

DEVELOPMENT OF A SKID RESISTANCE MEASUREMENT
METHOD FOR CITIES AND COUNTIES
(A Diagonal Braking Vehicle)

Prepared

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DISCLAIMER

The conclusions and opinions expressed in this report are those of the authors and do not necessarily represent those of the State of Texas, the State Department of Highways and Public Transportation, or any political subdivision of this state or the United States government.

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SUMMARY

The self-watering Diagonal Braking Vehicle (DBV) developed on this project could be an economical means by which cities and counties might determine levels of wet pavement friction. It has the advantage of being able to operate in the traffic stream with a minimum of interruption to traffic flow and requires a limited amount of traffic control in conjunction with its operation.

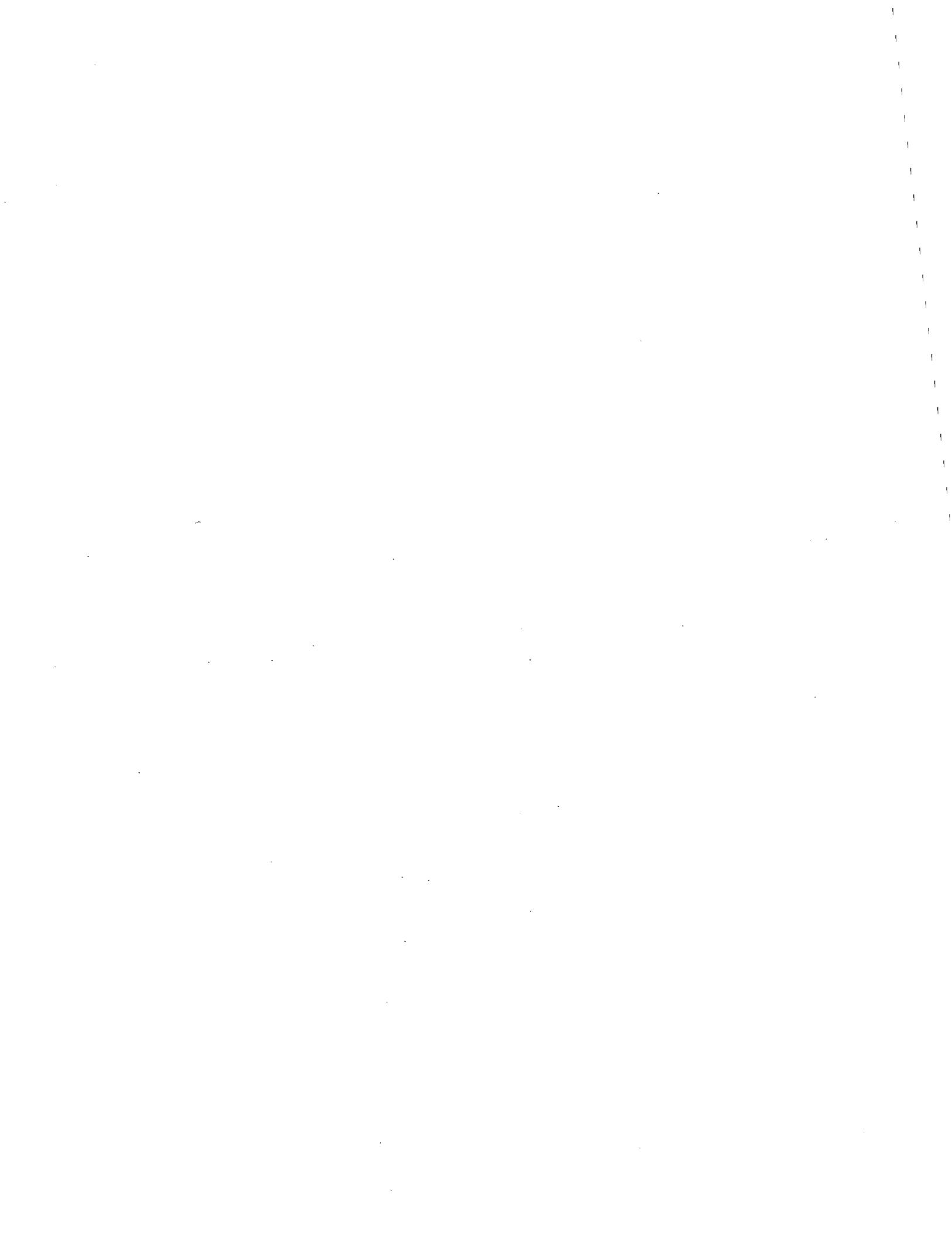
As shown in the report, this DBV locked-wheel mode of friction measurement is highly correlatable with the ASTM E 17 type of inventory skid measurement system.

The cost of a DBV is about one fourth that of a locked-wheel skid trailer.

It is not intended that the DBV, with a limited amount of instrumentation, be used as a road inventory type system.

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DEVELOPMENT OF AN ECONOMICAL AND PRACTICAL
METHOD OF SKID MEASUREMENT FOR CITIES AND COUNTIES

Investigation of vehicle skidding accidents on highways and streets often requires the measurement of the pavement skid resistance at the accident site to aid in determination of accident causation. This measurement should be made as quickly as possible after the accident to ensure that the pavement surface has not changed characteristics between the time of the accident and the time of the test. Due to the limited size of the present Texas skid measurement system fleet, it is often impossible to detail a skid trailer to support an accident investigation, and if a skid measurement is made, long delays can occur between the time of test and the time of the accident. Small cities and towns with low mileage street networks cannot justify buying a costly locked-wheel skid trailer to measure pavement skid resistance. Obviously, a need exists for an inexpensive and reliable test device or technique that can be used as an alternative or to supplement the current fleet of more expensive skid trailers in street accident investigations and to make non-routine skid resistance measurements on city or town streets and county road systems.

The purpose of this project was to evaluate both the static and dynamic friction measuring devices and systems in use at the present time. After an indepth review of the literature, the decision was made to build and test a self watering diagonal braking vehicle (DBV). From the literature review and personal contacts with people involved in friction measurement, it appears this is the first time the self-watering capability has been added to a diagonal braking vehicle. The diagonal braking concept has been used for many years by the National Aeronautic's

and Space Administration (NASA), the United States Air Force (USAF) and the Federal Aviation Administration (FAA). In the case of these using agencies, the application of water to the surface being tested has been accomplished by using a water tank truck, a sprinkler system or testing during natural rainfall or shortly after the rain had stopped.

FRICTION MEASUREMENT SYSTEMS OVERVIEW

A number of wet pavement friction measuring systems were investigated for use by cities, counties and traffic accident investigators. These systems vary widely in the method of measurement and the procedures followed to attain a wet pavement friction measurement. The differences between the systems are discussed briefly and the aspects of the systems that are common to all systems are compared in order to evaluate the abilities and/or limitations of a system when compared to the other systems as a group.

The systems fall into two basic catagories, static and dynamic. Static pavement friction measuring systems are systems that are placed on the test site and while the unit as a whole remains stationary, a measurement is taken. They are primarially used in laboratories but may be used on city street or highway surfaces.

Dynamic pavement friction measuring systems are systems that are, as a unit, moving across the test sight at the time the measurement is taken. These units are sub-divided into three modes of testing; locked-wheel (skid), brake slip and cornering slip modes.

A locked-wheel or skid mode is a condition where the rotation or angular velocity of the tire has stopped and the tire is heading in the direction of travel, as shown in Figure 1. There is a 0° angle between the tire plane and the direction of travel. This is the most common means of determining pavement friction.

The brake slip mode is a condition where the angular velocity of the slipping tire is less than the angular velocity of a rolling tire corresponding to vehicle speed (Figure 2). The brake slip is zero for a free rolling wheel and becomes 100 percent when the wheel is locked.

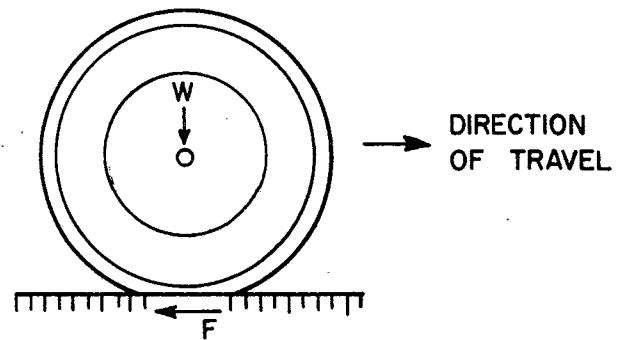
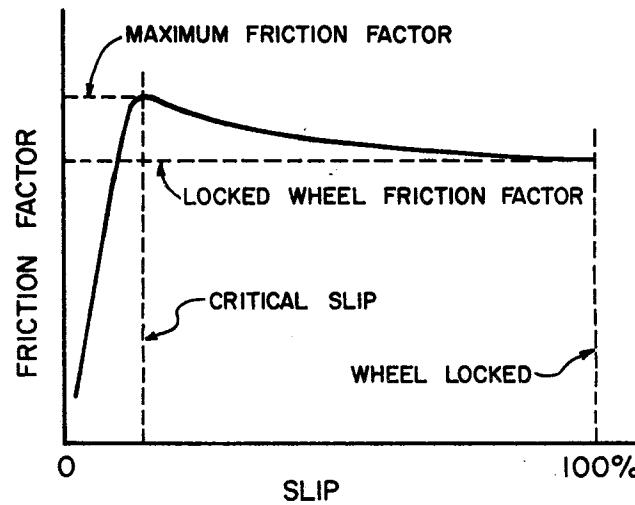


Figure 1 . Friction Characteristics of a Tire
Operating in a Locked-Wheel Mode. (1)

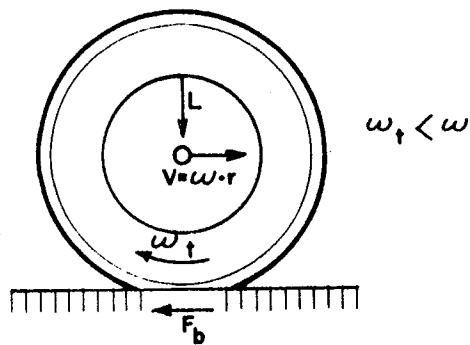
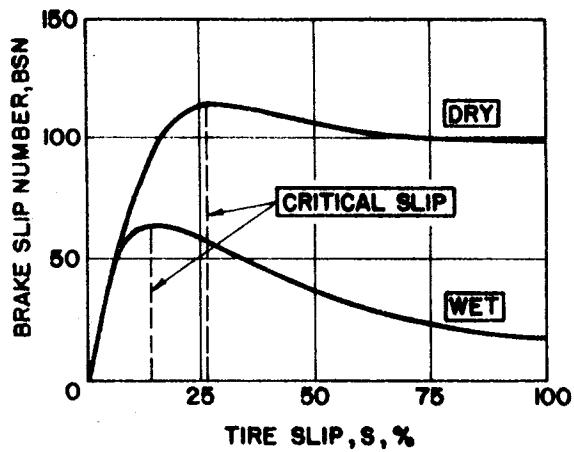


Figure 2. Frictional Characteristics of Tires
Operating in the Brake Slip Mode. (1)

Initially the pavement friction increases as the brake slip increases. At the critical brake slip, the available friction is at its maximum and any farther increase in the brake slip will result in the reduction of available friction. In the brake slip mode, there is a 0° angle between the tire plane and the direction of travel.

The cornering slip mode exists when there is no attempt to change or vary the angular velocity of the rolling tire and the angle between the tire plane and the direction of travel is some value other than 0° (Figure 3). The level of available friction initially increases as the slip angle, $\alpha \approx 0$, increases until it reaches the "critical slip angle". From that point on, the available friction decreases.

The aspects of skid measurement systems that are common to all systems include:

1. precision of measurement
2. accuracy of measurement
3. mobility and maneuverability
4. traffic interference
5. crew comfort and safety
6. durability
7. initial cost
8. maintenance and operating costs
9. ease of retrieval of data and giving it to user in a practical form

Precision refers to the ability of an individual system to repeatedly get the "same number" when testing the same site under identical conditions.

Accuracy is defined as conformity to truth or to a standard or model. The accuracy will be determined by the ability of a system to

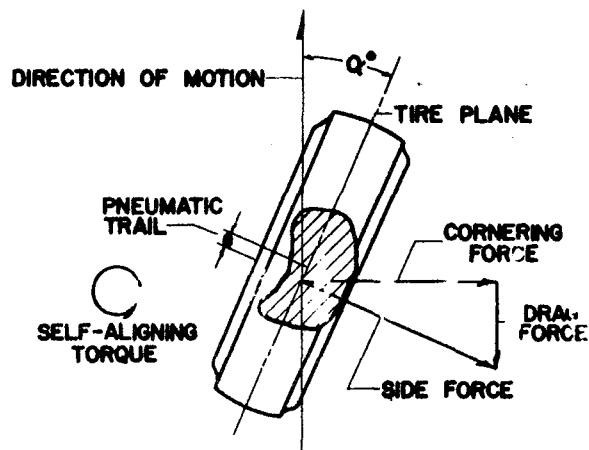
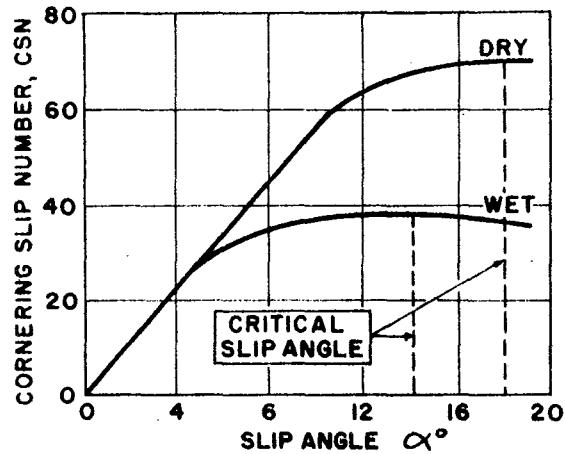


Figure 3. Frictional Characteristics of Tires
Operating in the Cornering Slip Mode. (1)

correlate with the standard. The locked-wheel skid trailer designed and fabricated in accordance with ASTM Method E-274 (2) is the most refined and most commonly used pavement friction measuring system used in the United States. For that reason, the E 274-79 locked wheel skid trailer will be considered the "standard or model" for this report.

Mobility and maneuverability, traffic interference, and crew comfort and safety refer to the physical bulk of the system. How it will mix into the traffic stream and any hazards created by these factors must be considered.

One must consider the initial and long term cost of owning and maintaining the system.

STATIC FRICTION MEASUREMENT SYSTEMS

British Pendulum Tester (BPT)

The most common static pavement friction measuring system is the British Pendulum (Portable) Tester (Figure 4). The British Pendulum Tester (BPT) is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider edge is propelled over a test surface. The tester is suited for laboratory as well as field tests on flat surfaces, and for polish value measurements on curved laboratory specimens derived from accelerated polishing-wheel tests.

The BPT was developed by Dr. P. A. Sigler of the U. S. National Bureau of Standards and later perfected by the British Road Research Laboratory. It is used extensively by the British.

The BPT consist of a stand on which is mounted a pendulum arm, a pointer and a scale. A three inch by one inch by one quarter inch block of tread rubber is mounted on the end of the pendulum arm at a 20° angle to the surface of the test specimen so that only the trailing edge makes contact with the specimen. The stand can be leveled by adjusting the three leveling screws on the base of the stand. Procedures for leveling, zero and slide length adjustments are described in detail in American Society for Testing Materials (ASTM) Standard E 303-78 (3).

The procedure for making a surface friction measurement is as follows:

1. Apply sufficient water to cover the test area throughly.
Execute one swing, but do not record reading.
2. Without delay, make four more swings, rewetting the test area each time and record the results.
3. Recheck the slide contact length.

The surface friction is determined by the energy loss in the pendulum which is indicated by the height of the swing of the pendulum after it passes over the surface.

The precision of the BPT is inconsistent as noted by Norbert L. Enrick (4). The inconsistency is due to the variances in operator technique rather than variances in the BPT. The BPT does not correlate well with the locked-wheel trailer. The British Portable Tester not only measures friction at relatively low speed (7 mph or less), but it also brings the edge of a rubber shoe into contact with the pavement or pavement sample. Consequently, any correlation with Method E 274 would be purely fortuitous.

The BPT is light, can be moved easily by one man, and is relatively rugged and dependable. However, when it is used in the field, the traffic on the street must be either stopped or diverted while the test is being made. This creates a safety hazard for the people making the test.

The BPT has a very low initial cost, approximately \$7,000. The only expendable item is the block of tread rubber which has to be replaced after 500 swings on the average surface. The tester is of a very simple design and should require minimal maintenance. It can test 20 to 25 sites per day and will require a minimum crew of two to three personnel. The crew requirement is due to the stopping or diverting the traffic.

The results of the test are numbers that are read off of the scale on the tester as shown in Figure 5. Errors in the results will come primarily from wrong adjustments during setup, improper water level on test surface, and/or incorrect reading of the scale.

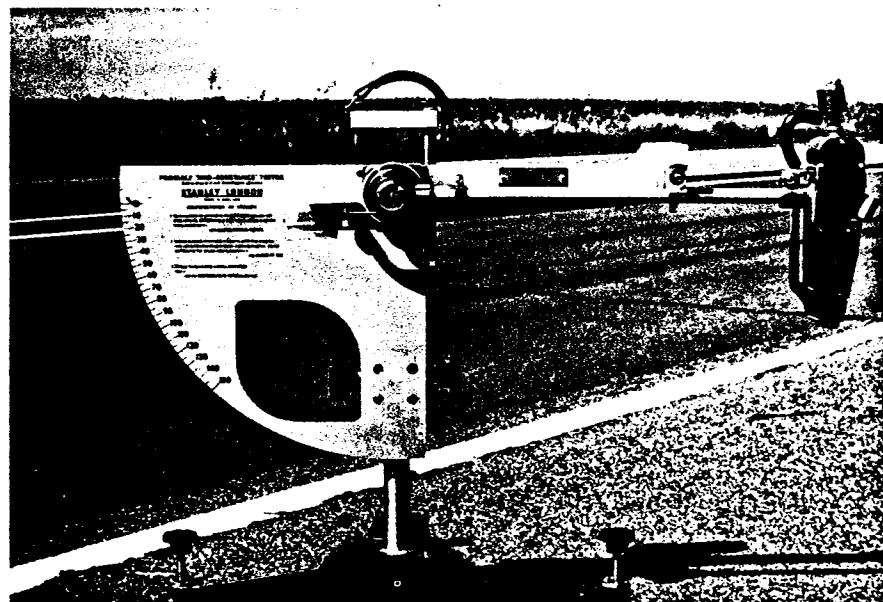


Figure 4 . BPT in Pre-Test Position.

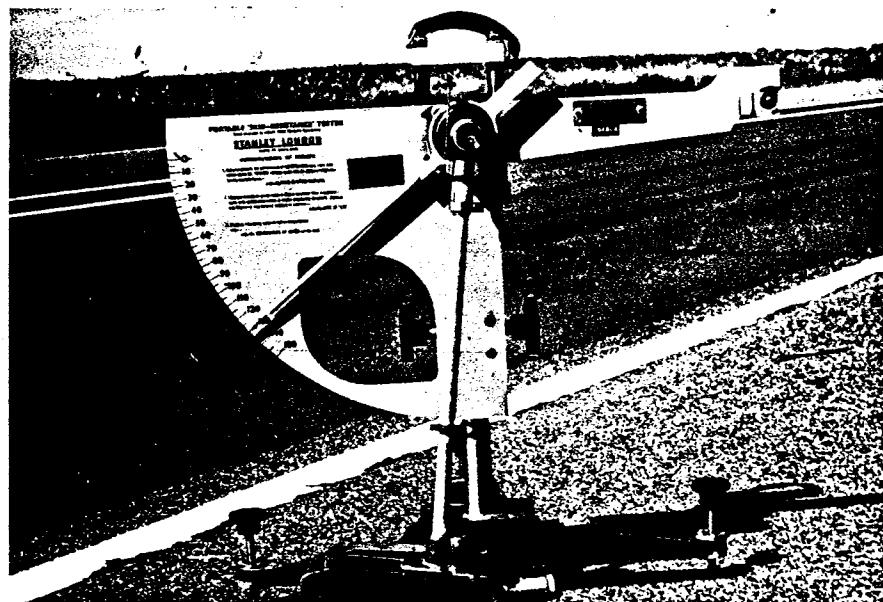


Figure 5 . BPT in Post-Test Position.

North Carolina Variable Speed Friction Tester (VST)

The Variable Speed Friction Tester (VST) is a pendulum type tester that measures the energy lost in friction when a locked wheel tire with smooth tread rubber contacts a wetted pavement. The effect of vehicle velocity on pavement friction is represented by a nozzle which directs a stream of water at test velocity across the surface being tested.

The VST (Figures 6 and 7) was developed under the Highway Research Program of North Carolina State University in cooperation with the North Carolina Department of Transportation and the Federal Highway Administration of the United States Department of Transportation.

The VST has been fabricated into three modules or assemblies. The principal module is the tester unit consisting of pendulum and wheel, frame, nozzle and associated controls. The water supply module contains the water supply tank, pump, valves and controls. The laboratory stand provides a mounting for the tester and water supply modules, a test specimen holder, and a plexiglas spray shield to collect the nozzle discharge and direct it to a drain.

There are adjustments such as leveling, zeroing, tire positioning, water pressure, nozzle position and so on that must be made in preparation for testing. The procedure for making the adjustments is outlined in the North Carolina State University Highway Research Program Report No. ERSD-110-76-2, Final Report, Part III (5) and ASTM Standard E 707-79 (6).

A normal test sequence for a single laboratory specimen or field pavement location will include determination of wet friction values at 8 mph and at three other test velocities. These are usually for 30, 40 and 50 mph.

The basic steps in a test procedure include:

1. Level VST arc
2. Zero pendulum swing
3. Set pendulum contact force
4. Adjust nozzle pressures
5. Adjust nozzle angle
6. Make VST friction measurements

The precision of the VST is consistent if the dead weight method is used to set the contact arc between the pendulum and the test surfaces.

The VST was correlated with the North Carolina DOT ASTM skid trailer on both bituminous surfaces and portland cement concrete surfaces. The correlation was conducted at 30, 40 and 50 mph. There is a high correlation between the VST and the ASTM locked wheel trailer at all three speeds. The correlation was unaffected by either pavement surface type or texture.

The VST requires a trailer to carry the test module and the water supply module to the test sites. Although the trailer is maneuverable enough in traffic, two men are needed to lift and move the test module into position. Once in position, traffic must be either stopped or diverted from that lane during the test. This creates a safety hazard for the men making the test.

The initial cost of the VST would include the fabrication of the test module, water supply module and the trailer used to transport it to the test site. A tow vehicle is required to pull the trailer.

The maintenance on a VST should be low. The wheel on the pendulum will require occasional replacement and parts on the water supply system will have to be replaced due to normal wear and tear.



Figure 6 . Overall View of North Carolina Variable Speed Friction Tester.

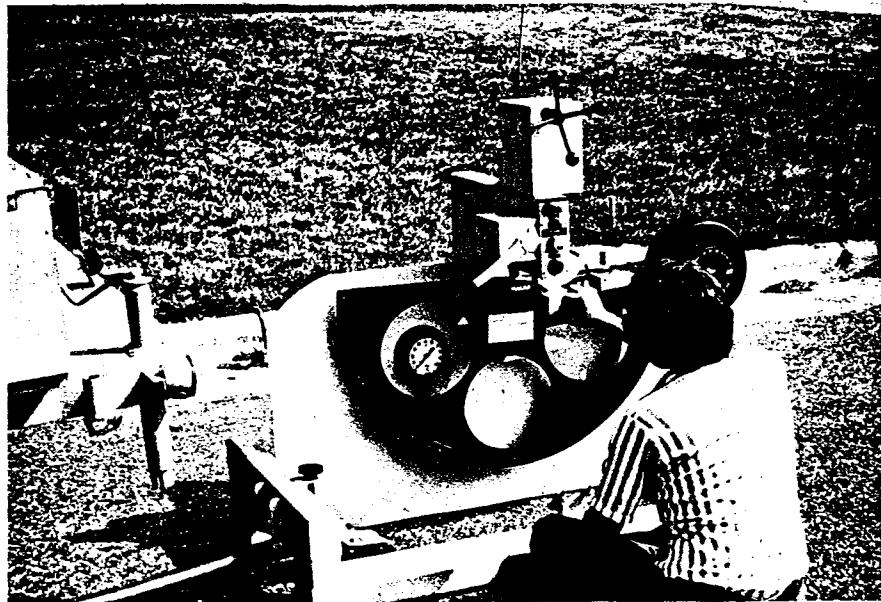


Figure 7 . North Carolina Variable Speed Friction Tester Apparatus.

It can test 8 to 12 sites per day and will require a crew of two to three personnel. The crew requirement is due to the stopping or diverting of the traffic at the site of the test.

The results of the test are numbers that are read off of a scale on the tester. Errors in the results will come primarily from wrong adjustments during setup, improper water supply adjustments and/or incorrect reading of the scale.

Photo-Interpretation

In Photo-Interpretation, the skid resistance is determined by analyzing stereo photographs of the pavement surface texture, where the macro and micro projections are measured and classified (7,8). Photo-Interpretation has been researched by Mr. R. Schonfeld of the Ontario Ministry of Transportation and Communications. ASTM Standard E770-80 is the Standard Test Method for this procedure (9).

The equipment used includes:

1. 35 mm S.L.R. camera with close-up lens
2. camera box (Figure 8)
3. flash unit
4. miscellaneous accessories

Stereo pairs of photographs are taken of the pavement and later studied and classified according to six texture parameters. The six parameters are as follows:

1. 'A' -height of macroprojections
2. 'B' -width of macroprojections
3. 'C' -angularity of macroprojections
4. 'D' -density of distribution of macroprojections
5. 'E' -harshness of macroprojection surfaces
6. 'F' -harshness of microprojection matrix surfaces

When examining the actual pavement surfaces or the stereophotographs, the photo interpreter gives the surface a six digit code referring to each of the above parameters. Once a section of pavement has been coded, the surface texture can be fully described by the parameter numbers, and the skid number for that surface can be calculated.

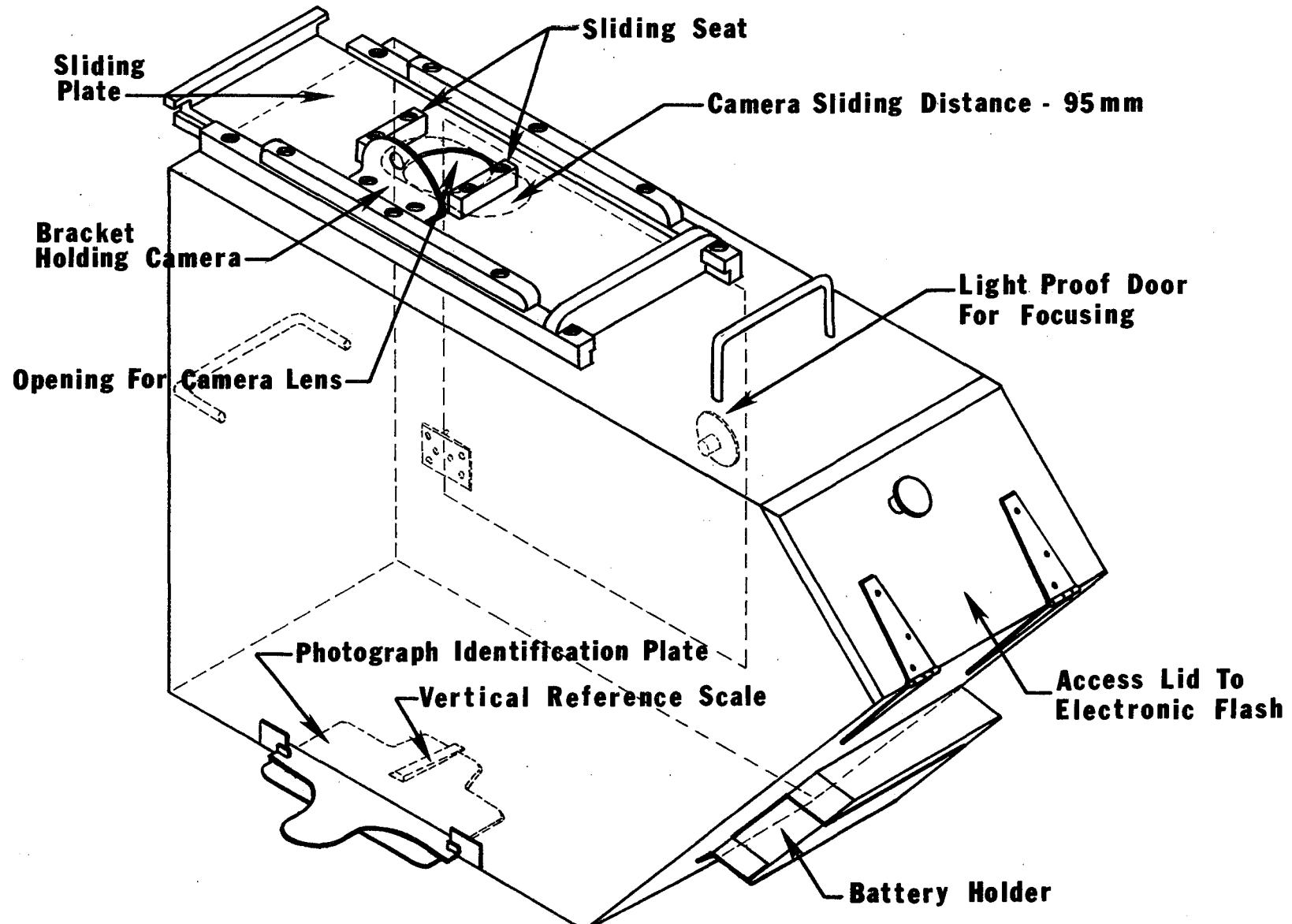


Figure 8 . View of Stereophotography Camera Box.

In a correlation with an ASTM locked-wheel trailer, the correlation coefficient of skid resistance between Photo-Interpretation and the locked-wheel trailer was 0.93 for speeds of 30 and 60 mph in a correlation conducted by the Ontario Department of Highways. The standard deviation was 2.96 at 30 mph and 2.24 at 60 mph. The results of the correlation shows a fair to good accuracy and precision when using Photo-Interpretation.

The equipment used in photo-interpretation is small and light. It can easily be moved and setup by one man and can be carried in a car or van. Because the unit is a stationary skid measurement system, traffic in the lane being tested must either be stopped or diverted. Again, this creates a safety hazard for the men making the photographs.

The initial cost of the system is about \$500.00, which includes the camera and box. Maintenance is minimal with routine care given to the camera.

The unit should be able to photograph 40 to 50 sites per day with a crew of two to three people. The extra personnel are needed to provide traffic control.

The handling and processing of the data once it has been collected will be the most expensive part of the skid resistance measurement. The man-hours involved in analyzing the photographs will quickly eliminate the advantage of a low initial cost. Training will be very important because of the errors that can be introduced by human analysis of the six controlling parameters.

One positive aspect is the photo interpretation of skid resistance is not affected by roadway geometry.

DYNAMIC FRICTION MEASUREMENT SYSTEMS

Locked-Wheel Trailer

Locked-wheel trailers measure the horizontal and vertical loads acting on a locked-wheel tire being pulled across a pavement at a constant rate of speed. The tow vehicle and trailer are equipped with a water supply, a metered water dispensing system as well as proper instrumentation and controls (Figures 9 and 10).

There are approximately 100 units in use in the United States.

The mechanical and electronic design and test procedure for a locked-wheel system is governed by ASTM Standard E 274-77 (2) The tire used is governed by ASTM E501 Treaded (10) and ASTM E 524 Smooth (11) Standards.

The locked-wheel trailer has shown a high degree of both precision and accuracy. The truck and trailer combination is highly maneuverable and obviously mobile. The speed during the test sequence remains constant, and therefore, the test provides very little to no interference with traffic. With environment control in the tow vehicle, the crew can remain comfortable in all types of weather.

The initial cost of a tow vehicle and ASTM E 274 locked-wheel trailer is approximately \$100,000. On the average day, this type of system can survey 150 - 175 miles of highway.

The maintenance on the unit is comparatively high due to the degree of sophistication incorporated in the new systems. Although the initial cost and maintenance of the unit is comparatively high, it is one of the most economical means to inventory pavement friction due to its high test cycle frequency. The locked-wheel trailer requires a crew of one or two personnel.

Data handling and processing has been completely automated in many of the locked-wheel trailer units. This reduces both the cost of data reduction and the amount of error entered by people handling the data.

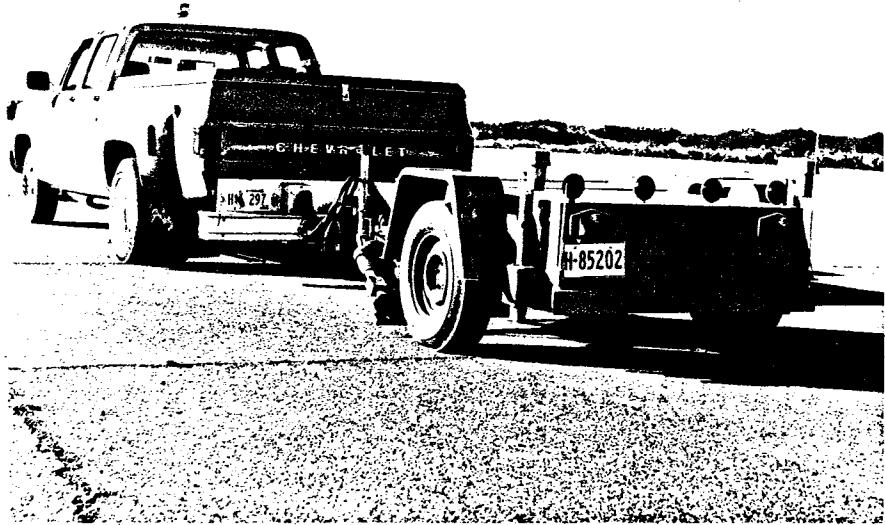


Figure 9 . Locked-Wheel Skid Measurement System.

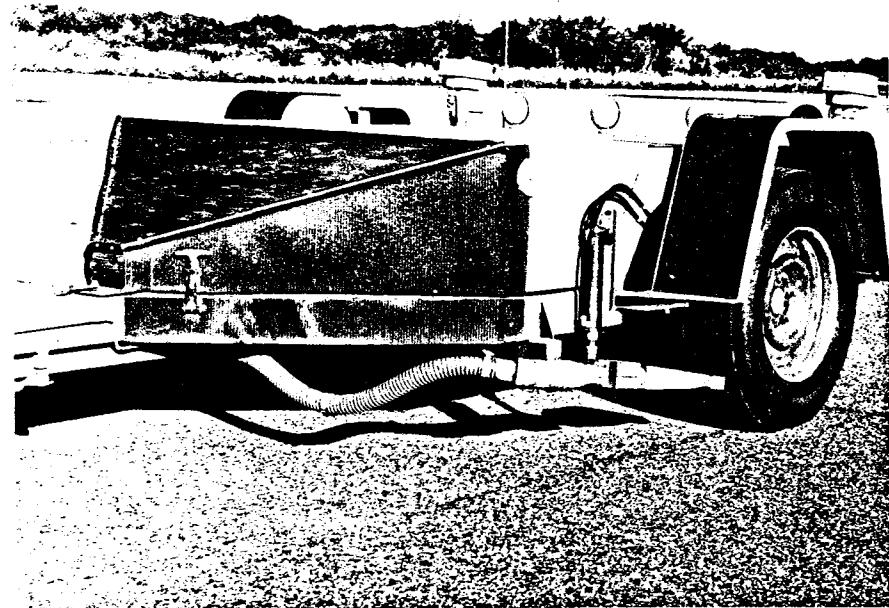


Figure 10. Locked-Wheel Skid Trailer.

Four-Wheel Lock Test Technique

The measuring instrument used is a passenger vehicle or light pickup with the necessary instruments added. This four-wheel and two-wheel locked vehicle test technique for measuring pavement skid resistance has been employed in the United States since 1937 and was begun at least several years earlier in Europe. Instrumentation required for this test has gradually evolved from a detonator on the test vehicle which fires a chalk bullet at the pavement at the instant of brake application and a steel tape for measuring the distance from the chalk mark on the pavement to the vehicle after it has come to rest at the end of the skid. The more modern technique uses a fifth wheel which is actuated by application of the brake pedal and records the speed at brake application and measures the distance through which the vehicle travelled while skidding to a stop. Some states still use this test technique to investigate highway accidents and to supplement trailer skid testing. ASTM E 445 is the procedure governing this method of testing (12).

The basic procedure is as follows:

- (1) Pavement Wetting -- Wet the test lane at the test site just prior to skid testing using a water wagon equipped with spray bar or other means of distributing water evenly and rapidly. Make at least two applications of water until the surface is well saturated (surface cavities filled with water and runoff results). Wet a sufficiently long segment of the test lane to permit the test vehicle to proceed onto a wet surface and to allow the driver to adjust the speed before brake application. Rewet the test lane between each test as required.
- (2) After the pavement in the test lane is wetted, bring the

vehicle above the desired test speed and permit it to coast (transmission gear in neutral) onto the wetted section until the proper speed is attained. Apply the brakes promptly and forcefully to cause quick lockup of the wheels and to maintain a locked-wheel condition until the vehicle comes to a stop. Note the speed at the moment of brake application.

- (3) Distance Counter Reading -- Set the distance counter to zero prior to testing and record the total counts accumulated during the skid. If a strip-chart recorder is used for the purpose of measuring stopping distance, the recorded pulses may be counted later, but the chart shall be properly identified.

The four-wheel lock system has shown a high degree of correlatability with the locked-wheel trailer and with a low standard deviation. The characteristics were demonstrated in the 1967 Florida Skid Correlation Study (13).

The four-wheel lock system is a passenger car or small truck and therefore is both mobile and manuverable. Because the test requires bringing the vehicle to a full stop, the system does interfere with the flow of traffic. This creates a safety hazard for the crew conducting the test and the general public.

In addition, there is no control over the direction of the vehicle while the wheels of the vehicle are locked. This can create a very dangerous situation if the test is conducted on a busy street.

The initial cost includes the vehicle and the necessary instrumentation. The initial cost is low compared to the other dynamic systems. Maintenance required is primarily routine upkeep of the test vehicle. The system can test 15 to 25 sites per day with a crew of three

to five people.

The data gathered is the distance traveled by the vehicle before coming to a full stop. This is represented in digital form and is subject only to errors in calibration of the equipment. By using a formula, friction number can be calculated with the data acquired. ASTM E445 is the standard test method used for four-wheel lock-up (12).

Mu-Meter

The Mu-Meter is a continuous recording friction measuring trailer (Figures 11,12). It measures the side-force friction generated between the test surface and the two pneumatic tires which are set at a fixed tow-out angle of 7-1/2 deg to the line of drag (cornering slip mode).

The Mu-Meter is manufactured by M. L. Aviation Company Limited of England and the basic design of the Mu-Meter is shown in Figure 13. The Mu-Meter was originally developed to measure the surface friction conditions of airport runways. In 1970, the Arizona Highway Department initiated a research program sponsored by the Federal Highway Administration. As part of the program, an evaluation of the adaptability of the Mu-Meter as a standard highway friction measuring trailer was conducted. During 1979, the ASTM Standard E 670 was approved and governs the measurement of side force friction on paved surfaces using the Mu-Meter (14).

Because of the 7 1/2 deg toe-out angle of the two tires, pulling the Mu-Meter over a surface produces a frictional force which tries to pull the tires outward and is sensed by a transducer located in the apex of the trailer's A frame. The resulting hydraulic pressure is transmitted through a flexible line on the recorder's bourdon tube and recording mechanism. The recorder stylus makes a trace on the moving pressure-sensitive chart paper (Figure 14). The chart paper moves at a rate of one inch for every 450 feet of surface tested.

The basic test procedure, as stated in ASTM Method E 670-79, is as follows:

1. Bring the apparatus to the test speed. Deliver water to the test tires approximately 1 second before the test is initiated

and continue until the test is completed. Indicate the beginning and end of the test by means of the event marker.

Stop the water delivery approximately 1 second after completion of the test.

2. Evaluate the recorded trace between the two event marks. The trace averaged between these two points is the Mu Number.

When, in the Arizona study, precision or repeatability of the Mu-Meter was being evaluated, it was determined that although the fluctuation in any particular test increased with speed, the standard deviation of the average friction number did not. At 40 mph, the standard deviation was found to be 1.4 friction numbers, which is considered good for a friction measuring trailer (15,16).

Correlations between the Mu-Meter and the ASTM locked-wheel trailer were found to be fairly good when both units were equipped with the treadless or smooth tires and the surfaces being tested were wetted in the same manner. The correlation coefficient ranged from 0.92 to 0.96 over the three speeds of 20, 40, and 60 mph (16).

When the Mu-Meter with smooth tires is compared with the locked-wheel trailer equipped with ASTM E-501 treaded tires, the correlation coefficients dropped to 0.86, 0.80 and 0.75 at 20, 40 and 60 mph, respectively. The decrease in the correlation coefficient with increased speed is attributed to the relative difference in the drainage capabilities of the smooth versus the treaded tires.

With the modifications developed by the Arizona study, the Mu-Meter is highly maneuverable and it is now possible to conduct numerous test without stopping or interfering with traffic flow.

Being a dynamic system, the test crew have the comfort and safety of

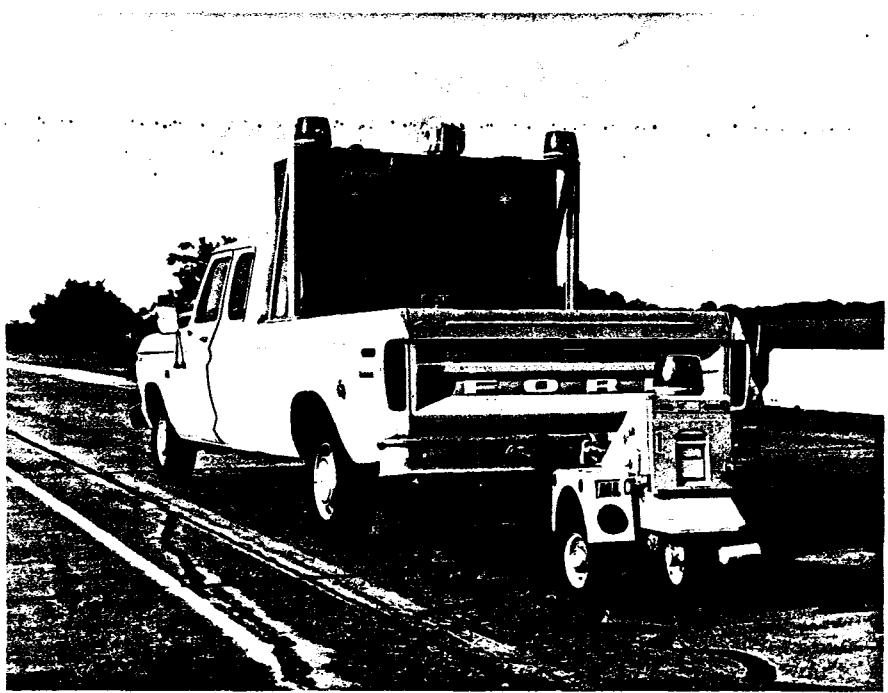


Figure 11. Overall View of Tow Vehicle and Mu-Meter Trailer.

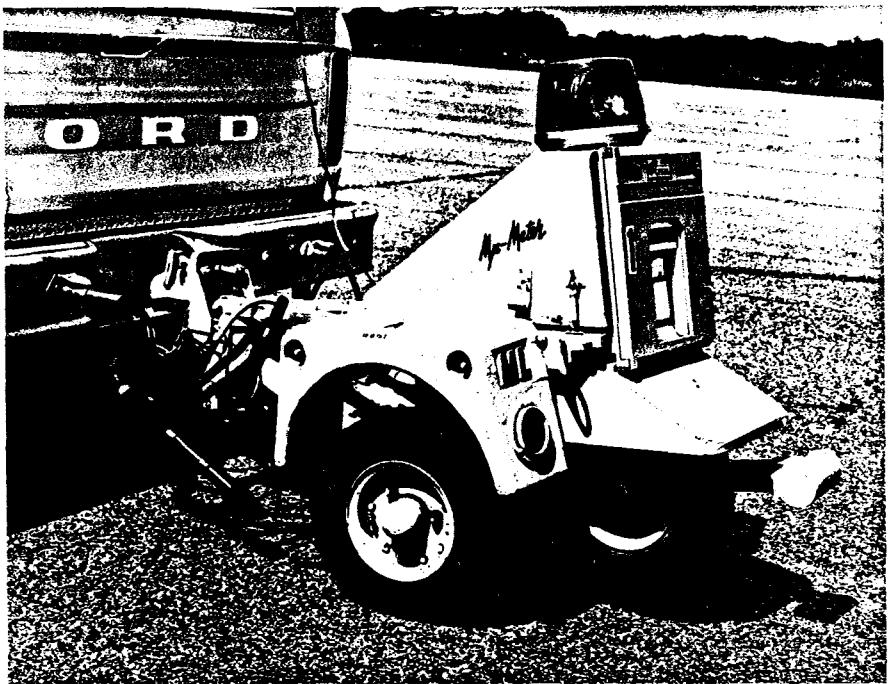


Figure 12. Mu-Meter Trailer

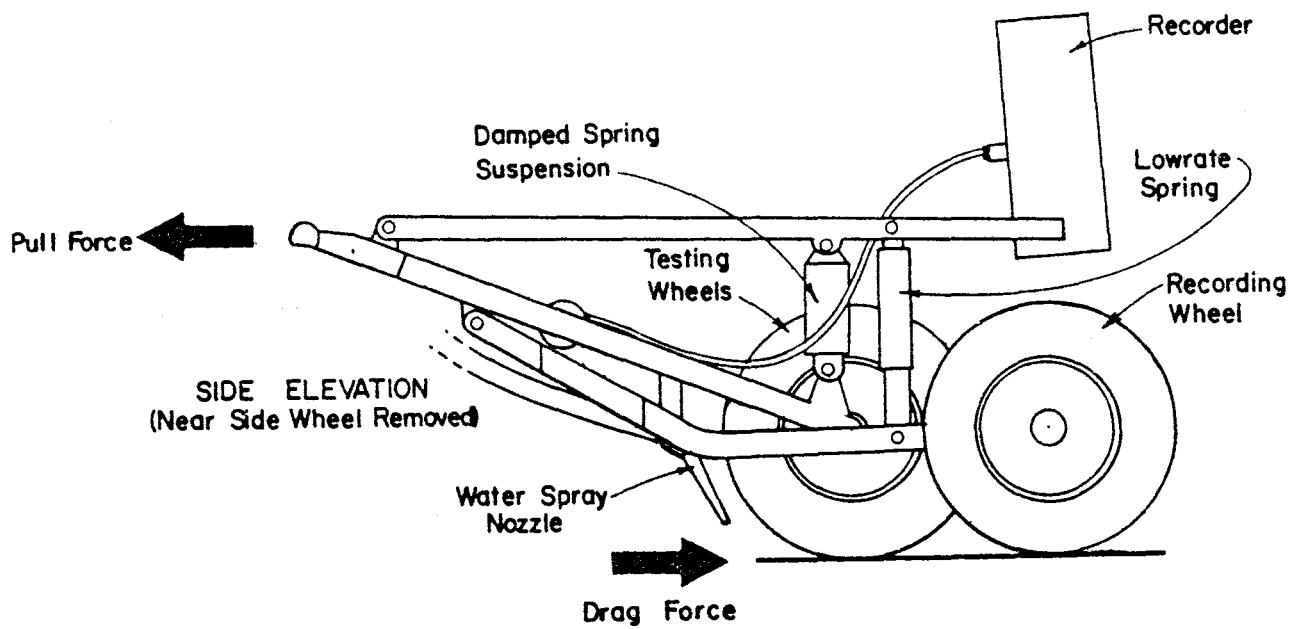
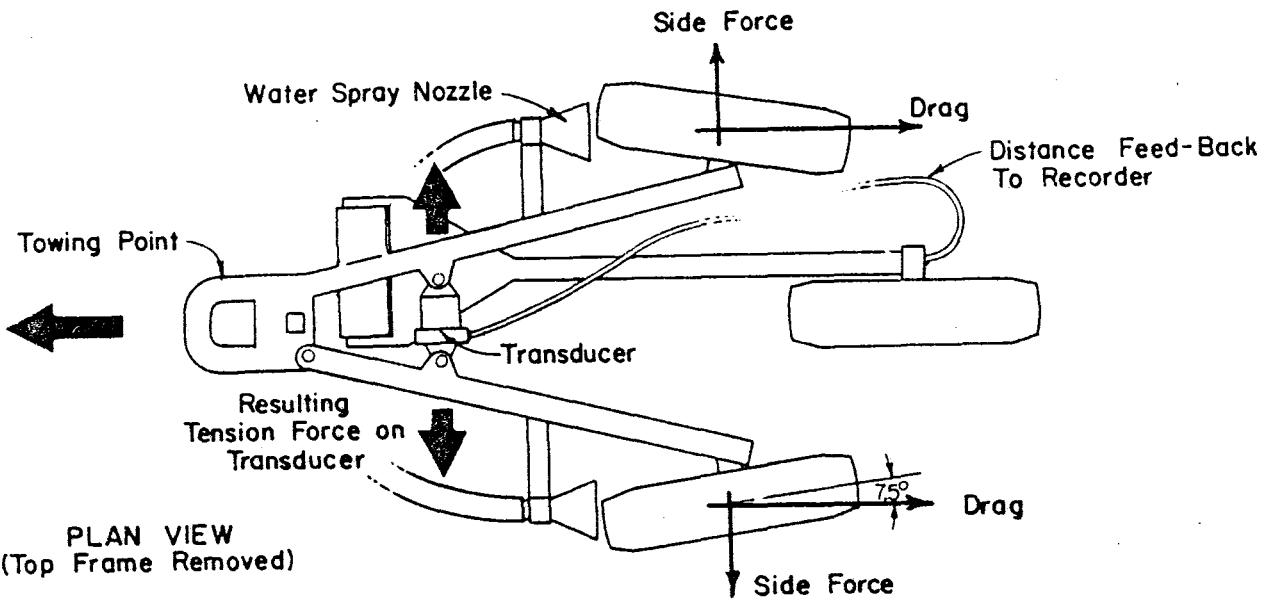


Figure 13. Mu-Meter Schematic.

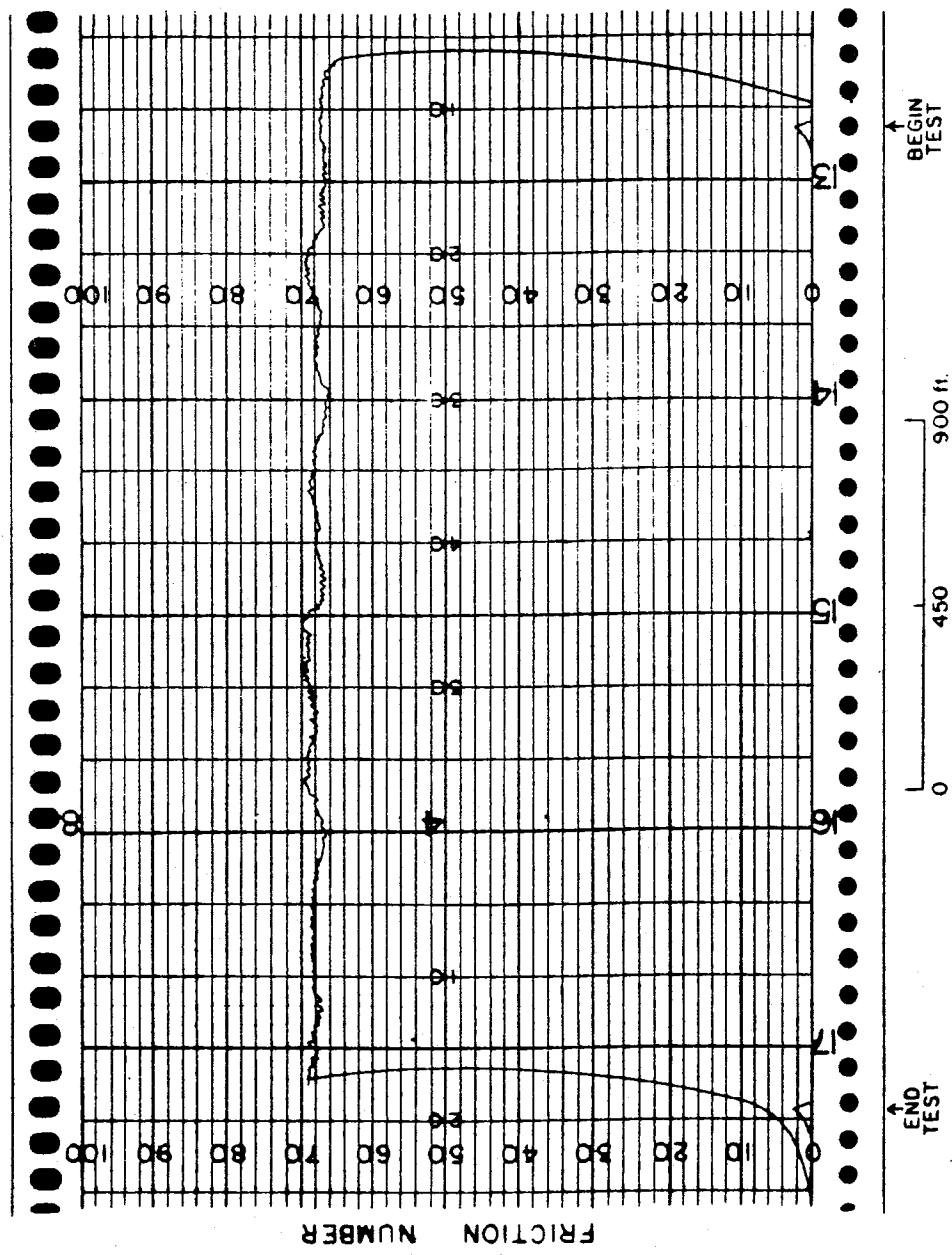


Figure 14. Mu-Meter Chart.

being in the truck cab and not exposed to the traffic on the street.

The Mu-Meter has a medium range price tag for both the Mu-Meter and tow vehicle and is approximately \$65,000. Routine maintenance of the two vehicles and calibration of the test unit is required.

Using this system, approximately 150 - 175 lane miles of highway can be tested in one eight-hour day. The normal test speed is 40 mph with higher speeds possible. The basic test crew consist of one or two people.

The earlier airport runway version had results on a graph which made data reduction an inefficient and slow process that increased the opportunity for error. Current models have been fitted with micro-processors used to coordinate the test cycle and compute and print the Mu-Number.

Saab Friction Tester

The Saab Friction Tester is a Saab front-wheel drive automobile with equipment added for the purpose of measuring wet pavement friction in the brake slip mode (Figure 15).

The tester is manufactured by Saab-Scania in Sweden. At this time, there are 79 units in existence, one in the United States, thirty seven in Sweden and forty one in other countries around the world. The tester was designed for use on airport runways and is just recently being modified for more efficient use on roadways.

In the car is installed a measuring wheel almost in line with the left rear wheel (Figure 16). The size of the measuring wheel is 4.00-8" and it is hydraulically loaded and retractable. During measuring cycles, the wheel has a constant braking slip of 15%. The braking torque is transferred via a chain transmission as a driving torque from the left rear wheel. The torque of the measuring wheel is measured by strain gauges feeling the tension in the chain. The measuring wheel is normally freewheeling and during measuring cycle is engaged to the rear wheel by a magnetic clutch thus allowing very short measuring sequences (down to 2 sec).

A water pump of the rubber impeller type is installed above the rear axle of the car and is driven by a belt from the intermediate axle of the measuring wheel system. This means that the pump rpm corresponds to the speed of the car, giving a constant water flow per travelled distance and independent of the speed. The pump is engaged by a magnetic clutch.

The test sequence is automated with the exception of lowering and raising the rear wheel. This measuring system is not controlled by an ASTM standard.

The only studies on the precision and accuracy of the Saab Friction Tester have been in relation to the friction available to landing aircraft. It is understood there has been a recent study made correlating the Saab Friction Tester to the ASTM locked-wheel trailer and other friction measuring systems. A report of that correlation has not been made available.

The tester is a dynamic system and should provide a minimum of interference with traffic on the street. The crew should be comfortable and well protected inside the vehicle. The initial cost of the Saab Friction Testers is approximately \$65,000. Maintenance will be moderate to high for the vehicle and the test unit.

The tester should be able to test 150 - 175 lane miles per day with a crew of one to two people. The data processing is completely automatic, printing both a tracing output and an average friction number for the test section.



Figure 15. Overall View of Saab Friction Tester.

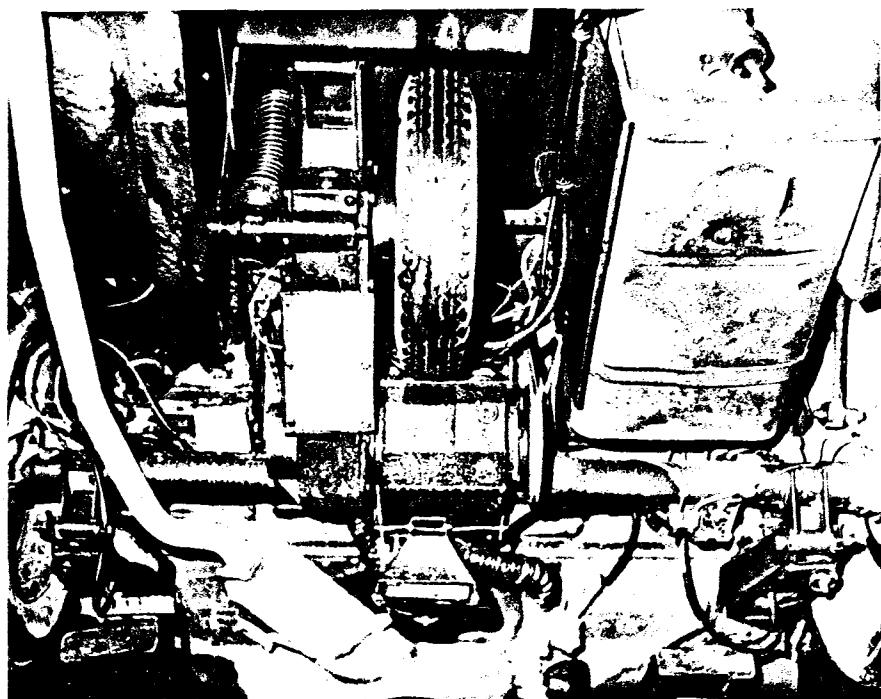


Figure 16. Test Wheel and Water Nozzle on
Saab Friction Tester.

SCRIM Measurement System

Another type of dynamic friction measuring system which was developed at the Transport and Road Research Laboratories in England is a device called SCRIM (Sideways-Force Coefficient Routine Investigation Machine). It has been in existence since the early 1930's and used primarily in England and Europe. At the present time, there are no SCRIM machines used in the United States.

The SCRIM (Figure 17) consists of a truck chassis with a water tank, controlled-flow water sprays mounted just ahead of the test wheels, two test wheels mounted centrally on each side of the vehicle and the necessary instrumentation to collect and record data from load cells in test wheel's axle. During testing, the test wheel is extended on an adjustable suspension to give a constant ground loading. The whole test wheel assembly is mounted so that the wheel's rotational direction is toed-in at 20° to the vehicle's straight-ahead travel. Running at a toed-in angle as it does, the test wheel is pushed inwards as the vehicle moves ahead. The greater this sideways force, the greater the skid resistance of the surface being tested.

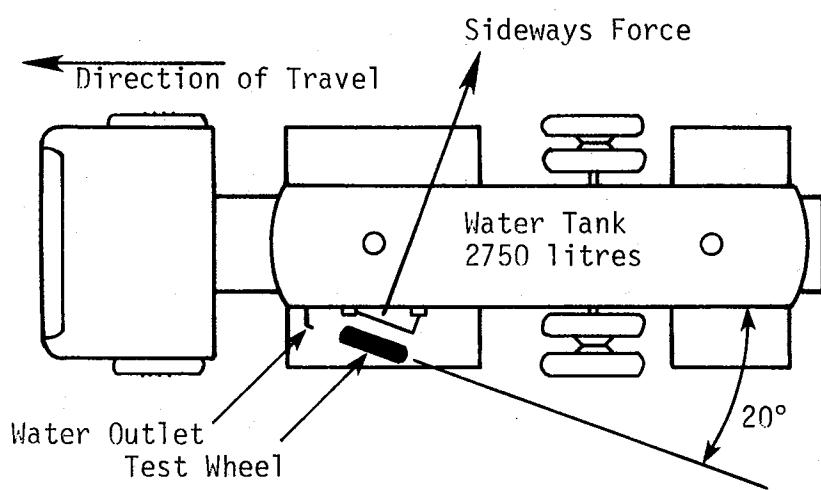


Figure 17. Diagram Showing Relative Location of SCRIM Components.

Comparison of Pavement Friction Testers

Before the decision was made to take the traditional diagonal braking vehicle and install an on board watering system, different factors were considered as to what type of friction measurement system would best suit the needs of a city or county.

These factors are summarized in Table 1.

CRITERION	PORTABLE TESTERS	STOPPING DISTANCE CAR	SKID TRAILERS	DBV
Efficient for road inventory	Poor	Poor to good	Excellent	Poor to good
Efficient for city streets	Poor to fair	Poor to fair	Good to excellent	Good to excellent
Meaningful measurement	Poor to good	Good	Excellent	Good
Accuracy of test data	Good	Poor to good	Good to excellent	Good
Data display	Indication	Indirectly derived	Recording	Recording
Test frequency	Poor	Poor	Good to excellent	Good
Non-interference with traffic	Poor	Poor	Excellent	Fair to good
Ruggedness	Good	Poor to good	Excellent	Poor to good
Hazard to test crew	High	High	Low	Medium
Required test crew (includes flagpersons)	1-2	4-5	1-2	3-4
Initial cost	Low to medium	Medium	High	Low to medium

Table 1. Comparison of Pavement Friction Testers

DEVELOPMENT OF A SELF-WATERING DIAGONAL BRAKING VEHICLE

A four-wheel locked technique stopping distance vehicle was considered in this project but ruled out because of the hazards involved if this method were used on city streets. A non-rotating locked wheel on the front of a vehicle gives the operator no steering control and the vehicle will veer from it's original direction due to external forces acting on the vehicle from cross wind, transverse pavement crown or differential friction levels in the wheel paths of the pavement.

Experience gained by working with NASA personnel and their Diagonal Braking Vehicle (DBV) at Texas Transportation Institute's Highway Safety Research Center in 1976 was a guiding factor in selecting this method of testing for further development applicable to the needs of cities and counties for wet pavement friction determination (17,18).

The full stop method of deceleration with a DBV was used for a number of years. Certainly this method of having to come to a full stop to acquire friction data would not be practical on city streets. It would necessitate the stopping of traffic or the blocking off of a number of sections to conduct testing.

In 1967, the DBV pulse braking vehicle deceleration test technique was the first used by the NASA Langley Research Center in Virginia. This method of test was adopted to provide adequate vehicle steering and directional control when testing runways for wet skid resistance at speeds up to 100 mph (19).

Figures 18 and 19 are typical recorder traces taken from the TTI-DBV. In the pulse braking method, Figure 18, the deceleration resulting from momentary diagonal wheel lockup is measured. The vehicle decelerates over a wetted pavement surface under specified limits of

static wheel load and at a desired speed. The vehicle should remain essentially parallel to its original direction of motion.

The DBV approaches the test surface at a speed in excess of the designated test speed such as 40 mph. At the moment the digital speed readout indicates 40 mph, the brake pedal of the vehicle is jammed to produce a full lock application on the diagonal wheels.

Brake application is released about 1 - 2 seconds after lockup and average deceleration is determined from the accelerometer trace for a time period. In this study, a one second average was used for data purposes.

Pavement diagonal braking number (DBN) as measured by the accelerometer is determined from the equation

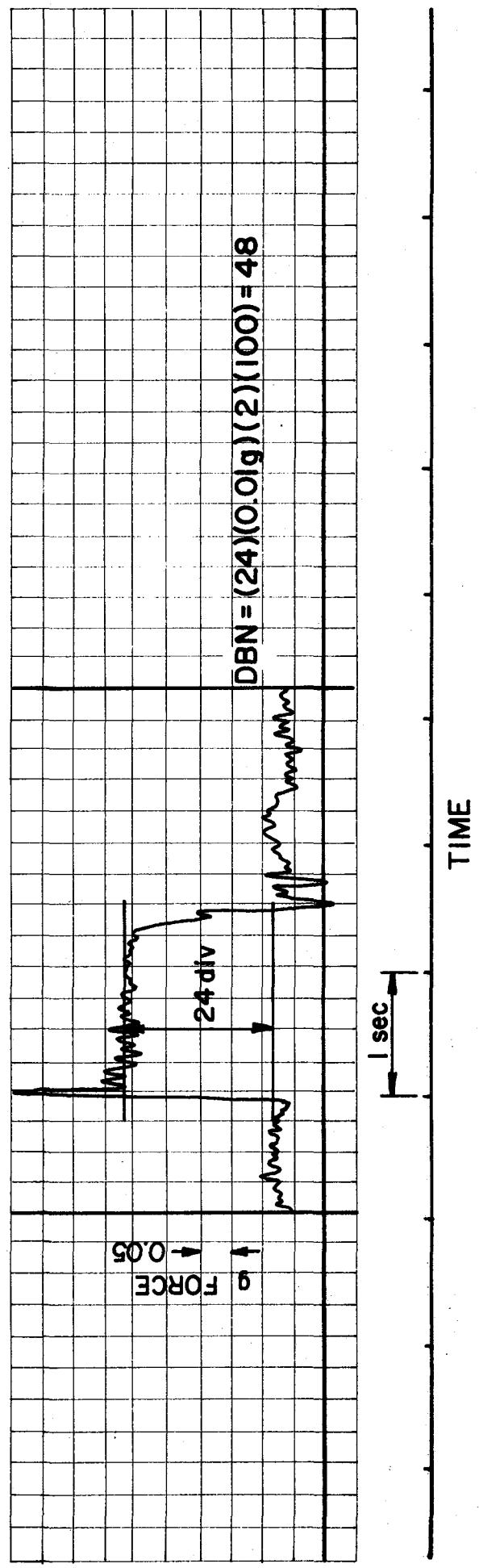
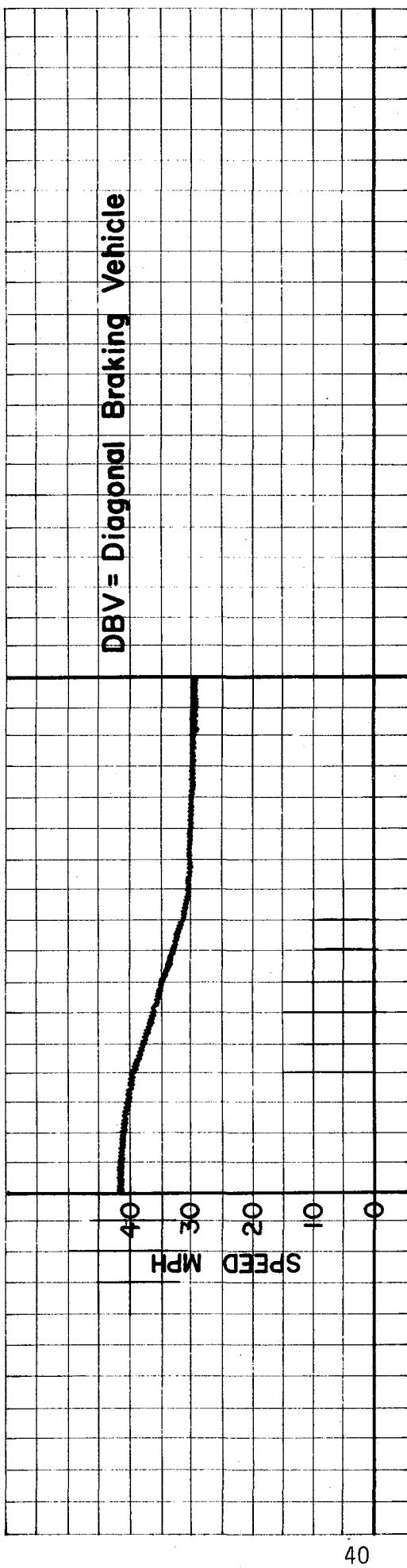
$$DBN = 2\alpha \times 100$$

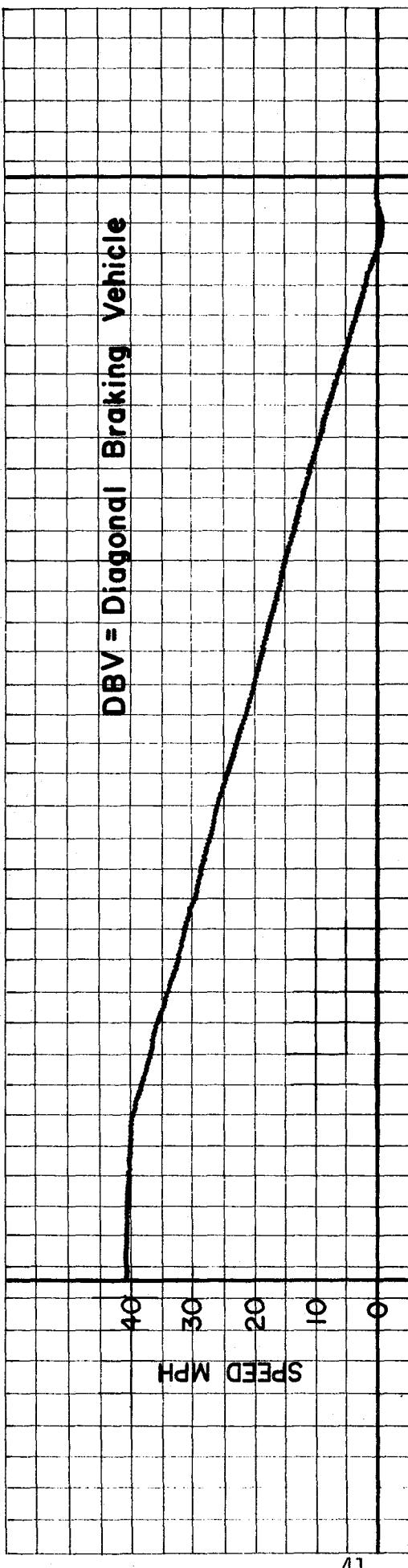
Where:

α = average locked-wheel deceleration corrected for vehicle free-rolling drag acceleration

Figure 19 would be a typical example of a data trace where the brake lock is held until the vehicle comes to a full stop in order to determine stopping distance number (SDN). In the case of SDN, the distance traveled from the time of brake actuation until the vehicle stops is measured. The measurement of distance is not shown on this trace.

By comparing Figures 18 and 19, one can see another reason why the pulse braking method was selected for this study. Not only is a considerable amount of time consumed in coming to a full stop (about 7 seconds in this case) but the additional time of skidding the locked wheel contributes to increased tire wear and excessive use of on board water. As discussed previously, stopping in the traffic stream is not desirable if it can be avoided.





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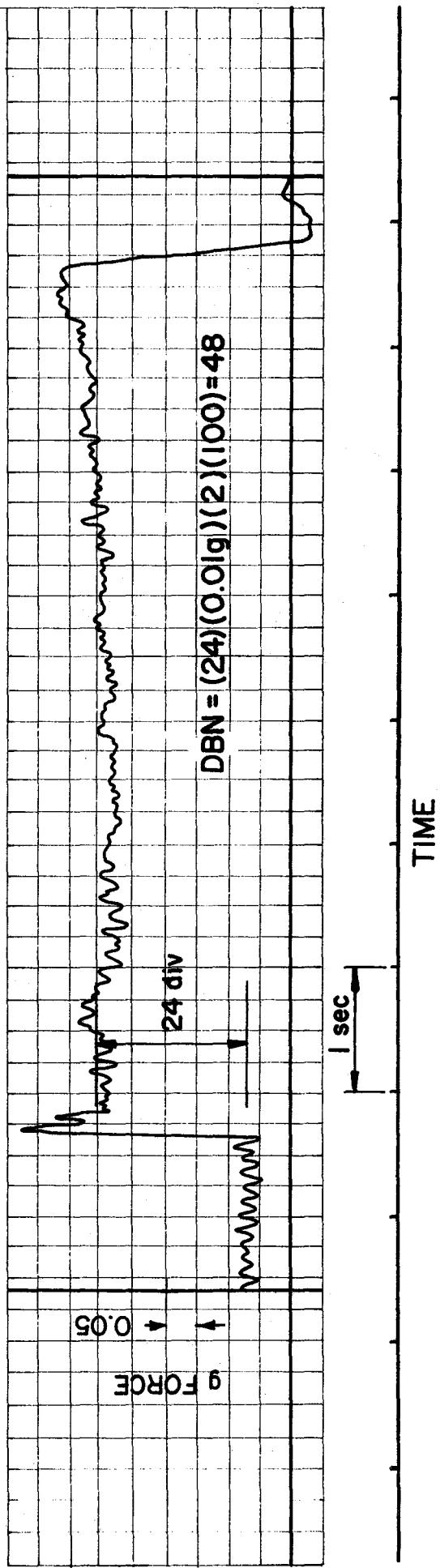


Figure 19. Measurement of Deceleration - Full Stop Method.

CORRELATIONS AND STUDIES

First Correlation

After the Diagonal Braking Vehicle (DBV) was constructed and calibrated, a correlation was conducted at Texas Transportation Institutes' Highway Safety Research Center. The correlation compared the DBV Diagonal Braking Numbers (DBN) with the FHWA Area Reference Skid Measurement System (ARSMS) locked-wheel skid numbers.

Figure 20 shows the DBV running with the ARSMS on one of the reference surfaces used to compare the two systems.

The first correlation consisted of eight skids on each of seven surfaces at speeds of 20, 30 and 40 mph. The average skid numbers/diagonal braking numbers are shown in Table 2 and the standard deviation of these numbers is shown in Table 3.

Considering all speed-surface combinations, the DBV system recorded higher Diagonal Braking Numbers in 19 of the 21 speed-surface combinations. The differences ranged from -0.6 SN/DBN on surface SRS 2 at 30 mph to 9.7 SN/DBN on surface SRS 1 at 30 mph. The average absolute difference being 4.4 SN/DBN, and it was furthermore observed that the DBV system had a slightly larger pooled standard deviation than the ARSMS, 1.94 DBN versus 1.79 SN.

The linear regression equations relating the measurements of the DBV system to those of the ARSMS are graphed in Figure 21. The 20, 30 and 40 mph lines all had slopes which were significantly different from 1.0. This indicates that the ARSMS and DBV system differed by more than just a constant in their measurement of skid numbers at all three speeds. The measured skid numbers of the two systems were highly correlated. A value of 0.99 was recorded for the correlation coefficient at 20 and 40 mph and

0.98 at 30 mph.

A description of pavement surfaces used for the correlation are described in Table 4.



Figure 20. ARSMS and DBV Correlation
on Reference Surfaces.

AVERAGE SKID NUMBER AND DIAGONAL BRAKING NUMBER						
REFERENCE SURFACE	20 MPH		30 MPH		40 MPH	
	ARSMS	DBV	ARSMS	DBV	ARSMS	DBV
PAD 1	22.8	25.1	21.3	22.5	15.6	16.4
PAD 2	50.3	55.6	45.1	48.9	40.7	45.4
PRS 2	53.7	59.4	50.6	54.5	48.3	56.0
SRS 1	53.8	60.4	47.2	56.9	47.2	54.0
SRS 2	17.4	19.0	19.0	18.4	10.7	10.4
SRS 6	50.6	57.8	45.6	50.0	41.4	44.3
SRS 8	54.7	61.9	50.0	54.1	46.0	52.4
AVERAGE	43.3	48.4	39.8	43.6	35.7	39.8

Table 2. First Correlation - Average Skid Number and Diagonal Braking Number ARSMS and DBV.

STANDARD DEVIATION OF SKID NUMBER AND DIAGONAL BRAKING NUMBER						
REFERENCE SURFACE	20 MPH		30 MPH		40 MPH	
	ARSMS	DBV	ARSMS	DBV	ARSMS	DBV
PAD 1	1.87	2.03	1.51	1.85	1.39	1.41
PAD 2	2.51	2.00	1.35	1.64	1.81	2.26
PRS 2	1.25	1.06	2.12	0.93	1.60	2.27
SRS 1	1.30	2.00	1.93	2.80	1.00	2.07
SRS 2	2.72	0.93	1.79	1.19	1.14	0.74
SRS 6	1.97	1.91	1.62	1.31	0.80	2.05
SRS 8	3.16	3.27	1.49	1.64	1.35	3.02
POOLED	2.21	2.01	1.71	1.72	1.34	2.08

Table 3 . First Correlation - Standard Deviation of SN and DBN
ARSMS and DBV.

- SN_{20} (ARSMS) = $1.069 + 0.872 DBN_{20}$ (DIAG. BRAKING VEH.)
 ——— SN_{30} (ARSMS) = $3.619 + 0.831 DBN_{30}$ (DIAG. BRAKING VEH.)
 ——— SN_{40} (ARSMS) = $2.600 + 0.831 DBN_{40}$ (DIAG. BRAKING VEH.)
 ——— SN_{ALL} (ARSMS) = $2.390 + 0.847 DBN_{ALL}$ (DIAG. BRAKING VEH.)

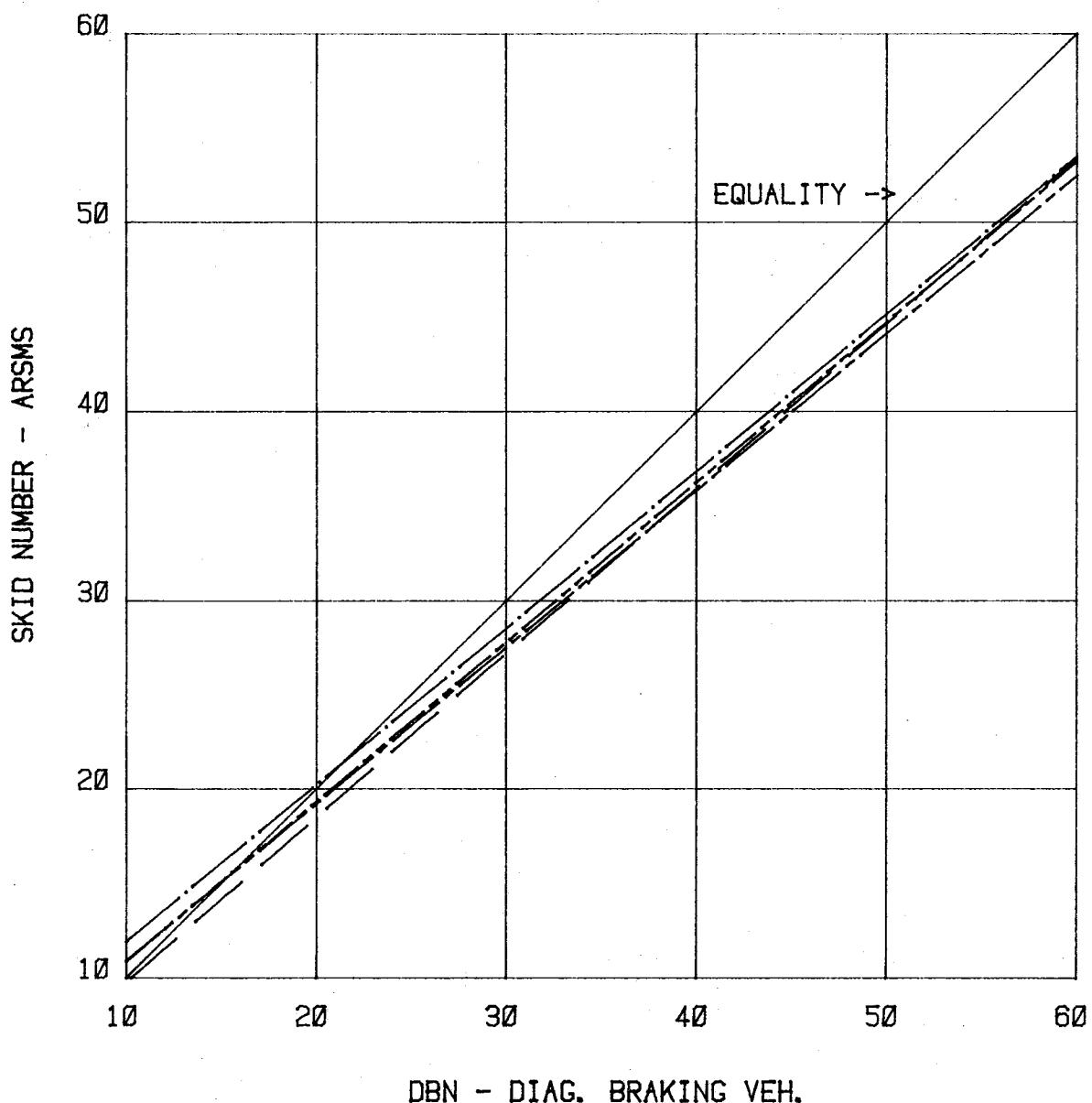


Figure 21. First Correlation Regression Equations ARSMS and DBV.

REFERENCE SURFACE	DESCRIPTION OF SURFACE
PAD 1	Emulsion with sand placed on a Portland Cement concrete
PAD 2	Rounded siliceous gravel hot mix
PRS 2	Rounded siliceous gravel seal coat epoxy bound
SRS 1	Portland Cement concrete with transverse burlap drag
SRS 2	Emulsion with sand placed on a dense graded hot mix pavement
SRS 6	Rounded gravel seal coat asphalt bound
SRS 7	Light weight aggregate seal coat asphalt bound
SRS 8	Light weight aggregate hot mix

NOTES: PAD = Vehicle Handling Surface
 PRS = Primary Reference Surface
 SRS = Secondary Reference Surface

Table 4 . Description of Pavements Used
 to Correlate DBV and ARSMS.

Second Correlation

During demonstrations of the DBV that followed the first correlation, it was noticed that the rear tire was not locking during some of the tests. The solution to the problem was a simple adjustment of the rear brake shoes; however, this did create a question as to the validity of the first correlation's data. For that reason, positive lock indicators were installed for the front and back wheels and a second correlation was conducted. The evaluation procedure for the second correlation was the same as that used in the first correlation.

The results of the second correlation are given in Tables 5 and 6. The DBV system recorded higher Digonal Braking Numbers in 16 of the 21 speed-surface combinations. The differences ranged from -2.5 SN/DBN to 5.1 SN/DBN with an overall average absolute difference of 2.5 SN/DBN. The DBV system had a slightly higher standard deviation than the ARSMS in five of the 22 speed-surface combinations. Overall, the DBV system had a pooled standard deviation of 1.32 DBN while the ARSMS had a pooled standard deviaiton of 1.94 SN.

The linear regression equations relating the measurements of the DBV system to those of the ARSMS are displayed both algebraically and graphically in Figure 22. The slopes of the three lines were again significantly different from one. Thus, the two systems differed by more than a constant in their measurement of skid numbers across the three speeds. The validity of using a linear relationship between the skid measurements of the two systems is reflected in the very high correlation in their measurement of skid number. There was a 0.99 correlation between the skid numbers of the ARSMS and the DBV system at 20, 30 and 40 mph.

AVERAGE SKID NUMBER AND DIAGONAL BRAKING NUMBER						
REFERENCE SURFACE	20 MPH		30 MPH		40 MPH	
	ARSMS	DBV	ARSMS	DBV	ARSMS	DBV
PAD 1	23.8	25.4	21.0	20.0	18.6	16.1
PAD 2	42.1	47.0	39.5	43.2	38.1	40.1
PRS 2	53.6	55.4	48.4	52.9	48.1	48.8
SRS 1	57.5	61.8	52.6	56.9	50.7	52.8
SRS 2	19.4	18.9	14.5	13.9	12.5	11.4
SRS 6	47.1	50.9	42.8	45.4	39.8	41.0
SRS 8	57.9	63.0	52.9	55.9	50.5	52.6
AVERAGE	43.1	46.0	38.8	41.2	36.9	37.5

Table 5. Second Correlation - Average Skid Number and Diagonal Braking Number ARSMS and DBV.

STANDARD DEVIATION OF SKID NUMBER AND DIAGONAL BRAKING NUMBER						
REFERENCE SURFACE	20 MPH		30 MPH		40 MPH	
	ARSMS	DBV	ARSMS	DBV	ARSMS	DBV
PAD 1	2.79	1.19	1.00	0.76	1.79	0.83
PAD 2	2.25	1.31	0.96	1.75	2.44	0.83
PRS 2	1.91	2.13	1.20	0.99	1.21	1.75
SRS 1	1.98	1.58	1.51	1.13	0.89	1.28
SRS 2	1.37	1.13	1.31	0.99	1.23	0.74
SRS 6	1.67	1.25	1.11	1.06	1.30	1.31
SRS 8	4.43	1.77	2.78	1.46	1.78	1.30
POOLED	2.53	1.52	1.53	1.20	1.59	1.20

Table 6 . Second Correlation - Standard Deviation of SN and DBN
ARSMS and DBV.

- SN_{20} (ARSMS) = $1.483 + 0.903 DBN_{20}$ (DIAG. BRAKING VEH.)
 ——— SN_{30} (ARSMS) = $2.698 + 0.877 DBN_{30}$ (DIAG. BRAKING VEH.)
 ——— SN_{40} (ARSMS) = $3.016 + 0.903 DBN_{40}$ (DIAG. BRAKING VEH.)
 ——— SN_{ALL} (ARSMS) = $2.713 + 0.887 DBN_{ALL}$ (DIAG. BRAKING VEH.)

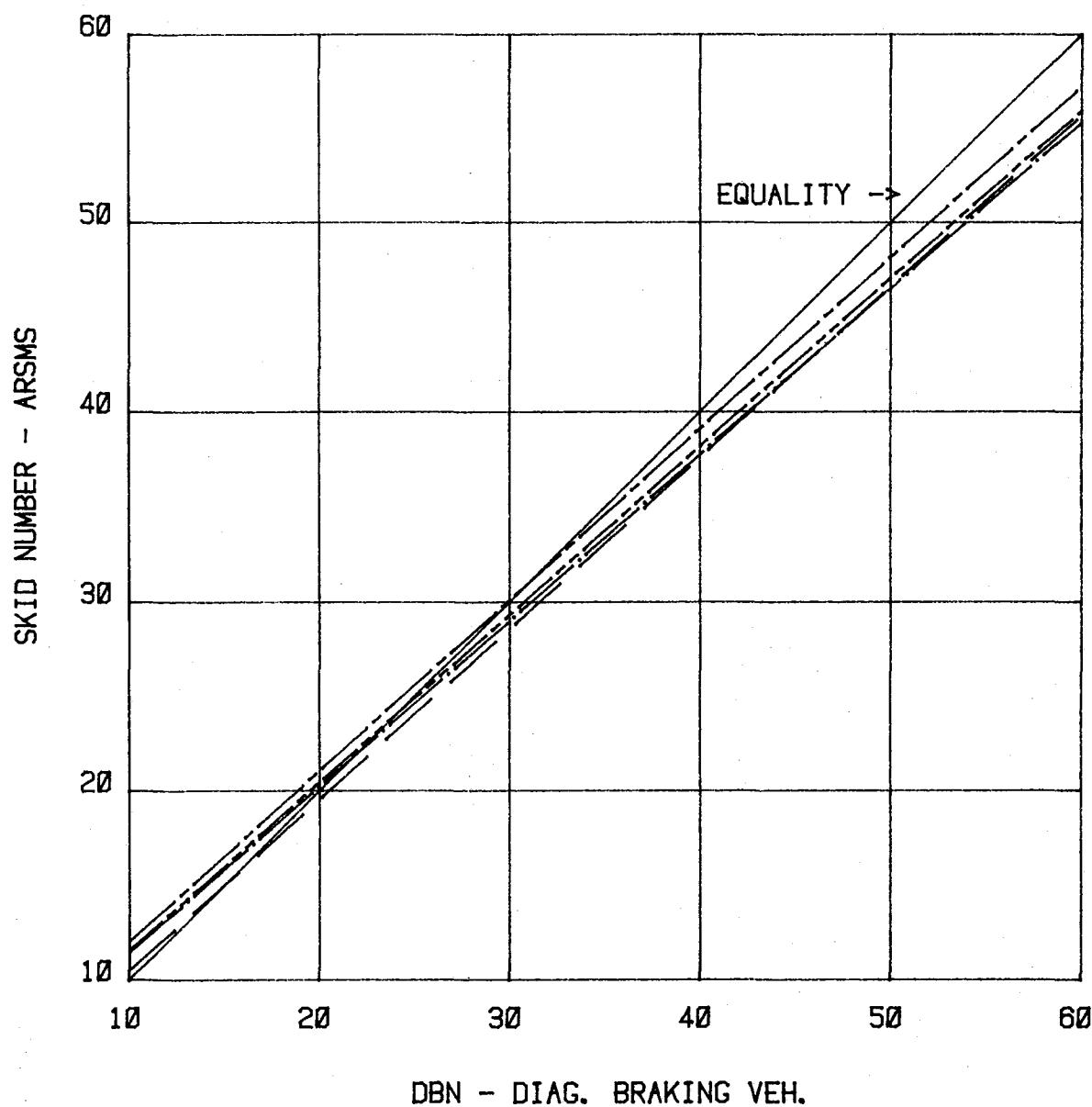


Figure 22. Second Correlation Regression Equations ARSMS and DBV.

Effect of Weight on DBN

The effect of vehicle gross weight on Diagonal Braking Number (DBN) was investigated. The DBV ran on three surfaces at speeds of 30 and 40 mph. The friction levels of the surfaces ranged from 11 DBN to 49 DBN at 40 mph. The gross vehicle weights used were 4,719 lb (low weight), 5,529 lb (medium weight), and 6,239 lb (high weight).

The test series consisted of eight runs each on SRS 2, SRS 6, and SRS 1. The series was run at 30 and 40 mph with a low vehicle weight and then repeated for medium and high vehicle gross weights.

The DBN results of the test are given in Table 7. Table 8 shows the weight configuration differences which were accomplished by running with the water tank at a low level, then a full water tank and then a full water tank with extra weight added to the pickup truck bed.

Though the test was somewhat limited, the weight of the DBV with relation to the vehicle speed and the test surface did not significantly affect the DBN.

AVERAGE DIAGONAL BRAKING NUMBER (DBN)						
REFERENCE SURFACE	30 MPH			40 MPH		
	LOW WT. (4719 lb)	MED. WT. (5529 lb)	HIGH WT. (6239 lb)	LOW WT. (4719 lb)	MED. WT. (5529 lb)	HIGH WT. (6239 lb)
SRS 2	13.3	15.5	14.0	11.1	11.3	11.8
SRS 6	43.4	43.8	42.9	38.9	40.4	38.9
SRS 1	52.5	52.5	53.1	49.1	48.8	48.8
AVERAGE	36.4	37.3	36.7	33.0	33.5	33.2

Table 7 . Effect of Varying Vehicle Weight on
Diagonal Braking Number (DBN).

Lower Weight (Low Water Tank/No Extra Weight)

LF - 1336		2644		4719
RF - 1308				
LR - 1009		2075		
RR - 1066				

Medium Weight (Full Water Tank/No Extra Weight)

LF - 1439		2853		5529
RF - 1414				
LR - 1321		2676		
RR - 1355				

Higher Weight (Full Water Tank/Extra Weight)

LF - 1452		2876		6239
RF - 1424				
LR - 1657		3363		
RR - 1706				

NOTES:

- (1) Weights shown are in pounds
- (2) LF = Left Front, RF = Right Front
LR = Left Rear, RR = Right Rear

Table 8 . Weight of Diagonal Braking Vehicle
During Varying Vehicle Weight Test.

Differential Friction

A pavement friction characteristic that is sensed by the DBV and not encountered by any other system except a four-wheel lock vehicle is differential friction. A test was designed to evaluate the effect of simultaneous measurement of two different friction levels, one in the left wheel path and one in the right wheel path, on the overall measurement of the DBN.

The test consisted of running on two sets of reference surfaces that were adjacent to each other so the DBV could drive down the joint of the two surfaces and have the left tires on one surface and the right tires on the other surface. The first set of pavements consisted of SRS 1, $SN_{40} = 48.1$, and SRS 2, $SN_{40} = 13.1$, for an overall differential friction of 35.0 SN. The second set consisted of SRS 6, $SN_{40} = 38.4$ and SRS 7, $SN_{40} = 57.0$ for an overall differential friction of 18.6 SN.

On each set of reference surfaces, the DBV was run first in one direction, so the front locking tire was on the higher friction surface and the rear locking tire was on the low friction surface, and then run in the opposite direction, so the front locking tire was on the low friction surface and the high friction surface. This was done in order to evaluate any affect the pitching of the vehicle weight might have on the DBN measurement. There were eight runs made in each direction on each set of reference surfaces. This was repeated for 20, 30 and 40 mph. The results are shown in Table 9.

The results of the test indicated that the DBN was dependent on whether the front tire was on the higher friction or lower friction surface. The DBN will be highest if the front locking tire is on the higher friction level surface and lowest if the front locking tire is on

the lower friction level surface. It should be noted that when we use the average DBN of the two individual surfaces as a reference, the DBN with the front tire on the high friction side is the same amount above the average as the DBN with the front tire on the low friction side is below the average. This point is illustrated in Figure 23. Also, if the mean of all the runs in both directions on a given set of reference surfaces were taken, it would equal the average of the two independent surfaces. The amount above or below the average that the DBN will vary is 5 to 15 percent of the difference in SN between the two surfaces.

One other point worth noting is that even in an extreme case of differential friction, there was no problem maintaining the straight line of travel needed to remain astraddle the two surfaces. In a four-wheel lock vehicle, a high degree of differential friction would create a very hazardous situation.

AVERAGE DIAGONAL BRAKING NUMBER (DBN)						
REFERENCE SURFACE	20 MPH		30 MPH		40 MPH	
	Front Tire High Fric.	Front Tire Low Fric.	Front Tire High Fric.	Front Tire Low Fric.	Front Tire High Fric.	Front Tire Low Fric.
SRS 1 & SRS 2	44.6	36.9	39.5	33.0	36.6	29.4
SRS 6 & SRS 7	61.3	55.9	53.8	49.6	50.6	46.6

AVERAGE DBN OF THE TWO SURFACES			
SRS 1 & SRS 2	40.8	36.3	33.0
SRS 6 & SRS 7	58.6	51.7	48.6

Table 9 . Study of Differential Friction - Diagonal Braking Numbers.

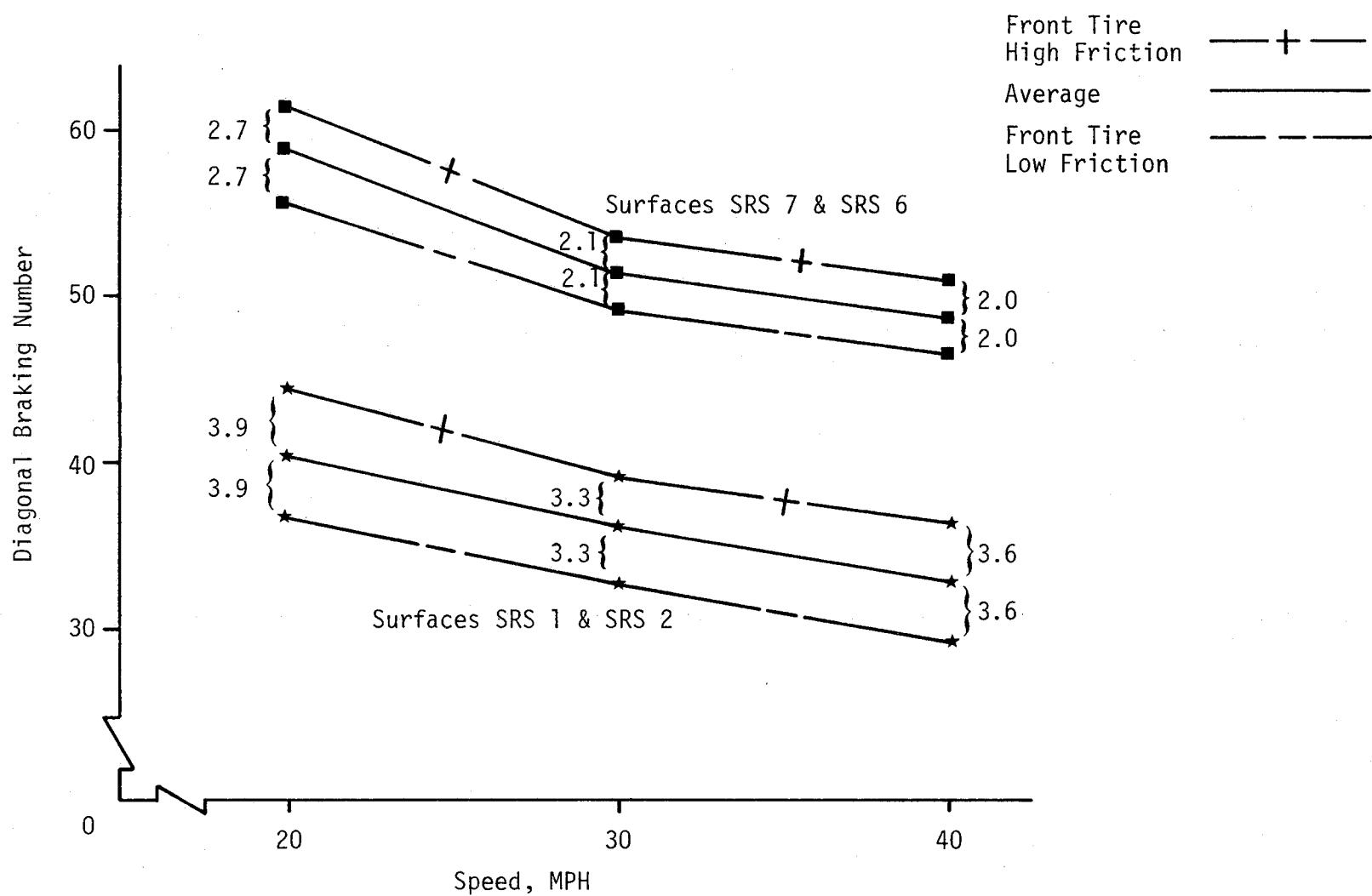


Figure 23 . Study of Differential Friction
Speed vs Diagonal Braking Number.

CORRELATIONS ON CITY STREETS

Duncanville, Texas

Correlation Between the DBV and Texas-Austin Skid Measurement System

In order to evaluate the effectiveness and efficiency of the DBV in a "real world" situation, the DBV was run with the Texas-Austin locked-wheel trailer in Duncanville, Texas. The Texas-Austin system is owned by the Texas State Department of Highways and Public Transportation and is used for both road inventory work and research purposes.

Twenty separate sections of city streets were evaluated for wet pavement friction levels. The DBV followed the Texas-Austin system and attempted to lock its wheels in the same place as the Texas-Austin system, in both a longitudinal and lateral position on the street. All tests were conducted at 20 mph.

Each section was defined by stating the street that was to be tested and given a starting and stopping point. For example, Section 6 is described as North Main Street, from Camp Wisdom Street to Center Street. Eighteen of the 20 sections were tested in both directions of travel; in the appropriate street lanes. When the test section was a four-lane road, the outer-most lane in each direction was used. In any one section, the test conducted in the direction of the section description was designated as "Section X with". For example, tests conducted on Section 6 from Camp Wisdom Street to Center Street were designated as "Section 6 with" and tests conducted on Section 6 from Center Street to Camp Wisdom Street were designated as "Section 6 opposite".

The absense of some data exists for the following reasons. Sections 9 and 17 were tested in only one direction. On Section 6, it was thought the DBV had a malfunction due to some unexpected occurrences in the

operation of the braking system. After investigation, the vehicle was found to be in perfect condition and it was concluded that the occurrences apparently were due to drastic variances of friction in the pavement surfaces. Section 15 was the first test of the day and we failed to achieve a total lockup of the tires. After a minor adjustment, this difficulty was not experienced again. In section 19, we overestimated our remaining water supply and ran out in the middle of the test.

The results of the correlation are given in Tables 10 and 11. The DBV recorded higher DBN's in all but one case, where the DBV diagonal braking number was equal to the skid number of the Texas-Austin system. The differences ranged from a low of 0 on Section 11W to a high of 15.6 on Section 4W with an overall absolute difference of 5.4. Furthermore, it was observed that the DBV had a slightly higher pooled standard deviation than the Texas-Austin system, 5.65 DBN vs. 5.50 SN.

The linear regression equation relating the measurements of the DBV to those of the Texas-Austin system is graphed in Figure 24. The line has a slope which is significantly different from 1.0.

The correlation regression coefficient (R^2) is 0.55 which is very poor when compared to the 0.99 regression coefficient obtained in the correlation with ARSMS. The low R^2 value appeared to be caused by two extreme observations since the R^2 without those data points increased to 0.65. It is also interesting to note that the R^2 value for the two systems traveling in the "with" direction is 0.46 while the R^2 value traveling in the "opposite" direction is 0.67.

The poor correlation and two extreme data points could have been caused by two factors. The first is the fact that it is virtually impossible to skid in "exactly" the same spot as the Texas-Austin system.

With the high degree of variability in both a longitudinal and transverse direction, this factor would show up between any two systems. It should also be noted that the reference surfaces used in the ARSMS and DBV correlation are more uniform across the entire surface.

The second factor is that, while the Texas-Austin system measures the pavement friction in only the left wheel path, the DBV gives the average pavement friction for both the left and right wheel path. The greater the degree of transverse variability, the greater the importance this factor will have.

TEST SECTION	AVERAGE DIAGONAL BRAKING NUMBER AND SKID NUMBER			
	WITH		OPPOSITE	
	DBV	TEXAS-AUSTIN	DBV	TEXAS-AUSTIN
1	46.0	43.2	48.0	45.2
2	40.4	38.5	40.7	37.0
3	37.5	33.0	40.3	39.0
4	50.6	35.0	55.3	43.4
5	47.2	39.0	41.6	31.8
6	38.8	31.1	--	28.7
7	45.2	40.4	45.6	42.7
8	45.5	40.5	49.5	42.9
9	51.4	39.3	--	--
10	33.5	30.0	30.6	29.3
11	29.3	29.3	34.4	28.2
12	44.3	40.6	46.1	44.0
13	38.8	31.8	33.5	31.5
14	38.8	34.3	40.2	32.4
15	--	44.3	54.6	43.7
16	43.0	38.2	46.0	37.2
17	33.9	30.7	--	--
18	47.7	44.4	46.6	44.0
19	--	46.4	46.1	40.3
20	49.9	45.7	49.0	44.0

Table 10 . Duncanville, Texas Correlation with Texas-Austin No. 1
Average DBN and SN.

TEST SECTION	STANDARD DEVIATION OF DBN AND SN			
	WITH		OPPOSITE	
	DBV	TEXAS-AUSTIN	DBV	TEXAS-AUSTIN
1	5.24	4.43	3.74	4.26
2	4.63	3.89	4.14	4.05
3	4.80	1.63	2.87	1.15
4	3.96	4.21	2.60	5.76
5	9.26	7.87	3.58	6.76
6	7.10	6.08	--	12.29
7	2.77	2.79	2.30	3.16
8	3.15	2.70	4.31	3.95
9	14.68	9.32	--	--
10	2.12	3.46	1.53	0.58
11	2.87	2.99	4.51	5.63
12	7.45	3.99	7.13	6.06
13	7.67	5.15	3.33	5.47
14	7.99	12.18	5.54	8.91
15	--	2.08	2.52	1.15
16	9.70	7.09	6.73	5.26
17	4.71	5.02	--	--
18	4.79	3.10	3.87	4.12
19	--	3.64	5.08	3.90
20	5.93	5.41	4.29	4.00

Table 11. Duncanville, Texas Correlation with Texas-Austin No. 1
Standard Deviation of DBN and SN.

$$SN_{20} (\text{TEX-AUS}) = 9.136 + 0.666 DBN_{20} (\text{DIAG. BRAKING VEH.})$$

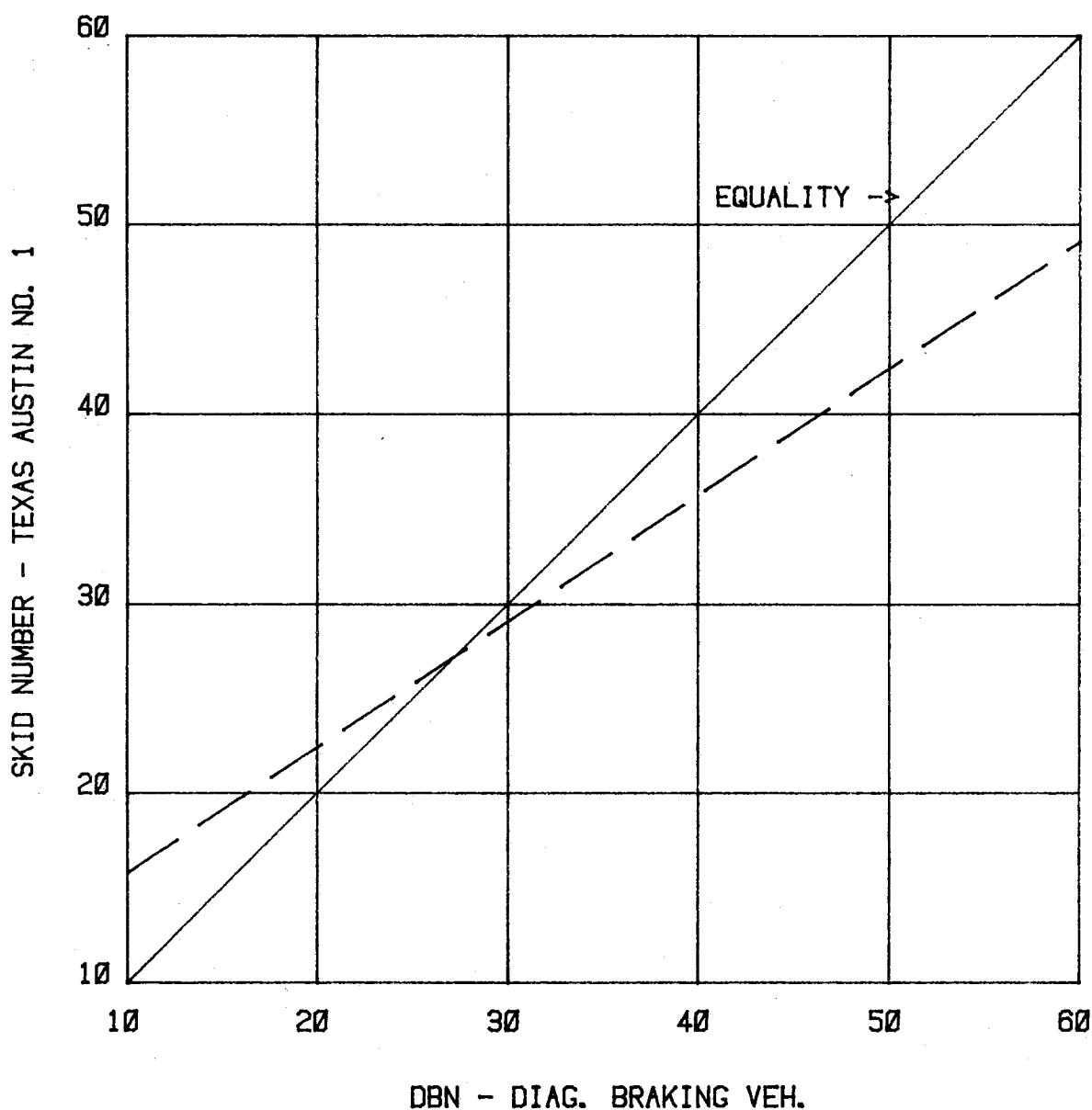


Figure 24 . Results of Duncanville, Texas Correlation DBV and Texas Austin No. 1 Skid Trailer.

El Paso, Texas

Correlation Between the DBV and Texas-Austin Skid Measurement System

After observing some of the problems associated with running the Duncanville, Texas correlation, the decision was made to run another correlation with the Texas-Austin skid measurement system.

As it turned out, this decision proved to be worthwhile and a much better correlation was obtained. The same procedures used in running the Duncanville correlation were repeated in the El Paso correlation. More attention was given to attempting to skid longitudinally in the "same spot" as the Texas-Austin system. The Texas-Austin operators placed their skids more away from the beginning or end of sections where the pavement surface changed noticeably, there were patches on the pavement, the left wheel path differed considerably from the right wheel path etc.

The results for the average diagonal braking numbers and skid numbers are shown in Table 12 while the standard deviations of these numbers are given in Table 13. In this correlation, the DBV recorded larger average numbers on all of the 38 sections with an overall absolute difference of 5.6 SN/DBN. The differences ranged from a low of 2.3 SN/DBN on section 110 to a high of 9.8 SN/DBN on section 29W. The pooled standard deviation for Texas-Austin was 7.85 while for the DBV it was 8.25.

Figure 25 shows the regression equation and plot of that equation for the 20 mph speed. This same speed was used in the Duncanville correlation. The regression coefficient R^2 for this correlation was 0.84 as compared to 0.55 for the Duncanville data which is a significant improvement. It was also interesting to note that the running "with" direction and running "opposite" R^2 was 0.86 and 0.82 respectfully. These were much closer than for the Duncanville correlation.

TEST SECTION	AVERAGE DIAGONAL BRAKING NUMBER AND SKID NUMBER			
	WITH		OPPOSITE	
	DBV	TEXAS AUSTIN	DBV	TEXAS AUSTIN
10	--	--	48.5	43.8
11	46.0	42.4	43.5	41.2
14	50.2	44.0	49.5	44.6
17	46.6	41.9	47.6	42.6
18	49.0	44.8	46.0	41.0
19	45.8	38.3	50.1	42.7
20	56.7	50.4	63.0	57.0
21	45.6	40.8	38.6	34.8
22	44.7	38.8	44.0	39.0
23	59.5	52.5	59.8	52.2
24	46.3	41.7	49.0	44.0
25	42.7	37.3	49.7	42.3
26	54.4	49.6	54.8	49.0
27	49.8	43.4	47.8	42.5
28	49.3	43.7	51.3	45.0
29	59.9	50.1	56.3	48.9
30	53.0	47.7	55.2	50.7
31	52.6	45.9	54.3	47.6
32	58.1	53.5	59.0	56.1
39	--	--	44.5	39.2

Table 12. El Paso, Texas Correlation with Texas Austin No. 1
Average DBN and SN.

TEST SECTION	STANDARD DEVIATION OF DBN AND SN			
	WITH		OPPOSITE	
	DBV	TEXAS AUSTIN	DBV	TEXAS AUSTIN
10	--	--	3.78	2.60
11	5.71	7.28	6.97	7.29
14	6.15	5.21	6.40	5.32
17	3.79	3.95	7.00	5.76
18	1.07	3.11	3.06	3.27
19	3.43	3.50	2.91	4.68
20	9.88	7.55	4.74	6.48
21	5.19	4.21	1.95	2.95
22	4.71	5.10	5.14	5.44
23	10.10	8.95	10.15	9.77
24	3.83	3.72	3.22	2.76
25	3.64	3.15	2.80	3.93
26	11.40	8.75	8.80	10.20
27	3.93	3.13	5.23	3.82
28	5.99	5.32	2.81	3.58
29	10.40	8.40	6.25	9.27
30	5.29	6.41	7.88	8.43
31	6.74	7.50	4.61	6.49
32	6.99	6.79	4.00	5.95
39	--	--	3.41	1.99

Table 13. El Paso, Texas Correlation with Texas Austin No. 1
Standard Deviation of DBN and SN.

$$SN_{20} (\text{TEX-AUS}) = 0.936 + 0.873 DBN_{20} (\text{DIAG. BRAKING VEH.})$$

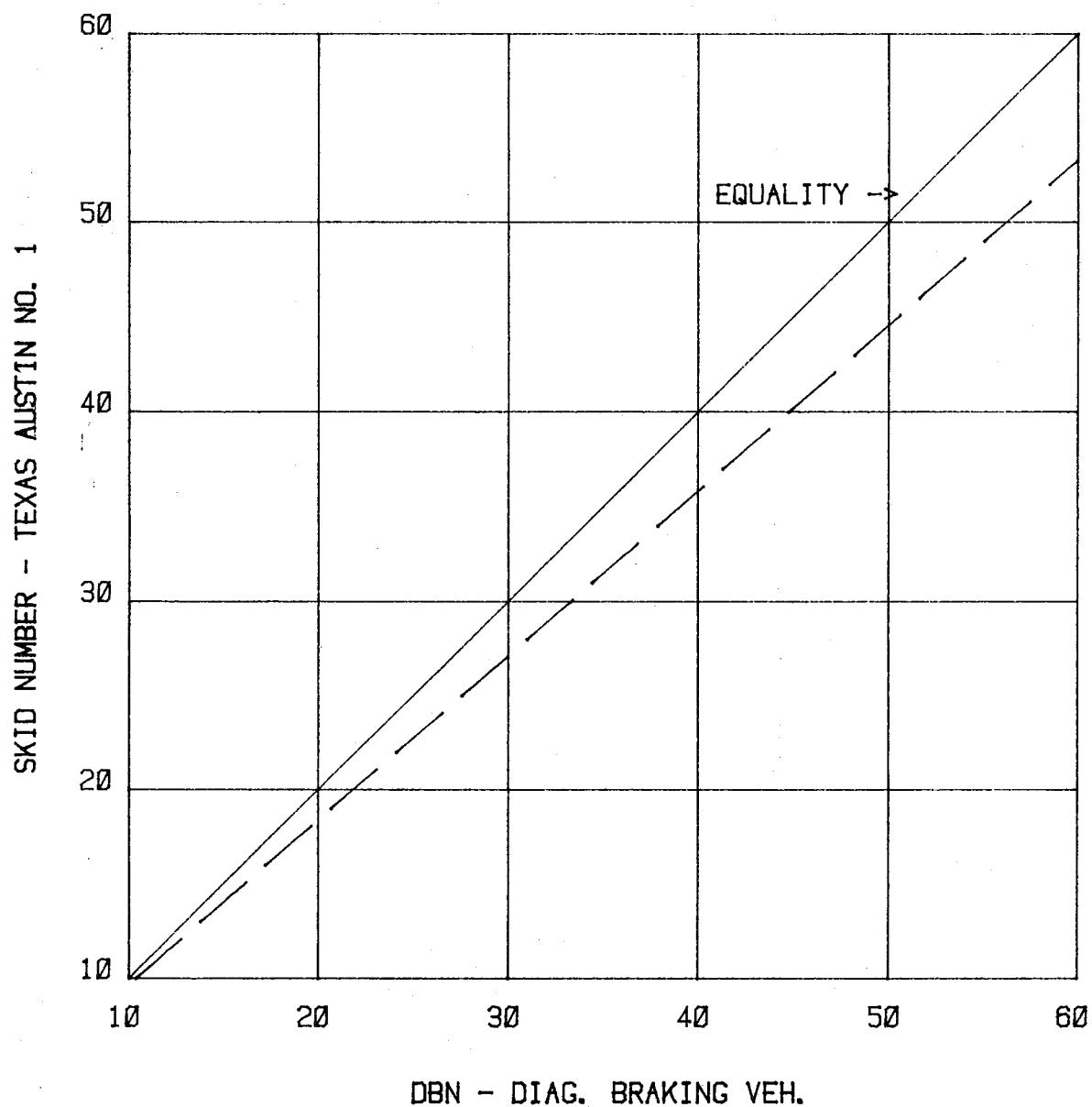


Figure 25. Results of El Paso, Texas Correlation
DBV and Texas Austin No. 1 Skid Trailer.

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APPENDIX A
Details of Design
of the
Diagonal Braking Vehicle

MECHANICAL AND ELECTRONIC SYSTEMS

The instrumentation, water delivery and brake control systems for this Diagonal Braking Vehicle (DBV) were developed with the objectives of being simple, easy to operate, low cost and accurate. The final design of these prototype systems will be described in the following sections to be used as guidelines for construction of similar systems. These systems are not intended to represent the ultimate in design but a working prototype which has been field tested.

1. VEHICLE: The typical vehicle used for DBV Tests is a passenger sedan modified as required in American Society for Testing and Materials (ASTM) Standard E-503. This type of vehicle was determined to be unsuitable for this study since pavement wetting was to be provided by the test vehicle and not a tank truck as has been used in the past. In order to carry an adequate amount of water a light duty pickup truck was chosen as a test vehicle. Specifically, the vehicle was a 1980 Chevrolet C-10, Figure A1, since this particular vehicle would accommodate the ASTM E-501 test tire which is a G 78-15 size. The truck was equipped with heavy duty rear springs, power brakes, and power steering as required in ASTM E 503-82. Additional equipment included air conditioning and heavy duty alternator with gages, to accommodate the instrumentation system. It was also required that this vehicle did not have Posi-Traction or other limited-slip differential as outlined in ASTM E 503-82.
2. PAVEMENT WETTING SYSTEM: The pavement wetting system was developed to be a self contained on-board system so as to free the test vehicle from the normal constraint of requiring a separate water

truck to wet the test surface. This system utilized components and specifications from ASTM E 274-79 which is a trailer type highway surface friction tester and has incorporated on-board water systems for many years.

2.1 Water Storage Tank: The water storage tank (Figure A2) was a fiberglass agricultural type with a capacity of 115 gallons, mounted in the bed of the truck just behind the cab. A small hole was cut in the floor of the bed to accommodate the tank which may not be necessary with other tank designs. The tank was held in place with steel straps, supplied with this particular unit, to the bed of the truck.

2.2 Water Pump: To comply with the ASTM E 274-79 requirement of at 40 mph "a flow rate of 4.0 gal/min per inch of wetted width" (tire path) which is 2x7in. or 14in., a 56 gpm pumping system was developed. In order to keep the system simple, no tie-in to the truck engine or drive train was made as in the typical E-274 system. An electric 12v motor was selected (Prestolite MDY 7022) to be coupled to the rotary gear water pump (Oberdorfer 13510) by means of a V-belt (Figure A3). This motor was found to draw considerable current while running but due to the short cycle times this was no problem since a heavy duty alternator was supplied with the truck. So as not to drop the voltage level at the vehicle battery, an auxiliary battery was located near the motor to provide all pumping power and was charged by means of a standard recreational vehicle isolator connected to the vehicle alternator.



Figure A1. Diagonal Braking Vehicle.



Figure A2. Water Tank.

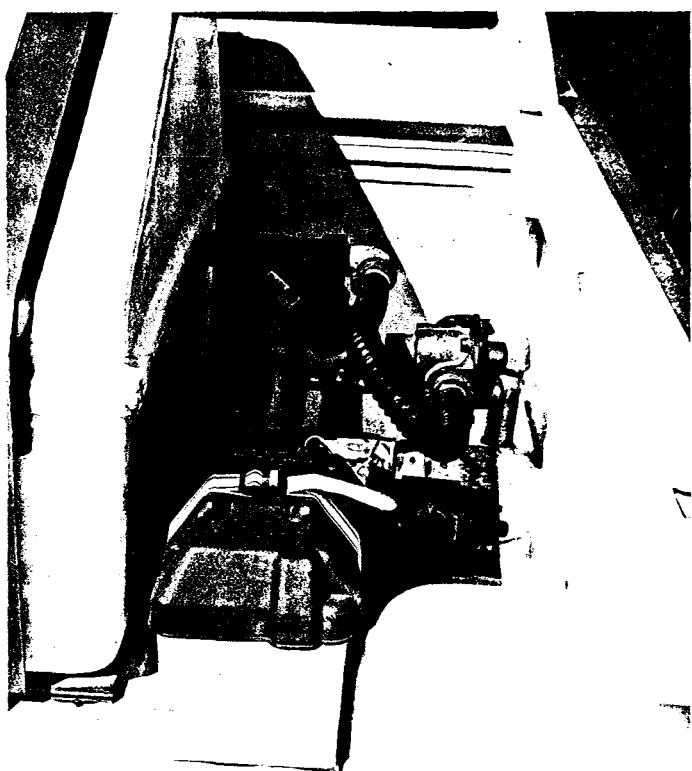


Figure A3. Water Pumping System.

The water flow from this system is fixed and was adjusted by means of various motor-pump pulley sizes. This particular pump required a shaft speed of approximately 1200 rpm to produce the required flow which was achieved by using a 1.5in. pulley on the motor and a 4.75in. pulley on the pump.

2.3 Water Nozzles: From the pump, the water flows through a "T" coupling and through 1.5in. rubber hose to two nozzles, one located ahead of the left front tire (Figure A4A), and the other ahead of the right rear tire (Figure A4B). These nozzles conform in design and in positioning to the requirements of ASTM E 274-79, Section 4.7. It should be noted that the test position for the nozzles is usually too low for every day vehicle use and some provision should be made to pivot the nozzles away from the pavement when not testing. A schematic of the watering system is shown in Figure A5.

3. VEHICLE BRAKE SYSTEM: In order to provide the capability of locking only the left front and right rear vehicle wheels during a test and retain four wheel braking at all other times, electrically operated hydraulic valves were installed in the brake lines. These two valves, (Fluid Controls, Inc. #7W21-13-125B) which are normally open, were installed in the brake line leading to the right front and left rear wheels as shown in Figure A6. As long as no power flows to the valves they will stay open allowing the brake system to perform normally. Just prior to a test, the driver activates a switch applying power to close the valves. As the test is completed or aborted, the driver returns the switch to off restoring normal braking should a panic stop be required.

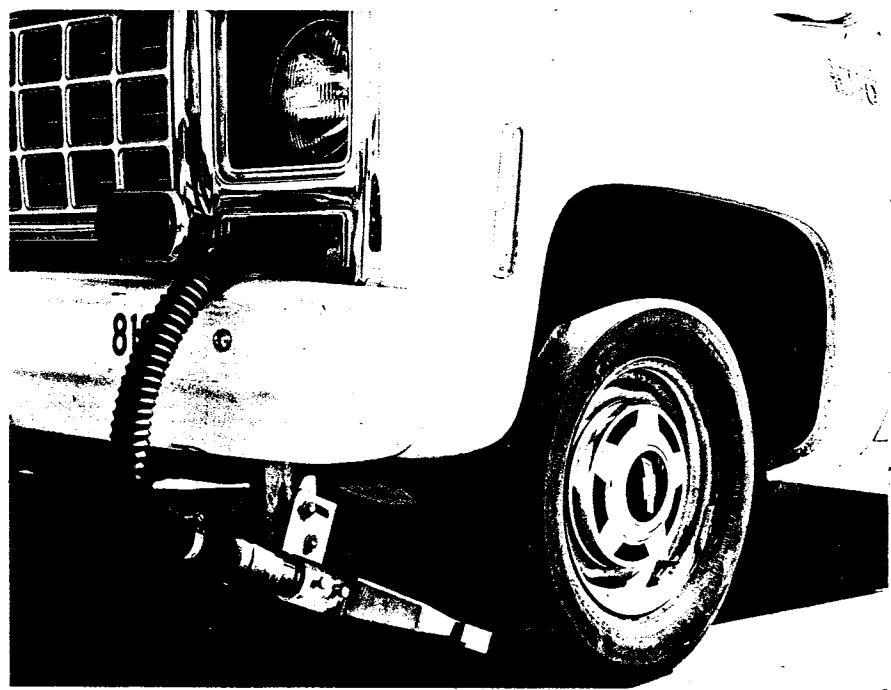


Figure A4A. Left Front Water Nozzle.



Figure A4B. Right Rear Water Nozzle.

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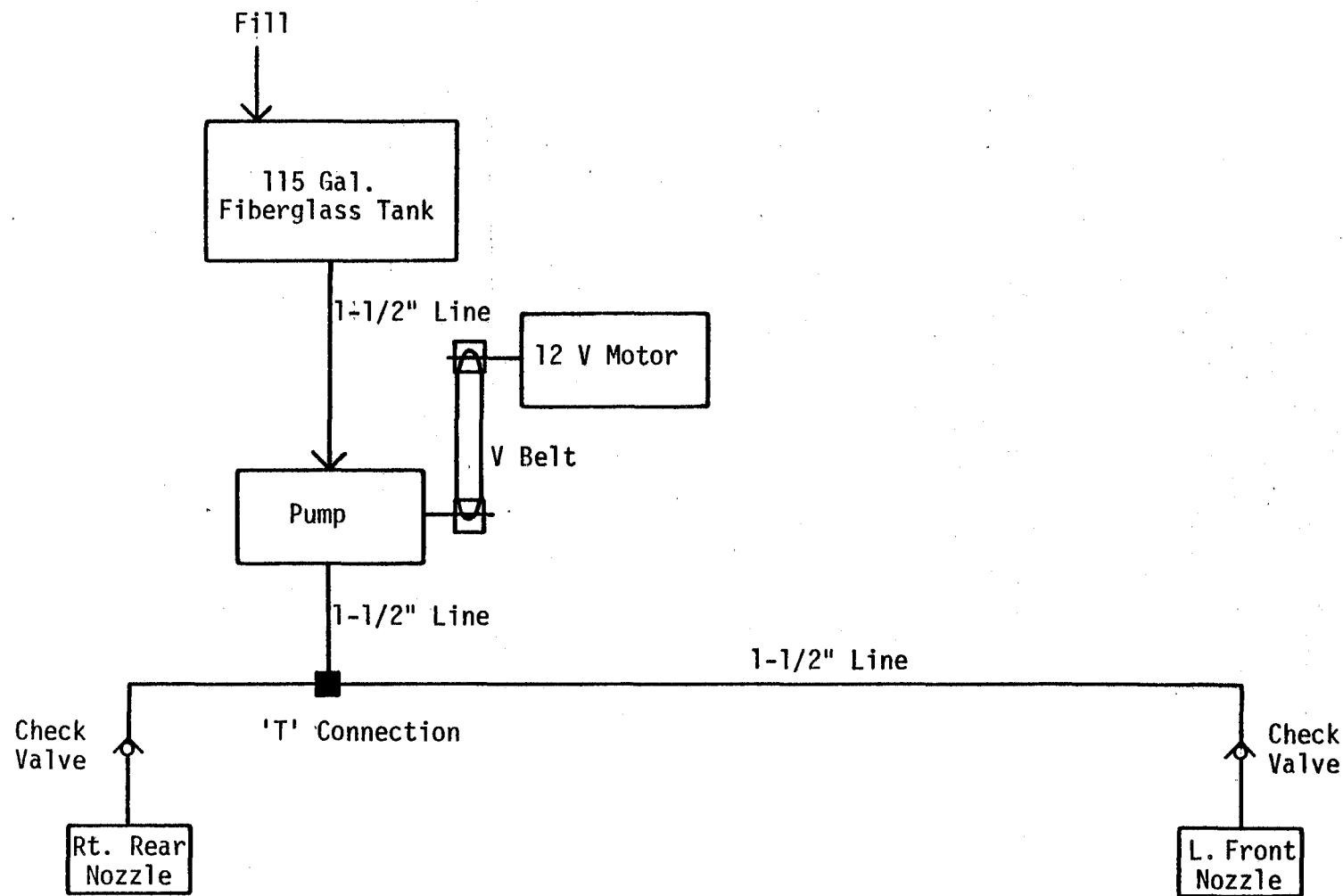
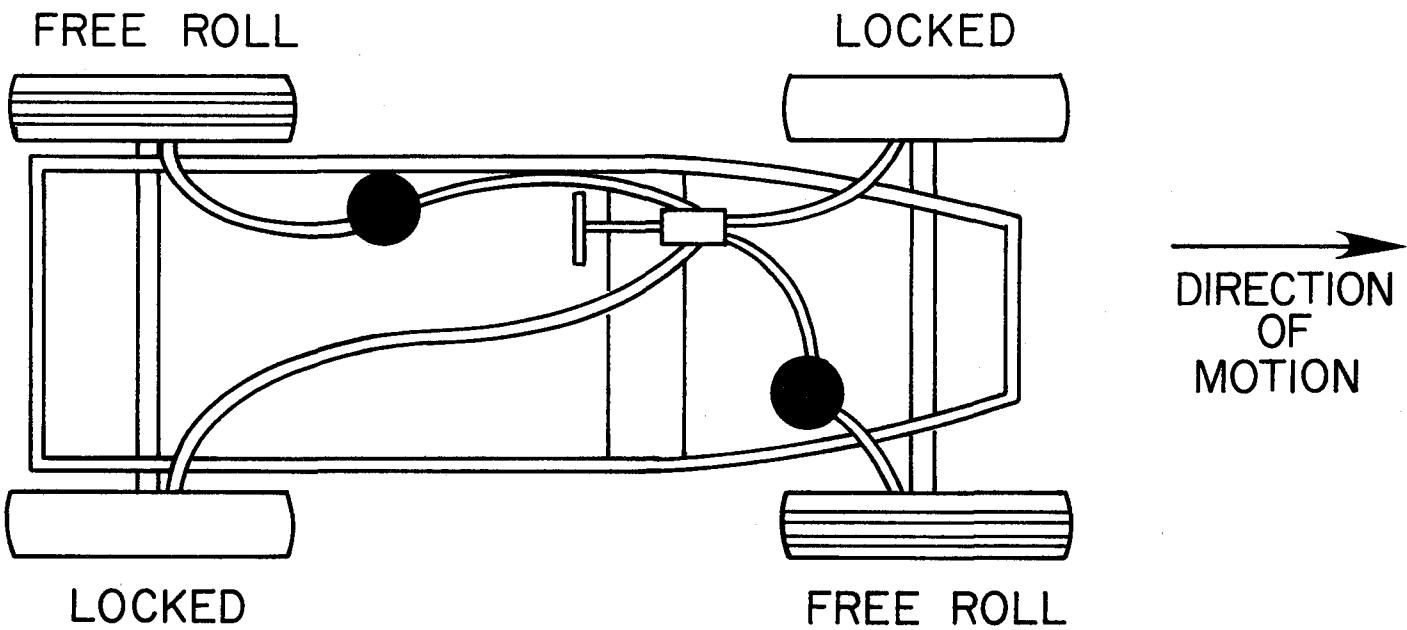


Figure A5. Watering System.



ELECTRIC VALVE - CLOSED DURING SKID TEST ONLY

Figure A6. Electric Brake Value Locations.

4. WHEEL LOCK SENSORS: During initial testing of the DBV, it was discovered that on high friction surfaces the driver would occasionally not apply enough brake pedal pressure to completely lock both test wheels. Since the driver had no way of knowing if a wheel was locked or not, an electronic device was developed to indicate a test wheel locked condition. The device shown schematically in Figure A7 is activated by a small magnet located on the rotating portion of the test wheels passing a reed switch on the stationary portion. As the magnet passed the switch each revolution, the circuit would cause an indicator lamp in the cab to illuminate for a period of 0.5 seconds. At speeds above 15 mph, the indicators would stay on steadily and positive lock would be indicated by both lamps remaining off for the duration of the test.
5. DATA ACQUISITION SYSTEM: This prototype system was equipped to perform both the ASTM E 503-82 full stop method, Section 9.1 and the pulse-braking method, Section 9.2. This was done mainly as a requirement of this study, so each set of instrumentation will be discussed. It is recommended though, that the full stop method not be considered as a routine method since skidding to a full stop on a congested roadway is hazardous and the amount of limited water expended is excessive. The full stop method is recommended for special cases only.
 - 5.1 Pulse-Braking Method Instrumentation: The requirements for the instrumentation system is covered in detail in E 503-82 and the following discussion is related to the hardware selected for the prototype DVB that meet the aforementioned specifications. To measure the momentary vehicle deceleration a Larson Mod.

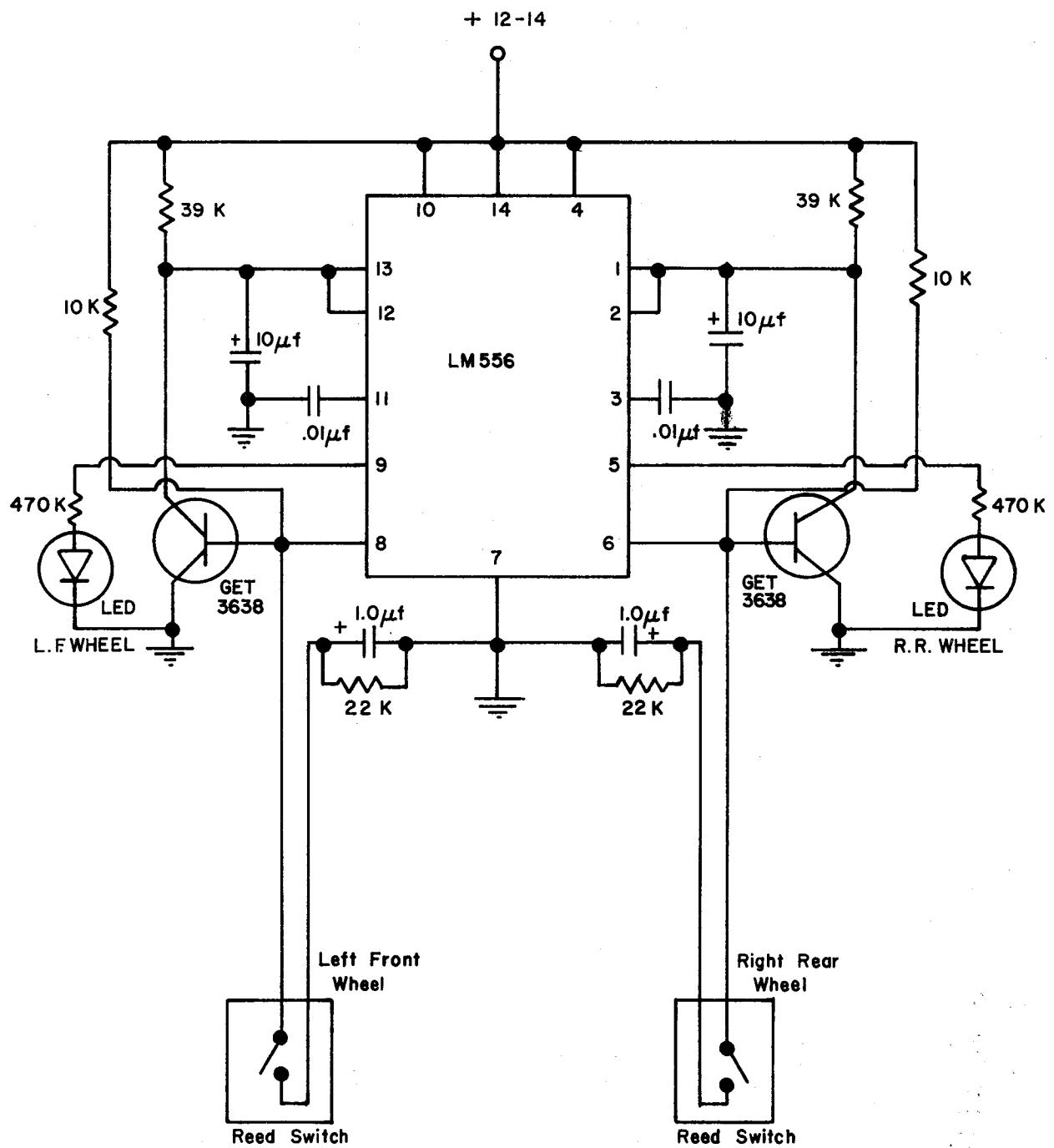


Figure A7 . Wheel Lock Indicator.

2FA8 Servo Accelerometer was mounted near the vehicle c.g. under the bench seat. The accelerometer was coupled to a signal conditioning unit shown in Figure A8 which provided the ± 15 VDC power along with the calibration circuitry and low pass data filtering at 5 Hz to reduce the effects of vehicle and road vibrations.

To record vehicle speed a standard Labeco fifth wheel was used with a Servo-Tek Products Tachometer (Mod. SN-763A-2), attached to provide a voltage vs. velocity output to the signal conditioner unit. Once in the signal conditioner, the velocity is filtered by means of 100 μ f capacitor and fed to the calibration push buttons.

Both the acceleration and velocity signals are connected from the signal conditioner unit to a Hewlett Packard Mod. 320 strip chart recorder shown in Figure A9 on the vehicle seat. This two channel recorder produces a permanent chart recording of each test for subsequent data analysis.

Since the signal conditioner and recorder require 117 Vac power, a 12 volt to 115 volt A.C., 250 watt, Nova inverter was installed on the floor of the truck cab and connected directly to the vehicle battery through a power relay as shown in Figure A9 and A10.

- 5.2 Full Stop Method: The instrumentation required for this mode of DBV operation is simply a method of recording the velocity at which the diagonal wheels locked up and the total distance required to come to a stop from that point. It has been a

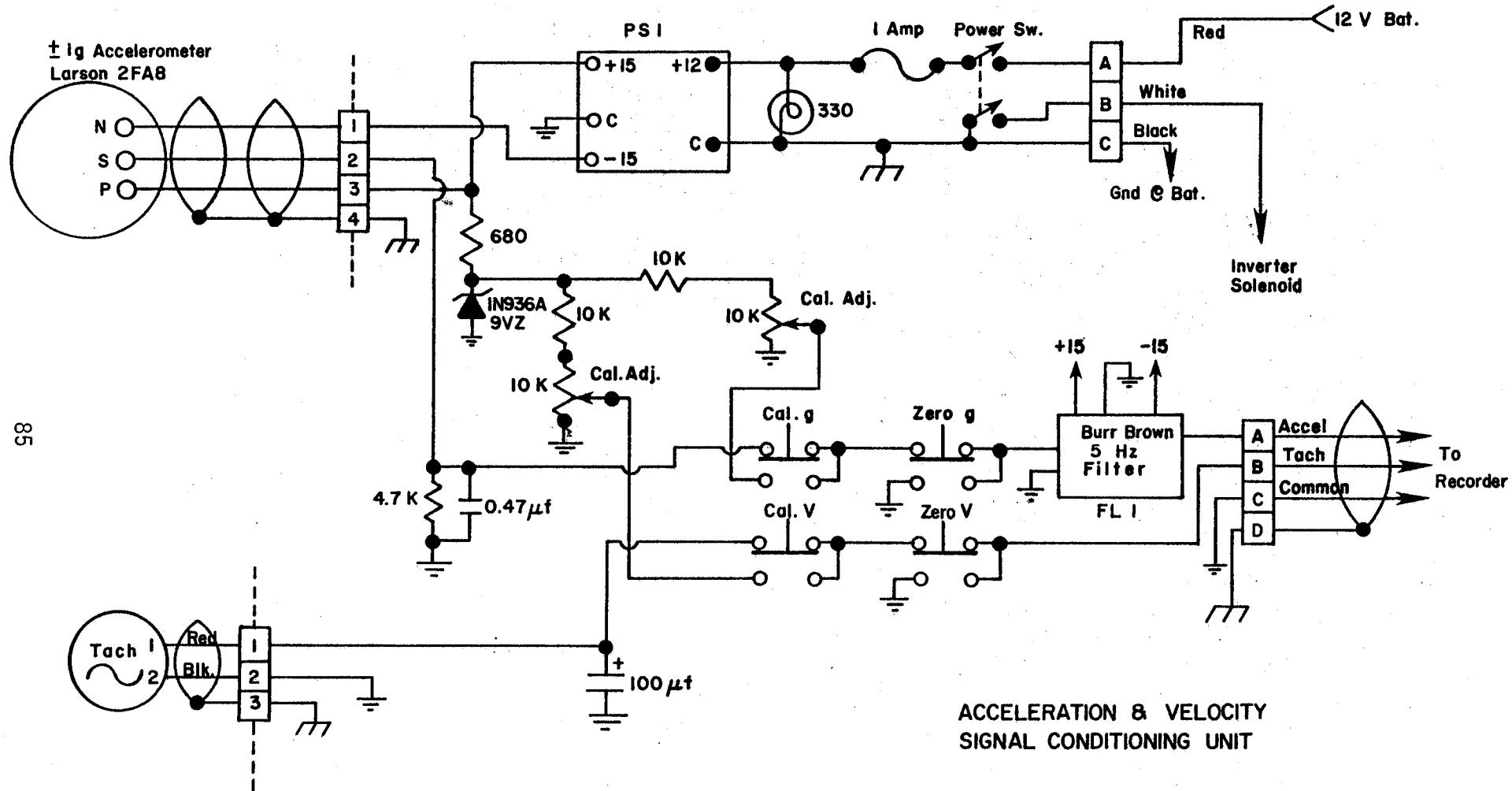


Figure A8 . Acceleration and Velocity Signal Conditioning Unit.

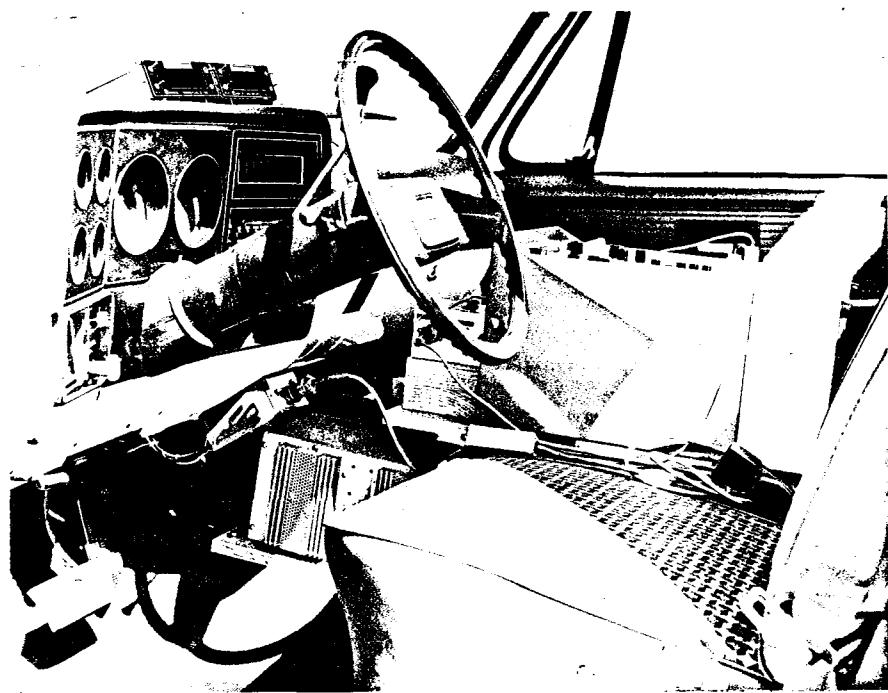


Figure A9. DBV Instrumentation System.

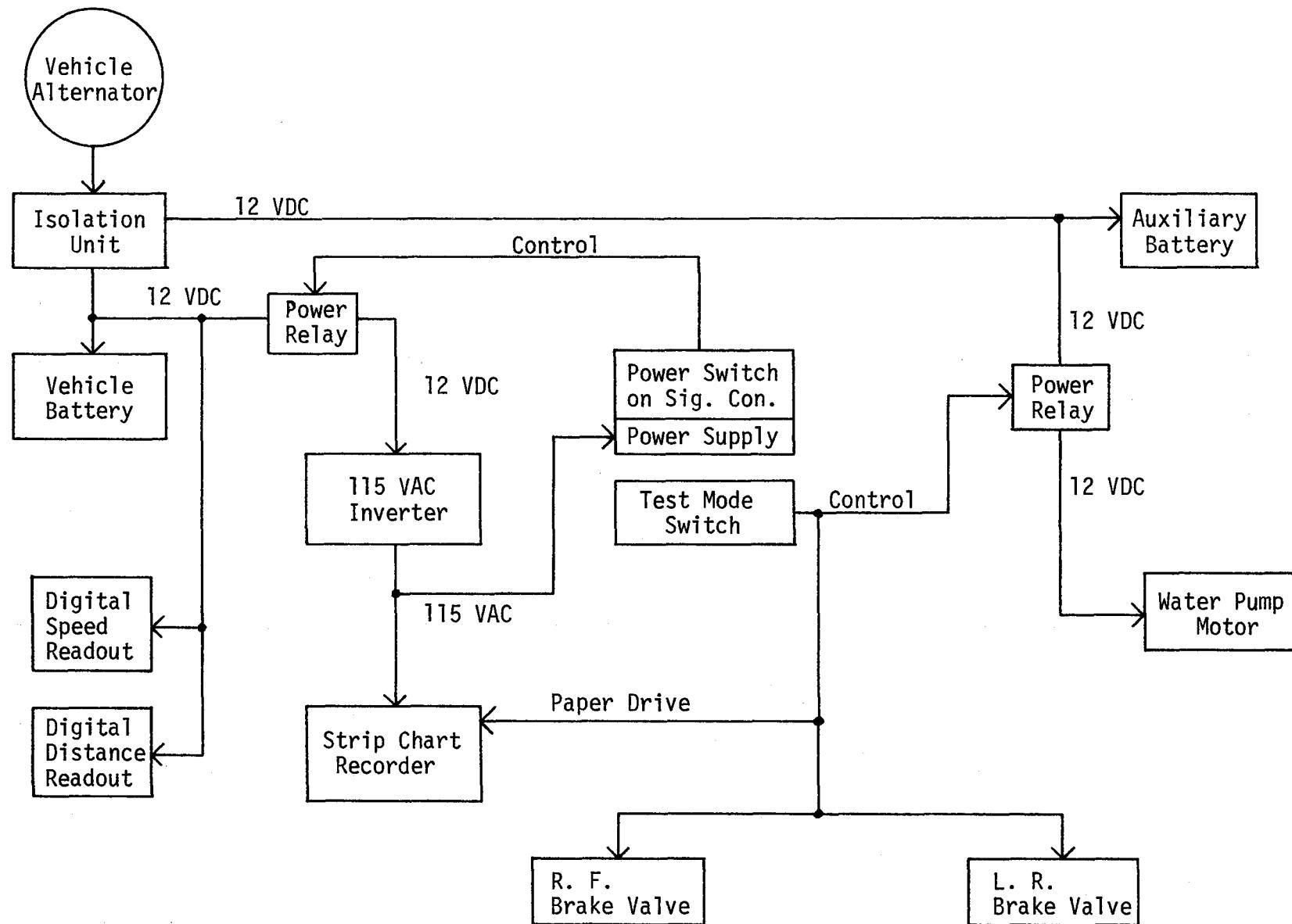


Figure A10. DBV Power and Control Systems.

standard practice to use a pressure switch in the brake line to initiate the speed and distance counters since a very rapid actuation of the brake pedal is required. The velocity and distance is measured by means of standard Labeco DD-1.1 speed and DD-2.1 distance dash mounted indicators shown in Figure A11. These indicators are coupled to the Labeco fifth-wheel pulse transducer. The initial velocity and stopping distance data is recorded after each test by hand and the units are reset for the next run.

A block diagram of these instrumentation systems is shown in Figure A11 with the only common element being the fifth wheel.

6. POWER AND CONTROL SYSTEM: Figure A10 illustrates the total prototype DBV power distribution and control interconnections. A small power switch on the signal conditioner unit operates the power relay to the inverter providing 115 VAC power to the recorder and signal conditioner. The Test Mode Switch is operated by the driver just prior to pressing the brake pedal to conduct a test. This switch converts the braking system to a diagonal braked mode, starts the water flow and starts the strip chart recorder paper drive. The switch is turned off just after a test returning all functions to normal.
7. CALIBRATION: Instrumentation calibration for both the full stop method and pulse-braking method is covered in detail in ASTM E 503-82 which should be consulted by anyone considering constructing or operating this type of system.

Basically the calibration of the full stop instruments (speed

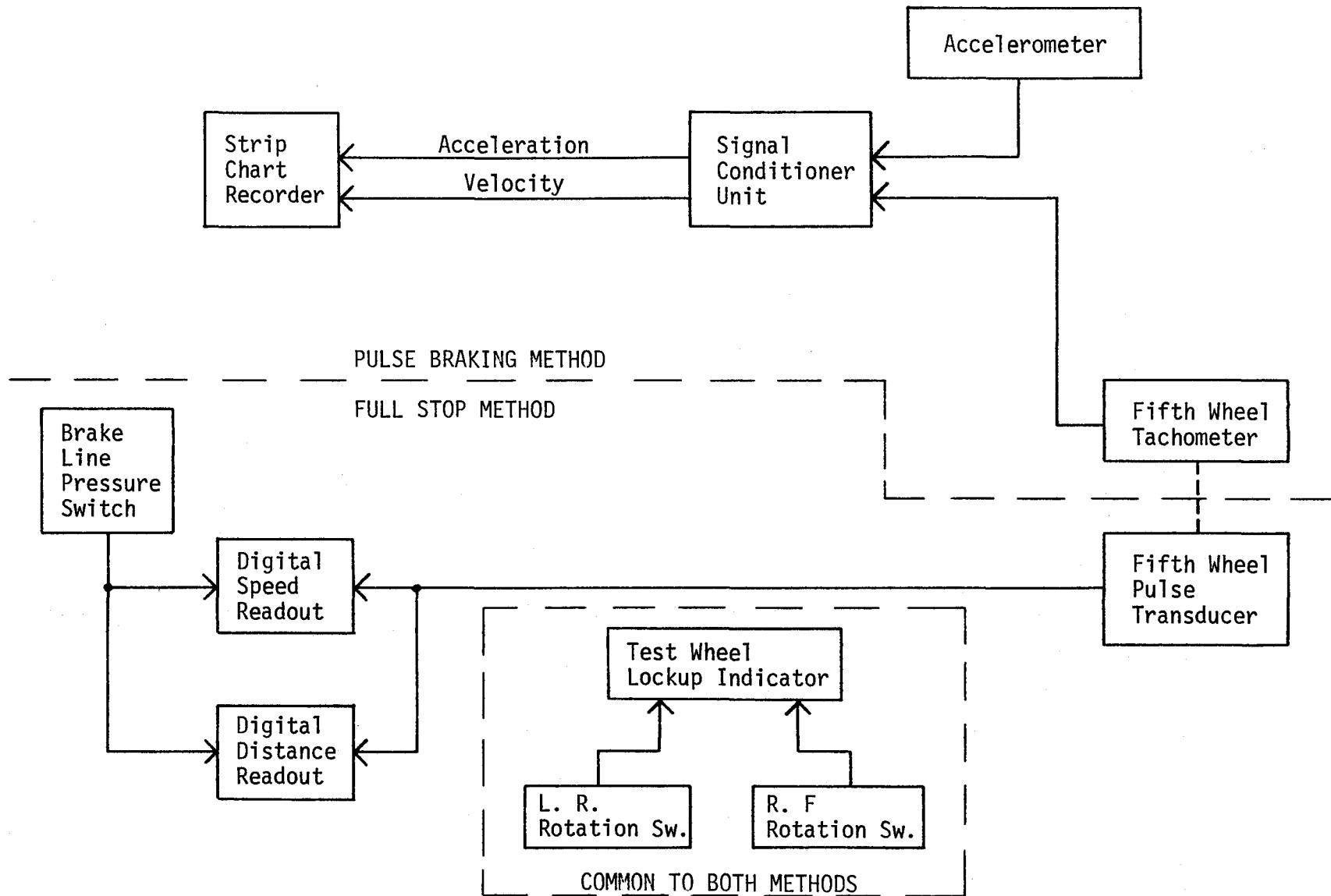


Figure A11. DBV Instrumentation Systems.

and distance) is conducted on a measured course of at least 0.5 mile and usually 1 mile. Speed is measured by timing a steady speed run over the measured distance and the distance readout is compared to the known distance, stopping at the start and end.

The accelerometer used in the pulse-braking method requires occasional calibration by simply titling the unit and measuring the angle vs. output. Since the force of gravity is considered to be equivalent to 1 g, any angle of tilt, from horizontal or zero g, can be converted g's by the equation

$$g = \sin \theta \quad (A1)$$

where:

g = force of gravity

θ = angle of tilt

Cost to Build Diagonal Braking Vehicle

The following costs are approximate for building a DBV similar to the one used in this project.

Pickup Truck ----- \$ 9,000

Instrumentation ----- 7,300

Self Watering System ----- 2,200

Miscellaneous Additional Equipment ----- 600

Sub-Total 19,100

5th Wheel For Digital Speed Readout 2,500

TOTAL \$21,600

APPENDIX B

ADDITIONAL REFERENCES

The following references are included should someone not too familiar with friction measurement systems and the skid measurement process care to do additional reading in this area.

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