

ACCIDENT RATES AND SURFACE PROPERTIES--
AN INVESTIGATION OF RELATIONSHIPS



MICHIGAN DEPARTMENT OF
STATE HIGHWAYS AND TRANSPORTATION

ACCIDENT RATES AND SURFACE PROPERTIES--
AN INVESTIGATION OF RELATIONSHIPS

L. F. Holbrook

A Final Report on a Highway Planning and Research Investigation
Conducted by the Testing and Research Division of the
Michigan Department of State Highways and Transportation
In Cooperation with the U. S. Department of Transportation,
Federal Highway Administration

Research Laboratory Section
Testing and Research Division
Research Project 73 G-193
Research Report No. R-994

Michigan State Highway Commission
Peter B. Fletcher, Chairman; Carl V. Pellonpaa,
Vice-Chairman, Hannes Meyers, Jr., Weston E. Vivian
John P. Woodford, Director
Lansing, October 1976

ACKNOWLEDGEMENTS

We wish to thank Fred Copple of the Laboratory's Pavement Performance Group for providing the skid testing data, Stanley Lingeman of the Traffic and Safety Division for providing the accident data, and Fred Nurnberger of the Department of Agriculture for providing the weather data. I also thank Charles Pasch, Laura Lintner, and David Schade of the Statistics and Analysis Group of the Research Laboratory for their data tabulation and analysis.

TABLE OF CONTENTS

	Page
ABSTRACT	1
INTRODUCTION	3
THE DATA	4
Weather	4
Wet Accident Locations	13
Skid Number	15
Accident Rates.	16
DATA GROUPING	17
THE MODEL	19
Rationale.	19
Fitting the Model to the Data for Each Surface Type Using Pilot Data Set (April - October)	21
Fitting the Model Using a Pooled Surface Data and Using Full Data Set (January - December)	30
How the Variables Behave.	33
APPLICATIONS	41
Before and After Comparisons	41
Plans for Resurfacing on a Project Priority Basis	43
CONCLUSIONS	51
REFERENCES	53

ABSTRACT

Both urban and rural state trunkline intersections are examined with regard to their wet accident percentages. The examination first takes account of the estimated percentage of highway surface wet time for each month January through December. Because precipitation data are only available for the amount of precipitation for designated time intervals, a method is developed to convert these data into percent wet time—a factor necessary in assessing wet surface exposure. Using this conversion method, the precipitation data from 120 of Michigan's weather stations are transformed to give a month by month wetness profile for the entire State for the years 1963 to 1974. The range in monthly wetness for this period is from less than 1 percent to more than 25 percent. This potential 25 to 1 ratio is very influential in wet accident incidence and should be taken into account before other wet accident variables are examined.

The method chosen to introduce wet time exposure into the analysis was to incorporate it as a variable in a mathematical model. Thus, it is assumed that wet accident proportion $\frac{WA}{TA}$ is proportional to wet time proportion $\frac{WH}{TH}$ and skid number (SN) as shown:

$$\frac{WA}{TA} = \left(\frac{WH}{TH} \right) g(SN)$$

This form is desirable since it satisfies theoretical boundary conditions at $\frac{WH}{TH} = 1.0$ and $\frac{WH}{TH} = 0$.

Nearly 40,000 accidents occurring at over 2,000 intersection locations for which a SN value was available were tabulated to provide wet accident proportions. These data together with the location's wet time proportion, as estimated from the nearest weather station, provided an opportunity to statistically fit the wet accident model for the variables included, and for each of three surface types in common use. The fit is satisfactory and suggests an accelerating function for SN: For all levels of wetness, and taking all surfaces together, an SN less than about 30 is accompanied by an accelerating increase in wet accident percentages; although the actual shape of the curve depends on wet time.

accident incidence. Consequently, nearly 40,000 Michigan State Trunkline accidents, together with all available precipitation records for the relevant accident periods and locations, were processed in order that a suitable mathematical model relating the most important variables could be developed. This paper is concerned with the measurement of suitable surface, weather, seasonal, and accident variables, their quantitative inter-relationships and the incorporation of these findings into a beneficial maintenance plan as envisaged in the proposal.

THE DATA

Wet accident causation is not univariate even though some variables undoubtedly influence accident statistics much more than others. Observers have identified as many as 250 to 300 potential accident causes with an average of about four primary causes per case (6). Measurement and incorporation into models of any but the smallest fraction of these causes is a practical impossibility. What we seek is the identification and modeling of the principal causes; treating the minor ones as random disturbances. Among the potential variables for which records were available, the following were found to be the most important.

Weather

If pavements could be kept dry, the skidding accident problem would be greatly diminished. Virginia estimates that about 34 percent of its intersection accidents occur under wet surface conditions, and that about 57 percent of these are attributable to wet conditions alone (5). It is also estimated that up to 33 percent of all wet weather accidents involve skidding (7). While perceptual judgements by investigating officers on skidding do not tell us whether or not an accident would have occurred if the pavement had not been wet, it is well known that surface wetness reduces tire-pavement friction, and that friction correlates well (0.90) with stopping distances for fixed speed (8). Increased stopping distances certainly increase accident incidence as is borne out by statistics. Surely, wet pavement exposure is an important factor, but how is it to be measured? We wish to measure it not only for incorporation into our wet accident model, but also for maintenance purposes, since it is likely that Michigan pavements will not all experience identical weather conditions. Most studies assume that wetness exposure per unit time is generally constant throughout an area so that the measurement problem does not arise.

Clearly, precipitation in inches as commonly reported by the Federal Weather Bureau is not, in itself, a suitable variable for the estimation of wet time. This can be seen immediately when one recognizes that an inch of precipitation can be spread over a few hours or a few weeks. Figure 1 shows that for Washington, D. C., a ten-minute storm will typically produce about an inch of rainfall. A 60 minute storm, on the other hand, will typically produce only about 2.2 inches of rainfall. Thus, the longer storm will rain six times as long, but produce only about twice as much rainfall. This is especially a problem in a Great Lakes state such as Michigan. In the fall months of the year, the Upper Peninsula experiences long periods of drizzle in which much wet time, but perhaps little aggregate precipitation, is accumulated. On the other hand, the Detroit area can receive considerable thundershower precipitation during a short summer afternoon. This is partly due to Detroit's more southerly location and partly due to the effects of pollutants and urban heat on the weather system. The variability of Michigan's precipitation regions is summarized by Strommen:

Summer precipitation falls primarily in the form of showers or thunderstorms, while a more steady type of precipitation of lighter intensity dominates the winter months. The annual number of thunderstorms observed decreases from about 40 in the south to around 25 in the Upper Peninsula area with nearly 50 percent of these recorded during the summer months, June through August (9), see Figure 2 of this report.

This means that if only precipitation records in inches of rainfall per day or month are available (as is generally the case) they should not be used directly to estimate wet exposure time. How, then, should the transformation be made?

Suppose we choose 0.24 in. per day as the daily wetness criterion. If it rains at the rate of 0.01 in. per hour for 17 hours, we will accumulate 17 hours of rain, but only 0.17 in. of precipitation; hence, our 0.24 criterion will reject the day as wet and register a 0 for that day. Weather of this type will tend to make the 0.24 criterion underestimate monthly wetness. On the other hand, if it rains 0.50 in. in one hour, and 0 in. in all other hours of the day, we will have one hour of wetness, but the 0.24 criterion will classify the day as wet and contribute 24 hours to our wetness accumulation. Weather of this type will tend to overestimate monthly wetness. This problem will appear for any figure other than 0.24 as well; hence, we need a criterion that corrects for the net bias of the inches per day criterion.

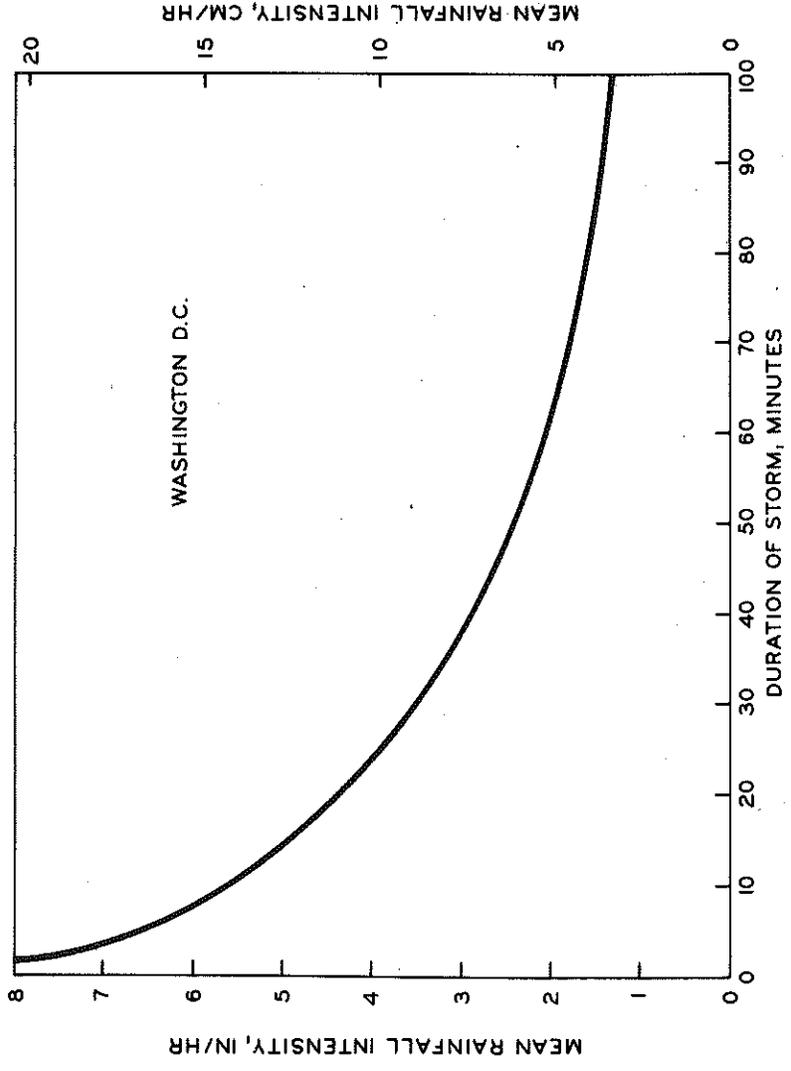


Figure 1. Intensity of mean rainfall vs. duration of storm in the Washington, D. C. vicinity.

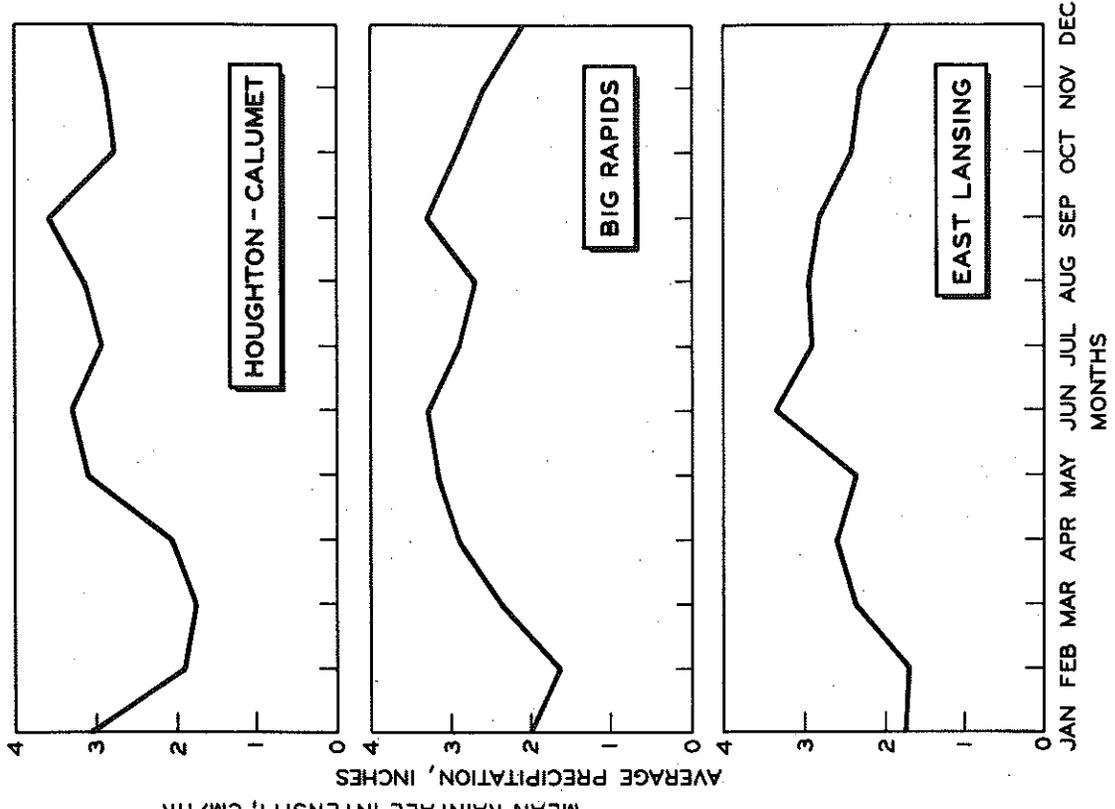


Figure 2. Precipitation variability displayed among three different regions in Michigan.

One method of transforming precipitation into wet time with minimum biasing is to count an hour as wet if there was a minimum amount of precipitation (10). Thus, if the minimum is 0.01 in. (the presumed amount of precipitation necessary to resupply loss by evaporation) the full hour is considered wet if it rains at least that amount. The method may give acceptable results if the threshold minimum is reasonable. However, of 120 Federal Weather Bureau stations in Michigan, only 42 recorded hourly precipitation for the study period (1963 to 1974). For these stations, percent wet time could be computed for each month. The winter months were excluded from the initial analysis because ice, snow and its removal, and rain together with salting—particularly in the Detroit area where most accidents occur—are factors which complicate the transformation of precipitation into percent wet time. These 42 stations gave a relatively weak picture of monthly and yearly wetness patterns around the State. The remaining 78 stations would contribute to a more detailed wetness picture if they could be brought into the analysis. While these stations did not measure hourly precipitation, they did record monthly precipitation totals. The question arises as to whether one can estimate monthly percent wet time from monthly precipitation. If this could be done, then two sources of wetness data could be used to develop wetness maps for the State, thereby allowing a more exact wetness exposure determination for each accident location.

Turning briefly to the 42 weather stations recording hourly precipitation, we find that on a monthly basis, correlation exists between precipitation in inches and percent wet time. Figure 3 shows a single selected weather station for the month of June. In this graph, the data points represent June precipitation and wet time totals for the years 1961 to 1973. The linear relationship, $W = \alpha p$, where W = percent monthly wet time and p = monthly precipitation, is generally well defined and designates α as the transformation of p to W . Regressions similar to the one in Figure 3 were used to generate α 's for each of the 12 months for each of the 42 weather stations which recorded hourly precipitation data. Examination of the station - α matrix showed that neighboring stations tended to have similar α 's for the same month. Consequently, it was thought that a regional α grouping would be possible. Moreover, an α grouping would solve the problem of assigning α 's to stations that did not record hourly precipitation. Often these stations were geographically surrounded by a number of hourly stations, thus making the assignment ambiguous. If α 's could be combined into a regional classification system, then non-hourly stations in each region could be assigned the pooled regional α estimate.

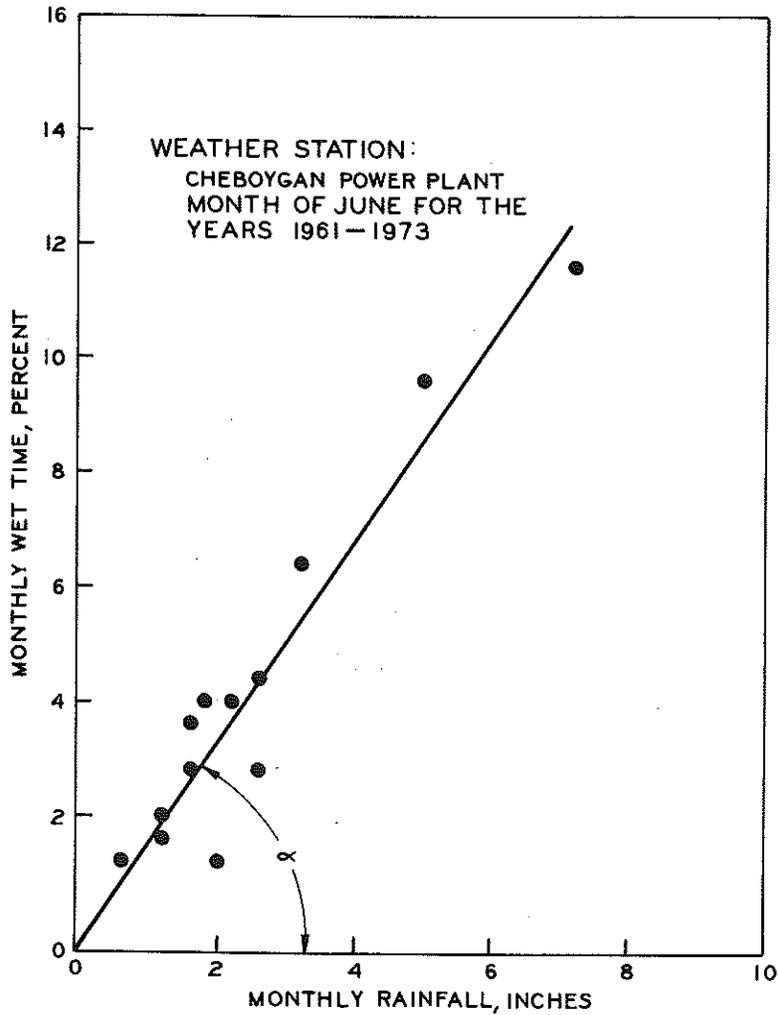


Figure 3. Relationship between monthly rainfall and monthly wet time.

A standard method of classification for intercorrelated variables is factor analysis. Using the principal axis method, two distinct seasonal groups emerged: November, December, January, February comprised one group and the remaining months comprised the second group. A second factoring of station locations within seasonal groups revealed three distinct regions for each seasonal group (Fig. 4). Further grouping explained very little additional variance in the α intercorrelation matrix. By assigning each station to the group with which it had its highest correlation (factor loading) all 42 hourly stations could be regionally classified. There was no station which had its highest correlation with a fourth group (factor). The regional α estimate, designated $\bar{\alpha}$, was then obtained as a factor loading

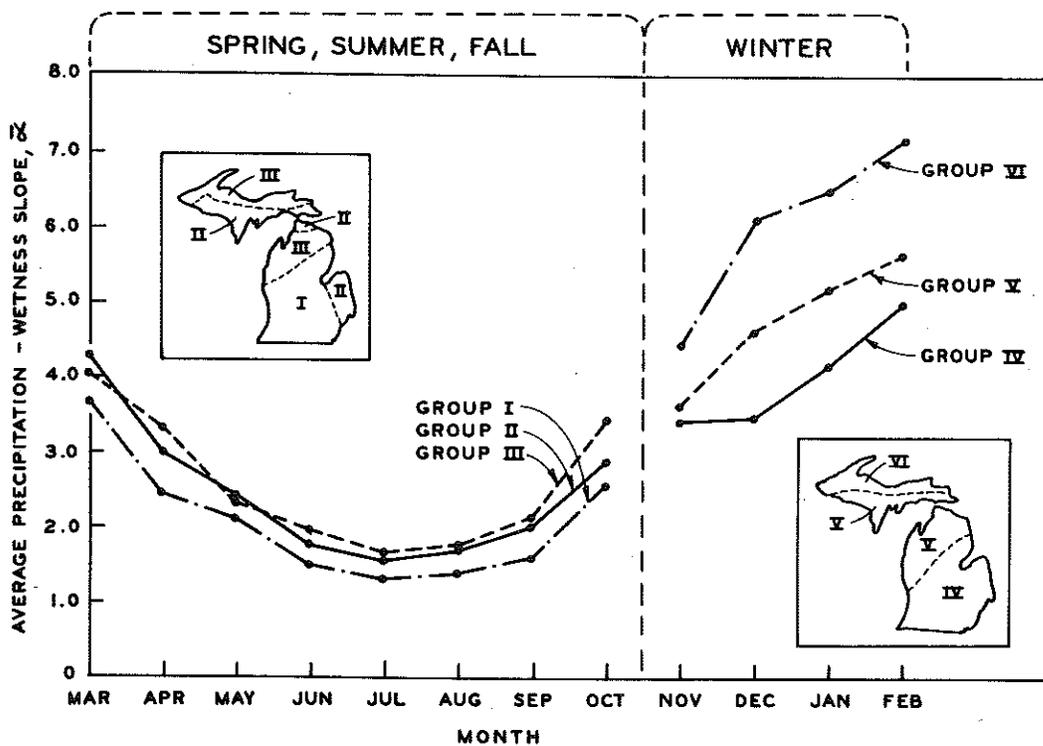


Figure 4. Regional and seasonal variation in the transformation of rainfall into monthly wet time.

weighted average of all member station α 's. Since non-hourly stations fall geographically within one of the three groups, each of these could be assigned the group $\bar{\alpha}$. Examination of the $\bar{\alpha}$, month, region matrix immediately revealed that for all regions, $\bar{\alpha}$ varied considerably from month to month. In particular, the $\bar{\alpha}$'s for spring and fall were larger than those of summer (Fig. 4). The Lake Superior coastal areas tend to have the highest $\bar{\alpha}$'s for each month, although the more inland Upper Peninsula and northern Lower Peninsula areas are comparable except for winter. The most highly differentiated region contains all stations in the central and southern Lower Peninsula. This region has lower $\bar{\alpha}$'s for all months, which means that an inch of precipitation yields the least wet time for each of the 12 months. The three regions were designated as north coastal (a belt along the southern shore of Lake Superior extending about 50 miles inland); north inland (the remaining portion of the Upper Peninsula together with the northern part of the Lower Peninsula); and south continental (the southern half of the Lower Peninsula). The north coastal region having generally high $\bar{\alpha}$'s would be characterized by longer, less intense rainfall (e. g., drizzle), particularly in the spring and fall. It is well known that

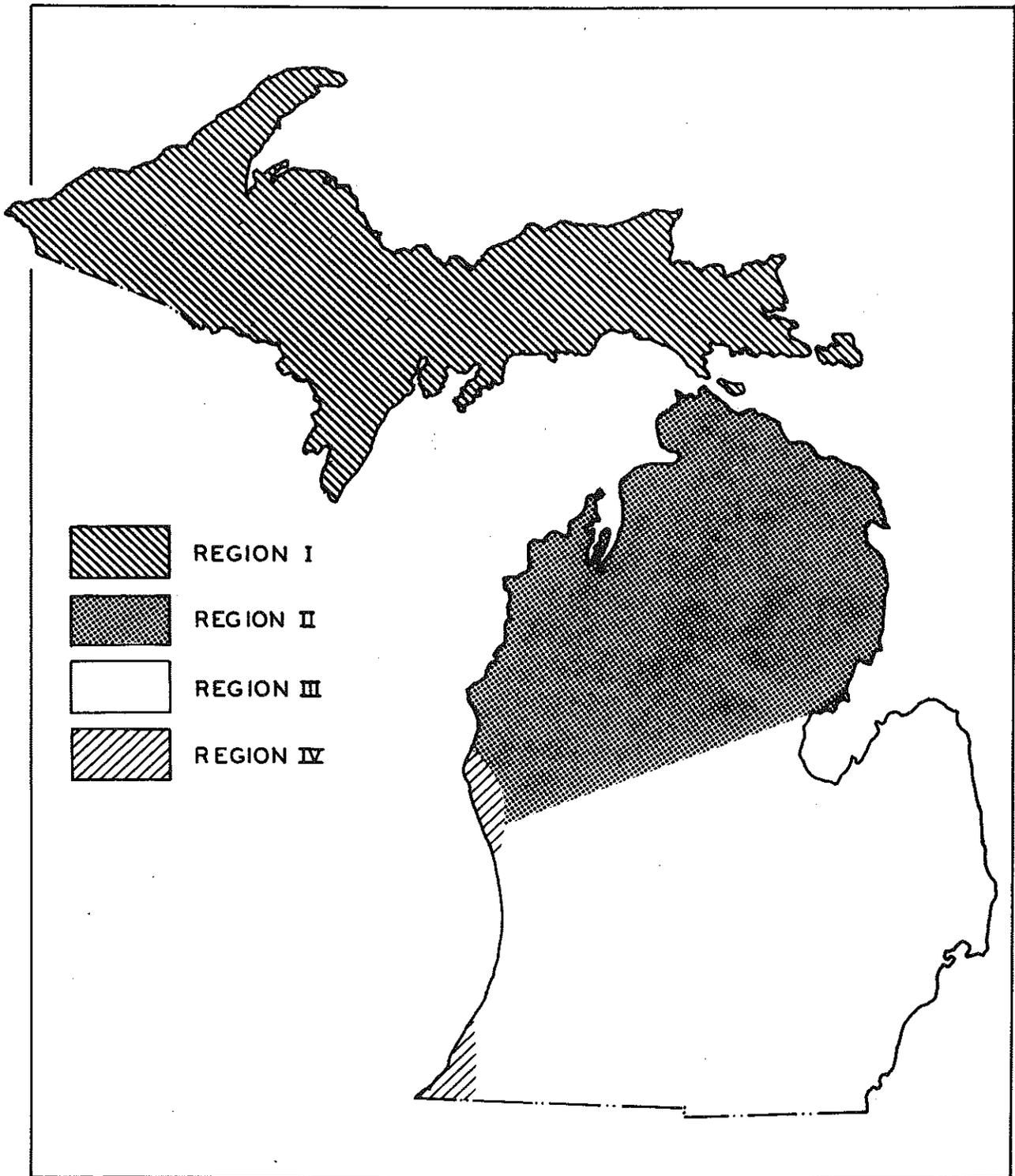


Figure 5. Wetness regimes for Michigan.

coastal areas are drizzle prone (11). The south continental region, on the other hand, would tend to have more intense rainfall of less duration (e.g., summer thunderstorms). It is clear from Figure 4 that even though there are regional differences in α , the predominant variation is monthly. From this analysis it is evident that for Michigan, regional and seasonal factors should both be part of any method which estimates monthly wet time from monthly accumulated precipitation.

The development of a precipitation transformation method facilitated the incorporation of the 78 non-hourly weather stations into the wet time analysis by transforming monthly precipitation or accumulated rainfall data into estimated percent wet time for each station. At this point, the same question arose concerning grouping or classification as had arisen with the α 's. Could stations be classified into regional groups of internally consistent weather patterns? This time, monthly wet time percentages were of interest. Assembling all weather stations, both those having actual and those having estimated monthly wet time percentages into a station-wet time matrix, a factor analysis similar to the one performed on the α matrix was used for classification purposes. Three very distinct major, and one minor factor emerged suggesting that Michigan wet time is amenable to several stable regimes. Figure 5 shows these regimes and their geographical boundaries.

It is interesting to examine these boundaries in light of what is known about weather patterns in Michigan. In general, it has been recognized that:

... certain macroscopic features of the general circulation were effective in steering the individual cyclones and anticyclones along determined paths. Multanovsky discovered large-scale weather situations during which individual systems followed a particular track or axis (12).

Furthermore, it is known that particular cyclone paths converge north and eastward toward the Great Lakes (13). Cyclones are not necessarily violent storms but are designated by meteorologists as fronts or boundaries between adjacent air masses of different temperature, pressure, and humidity composition. Cyclones do not necessarily always follow the same pathway, but they do seem to have rather narrow preferred routes (14, Fig. 6). The boundary between the Upper and Lower Peninsula (Regions I and II) corresponds to the 'Alberta' cyclone path, and the boundary dividing the northern and southern halves of the Lower Peninsula (Regions II and III) corresponds to the 'North Pacific' cyclone path (12, Figs. 5 and 6). Further agreement is found with the work of Steiner who performed a statistical analysis of continental U. S. weather and shows that for Michigan,

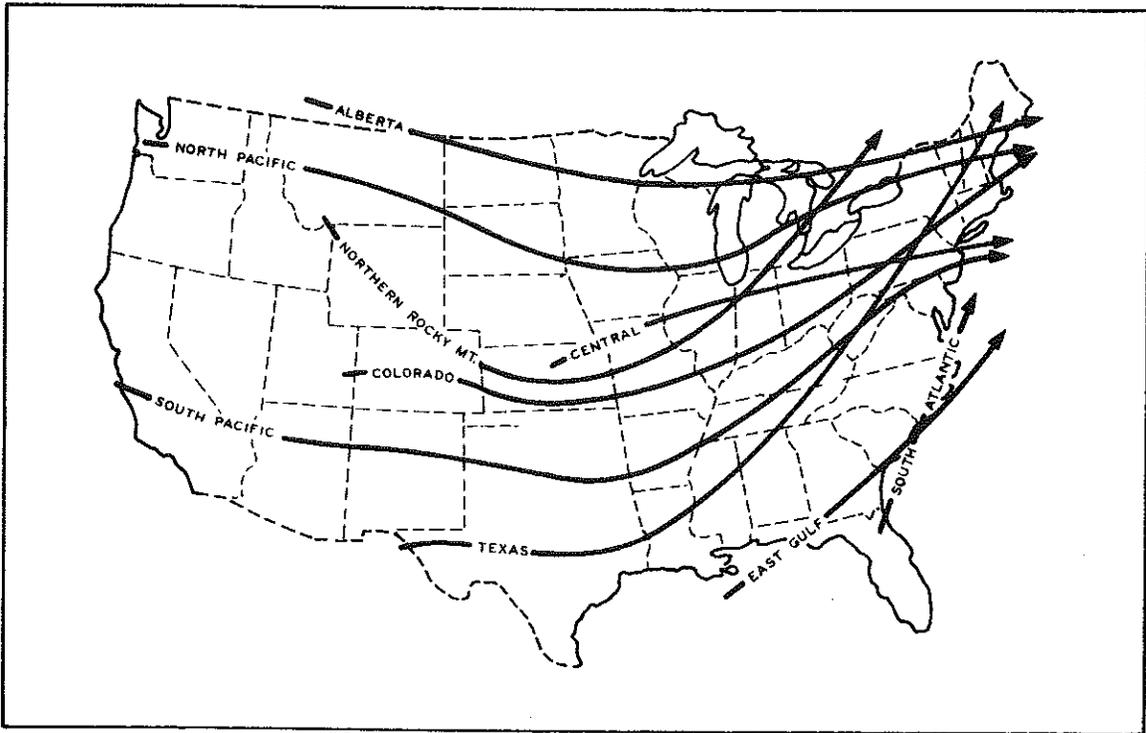


Figure 6. Cyclone paths for the U. S., after Blair.

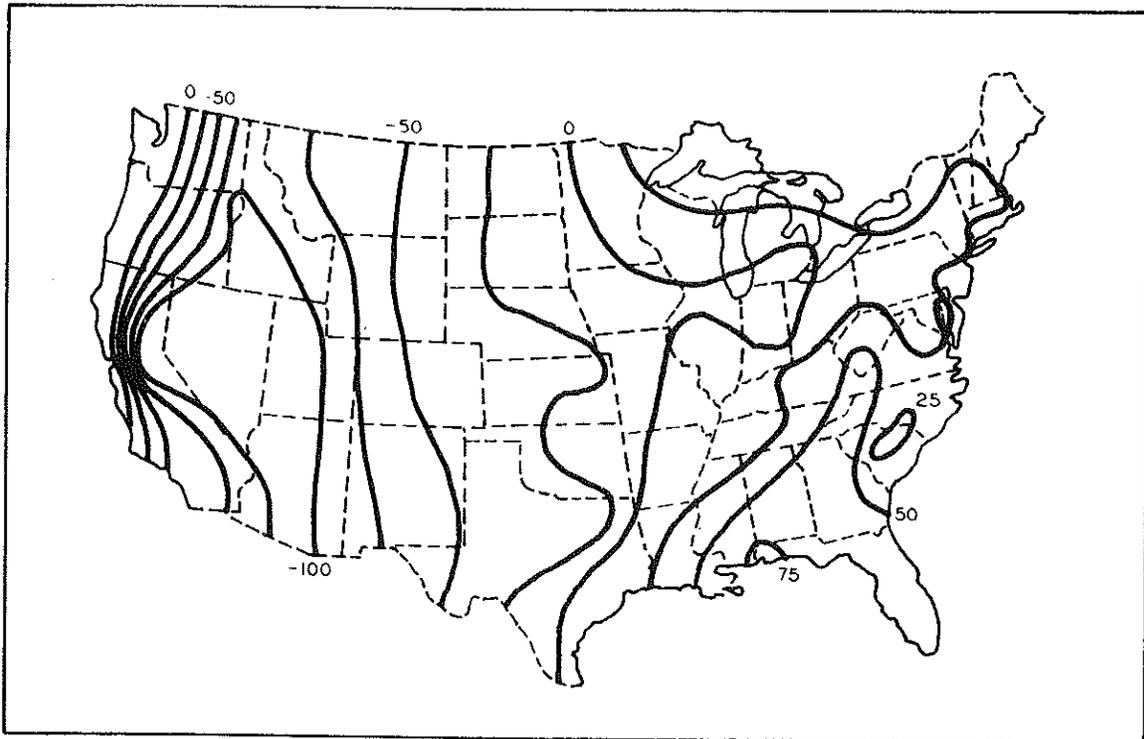


Figure 7. Humidity regions of the U. S., after Steiner.

'humidity' falls into three geographic classes corresponding to Regions I, II, and III found in the present study (15, Fig. 7). Region IV, which does not show up in the literature cited, was the weakest factor in terms of explained variance. Nevertheless, Region IV seems to correspond, at least for winter weather patterns, with an area famous for its heavy snowfalls.

Convection bands, a result of shoreline contours and even minor topographic features may extend 50 miles downwind from lakes, yet have widths of only a few miles. One well known band recurs in the same location on the southeast side of Lake Michigan during west-northwest winds; the band is oriented along the wind. No less than 37 in. of snow was recorded here during a single storm in February 1958. This equaled the mean February precipitation, which in this narrow-lake-snow corridor is 1 in. (of water) higher than in the areas around it (16).

All four regimes follow about the same seasonal pattern: wetness is greater in winter and fall, and least in summer (Fig. 8). These wetness patterns are important to this study because both locational and seasonal wetness differences will have considerable impact on wet pavement exposure and consequently on wet accident incidence. Regional wet time regimes will be of value in forecasting wet time exposure and will thereby facilitate maintenance planning. A reasonably precise monthly wetness estimation, such as the one used here, will provide a method by which missing weather station data can be recovered. More importantly, it makes possible forecasting regional wet time for those stations not measuring hourly precipitation. Therefore, either actual, or regionally estimated percent wet time was computed for each weather station for each of the 12 months for each year, 1961 to 1974. The monthly percent wet time appropriate to monthly accident statistics for each accident location was estimated from data obtained from the nearest weather station to that location. Since actual pavement wet time data were not available, this was the only method that could be used.

Wet Accident Locations

The selection of wet accident locations is complicated by the opposing problems of surface friction uniformity and accident frequency. Ideally, an accident location should be short enough to provide uniform surface friction, and long enough to experience reliable accident statistics. It is doubtful if non-intersection roadways could satisfy these criteria unless volumes of traffic were extraordinarily high. Because of these requirements, intersections are analytically preferable to ordinary roadways and

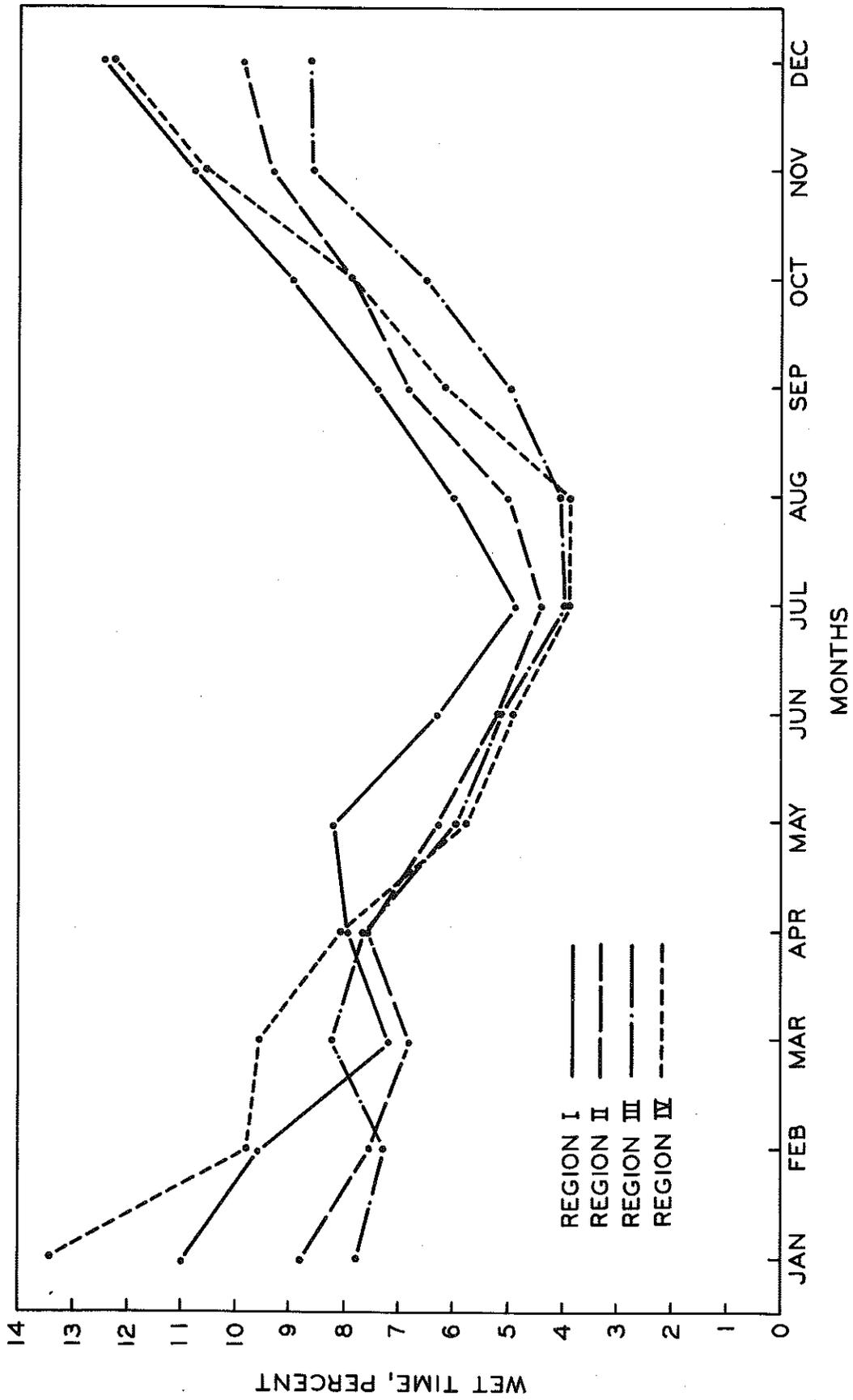


Figure 8. Seasonal variation of four wetness regimes in Michigan.

consequently were exclusively selected for analysis. In particular, Michigan's 'high accident' State trunkline locations, selected since 1963 for skid resistance testing, provided the best compromise data set. Of course not all accidents, even at these locations, were examined since records exist of only those accidents (in Illinois only 25 percent) serious enough to be reported (17, 18). It is felt that the biasing introduced by the reporting problem is slight in that intersection accidents almost always involve at least two vehicles--a fact which would encourage reporting for liability and insurance purposes. All types of reported accidents were combined so that the ratio of wet accidents to total accidents for each intersection for each of the 12 months could be computed. Thus, basic data points were defined for the years 1963 to 1974 which would ultimately be grouped with other data points according to weather and surface type criteria.

Skid Number

Michigan's 'high accident' locations are routinely skid tested and each has, for a given year, an average skid number (SN) comprised of surface friction measurements taken from each wheel track of the main intersection approach. The skid number used is generally an average of a number of tests conducted in each wheel track under wet conditions. These locations were generally tested between June and September of the year following the high accident year that signaled the test itself. This average SN value, strictly speaking, was relevant only for the period of the test itself. However, it was the only value available and had to be assigned to all months used in the analysis, even though it is recognized that seasonal variations in SN probably exist (1, 2, 3, 19). This would mean that a single skid number value would not apply to all months equally well. In order that this possibility be accommodated, seasonal (monthly) flexibility was incorporated into the model. Monthly temperature, while correlated with wet accident incidence, did not improve predictions as well as monthly factors which took account of both temperature and humidity conditions. Therefore, temperature, per se, was not retained as a variable in the model.

Since considerable evidence exists showing that the traffic and passing lanes of multi-lane state trunklines experience different traffic volumes, it was considered reasonable to differentially weight the different lanes. Because lane volumes were not known, some approximate method had to be developed to estimate lane exposure differences. Some investigators suggest a traffic lane-passing lane weighting ratio of 4:1 (4). Since many of Michigan's high accident intersections are six or eight lane, this method would not be appropriate for the present analysis. Rather, SN values for each lane were weighted by least squares fitting parameters provided in

the model. Preliminary calculations didn't suggest that selective weighting of the SN value for each lane was in any way superior to simple averaging of all lane SN values. Hence, no further attention was given to lane SN as an important variable in determining wet accident hazard.

Accident Rates

Accident data can be used in a variety of ways, usually called rates, to measure intersection hazard. Traditionally, the following have been used:

1) Accidents per vehicle mile. This statistic is designed to correct for differential mileages driven so that roadways can be compared independently of the arbitrary effects of usage. It is more applicable to long roadway sections than to intersections, since the mileage accumulated at intersections is small and difficult to measure (20). For this reason, the statistic was rejected for use in the present study. Moreover, correcting for mileage driven does not remove the substantial effects of local idiosyncratic hazards caused by visibility, geometry, or control problems.

2) Accidents per unit time. In an effort to solve the problem of short mileage at such locations as bridges and intersections, some investigators have substituted time for mileage (21). Of course, this statistic is particularly sensitive to traffic volume and its time dependency. For this reason, the time - rate concept was not considered for use in this study.

3) Accidents per vehicle. This statistic attempts to measure hazard in terms of a standard number of vehicles registered or passing a selected location (22). It eliminates the linear effects of volume, but not mileage driven nor differential locational hazard. For these reasons it was also not considered useful for this study.

The above statistics, particularly accidents per vehicle mile, may also be non-linear functions of traffic volume (23, 24, 25, 26). Thus accident rates may increase with ADT up to a critical point and then decline. Presumably, the very large ADTs impose discipline on driver behavior. The matter must be considered controversial since other investigators have been unable to find the same non-linearities (27, 28).

The accident statistic sought for this study had to be free of at least the linear effects of different traffic volume conflicts, mileages driven, and local hazard. The simplest measure presumably satisfying this requirement was monthly percent wet accidents computed from accident data occurring within the intersection and approach areas (± 0.1 mile from the

minor roadway centerline and on the state trunkline). This was the shortest time period considered feasible in terms of seasonal variations in weather and traffic behavior. There is some evidence that this statistic is immune to the above effects and to others such as roadway type (8). It was hoped that major linear effects of unwanted variables would be nullified, thereby allowing intersections to be grouped and compared. Nevertheless, it is possible that disturbances remain because of the measure's sensitivity to some of the following considerations:

1) Intersections differ with respect to lighting and proportion of night traffic. Moreover, wet nighttime accident percentages may be influenced by glare, particularly in urban areas. Thus, these intersections could experience a disproportionately high wet accident percentage because of non surface friction variables.

2) During rainstorms, daytime visibility may decrease enough to affect wet accident percentages. Depending on relative daytime traffic volumes, this could bias a location's wet accident percentage from that expected from surface friction alone.

3) Travel through some intersections may be discretionary and, consequently, traffic volumes may be affected by wet weather and seasonal considerations. Michigan's vacation traffic may be more subject to this effect than its urban commuter traffic.

4) Average traffic speed may be decreased by wet weather for some intersections and not others. This would have the effect of biasing the wet accident percentages downward for these intersections.

5) Increased driver caution on wet surfaces may not apply equally to all intersections.

DATA GROUPING

Since a small number of variables will not usually characterize wet accident occurrence, there is no simple quantitative specification which relates these variables such that reliable prediction is possible.¹ Because large numbers of variables are involved, wet accident percentages fluctuate considerably over time and from location to location. For purposes of reliability and model simplicity, most of the variables contributing to these

¹Research on this point has identified as many as 289 variables with an average of 4.3 per accident (6).

fluctuations must be treated as random disturbances under the assumption that they do not interact with those measurable variables isolated for incorporation into the model. In this study, monthly wet accident percentage, monthly percent wet time, the month itself, skid number, and surface type were considered the most important variables for which complete data were available.

Wet accidents, even at high accident intersections, do not generally occur with enough frequency to enable the calculation of really reliable percentage estimates for each intersection. Table 1 shows the 95 percent confidence range for various wet accident percentages and sample sizes.

TABLE 1

True Wet Accident Percentage	Total Number of Accidents Required to Provide Sample Wet Accident Estimates Within the Indicated Range 95 Percent of the Time		
	100	500	5,000
10	4 - 16	7 - 13	9 - 11
20	12 - 28	16 - 24	19 - 21
30	21 - 39	26 - 34	29 - 31
40	30 - 50	36 - 44	39 - 41
50	40 - 60	46 - 54	49 - 51
60	50 - 70	56 - 64	59 - 61
70	61 - 79	66 - 74	69 - 71

Even with an unrealistic 500 accidents occurring per month at a given location, where the history percentage of wet accidents equals 50, sample wet accident percentages will range between 46 and 54, 95 percent of the time. For the more typical intersection, experiencing no more than 10 accidents per month, the variation will be much greater.

It is necessary, therefore, to pool accident locations if relatively stable wet accident percentages are to be used to construct a wet accident model.

With this in mind, accident locations were grouped into skid number, percentage wet time, monthly cells. Percentage wet time was classified into five groups:

- 0.00 - 3.99 percent wet time
- 4.00 - 7.99 percent wet time
- 8.00 - 11.99 percent wet time
- 12.00 - 15.99 percent wet time.
- 16.00 and over

Skid numbers were classified into eight groups:

- | | |
|----------|-------------|
| under 24 | 45 - 49 |
| 25 - 29 | 50 - 54 |
| 30 - 34 | 55 and over |
| 35 - 39 | |
| 40 - 44 | |

Thus, each accident location could be assigned to any one of 12 months x five wet time x eight skid number = 480 groups. Hopefully, these groups would then contain enough accidents to allow a good statistical fitting of the model.

THE MODEL

Rationale

As wet exposure increases, so should wet accident proportion. That is,

$$\frac{WA}{TA} = f \left(\frac{WH}{TH} \right) \uparrow$$

where, $\frac{WA}{TA}$ is defined as wet accident proportion and $\frac{WH}{TH}$ is defined as wet time proportion. The vertical arrow merely means that the function f increases with increasing $\frac{WH}{TH}$. The original criterion for a wet hour, i.e., 0.01 in. of precipitation, seemed reasonable. However, it was still a guess since the quantity of rainfall required to maintain an hour's wetness on partially drained pavement surfaces was not known. Moreover, rainfall evaporates in accordance with seasonal patterns of temperature and wind. Therefore, the model must be sufficiently flexible to allow for seasonal variations in the wetness criterion. Since we do not know how to specify

the criterion's monthly drift (defined as $M(i)$) one can do no more than specify a polynomial of sufficient degree to follow any major variations. In the present case, percent wet time was multiplied by a third-order polynomial: $M(i) = \theta_1 i + \theta_2 i^2 + \theta_3 i^3 + 1$. The θ 's are seasonal fitting parameters to be estimated from the data, and the i 's designate the months one (January) through 12 (December).

As monthly wetness varies, wet accident proportions must conform to certain necessary limitations. For example, if there was no wet time during the month, there would necessarily be zero percent wet accidents. Also, as wet time approaches the limit of 100 percent, so, too, should wet accident percentage. Therefore, any other variables affecting wet accident incidence should be introduced in such a way as to permit these boundary conditions. One method is to specify them as a wet time exponential function:

$$\frac{WA}{TA} = \left[M(i) \frac{WH}{TH} \right] g(\text{other variables})$$

Of the measured variables available, lane, skid number and surface type seemed most promising. A preliminary analysis with lanes was not conclusive so that skid number and surface types were the only variables remaining to be specified. Surface type was handled by segregating the data into three basic surface groups and performing independent analyses on each group. Since the role of skid number in the model is of primary importance, a second very flexible polynomial specification was used. This was done since it could not be assumed that skid number would enter into the model in a linear fashion. The only parameter reducing restrictions made were the obvious ones which require that as SN approaches 100, wet accident incidence should approach the fraction wet time encountered that month; and as SN approaches 0, friction is so reduced that wet accident percentages approach 100. These restrictions result in the following third-degree polynomial written in terms of the skid coefficient, $\mu = \frac{SN}{100}$:

$$g(\mu) + \theta_4 \left[(\mu)^3 - (\mu) \right] + \theta_5 \left[(\mu)^2 - (\mu) \right] + \mu$$

so that the model becomes:

$$\frac{WA}{TA} = \left[M(i) \frac{WH}{TH} \right] g(\mu) \quad (1)$$

Again, θ_4 and θ_5 are fitting parameters to be determined by the data.

Fitting the Model to the Data for Each Surface Type Using Pilot Data Set
(April - October)

The locations for which intersection skid numbers were available spanned 11 years and provided a data set of over 20,000 accidents, from which wet accident percentages were formed for the seven months selected for analysis. This reduced over 20,000 accidents to 280 possible wet accident ratios which constituted the derived data set.

Since the functional form of the model is inherently non-linear, ordinary least squares methods could not be used. Instead, a non-linear least squares computer program was used for the estimation of θ_1 through θ_3 for the full data set, and θ_4 and θ_5 for each bituminous aggregate, bituminous concrete, and portland cement concrete surface classifications, as well as all surfaces combined. Since the $M(i)$ polynomial related to seasonal variation, it was estimated from 12 month data. Figure 9 shows the shape of the wetness adjustment polynomial $M(i)$ for the combined data set. Notice that the 0.01 in. precipitation criterion overestimates June wet time percentages (adjustment factor of about 1.5). This is to be expected since mid-summer would experience the most intense convective storm rainfall as well as higher temperature evaporation rates. Both factors would tend to reduce to a minimum the wetness surface time resulting from a given quantity of rainfall. From the minimum of June, the adjustment polynomial increases through January, suggesting that as fall approaches, reduced precipitation intensities and evaporation rates result in greater surface wetness times for each inch of rainfall. Pilot data provided approximately the same parameters except for the portland cement concrete which produced a relatively flat $g(\mu)$ in the 20 to 50 SN range (Fig. 10). For all skid number and wet time groups, as well as for all months, bituminous aggregate intersections had less accident incidence than any other type. This difference, at first sight, appears to be due to a somewhat higher average skid number for these bituminous intersections than the other groups (Table 2).

TABLE 2

Surface Type	Weighted Average SN
Bituminous Aggregate	40.0
Bituminous Concrete	33.5
Portland Cement Concrete	35.5

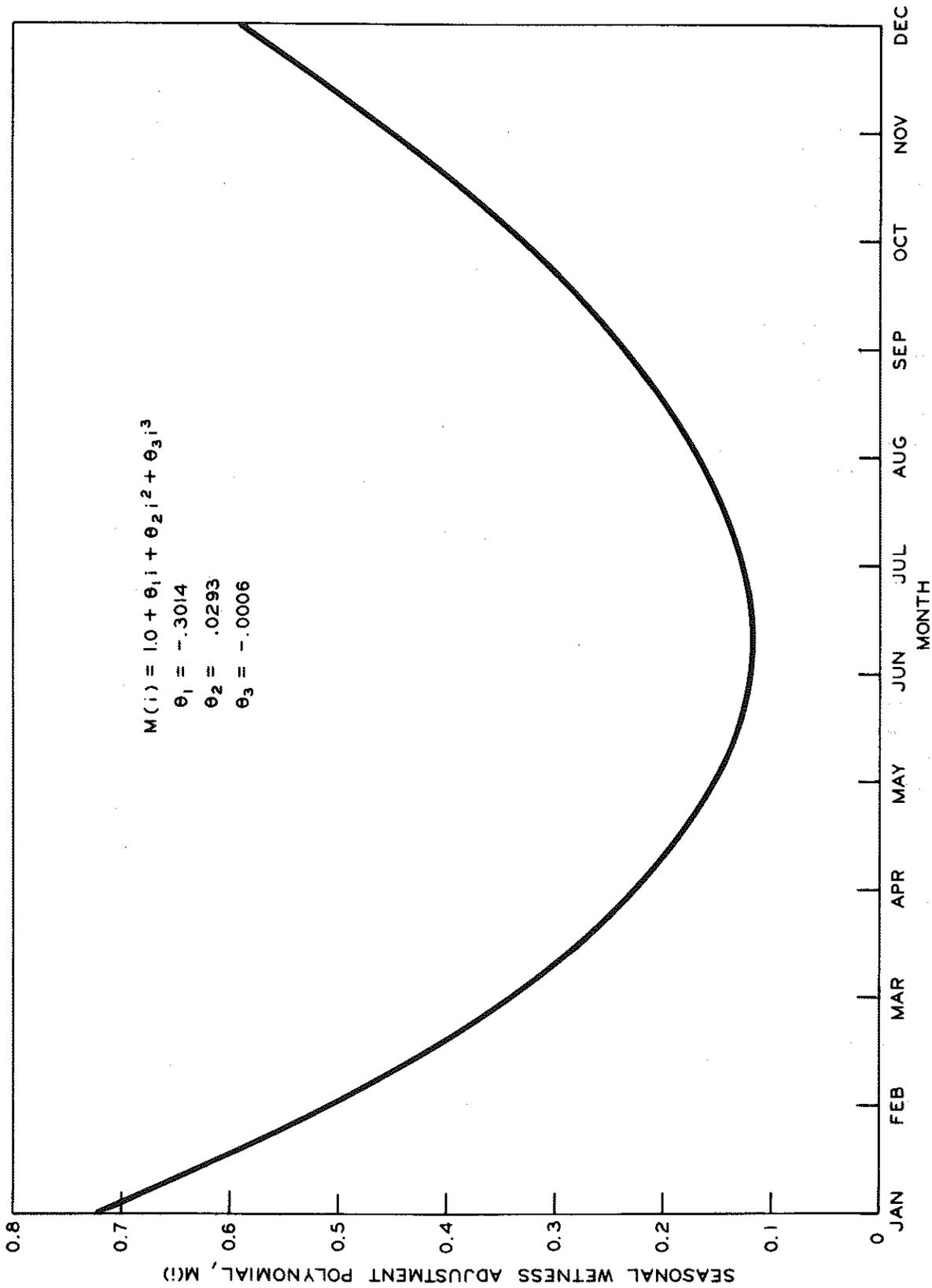


Figure 9. Seasonal witness polynomial M(i) as a function of month.

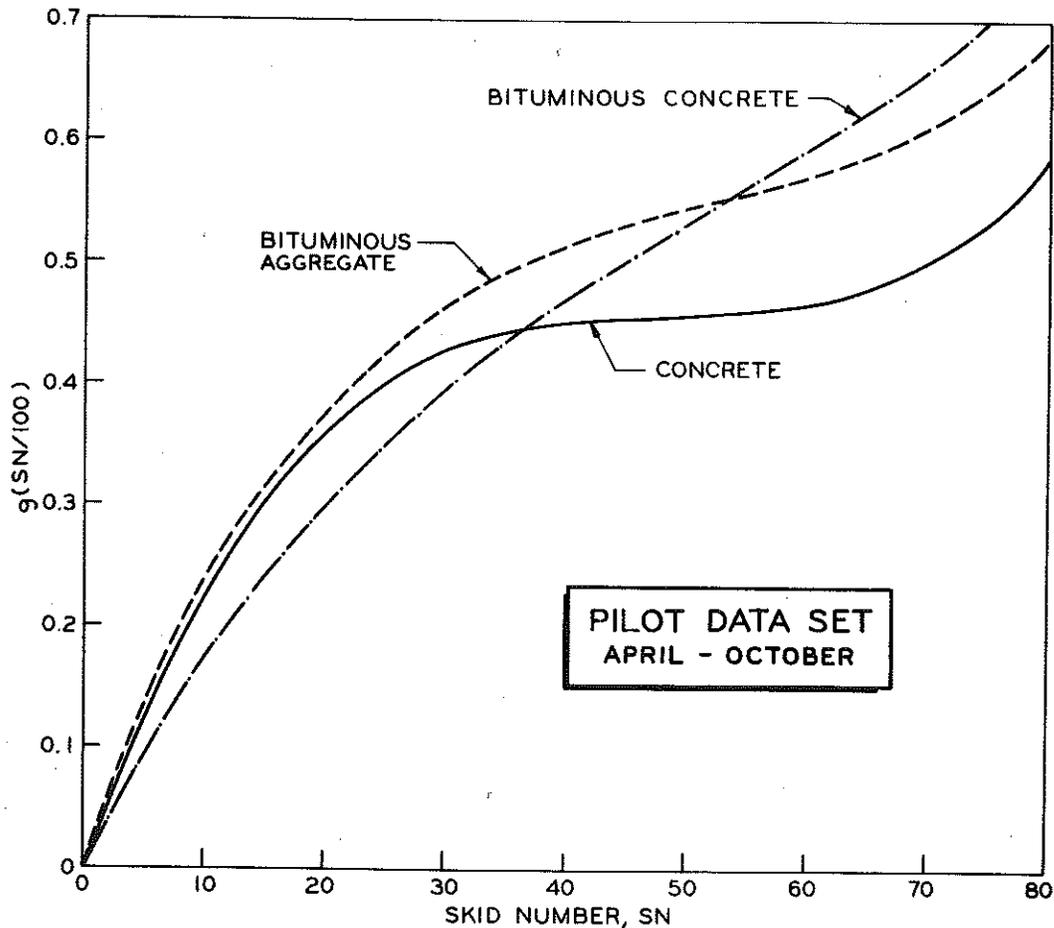


Figure 10. Skid number polynomial for various surface types.

Examination of the $g(\mu)$ function for bituminous aggregate in Figure 10, however, shows that over the practical range of interest ($SN = 20$ to 60), $g(\mu)$ is greater for this surface type for nearly all SN values. In the model, $g(\mu)$ is an exponent of a fraction ($M(i) = \frac{WH}{TH}$); hence, as $g(\mu)$ increases, wet accident proportions ($\frac{WA}{TA}$) will decrease. From this analysis, we conclude that the lower wet accident proportions found with the bituminous aggregates are due to factors other than generally higher surface friction or wetness conditions. Portland cement concrete generally has the lowest $g(\mu)$ function over the range of interest which indicates that with this surface type, we will find higher wet accident percentages for each of the seven months under any wetness condition or most any skid number value. The

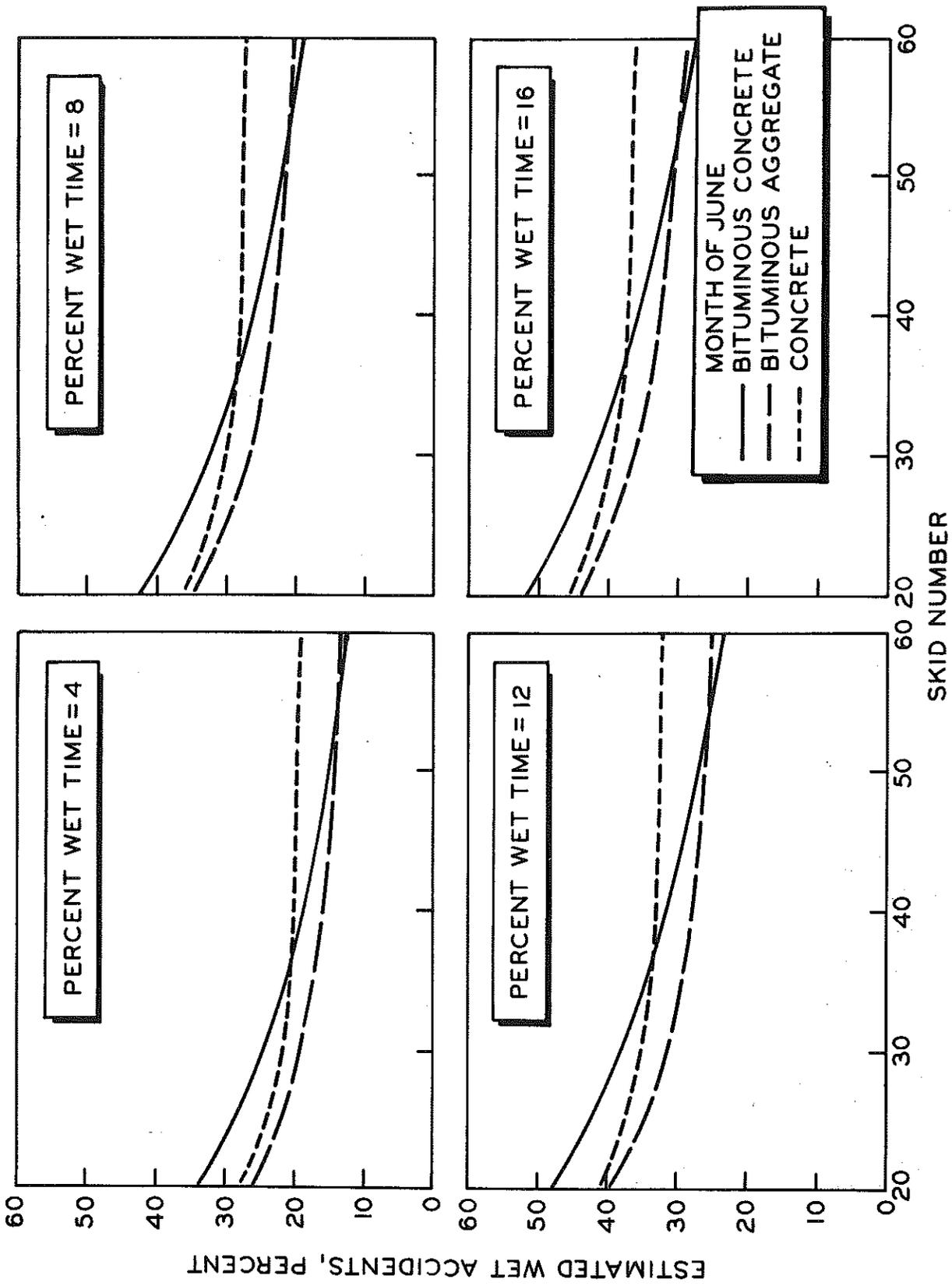


Figure 11. Relationship between skid number and wet accident percentages for various wet times and surface types.

reason for this is not clear; however, it may not be due to any property of the surface type itself. Rigid pavement state trunklines may be statistically associated with higher average traffic speeds. Since stopping distance is a function of speed as well as skid number, this may account for a generally greater percentage of wet surface accidents.²

Further, examination of the $g(\mu)$ function for portland cement concrete shown in Figure 10 indicates that over the skid number range of interest (20 to 60), wet accident incidence is related to skid number only in the 20 to 30 region. Above about 30, the polynomial is flat, reflecting the fact that for these data, wet accident percentage is not related to skid number in this region. This point becomes clear after examination of Figure 11 which shows the model's estimate of wet accident percentage for various skid numbers. The presentation in Figure 11 is more intuitive than that of Figure 10; it estimates actual performance for the month of June and holding wet time constant. The bituminous concretes, on the other hand, show a fairly strong relationship between SN and wet accident percentage (Fig. 11). Figures 12 through 20 show the degree of the model's fit to the data for groupings of each of the incorporated variables. The fit is usually quite good as evidenced by the closeness of each point to the line of exact fit (45 degrees). The points showing the greatest deviations from this line are those for which a relatively small number of accidents (under 200) occurred in the data cell. As discussed earlier, this leads to reliability problems. The apparent lack of correlation of skid number with percent wet accidents for portland cement concrete and bituminous aggregate surfaces is probably due to the relatively restricted skid number range of these surfaces. Bituminous concrete surfaces cover a wide range of skid numbers in this data set (less than 22 and greater than 62) which probably accounts for the higher correlation (Fig. 18).

Figures 12 through 20 also show that the model discriminates seasonal and wet exposure time differences quite well. It is assumed that this is because of the broad ranges encountered with these variables. By implication, the skid number range relative to random variation encountered with portland cement concrete and bituminous aggregate surfaces is not as large

² The relation between initial speed (V_0) and stopping distance (SD) is approximately:

$$\frac{V_0^2}{\left(\frac{SN}{50}\right)g}$$

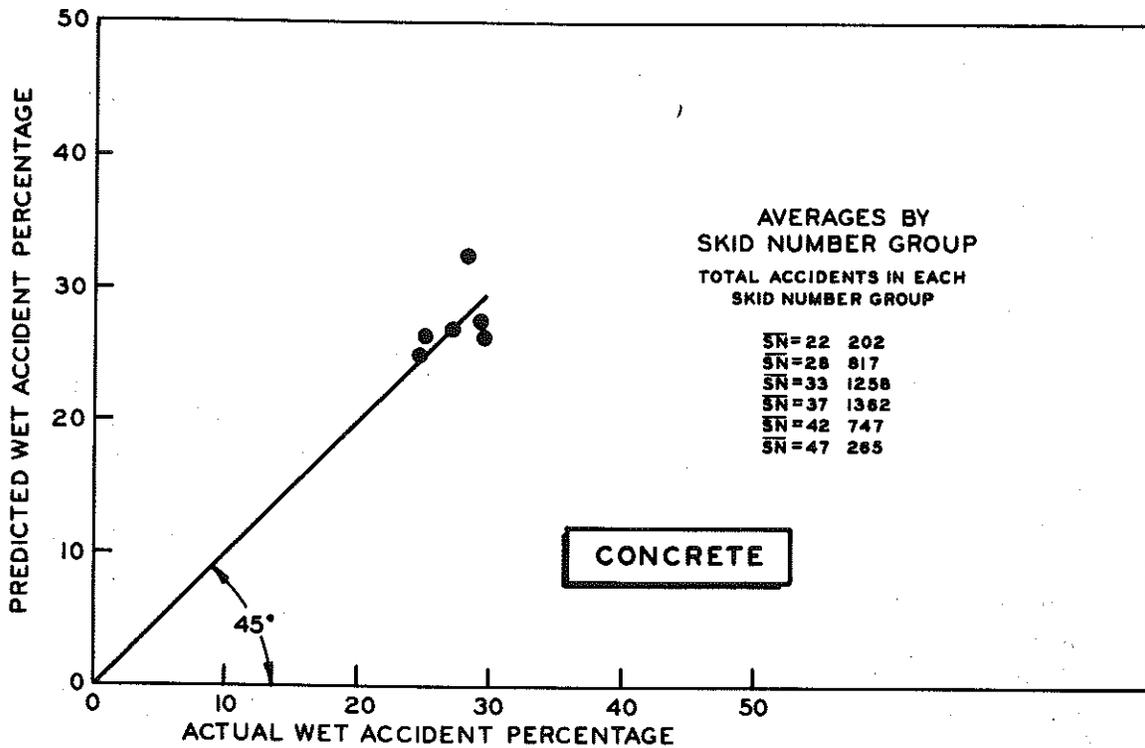


Figure 12. Relationship between actual and predicted wet accident percentages for each skid number.

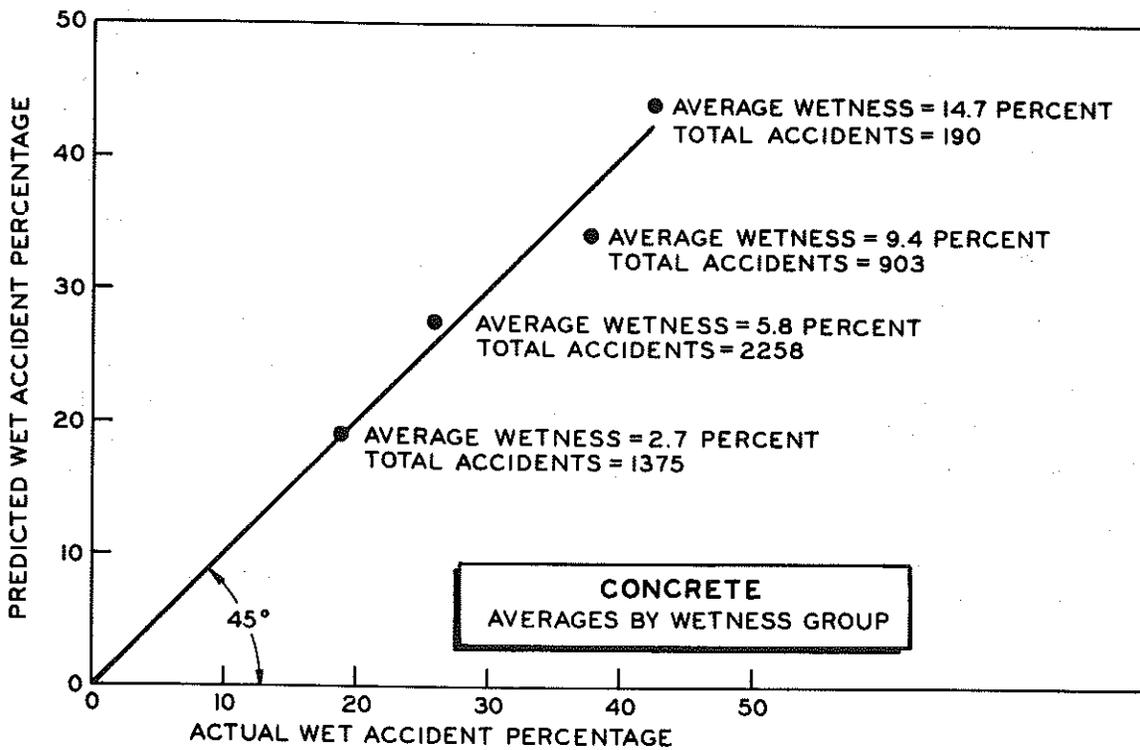


Figure 13. Relationship between actual and predicted wet accident percentages for each wetness group.

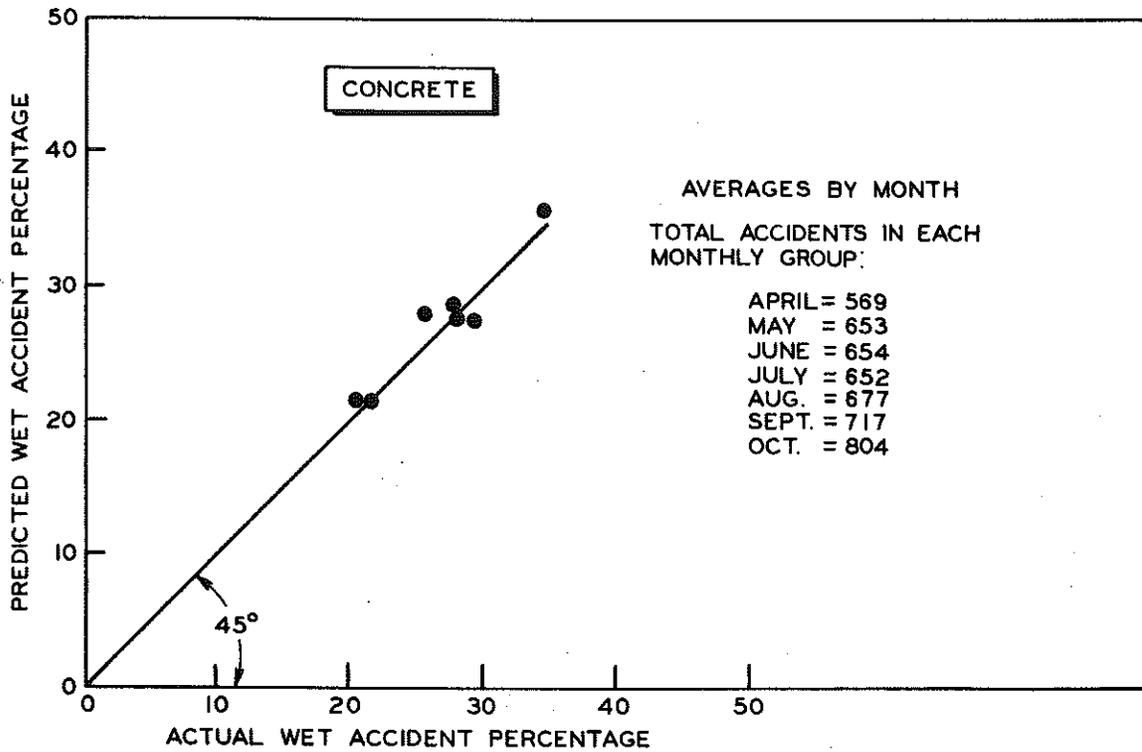


Figure 14. Relationship between actual and predicted wet accident percentages for each month.

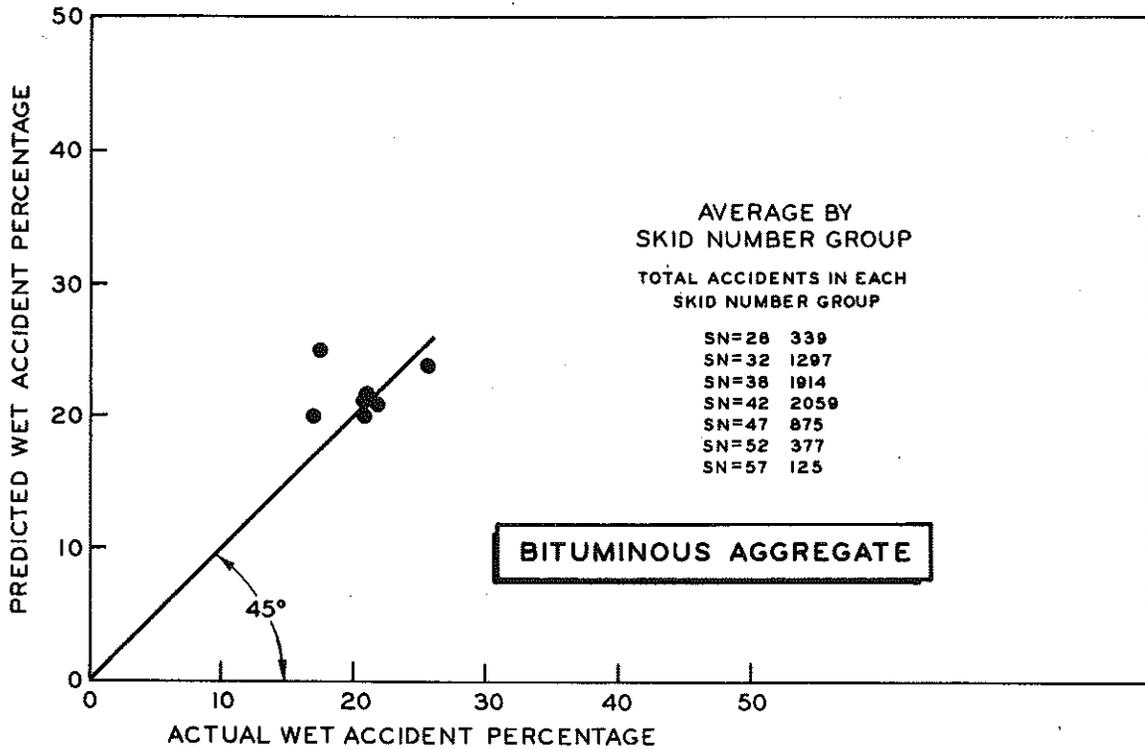


Figure 15. Relationship between actual and predicted wet accident percentages for each skid number group.

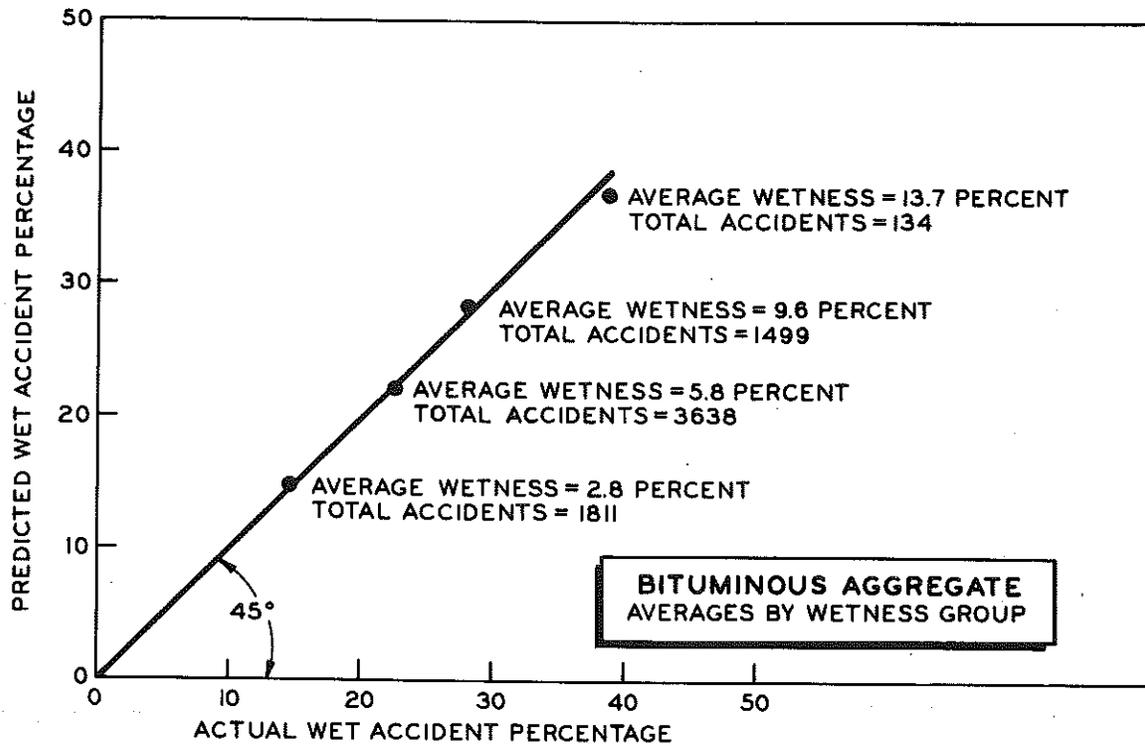


Figure 16. Relationship between actual and predicted wet accident percentages for each wetness group.

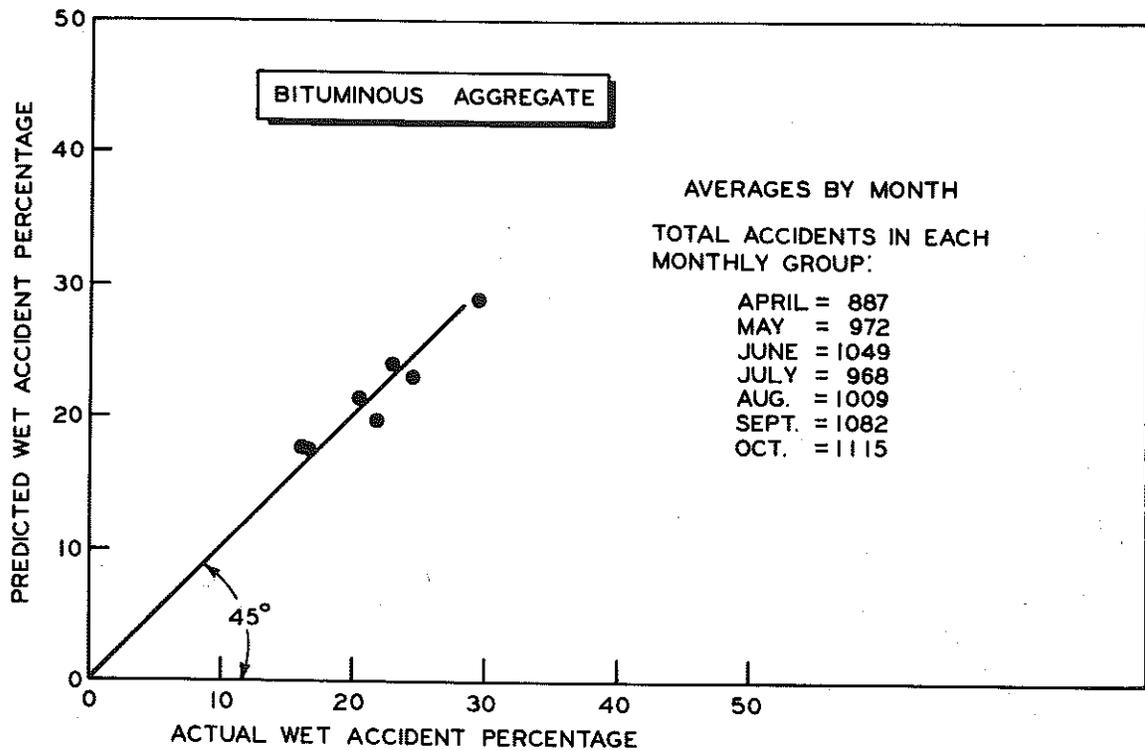


Figure 17. Relationship between actual and predicted wet accident percentages for each month.

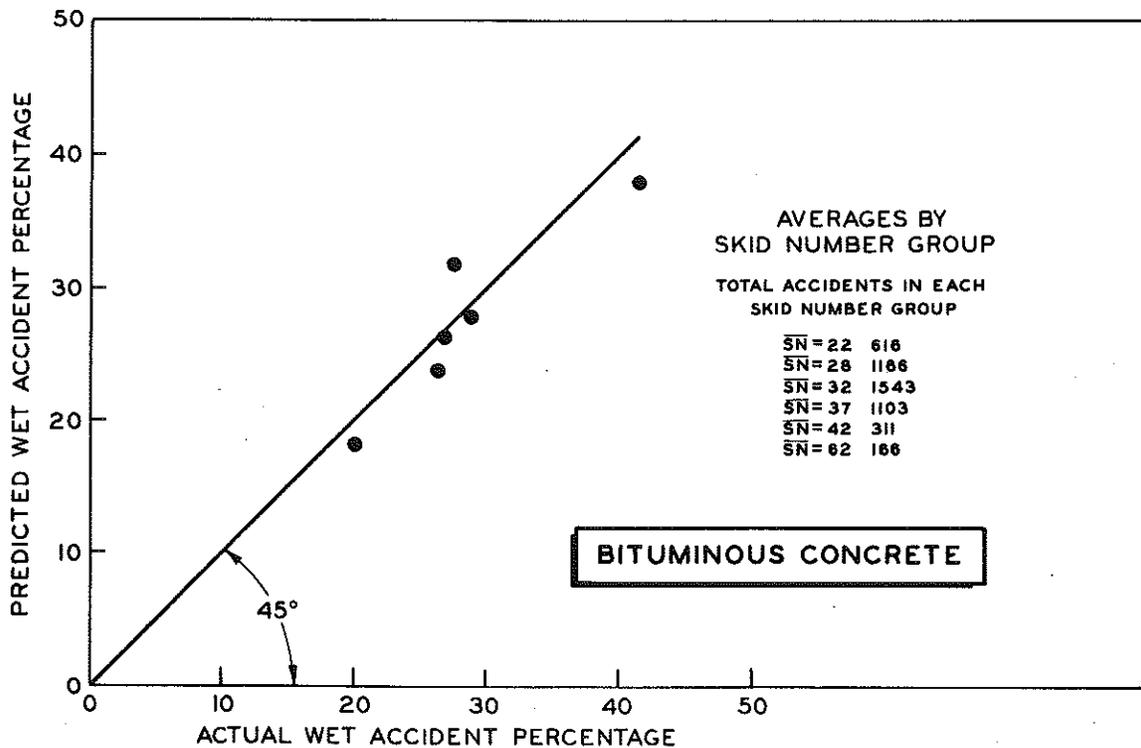


Figure 18. Relationship between actual and predicted wet accident percentages for each skid number group.

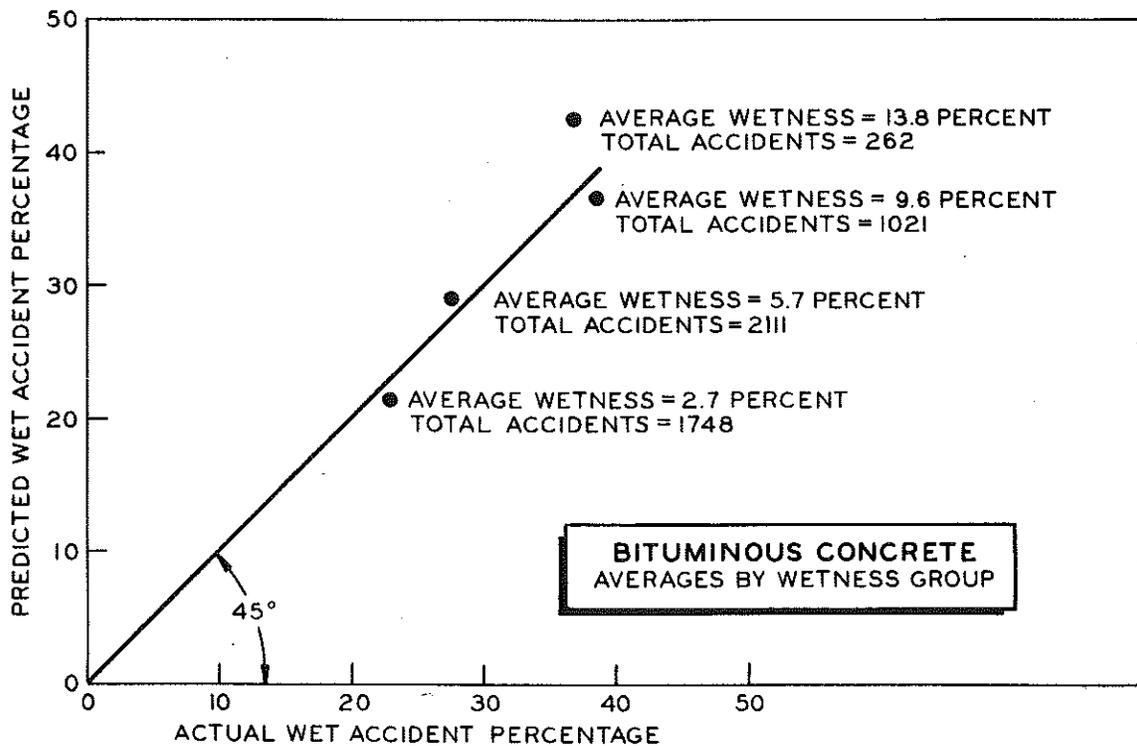


Figure 19. Relationship between actual and predicted wet accident percentages for each wetness group.

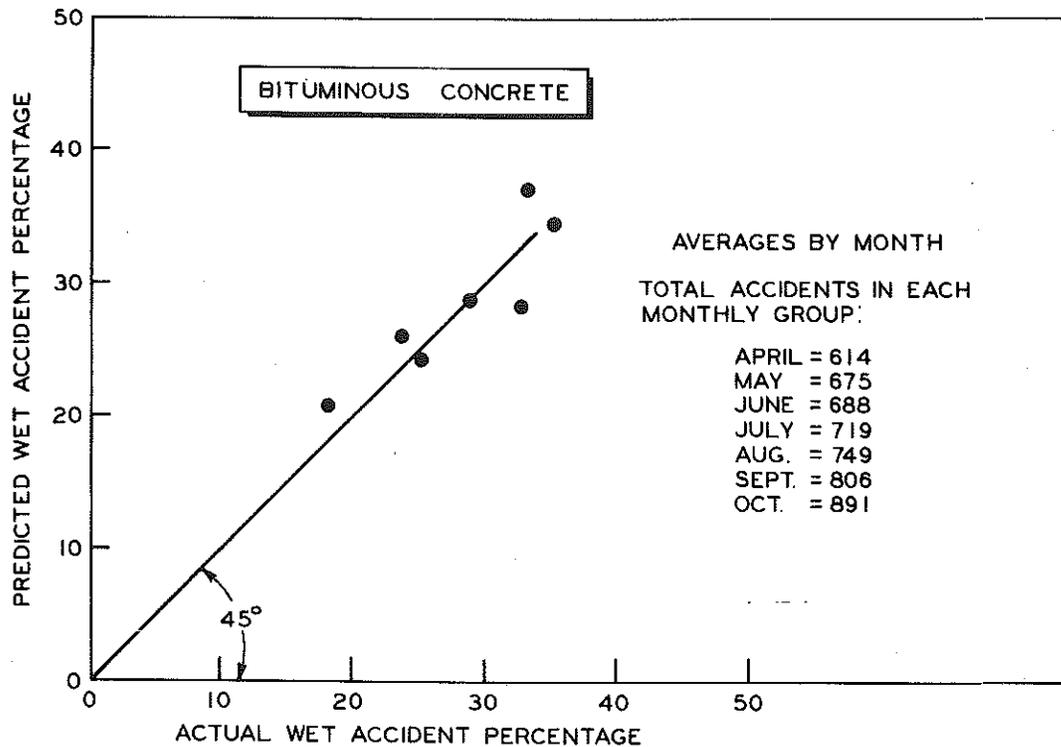


Figure 20. Relationship between actual and predicted wet accident percentages for each month.

as that for the other variables. This suggests that for practical purposes, seasonal and wet exposure considerations have considerable influence on skid number in predicting wet accident incidence for these surfaces taken separately.

Fitting the Model Using a Pooled Surface Data and Using Full Data Set (January - December)

When all accident locations for all surface types are pooled, the non-linear least squares procedure provides parameter values which bring the model into closer agreement with wet accident averages. Figures 21 through 26 illustrate the relationships between actual and predicted wet ac-

³ This point is not altogether clear since averages by month and wetness groups generally were formed from a large enough number of accidents to ensure reliability. The extreme skid number groups, however, often did not contain enough intersections to guarantee comparable reliability.

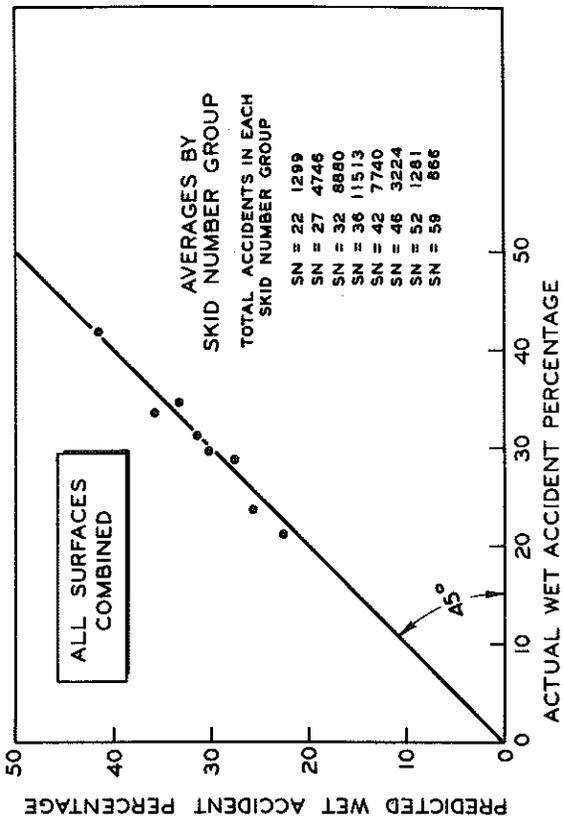


Figure 21. Relationship between actual and predicted wet accident percentages for each skid number group.

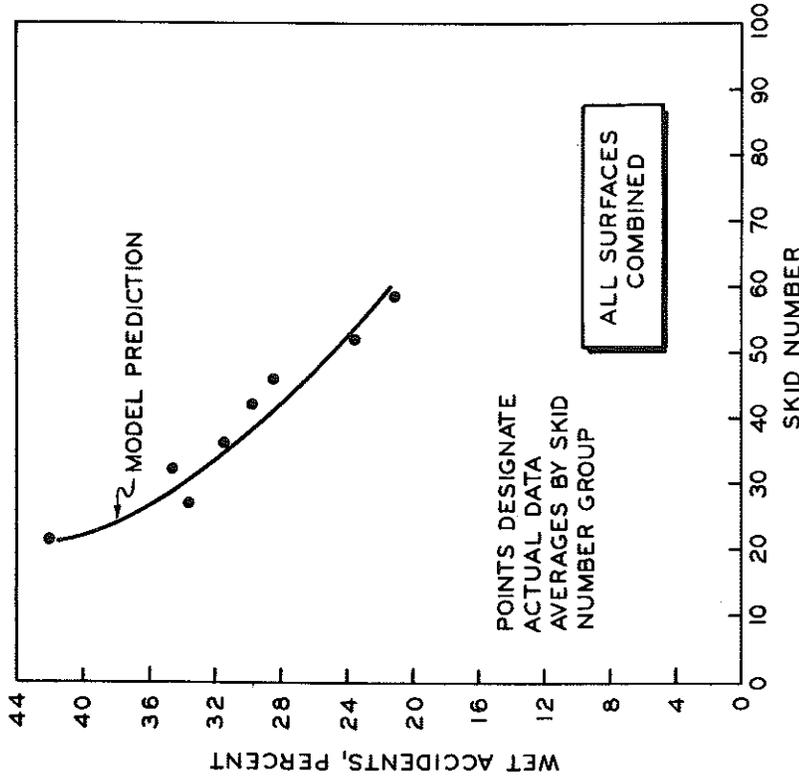


Figure 22. Overall relationship between skid number and wet accident percentage.

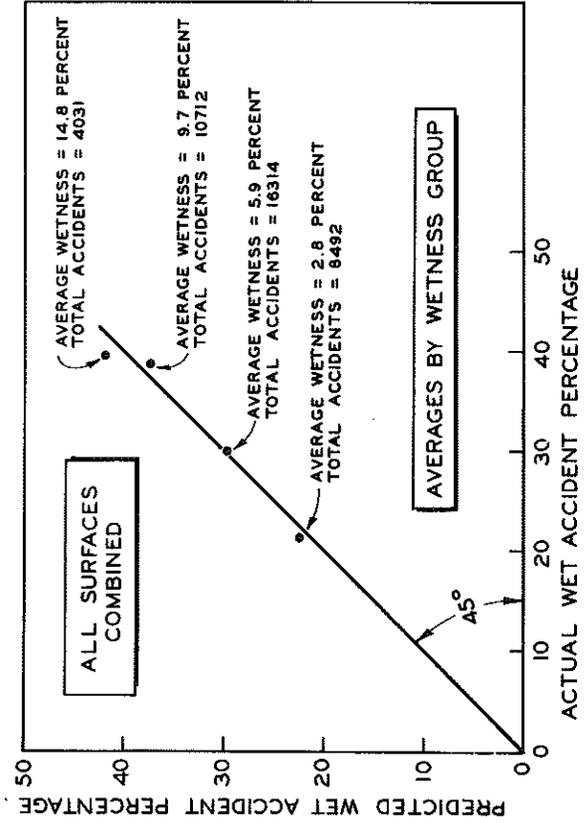


Figure 23. Relationship between actual and predicted wet accident percentages for each wetness group.

Figure 24. Relationship between wetness and wet accident percentage.

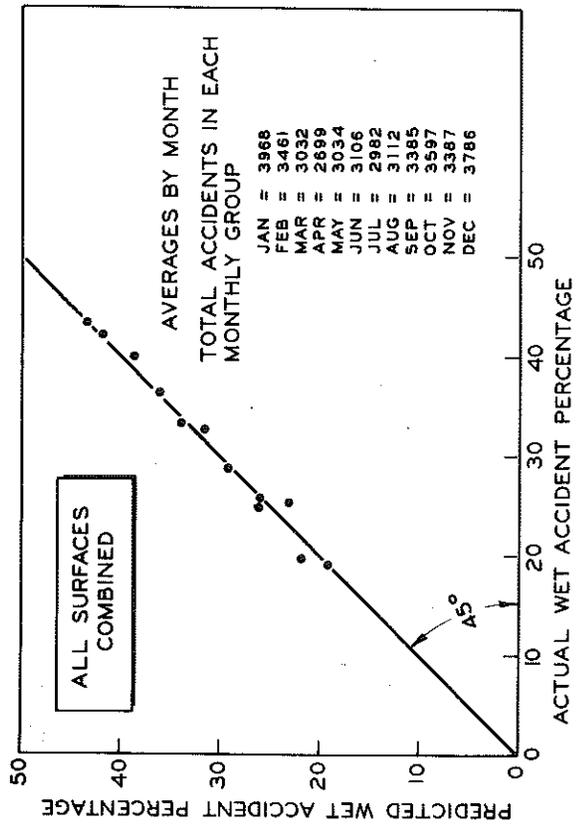
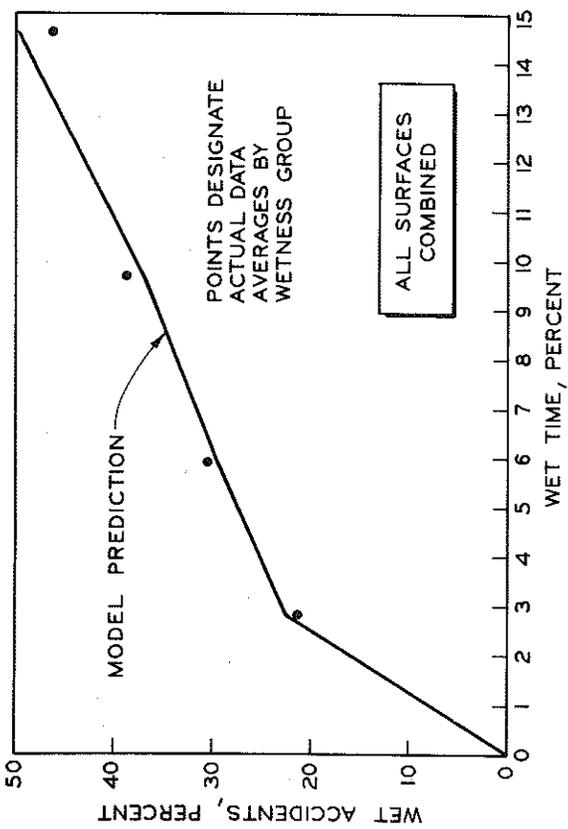


Figure 25. Relationship between actual and predicted wet accident percentages for each month.

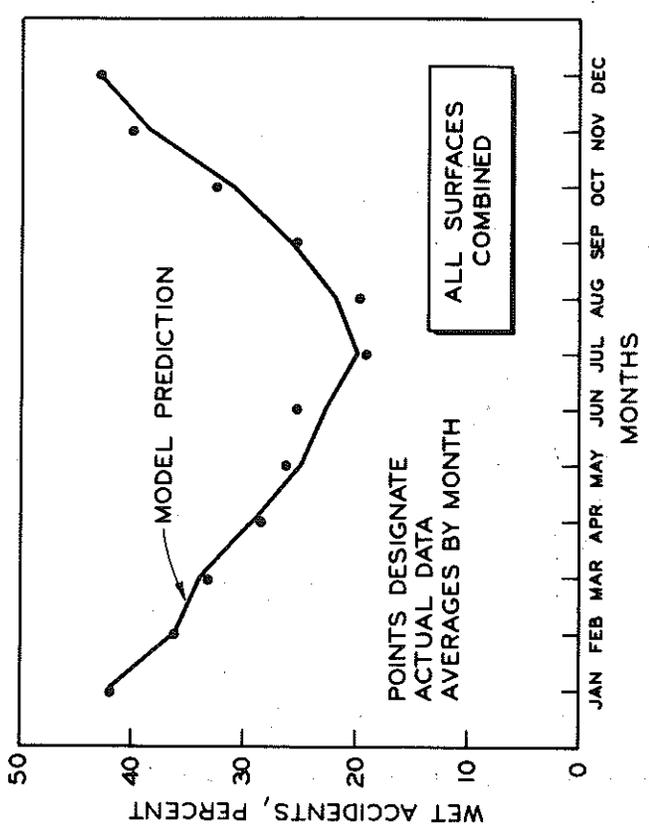


Figure 26. Relationship between wetness and wet accident percentage.

cident percentages for the group averages of the primary variables incorporated into the model. In general, when the group wet accident percentage is computed from a very large number of accidents (e.g., 2,000 or more) the difference between it and the model's prediction is only of the order of 1 or 2 percent. As would be expected from Table 1, group percentages computed from only several hundred or so accidents deviate from expectations somewhat more. This explains why the combined surface data set produces a better fit for the model even for skid number (Figs. 21 and 22). Wet time and month fit very well, but they generally benefit from several thousand accidents per data cell.

Figure 27 shows the skid number polynomial $g(SN)$ for all surfaces taken together. The important point here is that the polynomial is not 'flat,' that is, it changes rapidly over the skid number range of interest. This indicates that when the three basic surfaces are taken together, skid number is an important variable in the model and that the lower the skid number, the higher wet accident percentages will be.

How the Variables Behave

It is difficult in one graphical presentation to show the interrelationship of all variables in the model. Consequently, they are shown pairwise in Figures 28 through 33. The relationships between SN and wet accident percentage for selected wet times and the month of June are shown in Figure 28. It is obvious from these graphs that regardless of wetness exposure, wet accidents decline as skid resistance increases. There is no evidence of any critical skid number below which wet surfaces are hazardous, even though wet accident incidence increases in a non-linear fashion as skid number decreases. This point is of interest in view of the desire to establish safe skid number limits:

The Federal Highway Administration has been actively encouraging states to have programs to improve areas of low skid resistance. To this end many states have started accumulating statewide skid resistance inventories. In addition, some have called for the establishment of a minimum SN. Although this may be desirable from an engineering standpoint in terms of a guideline for scheduling remedial action, it would nevertheless have very serious legal implications as a possible legal standard of care. For example, if a minimum SN of 35 were adopted, and a given stretch of highway had a lower SN but a good accident history, the failure of the public entity to comply with the minimum standard could be used against it in court to prove that the highway is dangerous. This SN is for maintenance purposes only, not for

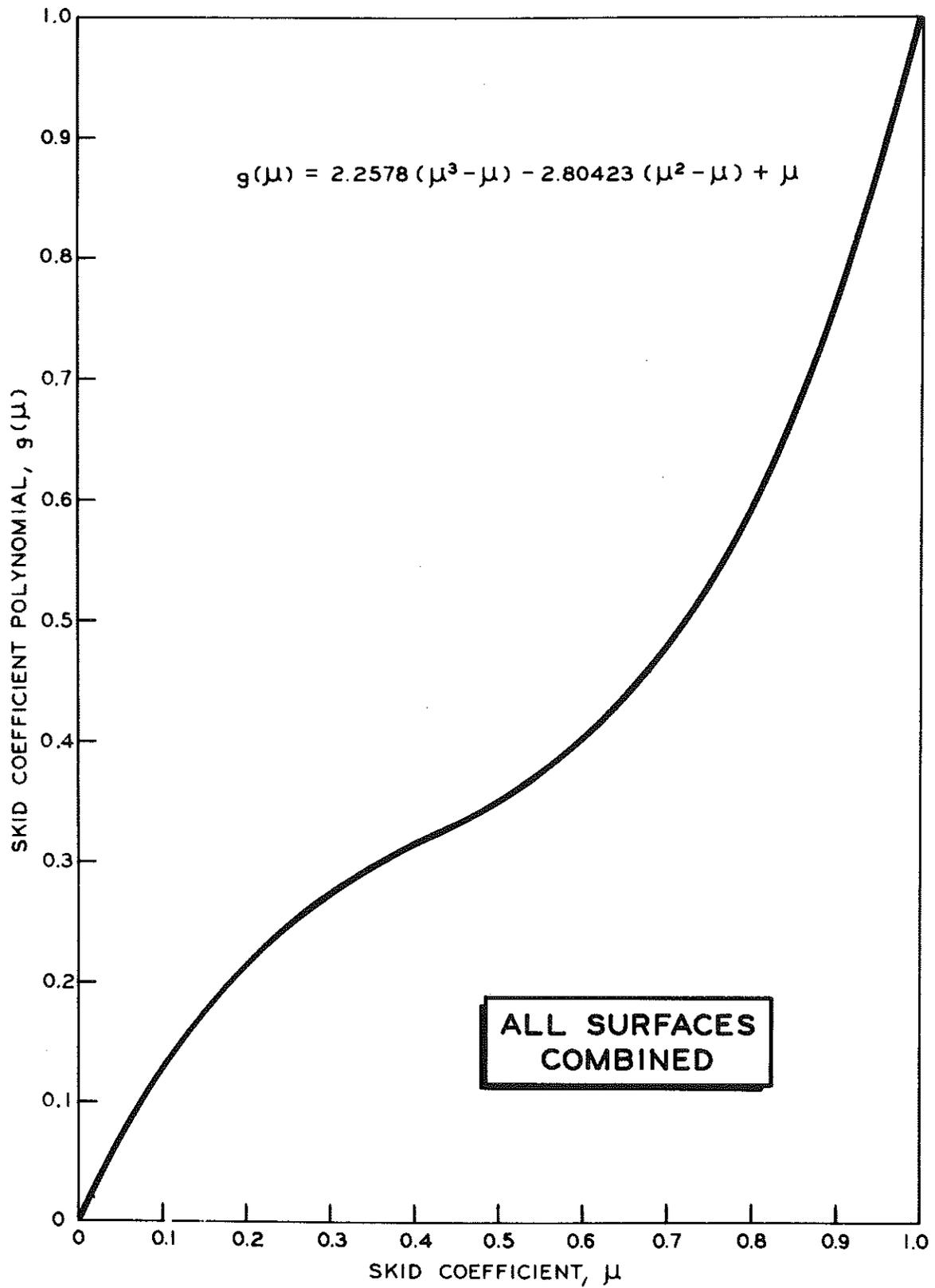


Figure 27. Skid coefficient polynomial.

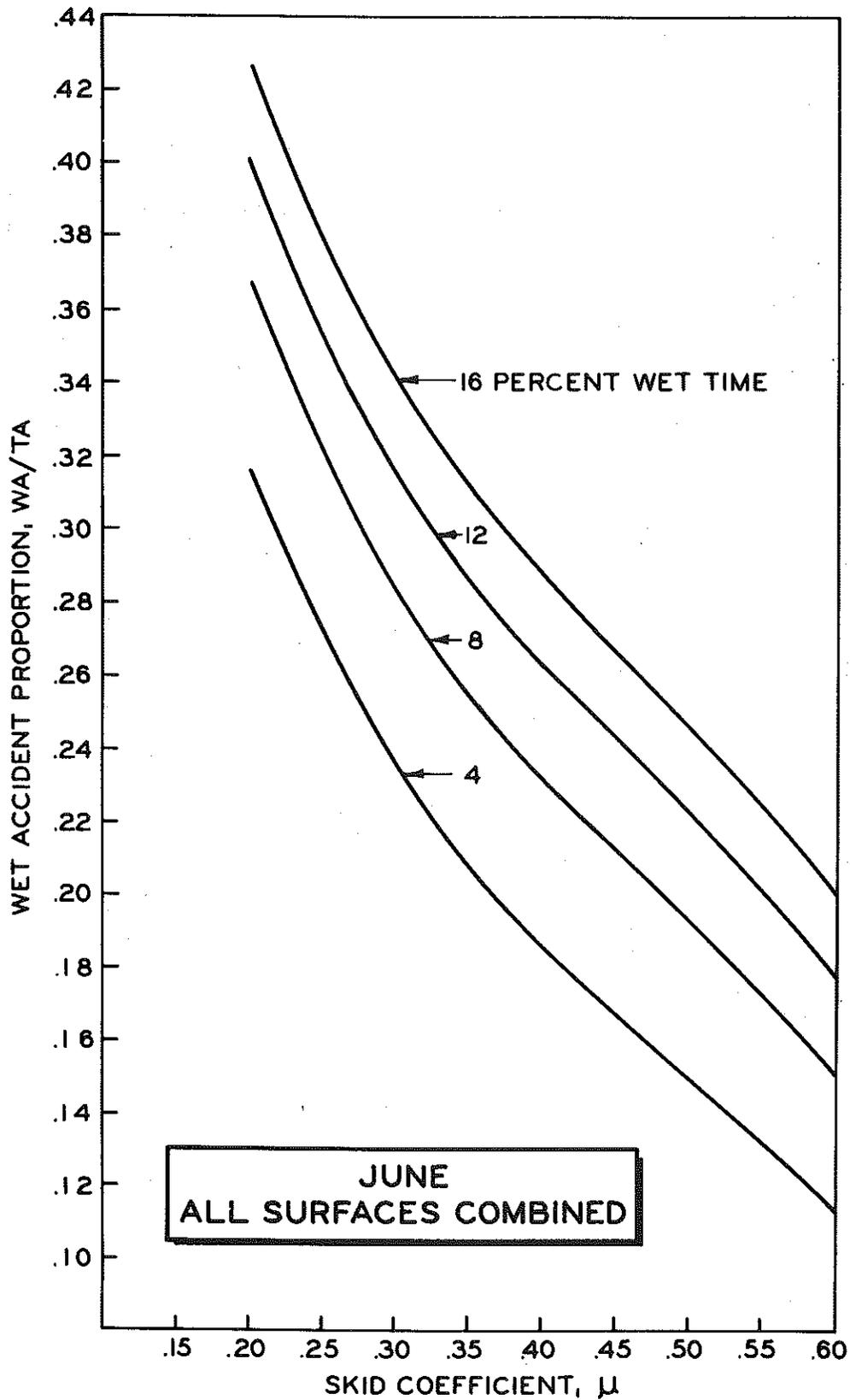


Figure 28. Relationship between skid coefficient and wet accidents for various wet times.

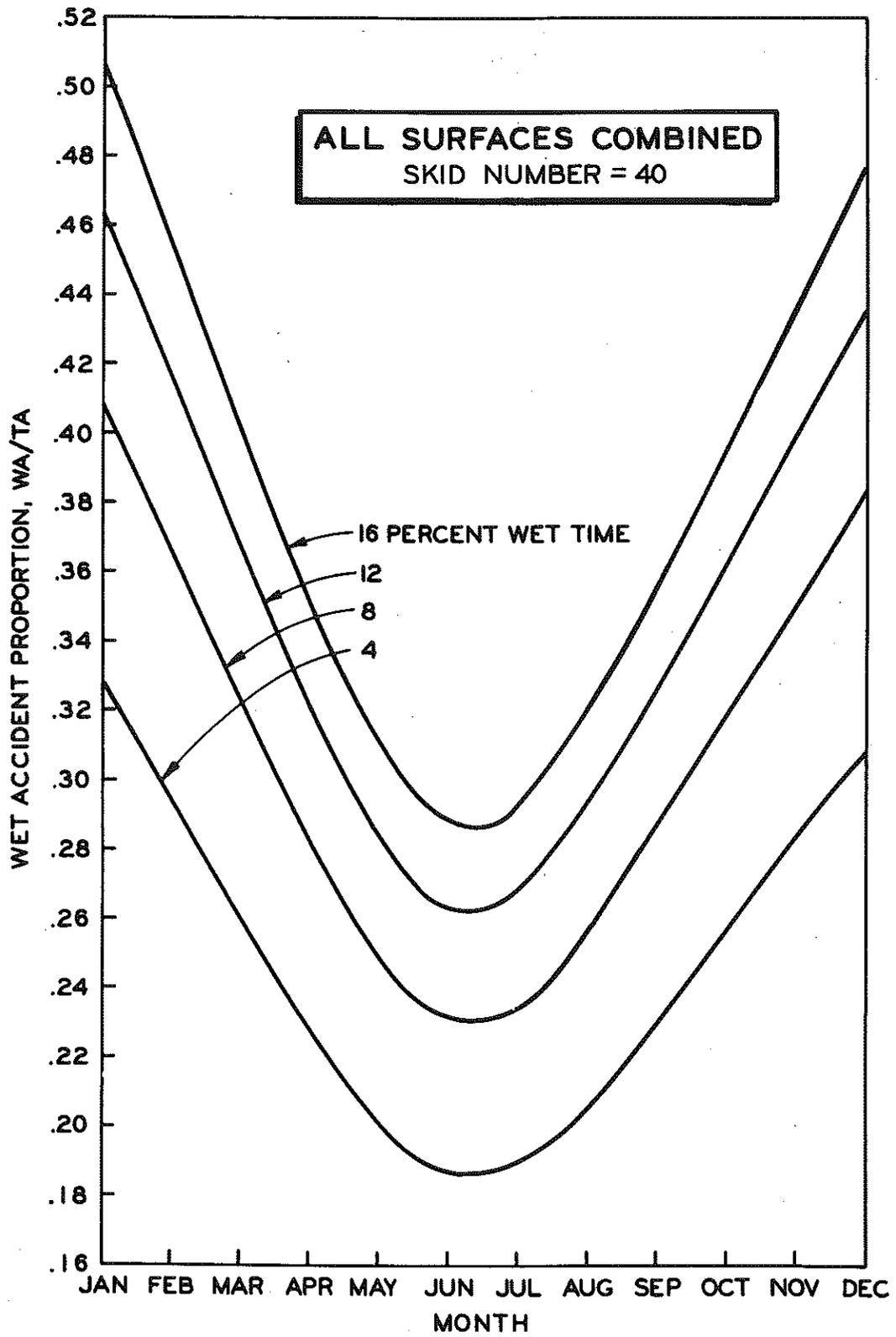


Figure 29. Monthly effect on wet accidents for various wet times.

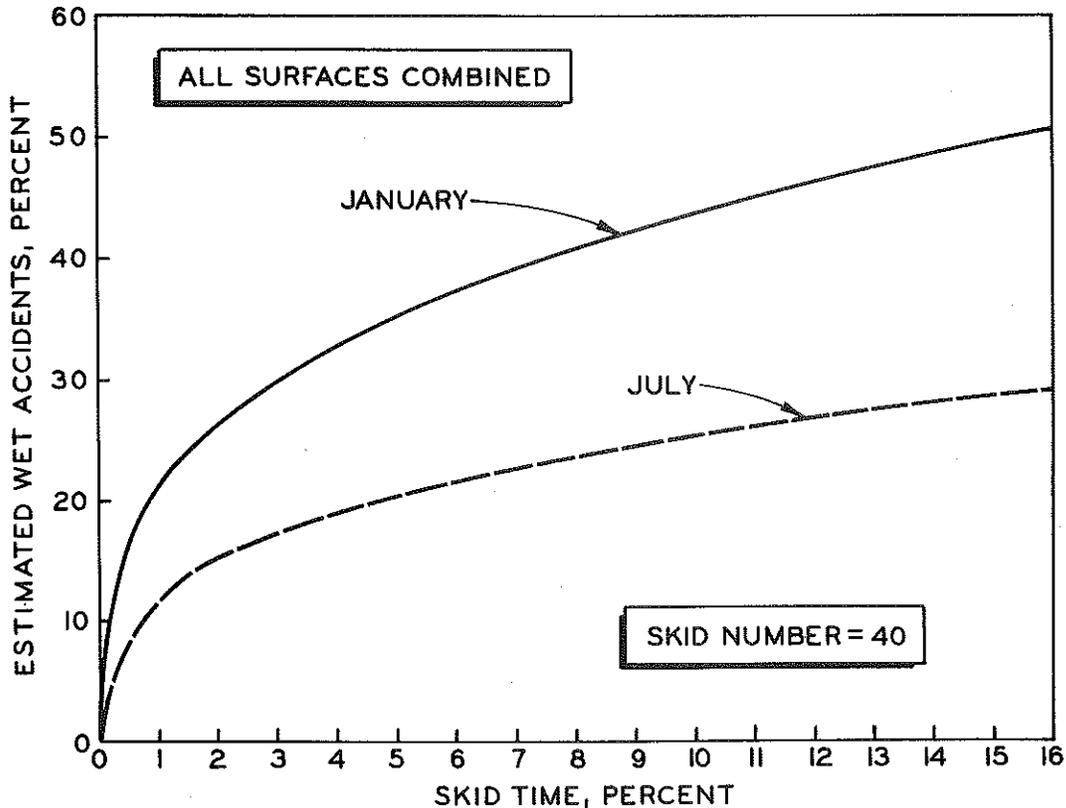


Figure 30. Effect of wet time on wet accidents for extreme months.

design. Many states already have minimum design SNs specified in their construction contracts. Typically the contract calls for spot testing of the highway to determine compliance with these contract provisions before the highway is ever opened to traffic. The SN itself, rather than the actual safety history of the highway, becomes the criterion.

It is conceded by even the most adamant supporters of the establishment of minimum SNs that many states do not have the funds or manpower, even with Federal aid, to bring all their highways up to par immediately. In the interim, these same states would face a further drain on their treasury in the form of judgements to plaintiffs who are able to convince juries that the minimum SN is a legal standard of care, and that noncompliance with it establishes a *prima facie* dangerous condition of the highway. Determining whether a highway is dangerous is not simple. It cannot be said arbitrarily that a location with a SN of 34 is dangerous and that one with a SN of 35 is not (29).

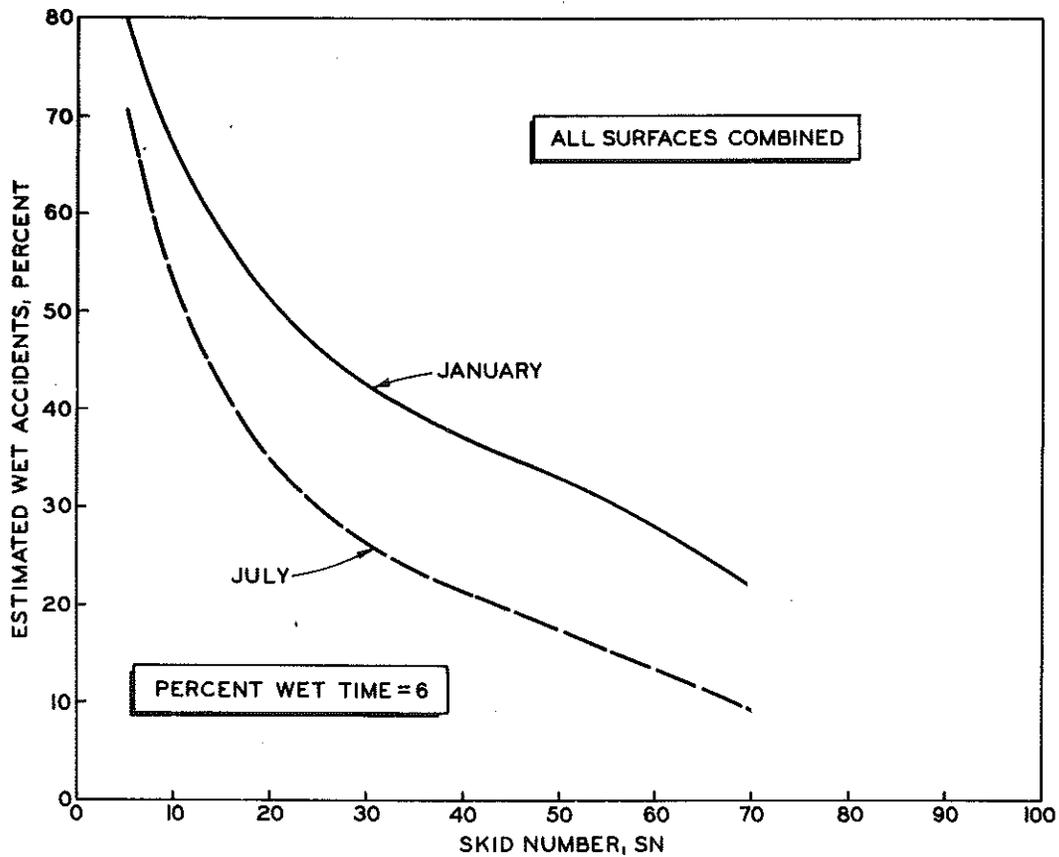


Figure 31. Effect of skid resistance on wet accidents for extreme months.

The monthly effect for fixed skid numbers and for fixed wet times is shown in Figure 29, which shows clearly that wet time as measured by the 0.01 in. per hour criterion requires seasonal modification of the sort provided by M(i). The extent of the modification is greater for increased wet time as measured by weather station hourly rainfall. In Figure 30, we see the effect of wet time on wet accidents for fixed skid number and the extreme months of July and January. Wet time has a profound affect on wet accident incidence, especially in the fall when weather conditions extend the wet surface time for a given quantity of rainfall. Figures 31 to 33 show the same relationship between these variables and other conditions.

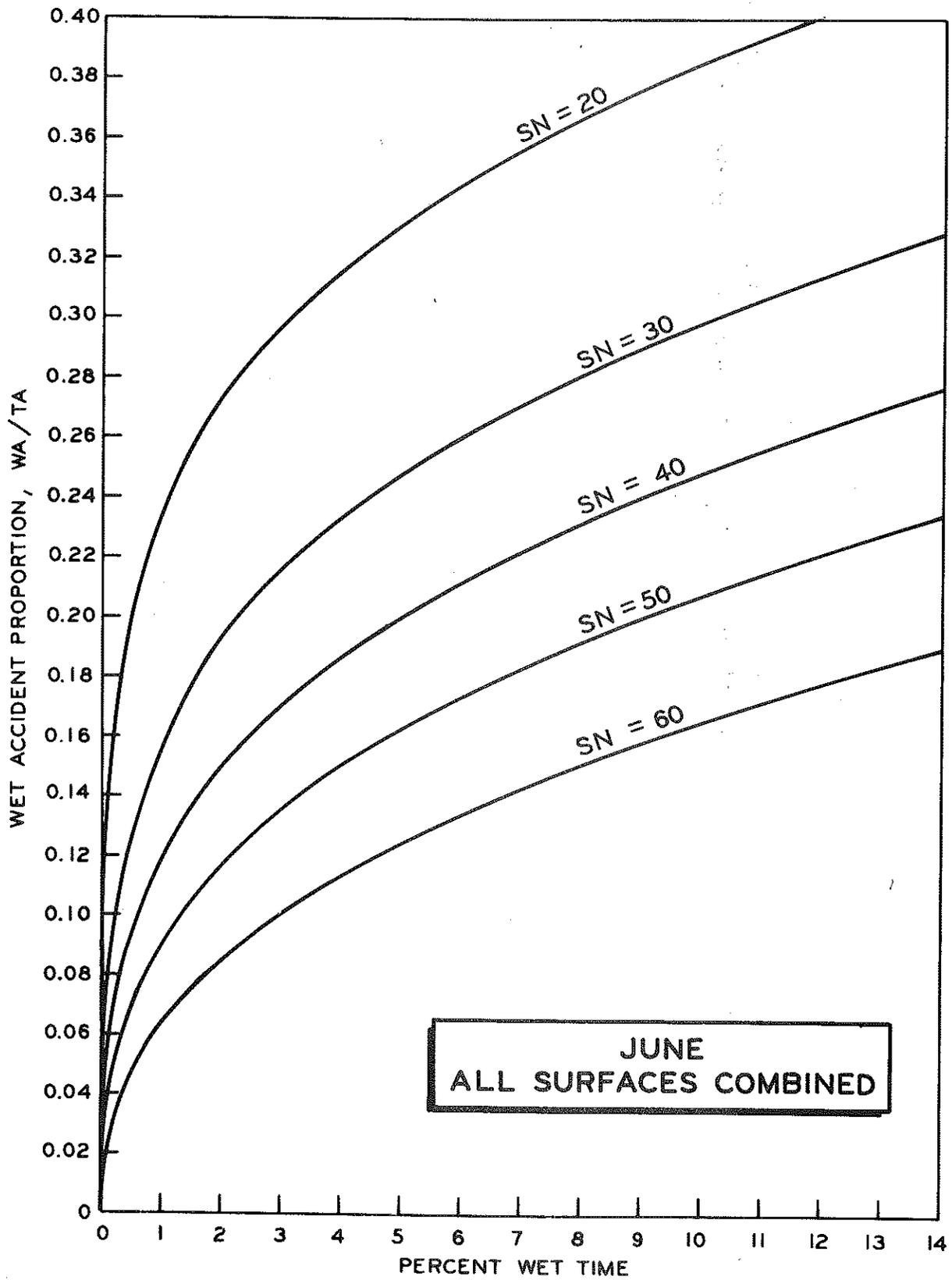


Figure 32. Effect of wet time on wet accident proportions for various skid coefficients.

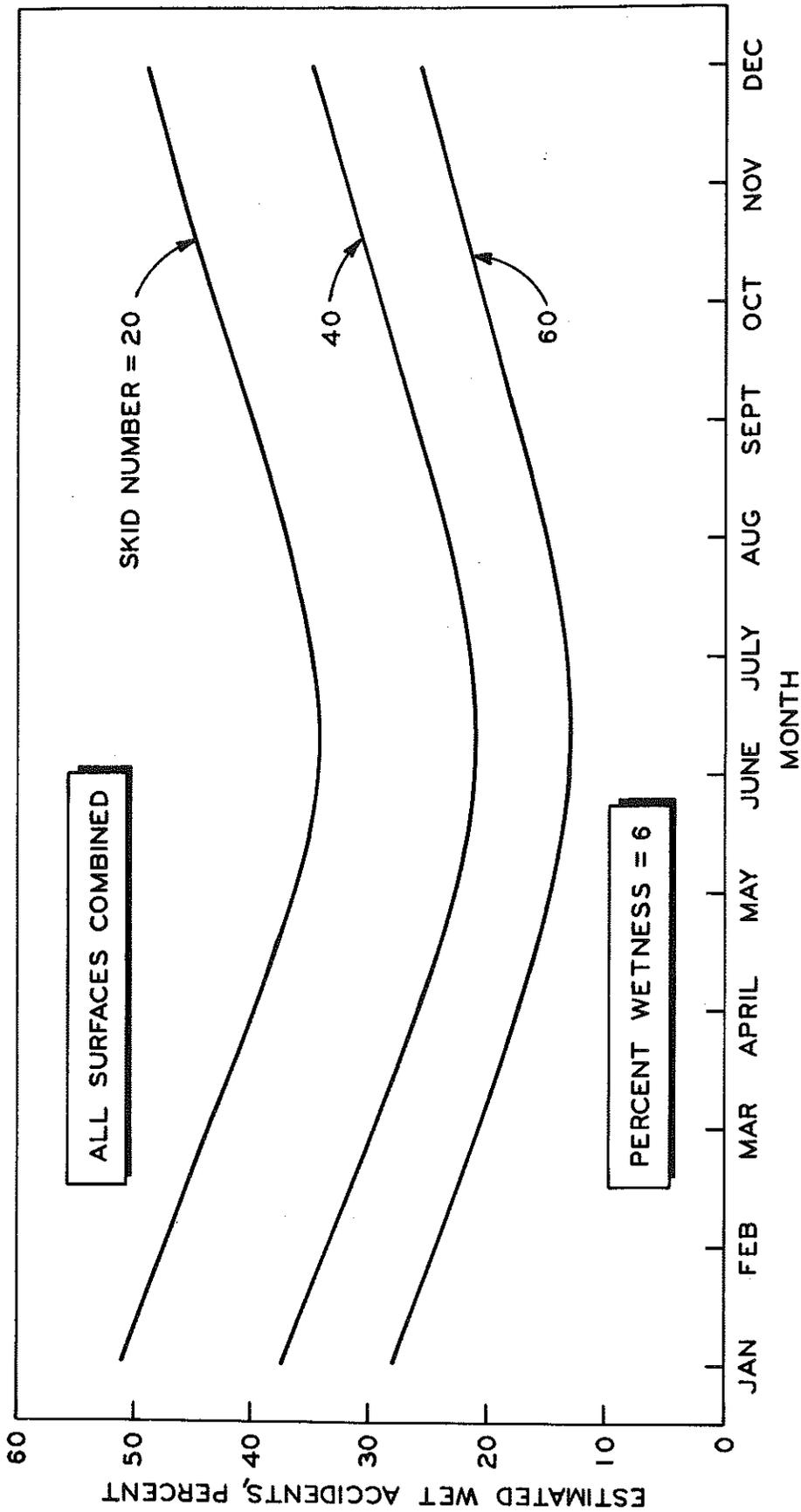


Figure 33. Effect of seasonal variations on wet accidents for selected skid numbers.

APPLICATIONS

Before and After Comparisons

When low skid resistance pavements are resurfaced it is assumed that a resulting benefit will be lowered wet accident incidence. The question is how much benefit can be expected from resurfacing a given location. Using regional or nearby weather station wet time percentages, together with a minimum permissible or sample location skid number, an estimate can be made of yearly wet accident percentages. This estimate can be compared with actual wet accident percentages in order to determine whether or not current accident experience is realistic, or merely the result of random fluctuation commonly found with small samples. This would provide the basis for development of a quality control procedure of the type used in the detection of defective items and recommended in accident analysis investigations (30, 31, 32, 33, 35).

Beyond high accident location detection, the model also has applications in resurfacing policy evaluation. At the time locations are considered for resurfacing, it should be possible to employ the model to predict expected accident reduction for each location, thereby facilitating a resurfacing priority list based on maximum accident prevention. As an example, in Figure 34, the model was used to predict accident prevention for various variable settings and a resurfacing skid number of 60. Charts such as this can be made up for any other set of weather or resurfacing friction assumptions. More than likely, general weather patterns, as provided by regional histories, would be used together with more exact knowledge of resurfacing skid number values.

As an example of resurfacing policy evaluation, the model was used to estimate 'before' and 'after' wet accident percentage differences for 30 resurfaced intersections. The data were 'fresh' since they had not been part of the set used to develop the model.⁴

For each resurfaced location, accident statistics were compiled for the 24 month period preceding, and the 24 month period following resurfacing,

⁴ This had to be the case anyway since 'before' and 'after' studies should not include accident statistics for the period originally used in the location selection. Failure to discard this period will always bias the preceding year's accident percentage upward, thereby overestimating the improvement attributed to resurfacing. This point has been made in the literature (34) but it is not clear that all studies of this type acknowledge it.

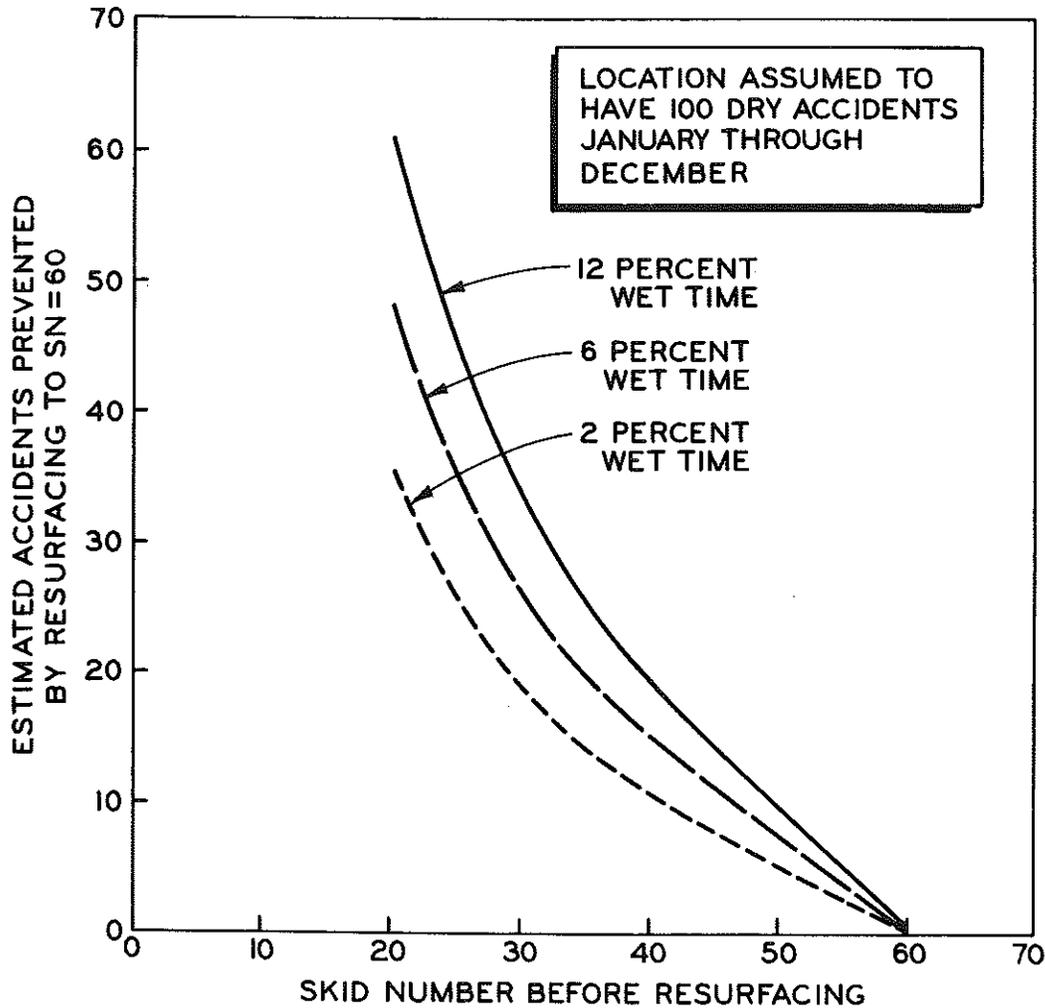


Figure 34. Expected first year accident reduction due to resurfacing.

except for those months which were used in the location selection procedure. Before and after wet accident estimates were then calculated. The resulting values are shown as points in Table 3.⁵ The repeatability of this phenomenon is not known. However, the model, using known monthly wet time figures and a two year resurfacing skid number of 45 gave wet acci-

⁵ The data presented probably underestimate total accident reduction due to the possible reduction in dry accidents following the resurfacing of particularly slippery intersections. Some investigators have reported this effect (35) and it should be assumed that any reduction in dry accidents will result in an underestimation of percent net accident improvement. Therefore, our presentation is considered conservative.

dent percentage reductions consistent with those estimated from police records. ⁶

TABLE 3
WET SURFACE ACCIDENT PREVENTION BENEFITS
WITH INTERSECTION RESURFACING

Basis of Computations	Number of Wet Accidents		Location-Months		Wet Accidents Per Location Per Month		Wet Accident Rate Decline, percent	Estimated Number of Wet Accidents Prevented During the First Year After Resurfacing
	"Before" Period	"After" Period	"Before" Period	"After" Period	"Before" Period	"After" Period		
Police Files	556	590	384	526	1.45	1.12	23	120
Model Prediction	618	635	384	526	1.61	1.21	25	144

Plans for Resurfacing on a Project Priority Basis

The plans herein investigated all depend upon, first the assembly of a skid testing list which dictates the priority in which intersections are to be skid tested. This is in contrast to the 'spot map' approach in which colored pins are placed at map locations. A large cluster of pins would indicate the need for skid testing or resurfacing (36, 37). A spot map used for skid testing purposes does not, in itself, take into account wet accident percentages nor their relative rank. If used for resurfacing, the spot map does not take account of skid number and is therefore subject to such problems as regression toward the mean (34). Second, once skid numbers are available, the plan provides a resurfacing priority list which dictates the order in which intersections are to be resurfaced or otherwise upgraded. It is precisely the order in which selected intersections are resurfaced that requires our attention. The set of intersections selected and the order in which they are upgraded are vital factors in determining the number of accidents prevented through maintenance programs.

Plan I seeks to first identify, and second to upgrade, low skid number intersections. The philosophy governing this plan is that low skid resistance areas, per se, must be found and repaired. No attention is given to traffic volume or any other variable. An administration following this plan might be concerned with complaints of very slippery intersections or it might feel its duty was to maintain a minimum standard for all intersections. The testing priority for Plan I is based upon a rank order of per-

⁶A few surfaces had been skid tested after resurfacing and they suggested an initial mean resurfacing skid number of about 50.

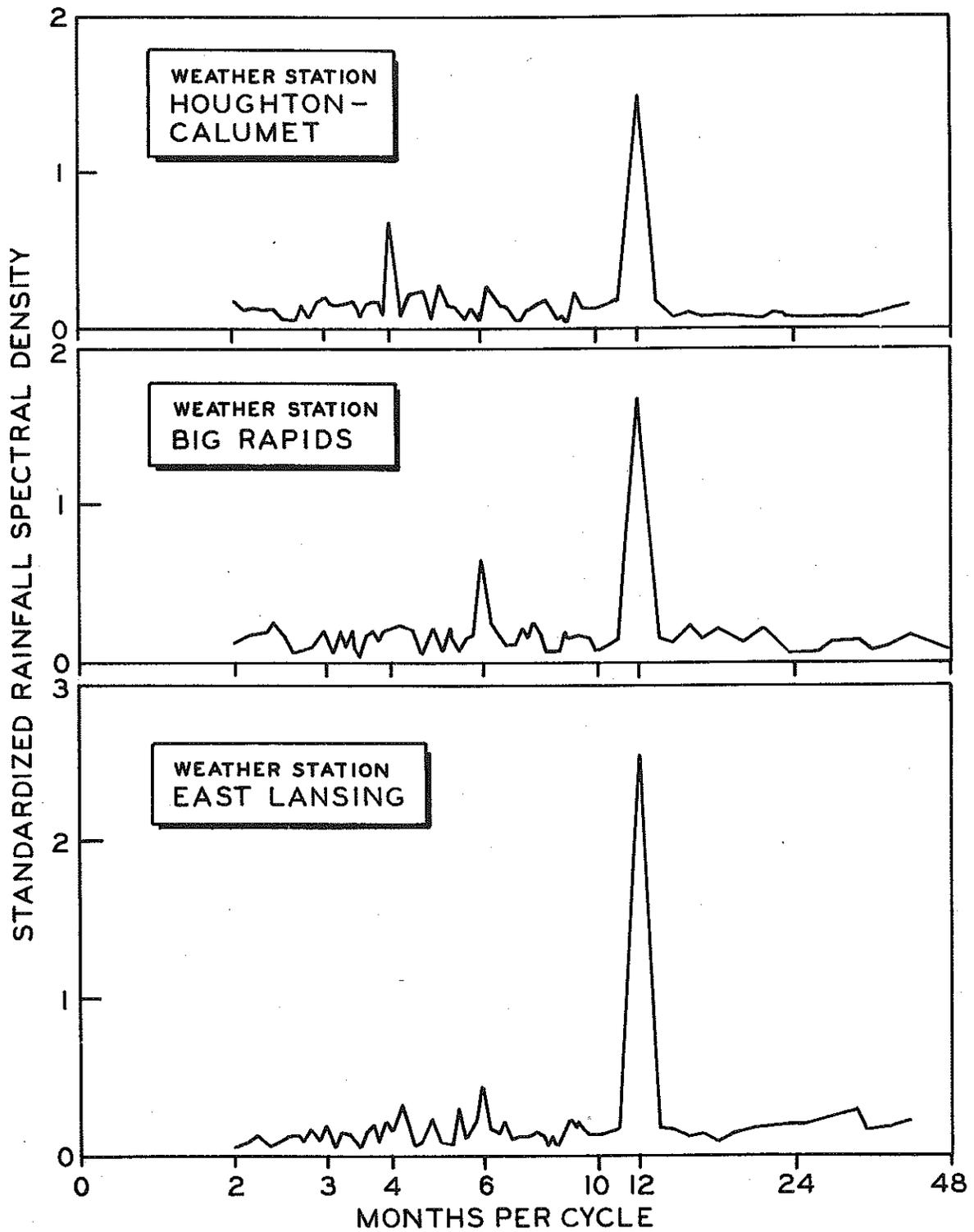


Figure 35. Precipitation power spectra for three weather stations.

centage wet accidents from state trunkline accident records. It is presumed in this plan that the wet accident percentage rank order should correlate with skid number rank order, thereby enabling the testing program to proceed on a rational basis. After the testing program has produced as many skid numbers as is feasible (considering manpower, equipment, time, etc.), the resurfacing priority list is assembled from a rank order of skid numbers. At this point, resurfacing is based upon the priorities dictated by this list and proceeds until allocated funds are exhausted.

Plan II differs from Plan I in that expected accident prevention benefits are used to form both the testing and resurfacing priority lists. For the testing priority list, wet accidents, dry accidents, and a presumed skid number of 40 are used in the wet accident model to estimate the accident reduction expected if the given intersection were to be resurfaced to a skid number of 60. In order to incorporate the deterioration of surfaces with time, the resurfacing skid number is assumed to decline linearly with time t , from 60 to 40 in five years. Thus, we have:

$$E \Delta (WA) = 5E(WA)_{SN = 40} - \sum_{t = 0.5}^{t = 4.5} E(WA)_{SN(t)} \quad (2)$$

where, $SN(t) = 0.60 + \left(\frac{\frac{SN}{100} - 0.60}{5} \right) t$
 $t = 0.5, 1.5, \dots, 4.5$ years

and $E(WA)$ is recovered from Eq. (1) for the case of $SN = 40$ and for appropriate regional and monthly $\frac{WH}{TH}$ estimates. After analysis of three weather station precipitation histories, it was concluded that the best predictor of monthly precipitation is the average of that month's precipitation recorded for all preceding years. No other than yearly precipitation cycles were discovered when power spectra for three stations, each with over 100 year weather histories, were examined (Fig. 35).

The philosophy governing Plan II is that whatever the skid number, it is accident reduction which is most important. Even though skid number might be low, regional rainfall and traffic volumes might be such that an intersection ranks low in resurfacing priority. Administrators adopting Plan II would be more concerned with wet accident prevention and less concerned with upgrading an intersection just because it has a low skid number.

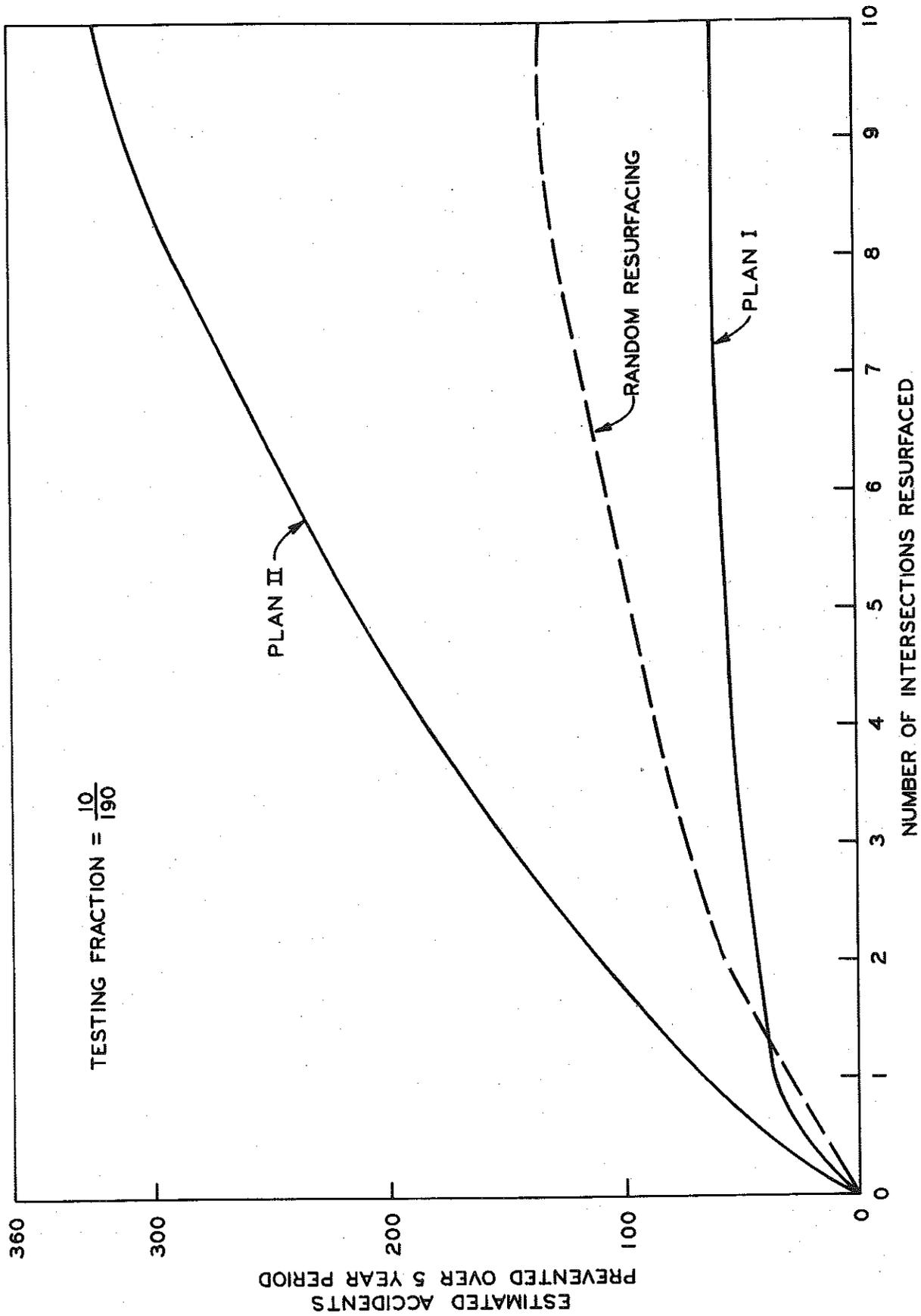


Figure 36. Accumulated intersection accident prevention benefits for three resurfacing priority plans.

A comparison of the plans is given in the table below:

Plan	Skid Testing Priority List	Resurfacing Priority List	Goal
I	Rank order of $\frac{DA}{WA + DA}$	Rank order of SN	Repair of low SN intersections
II	Rank order of estimated wet accidents prevented by knowing WA, DA, $\frac{WH}{TH}$, WA	Rank order of estimated wet accidents prevented by knowing DA, SN, $\frac{WH}{TH}$	Minimization of wet accidents at intersections

Each of the above plans is designed for a specific goal and should function best relative to that goal as a criterion. Any comparison of these plans must assume a common criterion which will necessarily favor one plan over the others. For comparison purposes, we have chosen wet accident prevention as the criterion since we assume that most administrators would give this as their resurfacing program goal. The data used for plan comparison were the 1973 Michigan high accident intersection list, together with the corresponding skid numbers and nearby weather station monthly wetness estimates. Each skid testing plan was based upon a testing fraction composed of the top 10, 25, 50, and 100 of the 190 intersections rank ordered as specified by the skid testing plan. Expected wet accident reduction benefits were then accumulated as though 1 or 2 or 3 or . . . up to T. F. intersections had been resurfaced according to the resurfacing priority list provided by each plan. Figures 36 through 39 show the expected accidents prevented for each plan using testing fractions of 10, 25, 50, and 100, respectively. Also shown in each figure is the expected wet accident reduction benefit obtainable with a policy of random resurfacing. In this case, resurfacing priority lists are based on random selection of intersections from the 190 used for plan comparison. If a plan does not produce more accident reduction than that obtainable with random selection, it has little to recommend it.

Inspection of Figures 36 through 39 shows that, of the two plans, Plan II succeeds in producing the greatest expected wet accident reduction for skid testing fractions of 10, 25, 50, and 100 and for any number of intersections resurfaced up to the number tested in each case. Plan I always falls short of the other plans in expected wet accident reduction, and in some cases does not do as well as random resurfacing (Fig. 37). This is probably because Plan I specifies resurfacing on the basis of skid number alone and does not take into account regional wetness or dry accident incidence. Dry accident incidence is an important variable since it is a reflection of traffic volume and location hazard.

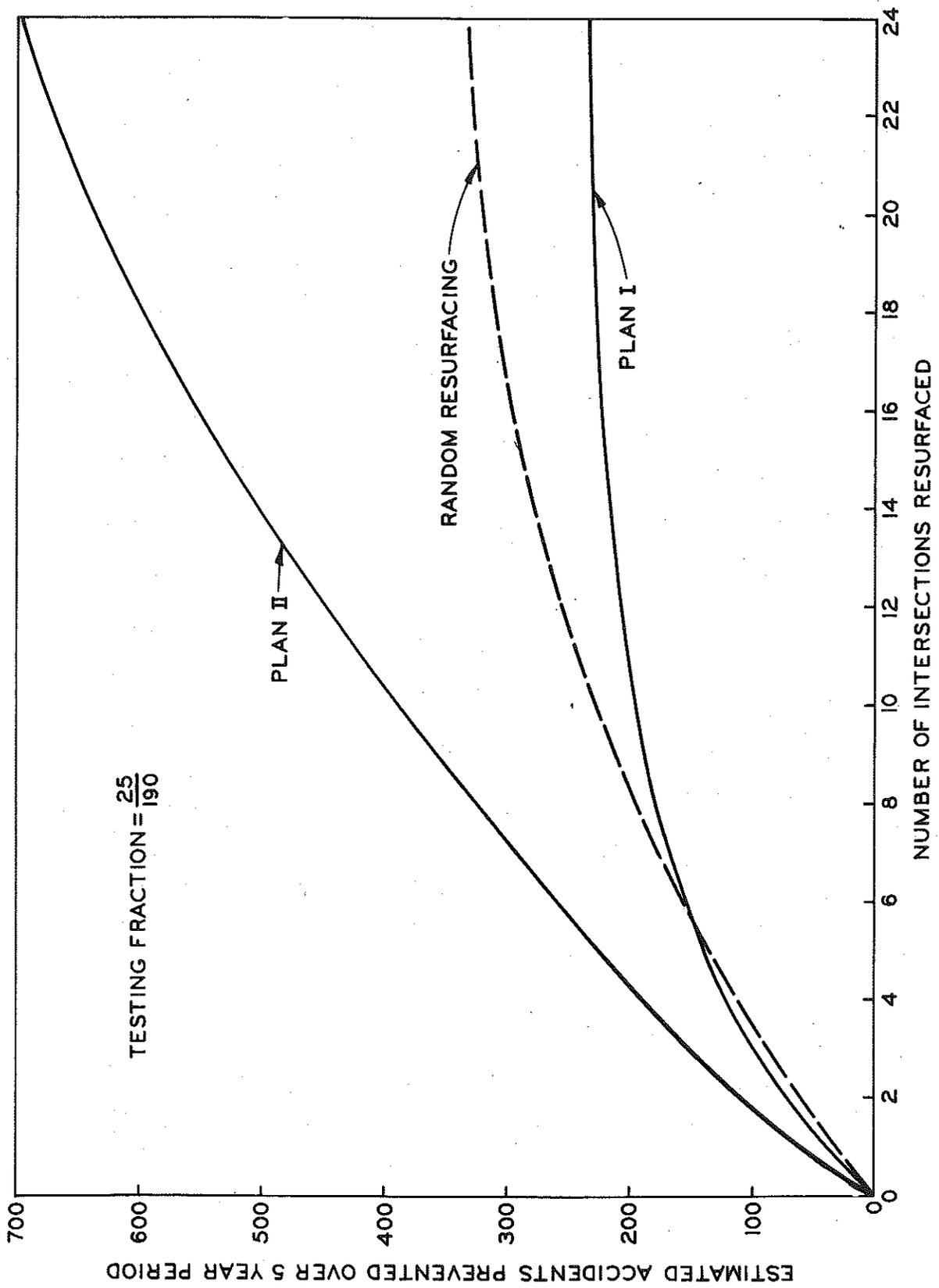


Figure 37. Accumulated intersection accident prevention benefits for three resurfacing priority plans.

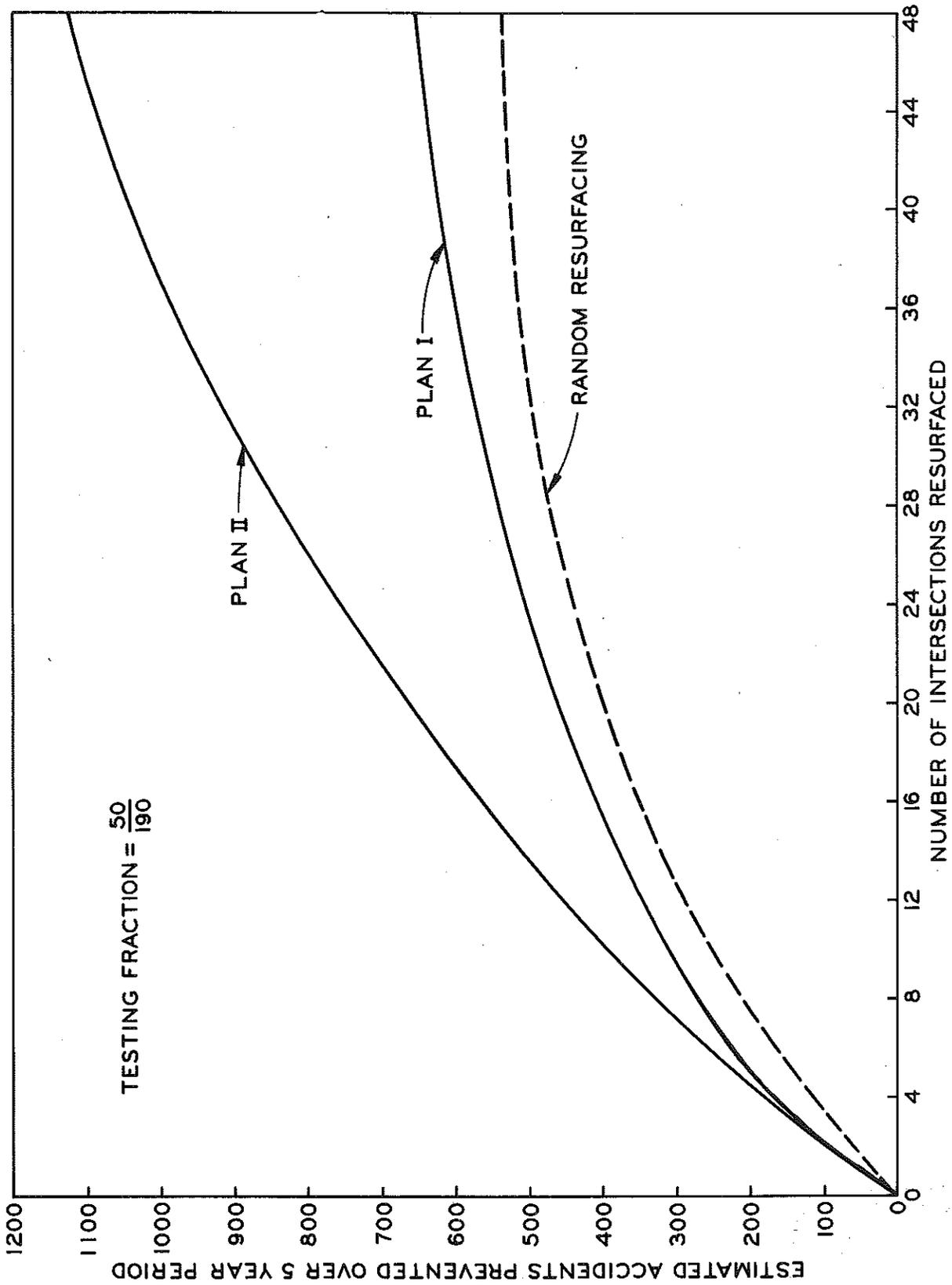


Figure 38. Accumulated intersection accident prevention benefits for three resurfacing priority plans.

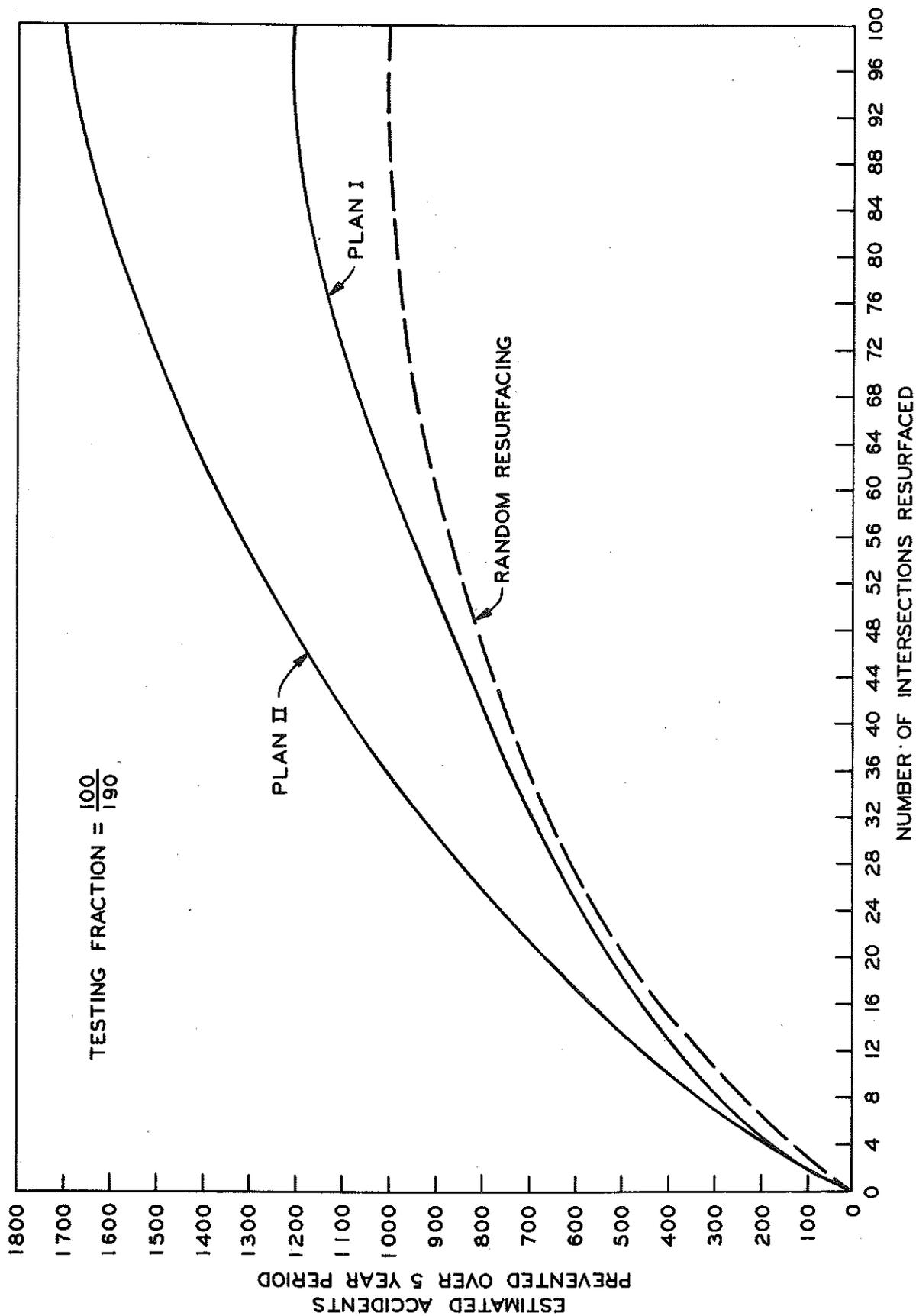


Figure 39. Accumulated intersection accident prevention benefits for three resurfacing priority plans.

In the light of Figures 36 through 39, it would seem that resurfacing plans based exclusively on skid numbers are very poor in achieving wet accident reduction; by giving too much weight to skid number at the expense of other important variables, they may even be inferior to resurfacing on a random basis.

CONCLUSIONS

By using some 40,000 accidents recorded at 2,000 intersections, a wet surface accident model was developed which incorporates skid number, wet time, and season. In order to estimate wet time, considerable effort must be expended in developing a method which will reflect seasonal as well as geographic considerations. This can be accomplished through suitable transformation of precipitation data.

Because wet accident percentages tend to be unreliable for small samples, accident locations must be grouped into cells. The model's fit to these pooled data is generally within reasonable tolerances for proportions of corresponding sample size.

Both estimated surface wet time and skid number are important factors in wet accident involvements as expected; however, no critical skid number emerged as a point above which wet accident hazard disappeared. Rather, wet accidents appear to be a continuously decreasing function of surface friction. Below a skid number of approximately 30, wet accident incidence increases at an increasing rate with declining surface friction. This is true for all months and wetness categories.

The effect of monthly wet time on wet accident incidence is considerable. It was the most important variable discovered in this study. Its effect on wet accident percentages is approximately logarithmic for all months and surface friction conditions. Naturally, this variable cannot be controlled. However, the present study makes it clear that variations in monthly wet time occur in Michigan on a predictably yearly basis. To the extent that traffic volumes also have seasonal variation, monthly wet time should be included in resurfacing decisions. For example, if traffic volume peaks at a location in the fall months, particularly October, resurfacing of this intersection would be of higher priority than if it peaked in July. While there are considerable variations from year to year and region to region, a resurfacing policy which takes account of regional and monthly wetness patterns would be rational. The increase in wet accident percentages due to a drop in skid number of 10 units (40 to 30) would be of the order of 4 percent. On the other hand, a rainfall increase of 4 percent from July to October would produce a 15 percent increase in wet accidents. Thus, a

seasonal change of only 4 percent in wet time can have four times the impact on wet accident incidence as a 10 unit decline in skid number. For this reason, we conclude that for a state such as Michigan, where seasonal and regional wetness patterns exist, consideration of surface friction improvements should include expected locational wet time as well as skid number. As experimental skid testing and resurfacing plans have shown, consideration of skid number alone will not result in the minimization of wet accidents.

Models, such as the one developed in this study can be used to evaluate alternative skid testing and resurfacing plans which seek to identify and select on a priority basis those intersections which require prompt attention. Once a plan is developed, regional and seasonal wetness patterns must be estimated, and previous wet accident experience must be retrievable if beneficial skid testing plans are to be implemented. Once locations are skid tested as dictated by the testing plan, resurfacing can proceed for those locations selected on a priority basis as determined by the resurfacing plan.

The selection of a testing-resurfacing plan system is critical since plans vary considerably in their ability to minimize wet accidents for fixed fund allocations. Based on a limited computer experiment with one year's field data we suggest that mathematical models can profitably be used in constructing a fixed cost, wet intersection accident minimization program. Since the model should take full account of precipitation and seasonal wetness factors, it can be used to develop plans which are more cost effective than those based only on skid number and/or previous accident experience alone.

We have attempted to show that wet accident prevention is highly dependent upon the type of plan used for intersection skid testing and resurfacing. Further, plan design should proceed from a clear delineation of program goals since goals may be inconsistent in the results they produce. The accident prevention plans presented by this study are highly tentative and weakly generalizable since they are based on a limited analysis incorporating assumptions in keeping with the particular aforementioned goals. Plans serving other goals and embodying different assumptions would, of course, give somewhat different results.

REFERENCES

1. Giles, C. G., Sabey, B. E., and Cardew, K. H. F., "Development and Performance of the Portable Skid Resistance Tester," ASTM Special Technical Publication No. 326, pp 50-74, 1962.
2. Kummer, H. W., Meyer, W. E., "Tentative Skid-Resistance Requirements for Main Rural Highways," NCHRP Report No. 37, 1967.
3. Sabey, B. E., Storie, V. J., "Skidding in Personal - Injury Accidents in Great Britain in 1965 and 1966," Road Research Laboratory Report No. LR 173, p 19, 1968.
4. Mahone, D. C., Ramkle, S. N., "Pavement Friction Needs," HRB Record No. 396, pp 1-11, 1972.
5. Campbell, E. M., "The Wet-Pavement Accident Problem: Breaking Through," Traffic Quarterly, Vol. 25, No. 2, pp 209-214, April 1971.
6. Johnson, E. M., "An Experimental Study of Accidents," Traffic Digest and Review (2 parts), Vol. 9, No. 8, pp 12-18, August 1961.
7. Mills, J. P., Jr., and Shelton, W. B., "Virginia Accident Information Relating to Skidding," Proc. First International Skid Prevention Conference, Part 1, pp 9-20, 1959.
8. Mahone, D. C., Runkle, S. N., "Pavement Friction Needs," HRB Record No. 396, p 3, 1972.
9. Strommen, N. D., "Climate of Michigan," U. S. Government Printing Office, 1967.
10. Karr, J. I., Guillory, M., "A Method to Determine the Exposure of Vehicles to Wet Pavements," State of California, Division of Highways, January 1972.
11. Day, J. A., and Sterns, G. L., "Climate and Weather," Addison and Wesley, p 232, 1970.
12. Barry, R. G., Perry, A. H., "Synoptic Climatology," Methuen and Co., 1973.
13. Petterssen, S., "Introduction to Meteorology," McGraw-Hill, 1969.

14. Blair, T. A., Fite, R. C., "Weather Elements," Prentice Hall, Chapter 8, 1965.
15. Steiner, D., "A Multivariate Statistical Approach to Climatic Regionalization and Classification," Tijds. Kon. Ned. Aardrijksk., Genoot. 82, pp 329-347, 1965.
16. Riehl, H., "Introduction to the Atmosphere," McGraw-Hill, p 259, 1965.
17. Kihlberg, J. K., and Tharp, K. J., "Accident Rates as Related to Design Elements of Rural Highways," NCHRP Report No. 47, p 13, 1968.
18. Billingsley, C. M., Jorgenson, D. P., "Analysis of Direct Costs and Frequencies of Illinois Motor Vehicle Accidents, 1958," Public Roads, Vol. 32, No. 9, pp 201-213, 1963.
19. Finney, E. A., and Brown, M. G., "Relative Skid Resistance of Pavement Surfaces Based on Michigan's Experience," Proc. 1st International Skid Prevention Conference, Virginia Research Council, Part II, 1959.
20. Stewart, R. G., "Driving Exposure: What Does It Mean? How Is It Measured?" Traffic Safety Research Rev., Vol. 4, No. 2, pp 9-11, January 1960.
21. Breuning, S. M., and Bone, A. J., "Interchange Accident Exposures," HRB Bulletin No. 240, pp 44-52, 1960.
22. Mathewson, H. R., and Brenner, R., "Indexes of Motor Vehicle Accident Likelihood," HRB Bulletin No. 161, pp 1-8, 1957.
23. Belmont, D. M., "Effects of Average Speed and Volume on Motor Vehicle Accidents on Two-Lane Tangents," Proc. HRB, Vol. 32, pp 283-395, 1953.
24. Raff, M. S., "Interstate Accident Study," HRB Bulletin No. 74, pp 18-45, 1953.
25. Schoppert, D. W., "Predicting Traffic Accidents From Roadway Elements of Rural Two-Lane Highways with Gravel Shoulders," HRB Bulletin No. 158, pp 4-26, 1957.

26. Veg, A., "Relationship Between Daily Traffic and Accident Rates," Amer. City, Vol. 52, No. 9, p 119, Se. 1937.
27. Bitzl, F., "Accident Rates on German Expressways in Relationship to Traffic Volumes and Geometric Design," Roads and Road Construction, pp 18-20, January 1957.
28. Stohner, W. A., "Relation of Highway Accidents to Shoulder Width on Two-Lane Rural Highways in New York State," Proc. HRB, Vol. 35, pp 500-504, 1956.
29. Carlson, R. F., "A Review of Case Law Relating to Liability for Skidding Accidents," TRB Record No. 523, p 5, 1974.
30. Norden, Monroe, Orlansky, J., Jacobs, H., "Application of Statistical Quality Control Techniques to Analysis of Highway-Accident Data," HRB Bulletin No. 117, pp 17-31, 1956.
31. Rudy, B. M., "Operational Route Analysis," HRB Bulletin No. 341, pp 1-17, 1962.
32. Brenner, R., Fisher, G. R., and Mosher, W. W., Jr., "Statistical Analysis of Accident Data as a Basis for Planning Selective Enforcement," HRB Record No. 188, pp 44-71, 1967.
33. Morin, D. A., "Application of Statistical Concepts to Accident Data," HRB Record No. 118, pp 72-79, 1967.
34. Baldwin, D. M., "Assembly and Use of Accident Data," HRB Record No. 376, pp 14-17, 1971.
35. Campbell, E. M., and Titus, R. E., "Spotting Skid-Prone Sites on West Virginia Highways," HRB Record No. 376, pp 85-96, 1971.
36. Blindaver, H. H., and Michael, H. L., "An Analysis of High Accident Rates," Traffic Safety Research Rev., Vol. 3, No. 4, pp 15-20, December 1959.
37. May, J. F., "A Determination of an Accident Prone Location," Traffic Engineering, Vol. 34, No. 5, pp 25-28, 56, February 1964.