SURFACE FRICTION STUDY OF ARIZONA HIGHWAYS

FINAL REPORT

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CHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
Report No. 3

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
SURFACE FRICTION STUDY OF ARIZONA HIGHWAYS

5. Report Date
July 1972

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Materials Division (Research)
1745 West Madison
Phoenix, Arizona 85007

10. Work Unit No.

11. Contract or Grant No.
HPR-1-9(162)

12. Sponsoring Agency Name and Address
Arizona Highway Department
206 South 17th Avenue
Phoenix, Arizona 85007

13. Type of Report and Period Covered
Final Report
August 1970 to March 1972

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared by the Arizona Highway Department in cooperation with the Federal Highway Administration, Department of Transportation. The opinions and conclusions are those of the authors and not necessarily those of the Federal Highway Administration.

16. Abstract

An evaluation of the "sideway force method" for the prediction of the frictional characteristics of pavement surfaces was undertaken. As part of the program, an evaluation of the adaptability of the Mu-Meter as a standard highway friction measuring trailer was conducted. In the evaluation such items as repeatability, speed, temperature, and tire pressures versus friction and the ability to correlate with other friction measuring devices were of prime interest.

The research indicated that the Mu-Meter, when modified, is a highly accurate and functionable friction measuring trailer capable of testing 250 lane miles per working day. At a total cost of $10,600, the Mu-Meter test unit is inexpensive as compared to other skid trailers. Since the unit is an accurate form of testing, it appears that such a unit would be a highly economical method to measure pavement friction.

A friction inventory was conducted of the Arizona Highway system through which a series of correlations dealing with seasonal variations, rainfall amounts, remedial measures and accident analyses were made.

A condition called differential wheelpath friction was studied and it was found that a difference as low as ten wet stopping distance numbers at 40 MPH between wheelpaths can cause a braking car to spin out of control.

The study indicated that emulsified petroleum resin can be safely applied, provided the pavement surface is then sanded and broomed and initially had an acceptable friction level.

17. Key Words
Pavement friction, Mu-Meter, skid trailer, side force, differential wheelpath friction, emulsified petroleum resin, correlations, skid car, inventory, seasonal variations, accident analysis, remedial measures.

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
75

22. Price

Form DOT F 1700.7 (8-69)

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ABSTRACT

The specific aims of the program were to investigate "the sideway force method" for the prediction of frictional characteristics of pavement surfaces in terms of pavement types, layout features, and traffic conditions. As part of the program, an evaluation of the adaptability of the Mu-Meter as a standard highway friction measuring trailer was conducted. In the evaluation such items as repeatability, speed, temperature and tire pressure versus friction, and the ability to correlate with other friction measuring devices were of prime interest.

The research indicated that the Mu-Meter, when modified, is a highly acceptable and functionable friction measuring trailer capable of testing 250 lane miles per working day. At a total cost of $10,600, the Mu-Meter test unit is inexpensive as compared to other skid trailers. Since the unit is an accurate form of testing, it appears that such a unit would be a highly economical method to measure pavement friction.

The Mu-Meter was used in an inventory of 3,439 miles of the Arizona Highway system with the following results. Only 2.8 percent of the system fell below a Mu-Meter reading of 40, but 29 percent of the wet weather accidents fell in the same range. It was also found that when considering the wet weather accidents for a 20 mile section of concrete highway that only 23 percent of the wet weather days had greater than 0.11 inches of rain, but were responsible for 74 percent of the wet weather

accidents. This indicates that approximately a tenth of an inch or greater rain per day may be necessary to create a hazardous condition.

As noted by others, there appeared to be a seasonal variation in friction; however, results indicated that this phenomena is not satisfactorily explained by temperature, or days since last rain alone. The variation seemed consistent for all pavement in a particular area.

A condition called "differential wheelpath friction" was studied and it was found that a difference as low as ten wet stopping distance numbers at 40 MPH between wheelpaths, even when both wheelpaths have an acceptable friction, can cause a braking car to spin out of control. For this reason it may be necessary to test both wheelpaths in the future.

Such methods as chip seals, slurry seals, and heater scarifying are acceptable short-term solutions to slick pavements. Nevertheless, when possible, the application of an open graded asphaltic concrete finishing course should be used for a permanent remedial action.

The studies indicate that asphalt rejuvenating agents (emulsified petroleum resins) can be safely applied, provided the surface is then sanded and broomed and initially had an acceptable friction level.

Consideration should be given to the development of a complete skid potential evaluation system other than the acceptance or rejection based solely on a recorded friction value.

IMPLEMENTATION

The Mu-Meter, when modified, is a highly acceptable and functionable friction measuring trailer capable of testing 250 lane miles per working day. At a total cost of $10,600, the Mu-Meter test unit is inexpensive as compared to other skid trailers. Since the unit is an accurate form of testing, it appears that such a unit would be a highly economical method to measure pavement friction. It is completely mechanical thus eliminating most of the problems that occur with more sophisticated testing units. It is believed that the unit should also be considered an acceptable method and that a new test procedure should be designed based on its use.

With the information presented in this report, any agency should be able to duplicate the test unit at a cost much less than $10,600.

The general savings for this unit could range from $25,000 to $85,000 as related to the skid trailers presently available.

Our studies indicated that further research should be initiated into the problem of differential wheelpath friction, which, thus far, has been undetected but may be a serious problem to the driving public. Our research also indicated that there should be further investigation into deslicking methods, including further research into constructing skid resistant portland cement concrete pavements. Such studies should consider texturing techniques including the addition of skid resistant aggregate to the finished surface, and the frictional effects of grooving.

SURFACE FRICTION STUDY OF ARIZONA HIGHWAYS

On August 18, 1970, the Arizona Highway Department initiated a research program entitled "Surface Friction Study of Arizona Highways," sponsored by the Federal Highway Administration. The research was conducted by the Materials Division's Research Branch. The specific aims of the program were to investigate "the sideway force method" for the prediction of frictional characteristics of pavement surfaces in terms of pavement type, layout features, and traffic conditions. As the research progressed, the program aims were altered to place greater emphasis on traffic conditions and less emphasis on layout features. As part of the program, an evaluation of the adaptability of the Mu-Meter as a standard highway friction measuring trailer was conducted. In the evaluation such things as repeatability, speed, temperature and tire pressure versus friction, and the ability to correlate with other friction measuring devices were of prime interest.

MU-METER

The Mu-Meter is a continuous recording friction measuring trailer (Figure 1). It measures the side-force friction generated between the test surface and the two pneumatic tires which are set at a fixed toe-out angle of 7-1/2 degrees to the line of drag (Figure 2). Pulling the Mu-Meter over a surface produces a frictional force which 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 (Figure 3). The recorder stylus makes a trace on the moving pressure-sensitive chart paper (Figure 4). The chart paper moves at a rate of one inch for every 450 feet of surface tested.

The Mu-Meter was originally designed to measure the actual surface friction conditions of airport runways. For this reason, the unit was a completely mechanical device which had to be put manually into the testing position before a test could be made. After a test was completed, the tester had to again be manually taken out of the test position before moving on to another site. Since this method was extremely time consuming and unsatisfactory for highway work, it was decided to make the test sequence completely automatic. To do this, an observation was made of the means employed by the Utah Highway Department in converting their Mu-Meter to a more automatic system. Their ideas were then expanded upon including the hydraulic system that was added to the test unit. It consisted of two hydraulic rams and a hydraulic control system for moving the test wheel in and out and moving the recording wheel up and down (Figure 5). The hydraulic system worked extremely well and enabled tests to be made by the operator from the cab of the towing vehicle. Thus, testing could be accomplished without stopping.

In order to simulate wet pavement conditions, a watering system was added to the skid test unit. The watering system enabled a uniform .018 inch layer of water to be placed in front of the test tires. A valve regulated the flow, insuring the water layer would remain consistent at all speeds.

A special electrical monitoring system was integrated into the hydraulic and water systems (Figure 6). The system included a number of micro switches which enabled the driver to determine the condition of all systems through a series of lights on the control panel. The system was very efficient and easy to install.

The towing vehicle, which has now become a part of the skid test unit, is a one-ton truck which carries a 300 gallon water supply and all of the support equipment (Figure 7).

A breakdown of the costs are as follows:

Mu-Meter	$5,585
Truck	$2,700
Labor and Parts	$2,300

Thus, the total cost to create an acceptable friction measuring test unit was approximately $10,600. This price is much less than the normal costs for other skid trailers. When it is considered that a test tire ($24.00) will last for a complete inventory of the Arizona highway system, it can be seen that the upkeep of the unit is also very economical.

With the modifications of the Mu-Meter complete (Figure 8), the unit is highly maneuverable, and it is now possible to conduct numerous tests without stopping or interfering with traffic flow. Using this system, approximately 250 lane miles of highway can be tested in one eight-hour day. The normal test speed is 40 MPH with higher speeds possible between test sites. In addition, an automatic speed control on the truck insures the desired test speed.

EVALUATION

Water Layer Thickness

In an attempt to determine what a satisfactory water layer thickness under the Mu-Meter tires would be, a water regulation valve was added to the watering system. The water layer was adjusted from 0 to 0.018 inch of water (at 40 MPH) and tested at seven sites with different friction levels. In all cases, the minimum coefficient of friction was reached after the application of 0.005 inch of water and remained constant with increasing water levels. However, it is believed that if lesser water thickness had been used the results would have shown that 0.001 inch of water would have yielded the lowest coefficient of friction, as was seen in all of the cases in which the water thickness was reduced to this level (Figure 9).

It appears that the Mu-Meter's smooth tires need only an application of 0.001 inch of water to represent a wet roadway instead of the 0.02 inch required by the ASTM E249 ribbed tire. At the present time, however, the 0.018 inch water setting is being used for all testing and was the amount used for all the tests and correlations that are presented in this report.

Repeatability

In evaluating the Mu-Meter, the second variable studied was its repeatability. To do this, 29 sites of varying surface and friction types were studied (Figure 10). (The grading specifications for all of the designs in the paper are shown at the end of the report, Figure 43.)

The Mu-Meter made a series of six passes over each site at speeds of 20 and 40 MPH. It also made six passes over selected sites at 10, 20, 30, 40, and 50 MPH. Twelve passes were made over each site at 40 MPH. All passes were 500 feet in length. It was found that when the selected sites were evaluated between 10 and 50 MPH that there was no significant increase in the standard deviation with an increase in speed. However, the fluctuation about the average for individual tests increased significantly with increasing speed (Figure 11). The Mu-Meter reading for each pass was calculated by the operator through a visual averaging of the entire reading over the 500 feet of test area. The averages from these individual readings were used to calculate all of the standard deviations for a series of passes. Thus, the standard deviations include an error in the averaging of the actual recorded friction. This method was used, however, because it is the method that would normally be used in field testing and inventory work. Even with the included interpretation error, the standard deviation for 29 different sites and six passes at each site was found to be 1.4 friction values at 40 MPH, which is very good for a friction measuring trailer. It was also found that, when all locations were averaged, the standard deviation was the same for six passes as it was for 12 passes at the same speed. A question arose as to whether the standard deviation might be related to the friction value at a particular site. For this reason, the average Mu-Meter reading for each site was compared to the standard deviation. It was concluded that the standard deviation was not significantly effected by the friction value of the pavement surface.

Tire Pressure

The next variable measured was the effect of tire pressure change on the measured surface friction. The results of numerous tests indicated that there is an increase of 0.5 friction numbers with an increase of one pound of tire pressure (Figure 12).

Temperature

A comparison of temperature versus friction was made, but a relationship could not be found (Figure 13). This is probably due to the non-destructive method of the Mu-Meter's test and the type of rubber used in its pneumatic tires.

Speed

When test speed was compared to friction, it was found that there was a strong correlation. With increasing speed, the coefficient of friction, as measured by the Mu-Meter, is reduced (Figure 14). Although the texture of the surface is reflected in the slope of the speed gradient, it can be assumed that there will be a decline of 4.0 friction numbers for every ten miles per hour increase in test speed. From these correlations, a prediction can be made of what the friction value would be at higher speeds if the friction value is ascertained at a lower speed (Figures 15, 16, 17, and 18).

Geometry

The slope of the highway did not appear to effect the Mu-Meter. However, a sharp curve may cause the unit to record a lower friction than may actually exist, as is the case with other skid trailers. Fortunately, the curves present on modern highways are not sharp enough to significantly effect the Mu-Meter.

CORRELATIONS

The final test of the Mu-Meter came with the evaluation of its capabilities to correlate with other friction-measuring devices. These devices were broken into three categories which were:

1. locked wheel trailers (Figure 19),
2. stopping distance cars (Figure 20), and
3. pendulum testers such as the British Portable Tester (BPT) (Figure 21).

The various correlations are shown in Figures 22, 23, 24, and 25, with the data shown in Figure 26. In the case of all skid trailer correlations, the test procedure was carried out with the Mu-Meter and skid trailer traveling one behind the other at 40 MPH, and tests being conducted at the same location and wheel track. The Mu-Meter would make one continuous test while the skid trailer made two consecutive tests on the same pavement by locking only one wheel. Since the two Mu-Meter tires are separated by a short distance, the skid trailer's wheelpath would be centered between the Mu-Meter wheelpaths. In this manner, neither unit was affected by the other's watering system. Since the tires do not track across exactly the same pavement, due to the different forms of testing, a slight but acceptable error may have been added to the correlations using this method.

The Mu-Meter was correlated simultaneously to the Arizona Highway Department's skid car and the British Portable Tester (BPT). The test sequence was as follows:

1. Mu-Meter tested the section using its own watering system at 20 and 40 MPH.

2. A water truck saturated the test area and the Mu-Meter made tests at 20, 40, and 60 MPH. In between these tests and directly after the Mu-Meter, the skid car made five tests each at 20 MPH and 40 MPH with the surface being wetted by the water truck just prior to each skid. (Some 50 MPH skids were attempted but were discontinued because of the hazards created.)

3. After the series was completed, the BPT was used to test the surface at three locations in the wheelpaths using the recommended BPT test method.

This concluded testing at a particular site. In all, 29 sites were tested. The correlations produced are shown in Figure 27 and the data in Figure 28. The correlation between the Mu-Meter and BPT was low, as was expected, due to the inconsistency of the BPT on coarse textured surfaces.

The results of these correlations indicate that the Mu-Meter correlates extremely well to another Mu-Meter similarly modified, to standard skid trailers, and to the stopping distance car, and that the Mu-Meter reading can be interchanged by simple equations with the values recorded by other accepted friction measuring equipment. The results also indicate that the Mu-Meter correlates much better to other equipment when its own watering system is used instead of an externally wetted pavement such as created by a water truck or sprinkling system. This may have been the cause of the lower correlations reported by Gallaway and Rose . Since the friction range is generally greater for the Mu-Meter, it also appears to be more sensitive than the other units.

Figure 29 shows the independent correlation between the Utah Mu-Meter and the Arizona and Colorado testers. This relationship was used to calculate the theoretical correlation used in Figure 30, which shows all of the major correlations plotted together. This figure brings out an interesting and significant conclusion. As can be seen from the graph, there seems to be an inconsistency as to where a minimum friction level exists. At a point when California's skid trailer is reading 35 (which is considered unacceptable), other units can be reading anywhere from 50 to 60 (which they would consider satisfactory). If 40 is chosen for California, the corresponding reading for other units is 60 to 70, which would be considered highly acceptable. In this case, one agency would consider remedial action while another would classify it as having an adequate coefficient of friction and possibly design for such a friction level. We believe everyone will agree that this inconsistency adds further incentive to establish standardization centers as soon as possible and also evaluate a pavement on more than just a determination of its coefficient of friction.

It was hoped that we could evaluate the minimum acceptable Mu-Meter reading at 40 MPH by calculating the corresponding Mu-Meter reading for a recorded value of 35 for other skid trailers and a 46 for the skid car (as described in NCHRP Report 37)[2]. There was a wide range in the calculated values, due to the inconsistencies of the trailers. When all units were averaged, a value of 42 was calculated. When only the skid trailers were averaged, a value of 43 was calculated. For this reason and because the accident analysis indicated a braking point of approximately the same value, a wet Mu-Meter reading of 43 at 40 MPH is considered to correlate best with other skid trailers' values of 35. In the future, when units have been standardized, this value may be changed to conform with other devices.

GENERAL OBSERVATIONS

The Mu-Meter, being completely mechanical, proved to be an extremely trouble free testing unit. The only inoperative time recorded was due to a broken hitch and an initially defective recorder, which was promptly replaced. The unit proved itself more than acceptable for highway use up to 85 MPH (limits of tow truck) and has suspension superior to most highway vehicles. It is a rugged unit which can be towed anywhere a truck can travel. In the two years we have had the unit, it has been out of operation for approximately two weeks.

SKID INVENTORY

During the program, a complete inventory of our State's highway system was conducted. The inventory consisted of skid tests made at every other mile post for one-tenth of a mile. When traveling in the increasing mile post direction, the tests were made at the even-numbered mile posts. When traveling in the decreasing mile post direction, the tests were conducted on the odd-numbered mile posts. In this way, a test was made at least once at every mile post (Figure 31). A total of 3,439 miles of highway was inventoried.

The surface friction inventory made by the Mu-Meter will be used to locate low friction areas and monitor the yearly frictional changes of the entire highway system. Using this inventory, pavement problem areas can be detected. Predictions can also be made as to when borderline cases will, if ever, fall to questionable friction levels. This will allow advance planning for their correction, prior to the existence of hazardous conditions.

SEASONAL VARIATION

The research studies have shown that there appears to be seasonal variation in the coefficient of friction which follows similar patterns at any particular location in a given area (Figure 32). In our research program, a 20 mile area was investigated and the average pattern for each direction of the highway is shown in Figure 33. As can be seen, the patterns and values are almost identical for each direction. A climatological investigation of these results was generated and included a comparison of 1) temperature versus friction and 2) days since the last .01 inch or more of rain versus friction. The results are shown in Figure 34. The results indicate that the variation is due to a combination of factors; however, temperature and days since last rain do not explain the phenomena satisfactorily. Correlations were made with higher amounts of rainfall, but the correlation was lower than with the .01 inch of rain, so they are not presented.

It was noted that after rainstorms there was usually an increase in friction; however, in some cases the friction dropped to its original friction value within a few days and in other cases it took longer or did not return at all but kept increasing. The amount of rain did not seem significant because in some cases, even after the heaviest rain, the friction level did not increase even though it was at one of its lowest levels. Further examination of the data is necessary to determine the significance of all the variables effecting this variation.

The data indicated that there might have been a general trend between temperature and friction. Our previous studies had indicated that none existed, so further tests were conducted during the summer when the friction level was at a low value. Tests were run during the coolest and hottest part of the day (50°F pavement temperature difference) over the 20 mile section of highway. Negligible change in the friction coefficient was recorded. Arizona is unique in its wide range of daily pavement temperatures which lends to evaluating temperature versus friction without the influence of seasonal variables. These tests have shown that when evaluating temperature versus friction, a short time period should be involved; otherwise, an incorrect interpretation of the results could be made.

The seasonal variation must be considered when analyzing skid data. This is necessary because a pavement that may have a satisfactory friction level at one time of the year could have an unsatisfactory value at another time of the year. Present information indicates that the lowest friction level is reached during the summer months in Arizona. For this reason, the Arizona Highway Department plans to conduct its friction inventories during these months.

DIFFERENTIAL WHEELPATH FRICTION

During our testing, a condition was noted that we feel warrants special attention and further investigation. The condition occurs when the two wheelpaths in which a vehicle rides have a different coefficient of friction. We are aware that there will usually be a small difference, but this is not the condition we are describing. The differential wheelpath friction (DWPF) we are considering is one in which a vehicle may be riding on two different surface types, two different ribbons of asphaltic concrete or concrete pavement, or a condition where one wheelpath is flushed or polished while the other is not. To our surprise, a very small difference in the wheelpath frictions will cause a car to spin out of control when braking. An example of two conditions are shown in Figures 35 and 36. In Figure 35, the wet stopping distance number at 40 MPH (SDN_{40}) was 50 for the right wheelpath and 60 for the left wheelpath, which is only a 17 percent difference. In picture A, the car skidded at 30 MPH and rotated 25^{o} counterclockwise. In picture B, the car skidded at 40 MPH and rotated 40^{o} counterclockwise. In picture C, the car skidded at 50 MPH and rotated 95^{o} counterclockwise. When the direction of skidding was reversed, the same values were recorded with the car turning clockwise. In Figure 36, the right wheelpath had a wet SDN_{40} of 67 and the left wheelpath had a SDN_{40} of 41, a 39 percent difference. In picture A, the car skidded at 40 MPH and rotated 90° clockwise. In picture B, the car skidded at 50 MPH and rotated 270° clockwise. Again, when the direction of skidding was reversed the same values were recorded with the car rotating counterclockwise.

Figure 36 is an extreme case used to portray what might happen if one wheelpath were flushing while the other was not. However, the first case is one that is fairly common and, although both wheelpaths have a satisfactory level of friction, a hazardous condition occurs due to their difference. As the speed increases, the effects increase dramatically. Under such conditions, the normal driver tends to remove his foot from the brake as he begins to rotate. When he does, his car is propelled in the direction the vehicle is turned, perhaps off the road or into the oncoming traffic lane.

Since 1) construction practices at the present time can produce lanes containing two ribbons, and 2) that a friction inventory would not detect unsatisfactory friction differences in the wheelpaths (since only one wheelpath is tested), it is the opinion of the author that an investigation should be conducted to determine if both wheelpaths should be tested for a meaningful evaluation of the pavement. In the case of skid trailers, the trend is to lock only one wheel, but if both were locked and had independent recorders, such DWPF areas could be located and corrected. In such a case, some form of stabilizing unit would have to be added to the trailers. Hopefully, further research will be conducted so that an acceptable differential wheelpath friction level can be determined.

FRICTION ANALYSIS

As part of the study, an analysis of the percent of the highway system falling into each friction range was made (Figure 37). These and following interpretations are made from the highway inventory previously mentioned. The results showed that only 2.8 percent of the Arizona highway system fell below a skid number of 40. This figure must be considered when evaluating the accident analysis. It was found that approximately 50 percent of the highway system fell within the Mu-Meter frictional range of 71 to 80. These results indicate that the skid resistance level of the Arizona highway system is predominantly very good and that the present pavement designs and aggregate types are producing satisfactory skid resistant surfaces.

ACCIDENT ANALYSIS

During the research study, the question arose as to what a satisfactory level of friction might be. To determine this, an accident analysis was made of the entire Arizona highway system and correlated to the skid inventory previously described. The results of this analysis were most revealing. The accident types were broken into three categories for the analysis. These were:

1. Dry pavement accidents,
2. Wet pavement accidents, and
3. Wet skidding accidents.

The number of samples falling into each friction range was not uniform since the majority of the highway system inventoried fell into the higher than 50 range. For this reason, the accident analysis had to be in a form which would take this into consideration. To do this, a ratio was made by dividing the percent of any particular accident type in a given friction range by the percent of the highway system falling in the same range. The results of the analysis are shown in the upper portion of Figure 38. It is evident from these graphs that the majority of wet weather accidents fall into the low skid resistance ranges. The analysis also indicated that, although less than three percent of the total Arizona highway system had a coefficient of friction below 40, 29 percent of the wet weather accidents occured in these areas. When a friction level of below 50 is considered, it relates to less than seven percent of the highway system but 43 percent of the wet weather accidents.

The lower portion of Figure 38 shows the difference between dry and wet, dry and wet skidding, and the wet and wet skidding accident indices for the entire highway system in Arizona. It is a truer representation of the effects of wet pavement and was calculated from the figures above them. These graphs depict the increase of the accident index in the lower friction ranges especially in the below 40 ranges for wet and wet skidding accidents. It can be seen that above a friction value of 50, the difference in the accident indices becomes equal and even become negative. We are aware of the other methods possible in relating accident analysis to the coefficient of friction. However, after a thorough evaluation of all methods, we believe that on a large scale in Arizona, this particular analysis yields a very meaningful evaluation.

In evaluating the accident analysis, a study of the amount of rainfall occurring on the days of the accidents was made. In this way it was hoped to determine if there was a significant amount of rainfall necessary to create a hazardous condition. In this study, a 50 mile section of portland cement concrete freeway was selected and the accidents were analyzed for a three-year period of recorded information. The analysis was based on the relationship between the total number of accidents occurring at various daily rainfalls. These accidents per amount of rainfall were compared to the percent of the three years that the particular amount of rainfall was present. The accumulated percents were calculated and then plotted (Figure 39). The location where the curve reached a one-to-one slope was picked as the point where the accumulated percent of accidents begin increasing faster than the accumulated percent of days. This point was related to the accumulated percent of accidents which were present at a Particular amount of daily rainfall. The results revealed that the slope reached unity at approximately 26 percent of the accumulated accidents. This percent relates to a rainfall amount of approximately 0.11 inch of water per day. In simple terms, this means that a tenth of an inch or more occurred only 23 percent of the time but was responsible for 74 percent of the accidents. The same relationship holds true when only sections with a Mu-Meter reading of 40 or below were considered. Apparently, although a small amount of water is necessary to reduce the friction level as recorded by the Mu-Meter, at least a tenth of an inch per day is necessary to create a significant increase in the wet weather accident rate.

CORRECTIVE MEASURES FOR SLICK PAVEMENTS

In our studies we found that the methods of correcting low friction pavements by the use of chip seals, slurry seals, and heater scarifying are very effective and all have an adequate coefficient of friction after construction. However, as others have also noted, there is a question of how long each method can last prior to the reappearance of the original or a lower friction value. In our opinion, the slurry seal should only be used as an intermediate step in the correction of low friction pavements, since it could flush and create even a worse condition after a short period of time. As for heater scarifying and chip seals, the predicted life may vary significantly with construction techniques.

It is generally agreed that an asphaltic concrete finishing course (ACFC) should be used as a lasting remedial action. The question arises as to whether a dense or open graded ACFC is a better skid resistant surface. In our research, two sections were compared which were constructed in an area where the only difference was that one was an open graded mix and the other a dense graded mix. The results are shown in Figures 40 and 41. The conclusions from these tests indicate there is little difference when the normal application of water is used; however, when the surface is flooded (unexposed surface aggregate), the dense graded ACFC's friction decreased significantly with speed while the open graded ACFC remained approximately the same as with normal water. The higher skid resistance under such circumstances is due to the open graded

ACFC's greater drainage abilities. In Arizona, where rainstorms are of an intense nature, such drainage is required for higher freeway speeds and, for this reason, the Arizona Highway Department is considering a greater use of the open graded ACFC, especially in the correction of pavements with low friction levels. Some engineers believe that such open graded mixes and, in some cases, all exposed asphaltic concrete should be treated with an asphalt rejuvenating agent. Since these agents are being used and appear to cause the pavement to become slick, an investigation into the frictional effects of asphaltic rejuvenating agents was undertaken.

FRICTIONAL EFFECTS OF ASPHALT REJUVENATING AGENTS

(Emulsified Petroleum Resin)

In the evaluation of asphalt rejuvenating agents (ARA), various surface types and amounts of applications were studied. The results from these tests are shown in Figure 42. The analysis began by measuring the surface friction prior to the application of ARA. As soon as the ARA was placed and demulsified (turned brown), the friction was remeasured and the value recorded (shown as point A). The friction level was measured each hour after the application demulsified as shown on the graph. In some cases, the pavement was sanded or broomed; these points are shown on the graph as the letters S and B, respectively. A marked increase in the friction can be seen after each of these procedures. From these tests the following conclusions can be drawn:

1. The application of an asphalt rejuvenating agent (emulsified petroleum resin) causes an initial drop of approximately 53 percent in the Mu-Meter reading.

2. The application of sand is beneficial but, when combined with brooming, increases the surface friction significantly and raises it to a satisfactory level.

3. In all of the cases tested, a satisfactory level of friction was achieved when the surface was sanded and broomed.

4. In the cases tested, all of the surfaces that were sanded and broomed regained most of their original friction within 24 hours.

5. It is possible for the pavement to reach an acceptable level without sanding or brooming; however, it may take a much longer time and in some cases may never recover its original level.

6. When an ARA is applied to a pavement, the wet and dry friction is the same up to a Mu-Meter reading of 60. This phenomena is unique and has only been observed after such applications.

7. If a surface originally has a low friction value, an application of ARA may create a hazardous condition that may not be easily corrected.

Present tests indicate that it is possible to safely use an asphalt rejuvenating agent if the pavement is sanded and broomed afterward. If the original pavement friction is low, however, friction tests should be performed prior to opening the pavement to traffic, thus, insuring that the pavement has risen to an acceptable friction level.

CONCLUSIONS AND RECOMMENDATIONS

1. The Mu-Meter, when modified, is a highly accurate friction measuring trailer. It has a standard deviation of 1.4 and correlates extremely well to other skid trailers and the stopping distance car. A wet Mu-Meter reading of 43 at 40 MPH appears to correlate best to other skid trailers' wet values of 35 at 40 MPH.
2. At a total cost of $10,600, including tow truck and modifications, the Mu-Meter test unit is inexpensive as compared to other skid trailers. Since research indicates that it is an accurate form of testing, it appears that such a unit is a highly economical method to measure pavement friction.

3. This unit can test 250 lane miles of highway per day with a minimum of maintenance. It is highly sturdy and more manuverable than most skid trailers.
4. The Mu-Meter inventoried 3,439 miles of the Arizona highway system with the following results: Only 2.8 percent of the system fell below a Mu-Meter reading of 40, but 29 percent of the wet weather accidents fell in the same range. It was also found that only 23 percent of the wet weather days had greater than 0.11 inch of rain but 74 percent of the wet weather accidents occurred on these days. This indicates that it may be necessary to have greater than a tenth of an inch per day of rain to create a hazardously wet condition.
5. The seasonal variation was studied but temperature and days since last rain do not satisfactorily explain the phenomena. The variation seemed consistent for all pavement in a particular area.
6. The effect of different wheelpath frictions was studied with the following results. A difference of 10 wet stopping distance numbers between wheelpaths can cause a braking car to spin out of control even though both wheelpaths have an acceptable level of friction. For this reason, it may be necessary to test both wheelpaths in the future.

7. Initial studies indicate that chip seals, slurry seals, and heater scarifying are acceptable short term solutions to slick pavements, but an open graded asphaltic finishing course should be considered as a permanent remedial action.
8. Asphalt rejuvenating agents can be safely applied if the surface is then sanded and broomed and if it initially had an acceptable friction level.
9. Consideration should be given to the development of a complete pavement evaluation system other than the acceptance or rejection based solely on a recorded friction number.
10. Further research should be initiated to investigate various deslicking methods including methods to insure permanent skid resistant surfaces on portland cement concrete pavements. The studies should evaluate texturing techniques, addition of skid resistant aggregate to the finished concrete, and the frictional affects of grooving.

ACKNOWLEDGEMENTS

The authors wish to extend their appreciation to George W. Tharp (Engineering Assistant III), who operated the skid test equipment during the program and compiled the friction data; Arthur E. Bishop (Welder), who assisted in the design and the modifications on the Mu-Meter and support equipment; Elliot D. Gappinger (Draftsman I) for his drafting work; to the Highway Districts, who assisted in the success of this program; and to the Materials Division's clerical staff, for their assistance in the preparation of this report.

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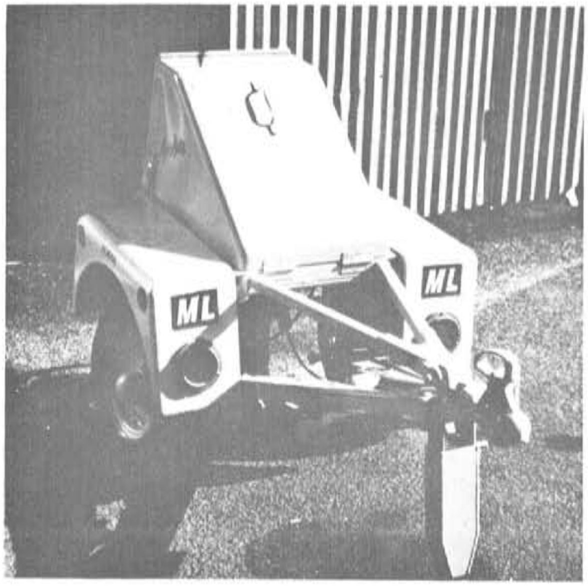
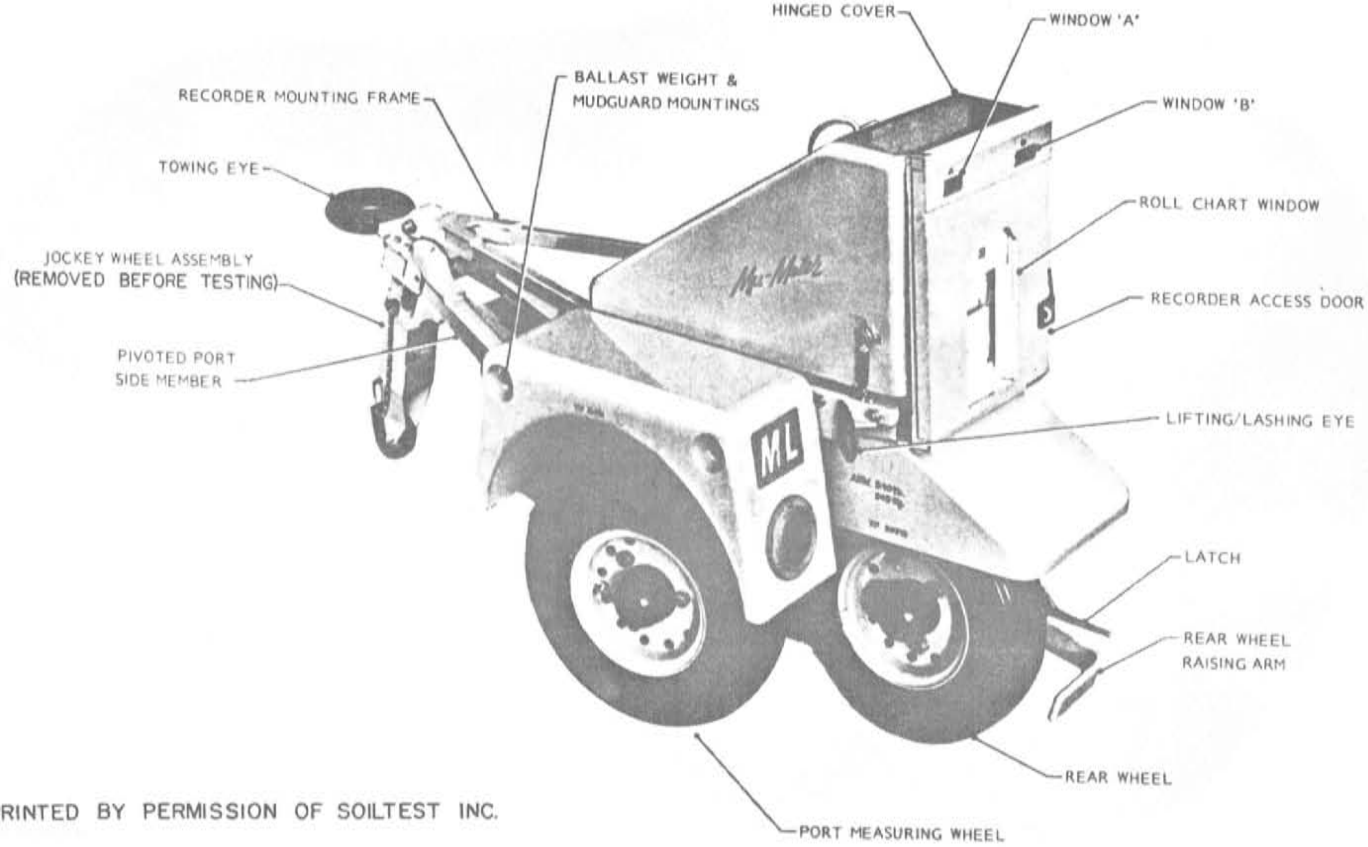
1. Gallaway, B. M. and Rose, J. G., "Comparison of Highway Pavement Friction Measurements Taken in the Cornering Slip and Skid Modes," Texas Transportation Institute, Texas A and M University, January 1971.

2. Kummer, H. W. and Meyer, W. E., "Tentative Skid Resistance Requirements for Main Rural Highways," National Cooperative Highway Research Program Report No. 37, Highway Research Board, 1967.





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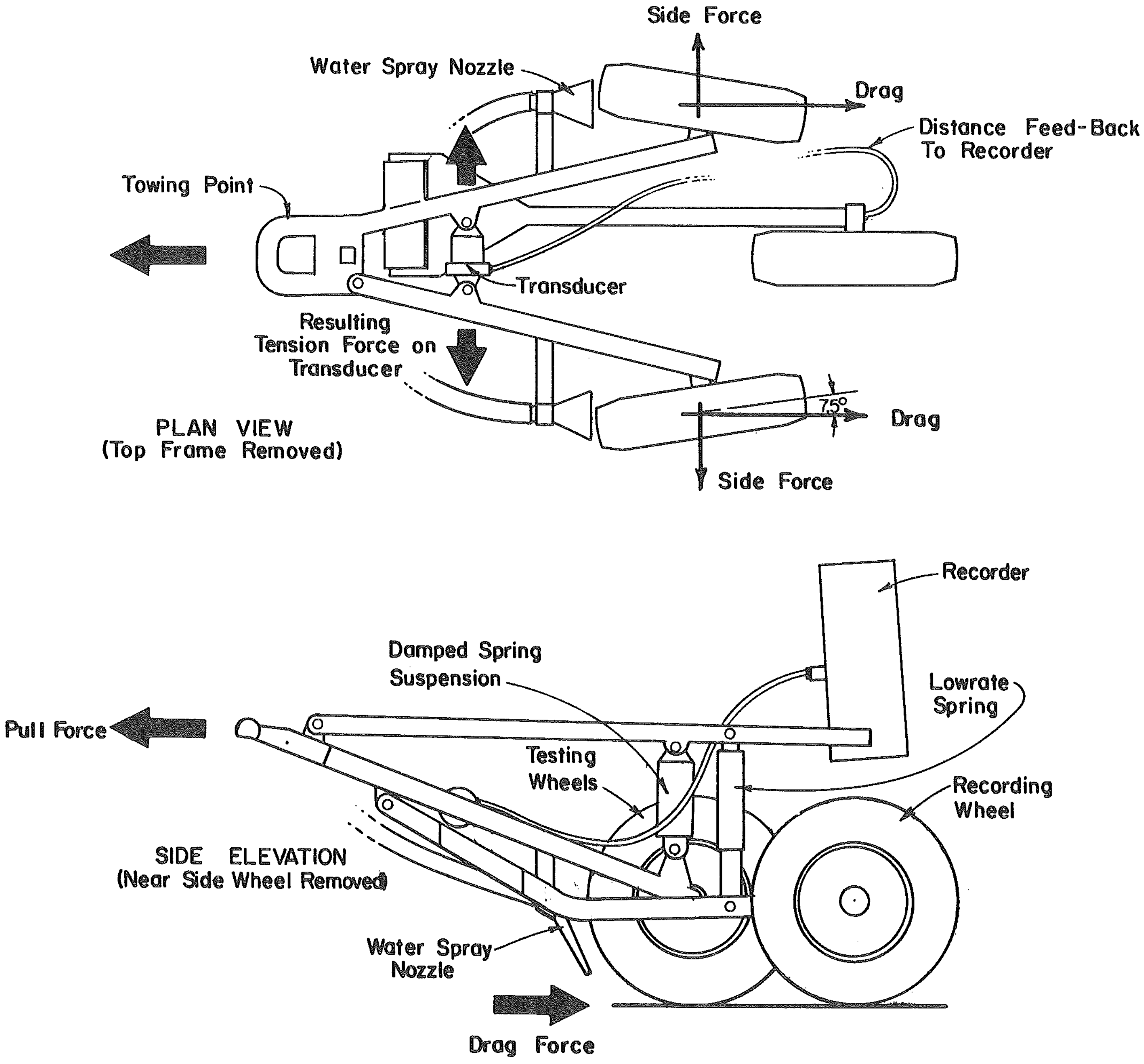
ORIGINAL MU-METER
(UNMODIFIED)
Figure 1

MU-METER SCHEMATIC



Lower "A" frame (plan view) carries two friction test wheels on pivoted stub axles and king pins. Left wheel pivots from 7-1/2 degree toe-in to 7-1/2 degree toe-out position, which creates a total included angle of 15 degrees between the tires. The trailer is pulled with wheels yawed outward which produces a drag as the wheels continue to rotate. The transducer between the forks senses lateral movement of the hinged left hand fork pulled by side force. The center recording wheel rides on a separate arm and turns the flexible cable which drives the chart paper and two mechanical digital readouts in the recording unit.

Figure 2

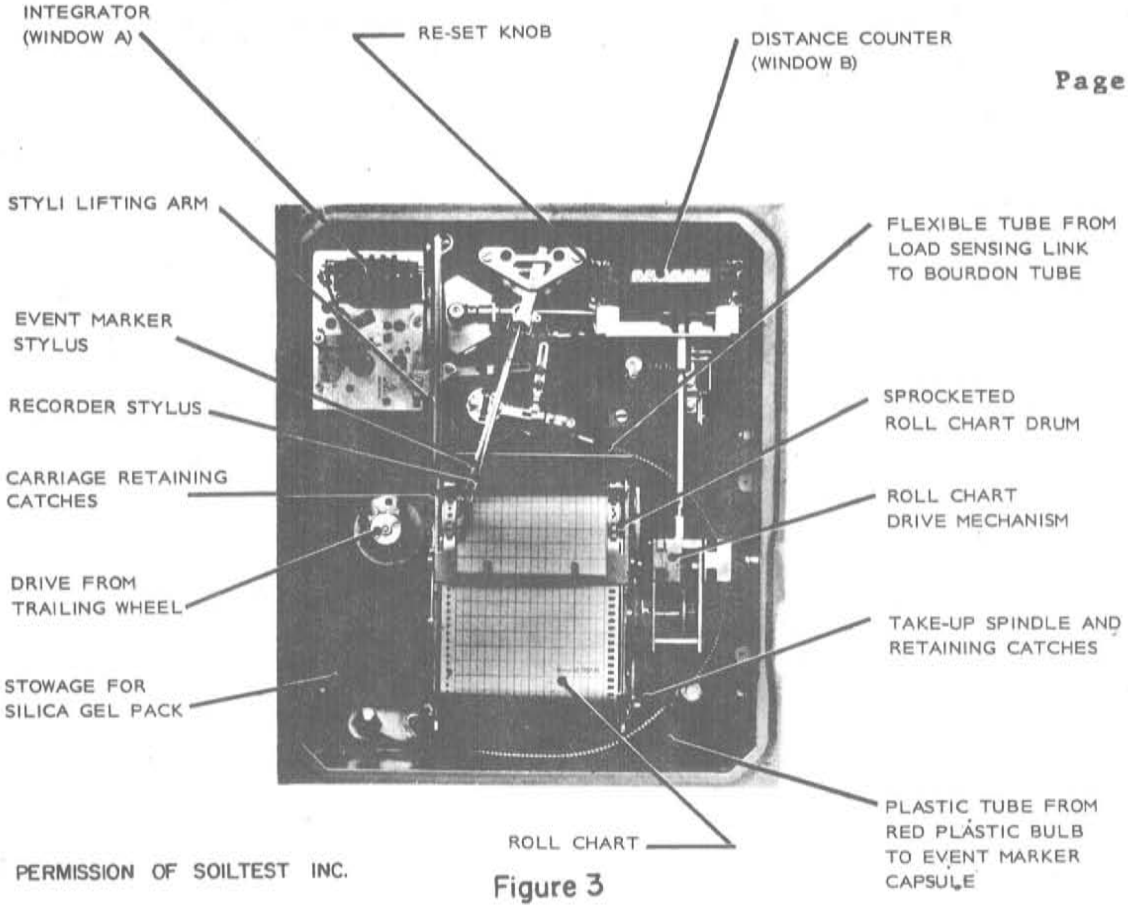


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Figure 3

MU METER CHART

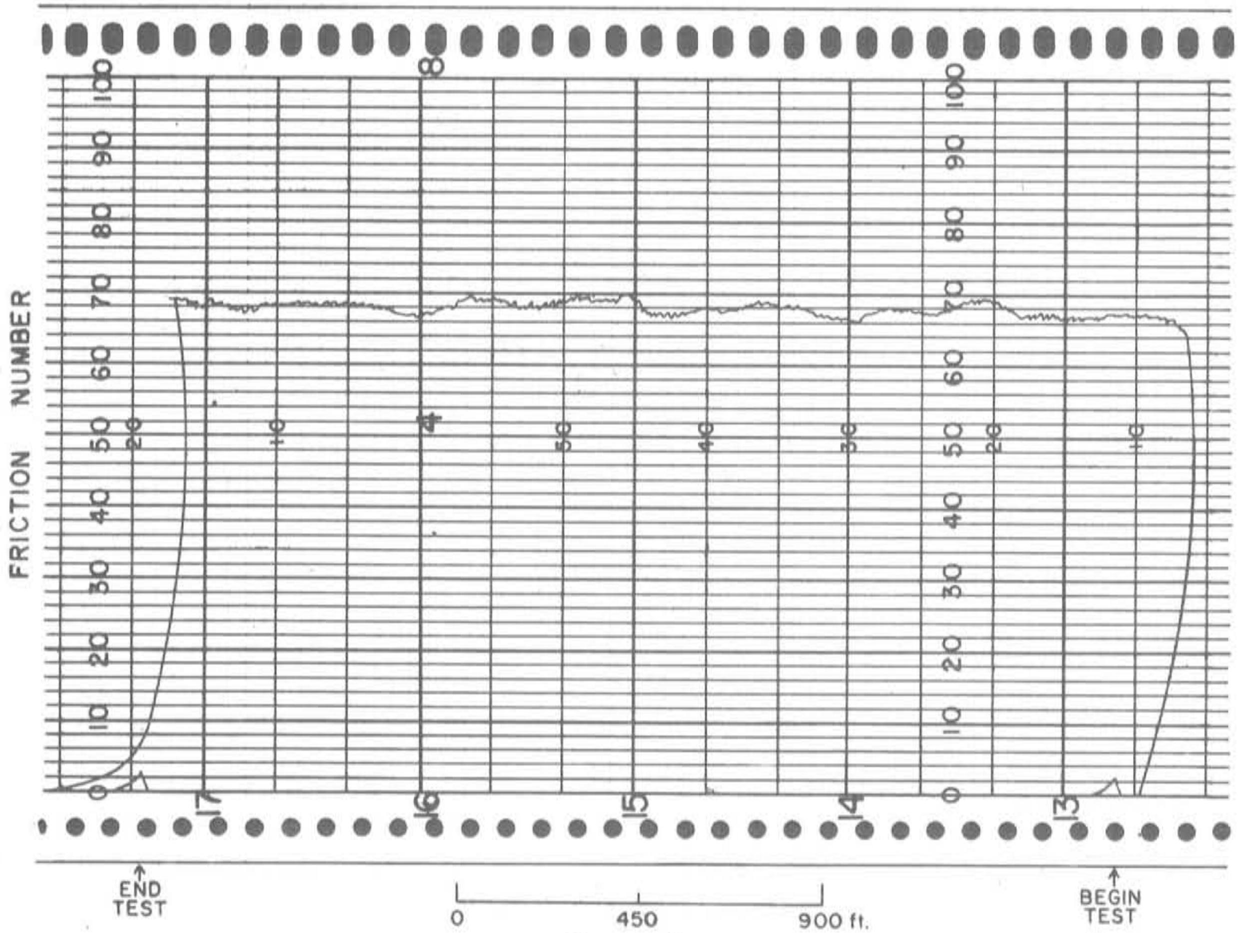


Figure 4

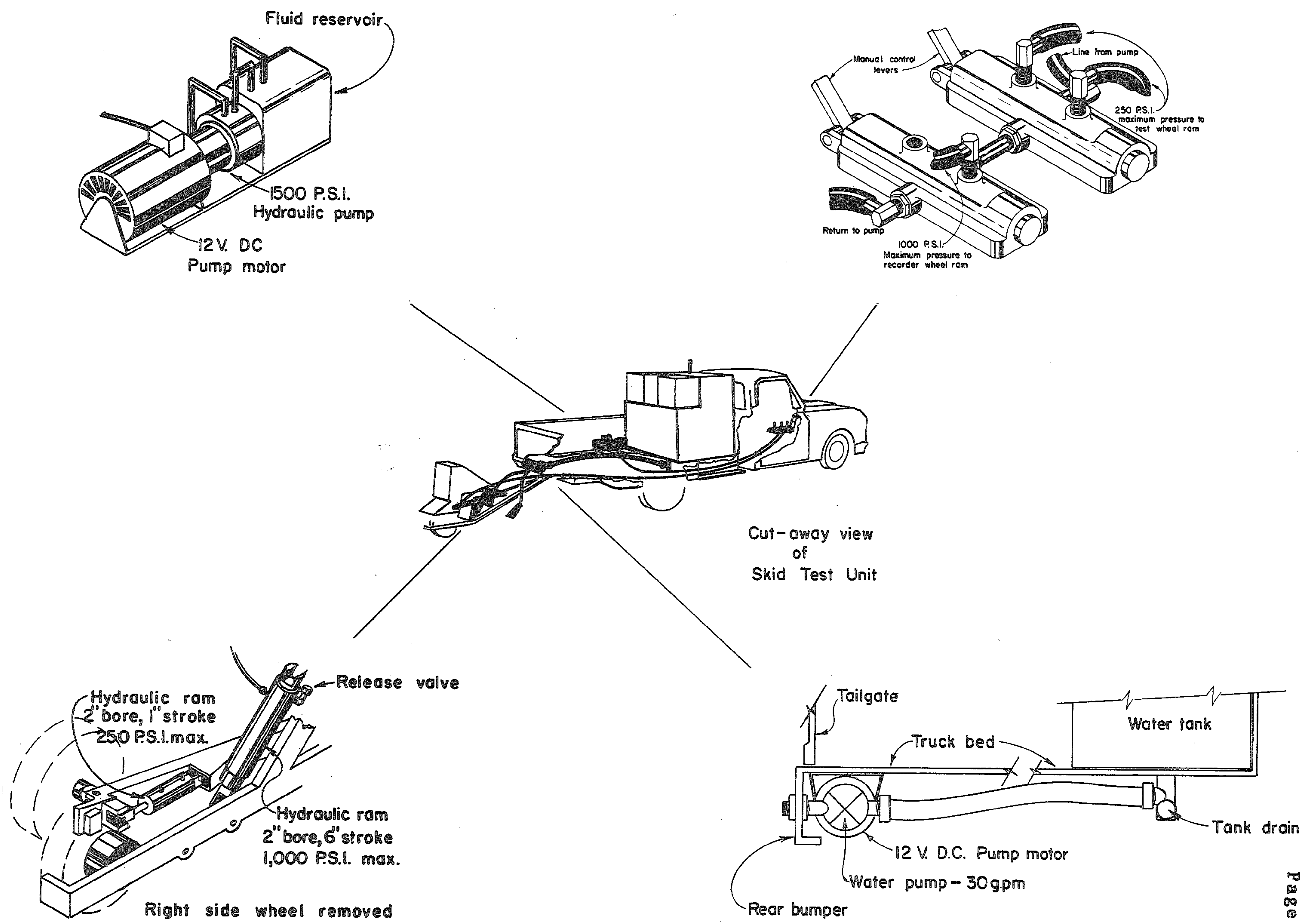
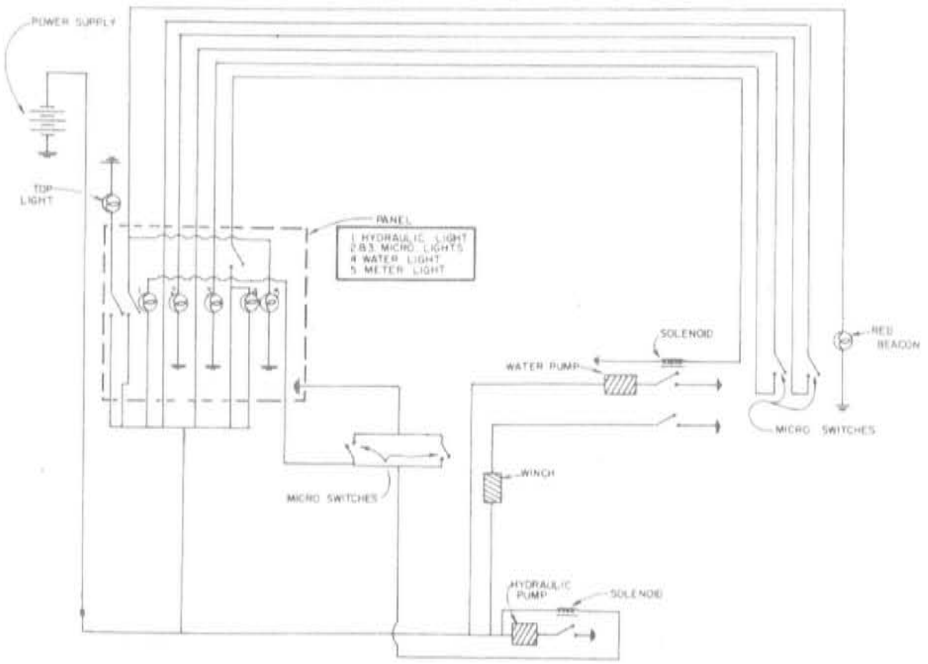

Fluid reservoir
1500 P.S.I. Hydraulic pump
12 V. DC Pump motor
Manual control levers
Line from pump
250 P.S.I. maximum pressure to test wheel ram
Return to pump
1000 P.S.I. Maximum pressure to recorder wheel ram
Cut-away view of Skid Test Unit
Release valve
Hydraulic ram 2" bore, 1" stroke 250 P.S.I. max.
Hydraulic ram 2" bore, 6" stroke 1,000 P.S.I. max.
Right side wheel removed
Tailgate
Water tank
Truck bed
Tank drain
12 V. D.C. Pump motor
Water pump - 30 g.p.m
Rear bumper

Figure 5

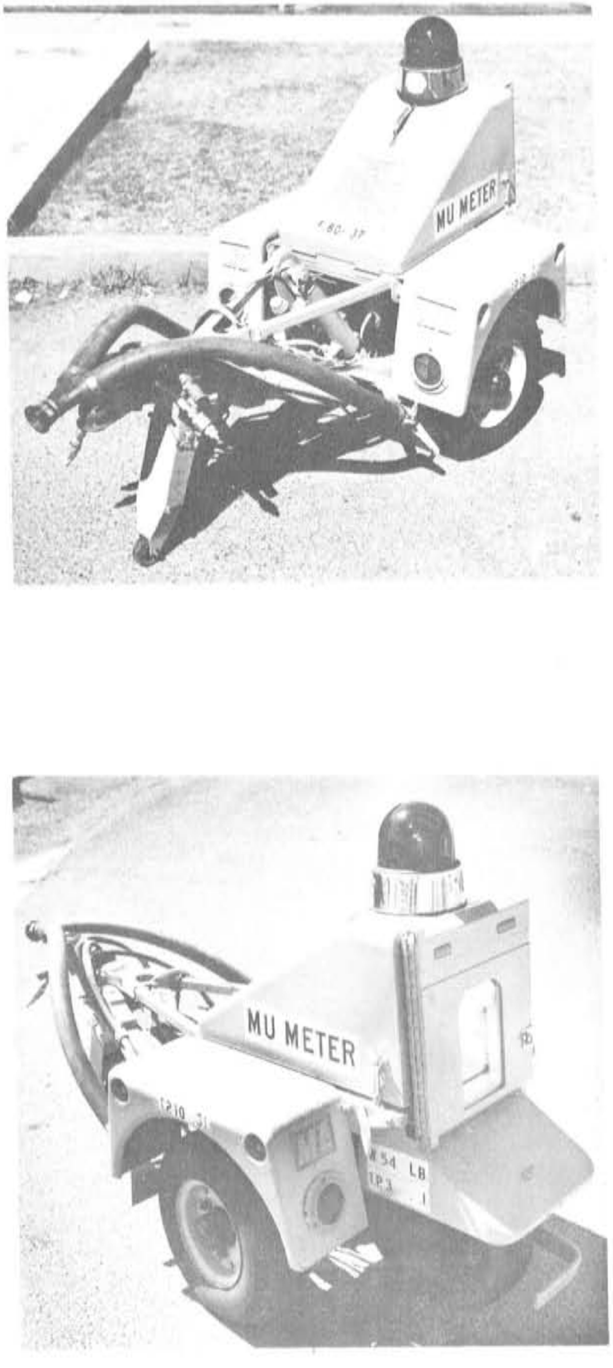


ELECTRICAL SCHEMATIC

Figure 6

COMPLETE SURFACE FRICTION TEST UNIT

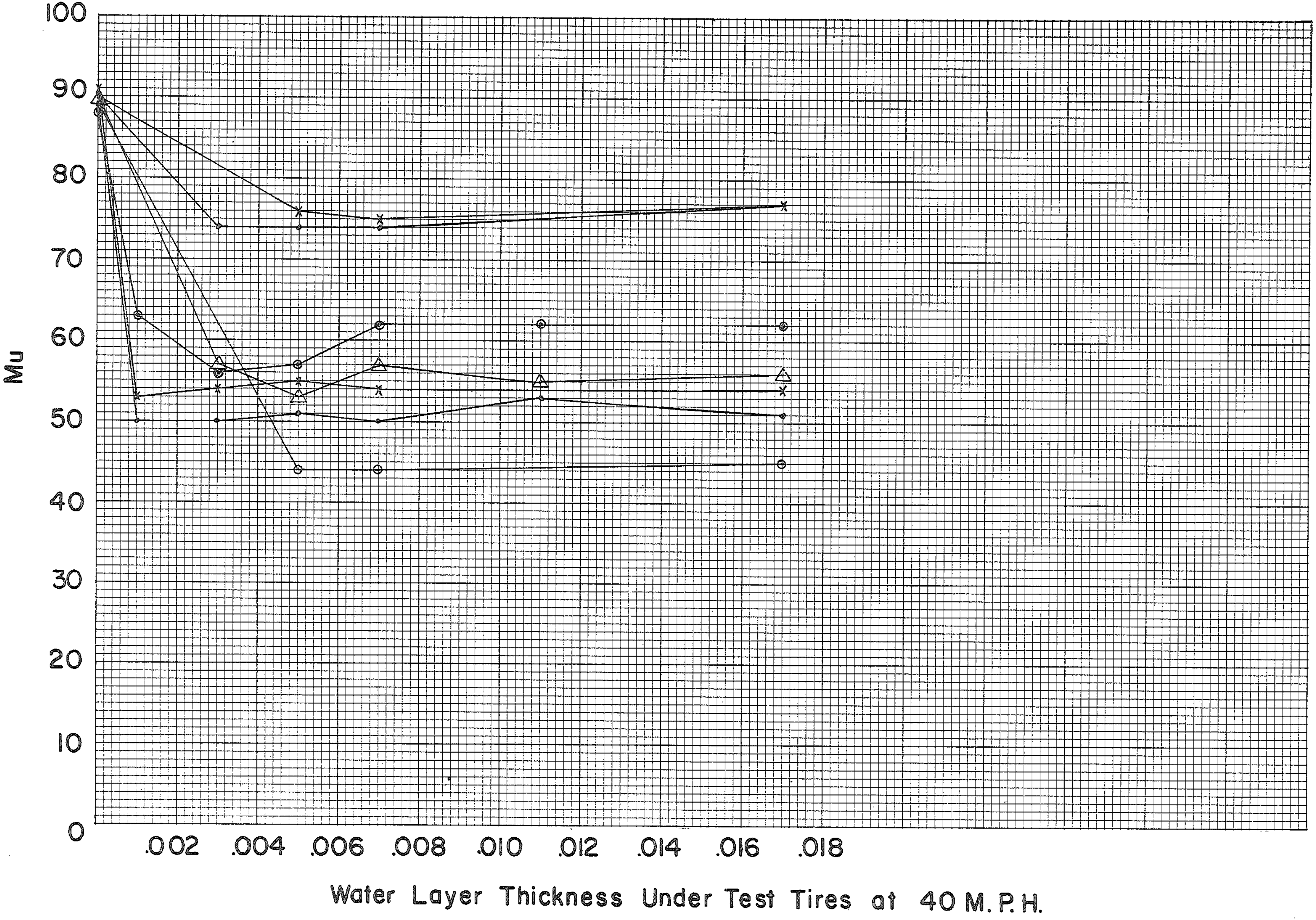
Figure 7



ARIZONA HIGHWAY DEPARTMENT'S
MODIFIED MU-METER
Figure 8

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 9
WATER LAYER VERSUS FRICTION



TEST SITE DATA

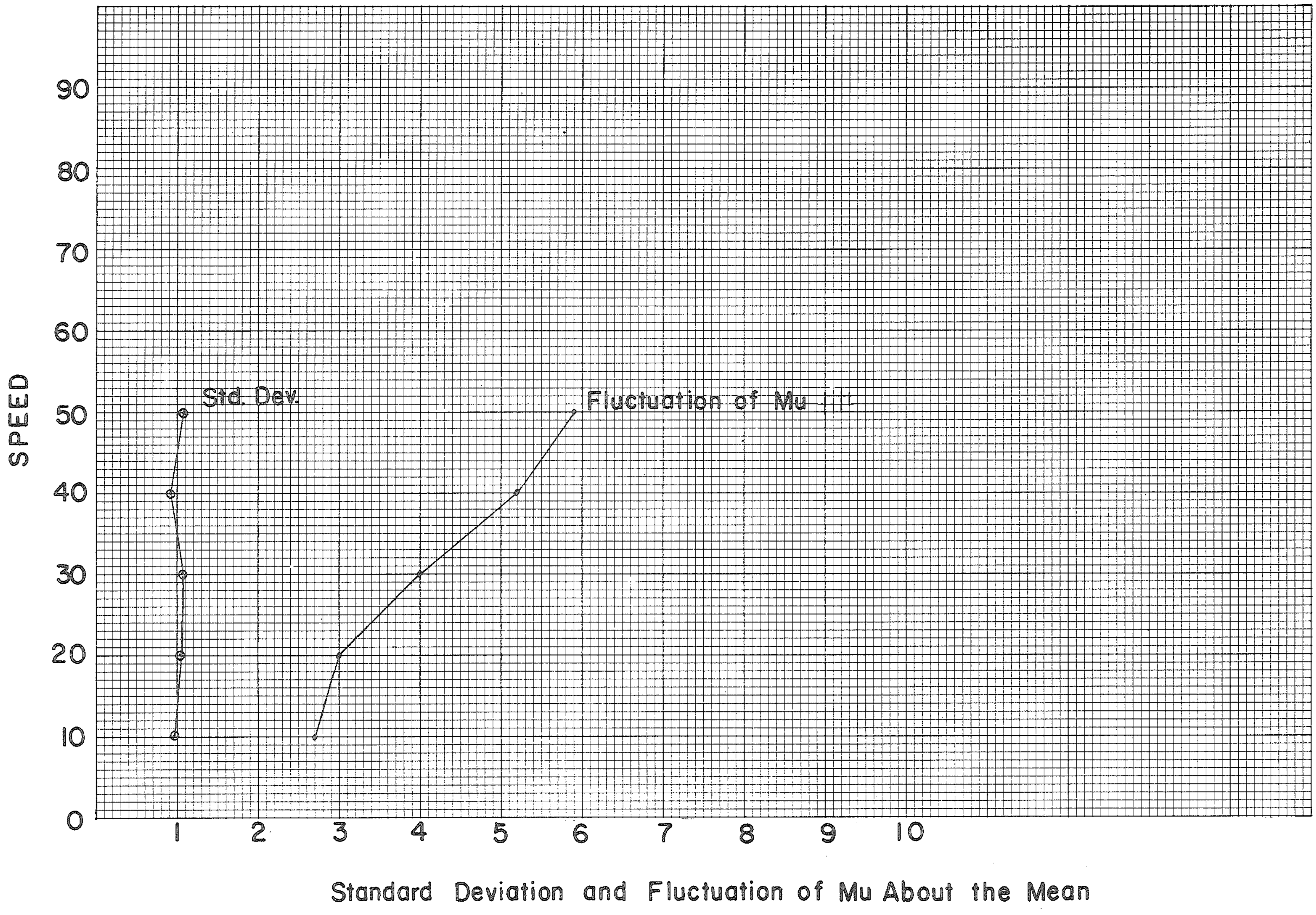
Section	* Surface Type	σ 10 MPH	** Average Variation	σ 20 MPH	Average Friction	** Average Variation	σ 30 MPH	** Average Variation	6 Tests 40 MPH	12 Tests σ 40 MPH	Average Friction	** Average Variation	σ 50 MPH	** Average Variation
1	PCCP			1.5	51.7	6.7			1.4		40.7	15.5		
2	MA-7			1.0	63.8	6.2			1.5	1.2	60.7	10.9		
3	MA-6			2.9	59.0	5.2			1.2	1.6	55.2	8.5		
4	MA-2			1.2	70.2	5.2			1.8	1.7	63.0	9.1		
5	MA-7			1.4	56.5	3.5			1.2	1.4	56.5	4.3		
6	MA-7			2.5	59.8	4.5			2.3	1.9	58.9	5.8		
7	MA-7			1.9	57.5	3.3			1.5	1.7	53.8	4.3		
8	MA-6			2.0	61.0	3.3			2.0	1.6	60.0	5.0		
9	MA-7			1.2	76.1	4.1			2.0	1.9	69.1	3.8		
10	MA-3	0.5	1.7	0.8	81.5	2.0	1.9	2.5	2.0	1.0	75.3	3.1	1.5	3.2
11	MA-7	0.8	4.2	2.1	70.2	4.2	0.6	4.7	1.6	1.4	65.1	5.3	1.7	7.5
12	MA-3	1.5	2.7	1.4	70.7	3.0	1.6	5.0	0.5	0.6	63.2	6.8	1.4	7.8
13	MA-2	0.9	2.5	0.5	81.7	2.2	1.0	2.8	0.8	0.8	77.3	3.3	1.3	3.3
14	MA-7			1.5	59.8	7.0			1.6	1.4	54.1	8.6		
15	MA-6			2.2	60.5	4.2			1.5	1.2	57.5	4.6		
16	CM-3			1.5	45.7	7.0			1.4	1.3	42.7	12.3		
17	MA-6			2.8	56.8	6.8			1.9	1.8	52.1	8.9		
18	CM-3			1.5	50.8	5.3			1.6	2.0	50.8	6.4		
19	MA-7			1.5	61.3	3.8			1.3	1.5	61.2	4.8		
20	MA-7	1.9	3.5	1.5	83.5	2.3	1.2	2.8	0.4	1.0	85.7	2.8	1.0	3.3
21	MA-7	1.5	4.5	1.7	74.8	5.7	1.8	5.7	2.4	2.9	73.3	7.3		
22	CM-3			1.5	61.2	4.5			1.5	1.5	55.3	8.5		
23	MA-6			1.5	53.0	4.7			2.0	1.9	42.8	6.5		
24	CM-6	0.8	1.8	1.0	94.2	1.5	1.2	2.0	1.3		91.2	2.7	0.8	2.8
25	MA-7	0.8	1.0	1.0	80.5	1.2	1.3	2.0	0.8		83.2	3.3	0.8	5.0
26	PCCP	0.8	2.7	1.0	77.5	7.0	0.4	10.5	0.5		64.7	14.5	1.0	15.0
27	CM-8	1.0	1.2	0.5	89.3	1.2	0.9	1.3	1.8		89.0	2.0	0.8	3.2
28	CM-7	0.8	5.5	0.5	73.5	5.3	0.5	6.2	0.5		73.3	7.8	0.5	8.2
29	PCCP			0.8	88.5	2.8			1.8		80.0	7.5		

* See Mix Design
** Average Variation In Single Reading
σ = Standard Deviation

Figure 10

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 11
SPEED VERSUS STANDARD DEVIATION



ARIZONA HIGHWAY DEPARTMENT
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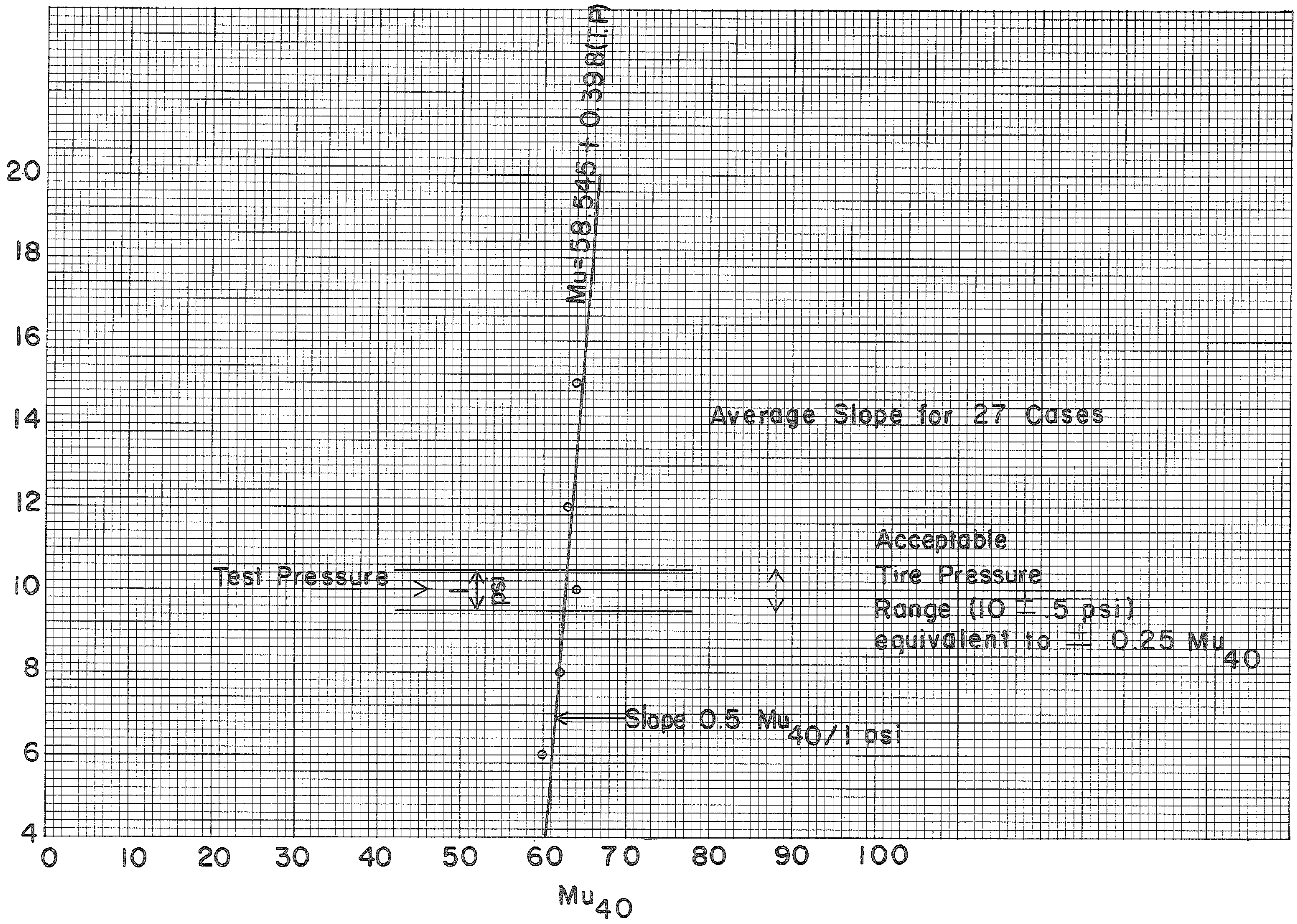
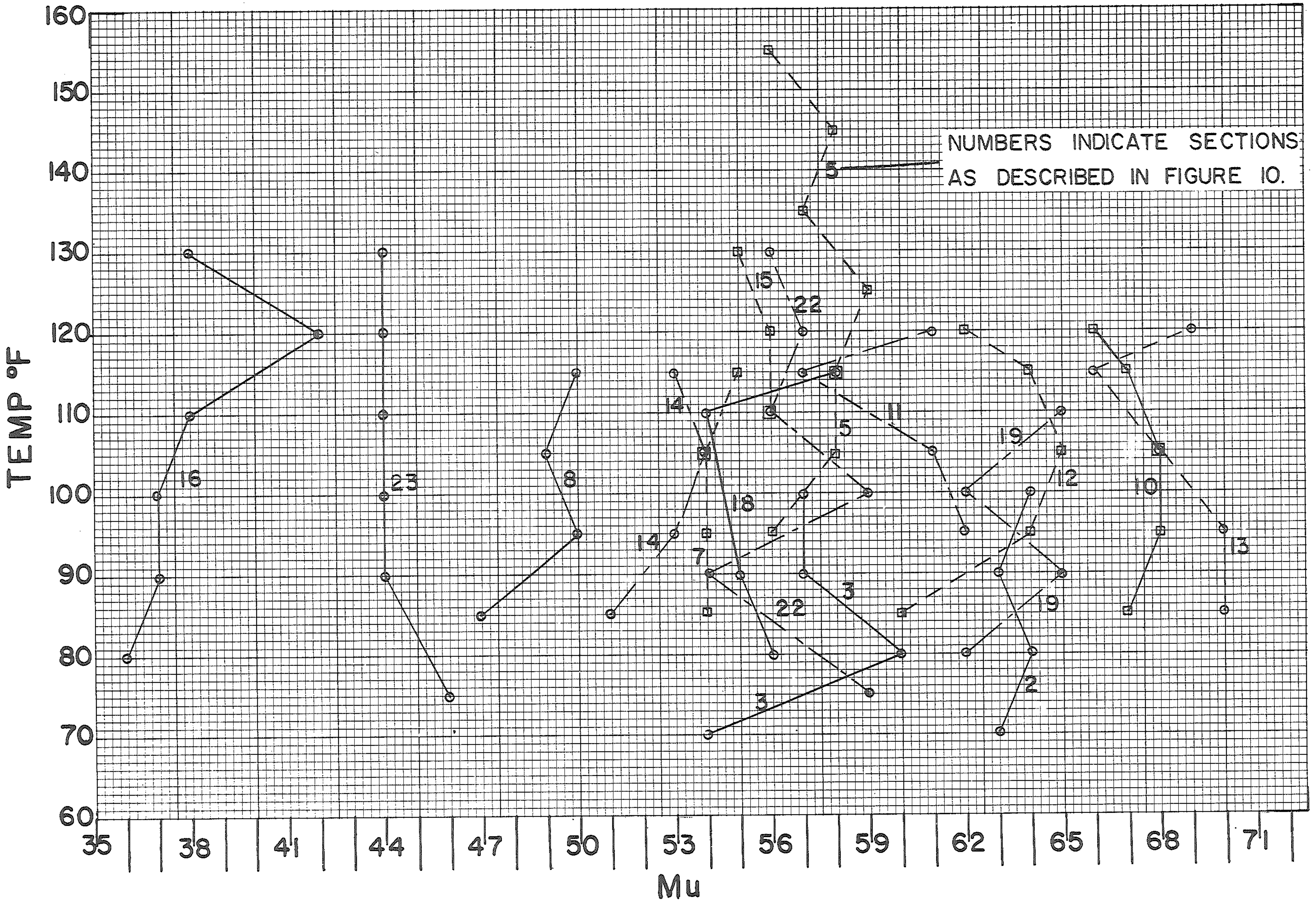
Figure 12
TIRE PRESSURE VERSUS FRICTION



ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 13

TEMPERATURE VERSUS FRICTION



MU-METER
SPEED VS. FRICTION GRADIENTS

Figure 14

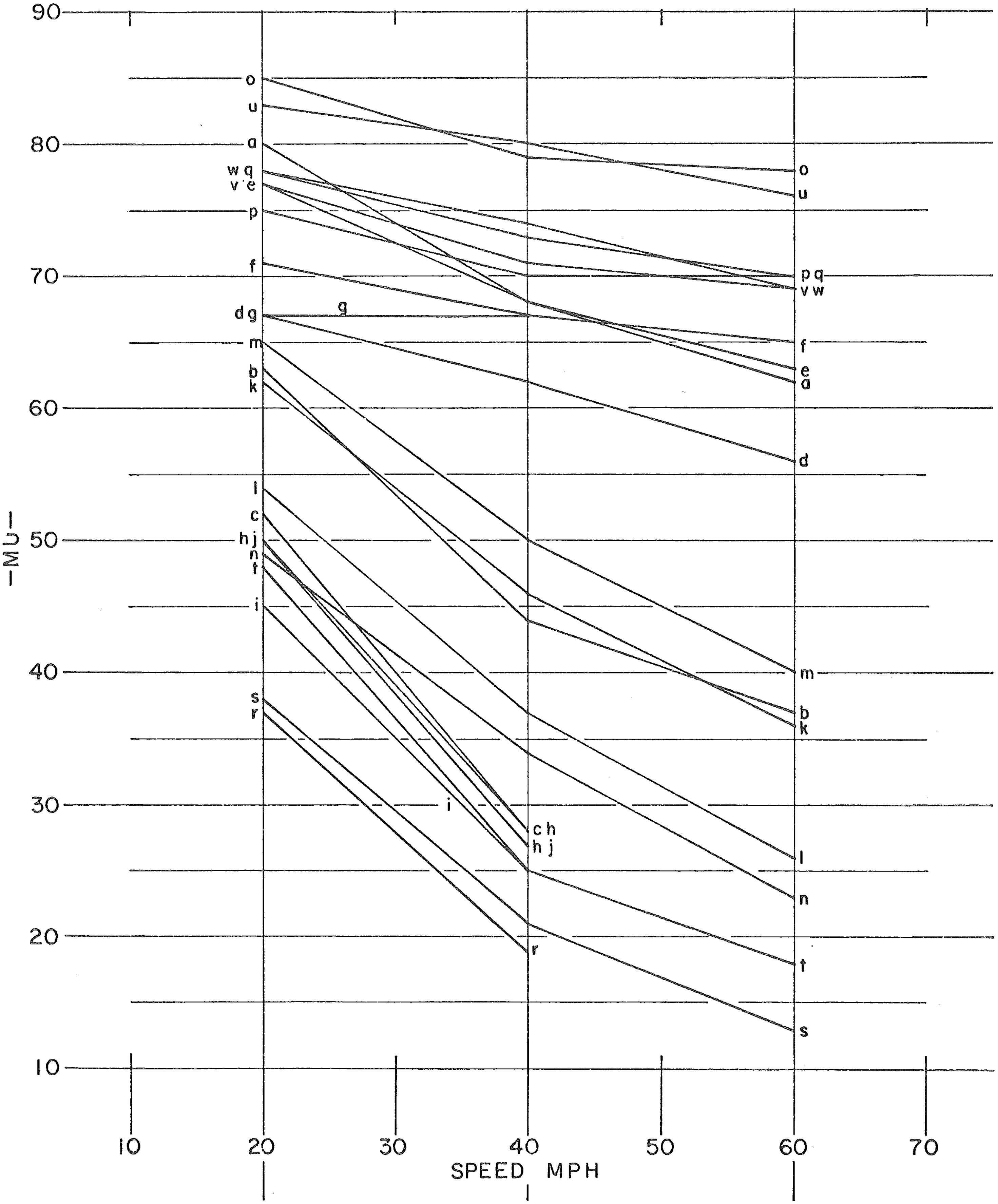


Figure 14 (Cont'd)

MU-METER

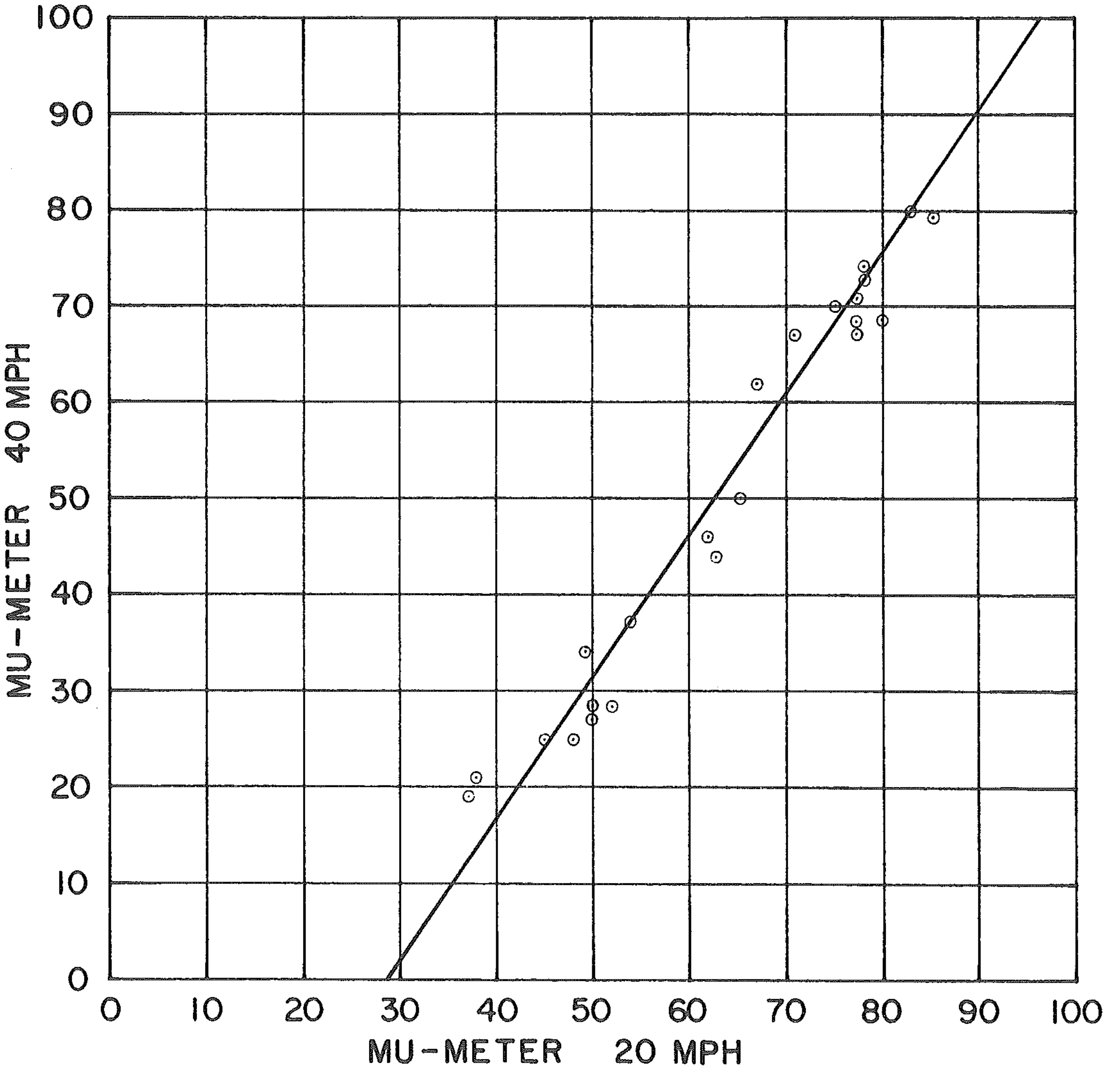
SPEED VS. FRICTION GRADIENTS

Site	20 MPH	40 MPH	60 MPH
a	80	68	64
b	63	44	37
c	52	28	
d	67	62	56
e	77	68	63
f	71	67	65
g	67	67	
h	50	28	
i	45	25	
j	50	27	
k	62	46	36
l	54	37	26
m	65	50	40
n	49	34	23
o	85	79	78
p	75	70	70
q	78	73	69
r	37	19	
s	38	21	13
t	48	25	18
u	83	80	76
v	77	71	69
w	78	74	69

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 15

Mu_{20} versus Mu_{40}



Number of cases = 23
$Mu_{20} = 28.8912 + 0.67627\ (Mu_{40})$
Correlation coefficient = 0.97515
Standard error = 3.365

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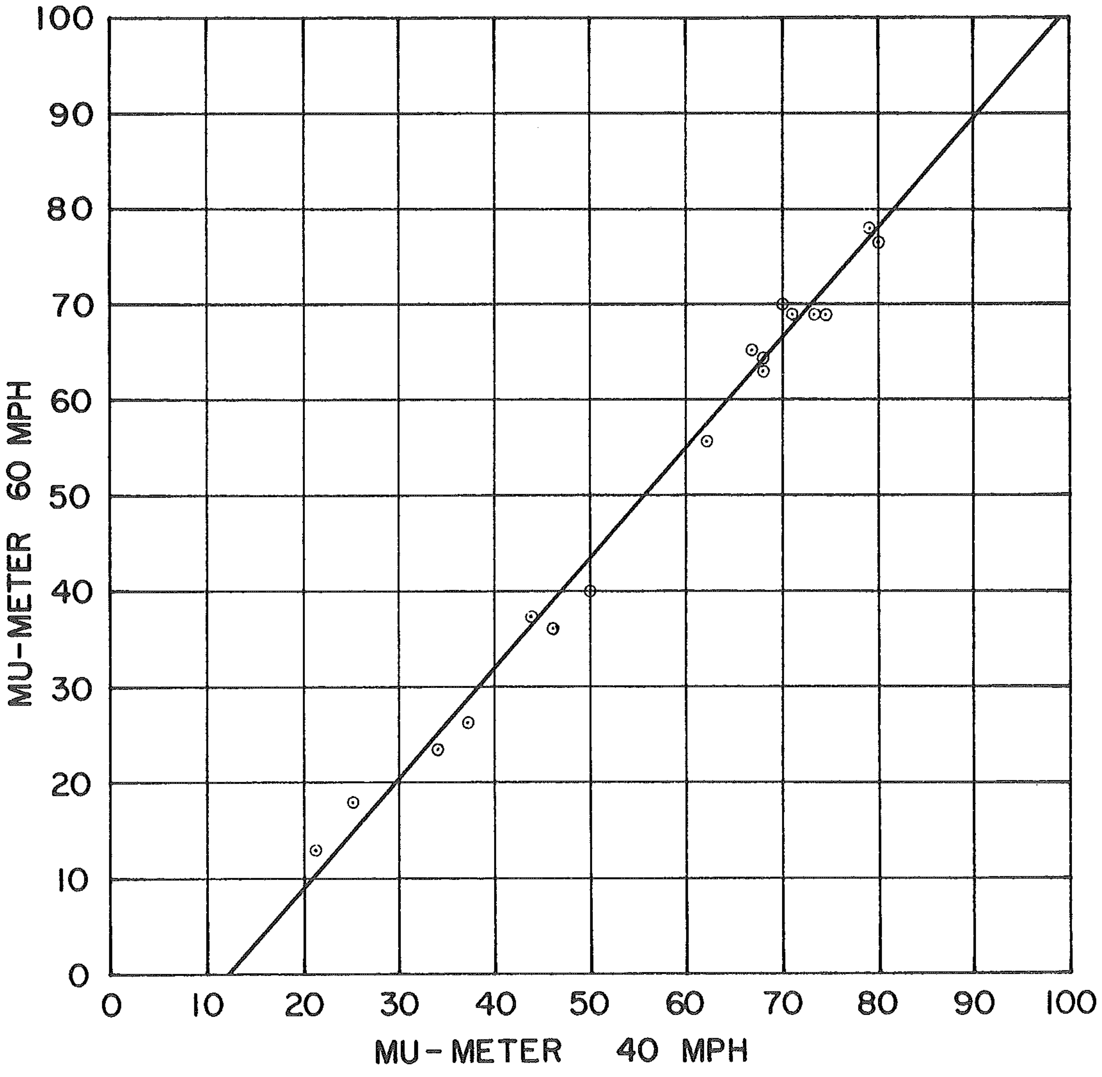
Figure 16

Mu_{40} versus Mu_{60}



Number of cases = 17
$Mu_{40} = 12.4279 + 0.86895\ (Mu_{60})$
Correlation coefficient = 0.99478
Standard error = 2.0204

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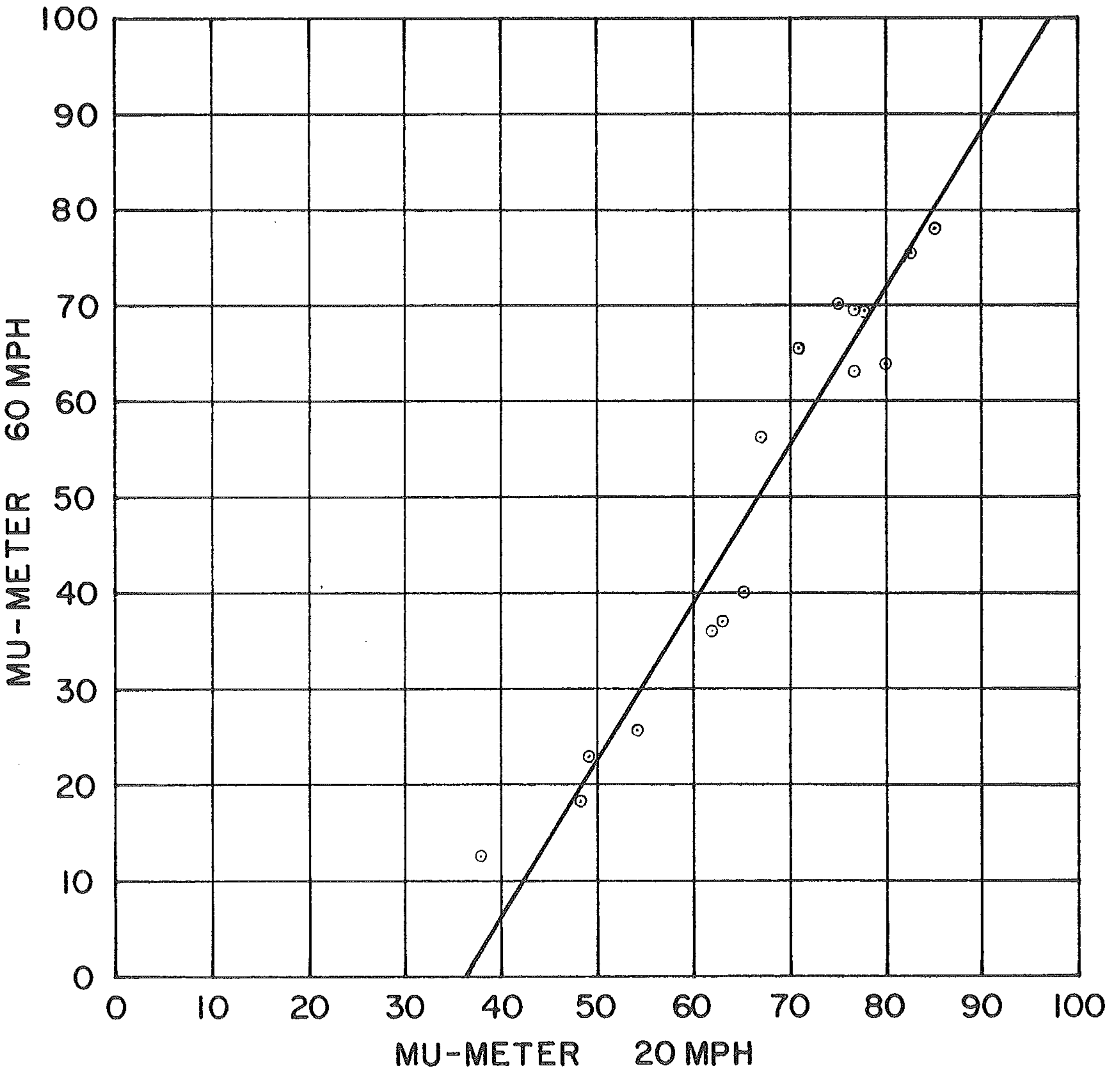
Figure 17

Mu_{20} versus Mu_{60}



Number of cases = 17
$Mu_{20} = 36.573 + 0.60580\ (Mu_{60})$
Correlation coefficient = 0.97013
Standard error = 3.433

ARIZONA HIGHWAY DEPARTMENT
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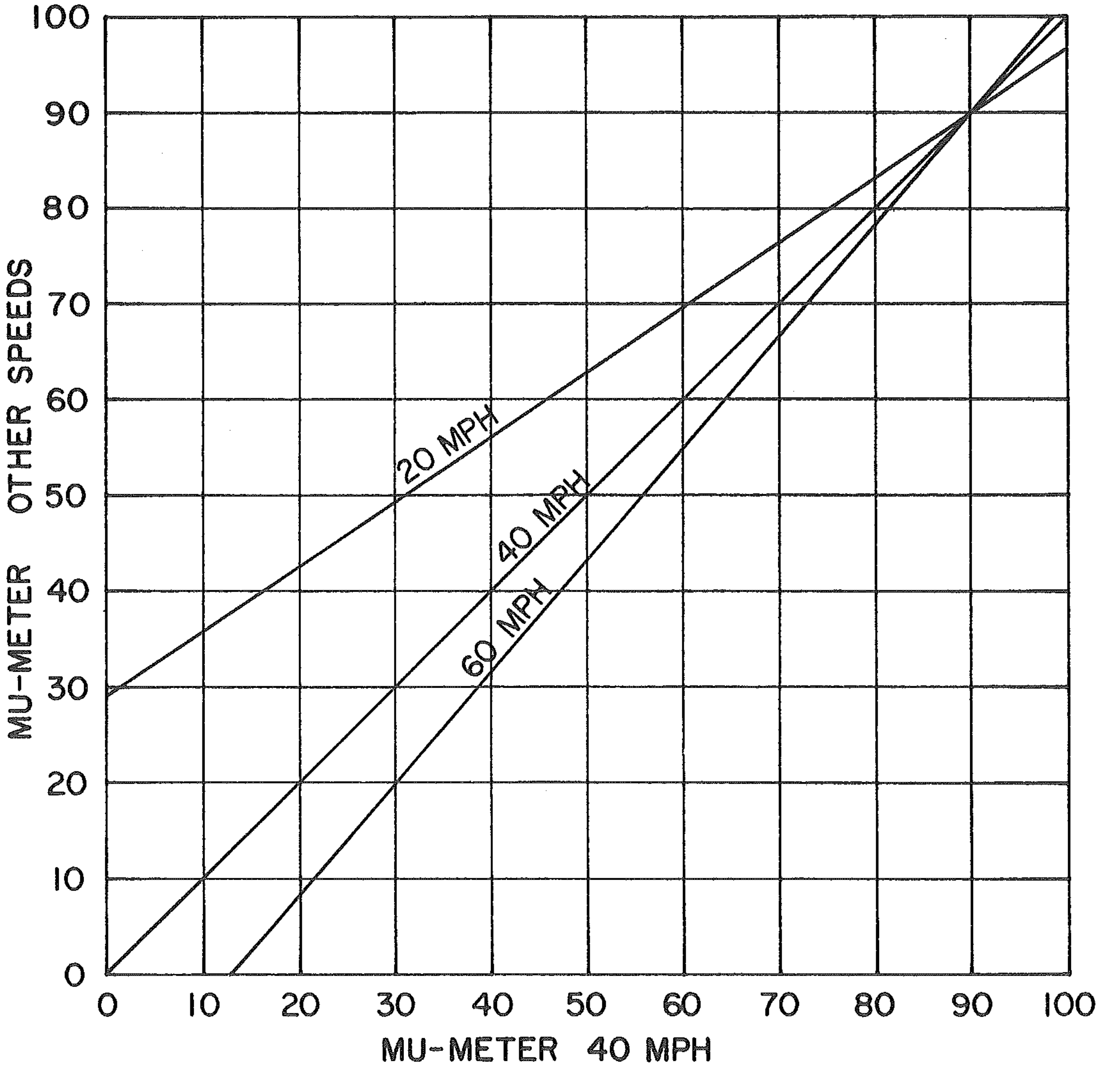
Figure 18

Mu_{40} versus Other Speeds



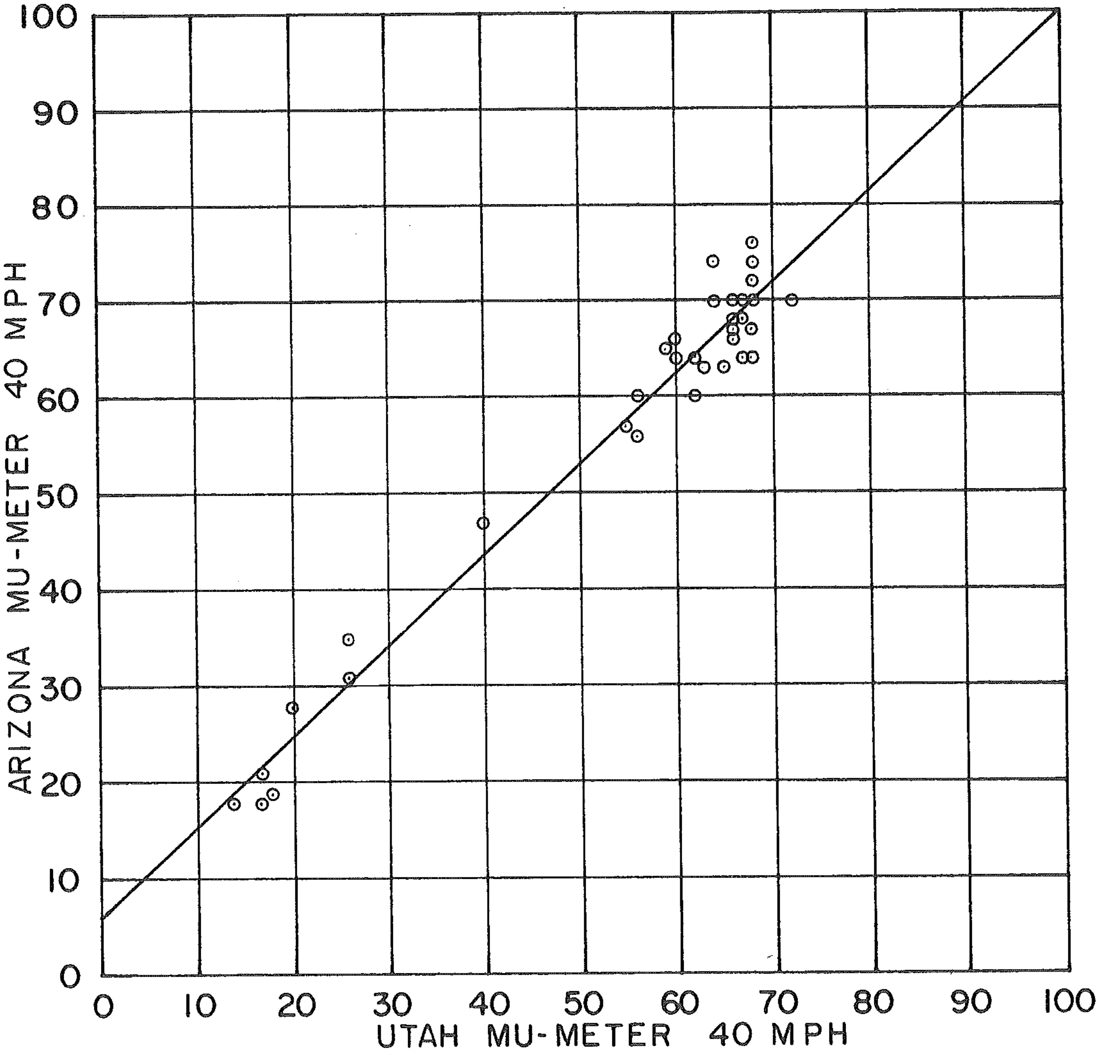
EXAMPLE OF A LOCKED WHEEL SKID TRAILER
Figure 19

ARIZONA HIGHWAY DEPARTMENT'S SKID CAR
Figure 20

BRITISH PORTABLE TESTER
Figure 21

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH
Figure 22

UTAH MU-METER CORRELATION
NOV. 17, 1969

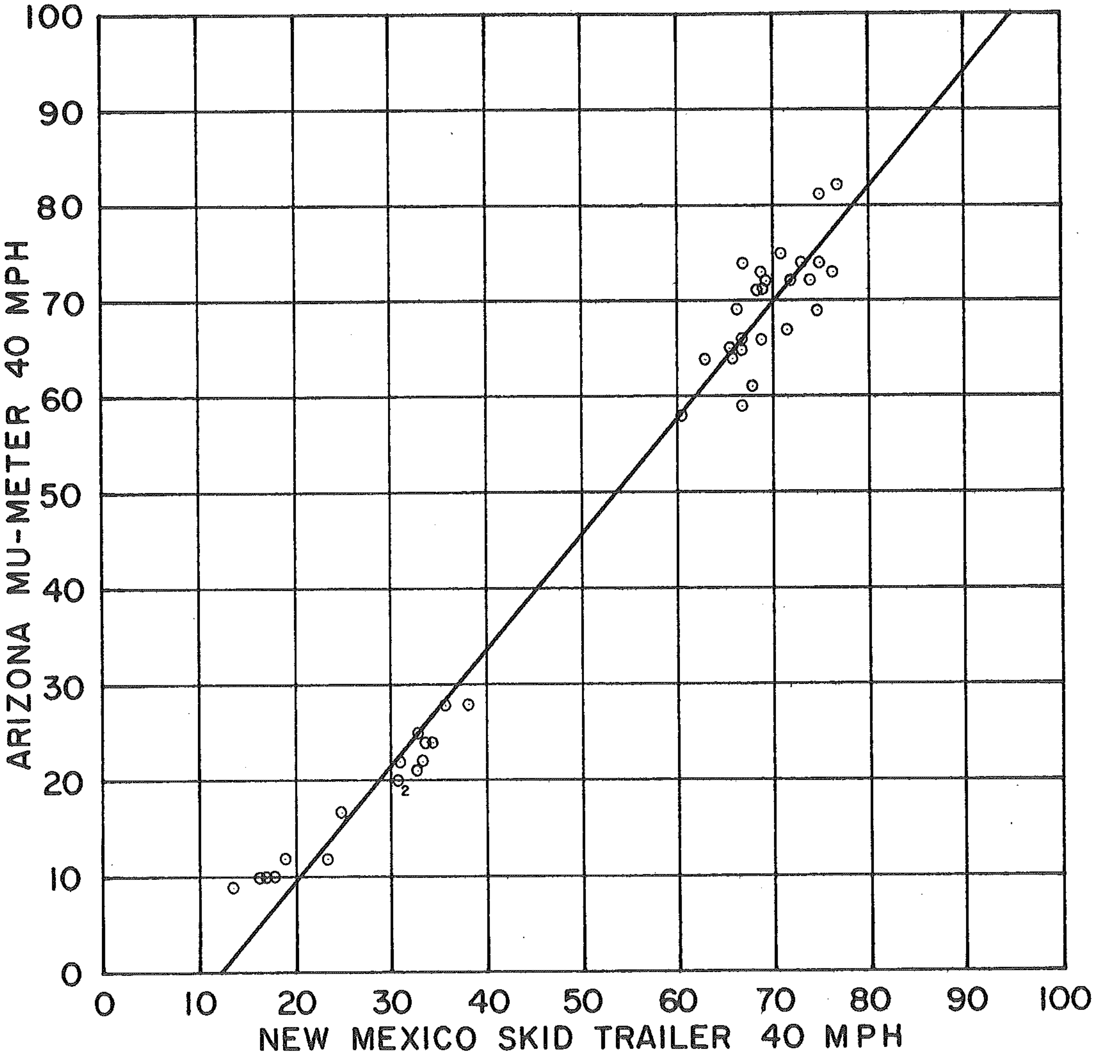


Number of cases = 34
Arizona = 5.923 + 0.9430 (Utah)
Utah = -6.281 + 1.0605 (Arizona)
Correlation coefficient = 0.9820
Standard error = 3.45 Az values

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 23

NEW MEXICO SKID TRAILER CORRELATION
SEPTEMBER 14, 1971

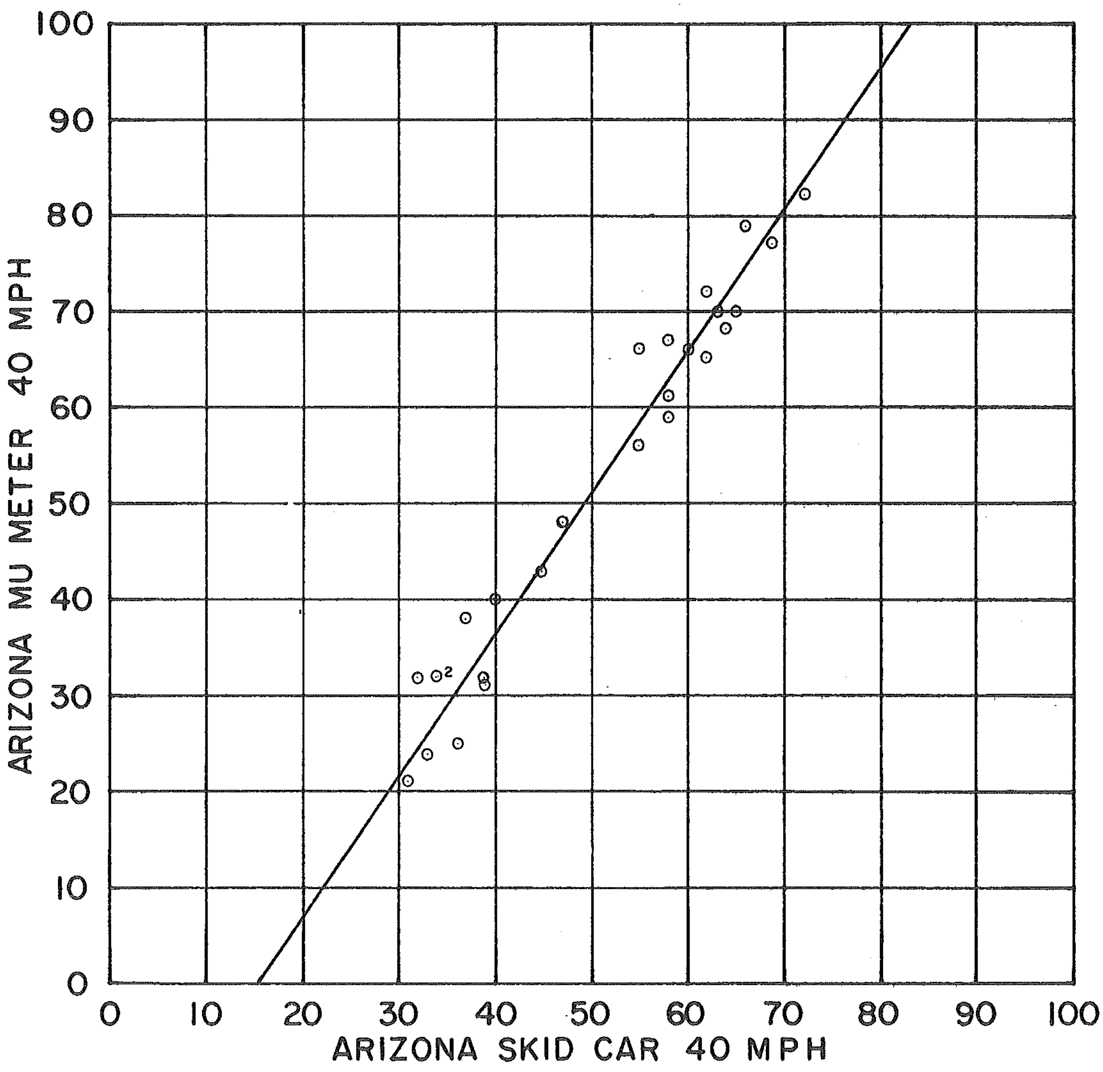


Number of cases = 42
Mu-Meter = −14.939 +1.2105(Skid Trailer)
Skid Trailer = 12.341 + 0.8261 (Mu-Meter)
Correlation coefficient = 0.9897
Standard error = 3.16 N.M. values

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 24

SKID CAR CORRELATION
JANURARY 1972

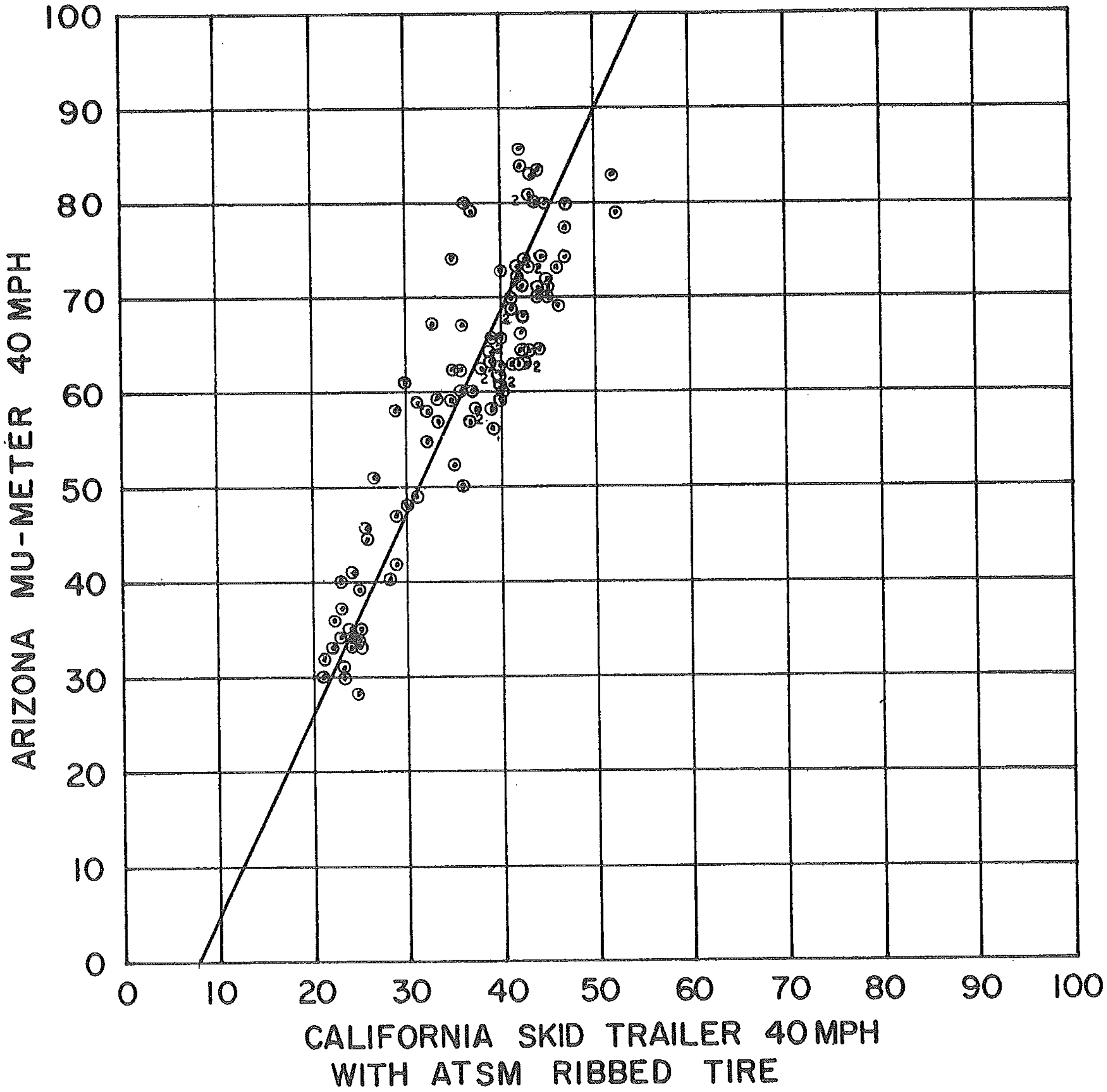


Number of cases = 26
Skid Car = 15.219 + 0.6777(Mu-Meter)
Mu Meter = −22.456 + 1.4755(Skid Car)
Correlation coefficient = 0.9802
Standard error = 2.72 Car values

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH
Figure 25

CALIFORNIA SKID TRAILER CORRELATION

MARCH, 1972



NUMBER OF CASES = 111
MU-METER = −17.829 + 2.1416(Calif)
CALIF. = 8.325 + 0.4669(Mu-Meter)
CORRELATION COEFFICIENT = 0.9172
STANDARD ERROR = 3.21 Calif values

DATA FOR MAJOR CORRELATIONS

Fig. (22)		Fig. (23)		Fig. (24)		Fig. (25)					
Arizona Mu-Meter 40 MPH	Utah Mu-Meter 40 MPH	Arizona Mu-Meter 40 MPH	New Mexico Skid Trailer 40 MPH	Arizona Mu-Meter 40 MPH	Arizona Skid Car 40 MPH	Arizona Mu-Meter 40 MPH	California Skid Trailer 40 MPH	Arizona Mu-Meter Cont'd	California Skid Trailer Cont'd	Arizona Mu-Meter Cont'd	California Skid Trailer Cont'd
63	65	64	63.0	31	39	64	43	69	46	41	24
64	62	82	77.5	25	36	62	39	70	44	60	37
70	66	81	75.0	32	34	60	36	71	45	66	39
66	66	74	67.0	48	47	59	33	68	40	30	21
68	66	17	25.5	32	39	62	36	73	42	33	22
18	17	28	36.0	61	58	83	43	73	43	28	25
60	56	61	68.5	65	62	86	42	71	44	32	21
18	14	66	69.0	66	60	81	43	61	30	40	23
57	55	66	67.5	59	58	84	42	80	37	37	23
56	56	10	18.0	40	40	74	35	62	35	34	23
70	67	12	19.0	38	37	72	42	62	38	56	39
72	68	21	33.0	43	45	74	44	57	37	63	39
68	67	22	31.5	32	32	71	41	59	35	63	38
64	60	24	34.0	79	66	77	47	79	37	62	39
60	62	24	34.5	70	65	79	52	51	27	58	39
65	59	12	23.5	68	64	66	42	42	29	58	37
70	68	72	72.0	72	62	70	41	35	25	67	33
64	67	74	75.0	77	69	80	45	33	25	58	39
67	66	71	68.5	67	58	81	43	48	30	60	40
21	17	69	66.5	21	31	80	44	80	47	65	38
31	26	72	69.5	23	33	44	26	73	43	72	41
19	18	75	71.0	32	34	58	29	63	39	74	42
64	68	73	69.0	56	55	40	28	66	40	28	22
28	20	65	67.0	66	55	83	52	69	41	26	21
67	68	22	33.5	70	63	63	41	47	29	26	21
35	26	25	33.0	82	72	62	36	59	40	39	25
70	72	28	38.5			64	39	62	40	36	22
47	40	20	31.0			58	32	73	40		
74	68	20	31.0			52	35	74	43		
74	64	65	65.5			50	36	73	43		
76	68	58	60.5			49	31	63	43		
70	64	64	66.0			67	36	68	42		
66	60	69	75.0			55	32	61	40		
63	63	73	76.5			59	31	63	42		
		67	71.5			57	33	64	43		
		71	69.0			69	41	30	23		
		72	74.0			64	42	34	25		
		74	73.0			71	42	33	24		
		59	67.0			72	45	31	23		
		9	13.5			70	45	35	24		
		10	16.5			74	47	34	24		
		10	17.0			73	46	46	26		

Figure 26

MU-METER - CAR - BPT CORRELATIONS

VARIABLES		NUMBER OF OBSERVATIONS	REGRESSION EQUATION	CORRELATION COEFFICIENT	STANDARD ERROR
Y	VS X				
			(1)		
3	1	26	$Y=8.349+.8590(X)$	.9383	4.44
7	1	25	$Y=-3.424+.8030(X)$	.8661	6.55
1	4	26	$Y=13.138+2.2416(X)-.01886(X)^2$	.8539	7.45
1	5	19	$Y=26.208+4.1320(X)-.09857(X)^2$	.8535	6.53
6	1	24	$Y=21.169+.4741(X)$	.7946	5.23
8	1	24	$Y=35.154+.2717(X)$	.6130	4.97
			(2)		
7	2	26	$Y=15.219+.6777(X)$	.9802	2.72
3	2	27	$Y=11.915+1.6450(X)-.01024(X)^2$	.9438	4.46
2	4	30	$Y=-13.309+2.3952(X)-.01650(X)^2$	.9394	6.93
2	5	18	$Y=15.377+2.8023(X)-.02864(X)^2$	.8760	9.28
6	2	24	$Y=31.744+.3789(X)$	.8527	4.69
8	2	22	$Y=40.866+.2371(X)$	.7652	4.09
			(3)		
3	4	24	$Y=9.339+2.3903(X)-.02031(X)^2$	.9506	4.24
3	2	27	$Y=11.915+1.6450(X)-.01024(X)^2$	.9438	4.46
3	1	26	$Y=8.349+.8590(X)$	.9383	4.44
3	5	19	$Y=27.850+3.7960(X)-.08719(X)^2$	.9163	4.56
3	7	26	$Y=22.001+.8793(X)$	.8894	6.14
6	3	23	$Y=16.870+.5499(X)$	.8703	4.24
8	3	22	$Y=35.621+.2520(X)$	.6656	3.17
			(4)		
3	4	24	$Y=9.339+2.3903(X)-.02031(X)^2$	.9506	4.24
4	5	18	$Y=20.011+.7971(X)$	.9499	6.29
2	4	30	$Y=13.309+2.3952(X)-.01650(X)^2$	.9394	6.93
7	4	28	$Y=24.426+.5883(X)$	.9212	5.16
1	4	26	$Y=13.138+2.2416(X)-.01886(X)^2$	.8539	7.45
6	4	25	$Y=37.426+.3521(X)$	.7919	5.38
8	4	23	$Y=42.561+.2685(X)$	.7896	3.95
			(5)		
4	5	18	$Y=20.011+.7971(X)$	.9499	6.29
3	5	19	$Y=27.850+3.7960(X)-.08719(X)^2$	.9163	4.56
2	5	18	$Y=15.377+2.8023(X)-.02864(X)^2$	.8760	9.28
1	5	19	$Y=26.208+4.1320(X)-.09857(X)^2$	.8535	6.53
8	5	18	$Y=47.224+.2025(X)$	.7076	4.85
7	5	19	$Y=41.488+.3741(X)$	.6951	9.06
6	5	19	$Y=46.947+.2103(X)$	.5376	7.73
			(6)		
6	7	24	$Y=21.718+.6025(X)$	.8860	4.16
6	3	23	$Y=16.870+.5499(X)$	.8703	4.24
6	2	24	$Y=31.744+.3789(X)$	.8527	4.69
6	1	24	$Y=21.169+.4741(X)$	.7946	5.23
6	4	25	$Y=37.426+.3521(X)$	.7919	5.38
8	6	24	$Y=26.816+.4995(X)$	.7729	3.51
6	5	19	$Y=46.947+.2103(X)$	.5376	7.73

Figure 27

Figure 27 (Cont'd)

MU-METER - CAR - BPT CORRELATIONS

VARIABLES Y	VS X	NUMBER OF OBSERVATIONS	REGRESSION EQUATION	CORRELATION COEFFICIENT	STANDARD ERROR
			(7)		
7	2	26	Y=15.219+.6777(X)	.9802	2.72
7	4	28	Y=24.426+.5883(X)	.9212	5.16
3	7	26	Y=22.001+.8793(X)	.8894	6.14
6	7	24	Y=21.718+.6025(X)	.8860	4.16
7	1	25	Y=-3.424+.8030(X)	.8661	6.55
8	7	23	Y=35.878+.3570(X)	.7573	4.09
7	5	19	Y=41.488+.3741(X)	.6951	9.06
			(8)		
8	4	23	Y=42.561+.2685(X)	.7896	3.95
8	6	24	Y=26.816+.4995(X)	.7729	3.51
8	2	22	Y=40.866+.2371(X)	.7652	4.09
8	7	23	Y=35.878+.3570(X)	.7573	4.09
8	5	18	Y=47.224+.2025(X)	.7076	4.85
8	3	22	Y=35.621+.2520(X)	.6656	3.17
8	1	24	Y=35.154+.2717(X)	.6130	4.97

Variable

1 = Mu-Meter using own watering system at 20 MPH
2 = Mu-Meter using own watering system at 40 MPH
3 = Mu-Meter using external watering system at 20 MPH
4 = Mu-Meter using external watering system at 40 MPH
5 = Mu-Meter using external watering system at 60 MPH
6 = Skid Car using external watering system at 20 MPH
7 = Skid Car using external watering system at 40 MPH
8 = British Portable Tester

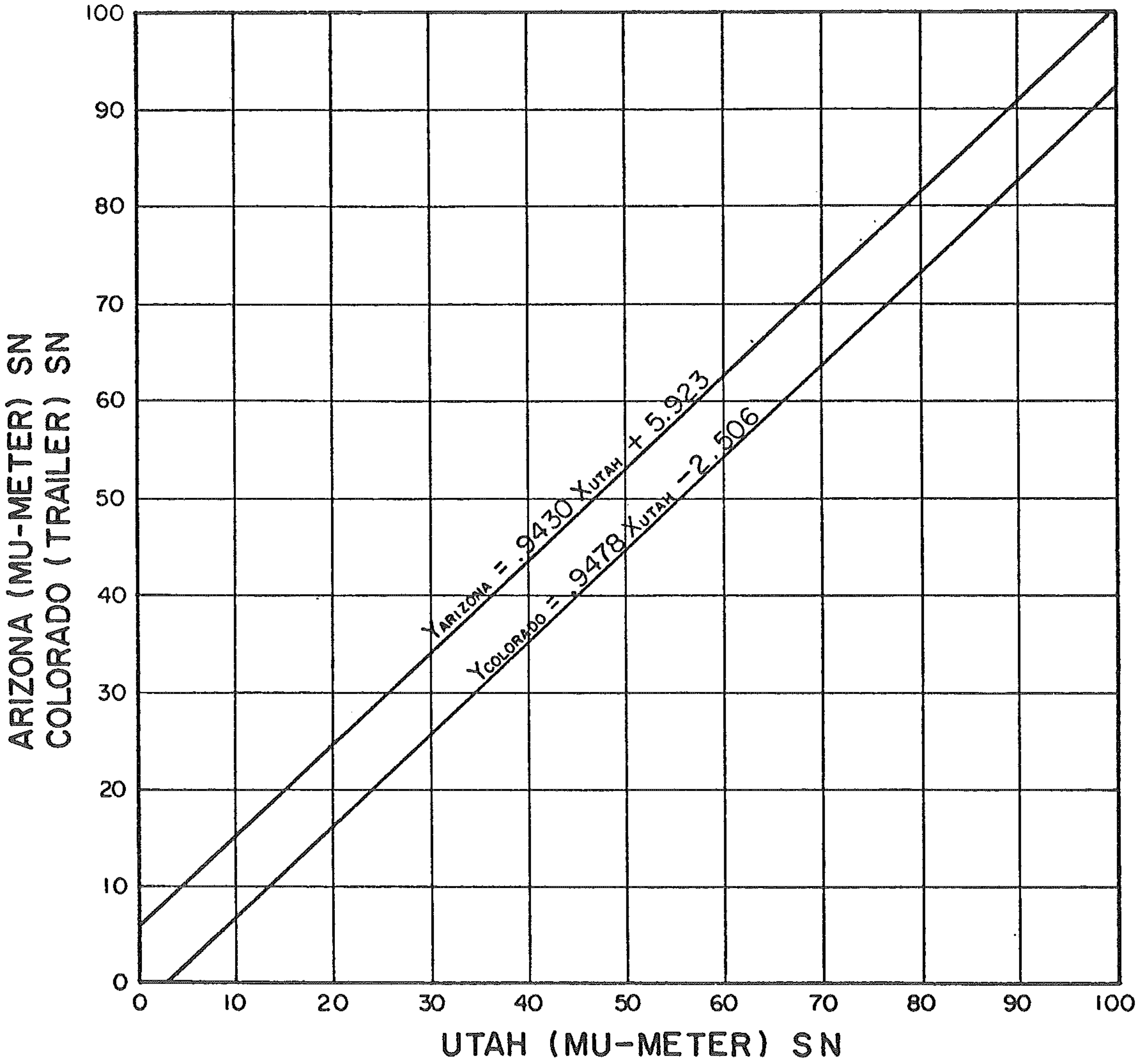
MU-METER - SKID CAR - BRITISH PORTABLE TESTER CORRELATION DATA

Variable	Mu-Meter External H_2O 20 MPH (1)	Mu-Meter External H_2O 40 MPH (2)	Mu-Meter External H_2O 20 MPH (3)	Mu-Meter External H_2O 40 MPH (4)	Mu-Meter External H_2O 60 MPH (5)	Skid Car 20 MPH (6)	Skid Car 40 MPH (7)	British Portable Tester (8)
1	51	31	57	28		55	39	53
2	44	25	42	20		42	36	47
3	56	32	53	29		49	34	53
4	75	48	70	32	12	58	47	55
5	81	75	77	46	22	63	56	59
6	54	32	63	30		49	39	57
7	68	61	72	36	18	58	58	56
8	82	65	80	50	25	63	62	54
9	76	66	73	45	19	60	60	55
10	67	59	63	45		54	58	54
11	65	40	65	24	13	40	40	52
12	61	38	58	24	10	45	37	48
13	69	43	70	33	27	44	45	51
14	51	32	55	24	12	40	32	45
15	82	79	79	66	56	57	66	62
16	70	70	74	71	68	64	65	65
17	72	68	74	68	56	60	64	51
18	78	72	79	67	18	60	62	73
19	82	77	78	77	74	62	69	67
20	78	74	76	71	69	54	56	55
21	75	67	72	42	18	49	58	46
22	77	71	76	50	35	53	56	49
23	36	21	36	13		38	31	45
24	40	23	43	18	5	41	33	45
25	57	32	52	20	9	40	34	46
26		56		58			55	
27		66		68			55	
28		70		67			63	
29		82	86	72			72	

Figure 28

INDEPENDENT CORRELATION STUDIES WITH THE UTAH MU-METER

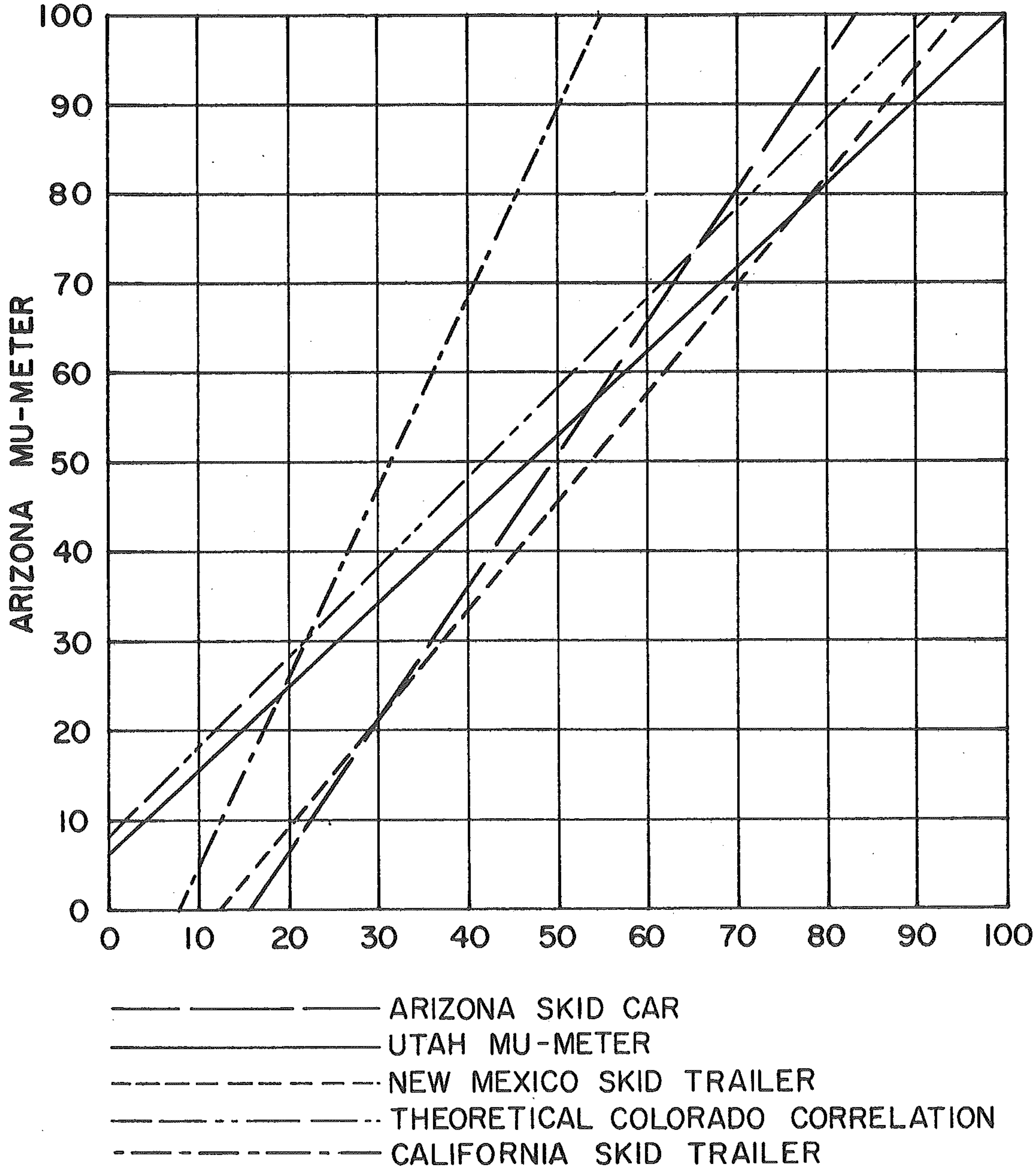
Figure 29



ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 30

SKID CORRELATIONS



FRICTION INVENTORY

TESTS ARE CONDUCTED IN LEFT WHEEL PATH OF OUTSIDE LANE

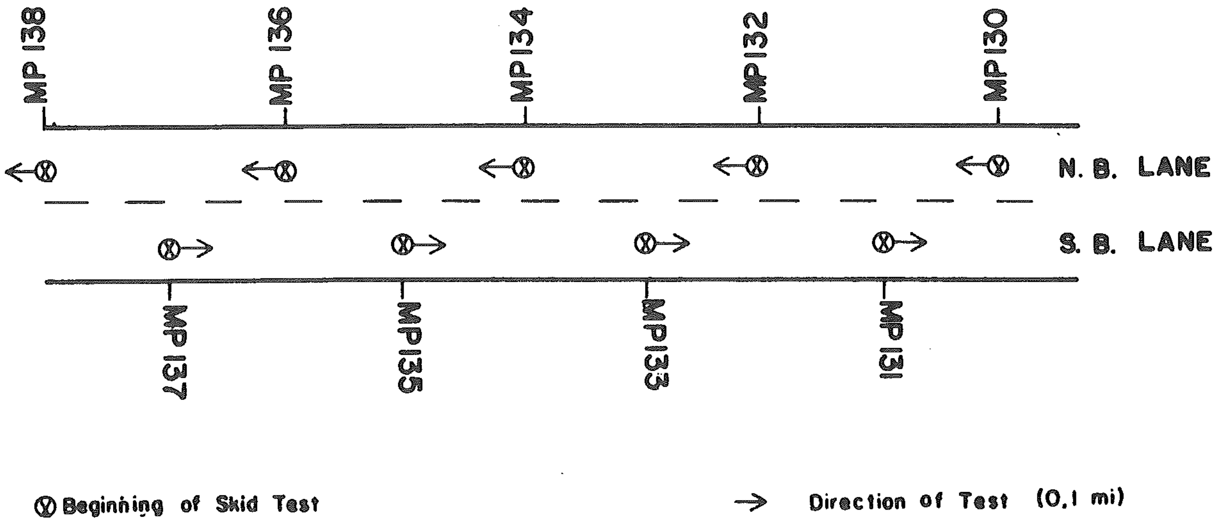


Figure 31

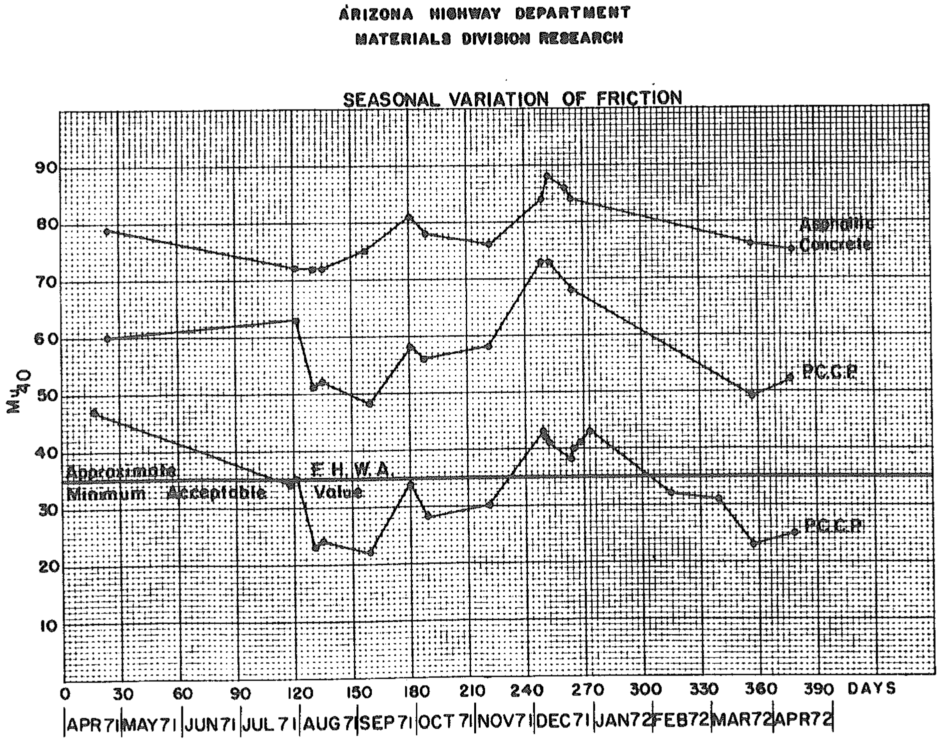
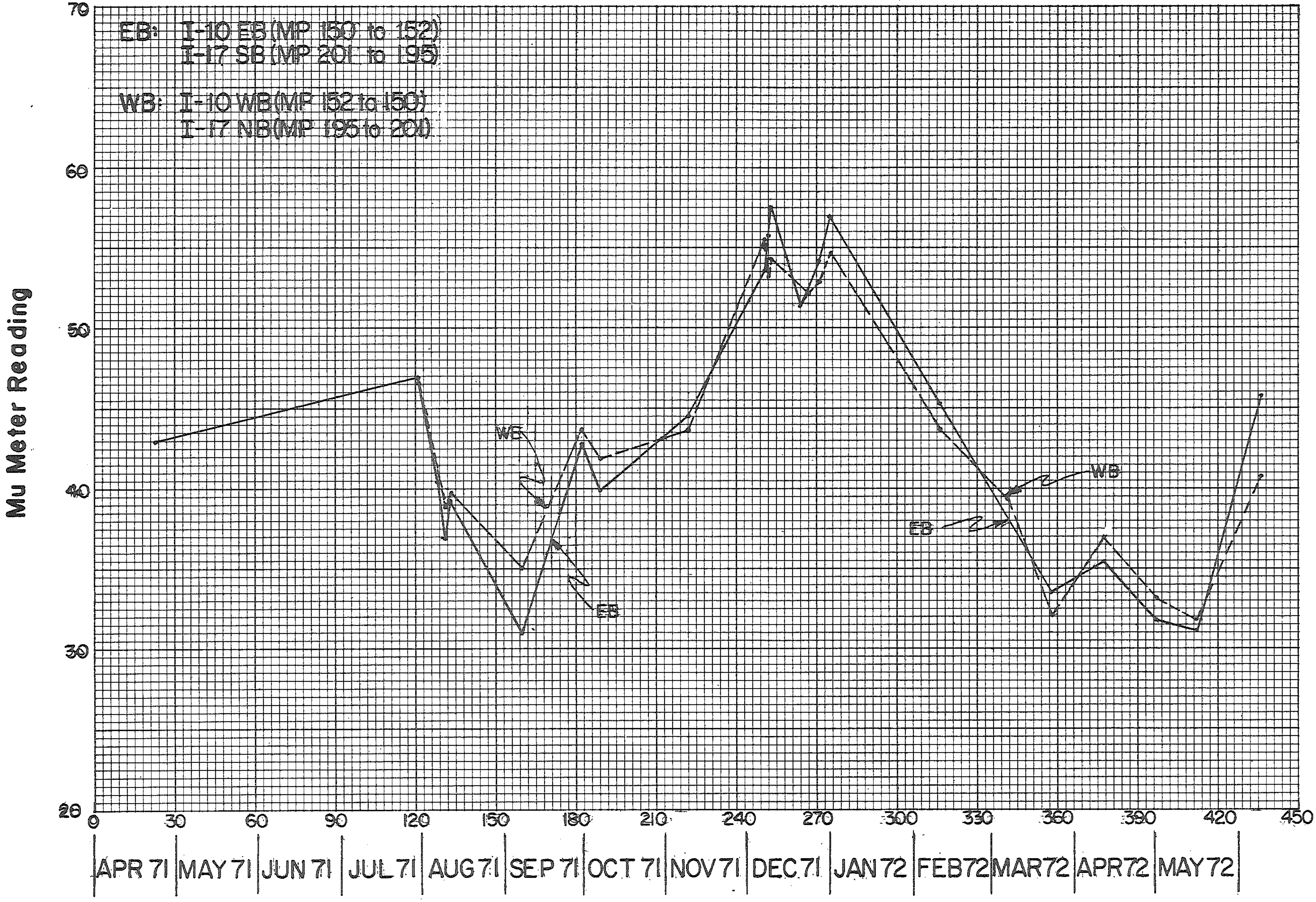


Figure 32

ARIZONA HIGHW DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 33

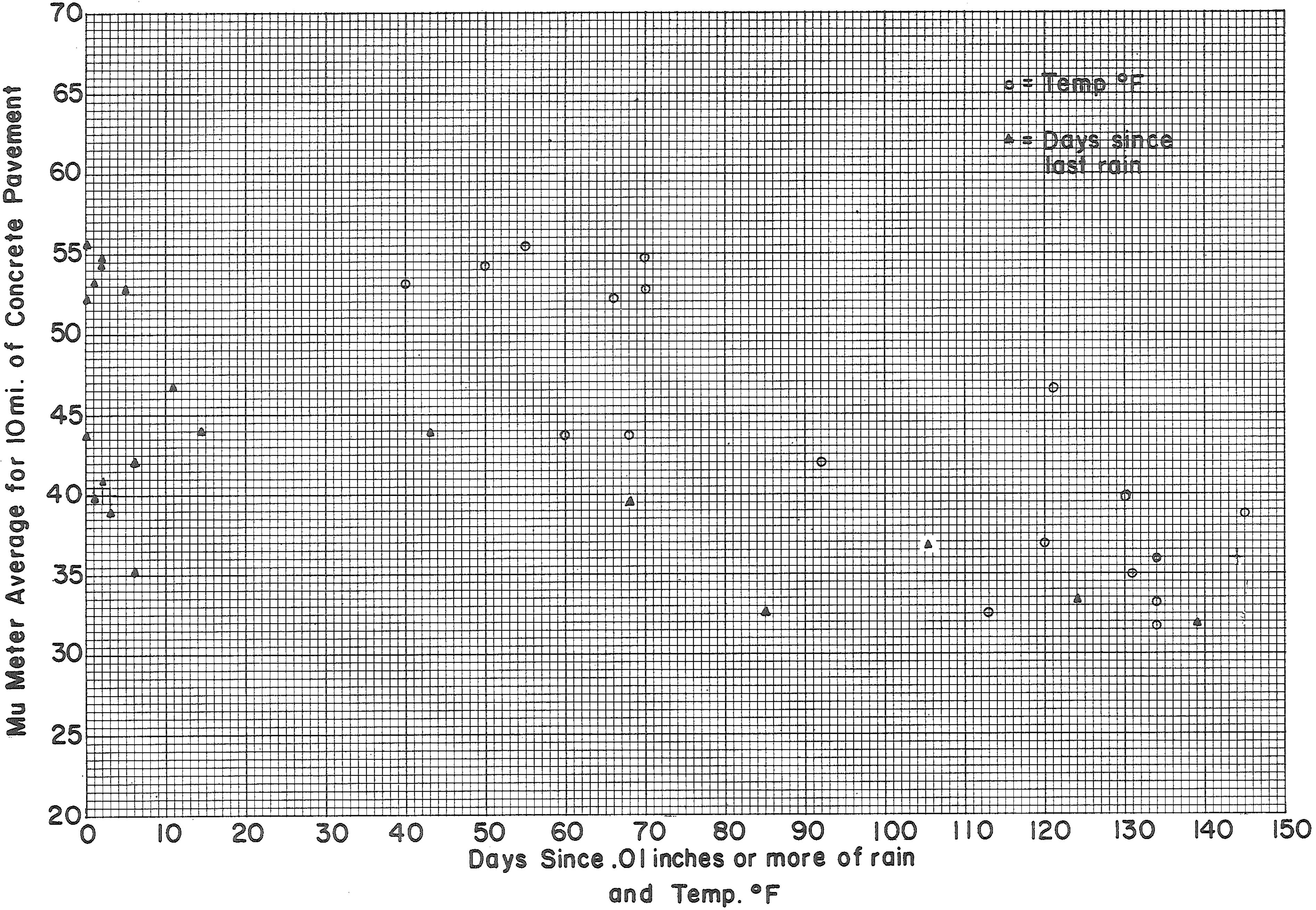
SEASONAL VARIATION ON CONCRETE PAVEMENT



ARIZONA HIGHW. DEPARTMENT
MATERIALS DIVISION RESEARCH

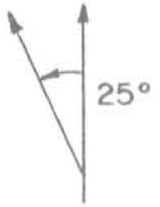
Figure 34

EFFECTS OF RAINFALL

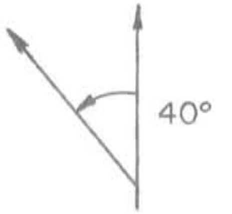


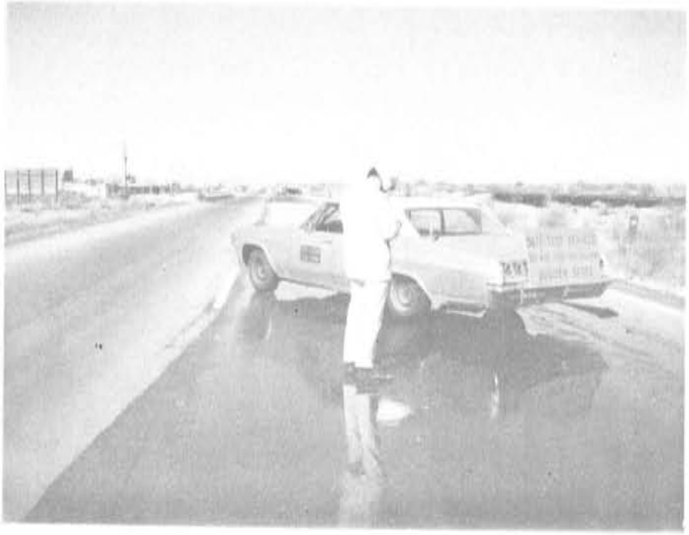
RIGHT WHEEL PATH = SDN_{40} 50 $\rangle$ 17% Difference
LEFT WHEEL PATH = SDN_{40} 60

← (A) Car skids at 30 MPH and rotates 25° counterclockwise



→ (B) Car skids at 40 MPH and rotates 40° clockwise





← (C) Car skids at 50 MPH and rotates 95° counterclockwise

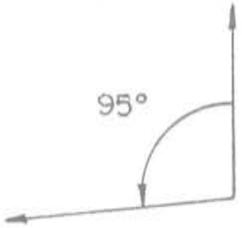


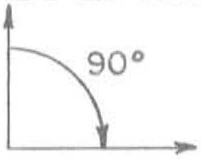
Figure 35

RIGHT WHEEL PATH = SDN_{40} 67

LEFT WHEEL PATH = SDN_{40} 41

39% Difference

(A)
Car skids at 40 MPH and rotates 90° clockwise



(B)
Car skids at 50 MPH and rotates at 270° clockwise

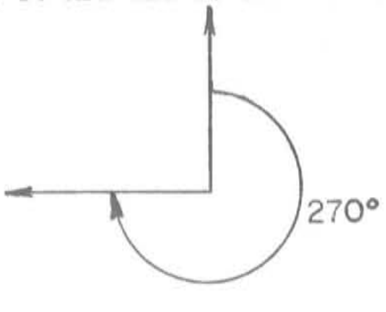
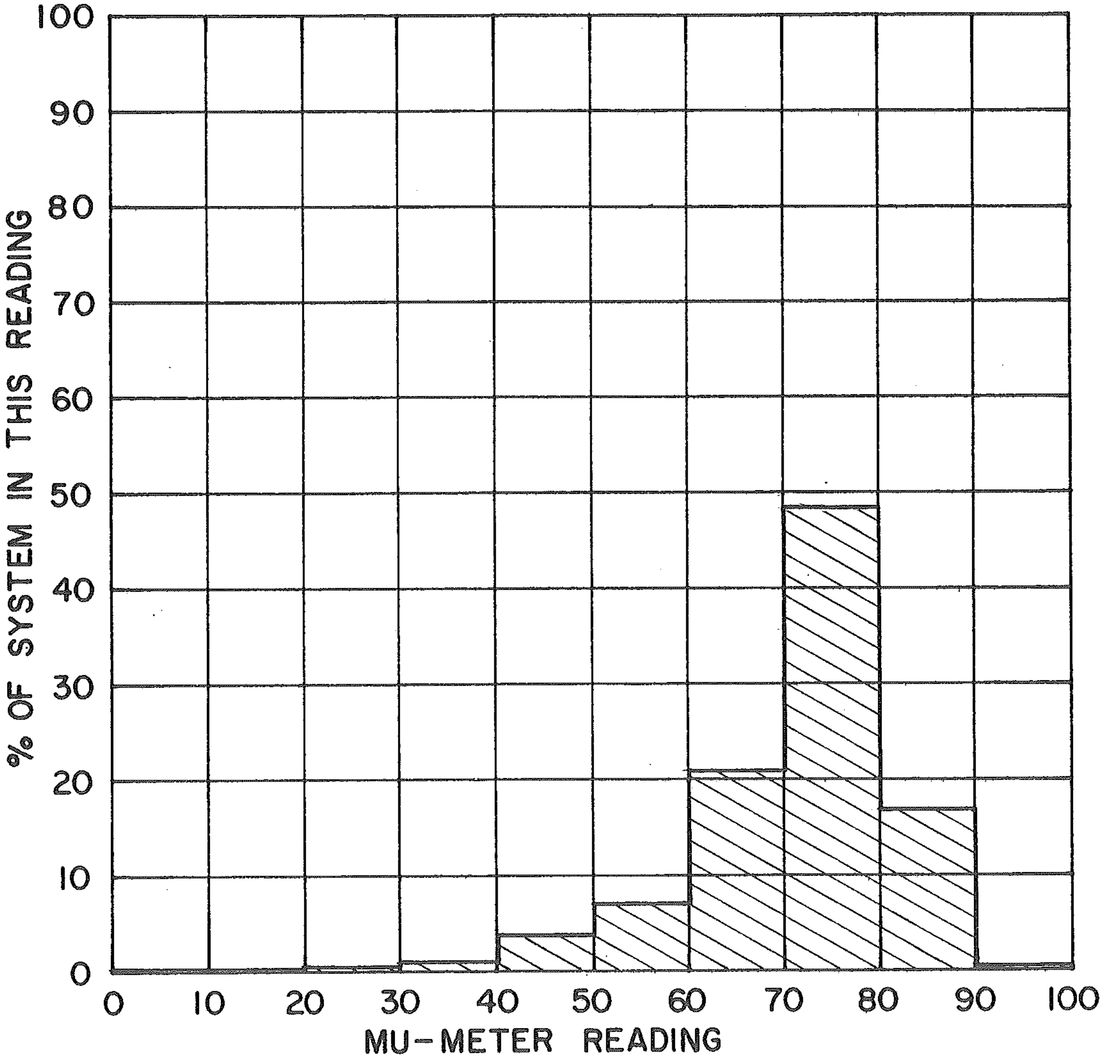


Figure 36

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

INTERSTATE, STATE AND U.S. HIGHWAYS IN ARIZONA



%									
0.02	0.08	0.61	2.06	3.98	6.57	20.85	48.45	17.01	0.31

Figure 37

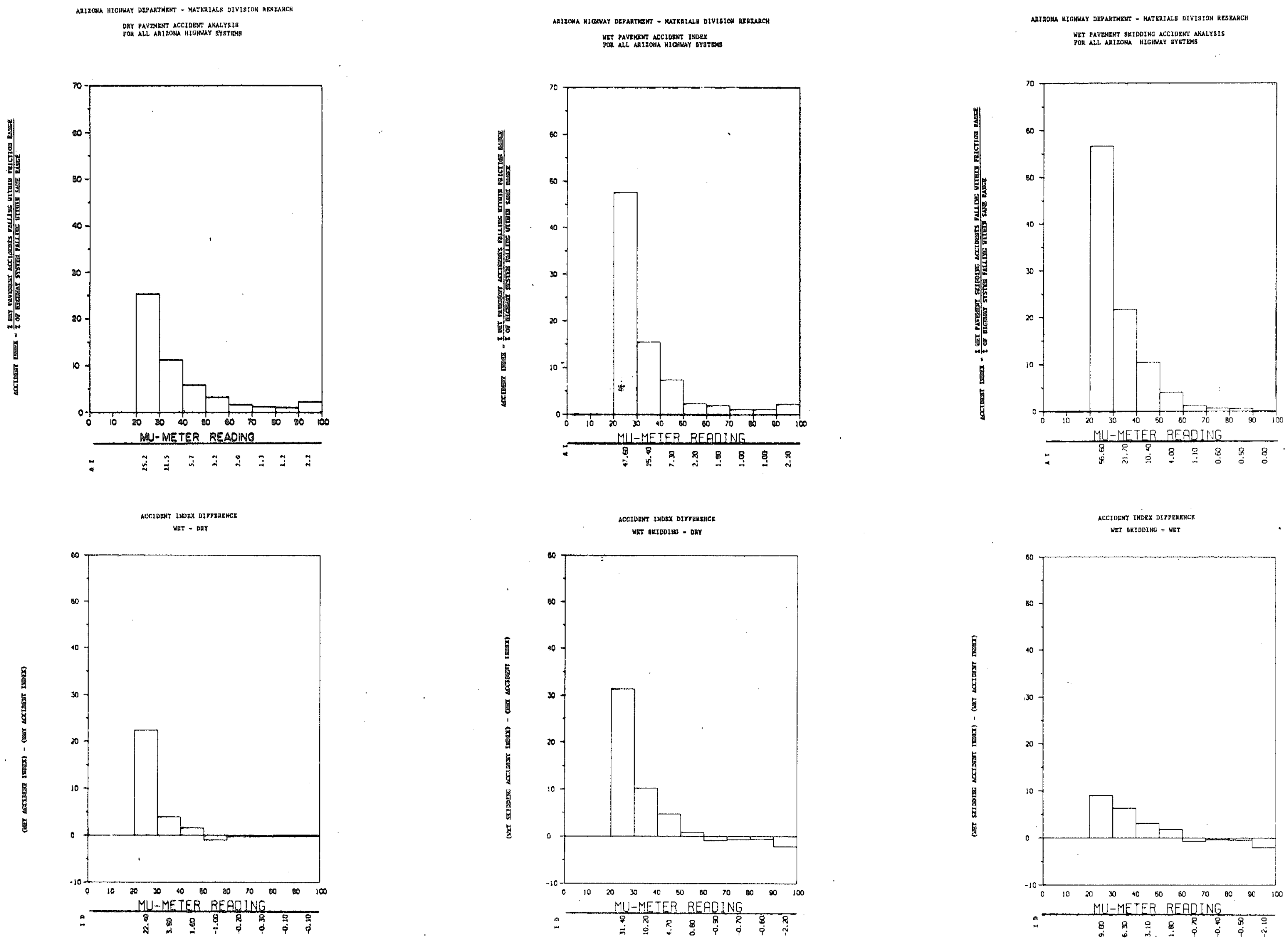

ARIZONA HIGHWAY DEPARTMENT - MATERIALS DIVISION RESEARCH
DRY PAVEMENT ACCIDENT ANALYSIS
FOR ALL ARIZONA HIGHWAY SYSTEMS
ACCIDENT INDEX = % DRY PAVEMENT ACCIDENTS FALLING WITHIN FRICTION RANGE / % OF HIGHWAY SYSTEM FALLING WITHIN SAME RANGE
0
10
20
30
40
50
60
70
MU-METER READING
A I
25.2
11.5
5.7
3.2
2.6
1.3
1.2
2.2
ARIZONA HIGHWAY DEPARTMENT - MATERIALS DIVISION RESEARCH
WET PAVEMENT ACCIDENT INDEX
FOR ALL ARIZONA HIGHWAY SYSTEMS
ACCIDENT INDEX = % WET PAVEMENT ACCIDENTS FALLING WITHIN FRICTION RANGE / % OF HIGHWAY SYSTEM FALLING WITHIN SAME RANGE
MU-METER READING
A I
47.60
15.40
7.30
2.20
1.60
1.00
1.00
2.10
ARIZONA HIGHWAY DEPARTMENT - MATERIALS DIVISION RESEARCH
WET PAVEMENT SKIDDING ACCIDENT ANALYSIS
FOR ALL ARIZONA HIGHWAY SYSTEMS
ACCIDENT INDEX = % WET PAVEMENT SKIDDING ACCIDENTS FALLING WITHIN FRICTION RANGE / % OF HIGHWAY SYSTEM FALLING WITHIN SAME RANGE
MU-METER READING
A I
56.60
21.70
10.40
4.00
1.10
0.60
0.50
0.00
ACCIDENT INDEX DIFFERENCE
WET - DRY
(WET ACCIDENT INDEX) - (DRY ACCIDENT INDEX)
-10
MU-METER READING
I D
22.40
3.50
1.60
-1.00
-0.20
-0.30
-0.10
-0.10
ACCIDENT INDEX DIFFERENCE
WET SKIDDING - DRY
(WET SKIDDING ACCIDENT INDEX) - (DRY ACCIDENT INDEX)
MU-METER READING
I D
31.40
10.20
4.70
0.80
-0.90
-0.70
-0.60
-2.20
ACCIDENT INDEX DIFFERENCE
WET SKIDDING - WET
(WET SKIDDING ACCIDENT INDEX) - (WET ACCIDENT INDEX)
MU-METER READING
I D
9.00
6.30
3.10
1.80
-0.70
-0.40
-0.50
-2.10

Figure 38

DAILY RAINFALL AS RELATED TO ACCIDENT RATES

January 1968 to December 1970

Amount of Rainfall In Inches Per Day	No. Accidents	%	Accumulated %	No. of Days Occurred	%	Accumulated %
<.01	11	4.60	4.60	92	46.23	46.23
.01	12	5.02	9.62	12	6.03	52.26
.02	14	5.85	15.48	13	6.53	58.79
.03	4	1.67	17.15	5	2.51	61.30
.04	3	1.25	18.41	11	5.52	66.83
.05	2	.83	19.24	3	1.50	68.34
.06	4	1.67	20.92	3	1.50	69.84
.07	3	1.25	22.17	3	1.50	71.35
.08	4	1.67	23.84	7	3.51	74.87
.09	2	.83	24.68	3	1.50	76.38
* .11	2	.83	25.52	2	1.00	77.38
.12	3	1.25	26.77	4	2.01	79.39
.13	9	3.76	30.54	2	1.00	80.40
.14	4	1.67	32.21	3	1.50	81.90
.15	2	.83	33.05	1	.50	82.41
.16	9	3.76	36.82	3	1.50	83.91
.17	11	4.60	41.42	2	1.00	84.92
.18	4	1.67	43.09	1	.50	85.42
.19	5	2.09	45.18	1	.50	85.92
.20	8	3.34	48.53	5	2.51	88.44
.21	1	.41	48.95	1	.50	88.94
.26	5	2.09	51.04	3	1.50	90.45
.27	2	.83	51.88	1	.50	90.95
.28	4	1.67	53.55	1	.50	91.45
.29	3	1.25	54.81	1	.50	91.95
.34	20	8.36	63.17	2	1.00	92.96
.36	4	1.67	64.85	1	.50	93.46
.37	3	1.25	66.10	1	.50	93.96
.38	8	3.34	69.45	1	.50	94.47
.43	8	3.34	72.80	1	.50	94.97
.45	2	.83	73.64	1	.50	95.47
.52	10	4.18	77.82	3	1.50	96.98
.59	3	1.25	79.07	1	.50	97.48
.64	8	3.34	82.42	1	.50	97.98
.74	14	5.85	88.28	1	.50	98.49
.77	13	5.43	93.72	1	.50	98.99
1.33	4	1.67	95.39	1	.50	99.49
2.43	11	4.60	100.00	1	.50	100.00

* Point at which accident rate increases faster than the accumulated % of days.

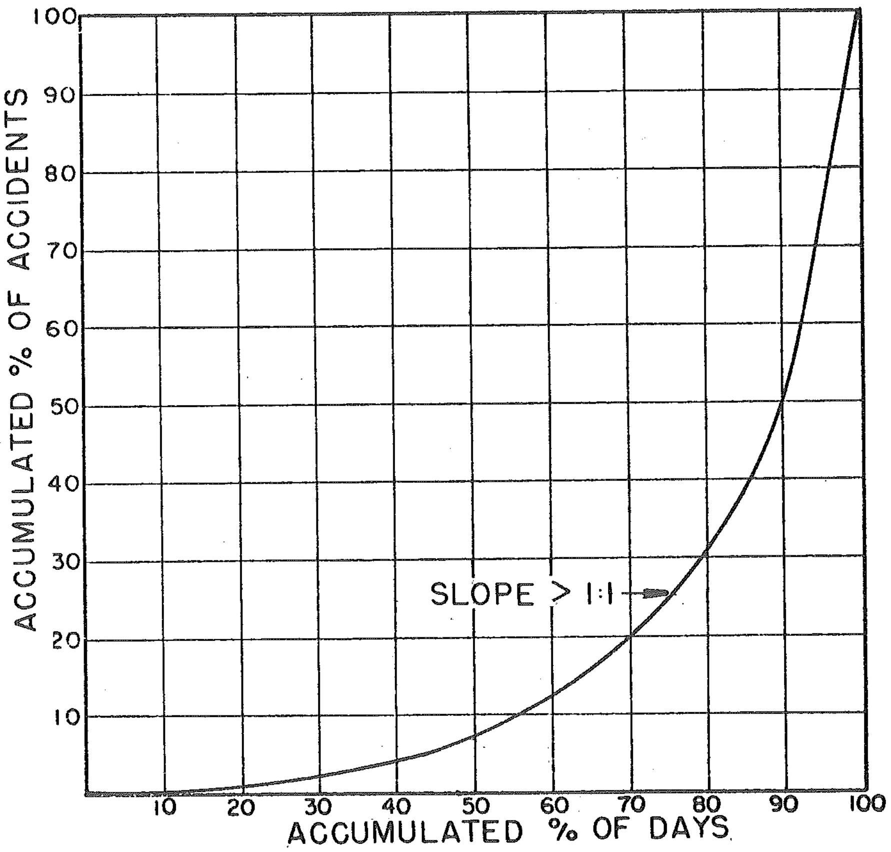
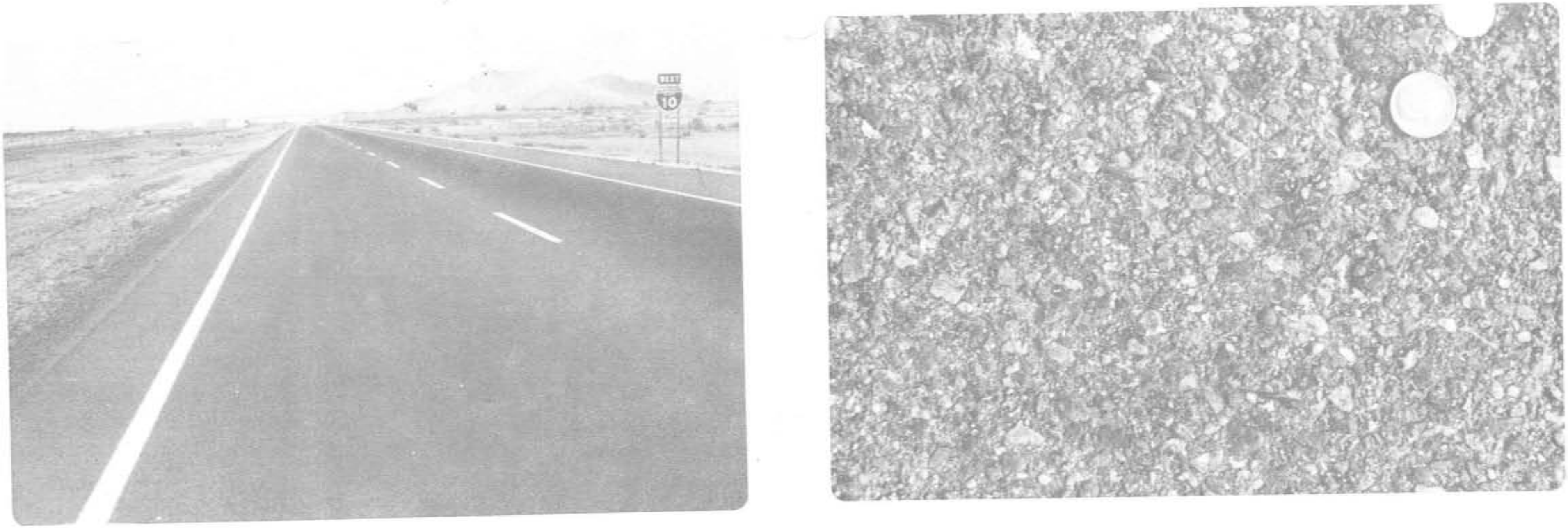


Figure 39



I-10-M.P. 175.2, N.B. INSIDE LANE

SURFACE - 3/8 INCH DENSE GRADED ASPHALTIC CONCRETE

AGGREGATE SUPPLY - GILA RIVER PIT #6651

BINDER - AC 85-100

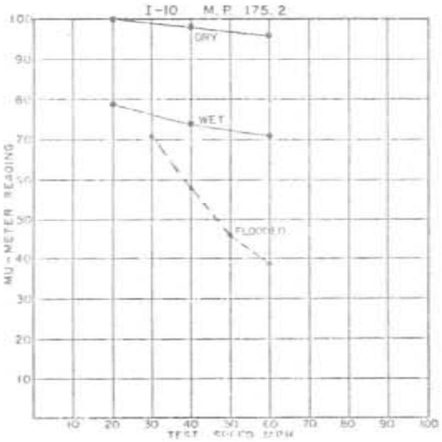
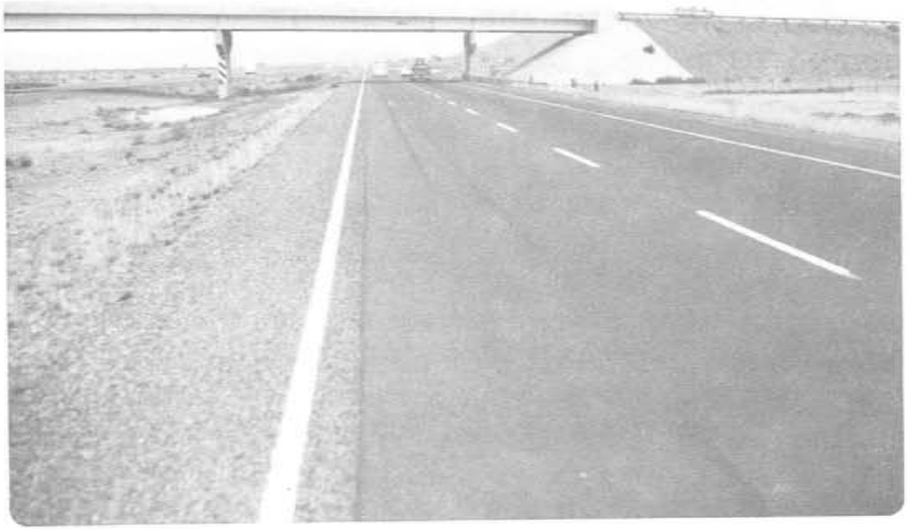
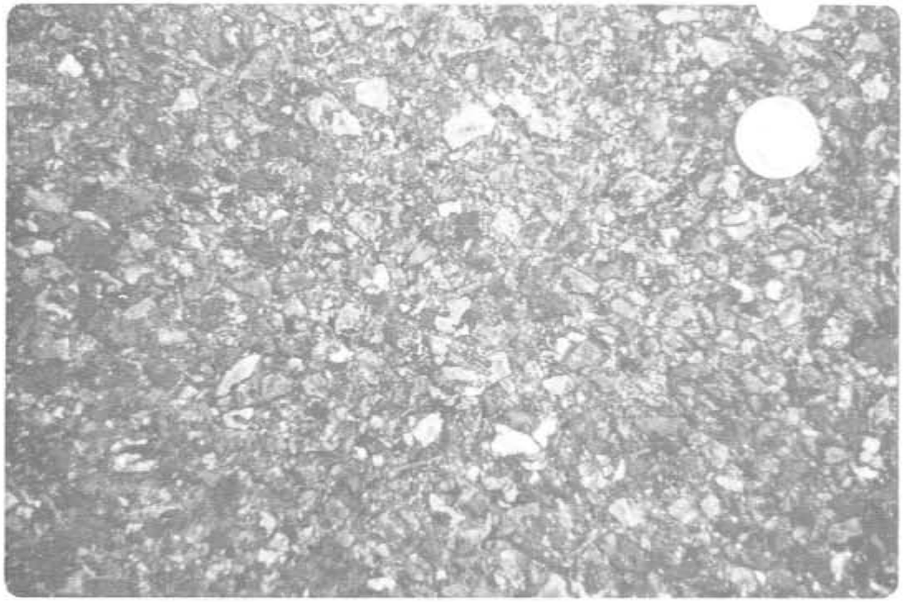


Figure 40





I-10 M.P. 175.9, N.B. INSIDE LANE

SURFACE - 3/8 INCH OPEN GRADED ASPHALTIC CONCRETE

AGGREGATE SUPPLY - GILA RIVER PIT #6651

BINDER - AC 85-100

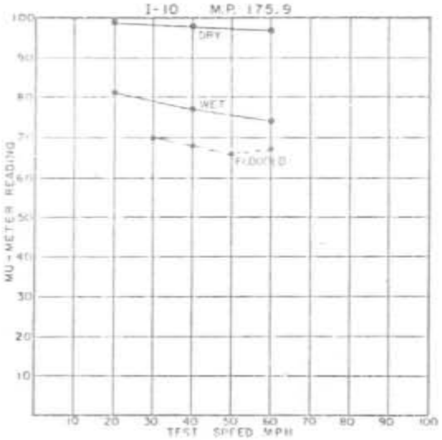
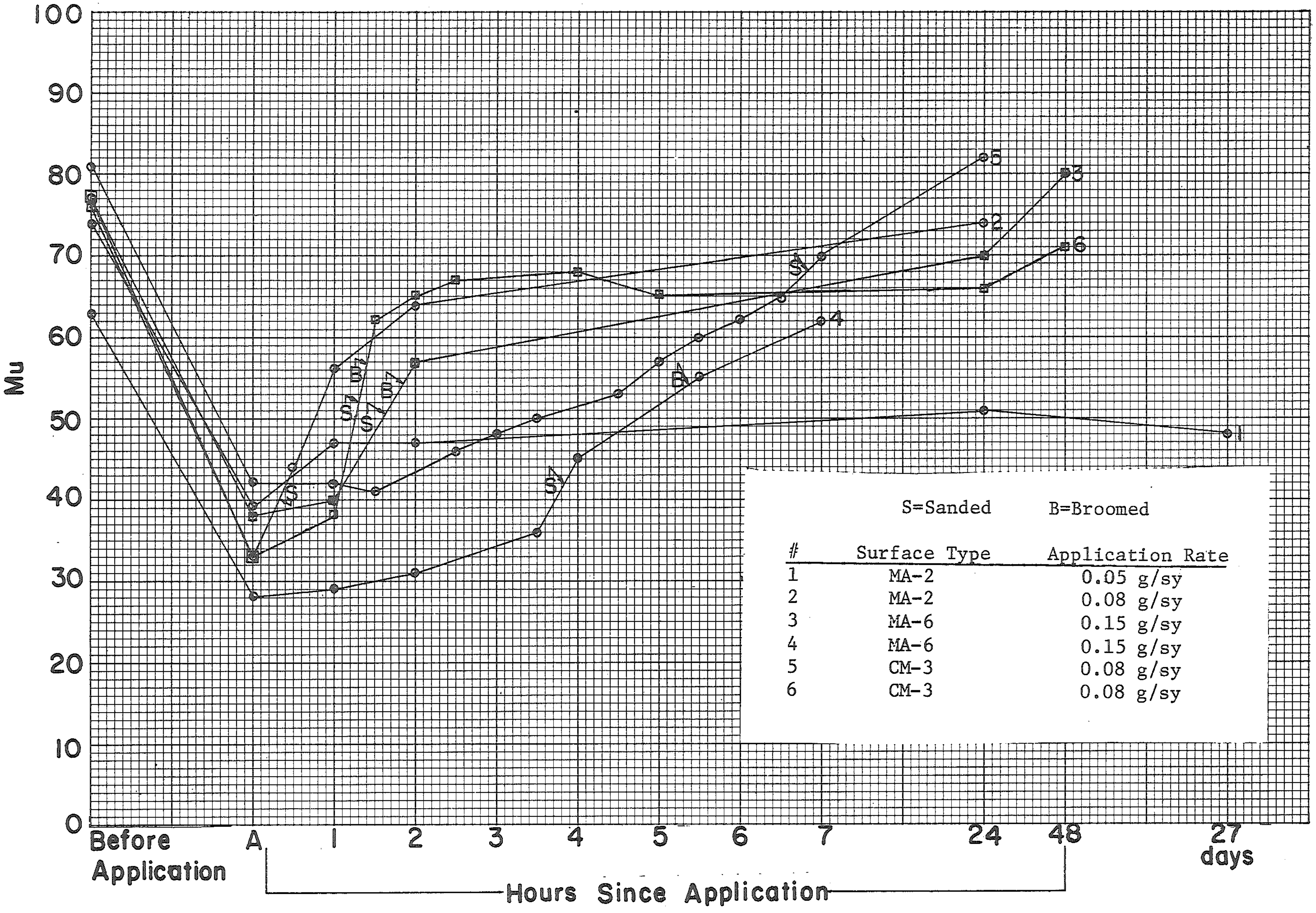


Figure 41

ARIZONA HIGHWAY DEPARTMENT
MATERIALS DIVISION RESEARCH

Figure 42
FRICTIONAL EFFECTS OF EMULSIFIED PETROLEUM RESIN



S=Sanded B=Broomed

#	Surface Type	Application Rate
1	MA-2	0.05 g/sy
2	MA-2	0.08 g/sy
3	MA-6	0.15 g/sy
4	MA-6	0.15 g/sy
5	CM-3	0.08 g/sy
6	CM-3	0.08 g/sy

TABLE 704 - 1 AGGREGATE FOR COVER MATERIAL AND SLURRY SEAL

Type Specification Designation	% Passing Sieve (Note 1)												Crushed Faces	Swell, Maximum,	Plasticity Index	Abrasion, Maximum, % (Note 2)
	¾ inch	½ inch	⅜ inch	¼ inch	No. 4	No. 8	No. 16	No. 30	No. 40	No. 50	No. 100	No. 200				
CM-1			100									0-8		(Note 6)	(Note 7)	
CM-2			100	65-100		0-15			0-5			0-2	(Note 3)			45
CM-3			100	65-100		0-20			0-5			0-2	(Note 4)			45
CM-4			100	85-100		0-20			0-5			0-2	(Note 4)			45
CM-5		100	97-100	65-100		5-30			0-7			0-2	(Note 5)			45
CM-6			100	65-100		0-20			0-7			0-4				45
CM-7	100	70-90		0-25		0-5						0-2	(Note 4)			45
CM-8					100	70-90	40-75	25-50				8-15			(Note 8)	
CM-9			100		70-90	45-70	28-50	19-24		12-25	7-18	8-15			(Note 8)	

Note 1. Percentage by weight when tested in accordance with the requirements of AASHO T 27.
Note 2. Percentage by weight when tested in accordance with the requirements of AASHO T 96.
Note 3. At least 30 percent by weight of the material retained on the No. 8 sieve shall have at least one rough angular surface produced by crushing.
Note 4. At least 70 percent by weight of the material retained on the No. 8 sieve shall have at least one rough angular surface produced by crushing.
Note 5. At least 85 percent by weight of the material retained on the No. 8 sieve shall have all surfaces which are rough and angular and have been produced by crushing.
Note 6. The material shall show no more than 0.06 inch swell when tested in accordance with the requirements of AASHO T 101, Method B.
Note 7. The plasticity index shall not exceed 5 when tested in accordance with the requirements of AASHO T 90.
Note 8. That portion of the material passing a No. 40 sieve shall be nonplastic when tested in accordance with the requirements of AASHO T 90.

TABLE 703-1 MINERAL AGGREGATE

Type Specification Designation	% Passing Sieve (Note 1)										Swell, Maximum, inch (Note 2)	Abrasion, Maximum, % (Note 3)	Crushed Faces	Plasticity Index, Maximum (Note 4)	Sand Equivalent, Minimum
	1 inch	¾ inch	½ inch	⅜ inch	¼ inch	No. 4	No. 8	No. 40	No. 100	No. 200					
MA-1	100	90-100		55-80			20-45			2-6	0.06	40	Note 5	5	55
MA-2	100	90-100		60-85			25-50			2-6	0.06	50		5	55
MA-3	100	90-100		65-90			35-60			2-8	0.06	50		5	55
MA-4		100	90-100	70-100			25-55			2-8	0.06	50		5	55
MA-5		100	90-100	70-100			35-65			2-10	0.06	50		5	55
MA-6				100		35-70	10-18			0-4	0.06	40	Note 6	NP	55
MA-7				100		70-85	45-70	20-40	5-15	3-8	0.06	50		5	55
MA-8	100	90-100			45-75					0-8	0.06	50		5	55
MA-9	100	90-100					40-65			0-10	0.06	50		5	55

Note 1. Percentage by weight when tested in accordance with the requirements of AASHO T 27.
Note 2. When tested in accordance with the requirements of AASHO T 101, Method B.
Note 3. Percentage by weight when tested in accordance with the requirements of AASHO T 96.
Note 4. When tested in accordance with the requirements of AASHO T 90.
Note 5. At least 50 percent by weight of the material retained on the No. 4 sieve shall have at least one rough angular surface produced by crushing.
Note 6. At least 70 percent by weight of the material retained on the No. 10 sieve shall have at least one rough angular surface produced by crushing.

Figure 43