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FURTHER EVALUATIONS
OF
SKID RESISTANCE CHARACTERISTICS
OF
CARBONATE ROCK AGGREGATES

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The New Jersey Department of Transportation
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16. Abstract

Due to poor skid resistance characteristics, in 1975 carbonate coarse aggregate was prohibited from use in the bituminous surfacings of NJDOT maintained highways. Proposals for less restrictive use criteria have since been made by the carbonate aggregate industry. The status of the Department's evaluations of those proposals is documented in this report.

The principal recommendation by industry has been to adopt the PennDOT SRL (Skid Resistance Level) aggregate classification system. With the SRL system, an aggregate can be used in all roadways having traffic volumes up to some limiting ADT, established from its ADT vs Skid Number relationship. The SRL system proved to be inappropriate for Department needs, however, the existence of a definable relationship between skid number and traffic volume was verified. It was also established that roadway speed limit has a significant effect on skid number values. Based on these findings, a probabilistic procedure was formulated for determining the speed limit and ADT conditions which permit a given carbonate aggregate to be used without causing inordinately low pavement skid resistance. Application of this procedure established that aggregate from two ledger dolomite quarries can be used in bituminous pavements with speed limits up to 50 mph, and with design traffic volumes up to 4,000 vpd.

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TABLE OF CONTENTS

Page

LIST OF FIGURES AND TABLES

I. CONCLUSIONS

The investigative work described in this report has lead to the following conclusions:

1. Use of the PennDOT SRL (Skid Resistance Level) system to analyze New Jersey skid resistance data yields no new information on the adequacy of carbonate aggregates for bituminous surfacings. However, the appropriateness of the PennDOT approach for such an analysis is somewhat in question. A key part of this system is the determination of an equation relating skid number, SN, to traffic volume, ADT. Data variation frequently causes the equation to be relatively imprecise. Unfortunately, the SRL system includes no means of accounting for that imprecision.

2. The skid resistance of dense-graded, bituminous concrete surfaces on New Jersey Department of Transportation maintained highways is significantly affected by roadway speed limit and level of traffic volume. For any given range of traffic volumes, skid number is related to speed limit in essentially a linear fashion with low skid numbers being associated with low speed limit conditions. Traffic volume has a different effect on skid resistance as low ADT levels are conducive to high SN values. The relationship between SN and ADT can also be roughly approximated by a linear equation. However, it is apparent that ADT has a more pronounced affect on skid numbers at low traffic volumes (less than 20,000 vehicles per day) than at high volumes.

3. A procedure has been developed for determining the speed limit and ADT conditions that permit the coarse aggregate from a carbonate quarry to be used without causing inordinately low pavement skid resistance. The procedure relies on probabilistic methods and the skid resistance relationships found in this study. It selects permissible levels of ADT and speed limit in such a way that the probability of producing a low skid number pavement (an SN value lower than that recommended in NCHRP Report #37) is, no greater than, the probability of finding a low SN value anywhere on the NJDOT's bituminous pavement network. The mechanics of the new procedure are highlighted in Figure 5 of this report and given in detail in the Appendix.

4. By applying the procedure mentioned above, permissible levels of ADT and speed limit were determined for ledger dolomite Quarries 100 and 102. It appears that coarse aggregate from these quarries can be used in bituminous pavement with speed limits up to 50 mph and with design traffic volumes up to 4,000 vehicles per day (vpd). For material from carbonate Quarry 104, no basis was found to modify the current restrictions on its use.

5. It is considered desirable to carry the work of this investigation further so that still more knowledge can be gained about the interaction of SN, speed limit, traffic volume, and other factors at low ADT conditions. The data base used in this study, although extensive, would have to be expanded to permit such further assessments.

II. RECOMMENDATIONS

1. It is proposed that the NJDOT's current restrictions on use of carbonate aggregate in bituminous concrete surface course not be applied to ledger dolomite Quarries 100 and 102. Instead of these restrictions, it is recommended that coarse aggregate from Quarries 100 and 102 be tentatively permitted in bituminous pavements with design traffic volumes up to 4,000 vpd and design speed limits up to 50 mph. These criteria will, no doubt, have minimal impact on carbonate usage for the Department's route system. However, they may result in significant increases in carbonate use on local government roads.

2. Because of insufficient data, it was not possible to investigate all carbonate quarries that have supplied New Jersey paving projects. Only the major quarries could be evaluated. If additional data can be found from other sources (county or municipal routes in New Jersey or routes in neighboring states), the procedures developed in this study should be used to establish new use criteria for the other carbonate quarries. In this regard, an analysis of Penn DOT data for ledger dolomite Quarry 103 has already been accomplished and indicates that it can be treated in the same fashion as Quarries 100 and 102.

3. An effort should be made to expand the data base used in this investigation to permit an assessment of other factors that may have a detectable affect on skid resistance. The work reported herein could only consider the roles that roadway speed limit and traffic volume play in establishing the SN level of a pavement. Other factors such as pavement age and number of traffic lanes may also be important. The use criteria proposed for Quarries 100 and 102

should be considered tentative until these other factors can be evaluated.

4. It is proposed that a study be initiated to determine if the procedures used in this investigation can be adopted as a standard NJDOT method for establishing use criteria for all quarries serving Department projects. This would seem to be both a feasible and beneficial endeavor.

III. INTRODUCTION

During the ten year period from 1965 to 1975 the New Jersey Department of Transportation carried out numerous investigations to determine the causes of slippery pavements and the means for preventing their occurrence. The impetus for these efforts was the observation that low skid resistant pavement incurred inordinate numbers of wet weather, skidding type accidents. With bituminous pavements it was found that low skid resistance was often associated with the use of carbonate rock coarse aggregate in the riding surface. To preclude the perpetuation of such conditions, the Department took action in the spring of 1975 to restrict the use of carbonate rock in bituminous paving operations.

Two types of restrictions were adopted. For all highways under the maintenance jurisdiction of the Department, a total ban was placed on the future use of carbonate rock aggregates in surface courses of bituminous type pavement. For county and municipal roads constructed with state funding aid, carbonate aggregate was only permitted in surface course if a surface renewal (overlay, surface treatment, etc) would occur prior to the carbonate surfacing receiving more than 2 million vehicle coverages. The coverage criteria was based on previously measured polishing rates for carbonate paving mixtures on state highways. No restrictions, whatsoever, were placed on use of carbonates in bituminous mixtures below the riding surface.

In the months that followed the Department's decision to limit carbonate usage, numerous meetings were held with representatives of both the aggregate supply and bituminous paving industries. Industry expressed a strong concern over the economic effects of the new restrictions and offered several suggestions as to how carbonates might be used without posing a detriment to driving safety. It is the intent of this report to review the Department's efforts in evaluating industry's various proposals and to present results for those evaluations that have been completed.

IV. BLENDING OF COARSE AGGREGATES

One of industry's initial suggestions was that a blending of coarse aggregate from carbonate and non-carbonate sources would be an effective means of producing a bituminous mixture of adequate skid resistance. Work done in both Pennsylvania and New York was cited as a valid precedent. Department engineers responded by pointing out that they had tried blending and it had proved unsuccessful.

On U.S. Route 1 near the State's capitol, the Department had constructed several test sections for which a carbonate aggregate was blended with various other aggregates. Unfortunately, no beneficial effect on skid resistance was achieved.(1&2) The carbonate material used in these tests was from a single source, the principal supplier of carbonate aggregates for Department projects. This particular quarry (designated as Quarry 104 in this report) was supplying approximately 3/4 of all the carbonates being used in NJDOT pavements.

NOTE: Numbers in parenthesis refer to references listed at the end of this report.

Other carbonate quarries had been contacted at that time, but for one reason or another did not participate in the test.

Industry representatives for those carbonate quarries other than Quarry 104 voiced an opinion that the Department's blending trials were not applicable to their materials. In particular, a delegation representing several Pennsylvania quarries, whose material is identified as "ledger dolomite",noted that PennDOT rated ledger dolomite as possessing better skid resistance properties than aggregates from Quarry 104. It was subsequently agreed that another field trial of the blending concept, but with a ledger dolomite, would be desirable.

At the writing of this report, a Maintenance contract has been let for bituminous concrete mixtures of carbonate blends to be placed on Route 130 near Yardville, New Jersey. The coarse aggregates for these mixtures will be a ledger dolomite and a non-carbonate, non-sedimentary rock, probably diabase trap rock. Placement of the ledger dolomite blends will be accomplished in April 1978.

V. TRIAL APPLICATION OF PENNSYLVANIA SRL SYSTEM

Another proposal offered by industry was for the Department to use the aggregate classification criteria that had recently been adopted by the Pennsylvania DOT (adopted by Penn DOT January 1975). Representatives of the ledger dolomite quarries noted that PennDOT had rated their materials as "Good",from a skid resistance standpoint. and safe for use on roadways with average daily traffic up to 5000 vpd.

To evaluate industry's proposal, several officials of PennDOT were contacted and a draft copy of a paper outlining the new aggregate classification system was obtained.(3) With the PennDOT SRL (Skid Resistance Level) system, summer and early fall skid trailer (ASTM Skid Tester) measurements are plotted against Average Annual Daily Traffic (ADT) and a regression line is determined (Figure 1). The ADT which corresponds to a Skid Number (SN) of 40 on this line establishes an SRL rating in accordance with the criteria shown in Figure 2. The SRL rating then gives a range of traffic volumes for which the aggregate can be used in a pavement. The claimed purpose of the classification is to specify permissible use of aggregates in such a way as to increase the likelihood that a new, dense-graded surface would have a skid number of forty, or greater, throughout its service life. Based on recommended minimum skid resistance requirements given in NCHRP Report No. 37(4), if a pavement has a skid number of 40 and average speed gradient characteristics it should be adequate for all mainline, rural traffic conditions with speeds up to 55 mph.

After reviewing the SRL system, Department researchers were concerned as to its applicability to New Jersey pavements containing carbonates. At the heart of the SRL system is the assumption that minimum skid resistance (skid numbers) after the first year of traffic is an invariant with time. This did not completely agree with available data from New Jersey pavements which showed a tendency for carbonate rock mixtures to continue to decrease in

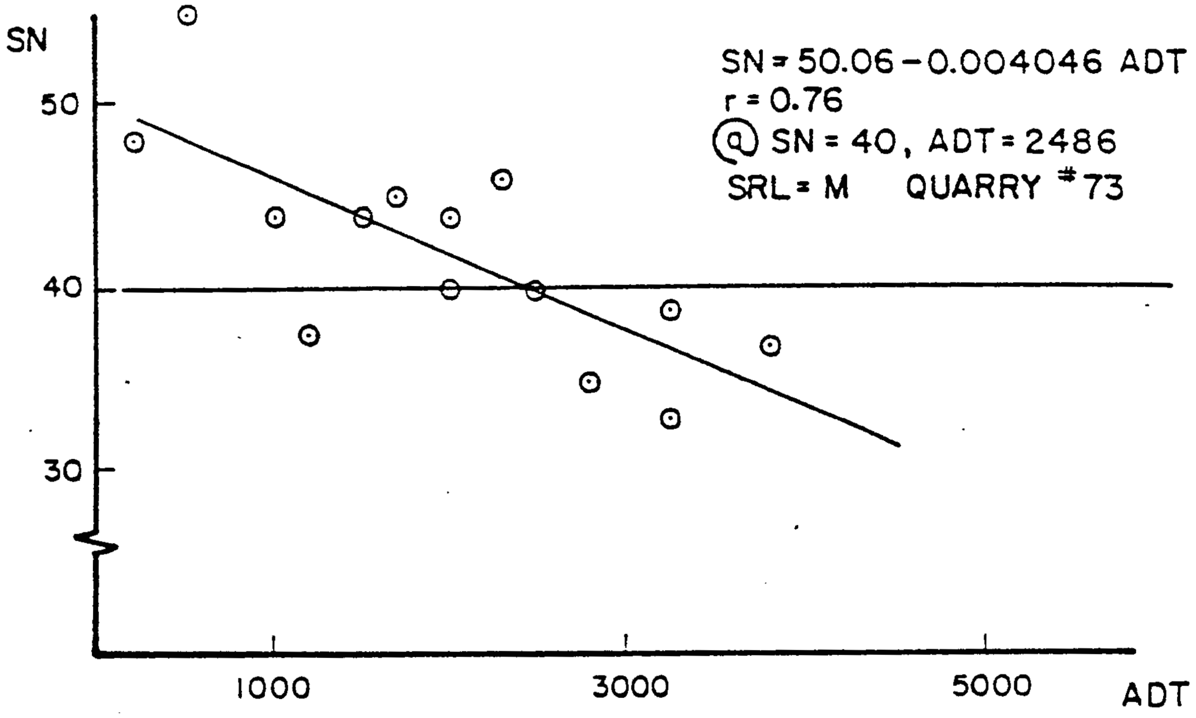


FIGURE 1. EXAMPLE OF SKID NUMBER vs TRAFFIC INTENSITY
(Taken from paper on Penn DOT's SRL System, Reference 3)

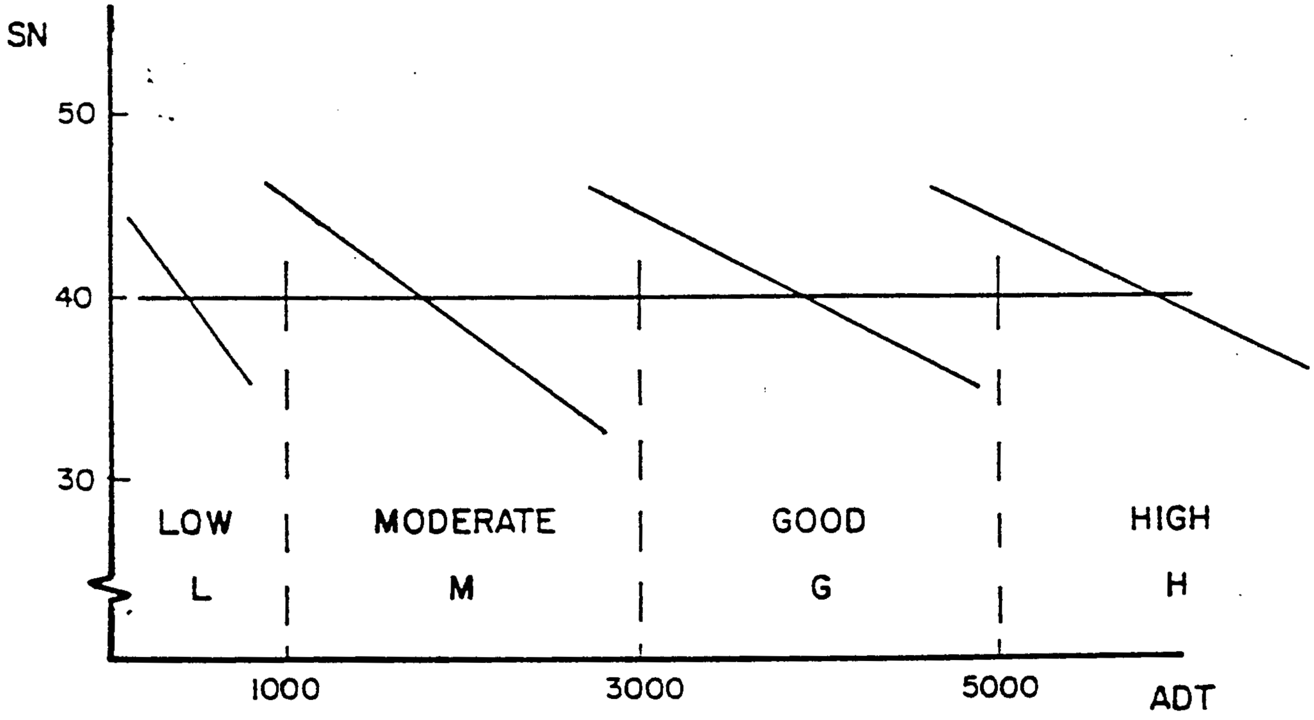


FIGURE 2. SKID RESISTANCE LEVEL (SRL) CLASSIFICATION
(Taken from paper on Penn DOT's SRL System, Reference 3)

skid resistance beyond the first year of use.(1) Also, even if the SRL system was basically correct, it appeared to make no allowance for data variability. The data used to generate the SN vs ADT regression line would no doubt vary around the regression line due to materials and measurement variation. An allowance for at least the materials portion of the variation would have to be made to be confident that a future pavement containing the classified aggregate would indeed have a skid number of at least 40.

In spite of the questions raised, the SRL system was applied to SN and ADT data available for bituminous pavements in the Department's highway system. Average skid tester measurements from the 1975 Skid Resistance Inventory were used along with the most recent (1974) ADT data. The key results of the trial application are shown in Table 1.

Table 1 - Trial Application of SRL System

Source of Aggregate	Number of Data Points[a]	Intercept (SN)	Slope (SN/ADT)	ADT at SN = 40	SRL Rating	Correlation Coefficient
Carbonate Quarry 104	204	39.8	-0.00026	less than zero	below poor	0.42
All Ledger Dolomite Quarries	53	39.5	-0.00011	less than zero	below poor	0.49
All Gneiss Quarries	176	48.2	-0.000092	89,000	high	0.23
All Trap Rock Quarries	413	46.4	-0.00011	58,000	high	0.32
Gneiss Quarry 206	36	49.8	-0.00011	89,000	high	0.23
Trap Rock Quarry 321	62	46.3	-0.00025	25,000	high	0.52

[a] The SN value for each data point was an average of from 3 to 5 skid tests per mile made on the outside lane at a 40 mph test speed.

Unfortunately, as the data of Table 1 indicates, the results of the SRL trial failed to shed any new light on the matter of carbonate usage. The carbonate quarries were shown by the SRL system to be inadequate for use in our standard surfacings at all levels of traffic volume. On the other hand, the gneiss and trap rock quarries which form the major source of paving aggregates for the Department were indicated to be acceptable for relatively high traffic volumes.

While these findings supported the Department's previous assessments of carbonate rock, there was still concern over the applicability of the SRL system to New Jersey conditions. The correlation coefficients for the regression lines were rather poor, generally less than 0.5 (1.0 is excellent correlation and 0 is no correlation) suggesting that there may not be a very strong linear relationship between skid number and ADT for New Jersey pavements. In an attempt to improve on those results, various non-linear regression techniques were then tried, along with modifications to the ADT values to account for traffic distribution on multi lane roadways. No significant changes from the original correlations could be obtained.

Industry was advised that the trial of the SRL system gave no new information to cause the Department to modify its restrictions on carbonate aggregate. Differences in gradations and asphalt levels of the bituminous mixtures used in New Jersey and Pennsylvania were suggested as possible reasons for the SRL system yielding different results in the two states.

VI. DEVELOPMENT OF NEW CARBONATE USE CRITERIA

In late 1976, representatives of several ledger dolomite quarries again proposed that consideration be given to results of aggregate classifications established by Pennsylvania. They pointed out that Pennsylvania had recently reclassified their quarries based on further skid resistance data. Their materials were now rated as "High" in skid resistance and could be used in bituminous pavements in Pennsylvania with traffic volumes up to 20,000 vehicles per day.

In response to industry's proposal, a new investigation was initiated to see if less restrictive but safe use criteria could possibly be developed for carbonates. For this work a special effort was made to expand the data base beyond that available for the trial of the SRL system. A variety of additional information sources were reviewed in an attempt to identify quarry sources for all sections of bituminous pavement in the Department's system. In the SRL trial only information available in the central laboratory's files was utilized. Also, to minimize erroneous input of skid resistance values, two Department engineers visually checked the surface of every section of pavement on the system which contained a carbonate aggregate. Any sections that appeared fatty or contaminated by crack sealer or oil drippings, so as to give false indications of aggregate skid resistance quality, were excluded from consideration.

A. Evaluation of Restrictions Based on Speed Limit

Because of the deficiencies found in the earlier trial of the SRL system, no major effort was made at this point to develop an adaptation of the PennDOT methods. Instead several new ideas for carbonate use criteria were formulated and then given a preliminary assessment by applying the criteria in a simulated fashion to the skid resistance data base. The idea which appeared to have the most merit was to relate use restrictions to roadway speed limit. The intent here was to take advantage of the fact that, as traffic speed decreases, the minimum required level of skid resistance (skid number measured at 40 mph) also decreases. Thus, it seemed a carbonate which is inadequate for say 50 mph travel conditions could possibly be safe at some lower speed.

The relationship between speed and minimum required skid numbers is shown in Table 2. The numbers in this table are based on recommendations given in NCHRP Report 37(4) and are minimum values for main rural highways having speed gradients (rate of reduction of skid number with test speed) between 0.5 and 0.8. The vast majority of NJDOT bituminous pavements tend to have a speed gradient near 0.5 while recent evaluations indicate our carbonate pavements exhibit gradients in the 0.6 to 0.8 range.

Although the requirements of Table 2 were originally only proposed for main, rural highways, they have become the yardstick that engineers generally apply to all roadway conditions since research has yet to produce valid alternate standards. The New Jersey Department of Transportation has been part of this trend, using the skid number requirements of NCHRP Report 37 as a general guide in all of its skid resistance investigations.

Table 2

[illegible] Skid Numbers[a]

	Skid Numbers (SN_{40})[b]			
	Speed Gradients			
Mean Traffic Speed (mph)	0.5	0.6	0.7	0.8
20	30	28	26	24
30	31	30	29	28
40	33	33	33	33
50	37	38	39	40
60	41	43	45	47
70	46	49	52	55
80	51	55	59	63

[a] Minimum skid numbers as recommended in NCHRP Report #37 and when measured in accordance with ASTM E-274 Method of Test.

[b] SN_{40} = skid number, measured at 40 mph, including allowance for the skid number reduction with test speed using the mean gradient cited.

In establishing a speed related use criteria for carbonates, it was considered necessary that some type of probabilistic approach be followed. The thought here was that, to be truly reliable, the developed criteria should account for the variable nature of the skid resistance characteristics of a quarry's materials. The laws of probability and statistical analysis could be used to achieve such an accounting. It was also believed appropriate that the use restrictions be so established as to achieve pavements of skid resistance quality equal to the average quality of the Department's present road systems. With such a concept, the average skid resistance quality of our present roads is considered adequate and the use of aggregates that could cause a pavement to have a worse quality would not be permitted.

With the preceding ideas in mind, it was planned to determine, for each carbonate quarry, the probability of its material yielding a pavement with a skid number below each of the limits given in Table 2. For any one limit, a good estimate of the probability involved is, simply, the percentage of below-limit skid number measurements that are found on pavements containing the quarry's aggregate. The percentage results could then be compared to a probability figure that characterizes the average skid resistance quality of the Department's current system of bituminous pavements. The appropriate probability statistic to use here would be the percent of below-limit skid numbers found for all bituminous roads. The highest acceptable or safe speed for using a particular quarry's aggregate would then be selected, so that, the probability of producing a low skid number pavement would be no greater than the current overall probability of finding a low skid number anywhere in the system. In this manner, use of any carbonate quarry would be restricted to those traffic speed conditions for which there would be no "inordinate" chance of the pavement deteriorating to an unsatisfactory level of skid resistance.

The first step in applying this approach was to compute the average overall skid resistance quality of the Department's bituminous pavements. Thus, a determination was made of the percent of all skid number measurements on bituminous pavements that fall below the limits of Table 2. Table 3 gives the results of that determination. All statistics were derived from an analysis of data gathered in the 1976 skid resistance inventory. For each speed limit category of our route system, the percentage of skid number measurements below the applicable NCHRP minimum skid number was determined. This determination was made both by direct count and by estimation using areas under the statistical normal curve.

From the weighted average percentage values at the bottom of Table 3, it is seen that approximately 24% of all skid resistance measurements of our bituminous pavements fell below the NCHRP recommended minimum requirements. Thus, based on the 1976 survey, we can say the probability of finding a low skid number pavement on our bituminous road system is about 24%.

According to the planned method of analysis, for each carbonate quarry, the 24% figure was to be compared to the quarry's speed limit related probabilities of low SN measurements. However, when reviewing the various information in Table 3, an extremely surprising relationship was noted which raised doubts as to the value of proceeding with that analysis. The average skid number recorded for each speed limit condition was seen to decrease with decreasing speed limit. This phenomenon had not been reported previously in skid resistance research

Table 3

Skid Resistance Quality of NJDOT Bituminous Surfaced Roads

Speed Limit MPH	Number of Measurements[a]	Average Skid Number	Skid Number Standard Deviation	Minimum Required Skid Number[b] (SN_{40})	Percent of Measurements Below Minimum SN: By Actual Count	Percent of Measurements Below Minimum SN: By Normal Table
55	624	44.6	7.4	39	18.6	22.4
50	1883	43.2	7.9	37	20.5	21.5
45	405	39.9	7.5	35	26.2	25.7
40	324	38.3	7.4	33	23.8	23.8
35	240	34.7	7.3	32	33.3	35.7
30	144	33.7	6.3	31	31.3	36.9
25	86	31.2	8.7	30.5	51.2	47.0
			Weighted Average Percent Below Minimum SN_{40}		23.3	24.4

[a] Each measurement was an average of from one to five skid tests run at 40 mph in an outside lane. Measurements for some low speed limit roadways were recorded at the speed limit and adjusted to 40 mph by applying the appropriate speed gradient.

[b] NCHRP #37 (Reference 4) recommended values for 40 mph measurements on surfaces with 0.5 speed gradient; some values obtained by interpolating between NCHRP SN minimums.

literature and was totally unexpected. However, it did seem to be a plausible finding. The lower speed limit roads usually have such speed limits because of the various constraints (frequent traffic lights, reduced sight distance, less forgiving geometric conditions and excess traffic side friction) which precluded safe high speed travel. These same constraints actually serve to increase the degrading action that vehicular traffic has on pavement skid resistance. Thus, it would seem reasonable to expect a given type of surfacing to exhibit lower skid resistance in pavements that warrant low speed limits than in pavements where high speed travel was possible.

A plot of the average skid number - speed limit data of Table 3 is shown in Figure 3. For comparison purposes, Figure 3 also contains the curves relating mean traffic speed and NCHRP minimum SN values applicable for the speed gradient range (G = 0.6 to 0.8) of our carbonate pavements. It is immediately apparent from this figure that the straight line which describes the average SN vs speed limit relationship approximately parallels the curves for required SN vs mean traffic speed. This indicates that the reduction in required skid resistance with reduction in traffic speed is just about equaled by the loss in mean skid resistance associated with the reduced speed. Thus, if this observed SN - speed limit relationship holds for the carbonate quarries, there would be little or no merit to the idea that a carbonate which is unsafe for high speed traffic might be safe for lower speed situations.

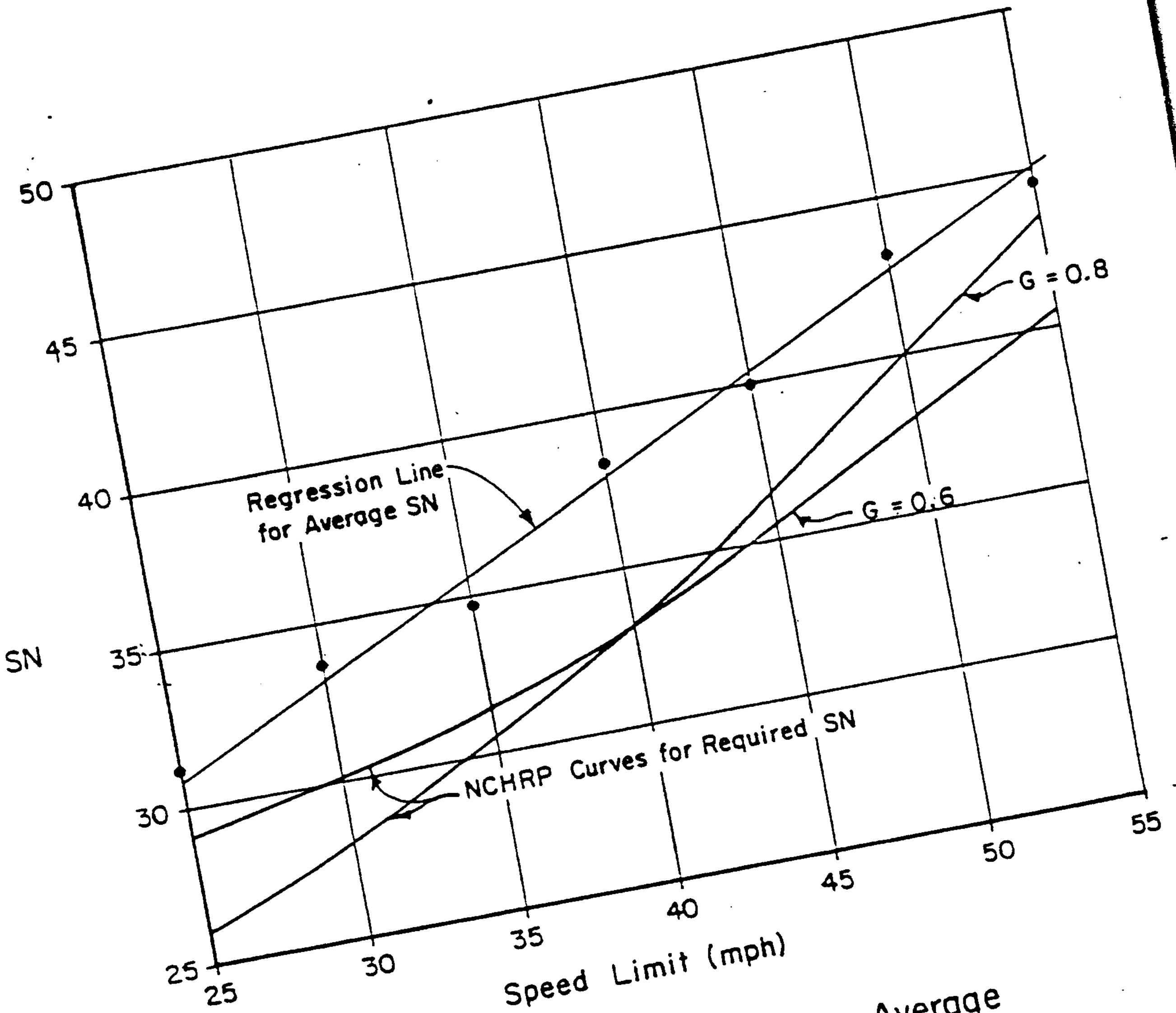


Figure 3- Effect of Speed Limit on Average SN and Required SN

A statistical check revealed that the SN - speed limit line found from the analysis of all our bituminous pavement did aptly describe the behavior of the ledger dolomite surfaces. However, for pavements with material from Carbonate Quarry 104 a steeper line was found to be more appropriate. With these latter pavements then, it would actually be worse from a skid resistance standpoint to subject them to the conditions associated with low rather than high speed traffic.

Although the speed limit effect just described seemed plausible, there was concern that possibly the observed pattern was actually due to ADT differences. Perhaps ADT was not uniform over the speed limit levels considered. Possibly, the ADT effect reported by PennDOT was responsible for the trend. To resolve this concern an average ADT was computed for those pavements considered in each speed limit category of Table 3. The averages so computed were found to vary in a random fashion between 16,500 and 26,000 vehicles per day. Based on the SN vs ADT relationship given in Table 1 of this report, the differences in the average ADT's were much too small and did not follow the pattern required to have caused the noted SN changes with speed limit. Thus, the effect of speed limit on skid number values appeared to be quite real.

Considering the significant nature of the SN - speed limit relationship, it was apparent that the Department's search for safe use restrictions for carbonates would have to proceed in another direction. In this vein, a review was made of the basis for the current State Aid restriction on the number of vehicle coverages prior to resurfacing. This criterion had been established predominantly from polishing rate data for Quarry 104 pavements. Perhaps the polishing rates for the ledger dolomite surface could be shown to be significantly less aggressive. A survey of the data available for such an analysis proved fruitless. There was very little reliable information as to the age of the ledger dolomite surfaces on our system. Also, the Department had never attempted to monitor closely skid resistance changes with time for such pavements.

B. Criteria Based on Speed Limit and ADT Effects

1. Initial Assessments

A reconsideration of PennDOT's efforts in the skid resistance area became the next logical step. The previous trial of the SRL System had of course been nonproductive. However, with the larger and more reliable data base now available, a second application appropriately tempered to account for skid resistance variability and traffic speed effects might prove successful. Before persuing this idea further, it was considered necessary to verify that New Jersey's pavements actually did exhibit a significant relationship between skid number and average annual daily traffic (ADT). Of concern here was the fact that the Department had previously obtained such poor correlation coefficients when comparing the two parameters in regression analysis.

If PennDOT's findings regarding SN and ADT were applicable to New Jersey riding surfaces, one would expect an overall analysis of the State's bituminous pavement system to show that higher skid numbers generally occur with low ADT conditions. Such an analysis was performed with an average skid number being calculated for each of several ranges of ADT. To avoid any bias in the analysis due to the speed limit effect of Table 3, all skid numbers were adjusted to a speed limit condition of 50 mph using the equation for the regression line of Figure 3. The results of this analysis are shown in Table 4 and plotted in Figure 4. The plot does show that SN tends to be higher with lower ADT pavements, particularly for situations where the ADT is less than 20,000 vehicles per day.

Table 4

Average 1976 Skid Numbers

for

Bituminous Pavements in Various ADT Ranges

(SN_{40} Values Adjusted to 50 mph Conditions)

ADT Range	Number of Measurements[a]	Average SN_{40}	Average ADT (vpd)
0 - 5,000	357	48.0	3,390
5,100 - 10,000	877	44.9	7,570
10,100 - 15,000	744	43.3	12,480
15,100 - 20,000	446	41.0	17,430
20,000 - 30,000	543	42.2	24,250
30,100 - 50,000	464	40.6	37,730
51,100 - 110,000	276	37.2	73,670

[a] Each measurement was an average of from one to five skid tests run in an outside lane at 40 mph or at a lower speed and adjusted to 40 mph by the appropriate speed gradient.

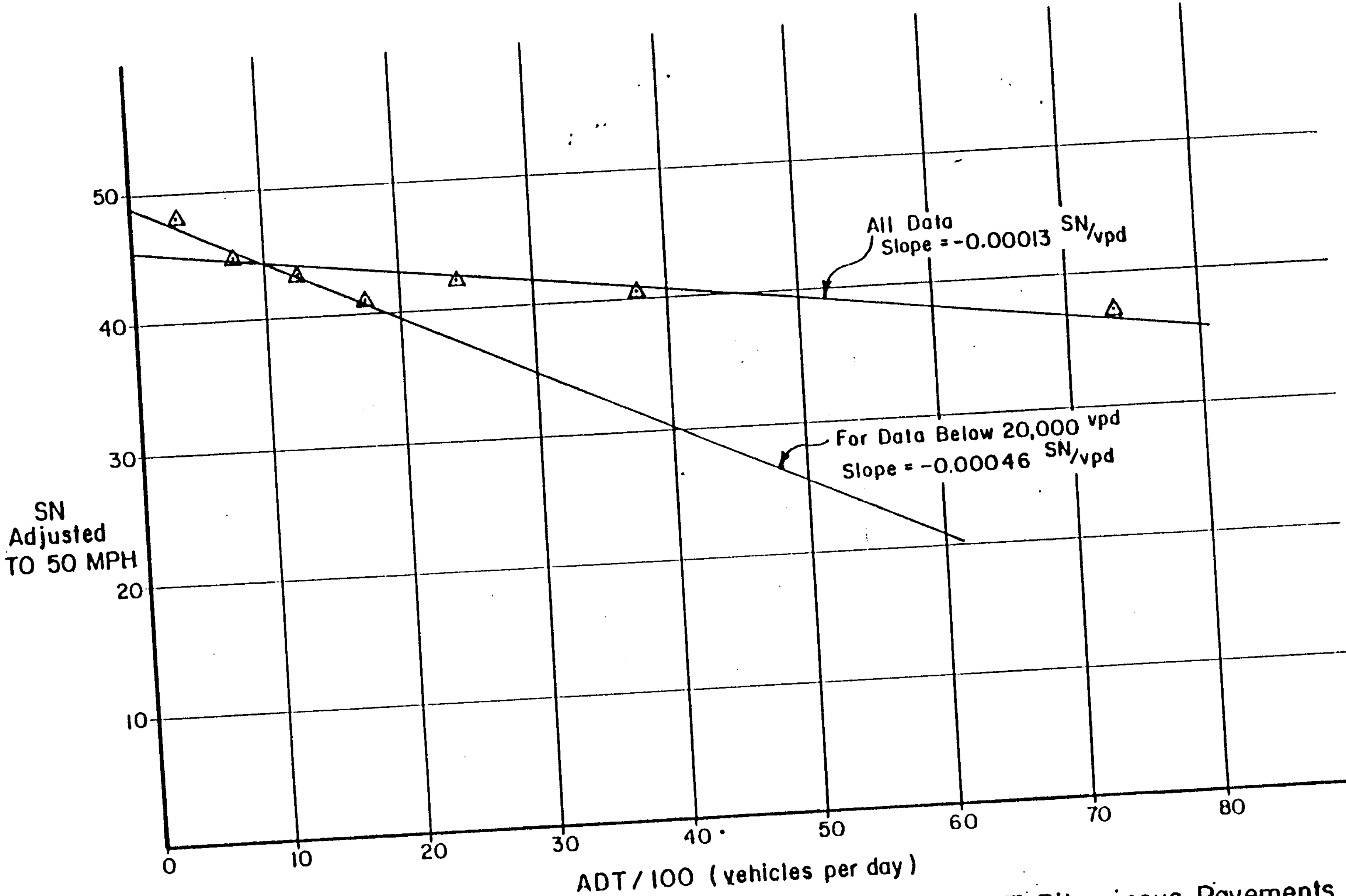


Figure 4 - Relationship Between SN and ADT for NJDOT Bituminous Pavements

As a further verification of the beneficial effect of low traffic volumes on skid number, the analysis of Table 3 was repeated for several ranges of ADT. If a beneficial effect did indeed exist, the percentage of skid number measurements below the NCHRP minimum values should decrease with decreasing ADT. The results of this particular analysis are given in Table 5; the beneficial effect of a reduction of ADT on skid resistance is clearly evident.

Table 5

Skid Resistance Quality

of

NJDOT Bituminous Pavements

as a

Function of Average Annual Daily Traffic (ADT)

Range of Average Daily Traffic (Vehicles per day)	Percent of Skid Number Measurements Below NCHRP Minimum SN_{40}
0 - 110,000*	24
0 - 20,000	20
0 - 12,000	14
0 - 10,000	12
0 - 5,000	7

*All bituminous pavements

With the ADT effect having been verified, the pursuit of safe use restrictions for carbonates could be continued. A particular pavement's skid resistance or skid number had been shown thus far to be a function of two traffic related parameters -- speed limit and volume. Also, required minimum skid number as defined by NCHRP Report #37(4) was known to be speed related. A carbonate usage criteria which adequately considered all these factors in a probabilistic fashion was desired. The probabilistic approach developed earlier had only taken into account the minimum skid number-speed relationship. However, it appeared that modifications could be formulated to appropriately deal with the effects of the other parameters.

With the preceding as a guide, it was decided that SN data for each carbonate quarry would be adjusted to some common speed limit and ADT level using appropriate adjustment factors. The adjusted data would then be analyzed to determine the percent of SN measurements that fall below the governing minimum SN value of NCHRP Report #37.(4) As with the previous probabilistic approach, the resulting percent below figure would subsequently be compared to a percentage figure that described the average skid resistance quality of the Department's bituminous pavement system.

If a given quarry's percent below minimum SN was excessive when compared to average skid resistance quality, then the reduction in ADT needed to bring a pavement to that average quality would be determined. ADT changes required to accommodate a quarry's material being used at other speed limits would also be calculated using the appropriate speed limit, ADT, and minimum SN adjustment factors. In this fashion maximum acceptable or safe ADT values would be established for a range of speed limits for each quarry. Adhering to these values would insure that the probability of producing a low skid number pavement, in the future, would be no worse than the probability of finding a low skid number anywhere on the Department's present bituminous pavement system.

Figure 5 provides a more complete and pictorialized explanation of the procedure outlined above. It sets forth in a stepwise manner the particular analysis techniques to be used in determining a carbonate quarry's maximum safe ADT for any selected level of traffic speed limit.

To carry out the analysis of each carbonate quarry's SN data,it appeared appropriate that only measurements for pavements having less than 20,000 ADT be considered. PennDOT's evaluation of ledger dolomite had indicated safe usage only up to an ADT of 20,000 vpd. Also, the plot of SN vs ADT for New Jersey pavements (Figure 4) suggested the presence of more pronounced ADT effects at ADT values less than 20,000 vpd.

Equations for adjusting the skid resistance data of each quarry to a common speed limit and ADT level were developed first. Regression lines relating SN to speed limit and SN to ADT were computed by analyzing the SN data for all bituminous pavements with ADT less than 20,000. The SN vs speed limit line was first determined, then all SN data was adjusted to the most prevalent speed limit condition (50 mph) and the SN vs ADT line established. The slopes of these lines were then compared statistically to the slopes obtained from

1. **Choose Levels of ADT and Speed Limit to which all SN Measurements are to be Adjusted:**

   a. Choose $ADT_{Adj.} \approx$ Average ADT for pavements containing quarry's material.

   b. $\text{Speed Limit}_{Adj.}$ = Selected speed limit.

2. **Adjust SN Data of Quarry to Chosen Levels of ADT and Speed Limit:**

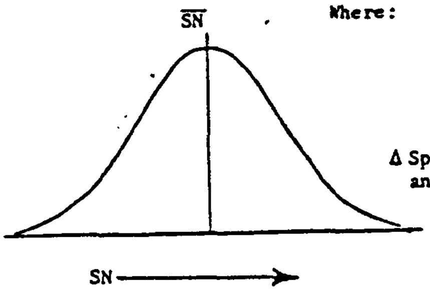
Adjust each SN value using equation: $SN_{Adj.} = SN + C_1 \Delta \text{Speed Limit} + C_2 \Delta ADT$

Where: SN = Individual skid number.

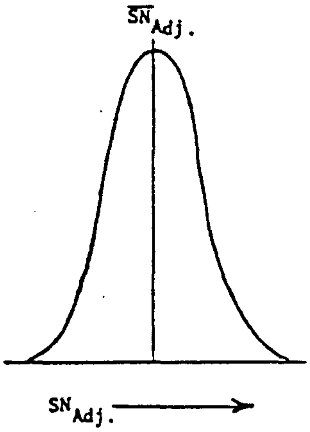
C_1 = Slope of SN vs speed limit regression line.

C_2 = Slope of SN vs ADT regression line.

Δ Speed Limit and Δ ADT = Difference between adjusted level and actual level for roadway on which SN was measured.

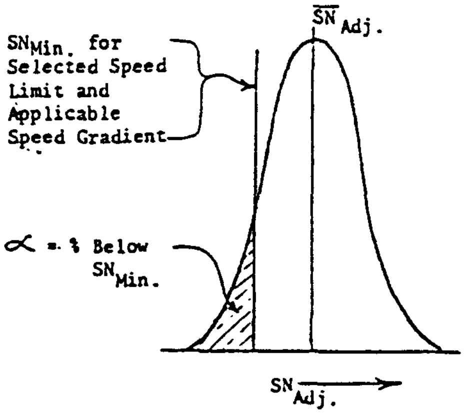


Distribution of Unadjusted SN data



Distribution of Adjusted SN Data

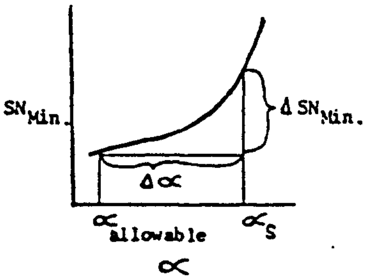
3. **By Histogram Analysis Determine Percent of Adjusted SN Values Below $SN_{Min.}$ and Compare to Allowable Percentage:**



If α is:	Then Maximum Safe ADT is:
a. Less than $\alpha_{allowable}$	a. Greater than $ADT_{Adj.}$
b. Equals $\alpha_{allowable}$	b. $ADT_{Adj.}$
c. Greater than $\alpha_{allowable}$	c. Less than $ADT_{Adj.}$

4. **Determine Maximum Safe ADT for $\alpha \neq \alpha_{allowable}$:**

   a. Develop plot of $SN_{Min.}$ vs α by repeating Step 3 for a range of $SN_{Min.}$ values.



   b. From plot determine $\Delta SN_{Min.}$ for:

$$\Delta\alpha = \alpha_S - \alpha_{allowable}$$

Where:

$\alpha_S = \alpha$ from Step 3 for selected level of speed limit

   c. Maximum safe ADT is given by:

$$ADT_{Max.} = ADT_{Adj.} + \Delta ADT$$

Where:

$\Delta ADT = \Delta\overline{SN}/C_2$

and

$\Delta\overline{SN} = \Delta SN_{Min.}$

Figure 5: Procedure for Determining a Carbonate Quarry's Maximum Safe ADT at a Selected Speed Limit.

a regression analysis of the SN measurements for each carbonate quarry.* If no significant difference existed, then the line developed from the analysis of all below 20,000 ADT bituminous pavements was considered appropriate for adjusting a given quarry's SN values. Only in the case of the speed limit adjustment equation for Quarry 104 was a significant difference found. In comparison to the average bituminous pavement, Quarry 104 pavements exhibited more pronounced reductions in skid number with decreases in speed limit.

The regression line slopes used to adjust each carbonate quarry's SN data to a common speed limit and ADT level are given in Table 6. It is interesting to note that the SN/ADT slope value cited compares favorably with the findings of PennDOT. PennDOT has observed that for those ledger dolomite quarries supplying New Jersey, the slopes of the SN vs ADT regression lines vary between -0.00040 and -0.00070, with a slope of -0.00065 resulting when all quarries are considered in a single analysis.(5) The PennDOT findings suggest the SN/ADT slope value of Table 6 to be a conservative figure.

Using the factors of Table 6, each carbonate quarry's SN data was adjusted to a common base speed limit of 50 mph and to a common base ADT of 15,000 vpd. These particular speed limit and ADT levels were selected since they approximately corresponded to the average use levels for carbonate pavements in the Department's road system. Because of this correspondence the magnitude of most of the SN adjustments would be relatively small. Thus, if the adjustment equations were somewhat in error, the effect of the error at this point in the analysis would be minimized.

*Only slopes require comparison as they are the only regression line parameters used in the SN adjustment process.

Table 6

Slopes of Regression Lines

For

Adjusting SN for Speed Limit and ADT Effects

(ADT Range 0 - 20,000)

Carbonate Quarry	Number of Points in Regression Analysis	Slope of Regression Line	
		SN Versus Speed Limit (SN/mph)	SN Versus ADT (SN/vpd)
Ledger Dolomites	2423	0.5474	-0.0004597
104	787	0.7683	-0.0004597

A histogram for the adjusted SN data of each carbonate quarry is given in Figure 6. The percent of SN measurements that fall below various NCHRP minimum SN values is listed in Table 7. These percent below figures were computed by actual count or, if the histogram was found to conform to a normal distribution, by normal curve approximations. Sufficient data for a histogram analysis was available only for carbonate quarries 104, 102, and 100: the later two being ledger dolomite quarries.

The data of Table 7 must be compared to a percentage measure describing the average skid resistance quality of similar pavements on the Department's road system. For pavements with ADT's less than 20,000 vpd, the analysis reported in Table 5 indicates that the average skid resistance quality of our system is characterized by a 20%

```
UPPER LIMIT      FREQUENCY
    16.0         1 X
    20.0         1 X
    24.0         0
    28.0         1 X                                                    X̄  =  40.3
SN  32.0         9 XXXXXXXXX                                            σ  =  6.05
    36.0        16 XXXXXXXXXXXXXXXX                                     N  =   136
    40.0        39 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    44.0        31 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    48.0        26 XXXXXXXXXXXXXXXXXXXXXXXXXX
    52.0        12 XXXXXXXXXXXX
```

Quarry 100 (Ledger Dolomite)

```
UPPER LIMIT      FREQUENCY
    32.0         1 X
    36.0        15 XXXXXXXXXXXXXXX                                      X̄  =  40.6
SN  40.0        17 XXXXXXXXXXXXXXXXX                                    σ  =  4.46
    44.0        22 XXXXXXXXXXXXXXXXXXXXXX                               N  =    72
    48.0        17 XXXXXXXXXXXXXXXXX
```

Quarry 102 (Ledger Dolomite)

```
UPPER LIMIT      FREQUENCY
    24.0        12 XXX
    28.0        52 XXXXXXXXXXX
    32.0       100 XXXXXXXXXXXXXXXXXXXXXX
    36.0       188 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX                X̄  =  36.7
SN  40.0       230 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX       σ  =  6.10
    44.0       117 XXXXXXXXXXXXXXXXXXXXXXXXX                                N  =   787
    48.0        56 XXXXXXXXXXXX
    52.0        22 XXXXX
    56.0         7 XX
    60.0         3 X
```

Quarry 104

Figure 6 - Computer Histograms of SN Measurements Adjusted to a Speed Limit of 50 mph and an ADT of 15,000 vpd.

Table 7

Distribution of Adjusted SN[a] for Carbonate Quarries

Carbonate Quarry	Average Adjusted SN	Standard Deviation of Adjusted SN		Percent of SN Measurements Below SN_{Min} Values(%)									
			SN_{Min} =	40	39	38	37	36	35	34	33	32	31
100[b]	40.3	6.05		49.3	38.2	32.4	25.0	20.6	14.0	11.8	10.3	8.8	3.7
102[b]	40.6	4.46		44.7	36.0	28.0	21.0	15.1	10.5	7.0	4.4	2.7	1.6
104	37.2	6.00		71.4	66.1	55.8	48.9	41.8	34.7	27.7	23.3	12.7	15.4

[a] SN adjusted to speed limit of 50 mph and an ADT of 15,000 vpd.
[b] Ledger dolomite quarry.

probability of having a skid number below the NCHRP minimums. Thus, 20% becomes the critical value for comparison.

If we consider the condition where a carbonate pavement has a speed gradient of 0.6, the NCHRP minimum SN for 50 mph is 38 (See Table 2). From Table 7 we note that the percent of SN measurements below an SN_{Min} of 38 is 32.4% for Quarry 100, 28.0% for Quarry 102, and 55.8% for Quarry 104; all figures are larger than the critical 20%. Therefore, at the base ADT of 15,000 the three carbonate quarries exhibit an inordinately high probability of producing pavement of low skid resistance. Since skid number will increase with reductions in ADT, it is likely that at some lower levels of ADT the histograms of Figure 6 will be shifted sufficiently to change the percent below the SN minimum of 38 to an acceptable value (either equal to or less than 20%). The amount of shift (change in mean SN) needed for the histogram,and the associated reduction in ADT,can be calculated using the information of Tables 6 and 7 and by applying the procedure given earlier in Figure 5. For other speed limit conditions, an acceptable or safe ADT can be determined by use of the slope parameters of Table 6 and the minimum SN values of Table 2. The complete details of both computational procedures are given in the Appendix.

By application of the above cited procedures, the adjusted SN data of each carbonate quarry was analyzed to find ADT levels at which the probability of yielding a low SN measurement (less than NCHRP minimum SN) was just below the critical 20% figure. ADT's corresponding to a 19% probability were used. Thus, in applying the procedure of Figure 5 the α allowable was set at 19%. The results of this analysis are provided in Table 8; all ADT values are reported to the nearest 100 vpd.

Table 8

Maximum ADT Values for 19% Probability of Yielding Low SN Measurements (Vehicles Per Day)

A. Quarry 100

Speed Limit	Speed Gradient 0.6	0.7	0.8
25	0	3,300	6,600
30	3,800	6,000	8,100
35	6,500	7,600	8,700
40	9,200	9,200	9,200
45	9,700	8,600	7,500
50	10,200	8,000	5,900
55	10,700	7,500	4,200

B. Quarry 102

Speed Limit	Speed Gradient 0.6	0.7	0.8
25	2,000	5,200	8,500
30	5,700	7,900	10,100
35	6,500	9,500	10,600
40	11,100	11,100	11,200
45	11,600	10,500	9,500
50	12,200	10,000	7,800
55	12,700	9,400	6,100

C. Quarry 104

Speed Limit	Speed Gradient 0.6	0.7	0.8
25	0	0	0
30	0	0	0
35	0	0	0
40	0	0	0
45	0	0	0
50	1,500	0	0
55	4,400	1,100	0

From field surveys we know that our carbonate aggregate pavements exhibit speed gradients ranging between 0.6 and 0.8. To allow for this variation, the actual maximum acceptable or safe ADT for any given speed limit is the smallest value of the ADT's listed in Table 8 for that speed limit and speed gradient range. Accordingly, it is observed that based on the use criteria developed in this investigation Quarry 104 has no ADT level at which its material can be safely used in a bituminous surface course. In striking contrast, coarse aggregate from ledger dolomite Quarries 100 and 102, apparently can be used in a variety of situations.

The safe ADT values for the ledger carbonates are actually quite similar in magnitude with only a slight performance advantage being indicated for Quarry 102. Since the two ledger dolomite sources are similar in skid resistance performance, it is considered appropriate that one common set of maximum safe ADT values be established from the separate quarry listings of Table 8. A common set of ADT use criteria would, of course, be easier to administer. The resulting listing of maximum acceptable or safe ADT values applicable to the ledger dolomite quarries of this study is given in the center of Table 9.

2. Finalization

In reviewing the results of the preceding analysis, it was realized that all of the computed safe ADT values (Table 9) were substantially less than the ADT base of 15,000 used in their development. There was concern that perhaps the adjustment equations used to account for the speed limit and ADT effects were being applied beyond their range of applicability. Possibly at the low ADT levels the slope parameters of these equations changed. To clarify this point, regression analyses were performed on all 1976 SN measurements for bituminous pavements with ADT less than 10,000 vpd. Based on an analysis of 1233 data points, the slope of the SN vs speed limit curve was found to be 0.4378 SN/mph and slope of the SN vs ADT line was -0.0008120 SN/vpd. In a statistical test these new slopes proved to be significantly different from those of Table 6 which were used to develop the safe ADT levels listed in the center of Table 9. Apparently at the very low ADT levels the beneficial effect on SN of ADT reductions is more pronounced than anticipated. In contrast, the degrading effect of speed limit reductions appears to become less pronounced.

Table 9

Maximum ADT Values (vpd) for

Ledger Dolomite Quarries 100 and 102

	Range of ADT Analyzed	
Speed Limit	0 - 20,000 vpd.	0 - 10,000 vpd
25	0	3,900
30	3,800	5,400
35	6,500	6,400
40	9,200	7,100
45	7,500	5,500
50	5,900	3,800
55	4,200	2,200

Based on the results of the regression line analysis of 0 - 10,000 ADT pavements, it was decided to redetermine safe ADT values using the new adjustment slopes and only considering SN data for pavements with traffic volumes less than 10,000. For this reassessment the base levels of speed limit and ADT were set at 50 mph and 10,000 vpd. To provide sufficient data for analysis, the SN measurements for the two ledger quarries were combined yielding a total data set of 158 SN values. Also, the permissible percent of SN measurements that could fall below the NCHRP minimum was set at 11% (α allowable = 11%), one percent lower than the average percentage figure for all bituminous pavements of 0 to 10,000 ADT (See Table 5).

Statistical checks established that the new adjustment slopes for SN were applicable to the combined Quarry 100 and 102 data file. With Quarry 104, a larger slope value for the speed limit effect was indicated; also, the slope data of its SN vs ADT regression line revealed that a zero adjustment factor for ADT changes was more appropriate. By applying the applicable slope factors for SN adjustments and the procedures given in Figure 5 and in the Appendix, a new set of safe ADT values were calculated. For Quarry 104, the results were essentially the same as that found in the 0 - 20,000 ADT analysis; there were no safe ADT levels indicated. The maximum allowable ADT values established for the Quarry 100 and Quarry 102 combination is given in the right side of Table 9.

The ADT levels found from the analysis of the 0 - 10,000 ADT range are seen generally to be somewhat lower than, but comparable to those that evolved from the more expansive analysis of pavements with traffic volumes up to 20,000 ADT. The only major differences of concern occur at the 25 mph and 55 mph speed limit conditions. At these speed levels the two analysis methods differ in the prediction of an extremely low value for the maximum safe ADT. The question as to which method is correct therefore becomes important. Fortunately, the lack of agreement at the 55 mph level is of no practical consequence since 55 mph routes in New Jersey would be dualized facilities and would never have design volumes as low as 4,200 vpd, let alone 2,200 vpd. Thus, regardless of which ADT limit applied, the ledger dolomites would not normally find application on 55 mph roads. At the 25 mph speed limit condition, it is believed that the results from the 0 - 10,000 ADT analysis have a better likelihood of being correct. The predictability of that analysis should be better at the lower ADT levels. However, some type of verification of the 25 mph level prediction is desirable.

A rough check on the maximum safe ADT value for 25 mph traffic could be obtained by assuming that both analysis approaches are correct, but for different, non-overlapping ranges of traffic volume. It would seem that the 0 - 20,000 ADT analysis (Analysis A) should be fairly accurate for traffic conditions from 20,000 vpd down to 10,000 vpd, with the 0 - 10,000 ADT analysis (Analysis B) applying below that point. If this is indeed true, then SN distributions used in

Analysis A could be adjusted to the 10,000 vpd point common to both analyses and serve as new data for evaluation by Analysis B. This would yield an independent check of the results of Analysis B, provided the raw SN data of Analysis A was not the same data as that evaluated in Analysis B. The latter provision was somewhat satisfied in our prior treatment of skid resistance data for the ledger dolomites. Approximately 25% of the data used in Analysis A was not included in the subsequent Analysis B. Also, Analysis A treated each ledger quarry separately while combined SN data was evaluated in Analysis B.

By applying the preceding reasoning and using the SN vs ADT slope parameter of Analysis A, the SN distributions previously developed for Carbonate Quarries 100 and 102 (given in Figure 6) were adjusted to a traffic volume condition of 10,000 vpd. The adjusted distributions were then evaluated via Analysis B to establish a new estimate for the maximum safe ADT for 25 mph traffic. The resulting lowest maximum ADT value was found to be 4700 vpd, occurring with Quarry 100 at a speed gradient of 0.6. Considering the nature of the assumptions made in this verification effort, the 4700 vpd figure is believed to be in fairly good agreement with the 3900 vpd predicted previously by Analysis B. Thus, it would seem that the one questionable result of Analysis B is indeed valid.

The investigative work presented herein indicates that the Department's attempt to find alternate use restrictions for carbonates has been partially successful. Based on a review of the data of Table 9, it would appear that a conservative criterion would be to permit coarse aggregate from the ledger dolomite quarries (100 and 102) to be used on all bituminous pavements with design ADT's up to 4,000 vpd and with speed limits up to 50 mph. Such an approach would accommodate a certain amount of inaccuracy in the design process at the mid range of speed limits,which correspond to the most likely use levels for carbonate materials on non-Department projects. In the case of Carbonate Quarry 104, our investigation has failed to establish any justification for liberalizing the current restrictions on use of its material.

C. Other Considerations

It is to be realized that the analysis procedures developed herein have only given consideration to two factors effecting skid number: speed limit level and ADT level. It is possible that other variables such as pavement age and number of traffic lanes may also have a detectable effect. An effort should be made to obtain information that would permit an adequate assessment of these other factors. Also, any future investigation should look to the use of multiple regression analysis techniques so that interaction between factors can be more completely accommodated than was possible in this study.

The reader is to be advised that the Department's investigation of carbonates was based on a consideration of skid numbers for FABC (fine aggregate bituminous concrete) surface courses as that type of material predominates on our road system. However, the Department of Transportation is presently in the process of switching to an MABC (medium aggregate bituminous concrete) surface course for all bituminous paving work. It is also likely that many of the state's local governments will follow the Department's lead.

The new mixture will provide harsher riding surfaces that possess more macrotexture than an FABC pavement. Fortunately, this change would be beneficial from a skid resistance standpoint. Previous field comparisons involving pavements with trap rock aggregates indicate that MABC will provide for surfaces of higher mean SN and flatter speed gradients. It is therefore expected that, at the very least, MABC mixture with ledger dolomite will be as skid resistant as the present FABC surfaces containing such aggregate. Of course, the actual effects of the change in mixture type must be monitored with time to verify this assessment.

Another aspect of the carbonates study which requires further comment is the information given earlier describing the general skid resistance quality of the Department's bituminous pavements. In Table 5 it was shown that about 24% of all skid numbers fall below the minimum SN values of NCHRP Report #37. First, it must be pointed out that this number is inflated somewhat due to the normal variability or precision of the skid testing process. If one takes into account testing error, the percentage figure drops to almost 20%. Also, it is to be noted the Department is continually working to reduce the number of pavement sections that yield low skid numbers. Its skid resistance inventory program annually feeds a list of low skid number pavements to the Department's maintenance forces where corrective resurfacings are scheduled. The decision to switch to the MABC type of surface mixture was an additional move to upgrade the general skid resistance quality of Department maintained highways. Research efforts to effect still further improvements are also underway. The development of reliable design methods for open graded anti-skid mixtures is one particular research endeavor that should prove extremely beneficial in this regard.

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APPENDIX

Procedure for Finding Maximum Acceptable ADT Use Levels for A Particular Carbonate Coarse Aggregate in Bituminous Pavement

1. Gather SN, speed limit, and ADT data for all bituminous pavements on the Department's road system which fall in the ADT range under consideration. Perform linear regression analyses to determine the slopes of the SN vs Speed Limit and SN vs ADT lines. The SN vs Speed Limit regression should be done first. The slope value found in that regression should then be used to adjust the SN data to 50 mph and the SN vs ADT line established from the adjusted data.
2. Repeat Step 1 but only consider data for pavements that contain coarse aggregate from the particular carbonate quarry in question. Compare by statistical test the slope values found here with those obtained in Step 1. If there is no significant difference indicated, then the slope information of Step 1 is to be used for all subsequent data adjustments required in this procedure. When a significant difference does occur, subsequent data adjustments are to be made with the pertinent slope value found here in Step 2.
3. Adjust a quarry's SN data to some common ADT base and to a speed limit of 50 mph using the appropriate slopes established from the comparisons of Step 2. If the ADT base is set approximately

equal to the average ADT of pavements containing the quarry's materials, the impact of any error in the adjustment equation would be minimized. The adjustment of each individual SN value is to be made using the equation $SN_{Adj.} = SN + C_1 \Delta$ Speed Limit $+ C_2 \Delta$ ADT where C_1, C_2, Δ Speed Limit and Δ ADT are as given in Figure 5 elsewhere in this report.

4. Establish from a field skid resistance survey the speed gradient for pavements containing coarse aggregate from the quarry in question. Determine from Table 2, elsewhere in this report, the NCHRP(4) recommended minimum skid number for a 50 mph traffic speed on a pavement having the speed gradient identified in the field survey.
5. Perform a histogram analysis on the adjusted SN data of Step 3 and determine the percent of SN measurements that fall below the minimum SN found in Step 4. Also determine the percent of SN values below 40, 39.....31. At least fifty (50) individual SN data points would be needed to achieve reliable percentage determinations. Plot a curve of SN versus percent below minimum SN.
6. From a plot established in Step 5, determine the Δ SN required to shift the histogram of adjusted SN such that the percent below minimum SN will be 1% less than the average percent below figure for all pavements of the ADT range under consideration. (See Table 5 elsewhere in this report). SN is to be considered positive in magnitude if an SN increase is required and negative if a decrease is needed.

7. Now determine the amount of change in ADT from the base ADT required to achieve the Δ SN found in Step 6. This is determined by dividing Δ SN by the SN vs ADT slope value used to make the original SN adjustments in Step 3. Add the computed change in ADT to the base ADT and establish the maximum acceptable ADT value for use of that quarry's material on 50 mph speed limit roads. To compute maximum acceptable ADT's for other speed limit conditions follow subsequent Steps 8 thru 10.

8. For any other desired speed limit conditions compute the Δ SN that will occur with the change in speed limit from 50 mph to the desired speed limit. This is calculated by multiplying the change in speed limit, in mph, (reduction is given a minus sign, increase in limit is positive) by the slope of SN vs speed limit regression line as used in Step 3. The result of this computation is designated as $\Delta \text{SN}_{\text{speed}}$.

9. For the new speed limit condition determine the associated change in minimum SN (NCHRP recommended minimum value) from Table 2, elsewhere in this report. A reduction is given a minus sign; an increase is considered positive. The result is designated as $\Delta \text{SN}_{\text{limit}}$.

10. Subtract $\Delta \text{SN}_{\text{limit}}$ from $\Delta \text{SN}_{\text{speed}}$ being cognizant of sign. The result of this subtraction is designated as $\Delta \text{SN}_{\text{speed limit}}$.

    $\Delta \text{SN}_{\text{speed limit}}$ is then divided by the slope of the SN vs ADT line, as used in Step 3, to obtain the change in ADT needed to correct the shift in mean SN caused by the speed limit change. The Δ ADT so determined is then subtracted algebraically from the ADT value established for a 50 mph speed limit condition. The new ADT value becomes the maximum acceptable ADT for use of the quarry's material on a road having the speed limit in question.