1.1.5. and 5.1.2.6.) of this annex for each of the second, third and fourth phases used in the test prescribed in paragraph 5.1.1. of this annex as applicable.

5.1.2.6. The performance prescribed in paragraph 5.1.1.5. of this annex shall be deemed to be satisfied if, at the end of the fourth application, with the vehicle stationary, the energy level in the storage device(s) is at or above that required for secondary braking with the laden vehicle.

5.2. Utilization of adhesion

5.2.1. The utilization of adhesion by the anti-lock system takes into account the actual increase in braking distance beyond the theoretical minimum. The anti-lock system shall be deemed to be satisfactory when the condition • ≥ 0.75 is satisfied, where • represents the adhesion utilized, as defined in paragraph 1.2. of appendix 2 to this annex.

5.2.2. The adhesion utilization (•) shall be measured on road surfaces with a coefficient of adhesion of 0.3 6/ or less, and of about 0.8 (dry road), with an initial speed of 50 km/h. To eliminate the effects of differential brake temperatures it is recommended that zAL be determined prior to the determination of k.

5.2.3. The test procedure to determine the coefficient of adhesion (k) and the formulae for calculation of the adhesion utilization (•) shall be those laid down in Appendix 2 to this annex.

5.2.4. The utilization of adhesion by the anti-lock system shall be checked on complete vehicles equipped with anti-lock systems of categories 1 or 2. In the case of vehicles equipped with category 3 anti-lock systems, only the axle(s) with at least one directly controlled wheel must satisfy this requirement.

5.2.5. The condition • ≥ 0.75 shall be checked with the vehicle laden and unladen.

The laden test on the high adhesion surface may be omitted if the prescribed force on the control device does not achieve full cycling of the anti-lock system.

For the unladen test, the control force may be increased up to 100 daN if no cycling is achieved with its full force value 7/ . If 100 daN is insufficient to make the system cycle, then this test may be omitted.

5.3. Additional checks

The following additional checks shall be carried out with the engine disconnected, with the vehicle laden and unladen:

5.3.1. The wheels directly controlled by an anti-lock system must not lock when the full force 7/ is suddenly applied on the control device, on the road surfaces specified in paragraph 5.2.2. of this annex, at an initial speed of v = 40 km/h and at a high initial speed $v = 0.8\ v_{max} \leq 120$ km/h; 8/

5.3.2. When an axle passes from a high-adhesion surface (k_H) to a low-adhesion surface (k_L), where $k_H \geq 0.5$ and $k_H / k_L \geq 2$, 9/ with the full force 7/ applied on the control device, the directly controlled wheels must not lock. The running speed and the instant of applying the brakes shall be so calculated that, with the anti-lock system fully cycling on the high-adhesion surface, the passage from one surface to the other is made at high and at low speed, under the conditions laid down in paragraph 5.3.1.; 8/

5.3.3. When a vehicle passes from a low-adhesion surface (k_L) to a high-adhesion surface (k_H) where $k_H \geq 0.5$ and k_H / $k_L \geq 2$, 9/ with the full force 7/ applied on the control device, the deceleration of the vehicle must rise to the appropriate high value within a reasonable time and the vehicle must not deviate from its initial course. The running speed and the instant of applying the brake shall be so calculated that, with the anti-lock system fully cycling on the low-adhesion surface, the passage from one surface to the other occurs at approximately 50 km/h;

5.3.4. The provisions of this paragraph shall only apply to vehicles equipped with anti-lock systems of categories 1 or 2. When the right and left wheels of the vehicle are situated on surfaces with differing coefficients of adhesion (k_H and k_L), where $k_H \geq 0.5$ and k_H / $k_L \geq 2$, 9/ the directly controlled wheels must not lock when the full force 7/ is suddenly applied on the control device at a speed of 50 km/h;

5.3.5. Furthermore, laden vehicles equipped with anti-lock systems of category 1 shall, under the conditions of paragraph 5.3.4. of this annex satisfy the prescribed braking rate in appendix 3 to this annex;

5.3.6. However, in the tests provided in paragraphs 5.3.1., 5.3.2., 5.3.3., 5.3.4. and 5.3.5. of this annex, brief periods of wheel-locking shall be allowed. Furthermore, wheel-locking is permitted when the vehicle speed is less than 15 km/h; likewise, locking of indirectly controlled wheels is permitted at any speed, but stability and steerability must not be affected and the vehicle must not exceed a yaw angle of 15° or deviate from a 3.5 m wide lane;

5.3.7. During the tests provided in paragraphs 5.3.4. and 5.3.5. of this annex, steering correction is permitted, if the angular rotation of the steering control is within 120° during the initial 2 seconds, and not more than 240° in all. Furthermore, at the beginning of these tests the longitudinal median plane of the vehicle must pass over the boundary between the high- and low-adhesion surfaces and during these tests no part of the tyres must cross this boundary.

1/ Anti-lock systems with select-high control are deemed to include both directly and indirectly controlled wheels; in systems with select-low control, all sensed wheels are deemed to be directly controlled wheels.

2/ Until uniform test procedures have been agreed, the manufacturer shall provide the Technical Service with an analysis of potential failures within the controller(s) and their effects. This information shall be subject to discussion and agreement between the Technical Service and the vehicle manufacturer.

3/ The warning signal may light up again while the vehicle is stationary, provided that it is extinguished before the vehicle speed reaches 10 km/h when no defect is present.

4/ Until uniform test procedures have been agreed, the manufacturers shall provide the Technical Services with their test procedures and results.

5/ It is understood that devices changing the control mode of the anti-lock system are not subject to paragraph 4.4. if in the changed control mode condition all requirements to the category of anti-lock systems, with which the vehicle is equipped, are fulfilled.

6/ Until such test surfaces become generally available, tyres at the limit of wear, and higher values up to 0.4 may be used at the discretion of the Technical Service. The actual value obtained and the type of tyres and surface shall be recorded.

7/ "Full force" means the maximum force laid down in annex 3 to this Regulation; a higher force may be used if required to activate the anti-lock system.

8/ The purpose of these tests is to check that the wheels do not lock and that the vehicle remains stable; it is not necessary, therefore, to make complete stops and bring the vehicle to a halt on the low-adhesion surface.

9/ k_H is the high-adhesion surface coefficient
k_L is the low-adhesion surface coefficient
k_H and k_L are measured as laid down in appendix 2 to this annex.

Annex 6 - Appendix 1

SYMBOLS AND DEFINITIONS

TABLE: SYMBOLS AND DEFINITIONS

SYMBOL	NOTES
E	wheelbase
$\bullet$	the adhesion utilized of the vehicle: quotient of the maximum braking rate with the anti-lock system operative (z_{AL}) and the coefficient of adhesion (k)
$\bullet_i$	the $\bullet$ - value measured on axle i (in the case of a motor vehicle with a category 3 anti-lock system)
$\bullet_H$	the $\bullet$ - value on the high-adhesion surface
$\bullet_L$	the $\bullet$ - value on the low-adhesion surface
F	force (N)
F_{dyn}	normal reaction of road surface under dynamic conditions with the anti-lock system operative
F_{idyn}	F_{dyn} on axle i in case of power-driven vehicles
F_i	normal reaction of road surface on axle i under static conditions
F_M	total normal static reaction of road surface on all wheels of power-driven vehicle
F_{Mnd} 1/	total normal static reaction of road surface on the unbraked and non-driven axles of the power-driven vehicle
F_{Md} 1/	total normal static reaction of road surface on the unbraked and driven axles of the power-driven vehicle
F_{WM} 1/	$0.01\ F_{Mnd} + 0.015\ F_{Md}$
g	acceleration due to gravity (9.81 m/s^2)
h	height of center of gravity specified by the manufacturer and agreed by the Technical Service conducting the approval test
k	coefficient of adhesion between tyre and road
k_f	k-factor of one front axle
k_H	k-value determined on the high-adhesion surface
k_i	k-value determined on axle i for a vehicle with a category 3 anti-lock system

1/ F_{Mnd} and F_{Md} in case of two-axled motor vehicles: these symbols may be simplified to corresponding F_i - symbols.

TABLE: SYMBOLS AND DEFINITIONS (cont'd)

SYMBOL	NOTES
k_L	k-value determined on the low-adhesion surface
k_{lock}	value of adhesion for 100 % slip
k_M	k - factor of the power-driven vehicle
k_{peak}	maximum value of the curve "adhesion versus slip"
kr	k - factor of one rear axle
P	mass of individual vehicle (kg)
R	ratio of k_{peak} to k_{lock}
t	time interval (s)
t_m	mean value of t
t_{min}	minimum value of t
z	braking rate
z_{AL}	braking rate z of the vehicle with the anti-lock system operative
z_m	mean braking rate
z_{max}	maximum value of z
z_{MALS}	z_{AL} of the power-driven vehicle on a "split surface"

Annex 6 - Appendix 2

UTILIZATION OF ADHESION

1. METHOD OF MEASUREMENT

1.1. Determination of the coefficient of adhesion (k)

1.1.1. The coefficient of adhesion (k) shall be determined as the quotient of the maximum braking forces without locking the wheels and the corresponding dynamic load on the axle being brakes.

1.1.2. The brakes shall be applied on only one axle of the vehicle under test, at an initial speed of 50 km/h. The braking forces shall be distributed between the wheels of the axle to reach maximum performance. The anti-lock system shall be disconnected, or inoperative, between 40 km/h and 20 km/h.

1.1.3. A number of tests at increments of line pressure shall be carried out to determine the maximum braking rate of the vehicle (z_{max}). During each test, a constant input force shall be maintained and the braking rate will be determined by reference to the time taken (t) for the speed to reduce from 40 km/h to 20 km/h using the formula:

$$z = \frac{0.566}{t}$$

z_{max} is the maximum value of z ; t is in seconds.

1.1.3.1. Wheel lock may occur below 20 km/h.

1.1.3.2. Starting from the minimum measured value of t, called t_{min} , then select three values of t comprised within t_{min} and 1.05 t_{min} and calculate their arithmetical mean value t_m ,

then calculate: $$z_m = \frac{0.566}{t_m}$$

If it is demonstrated that for practical reasons the three values defined above cannot be obtained, then the minimum time t_{min} may be utilized. However, the requirements of paragraph 1.3. shall still apply.

1.1.4. The braking forces shall be calculated from the measured braking rate and the rolling resistance of the unbraked axle which is equal to 0.015 and 0.010 of the static axle load for a driven axle and a non-driven axle, respectively.

1.1.5. The dynamic load on the axle shall be that given by the formulae in annex 5 to this Regulation.

1.1.6. The value of k shall be rounded to three decimal places.

1.1.7. Then, the test will be repeated for the other axle(s) as defined in paragraphs 1.1.1. to 1.1.6. above.

1.1.8. For example, in the case of a two-axle rear-wheel drive vehicle, with the front axle (1) being braked, the coefficient of adhesion (k) is given by:

$$k_f = \frac{z_m . P . g \;\; 0.015 F_2}{F_1 + \frac{h}{E} \cdot z_m . P . g}$$

The other symbols (P, h, E) are defined in annex 5 to this Regulation.

1.1.9. One coefficient will be determined for the front axle k_f and one for the rear axle k_r .

1.2. Determination of the adhesion utilized (•)

1.2.1. The adhesion utilized (•) is defined as the quotient of the maximum braking rate with the anti-lock system operative (z_{AL}) and the coefficient of adhesion (k_M) i.e.,

$$\varepsilon = \frac{z_{AL}}{k_M}$$

1.2.2. From an initial vehicle speed of 55 km/h, the maximum braking rate (z_{AL}) shall be measured with full cycling of the anti-lock braking system and based on the average value of three tests, as in paragraph 1.1.3. of this appendix, using the time taken for the speed to reduce from 45 km/h to 15 km/h, according to the following formula:

$$z_{AL} = \frac{0.849}{t_m}$$

1.2.3. The coefficient of adhesion k_M shall be determined by weighting with the dynamic axle loads.

$$k_M = \frac{k_f \cdot F_{fdyn} + k_r \cdot F_{rdyn}}{P . g}$$

where:

$$F_{fdyn} = F_f + \frac{h}{E} \cdot z_{AL} . P . g$$

$$F_{rdyn} = F_r - \frac{h}{E} \cdot z_{AL} . P . g$$

1.2.4. The value of • shall be rounded to two decimal places.

1.2.5. In the case of a vehicle equipped with an anti-lock system of categories 1 or 2, the value of z_{AL} will be based on the whole vehicle, with the anti-lock system in operation, and the adhesion utilized (•) is given by the same formula quoted in paragraph 1.2.1. of this appendix.

1.2.6. In the case of a vehicle equipped with an anti-lock system of category 3, the value of z_{AL} will be measured on each axle which has at least one directly controlled wheel. For example, for a two-axle rear-wheel drive vehicle with an anti-lock system acting only on the rear axle (2), the adhesion utilized (•) is given by:

$$\varepsilon_2 = \frac{z_{AL} . P . g \;\; 0.010 F_1}{k_2 (F_2 \;\; \frac{h}{E} \cdot z_{AL} . P . g)}$$

This calculation shall be made for each axle having at least one directly controlled wheel.

1.3. If • > 1.00, the measurements of coefficients of adhesion shall be repeated. A tolerance of 10% is accepted.

Annex 6 - Appendix 3

PERFORMANCE ON DIFFERING ADHESION SURFACES

1.1. The prescribed braking rate referred to in paragraph 5.3.5. of this annex may be calculated by reference to the measured coefficient of adhesion of the two surfaces on which this test is carried out. These two surfaces must satisfy the conditions prescribed in paragraph 5.3.4. of this annex.

1.2. The coefficient of adhesion (kH and kL) of the high- and low-adhesion surfaces, respectively, shall be determined in accordance with the provisions in paragraph 1.1. of appendix 2 to this annex.

1.3. The braking rate (z_{MALS}) for laden vehicles shall be:

$$z_{MALS} \geq 0.75 \left(\frac{4 k_L + k_H}{5} \right) \text{ and } z_{MALS} \geq k_L$$

Annex 6 - Appendix 4

METHOD OF SELECTION OF THE LOW ADHESION SURFACE

1. Details of the coefficient of adhesion of the surface selected, as defined in paragraph 5.1.1.2. of this annex, must be given to the Technical Service.

1.1. These data must include a curve of the coefficient of adhesion versus slip (from 0 to 100 per cent slip) for a speed of approximately 40 km/h.

1.1.1. The maximum value of the curve will represent k_{peak} and the value at 100 per cent slip will represent k_{lock}.

1.1.2. The ratio R shall be determined as the quotient of the k_{peak} and k_{lock}.

$$R = \frac{k_{peak}}{k_{lock}}$$

1.1.3. The value of R shall be rounded to one decimal place.

1.1.4. The surface to be used must have a ratio R between 1.0 and 2.0 1/.

2. Prior to the tests, the Technical Service shall ensure that the selected surface meets the specified requirements and shall be informed of the following:

test method to determine R, type of vehicle, axle load and tyres (different loads and different tyres have to be tested and the results shown to the Technical Service which will decide if they are representative for the vehicle to be approved).

2.1. The value of R shall be mentioned in the test report.

The calibration of the surface has to be carried out at least once a year with a representative vehicle to verify the stability of R.

1/ Until such test surfaces become generally available, a ratio R up to 2.5 is acceptable, subject to discussion with the Technical Service.

Appendix B. Problems With Testing Vehicles to the ECE Method

Initial Test Conditions

The following is a list of initial test conditions that are not currently set forth in Annex 6:

Brake burnish – brakes should be burnished at least once and have no corrosion buildup at the start of testing. Any tire break-in requirements should be satisfied during the burnish procedure. Should a tire become damaged during braking and need replaced, the replacement tires should at least match the mileage accumulated during the brake burnish.

Tire pressures – Annex 3, 1.2.6 provides “at the start of the tests, the tires must be cold and at the pressure prescribed for the load actually borne by the wheels when the vehicle is stationary.” In the United States, tire load limits are regulated by FMVSS 110 S4.2. Many tires have a reserve load, where the weight on the stationary tire is less than the tire can support when inflated to the vehicle manufacturers recommended cold inflation pressure (placard pressure). For government compliance testing, it is better to test vehicles with the tires at placard pressure.

Initial brake temperatures (not currently set forth in Annex 6): See Annex 3, 1.4.1.1 – “The average temperature of the service brakes on the hottest axle of the vehicle, measured inside the brake linings or on the braking path of the disc or drum, is between 65°C and 100°C prior to any brake application.” This research used individual brake temps in the same temperature range. Annex 6 should have some mention of IBT conditions and preferably ones that deal with the manufacturer’s recommended operating temperature for the particular type of friction material.

What is the planned loading strategy of the vehicles? Though it is not directly set forth in Annex 6, Section 1.1.5 in Appendix 2 of Annex 6 gives the following oblique reference: “The dynamic load on the axle shall be that given by the formulae in annex 5 to this Regulation.” Unfortunately, what formulae are available deal more with weight transferred during a stop and do not address the issue of how to load the vehicle. Two methods from the ECE include:

> Most heavily laden – (maximize front axle first?): Examination of Annex 5, 3.2.2 reveals “laden; where provision is made for several possibilities of load distribution, the one whereby the front axle is the most heavily laden shall be the one considered”.

or

> GVWR achieved by loading the axles proportional to individual GAWR?. Annex 3, 1.4.1.2.1 holds “the distribution of the maximum mass among the axles must be such that the mass on each axle is proportional to the maximum permissible mass for each axle.”

Are water dummies to be used for user-accurate loading or sandbags in set locations? Sandbags are certainly more practical for testing. There is also the matter of balance between sides of the car per tested axle. A specification to evenly weight the two sides of an axle will reduce the chances of the lighter side wheel locking up and most probably will deliver better deceleration times. When a wheel locks, that brake is not doing any work while the other brakes are providing most of the stopping force for the entire car. A heat difference then forces extended cool down times between runs. It was also observed that when one side of the car was heavier the brake(s) on that side got much hotter than the other side (per axle), even when no wheel lock was observed.

Another problem that arises relating to weight is how to measure the height of the center of gravity with a vehicle that has load leveling or speed-dependant ride height.

Adhesion utilization

During single axle stops, testers are asked to find the value Z_M, which is then used to calculate K_r and K_f. If this method is to be used, it should be clarified that Z_M will be different for each axle tested and must be matched to the corresponding equation when K_r and K_f are found.

How many single-axle stops must be made before good data is obtained (not currently set forth in Annex 6)? This portion of the testing gathers data points so that an estimate of the coefficient of adhesion (K) can be calculated. It was found in post-processing of the Task 1 adhesion utilization data that it takes around 10 runs at what was considered to be peak brake line pressure to get 3 values within 5 percent of the best stop. ASTM's standard test method (E1337) for measuring the peak friction coefficient, or PFC, (equivalent to the calculated K in the ECE) recommends at least eight runs in order to develop an estimate. TRC surface monitoring uses ten runs while performing the same E1337 method.

Annex 6, 5.2.5, 3rd paragraph contains implicit flaws about the nature of adhesion utilization. If a test sequence is thrown out because lack of brake torque prevented the wheel from locking, that has direct implications on how much adhesion was used. Depending on the severity of this effect, the vehicle might have safety related issues in regards to stopping distance. Nevertheless, ABS adhesion utilization in this instance would be meaningless and it is appropriate to omit such testing. A fallback position might be considered here, where the vehicle is then tested on a surface with a lower PFC, such as cooler asphalt (tested in the morning) or wetting the same high-coefficient surface and repeating the same procedure.

Regarding the above paragraph, the safety concern about increasing pedal force to make the ABS cycle is that a portion of the driving public would be unable to exert the 1000 N required to use all the adhesion that the vehicle is capable of using. The 5th percentile female can typically deliver a maximum force of 445 N. There is also the matter of pedal travel, which is not covered in the ECE. This same 5th percentile female will have a limited range of leg extension that must be considered if this portion of the driving population is expected to be able to use the full stopping ability afforded by the manufacturer's design.

Some clarification is needed in regards to the use of variables, referring to the use of F_1 and F_2 in the equations used to calculate K_f and K_r, then the switch to F_f and F_r for the equations used to calculate F_{fdyn} and F_{rdyn}. It is probably safe to say that F_1 and F_2 are the same values as F_f and F_r but it should be explicit (or consistent) if these methods are adopted.

Functionality tests

How many test runs must one make to verify compliance with a standard? Annex 3, 1.4.1.2.4 holds "unless otherwise specified each test may comprise up to six stops including any needed for familiarization." FMVSS 135 testing uses six runs for its stopping tests, the same as Annex 3 does. To be clear, any adhesion utilization testing should include at least 10 runs, while the ABS performance tests could get by with a fewer number of runs.

Do the conditions laid out in Annex 6, 5.2.5 ("omit laden tests if 500N doesn't produce cycling" and "omit unladen test if 1000N doesn't produce cycling") extend to similar situations in Section 5.3 "Additional Checks"? Section 5.3.2 describes a situation where 500N is used ("full force applied to control device") but clearly assumes that the force is enough to cause the ABS to cycle on the high-co surface ("with the antilock system fully cycling on the high-adhesion surface"). See note on definition of fully cycling at the bottom of this page.

Annex 6, 5.3 – "The following additional checks shall be carried out with the engine disconnected…" – This is problematic in that getting up to and going slightly faster than 120 km/h and then coasting down to the target speed uses up more asphalt than is available, and for certain smaller cars loaded to GVWR it is impossible. Coasting down to the target speed while using the jennite is dangerous because of the layout of the test facility; it requires the driver to turn the vehicle 90° at over 80 mph. It is also unnatural since most drivers don't place a car in neutral during extreme braking events.

Annex 6, 5.3.1 – The high-speed test portion reads "… and at a high initial speed $v = 0.8\ V_{max} \leq$ 120 Km/h". This speed is too high for most of the surfaces at this facility and does not provide any additional information than those tests conducted at a more reasonable 90 km/h. In addition, the basalt surface is so slick that vehicles run off the end of it at higher speeds, and as stated previously, it places the driver and vehicle at unnecessary risk.

"Suddenly" is a term used to describe the brake pedal actuation without providing any parameters. To define this, the maximum pedal force and the ramp rate should be given. For example, Annex 5, Appendix 2, 3C holds "Pedal Force is increased at a linear rate between 100 and 150 N/sec for the 100 Km/h test speed, or between 100 and 200 N/sec for the 50 Km/h test speed, until the first axle locks or until a pedal force of 1 KN is reached, whichever occurs first."

The phrase "must not lock" (used in sections 5.3.1, 5.3.2, 5.3.4) takes a rigid approach to how ABS should manage slip. Section 5.3.6 modifies that position by providing "…brief periods of wheel-locking shall be allowed", but fails to describe what "brief" is in seconds. There is no mention of vehicle stability either. In a later sentence this same section allows for the locking of indirectly controlled wheels as long as "…stability and steerability..." are not affected and provides a maximum yaw angle, but fails to describe how steerability should be assessed. Ideally, brief periods of wheel lock (defined by a number) should be allowed at any wheel, regardless of the control type; the emphasis should be on vehicle stability and "steerability" not being affected.

Annex 6, 5.3.3 – In describing how the vehicle's brakes should respond upon transitioning from a lower coefficient surface to a higher one, this section provides "…the deceleration of the vehicle must rise to the appropriate high value within a reasonable time…" Absent are the values needed for compliance with "appropriate high value" and "reasonable time".

Definitions

"'Fully cycling' means that the anti-lock system is repeatedly modulating the brake force to prevent the directly controlled wheels from locking." There are several points to mention here. One concern of a regulatory body is to first access the amount and nature of the change in stopping performance that the addition of ABS causes, then construct a rule to ensure safety. Ignoring indirectly controlled wheels neglects any braking contributions or theoretical losses and will produce inaccuracies in adhesion utilization measurements. What should be considered is that all the ABS channels (regardless of control type) should be cycling while testing to see whether the maximum amount of pressure modulation negatively impacts stopping distance (or deceleration rate as the case may be), granted that some level of pedal force is not exceeded. It may be the case that at the 500N or 1000N levels of pedal force, the indirectly controlled wheels (i.e. rear wheels) of a heavily loaded vehicle on the high-co surface might not cycle.

Even if all the channels are cycling, there are certain ABS designs (with indirectly controlled wheels) that use less than the total amount of available adhesion. The two general types of control algorithms used for indirectly controlled wheels are select-low and select-high. An example of an indirect system would be a vehicle, say a pickup truck, that uses one brake line to actuate both brakes on the rear axle while the ABS estimates wheel slip at the drive shaft. The select-low algorithm dumps brake line pressure when the first wheel exceeds its slip threshold, the select-high dumps when both wheels exceed their threshold. When ABS is working, the isolate valve prevents the driver from applying any more pressure to the slipping wheels. Indirectly controlled select-low rear axles give up braking efficiency when ABS is active since the non-locked wheel cannot reach its peak pressure.

Miscellaneous issues

Annex 6, 3.1. – This section describes 3 categories of ABS but fails to provide any details as to what might distinguish one system from the next, only that it will fall into a particular category based on how many tests the ABS can successfully perform.

Annex 6, 4.4 – This section reads, "A manual device may not be provided to disconnect or change the control mode of the ABS." Preventing the operator from disabling the ABS is the surest way to guarantee that it is functioning when they need it. Footnote 5 leaves open the possibility of such a device as long as the ABS meets the requirements of the rule. However, one is left with the problem of ABS being operational when needed. The importance of this section is for countries that use gravel roads, where applying brakes on a steep hill might activate ABS and result in the vehicle not slowing down at all.

Somewhere in the final FMVSS 135 rule on ABS there should be a clause regarding system design that allows for the disabling of ABS only, without effecting stability control, brake assist, etc., if ABS on/off comparisons are to be used. This would also serve a purpose for testing the ABS failed mode.

When defining coefficients of test surfaces, a range of speeds should also be included, maybe even a surface temperature range also. An example of this would be "Test surface: PFC of at least 0.9 at 40 mph while temperature is between 90° and 120° F".

Practical Issues

The use of torque wheels in a heavily loaded condition creates an interference problem between the tires and rear fenders. Rear axle squat, observed during rear-axle stops, also causes the tires to rub the fender when torque wheels are in use. Testing with torque wheels is used for non-ABS equipped vehicles in FMVSS 135 and the ECE R13-H regulations.

During single axle testing, shut off valves placed in the brake lines disabled the untested axle by stopping the flow of brake fluid. However, under high pressure some of the shutoff valves would leak ever so slightly, which after numerous runs allowed pressure to build up on one side of the non-braked axle (the shutoff valve prevented pressure release). This had the affect of applying a brake torque that affected the deceleration time of the axle being measured and created heat in that brake. So single axle testing does require an inordinate amount of attention be placed on individual brake line pressures and temperatures, a time consuming task when collecting data.

It was observed that certain test vehicles appeared to have shorter stopping distances on the basalt tiles when they were in a 4-wheel locked slide. (Stopping distance was not a collected parameter.) This may be a result of not increasing the brake pedal force beyond the point where ABS began cycling. This also might be evidence that 4 wheels skidding provided better deceleration times then 2 wheels at their peak and the other 2 under their respective peaks (for example), again in support of a more precise definition of “fully cycling”.

Appendix C. Test Vehicle Information

Manufacturer: Honda	Model: CRV
Body style: 4D Compact SUV	VIN: JHLRD1874YS011248
Date of Mfg: 5/00	Odometer: 1843
Wheelbase: 103.2 in.	Track front/rear: 60.4/60.4 in.
GVWR: 4165	GAWR front/rear: 2030/2155

DRIVE TRAIN

Engine Type: I4	Displacement: 2.0 liter
Transmission: Auto	Forward speeds: 4

TIRES

Manufacturer: BF Goodrich	Model: Touring T/A
Size: P205/70R15 95S	OEM Pressure: 26psi

BRAKES

ABS Manufacturer: Nisshinbo	ABS type: 4 channel
Booster type: Power Vacuum	Brake type – front/rear: disc/drum

VEHICLE WEIGHT AS TESTED - All weights are with full fuel tanks, torque wheels on, 5th wheel in down position, and driver in vehicle.

Left front (LLVW):	1007 lbs.	Left front (GVWR):	1001 lbs.
Left rear (LLVW):	850 lbs.	Left rear (GVWR):	1065 lbs.
Right front (LLVW):	990 lbs.	Right front (GVWR):	1001 lbs.
Right rear (LLVW):	862 lbs.	Right rear (GVWR):	1097 lbs.

VEHICLE INFORMATION

Manufacturer: GMC	Model: Sonoma
Body style: Extended Cab Light Pickup	VIN: 1GTCS19W1Y8309638
Date of Mfg: 6/00	Odometer: 1461
Wheelbase: 122.9 in.	Track front/rear: 55.5/55.6 in.
GVWR: 4600	GAWR front/rear: 2500/2700

DRIVE TRAIN

Engine Type: V6	Displacement: 4.3 liter
Transmission: Auto	Forward speeds: 4

TIRES

Manufacturer: Uniroyal	Model: Tiger Paw
Size: P205/75R15	OEM Pressure – front/rear: 30/29

BRAKES

ABS Manufacturer: TRW	ABS type: 4 channel
Booster type: Power Vacuum	Brake type – front/rear: disc/drum

VEHICLE WEIGHT AS TESTED - All weights are with full fuel tanks, torque wheels on, 5th wheel in down position, and driver in vehicle.

Left front (LLVW):	1260 lbs.	Left front (GVWR):	1240 lbs.
Left rear (LLVW):	859 lbs.	Left rear (GVWR):	1335 lbs.
Right front (LLVW):	1131 lbs.	Right front (GVWR):	1236 lbs.
Right rear (LLVW):	850 lbs.	Right rear (GVWR):	1349 lbs.

VEHICLE INFORMATION

Manufacturer: Toyota	Model: Sienna
Body style: 4D Minivan	VIN: 4T332F19C1YU265879
Date of Mfg: 02/00	Odometer: 3063
Wheelbase: 114.2 in.	Track front/rear: 61.6/63.5 in.
GVWR: 5250	GAWR front/rear: 2725/2725

DRIVE TRAIN

Engine Type: V6	Displacement: 3.0 liter
Transmission: Auto	Forward speeds: 4

TIRES

Manufacturer: Dunlop	Model: SP40 A/S
Size: P205/70R15	OEM Pressure: 35psi

BRAKES

ABS Manufacturer: LSB	ABS type: 4 channel
Booster type: Power Vacuum	Brake type – front/rear: disc/drum

VEHICLE WEIGHT AS TESTED - All weights are with full fuel tanks, torque wheels on, 5th wheel in down position, and driver in vehicle.

Left front (LLVW):	1319 lbs.	Left front (GVWR):	1342 lbs.
Left rear (LLVW):	998 lbs.	Left rear (GVWR):	1340 lbs.
Right front (LLVW):	1213 lbs.	Right front (GVWR):	1247 lbs.
Right rear (LLVW):	970 lbs.	Right rear (GVWR):	1295 lbs.

VEHICLE INFORMATION

Manufacturer: Toyota	Model: Corolla CE
Body style: 4D Compact	VIN: 2T1BR18E6YC339254
Date of Mfg: 01/00	Odometer: 1600
Wheelbase: 97 in.	Track front/rear: 57.5/57.1 in.
GVWR: 3515	GAWR front/rear: 1815/1720

DRIVE TRAIN

Engine Type: I4	Displacement: 1.8 liter
Transmission: Auto	Forward speeds: 4

TIRES

Manufacturer: Michelin	Model: MX4 All Season
Size: P175/65R14	OEM Pressure: 32/32

BRAKES

ABS Manufacturer: Sumitomo	ABS type: 4 sensor
Booster type: Power Vacuum	Brake type – front/rear: disc/drum

VEHICLE WEIGHT AS TESTED - All weights are with full fuel tanks, LLVW, 5th wheel in down position, and driver in vehicle.

Left front (LLVW):	822 lbs.	Left front (GVWR):	957 lbs.
Left rear (LLVW):	660 lbs.	Left rear (GVWR):	667 lbs.
Right front (LLVW):	784 lbs.	Right front (GVWR):	938 lbs.
Right rear (LLVW):	690 lbs.	Right rear (GVWR):	711 lbs.

VEHICLE INFORMATION

Manufacturer: Buick | Model: LeSabre Custom Sedan

Manufacturer: Buick	Model: LeSabre Custom Sedan
Body style: Large	VIN: 1G4HP54K9Y4238033
Date of Mfg: 03/00	Odometer: 2100
Wheelbase: 112.2 in.	Track front/rear: 62.3/62.3 in.
GVWR: 4685	GAWR front/rear: 2517/2168

DRIVE TRAIN

Engine Type: V6	Displacement: 3.8 liter
Transmission: Auto	Forward speeds: 4

TIRES

Manufacturer: General	Model: Ameri GS60
Size: P215/70R15	OEM Pressure: 32

BRAKES

ABS Manufacturer: Delphi	ABS type: 4 sensor
Booster type: Power Vacuum	Brake type – front/rear: disc/disc

VEHICLE WEIGHT AS TESTED - All weights are with full fuel tanks, LLVW, 5th wheel in down position, and driver in vehicle.

Left front (LLVW):	1216 lbs.	Left front (GVWR):	1262 lbs.
Left rear (LLVW):	895 lbs.	Left rear (GVWR):	1142 lbs.
Right front (LLVW):	1182 lbs.	Right front (GVWR):	1278 lbs.
Right rear (LLVW):	857 lbs.	Right rear (GVWR):	1136 lbs.

Appendix D. Sensor Details

Type	Output	Range	Manufacturer(s)	Model Number
Multi-Axis Inertial Sensing System	Longitudinal, Lateral, and Vertical Acceleration Roll, Yaw, and Pitch Rate	Accelerometers: ±2 g Angular Rate Sensors: ±100°/s	Crossbow Systron Donner	DMU-VGX Gold Box
String Potentiometer	Handwheel Angle	20 in, Linear	UniMeasure (typical)	LX-PA-20
Ultrasonic Distance Measuring System	Front and Rear Vehicle Height	5-24 in	Massa Products Corp.	Measurement System: M-4000-D ranging modules: M-410/150
Load Cell	Brake Pedal Force	0-300 lb	GSE Inc.	11435-01301 – cell 3100A – meter
Pressure Transducer	Brake Line Pressure, Each Road Wheel and the Master Cylinder	0-2500 psi	PSI-Tronix, Inc.	PSI-100/2500-A2
Thermocouples	Brake Pad Temperature		Omega	
5th Wheel	Vehicle Speed	≈ 1-125 mph	Labeco	625
Reflective Brake Trigger	On/Off	Infrared Light	SunX Trading Co., LTD.	RS120-H
Wheel Torque Measurement System	Each Road Wheel: Torque Forces	7,000 in-lbs to 60,000 in-lbs	Sensor Developments	90360 Series

Appendix E. Alternative Split-Coefficient Deceleration Rates

$$Deceleration \geq \left(\frac{4K_L + K_H}{5}\right)$$

High Side (K_H)	Low Side (K_L)							
	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
0.50	0.260	0.300						
0.55	0.203	0.310						
0.60	0.210	0.320	0.360					
0.65	0.218	0.330	0.370					
0.70	0.225	0.340	0.380	0.420				
0.75	0.233	0.350	0.390	0.430				
0.80	0.240	0.360	0.400	0.440	0.480			
0.85	0.248	0.370	0.410	0.450	0.490			
0.90	0.255	0.380	0.420	0.460	0.500	0.540		
0.95	0.263	0.390	0.430	0.470	0.510	0.550		
1.00	0.270	0.400	0.440	0.480	0.520	0.560	0.600	
1.05	0.278	0.410	0.450	0.490	0.530	0.570	0.610	
1.10	0.285	0.420	0.460	0.500	0.540	0.580	0.620	0.660

$$Deceleration \geq \left(\frac{2K_L + K_H}{3}\right)$$

High Side (K_H)	Low Side (K_L)							
	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
0.50	0.300	0.333						
0.55	0.317	0.350						
0.60	0.333	0.367	0.400					
0.65	0.350	0.383	0.417					
0.70	0.367	0.400	0.433	0.467				
0.75	0.383	0.417	0.450	0.483				
0.80	0.400	0.433	0.467	0.500	0.533			
0.85	0.417	0.450	0.483	0.517	0.550			
0.90	0.433	0.467	0.500	0.533	0.567	0.600		
0.95	0.450	0.483	0.517	0.550	0.583	0.617		
1.00	0.467	0.500	0.533	0.567	0.600	0.633	0.667	
1.05	0.483	0.517	0.550	0.583	0.617	0.650	0.683	
1.10	0.500	0.533	0.567	0.600	0.633	0.667	0.700	0.733

$$Deceleration \geq \left(\frac{3K_L + 2K_H}{5}\right)$$

High Side (K_H)	Low Side (K_L)							
	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
0.50	0.320	0.350						
0.55	0.340	0.370						
0.60	0.360	0.390	0.420					
0.65	0.380	0.410	0.440					
0.70	0.400	0.430	0.460	0.490				
0.75	0.420	0.450	0.480	0.510				
0.80	0.440	0.470	0.500	0.530	0.560			
0.85	0.460	0.490	0.520	0.550	0.580			
0.90	0.480	0.510	0.540	0.570	0.600	0.630		
0.95	0.500	0.530	0.560	0.590	0.620	0.650		
1.00	0.520	0.550	0.580	0.610	0.640	0.670	0.700	
1.05	0.540	0.570	0.600	0.630	0.660	0.690	0.720	
1.10	0.560	0.590	0.620	0.650	0.680	0.710	0.740	0.770

$$Deceleration \geq \left(\frac{K_L + K_H}{2}\right)$$

High Side (K_H)	Low Side (K_L)							
	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55
0.50	0.350	0.375						
0.55	0.375	0.400						
0.60	0.400	0.425	0.450					
0.65	0.425	0.450	0.475					
0.70	0.450	0.475	0.500	0.525				
0.75	0.475	0.500	0.525	0.550				
0.80	0.500	0.525	0.550	0.575	0.600			
0.85	0.525	0.550	0.575	0.600	0.625			
0.90	0.550	0.575	0.600	0.625	0.650	0.675		
0.95	0.575	0.600	0.625	0.650	0.675	0.700		
1.00	0.600	0.625	0.650	0.675	0.700	0.725	0.750	
1.05	0.625	0.650	0.675	0.700	0.725	0.750	0.775	
1.10	0.650	0.675	0.700	0.725	0.750	0.775	0.800	0.825

Appendix F. Figure Descriptions For Visually Impaired Readers

Figure 2.1 Force and Dimension Variables From Equations 2.1 – 2.4
The picture shows a Ferrari, viewed from the side, with dimension lines locating the wheelbase, height of the center of gravity, and the static forces acting through these points.

Figure 3.1 Pneumatic Brake Ram
The picture shows a large piston attached to the brake pedal of a car. The piston is about twelve inches long and is attached to the vehicle floorboard for stabilization.

Figure 3.2 Torque Wheel Assembly
The picture shows the disc brake of a car with the wheel removed. Attached to the disc brake hub is the assembly that measures torque. The assembly is made of three basic pieces, two adapter plates with the transducer sandwiched between them. In short, the transducer gets mounted between the wheel and hub.

Figure 3.3 Transportation Research Center's Skid Measurement System
The picture shows a GMC long-bed pickup truck towing a low-profile trailer.

Figure 3.4 Basalt Tiles
The picture shows a car driving on tiles. The tiles are very similar to bathroom tiles, however they are arranged horizontally to make the road surface. The area between tiles contains water.

Figure 3.5 Layout of the Split-Mu Test
The drawing shows the overhead view of a vehicle spanning two surfaces. The centerline of the vehicle is parallel to where the asphalt and Jennite surfaces meet. Braking is performed with the passenger side tires on asphalt and the driver's side tires on (wet) Jennite.

Figure 3.6 Adjusting Maneuver Speed With an Automatic Brake Trigger
The drawing shows an overhead view of a vehicle driving onto Jennite from asphalt. Immediately prior to the transition there is a reflective plate that actuates the vehicles brakes. Moving the reflective plate would change the speed at which the vehicle crosses the transition, given that the approach speed is kept constant.

Figure 3.7 Vehicle Speed During Low-to-High Transition Test
The graph shows 3 plots, vehicle speed, wheel speed and the timing of the vehicle crossing reflective strips. Both the vehicle and wheel speed channels show an entry speed of 60 km/h, which goes to zero km/h by the end of the plot. The first dip in wheel speed occurs when the vehicle crosses the first reflective strip and the brakes activate. When the vehicle crosses the second reflective strip it marks the exact time that the vehicles front wheels crossed onto the asphalt. (Note there are only two blips on the timing channel where the vehicle crosses the reflective strips; otherwise the plot for that channel is at zero.) A vertical line is added that goes directly up from where the second reflective crossing occurs to the point where it touches the plot of vehicle speed. A horizontal line is added that goes to the left of that point so that one can determine the vehicle's speed at the transition was 54 km/h.

Figure 4.1 Coefficient of Friction (k):
The drawing is of a tire. There is an arrow pointing upward to the place where the supposed tire would touch the road surface; this represents the 'normal force'. There is another arrow pointing rightward at the same point on the tire; this represents the 'braking force'. The braking force divided by the normal force equals k.

Figure 4.2 Example of a Force vs. Slip Curve
This figure shows a graph of the force versus slip curve. The curve starts at 100 lbs. of force at 1 percent of tire slip, and sharply increases to a peak of 910 lbs. at 15 percent of tire slip. The curve then steadily decreases to about 725 lbs. of force at 82 percent of tire slip.

Figure 4.3 Graphed Wheel Speed Illustrating Slip
The figure shows two graphs. Each graph has two data plots, wheel speed and vehicle speed, both beginning at 50 km/h and going to zero. In the first graph there is a separation of wheel speed from vehicle speed that begins when the braking occurs. There is roughly 5 km/h difference between the two plots as the vehicle slows to zero. In the second graph there is a large separation between wheel speed and vehicle speed, as much 20 km/h in some places. The first graph was performed on asphalt and the second was performed on basalt tiles but otherwise were similar tests. These graphs show that the braked wheel is spinning slower than the vehicle is traveling, which is what slows the vehicle down.

Figure 4.4 Failed Single Axle Test: Wheel Locked at 32 km/h
The figure shows a graph of two plots, vehicle speed and wheel speed. The beginning speed for both speed plots is approximately 50 km/h. This time as the vehicle speed approaches 35 km/h, the wheel speed begins to quickly head towards zero. When the wheel speed reaches zero, the vehicle is still traveling at 32 km/h. This point is said to be 100 percent slip. The amount of separation between the two plots prior to 35 km/h is approximately 5 km/h.

Figure 4.5 Test Vehicle's Front Suspension at Maximum Compression
The two photographs show a Honda CRV with the hood up. Many sandbags were placed on the top of the engine and shock towers in order to compress the front suspension springs. Both photos show the front fenders nearly touching the front tires and the rear fenders lifted well above the rear tires. The photo on the left shows the front tires and sandbags well. The photo on the right shows the relationship between how much the front was compressed and how the rear lifted. The photos also show that the CRV is sitting atop a vehicle scale, where the individual loads from each of the four tires can be measured.

Figure 4.6 Plot of Decreasing Vehicle Speed While Wheel Torque Increases
The figure shows two graphs. The graph on top shows two plots, the vehicle speed and wheel speed being braked from 40 mph. The vehicle speed decreases to zero over an 8-second period. The wheel speed drops to zero immediately upon braking because the wheel locked up. The bottom graph shows a plot of wheel torque from the wheel mentioned above during the same time period as the previously described graph. What one can deduce from this pair of graphs is that once the wheel was locked there was around 200 lb-ft of torque, which increased to 600 lb-ft of torque as the vehicle slowed to zero. These were provided to demonstrate that the coefficient of friction increased as the vehicle speed decreased, even when the wheel was not rolling.

Figure 4.7 Example of the Force Generated by a Tire at 100 Percent Slip
This figure shows a graph of the force versus slip curve used in Figure 4.2 with additional information. The curve starts at 100 lbs. of force at 1 percent of tire slip, and sharply increases to a peak of 910 lbs. at 15 percent of tire slip. The curve then steadily decreases to about 725 lbs. of force at 82 percent of tire slip. The additional information extends this decreasing slope to 100 percent of tire slip, then brings a horizontal line from right to left to show that the sliding frictional force exerted by this test tire was 680 lbs.

Figure 4.8 Examples of Force vs. Slip on Basalt
This figure shows one graph of each of the two most common types of force versus slip curves found during the basalt surface testing. Both curves start around 75 lbs. of force at 2 percent of tire slip, and gradually increase to their respective peaks between 30 and 50 percent of tire slip. The curve tapers off only slightly as tire slip approaches 80 percent.

Figure 4.9 Examples of Force vs. Slip on Wet Jennite and Wet Concrete
This figure shows two graphs of force versus slip curves, one from the wet Jennite surface and the other from a wet concrete surface. The wet Jennite curve starts at 75 lbs. of force at 2 percent of tire slip, and sharply increases to a peak of 380 lbs. at 15 percent of tire slip. The curve then sharply decreases to about 260 lbs. of force at 87 percent of tire slip. The wet concrete curve starts at 85 lbs. of force at 2 percent of tire slip, and sharply increases to a peak of 745 lbs. at 18 percent of tire slip. The curve then steadily decreases to about 685 lbs. of force at 81 percent of tire slip.

Figure 4.10 Wheel Speed and Brake Line Pressure During Low-to-High Coefficient Test
The figure plots the right front wheel speed from 32 mph to zero along with the brake line pressure fluctuating due to ABS cycling. As pressure first begins to rise, one sees the wheel speed dropping dramatically while still on the low coefficient surface. The wheel speed increases slightly upon transitioning onto the high coefficient surface, but less than two mph. The transition can also be seen due to the SunX channel, the second spike from that channel marks the timing at which the front tires crossed onto the high coefficient surface. After the transition, brake pressure continued to climb until the point that there was sufficient pressure to lock the wheel on the high coefficient surface. Near this point there are two notations on the brake pressure channel. The first is called recovery, which marks the local pressure maximum achieved after the transition. The second is called saturation, which is the next local pressure minimum after “recovery”.

Figure 4.11 Plot of Wheel Speed and Brake Line Pressure
The plot represents a stop from 65 mph on a low-coefficient surface. When brake line pressure first increases, wheel speed drops suddenly. In response, the ABS drops brake pressure and wheel speed increases. This process continues throughout the course of the stop because the ABS is searching for traction threshold between the tire and surface. The more the vehicle slows, the slower wheel speed gets and the higher the brake line pressure goes.

Figure 4.12 Plot Illustrating Hydroplaning During Low Coefficient Test Condition
The plot represents a stop from 75 mph on a low-coefficient surface. Wheel speed drops from 75 down to 28 mph very abruptly. Brake pressure drops immediately to let the wheel speed

increase, but the wheel speed hovers around 30 mph for about 0.75 seconds. This indicates ‘no traction’ and is due to the fact that the water on the low coefficient surface is causing this tire to hydroplane.

Figure 4.13 Simplification of Braking Forces and Resulting Moment of Vehicle
The diagram is a force diagram of a split-coefficient stop. Looking down from above, it shows the vehicle moving forward (left-to-right) with its two left side tires on Jennite and its two right side tires on asphalt. When the brakes are applied, the forces generated by the tires on asphalt are greater than those on the Jennite, resulting in a clockwise rotation or moment.

Figure 4.14 Handwheel Angle During a Split-Coefficient Stop
The plot shows that the driver performs almost all of the steering effort within the first second from the time the brakes are applied. In the stop depicted, the driver steers 47 degrees from the reference angle. A maximum of 52 degrees was recorded in this same stop.