930-347

Skid Resistance of Asphalt Wearing Courses Made with Limestone Aggregates

FINAL REPORT

Submitted to

Alabama Department of Transportation
1409 Coliseum Boulevard
Montgomery, AL 36130

Prepared by

Larry Crowley
Principal Investigator

Frazier Parker, Jr.
Director, Highway Research Center

Date:

May 31, 2001

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Preserving and improving adequate wet-weather traction is centrally important to enhancing roadway safety. In Alabama, twenty-two percent of traffic accidents and fifteen percent of fatal accidents occur on wet pavement even though Alabama roadways are wet only four percent of the time.

While the benefits of wet-weather traction are high, costs in achieving these results are high as well. Today, most highways are resurfaced to remedy poor friction performance well in advance of any structural failure. Costly siliceous aggregates are routinely specified to improve friction and extend time between resurfacing. Many less expensive local aggregates, such as limestone, have been historically excluded from use in surface mixtures due to a perception of poor friction performance.

This 'surface course' limitation on limestone was changed for Alabama highways in late 1993 allowing up to 80% limestone depending on their value on the '9-hour British Pendulum Number' [BPN(9)] test.

This study was undertaken specifically to relate the observed skid resistance of dense-graded HMA pavement to the BPN(9) value and content of the limestone aggregate within the surface mixture. Later, concrete bridge deck surfaces made from limestone aggregates were added to the scope; however, at the close of the contract period only minor progress had been made on this subject.

The study utilized 'observational study' which is an approach to scientific inquiry where one learns through observing, organizing what one observed, and then explaining it. This is an 'experiential' approach to scientific inquiry, in lieu of the more familiar 'experimental' approach. In conducting research in this manner a large pools of natural-state data is used to allow investigators to observe factor relationships and formulate conceptual models that explain the actual variation in the underlying data.

The observational sample used in this study consisted of 7778 individual skid tests, which produced skid numbers as low as 21 to a high of 64. With testing every tenth of a mile, these tests effectively sampled close to 800 miles of roadway spread throughout 46 different counties within Alabama. These roadways ranged from a two-lane highway to a heavily traveled intercity freeway. Overall, these pavements reflected the outcome of 93 separate projects with limestone contents ranging from 14 to 80% and limestone quality measured by BPN(9) from 18 to 35.

These 7778 'skid performance' observations were explored to determine if any underlying 'order' exists within the data. In this context, each observed data point represents not only a single 'skid number' test result but also a singular record of 29 other associated factor measurements. These 29 associated factors include indications of pavement design and construction such as BPN(9), Percent Limestone, Tensile Strength Ratio, and Mix Number; indications of surface polishing action such as Cumulative Traffic, Days-In-Service, and Degree-of-Curvature; and indications of temporal influences in test responses such as Day-of-Test Rainfall, Seven-Day Rainfall and Maximum-Temperature on Test-Date. Each of the 29 factors was mapped in concert with every other factor providing a total of 399 separate factor pairings that were individually explored and reported in a two-volume document forwarded with the Quarterly Report of November 1999.

Explaining what is being observed is perhaps the most difficult of tasks related to the observational study approach. In recognition of its difficulty, the task of explaining is divided into two segments. First, the focus is on establishing a model of typical pavement wear to use as a baseline in identifying instances of accelerated wear. Three separate models were considered prior to adopting a service exposure-intensity model. While this statistical 'wear' model does not bring significant explanatory order to the data (accounting for only 12.3 percent of the variability); however, the influence of service exposure and intensity within the data is undeniable.

Second, the focus centers on the pavement influences that affect friction performance relative to the baseline wear. This task was approached deductively, moving from general effects to specific causes, using seven progressively more detailed statistical models as follows:

1. Considering a 'Project' Model. The project, as represented by its project number, serves as a surrogate to 'stand-in' for some as yet unidentified, but significant causal factors that are naturally shared within individual projects. This model when combined with the 'wear baseline' variables can account for 68.4 percent of the variation in the observed skid performance.

2. Considering a 'Limestone Aggregate Source' Model. Quarries produce aggregates with similar characteristics. Using limestone source as a variable in allows aggregate 'quality' characteristics into the model without specifically limiting it to BPN(9). This model accounts for 49.6 percent of the observed friction variability.

3. Considering a 'Limestone Content' Model. Limestone aggregates tend to polish overtime, thus losing micro-texture and impeding surface friction. The original research object was to determine a limit, if possible, of limestone content in the surface mix based on limestone BPN(9) values. When content is considering as a single continuous variable the model describes only 23.1 percent of the variability in skid numbers. However, when separate limestone contents can act as though they are independent variables the descriptive power is a high 47.6 percent.

4. Considering a 'Limestone Source and Content' Model. Combining limestone source and content in a single model is on track with the research objective, except in this case 'quality' is not solely based on the BPN(9) value. This model had a relatively high descriptive power of 55.7%, but the influence of quantity alone is not significant in the model. Only when combined with the quality, does quantity contribute to the model.

5. Considering a 'Limestone BPN(9)' Model. BPN(9) is included within the assortment of undifferentiated 'quality' factors contained in the previous models; however, here limestone quality is strictly defined by only its BPN(9) values. When used as a continuous variable, the BPN(9) model accounts for only 17.1% of the variation in friction performance. More descriptive power is assigned to the model when the variable is used as a class variable with 39.7%.

6. Considering a 'Limestone BPN(9) and Content' Model. This mathematically defines the research objective, but only describes 23.2% of the variation in the observed friction values. This is not in keeping with expectations if in fact there is a cause-and-effect relationship in play.

7. Considering a 'Natural Sand Content' Model. Natural Sand Content quantifies the amount of natural sand making up the fine aggregate fraction of the surface pavement. Using content as a continuous variable the model describes 22.9 percent of the variability in the data. When used as a class variable the model describes 39.0 percent.

The following seven **conclusions** are drawn from the study:

1. No apparent relationship exists in the observational data between long-term friction performance and limestone aggregate BPN(9) values and the pavement surface contents of these aggregates.

2. Friction is not well characterized in pavement-oriented research published to date.

3. The standard 40-mph skid-trailer test does not accurately replicate coarse-aggregate dependent friction performance.

4. Limestones polish most likely as a result – not a cause—of aggregate characteristics that lead to poor friction performance.

5. Observed friction performance is a composite effect of a multi-dimensional phenomenon.

6. BPN evaluation of limestone aggregates is an imperfect reflection of the characteristics being studied.

7. Frictional contribution of siliceous material is misrepresented and underrated.

The following seven **recommendations** are made:

1. There should be a continued collection and evaluation of skid test data on Alabama highways.

2. The skid performance data should be analyzed on the basis of silica content of limestone coarse aggregates.

3. These research findings should be focused on individually and progressively so as to craft a foundation on which to resolve the roadway friction problem.

4. A study of coincident conditions associated with skid accidents should be performed in order to better reflect actual critical conditions in our performance testing and evaluation methods.

5. Skid testing parameters should be modified to more closely match the identified critical conditions found in accomplishing recommendation 4 above.

6. A finite element model of the pavement surface should be created to reflect surface response, chemistry, geometry, and antecedent temporal conditions.

7. Trial surface mixes should be developed for test-track implementation.

1. INTRODUCTION

In Alabama, twenty-two percent of traffic accidents and fifteen percent of fatal accidents occur on wet pavements even though Alabama roadways are wet only four percent of the time. While these accidents may be partly blamed on diminished visibility during rain events, undoubtedly the single leading cause of these accidents is the loss of vehicular control at the tire/pavement interface. Preserving and improving adequate wet-weather traction is centrally important to enhancing roadway safety.

While the benefits of wet-weather traction are high, costs in achieving these results can be high as well. Today, most highways are resurfaced to remedy poor friction performance well in advance of any structural failure. Costly siliceous aggregates are routinely specified for the pavement surface courses in order to improve friction and extend the time between resurfacing. Many less expensive local aggregates, such as limestone, have been historically excluded from use in surface mixtures due to perceptions of poor friction performance and the resulting short intervals between resurfacing.

Although routinely excluded, limestone aggregates have much to recommend them for use in pavement mixtures. The resulting angular particle shape and rough surface texture of crushed limestones prove favorable in resisting structural failures such as rutting. The basic chemistry of this carbonate stone makes the potential stripping of these aggregates from the pavement surface remote. The absorption tendency and asphalt demand of this aggregate allows pavement mixtures to be produced relatively inexpensively. Finally, limestones are readily available at low costs.

Although routinely desirable, siliceous aggregates have many perceived disadvantages in its use for surface courses. The rounded particle shape and smooth surface textures may lead to rutting and other structural failures in the pavement. The acidic chemistry of siliceous aggregates allows stripping. The absorption and resulting higher asphalt demand for some siliceous aggregates can contribute to a relatively expensive pavement mixture. Siliceous aggregates are not always available and often are expensive.

The single limestone characteristic that tips the balance against its use (even with all of its advantages) in favor of siliceous aggregates (regardless of its disadvantages) is the tendency for limestones to polish. The generally held belief is that limestone polishes under the abrading action of traffic; pavements using these aggregates lose skid resistance from this loss of texture. For many years this perception has worked to limit the limestone amount used in surface course mixes.

This 'surface course' limitation on limestone was changed for Alabama highways in late 1993 with the issuance of a special provision allowing increased use of limestones aggregates beginning in the 1994 construction season. This special provision required a minimum of 30% crushed stone in surface mixes and allowed up to 80% limestone depending on the tested '9-hour British Pendulum Number' (BPN9) results for the limestone. Prior to this 1993 special provision, the use of limestones in surface course mixes were limited to 20% of the total aggregate with the additional restriction that all limestone passes the 3/8-inch sieve.

The increase in limestone usage resulted from the findings of two studies. The first study, funded by the Alabama Department of Transportation (ALDOT), compared the structural and frictional properties of surface mixes with 100% siliceous aggregates (crushed gravel coarse aggregate) versus surface mixes with up to 60% limestone. The comparisons based on laboratory tests proved inconclusive regarding any structural improvement or frictional degradation with increased limestone usage. Three field-test sections were constructed in Chilton, Fayette, and Hale counties with mixtures containing 33%, 30%, and 35% limestone, respectively. Skid tests over these roadway sections showed that these experimental mixes provide skid resistance as good as the control 'crushed gravel' mixes or in some causes better.

The second study, funded by the Auburn University Highway Research Center, compared the polish and frictional properties of Alabama limestones and crushed gravels. This study compared BPN9 values for limestone and crushed gravel and determined them to be similar. Based on this study, six additional field test sections were constructed during 1992-93 containing from 30 to 80% limestone. These sections provided skid resistance equivalent to the control sections after one to two-years exposure to traffic.

Implementation of the 1993 special provision resulted in a dramatic increase in limestone use in surface course mixes during the 1994 construction season. Ranging considerably in terms of limestone content and quality, these mixes will likely exhibit a varied skid performance record over time. There was a need to develop a database of these and subsequent projects to document and track the skid performance of surface mixes containing limestone aggregates.

The purpose of the present study is to develop a relationship between skid resistance of dense-graded HMA pavement surfaces and the limestone aggregate amount used in HMA and its relative quality in terms of polish/frictional characteristics. The results of this evaluation was to assist in formulating recommendations for acceptable specified ranges for limestone content as a function of its BPN9 value to be included in ALDOT's *Standard Specifications for Highway Construction.*

In November 1997, a solicited proposal was submitted to ALDOT to augment the scope of the original study to include considering the friction performance of concrete bridge decks constructed with limestone aggregates. This proposal was accepted with a corresponding increase in contract time and amount. However, at the close of the contract time only minor progress had been made in studying these bridge decks. The remainder of contract funds was returned to the sponsor at its request.

2. RESEARCH OBJECTIVES

The original study objective was to develop relationships between the skid resistances of dense-graded HMA pavement surfaces and the amount and quality (polish/frictional characteristics) of limestone aggregates used in constructing the pavement. Later, the project objective was broadened to include investigating the skid resistance provided by the bridge wearing surfaces made from concrete containing limestone coarse aggregate.

The tasks identified in accomplishing these objectives are partitioned below into two sections. One section deals with the original scope under 'Asphalt Wearing Course' and the other deals with the changed scope under 'Concrete Bridge Decks.'

Asphalt Wearing Course

The work in accomplishing the original study objectives was divided into six tasks:

Task I: Update Literature Review

This task involved updating and reviewing the available literature on limestone aggregate skid resistance that was made during the research effort entitled "Evaluation of

Limestone Aggregates in Asphalt Wearing Course – Phase II" conducted by the Highway Research Center and reported in March 1992.

Task II: Develop Research Design

The initial research design conducted during this task consists of performing preliminary statistical analysis, refining the list of potential factors of research interest, and developing a research approach. The preliminary statistical analysis was performed on early data in order to determine factors correlated with the degradation of observed skid resistance in asphalt using limestone coarse aggregates. This analysis provided insight into the study problem and allowed screening of potential factors contributing to the variation in skid resistance.

The list of potential factors was developed around three distinct categories: pavement, polishing, and response. The factor breakdown structure is illustrated in Figure 2.1. The 'pavement' category consists of factors that are descriptive of the pavement in terms of mix proportions, material properties, and performance indicators. As illustrated in the figure, many of the underlying material properties can be initially represented by their source. Later, if significant differences between sources are observed the underlying individual properties can be statistically scrutinized. The 'polishing' category represents factors that may contribute to the polishing action on the pavement; as such, it represents the mechanics of polishing. The 'response' category consists of factors dealing with the skid-test results both in terms of skid resistance number and factors impacting the tests that are unrelated to the actual pavement performance.

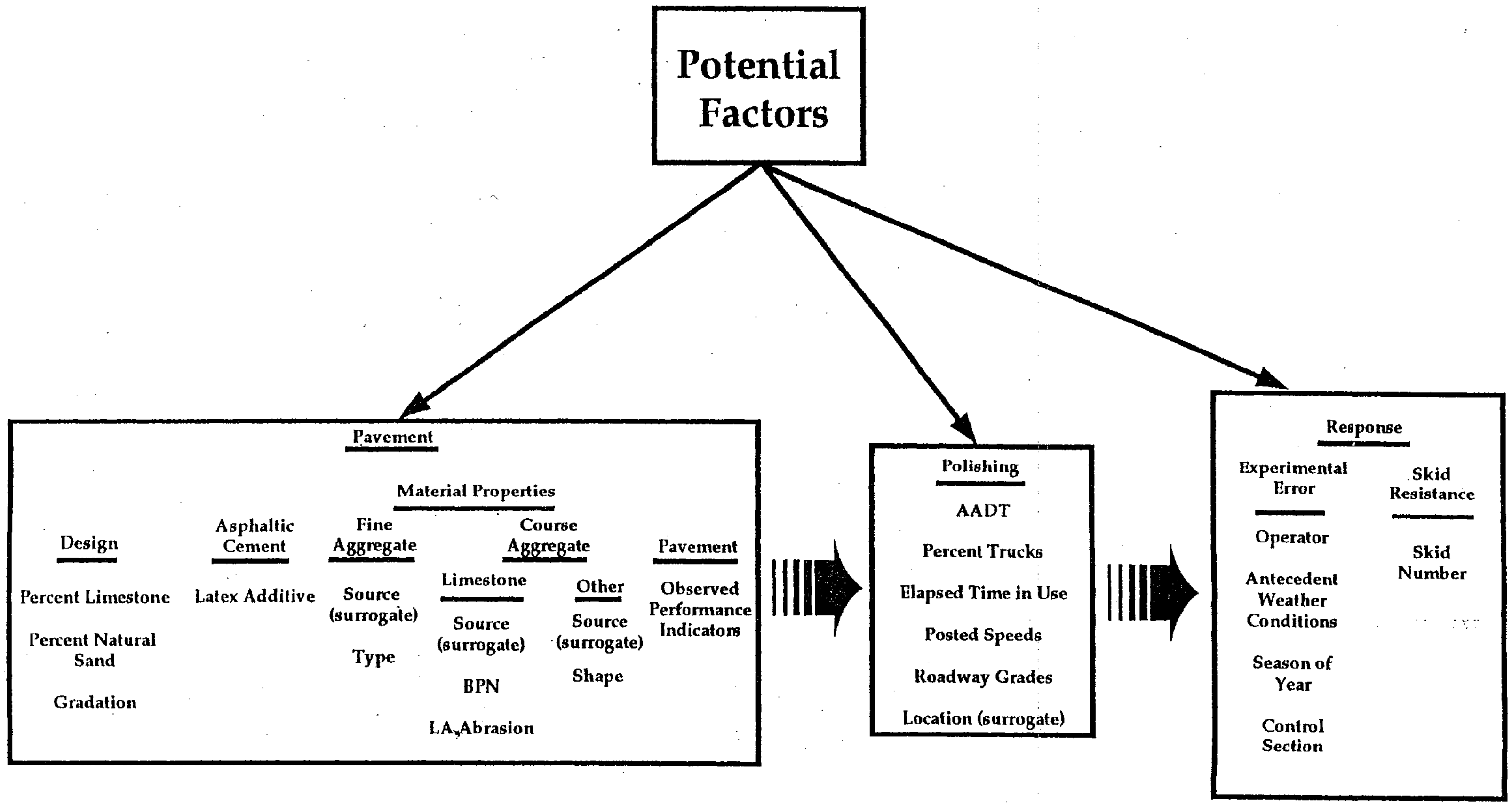


FIG. 2.1. Potential HMA Pavement Factors and Categories.

The research approach centered on a statistical model that attempts to explain through the factor structure outlined above the observed variation in the skid resistance number. As proposed, the research was performed in a sequential nature using a fractional factorial approach. This approach allows successive iterations of selecting and sampling certain sites where factors are at targeted levels. The fractional factorial aspect of the research approach is illustrated in Figure 2.2 using two potential factors. These two factors, percent limestone and AADT, are shown in the figure along with hypothetical skid numbers. The factor space is defined by the range over which the two factors are allowed to vary. In this example, limestone varies between 0 and 80 percent of the course aggregate and AADT varies between 0 and 30,000. Each of these are continuous variables, meaning an inexhaustible number of combinations; but, the factor space can be divided into regions and thus initially modeled by a limited number of tests sites; in this case, five test sites (marked by dots). Potential extension of the coverage is shown with circles. This technique allows complete coverage of the factor space, a methodical research approach, and the identification and subsequent emphasis on factors levels that show promising predictive power.

Finally, this task will include selecting approximately 72 initial test sites that will provide optimal coverage of the identified factor space.

Task III: Document Interim Analysis and Findings

An interim report was planned for delivery one year into the study to document the effort, results, and findings obtained to date. Depending on the relative strength of the statistical evidence, tentative conclusions and preliminary recommendations were planned to be included in the interim report.

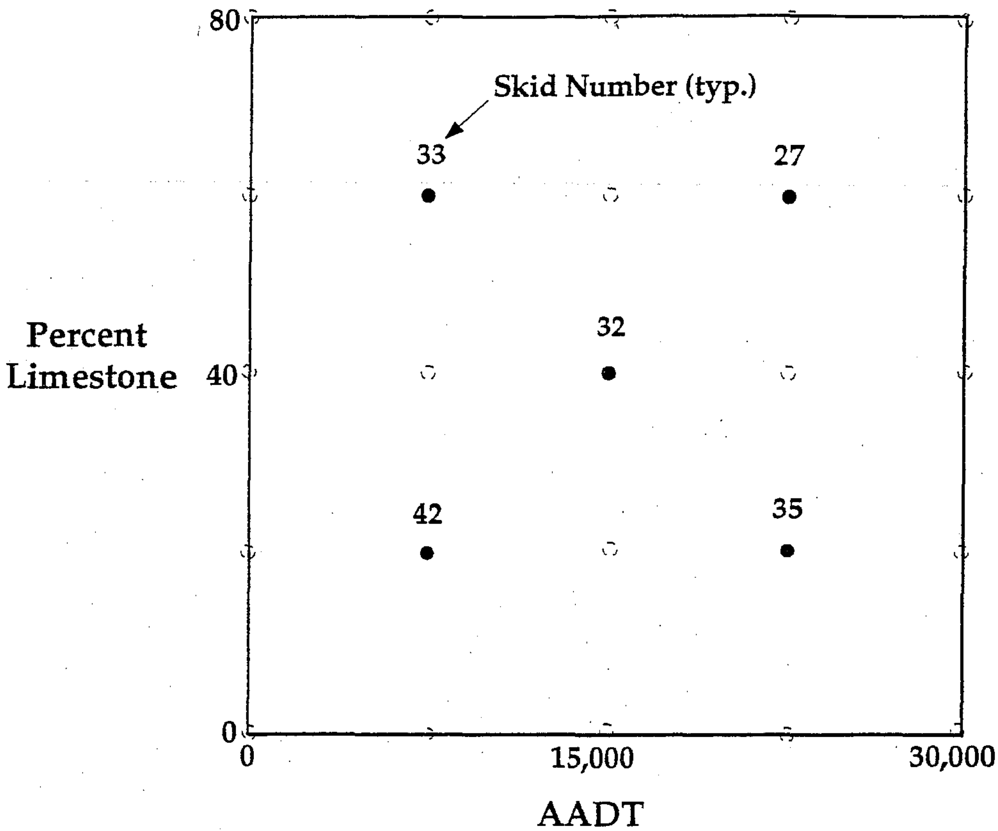


FIG. 2.2. Example of Fractional Factorial Approach.

Task IV. Select Project Test Sites

Based on the interim findings, the researchers were to select an additional 72 (+/-) 'skid resistance' test sites to include in the study at the beginning of both the second and third years of the study effort. These sites were to be selected to allow expanding the amount of variance definition in the more interesting factor space regions.

Task V. Perform Data Collection and Analysis

As an ongoing task of the study effort, skid resistance data was to be collected and analyzed on a quarterly basis.

Task VI. Document the Analysis, Conclusions, and Recommendations with Final Report

The final task in the original work was to submit a final report to ALDOT documenting the analysis that including conclusions and recommendations of the relationship between the use of limestone aggregate and the skid resistance of the asphalt wearing course.

Concrete Bridge Decks

Under a change requested by ALDOT, the project objective was broadened to include the investigation of skid resistance provided by concrete bridge wearing surfaces containing limestone coarse aggregates.

To incorporate the change, revisions were made to Tasks III through VI and new Tasks VII and VIII were added as described below.

Task III. Document Interim Analysis and Findings (revised)

The interim report, which was to be delivered one-year into the project, was delayed until November 1998 and should include both asphalt and bridge-deck wearing surfaces.

Task IV. Select Project Test Sites (revised)

Based on the interim findings, the researcher was to select sections and bridges that exhibit interesting characteristics with respect to skid resistance factors. This task was also postponed until after the interim report was delivered.

Task V. Perform Data Collection and Analysis (revised)

Skid resistance data was to be collected and analyzed as an ongoing task of the study effort. This task was to be broadened to include bridges as well as roadway sections.

Analysis of the factors affecting the skid resistance of bridge decks was to require collection of: (1) deck age; (2) traffic (AADT and percent of commercial vehicles), (3) skid numbers; (4) coarse aggregate (type, source, properties); (5) fine aggregate (type, source, properties); and (6) type of applied texture (burlap drag, broom, tine, sawed source, grooves). Data availability is extremely variable. Some data, such as traffic and skid number, are collected regularly and maintained in readily available databases. Other data, such as aggregate properties and surface texture, is available only in mix designs or construction records and is more difficult to obtain. Determining the availability of necessary data and collecting it for bridge decks was to comprise a significant effort.

Task VI. Document with Final Report (revised)

Submit a final report to ALDOT documenting the analysis. As revised, this report was to include conclusions and recommendations concerning the relationships between skid resistance and limestone aggregate properties of both wearing surfaces involving asphalt and concrete bridge decks. The delivery of this report was postponed until after the expiration of the two-year extension to the project.

Task VII. Review Bridge Deck Literature (new task)

This task involved reviewing available literature on contributing factors to bridge deck skid resistance.

Task VIII. Develop Bridge Research Design

The initial research design conducted during this task was to consist of performing a preliminary statistical analysis, refining the list of potential factors of research interest, and developing a research approach. The preliminary statistical analysis was to be performed on early bridge data in order to determine factors correlated with observed 'skid resistance' degradation on concrete bridge decks using limestone aggregates. This analysis would provide insight into the study problem and allow screening of potential factors contributing to the variation in skid resistance.

A list of potential factors would have been developed around three categories: bridge deck, polishing, and response. The factor breakdown structure is illustrated in Figure 2.3. The 'bridge deck' category consists of factors descriptive of bridges in terms of surface treatment, concrete mix designs, bridge design and maintenance, and construction techniques. Much of this information may not have been readily available on older bridges and therefore a trial search of available information was to be performed at an ALDOT division close to Auburn.

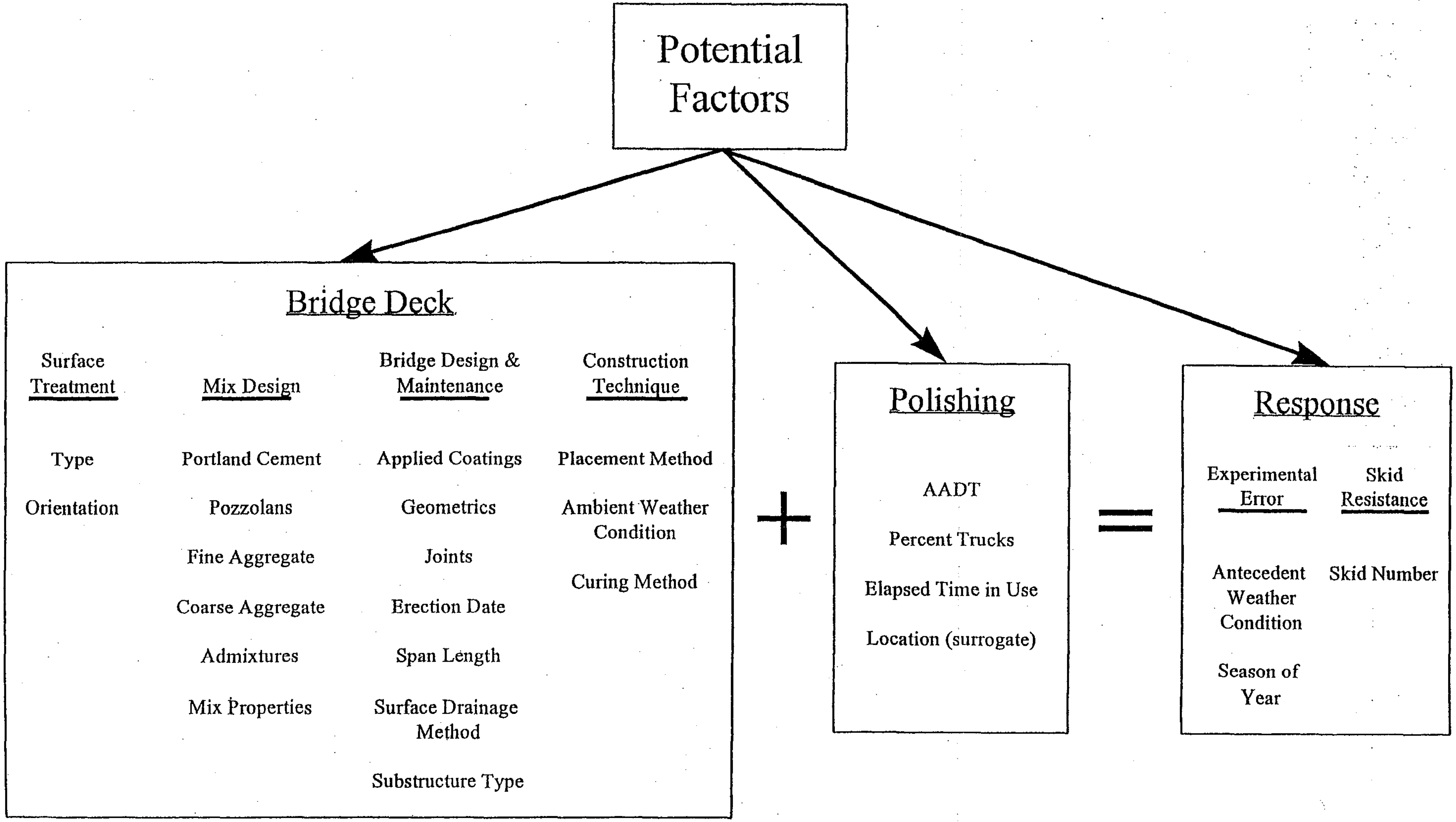


FIG. 2.3. Potential Concrete Bridge Deck Factors and Categories.

The 'polishing' category represents factors that may contribute to the polishing action on the bridge deck and as such represents the polishing mechanism identical to that experienced by asphalt pavement but over longer periods of time.

The 'response' category consists of factors dealing with the skid testing results both in terms of the skid number and factors unrelated to the actual deck performance but which impact the test results.

3. BACKGROUND AND LITERATURE REVIEW

The scientific 'root' of skid resistance is the natural law of *Conservation of Energy.* To start at any other point risks being misled into errors of belief not consistent with what is known to be true within a larger context.

Conservation of Energy is the principle that *energy can be neither created nor destroyed.* The energy level within a hypothetically closed system (one without energy leaks) will not change in total magnitude while energy is being converted from one form to another within the system. To illustrate this natural law, consider whether water is warmer at the top or bottom of a waterfall. In keeping with 'conservation of energy' principles, the energy at the top of the waterfall is equivalent to that at the bottom if proper 'energy accounting' is performed. Obviously, energy is present at the top of the falls with the enormous potential capacity for the water to do work in the process of changing elevations. If left unharnessed, this potential capacity is first converted to kinetic energy as the water cascades over the edge, gaining velocity as it freefalls. At the bottom of its fall, tremendous noise in generated in its receiving basin as the fall of water is broken. (Note: Noise is a form of energy.) Further downstream, the water resumes its relatively tranquil course along its streambed.

Apart from noise, where did the energy go within this system? Because of the *conservation* principle we can be certain that it didn't simply dissipate. But, finding all of it becomes an arduous undertaking -- a type of scientific accounting process. Most definitely some, but not all, of the energy was converted to heat, a kind of kinetic energy that is internal to the molecule itself. So water is in fact hotter at the bottom of the falls where this heat represents a fraction of the total energy that was so obviously present within water at the top of the falls.

How does this example relate to skid resistance? It relates at the level where the 'absolutes' of natural law governs. In a closed system, energy is neither created nor destroyed. This store of converted energy is constant within a 'waterfall' system as it is within a system directed toward venting the kinetic energy of a moving vehicle mass. The fact that vehicles stop without going through a visually apparent 'energy conversion' process doesn't mean that one didn't take place.

Skid resistance -- friction – is not a reversible process. Tires do not benignly 'grip the road' when called on to either vent kinetic energy or to change a given direction of motion in preference for another. A non-reversible conversion takes place. We can be equally sure that pavements do not simplistically disperse surface water through macro and micro-texture in order to allow intimate tire/pavement contact and thus slow the vehicle. Something transpires within the vicinity of the contact patch that allows the conversion of energy from one form to another.

The task of accounting for all energy types formed in this conversion example is overwhelming. Therefore, the problem is usually simplified with boundary conditions that allow ignoring much of the reality within which the problem exists. We redefine the problem as one involving 'friction' or 'skid resistance'. In isolation, these concepts may seem manageable, but only because there is so much that is ignored.

FRICTION

What is friction? How does it work? In a broad sense, friction remains a construct within all general scientific applications of an observed, but ill-defined, phenomenon. We know this phenomenon largely as a result of its observed effect. We rub our hands together rapidly during cold weather to heat them up. That is friction. We lubricate pistons to reduce the wear and tear on the engines. That is friction. Soil stands at a given angle of repose. That is friction. But, describing the actual mechanism of friction is purely speculative at this point in time.

Kummer (1966) grapples with four general friction theories in his report entitled *Unified Theory of Rubber and Tire Friction*. First, friction may stem from the mechanical interlocking of surface roughness. This is a typical context in which friction is viewed and plays to the macro/micro-texture characteristic often sought in surface aggregate selection. One aspect of this interlocking is that the kinetic energy of the vehicle mass is converted to potential energy as the tire element is lifted up to the tops of these asperities. But as Kummer points out, one cannot neglect the corresponding gain from this potential energy when it's converted back to its kinetic form by sliding down again. Another possible aspect of this interlocking is that a force derived from the vehicle mass in motion is opposed and overcome by a stationary force. But, where is the energy vented or lost in this system?

Second, friction may be a result of welding-shearing and plowing. Welding-shearing suggests molecular bonding and plowing suggests the harder asperities work their way through softer. These concepts suggest the macro force of a moving mass dissipates while performing micro-scale work. This concept is widely accepted by the scientific community, but can the loss of material inherent in this 'tire/pavement' system properly account for all the energy it is credited with venting. Also, how does this type of friction take happen?

Third, friction may be an effect of electrostatic forces. The rubbing of surfaces initiates electron flow producing opposite polarities at the interface. Kummer points out that there are problems with this concept as well. Fourth, friction occurs through molecular attraction. Energy is dissipated as atoms of one material are 'plucked' out of the mating surface material. Very likely what actually happens is some combination of the above concepts.

Without theoretical underpinning, most all of the friction research undertaken over the years has been experimental by necessity. The problem with this as pointed out by Kummer is that experimental results are often inconsistent among themselves and in relations to classic laws of physics.

Pavement friction, like all frictional processes, is an energy conversion process. In this particular case, many believe the energy of the moving vehicle is transferred and absorbed in one of two ways, either by adhesion or by hysteresis. 'Adhesion' describes the process of molecular bonding that forms at the tire/pavement interface. Through breaking these bonds, a torque is applied to the vehicle brake that in-turn dissipates kinetic energy or the forward momentum by waste heat generated through the brake, that is if the brake is allowed to turn.

If the brake is 'locked-up' as it is in the skid-trailer test, then heat is not released in the brake pad. Instead, the stretching of the underlying substrate material (tire/pavement) that lead up to breaking the bonds will result in generation of waste heat in the internal vibrations within the material itself. Because only one patch of tire is slid across the pavement the skid-trailer test registers a peak friction value that then degrades rapidly as a function of the excitation potential of the tire material. (This may be the reason for good 'tested' friction performance for tires constructed with a generous component of carbon black.) (Note: Limestones are isolated molecules cemented together. The excitation of underlying, non-surface molecules by plucking the surface molecule is unlikely. While silicia molecules exist in long interconnected chains where depth of excitation is possible by plucking only the surface.)

The second component of pavement friction, hysteresis, describes the flexing of tire and/or pavement materials as they deform when the tire slides or rolls over coarse aggregate. In this case, kinetic energy is dissipated by waste heat in the tire and pavement. This frictional component is thought to increase with higher speeds and may be due to the disturbance of non-surface materials.

LIMESTONE COARSE AGGREGATE

Limestone coarse aggregate is quarried limestone crushed to a particular size range for use as a major component in Portland Cement (PCC) or Hot Mix Asphalt

(HMA) concretes. The following discussion of this single component will be divided into two subsections, first discussing coarse aggregate then limestone.

Before moving into the body of the discussion I want to address two introductory questions. First, why combine the discussion of coarse aggregate and limestone into one section? The central reason for this combination is that this study focuses on the inseparable action of coarse aggregates made from limestone. Undeniably, coarse aggregates make significant contributions to pavement performance relative to friction, as well as, structural stability, texture, and the like. Some would even suggest that pavement friction resides entirely in how well a coarse aggregate can maintain its texture.

However, it must also be acknowledged that limestone material also makes its contributions to friction, structural stability, texture, and the like, as well. But all too often the frictional role of limestone is strictly judged on the perceived limitations of this material allowing coarse aggregate to maintain its texture. It must be kept in mind that these two descriptive characteristics of the same exposed object within the pavement surface – that it is a certain sized rock and that rock is made from limestone – are indeed inseparable. We cannot think clearly about the frictional contributions of limestone coarse aggregate and yet continue with the orientation that one descriptive element of this object (limestone) serves only the other (coarse aggregate texture).

Second, why discuss this single item in two separate subsections? In advancing our understanding of skid resistance with limestone aggregates, it is important to distinguish between the features of the coarse aggregate and that of the underlying limestone material. Friction is not strictly about *pushing* tire carcasses to excitation (hysteresis) in order to substitute external (velocity) for internal (heat) kinetic energy through contact with a roughened coarse aggregate. Friction is also about *pulling* tire elements (adhesion) in order to accomplish the same objective but in this case by developing and stretching molecular bonds between the contacting materials. These distinct contributions are indisputable; after all we readily acknowledge that a single friction coefficient (μ) is not sufficient to describe the affects that different materials have on the observed 'energy transfer rate' known as friction.

Just as we can't think of the two description elements as inseparable, we can't advance our understanding of skid resistance while believing these two separate features contribute in the same manner.

Coarse Aggregates

Coarse aggregate, what is it? Coarse aggregate is a rock large enough to be retained on a No. 4 sieve (3/16th inch square opening) and suitable for use within Portland Cement (PCC) or Hot Mix Asphalt (HMAC) concretes.

For this study, the rock is crushed from quarried limestones. Its processing takes place in a lengthy series of sequential steps beginning with actually producing the coarse aggregates from limestone quarries all the way to placing it in the finished surface course. These steps include locating the quarry, licensing for operation, extracting the rock, crushing to size, transporting, preparing for use, mixing into concrete, and finally placing the pavement. Each step has variable costs elements based on a multitude of factors that can make the resulting pavement anywhere from exorbitantly expensive to attractively priced. Many of these cost elements often work at cross-purposes to the resulting quality and serviceability of the roadway. This 'cost vs. quality' trade-off is no different when it comes to the use of limestone coarse aggregates for a friction surface. Locally available, relatively easy to crush, easy to dry, low demand on asphalt binder -- limestone coarse aggregates have much to recommend them for those paying the installation costs of the pavement. However, friction performance is the quality that is traded off. Many believe 'limestone coarse aggregate' surface pavements wear out quickly, need to be replaced early, and lacks long-term economic viability.

In terms of friction performance, the 'quality' characteristics deemed most significant for coarse aggregates are size, shape, and most importantly texture. Size and shape are seen to provide macro-texture. Aggregate size is specified by gradation and is therefore a feature of the design. An advantage of larger sizes within a wetted surface coarse is that the asperities penetrate greater 'surface water' depths in order to make intimate contact with the tires possible. Another advantage is the higher hysterisis element in friction performance associated with more severe distortion of the tires.

There are enumerable disadvantages of a larger aggregate size exposed to the contact patch, but only a few will be mentioned here. Larger sizes generate more noise, a form of waste energy, and have a higher residual hysteresis element. Consequently, these pavements have higher rolling resistances under normal operations. Larger sizes produce draping of the tire carcass over and bridging between the asperities as the tire traverses the roadway; a condition that leads to higher point loads, a more destructive 'use' environment, and higher vehicle operation costs.

Aggregate shape is a feature of the crushing process. Coarse aggregates made from limestone have 100% of the faces exposed from crushing action. This attribute is perceived to be beneficial for friction even though the operative mechanism at work has not been adequately identified. Some would reason the crushed face has more texture. Or, being more angular, perhaps the crushed aggregate has more interlocking potential with the opposing tire.

More likely, the crushing is a feature of the material that is being crushed which in this case is limestone. The 'crushing' energy of the jaw, gyratory, roller, or impact crusher in fracturing the rock is actually used in breaking molecular bonds at the newly exposed face and thereby creating an energetic 'surface energy' component. The proof of this enriched 'surface energy' concept can be observed within the data itself where an active 'surface energy' environment leads to more attachment potential for surface contaminates. These contaminates prove detrimental to friction performance. A steeper decline in friction performance can be observed in certain pavements over time periods when surface contamination can occur. These surface contaminates are then washed away after a significant rainfall event in conjunction with the scrubbing action of traffic. The energetic surface is then recovered, as is the lost friction performance.

Aggregate texture is the third characteristic affecting friction performance. This texture is key central in this study since this coarse aggregate characteristic is the one that is seen as easily worn away when using limestone. This texture is termed micro-texture as opposed to macro-texture that deals with gradation and shape. Micro-texture is surface roughness of the aggregate that is too small to be seen with the unaided eye. The perceived function of micro-texture in pavement friction is to allow a final penetration of the wetted sheen on the aggregates so that intimate contact can be made between tire and pavement aggregate. Some would say this is the holy grail of skid performance – with contact you have skid resistance without it you don't.

What is left unresolved with this explanation is … what then?! How does friction take place once contact is made? Why is it logical to reason that contact is both necessary and sufficient for friction to take place? It's not!

Limestone

Limestone – what is it? It is a rock formed from sediments deposited and cemented overtime in what might be styled as 'carbonate basins' that laid along shallow sea floors in tropical climates. As sediment, limestone is not a strictly homogeneous class of rock; these rocks are not all exactly alike. First, limestones are formed from different materials. Calcium carbonate skeletons, aragonite needles of algae, shell fragments, fecal pellets of carbonate ingesting organisms, reworked fragments of carbonate sediment, and non-carbonate minerals and rock fragments are some of the assortment of materials used in forming limestones and making them different.

Second, limestone-forming sediments are deposited in different environments. These differences reach from the high-energy environment of crashing waves and strong currents to the low-energy environment of backwater tidal basins. These environments alter the nature of limestone materials that are deposited and the style of rocks formed from these deposits.

Third, limestones follow different 'digenesis' processes. Changes occur to limestones through time where different physical and chemical processes alter the nature of the rock and its resulting characteristics. 'Compaction' occurs to limestone as overlying sediments exert pressure to compact the evolving rock strata. 'Cementation' occurs in allochemical limestones leading to a grain-supported rock structure and mineral saturation of internal pores. 'Recrystallization' occurs as the sediment is lifted above sea level with low-magnesium/high-calcium fresh water running through the sediment. 'Replacement' occurs where during digenesis some calcium in calcite is replaced with magnesium thus forming dolomite. These processes alter limestone and its characteristics.

The point to be made is that limestones are different and expectations of friction performance and wear characteristics will be different as well. While the workings of friction remain a mystery, limestone differences can be reasonably expected to play a predominate role in the friction performance of wetted surface pavements.

How can these differences in limestone be identified and once identified which limestone performs best and which worst? Limestones are so varied that one could probably classify each individual rock within a separate category based on some unique non-conforming parameter. However, the current task is more limited than accurately classifying limestones, it is to discriminate between limestones on a continuum of its friction-enabling characteristic(s). In doing this discrimination based on BPN(9)-values there is an implicit assumption that coarse aggregate micro-texture is what enables pavement friction.

Other methods have been used in attempting to discriminate limestones in reference to their potential friction performance. Petrographical analysis has been used in attempting to discriminate between the various 'friction performance' potentials of limestone. This analysis provides a description and classification of limestone based on careful inspection of the rock and knowledge of the various ways in which sediment is converted into rock. As a result of this analysis, a particular limestone might be described in part as follows:

> **Sample A-18**
>
> **Limestone:** mostly light gray (N7) and light olive gray (5Y 6/1). 100% -- poorly to moderately sorted oobiosparite (75-90% skeletal fragments, oolites, and intraclasts, 10-25% calcite cement); skeletal components are calcitic and include echinoderm… [Bishara 1992]

In using a petrographical analysis, a researcher is attempting to avoid making an assumption about the 'friction' process in limestone-aggregated pavements. So limestones are described as fully as possible using the full assortment of defining dimensions -- leaving nothing out in the description. From a research viewpoint, the problem becomes the lack of an organizing principle, which can be just as troublesome as making an inappropriate assumption about what causes friction. Without an organizing principle there is information overload and because of this overload the researcher is unable to bring ordered simplicity to the limestone-friction relationship.

Acid Irreducible Residue tests the amount of non-calcium material in the limestone mineral composition. Expectation of the frictional influence of high residue content is that a blend of hard/soft material causes a differential wear in the material. This is believed to enhance the resistance to polishing of the exposed aggregate texture.

The 'contact angle' measured between a drop of water and the limestone it contacts indicates the surface energy of the limestone material. The trial hypothesis supported by this measured characteristic is that surface energy is the operative mechanism dominating surface friction.

Micro-Deval Test of the limestone aggregate is an LA Abrasion-styled test altered by using lower energy in abrading the material. The tentative hypothesis is that perhaps friction is some function of how sound the material is when impacted.

The success of any of these techniques in properly classifying limestones according to their friction potential rests in how accurately the actual, but unknown, friction mechanism has been isolated and modeled. Therefore, it is fundamentally important to get the physics right in terms of what actually causes friction within the matrix of a finished pavement surface during critical vehicle operations. Only then can proper tests be developed and correct pavements designed.

PAVEMENT WEAR

Wear is a frictional process that exposes new surfaces through the loss of material. This process occurs as a response to the interaction and differential movement between two opposing contact surfaces. Many consider this to be a purely mechanical process; however, at its core is a molecular event of overcoming the stored energy that binds molecules together. Two forms of this wear mechanism are applicable to pavement friction, abrasive wear and adhesive wear. (A third form of wear, fretting or surface fatigue, is often used in describing aggregate quality as measured by the LA Abrasion or the Micro-Deval test as describe above.) Abrasive wear constitutes a loss of a softer material as a result of the 'plowing' action from a harder material. For example, loose sand on a highway can be an abrasive agent acting to wear particles from softer coarse aggregate as tires contribute shearing forces between the two materials.

Adhesive wear represents the loss of material due to 'plucking' -- rather than 'plowing' -- the small particles from the matrix where they are situated thus giving the surface a polished appearance. This type of wear occurs when the adherence forces between the two wearing surfaces are greater than the energy binding the aggregate particles together.

Adhesive wear is significant here because limestone aggregates are known to be particularly susceptibility to 'polishing'. Not only this, but one must keep in mind that other frictional attributes than simply its residual texture can be inferred from the worn surfaces of limestone. Rabinowicz (1961) documents that the size of the particles lost in polishing action is directly related to the energy of the surface being polished. Lower surface energy requires lower adherence to achieve abraded material; these abraded fragments will also be smaller in size.

Others indicate that surface energy is also reflected in the density and hardness of the material. Limestone is a soft material with correspondingly lower surface energy as the material approaches pure calcite.

An aggregate particularly susceptible to adhesive wear may respond differently to abrasive wear. Few would disagree with this possibility. And yet, the BPN(9) test uses an abrasive grit to accelerate the wear conditions placed on limestone aggregates. This test substitutes the relatively mild 'plucking' of surface molecules of adhesive wear by the more severe 'plowing' of surfaces with abrasive wear. Is this abrasive-wear test reflective of adhesive-wear performance? Perhaps, but this test bias has yet to be picked up and addressed within the scientific community.

Wear/Friction Relationship

There is a relationship between surface wear and pavement friction. Even though friction can take place without it, wear is a good indicator of the potential for work to be performed across surfaces and thus energy to be transferred. If the wear rate potential across a pavement-tire interface is minimal, the expectation should be that friction is minimal as well, except for the macro-effects of hysteresis.

With this dependency in mind, it is important to consider the factors affecting the rate at which pavement materials wear. Materials wear from a well-bonded pavement surface at different rates depending on interfacing materials, lifecycle stage, surface-use condition, and temporary environmental influences. The two factors most important to this study are interfacing materials and temporary environmental influences. 'Interfacing materials' would include both pavement and tires, although the discussion on tires is deferred to a following section. The material component under study is that of wear characteristics of limestone aggregates as measured by the BPN(9) friction performance. This scenario ranks the relative quality of limestones based on the friction potential of a constructed specimen after 9-hours of abrasive wear.

'Temporary environmental influences' is important because it describes under what circumstances pavement wear can be minimized. Wear can be minimized on limestone pavements when it is wet. Why does wet pavement have a lack of adhesion between pavement and tire and thus poor friction performance? The most often cited reason is that 'real' contact cannot be made if there is a lack of micro-textural asperities. These asperities serve to push through the last few microns of water. What is left unresolved by this explanation is what happens when 'real' contact is made. I believe the interplay between limestone aggregates and rainwater is somewhat of a neutralizing combination on the surface energy of limestone. Limestone is a basic material and thus an electron donor. In the present environment, rainwater is slightly acidic and an electron receptor. The combination of these two may satisfy the electrical imbalance at the aggregate surface and consequently lack adhesive capability when mated with the tire. So during rain conditions, not only can the final water sheen not be dispersed, but contact is electrically neutral when made.

PAVEMENT/TIRE INTERFACE

Pavement friction has two major mechanisms: hysteresis and adhesion. The less significant of these two is hysteresis, which some estimate to dissipate only 10% of the energy lost during braking. During hysteresis, a cyclical deformations in the bulk materials while traversing coarse aggregate asperities converts kinetic energy (velocity) to waste heat in the tire carcass and possibly in the upper pavement layers. The relative contribution of this component is a complex phenomenon dependent on speed, tire material compound (for example the amount of carbon black in the tire), and the height and frequency of asperities.

Adhesion is the more important of the two frictional components accounting for 90% of the dissipated energy. While not very well understood, it is believed that micro-texture plays a dominate role, providing the interfacial contact points on which adhesion is achieved on wet pavement. In pavement, micro-texture describes the degree of exposed surface roughness. This 'exposed' roughness is an attribute of two pavement surface components: (1) sand particles and (2) coarse aggregate surface roughness.

To affect the adhesion mechanism and thus the roadway friction performance, these pavement components must 'touch' the tread as the tire traverses the pavement. What pavement component and how much of each component relative to others actually 'touch' the tire is a complex phenomenon that is governed by many factors? However, if this pavement mating phenomenon were known along with the relative 'adhesion' strength of the contact, then friction performance could be designed into and/or accounted for in the pavement

What are some of the factors that govern the 'touch-ability' of exposed sand particles and coarse aggregate surfaces? Before taking up this question, it might prove beneficial to first briefly consider the simpler question of what makes them 'untouchable'. The straightforward answer is that sand and coarse aggregate surfaces don't touch the tire tread if there is a contaminating layer interfering with this contact. The most common contaminate is water and 'touch-ability' is only an issue on pavements when it is present. Ridding the contact patch of this contaminate is the central focus of most factors that govern 'touch-ability'.

'Touch-ability' factors that are directly and indirectly related to ridding the contact patch of water include:

- Increasing pavement cross-slope
- Decreasing on-pavement drainage area
- Providing open-drainage through the pavement
- Increasing the drainage capability of the tire tread
- Reducing travel speeds

- Increasing water storage areas on pavement and tire treads

If for whatever reason the water is only partially evacuated from the tire/pavement interface, then intimate contact will be limited to the relatively higher surfaces of the coarse aggregate fraction. Only in these select instances is the adhesion mechanism of friction limited to the contributions of the coarse aggregate micro-texture.

Also, 'touch-ability' relates to the draping or bridging characteristics of the tire. A tire can drape over coarse aggregate asperities and engage the sand/binder surface. Alternatively, a tire could bridge between coarse aggregate asperities, thus leaving the sand/binder unengaged.

'Touch-ability' relates to the course aggregate gradation and asphalt and sand content of the pavement mixture. Larger aggregates in the surface mix will cause a larger dependency on the hysteresis component of friction, while the adhesion component will be more dependent on the micro-texture associated solely with the coarse aggregate because of increase bridging between asperities. Alternatively, increasing asphalt and sand content will make the 'sand' pavement component more available for adhesive mating with the tire.

'Touch-ability' relates to wear of the coarse aggregate surface and the attrition of the sand/binder mix. With increased wear and/or decreased wear resistance, coarse aggregate micro-texture will be less available during critical conditions where the coarse aggregate peaks are the only surface that are exposed. From the attrition of the sand/binder mix, friction performance will become even more dependent on the surfaces of these coarse aggregate peaks as the sand particles recedes away from contact depths.

Pavement friction becomes progressively more dependent upon the 'touch-ability' of the coarse aggregate micro-texture as the pavement ages or during unusually severe conditions such as high water. This dependence is not realized if the pavement is relatively new or if the encountered conditions are not severe enough.

The 'BPN(9)' laboratory experiment isolates and measures the residual micro-texture of the pavement 'coarse aggregate' component. As described above, the coarse aggregate micro-texture becomes critical only when the contact patch is extensively limited to the coarse aggregate surfaces. Limiting conditions would include a high water layer where only the coarse aggregate peaks penetrate the water surface. Other limiting conditions can center on the inability to engage the sand/binder surface, thereby again limiting adhesion contact to the coarse aggregate surfaces.

4. RESEARCH METHODOLOGY

Scientific inquiry is looking into what is not known in order to explain what has been observed. Any inquiry of this nature organizes relationships in one of two ways: either around 'cause-and-effect' explanations (experimental method) or around 'tell-tale' patterns (observational method).

The experimental method is the classic approach to scientific inquiry where a trial hypothesis is proposed by the researcher and then later confirmed (or not) through a controlled, focused experiment in an isolated environment. The underlying premise of this method is one of cause-and-effect. The 'effect' is the presenting problem under consideration. For example, inquiring into the quality of pavement friction under this approach naturally leads to the 'effect' being some measure of either the observed surface friction or some other indicator of the likely resulting friction. The 'cause' is the presumed dominant reason why the 'effect' is observed.

Continuing the immediate example, the researcher may attribute the observed poor friction performance to the polishing of limestone aggregates in the pavement surface mix. Under this scenario, the researcher must then construct an experiment to adequately test the hypothesized cause-and-effect relationship between 'limestone aggregate polishing', the assumed dominant cause, and the resulting poor 'friction performance', the observed effect.

There are many advantages to this form of scientific inquiry including a manageable research scope and defined research deliverable. While the largest disadvantages stems from investigating possibly complex issues from a one-dimensional perspective.

Recently, a new scientific approach that is made possible by advances in computer technology considers actual observations and defining characteristics within the system environment itself. It is called 'observational study' and is the technique used for this research.

OBSERVATIONAL STUDY

The 'observational study' method is an approach to scientific inquiry where one learns through observing, organizing what we observe, and then explaining it -- an experiential approach to scientific inquiry. This approach utilizes large pools of natural-state data to allow the investigator to observe factor relationships and formulate conceptual models that explain variations in the observed data.

Why is this approach particularly suited for pavement friction research? The friction performance of pavement is a complicated phenomenon that is not yet adequately understood. Never the less, friction can be easily measured and pavements grouped accordingly. High measured friction values would naturally place pavements into a more desirable category, while low values would rank the pavement as less desirable. This situation of knowing what good friction performance looks like, while still being unable to explain why it looks that way is extremely frustrating within a scientific context. The underlying friction mechanisms need to be discovered so pavements may be designed with the necessary attributes for good, extended-life performance.

Observational methods have certain advantages including its problem orientation and its contribution in highlighting concepts that may be 'in-play' within the data. Some disadvantages include a possibly unwieldy scope and a heavy commitment of the researcher's time and energy.

This approach has two stages. First, the researcher explores a sample of the data to establish a conceptual framework or pattern of relationships within the set of data. And second, it is determined through statistical techniques if that pattern exists in the data. This approach is similar to pattern matching in artificial intelligence where a computer is used to identify relationships within the database. However, observational studies differs in that an expected pattern or model is established first and then checked by the computer, rather than allowing the computer to search for its pattern.

According to Cooley (1979) there are three critical features that give an observational study its clear and convincing proof while remaining consistent with statistical reasoning. These include a sampling framework, a theoretical model, and a statistical procedure.

Sampling Framework

In an observational study, the sampling framework is composed of one or more study populations that contain pertinent data relating to the problem under study. A single study population was used in this research and the sampling effort was considerable in terms of both its scope and diversity. There were 7778 individual skid tests included in the analyzed data. The skid tests produced results that ranged from a low skid number of 21 to a high of 64.

Skid numbers are similar to the more familiar coefficient of friction value, μ, except skid numbers are reported after multiplying by 100. For comparison consider that a tire on ice has a coefficient of friction of around 0.12 suggesting that a stopping force equivalent to 12 percent of the normal load could be applied; this would correspond to a reported skid number of 12.

The average skid test produced a value of 41.9 with 75% of the tests above 38 and only 25% above 46. Figure 4.1 shows the frequency distribution of skid numbers making up the sample. From this figure a definite bias in the recorded skid numbers is evident where even-numbered values are significantly more likely than odd-numbered. Most likely this reflects an operator bias within the data.

With testing every tenth of a mile, these tests effectively sample close to 800 miles of roadway spread throughout 46 different counties of the 67 within Alabama. These roadways ranged from a two-lane highway to a heavily traveled intercity freeway. The surfaces tested included both the far right lanes that carry a disproportionate share of the traffic (traffic lanes) and inner travel lanes that are comparatively lightly traveled (non-traffic lanes). These tests include pavement surfaces at signaled intersections with their brake-worn approaches.

Overall, these pavements reflected the outcome of 93 separate projects with the relative skid-test frequency of each project demonstrated in Figure 4.2. The median project was reflected in 60 skid tests while the average was higher at 83.6 indicating a

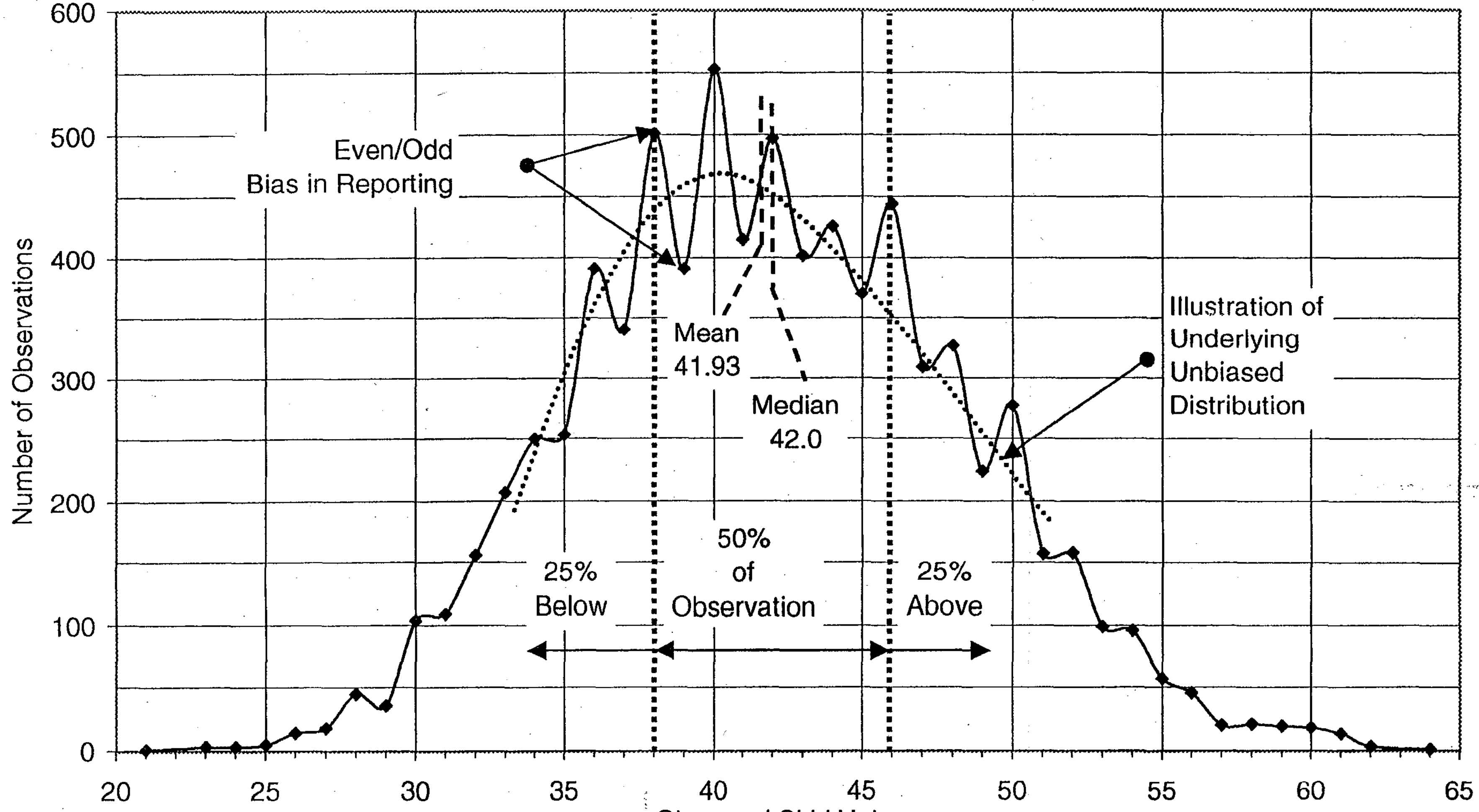


FIG. 4.1 Skid Value Frequency Distribution

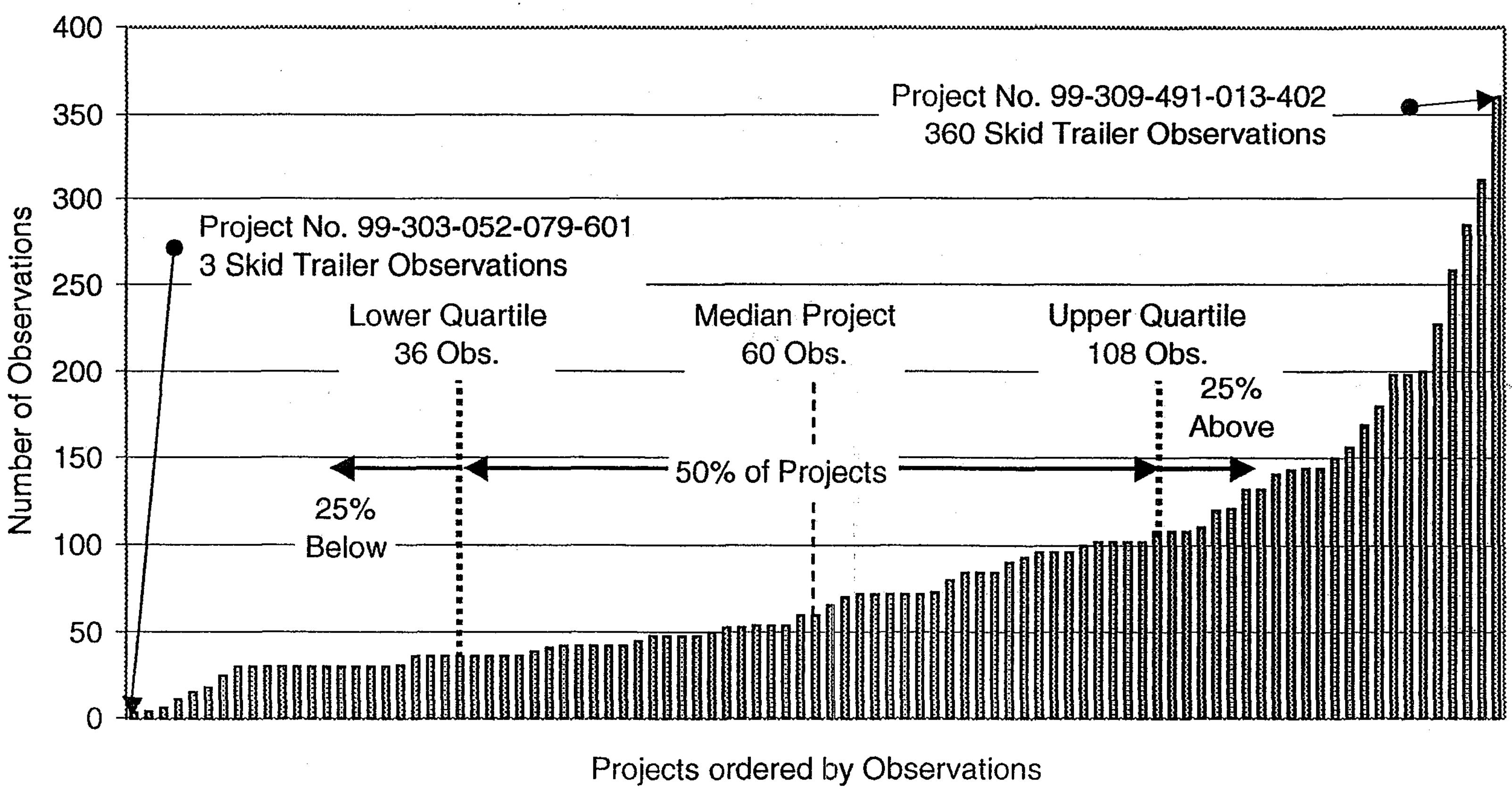


FIG. 4.2 Sampling Frequency Distribution of Individual Projects

skewed distribution. The fewest number of observation was three on project number 99-303-052-079-601 and the most skid tests were performed on project 99-309-491-013-402 where 360 separate tests are reported within the data. Twenty-five percent of the 93 projects had more than 108 skid-test data points while twenty-five percent had fewer than 36.

Not only considerable in scope, but this sample included a diversity of pavement mixtures, wear conditions, and temporary environmental influences, as well. Coarse aggregates included granite, slag, sandstone, and most germane to this research limestone. Limestone content within the coarse aggregate ranged from a low of 14 to as much as 80%. Figure 4.3 displays the sampling frequency of the various limestone contents within the pavement. This limestone came from 25 different sources from within Alabama and its surrounding states. Figure 4.4 indicates the relative frequency within the data of the various limestone sources.

Some of these limestones had relatively high polish resistance with measured BPN(9) values as high as 35, while many had low resistance as indicated by their BPN(9) values at 18. Figure 4.5 provides the relative frequency of the BPN(9) values within the sample.

The limestones were also diverse in parameters indicating its depository and constituent makeup. Bulk specific gravities of varying values were included, from a high of 2.825 to a low of 2.430. These values are an indication of how and by what manner the limestones were deposited.

The natural sand content and quality within the pavement mixture varied as well. Natural sand contents ranged from a low of 10 to a high of 57 percent of the pavement

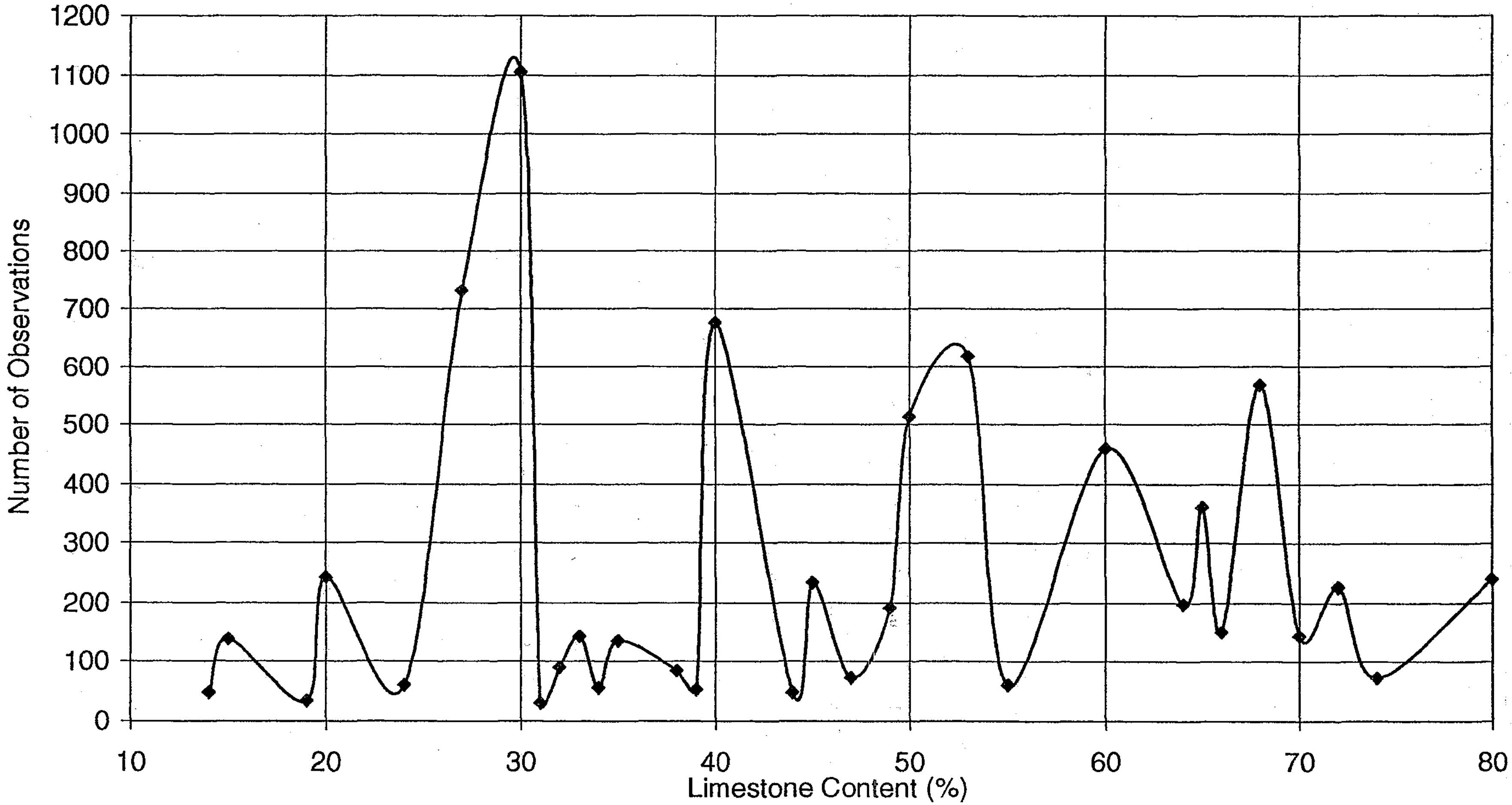


FIG. 4.3 Sampling Frequency of Limestone Content

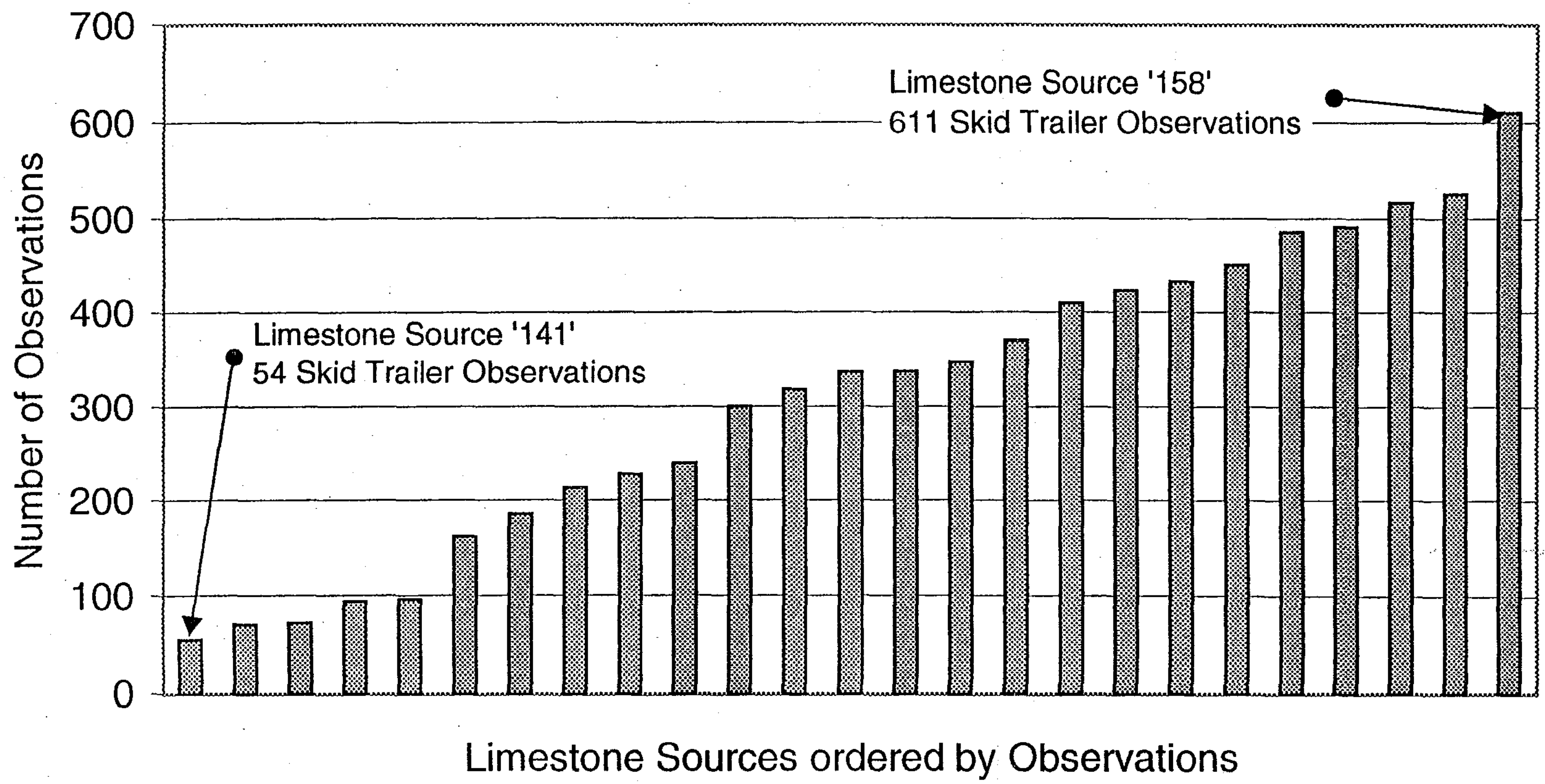


FIG. 4.4 Sampling Frequency Distribution of Individual Limestone Sources

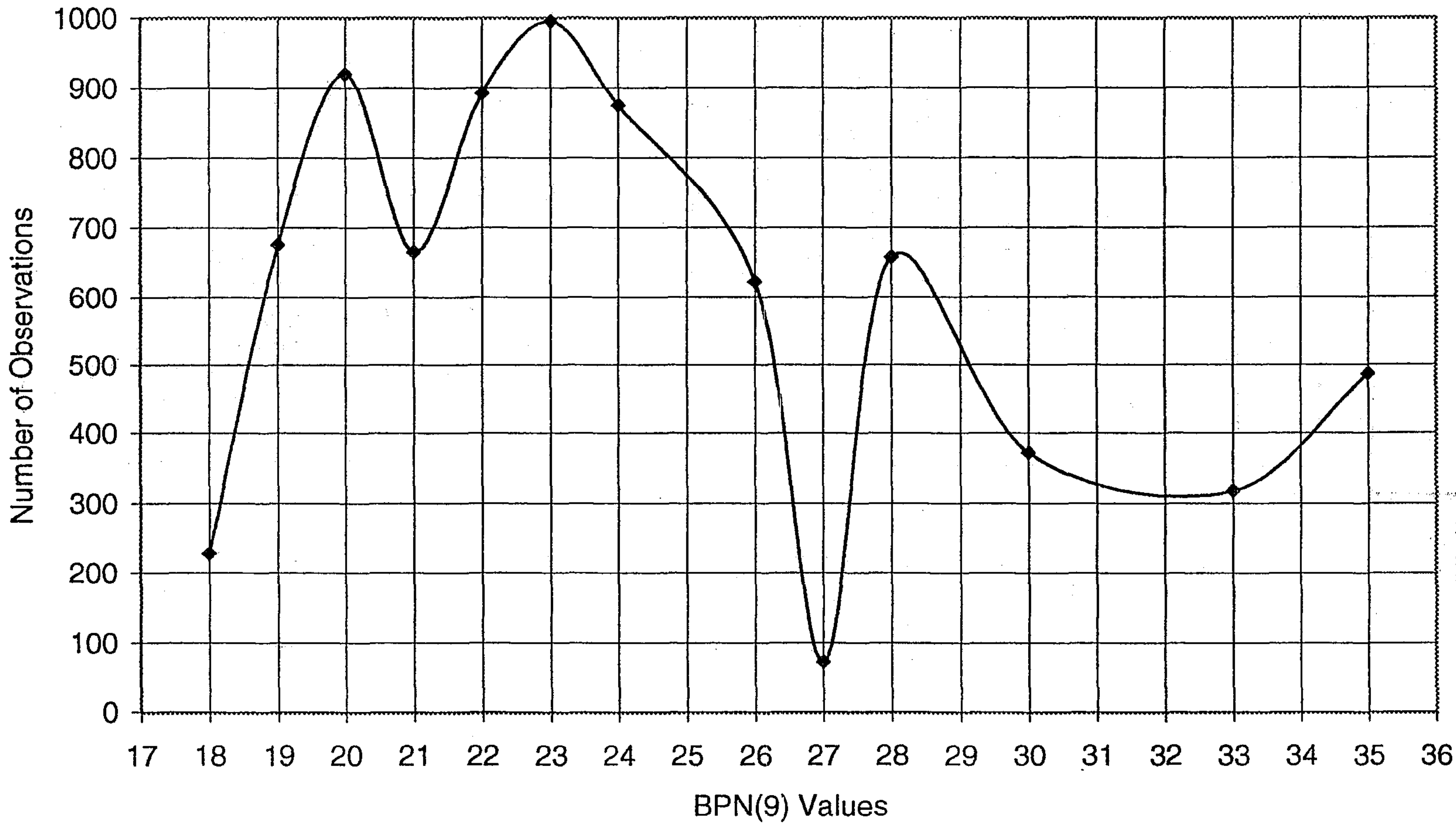


FIG. 4.5 Sampling Frequency of BPN(9) Values

mixture. Figure 4.6 provides the frequency distribution of the natural sand content within the sample. The quality of these sands was subjectively graded into three categories from good to poor based on the region of the state where the sand was produced. Manufactured sand was also included in some mixtures and mostly consisted of limestone by-products that met certain gradation requirements.

Another 'pavement mixture' variable that varied within the sampled pavements was asphalt contents that ranged from a high of 6.80 to a low of 4.95.

The wear conditions experienced by pavements surfaces within the sample varied considerably as well. Different traffic volumes, numbers of days in service, and the geometric orientations of the pavements are expressions of these diverse wear conditions. Traffic volumes ranged from a small daily volume of 240 vehicles per day to a relatively large volume of 53,100 per day.

Along with diversity in volumes, the length of service also was diverse with days-in-service from as few as 2 days to as many as 1529 days. Figure 4.7 demonstrates the diversity in exposures to service within the data.

Different geometric orientations of the pavement surface are included within the sampled pavements. Surface wear is a function of differential movement that imposes a tangential force between the tire and pavement surfaces. Thus, geometric orientation of grade, curvature, and cross-slope are key determinates in pavement wear. Differences in grade will be expressed by different wear profiles on the pavement surface. More work and correspondingly more wear occurs in moving vehicles up a grade. The steeper the grade the more work done in each contact patch as the vehicular mass is moved to a plane of higher stored potential energy.

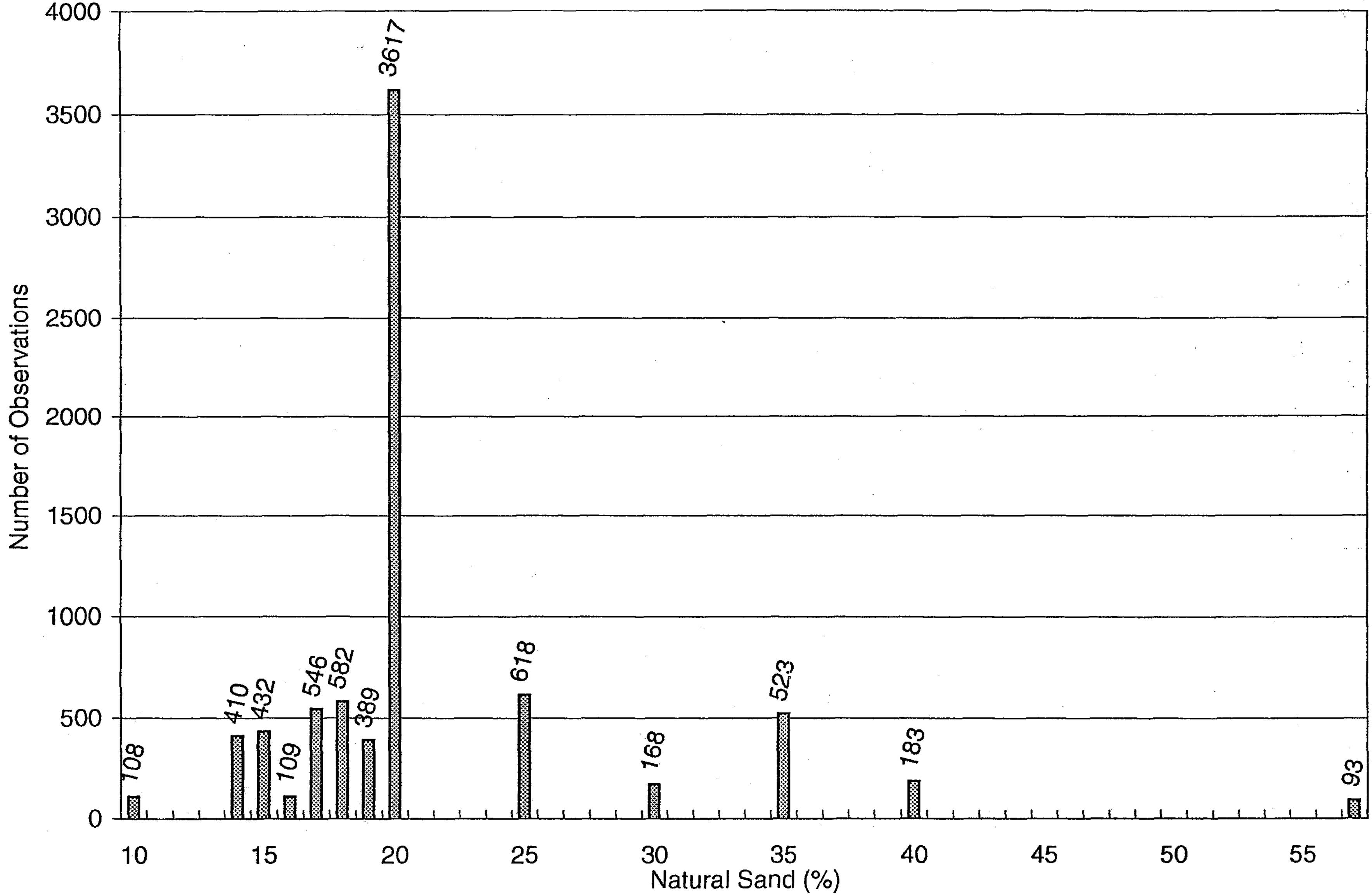


FIG. 4.6 Sampling Frequency of Natural Sand Contents

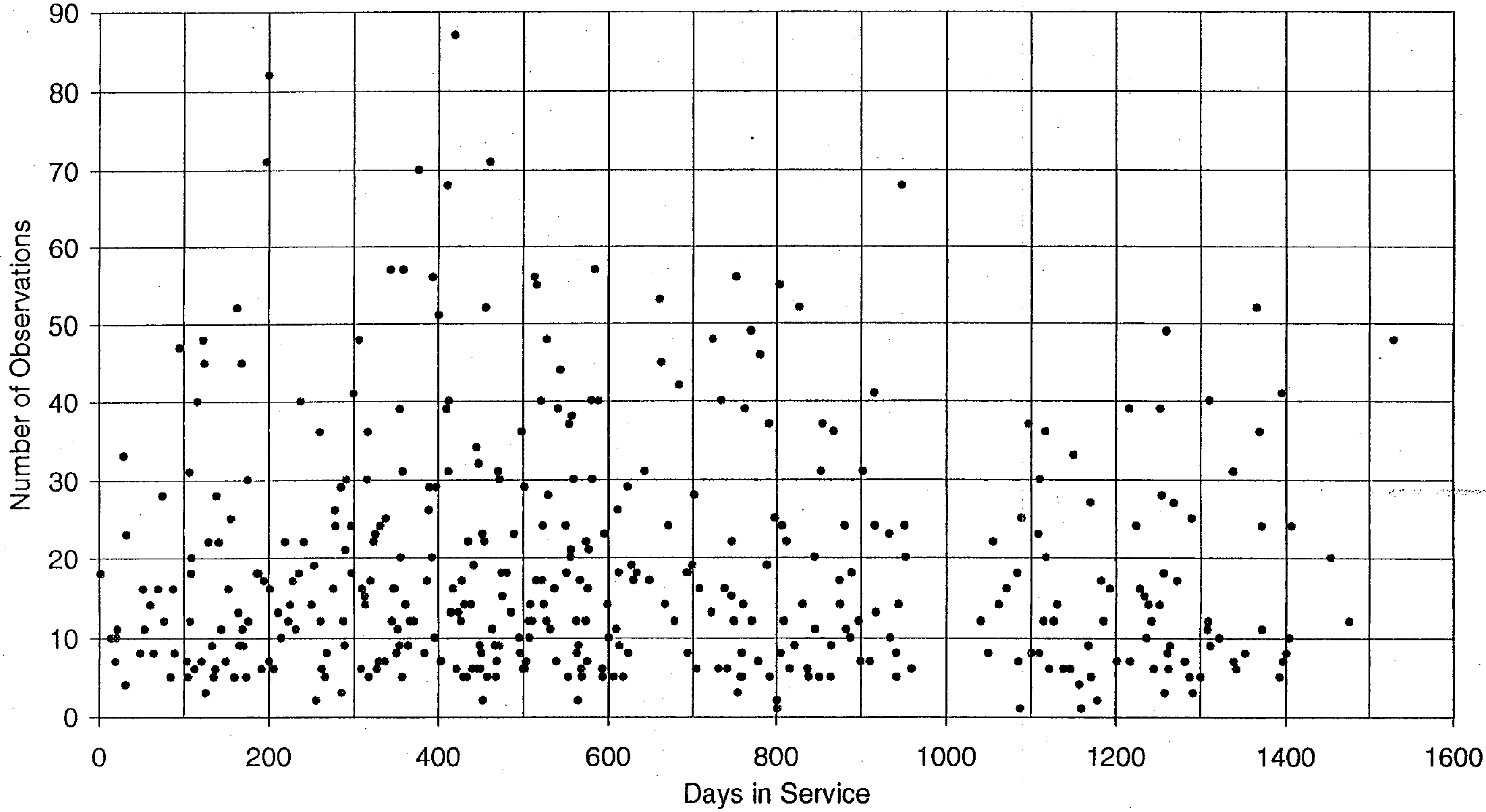


FIG. 4.7 Sampling Frequency of Days-in-Service

With moderate downhill grades the free-rolling of the tire has no slip, no differential movement, and thus limited wear. With steeper downhill grades – where braking might be imposed -- the potential for significant wear events increase dramatically. Pavement grade varied considerably within the exploratory sample ranging from an extreme uphill grade of + 9.1 to an extreme downhill grade –7.82.

Degree-of-curve also is an indicator of possible severe surface wear when coupled with cross slope. Certain requirements are placed on the contact patch as a vehicle navigates through a curve. The tighter the curve the more angular acceleration per contact patch is required. Many curves have super elevations to attempt to compensate by converting the tangential force component to a normal component on the pavement. Cross slope as a geometric property of wear comes into play as super-elevation. Roadway curvature varied from a severe curve to the left to an equally severe curve to the right. Cross slopes also varied considerably.

Field observations were performed in a wide variety of environmental conditions. The ambient temperature during skid test observations ranged from 34 to 96 degrees with an average test temperature of 59 degrees. Rainfall varied from extended dry periods to periods where there had been many days of significant rain just prior to skid testing the pavements.

Theoretical Model

Few would dispute the notion that simply observing the joint occurrence of two variables is not proof that one variable caused the other. Consequentially, 'proof' in observational studies is not through simple observation but through the proving out of 'cause-and-effect' interrelationship between variables supported by the underlying physics of the problem as reflected in a theoretical model.

Conventional wisdom abounds concerning possible cause-and-effect relationships related to friction performance. Each bit of wisdom is essential a 'reasoned' speculation concerning explanations of an effect. This effect is inferred as a dominant cause of friction based on some particular set of preceding conditions. If these 'cause-and-effect' relationships are present as expected, then the resulting patterns are visually discernable on graphs mapping these associated factors.

The graphical analysis is performed by contour mapping the factor space in pairs with the contour lines representing iso-friction or lines of equal friction. These iso-friction lines are similar to the more familiar isothermal or isobaric lines that reflect lines of equal temperature or pressure on a typical weather map. Here, the x and y coordinate axes represent factor dimensions and not the geographic coordinate dimensions provided on weather maps.

This technique provides the ability to visually identify covariant trends within the data, locate outlying observations, and isolate the affects of factors on friction resistance by producing cross-sectional representation of the data while holding constant or otherwise control one of the factors.

The attached figures illustrate the potential for evaluation using contour mapping. Figure 4.8 shows a representative analysis relating the percent of trucks, pavement grade, and observed skid numbers. Each dot represents an observation that was used in developing the friction number contour plots. The letter designation *A-F* represent

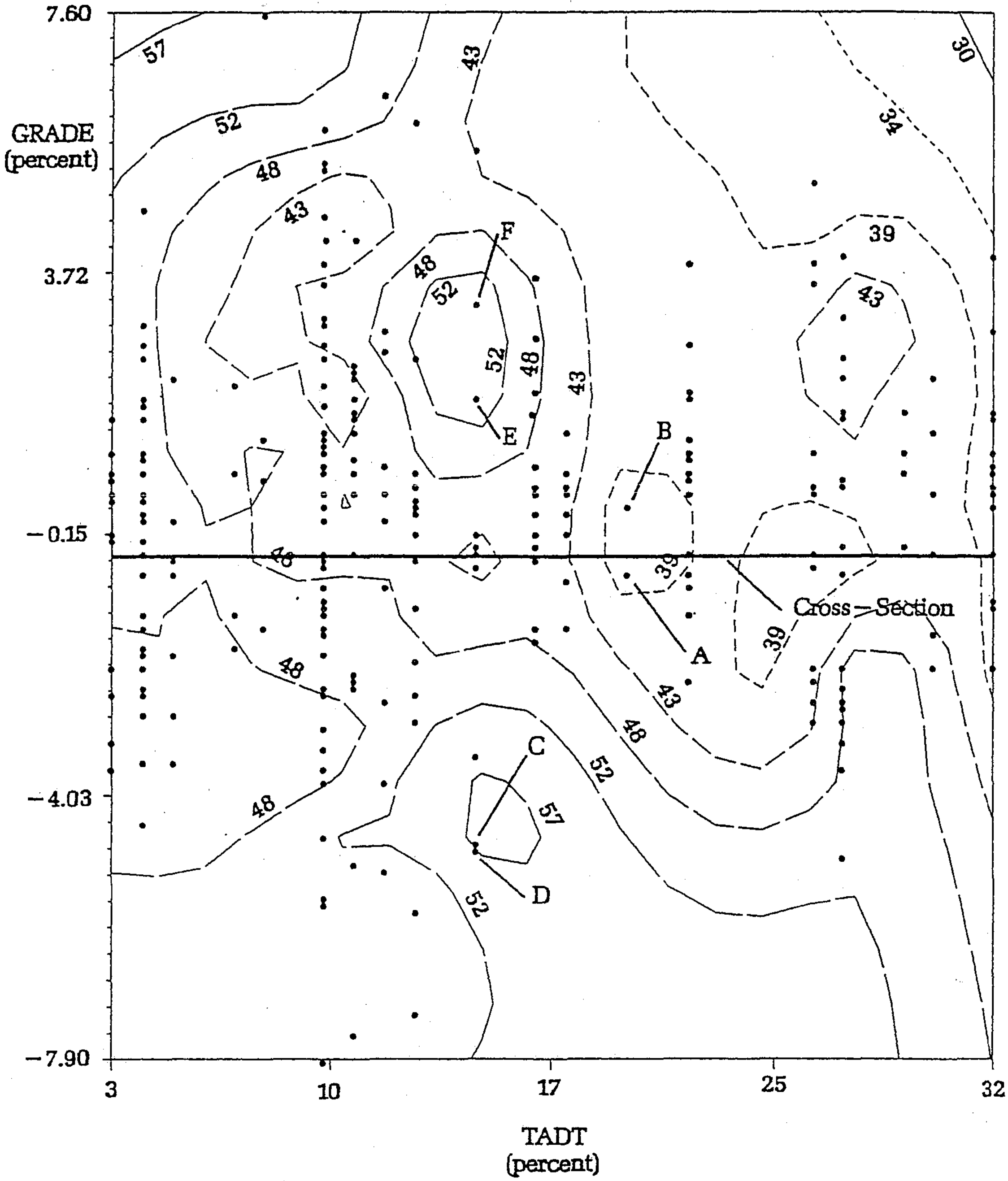


FIG. 4.8 Example of a Skid Number Contour Plot with Truck Average Daily Traffic (TADT) and Pavement Grade.

observations that are surprising when considering values of the nearby observations and are considered anomalies within the data.

Anomalies draw attention to potential factors that are not presently shown on the plot but which significantly alter the skid resistance capability of the pavement surface relative to its close cohort observations. For example, if unusually low observations *A* and *B* were identified as having extremely high limestone content, then a plausible explanation for the surprising values could be that "…except for the limestone content of these observations…" they would have been at normal levels.

A cross-sectional line is drawn across Figure 4.8 at a grade of –0.25 and is laid out in profile in Figure 4.9. The profile indicates the significant drop in friction number when increasing the percent trucks while holding constant a slight downhill grade.

Figure 4.10 relates grade, cross-slope, and friction number in one plot. This figure highlights a possible trend or interaction between cross-slope and grade that tends to drive skid numbers down as the hydraulic gradient of combining slope and grade flattens out. This suggests a concept that possibly the cleansing velocities during runoff events is inadequate to take contaminates off the roadway surface and thereby driving down the pavement skid resistance.

By using contour mapping and analysis as demonstrated above, the data can be observed as it jointly behaves in relation and response to individual factors.

'Cause-and-effect' relationships that prove-out during an exploratory analysis are modeled using latent factors, observations, and the directed interactions between them. These three model elements are demonstrated in Figure 4.11. First, the connecting arrows represent the directed interaction between factors or observations where the

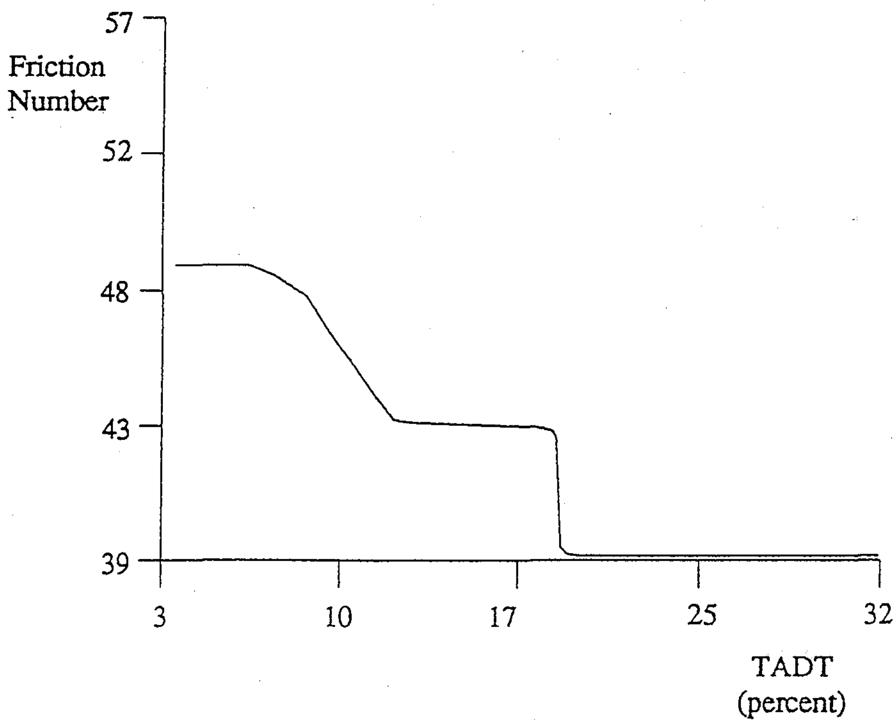


FIG. 4.9 Example of a Skid Number 'Cross-Sectional' Plot along TADT holding Pavement Grade at –0.25

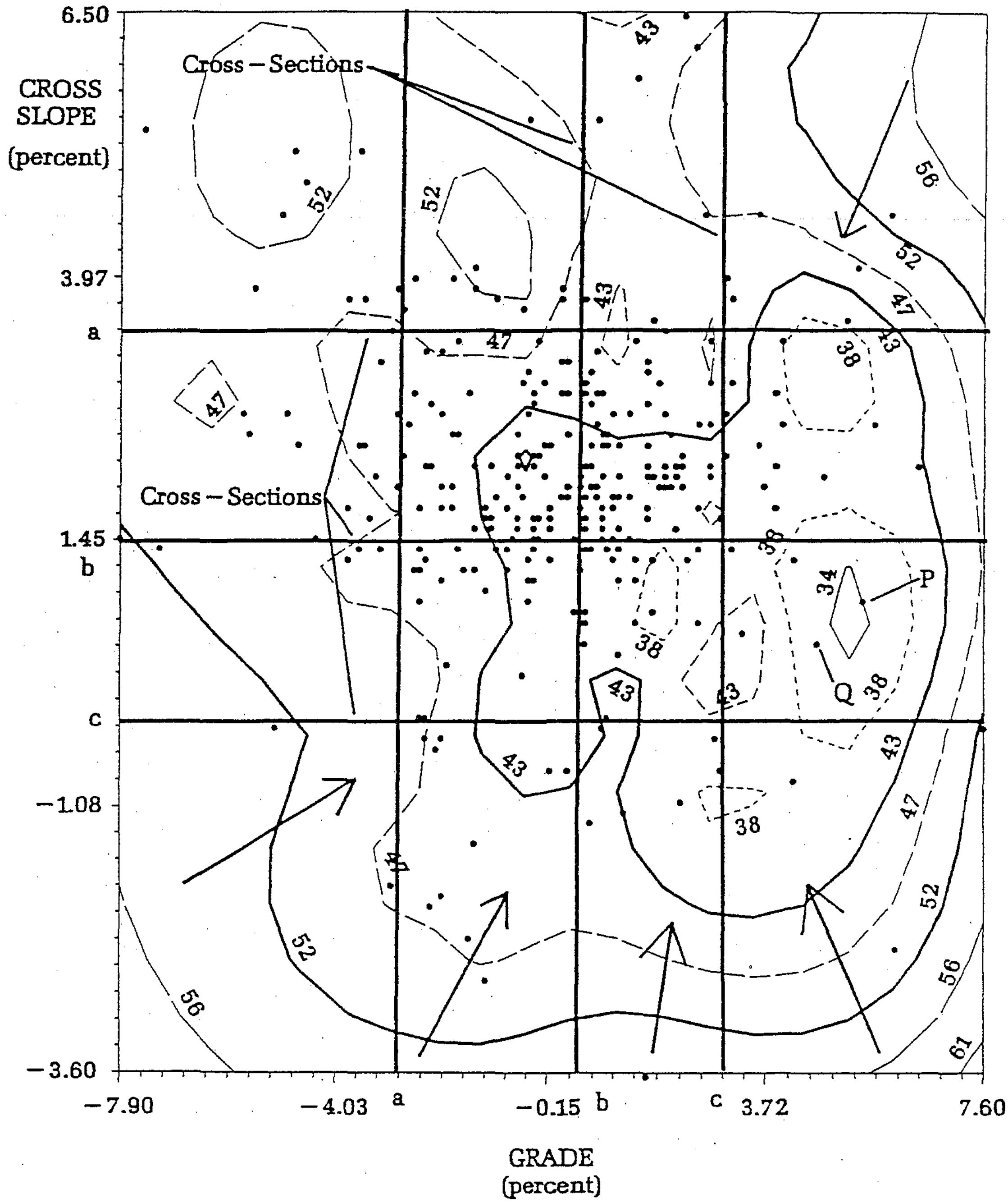


FIG. 4.10 Illustration of Factor Interaction Affecting Skid Performance

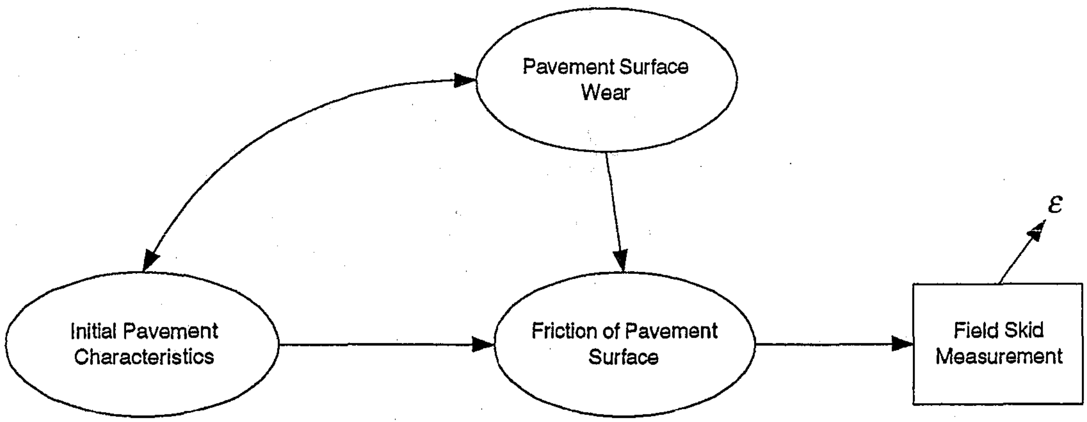


FIG. 4.11 Elements of a Relational Model

influence flows from tail-to-head with single-headed arrows and bi-directionally with two-headed arrows. To illustrate with an example from the figure consider the influence between the modeled elements 'Friction of Pavement Surface' and 'Field Skid Measurement'.

With a single-headed arrow directed from pavement friction to skid measurement, the relational model demonstrates that pavement friction influences the skid measurement and not the reverse. An example of bi-directional influence is found in the model between latent factors of 'Pavement Surface Wear' and 'Initial Pavement Characteristics'. This interrelationship is demonstrated by a two-headed arrow signifying that the 'surface wear' effect on friction is influenced in some respect by the 'initial pavement characteristics' and the 'pavement characteristic' effect on friction is influenced by surface wear.

Second, the labeled ovals represent latent factors that are the underlying structural backbone of the model. Most often, these latent factors are not directly observable, but are cautiously inferred from some test measurement or possibly a collection of correlated observations. For example, pavement surface friction is a latent factor described within an oval-shaped element. In a broader sense, friction remains a construct within all general scientific applications of an observed -- but ill-defined -- phenomenon. We know this phenomenon largely as a result of its observed effect and this is true for pavement friction as well. For this research model, friction is not directly observed but is indexed by its effect, which in this case is the measured ability to generate torque when coupled with a non-rotating wheel of a trailer skidding at 40 mph on a pre-wetted pavement. While this is not friction, it is how we currently measure it for pavements.

Third, the labeled rectangles represent measurable observations. Alone or in concert, these observations provide the ability to see through inference what cannot be seen directly. For example, pavement friction is not observed directly but is inferred through the quantified observation from a field skid measurement. Another example is that the polish resistance of limestone under wear is not directly observable but is inferred by its performance under BPN(9) testing.

This relational model serves as a working template upon which to develop and test hypotheses concerning why friction occurs on wet-pavements or perhaps more importantly why it doesn't occur.

Statistical Procedure

Statistical methods are used to determine how well the observed data matched expectations that are imputed in the theoretical model. In this research, a plausible association is tested that suggests friction and the polish-resistant quality of limestone are related. This association is described as 'plausible' since vehicles seem to have difficulty stopping on wet 'limestone-aggregated' pavement.

But, the relationship becomes more complex as the focus centers on the most unusual feature of limestone – its susceptibility to polishing wear. Is there evidence of a 'cause-and-effect' relationship between a polished aggregate and the observed inability to stop on wet pavements? This research question might be formulated into a hypothesis as follows: "Does using higher 'polish-resistant' limestone aggregates increase the observed friction performance on the pavement?". Or the reverse, "Does using lower 'polish-resistant' limestone aggregates decrease the observed friction performance of the pavement?". Determining the truth of this hypothesis requires careful consideration of field data using statistical procedures.

As used in this research, the statistical procedure serves two functions. One, the statistical procedure represents a structured mathematical model relating the chosen variables in a hypothetically 'right' relationship with each other. For example, traffic volume affects friction performance over time. A mathematical model can fit this relationship with a known or 'to-be-determined' parameter magnitude. In this mathematical model we have some indication of how right or wrong this hypothesis is by how well the data itself subscribes to the model.

This self-proving aspect of the procedure describes the second function, which is as an accounting tool. The variability in the data is described in terms of squared deviations from a central value that when summed reflects the variance within the data. The statistical technique that uses these sum-of-squares is known as *Analysis of Variance* (ANOVA); but could just as easily be called accounting of variance.

While background, theory, and applications of the ANOVA technique can be found in most any basic statistic textbook, insight into this technique can be garnered by exploring the output provided in Table 4.1. This output reflects the mathematical model presented in Equation 4.1.

$$\text{Skid Number} = \beta_0 + \beta_1(\text{days\_in\_service}) + \beta_2(\text{days\_in\_service})^2 + \beta_3(\text{traffic\_lane}) + \varepsilon \quad \ldots(4.1)$$

Table 4.1 Sample *Univariate Analysis of Variance* Output

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	38575.687[a]	3	12858.562	363.787	.000
Intercept	13675237.2	1	13675237.213	386891.676	.000
DAYS	28257.272	1	28257.272	799.438	.000
DAYS2	2201.169	1	2201.169	62.274	.000
TRF_LANE	8117.245	1	8117.245	229.648	.000
Error	274783.100	7774	35.346		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .123 (Adjusted R Squared = .123)

Parameter Estimates

Dependent Variable: Skid Number

					95% Confidence Interval	
Parameter	B	Std. Error	t	Sig.	Lower Bound	Upper Bound
Intercept	48.867	.269	181.333	.000	48.338	49.395
DAYS	-1.137E-02	.001	-16.205	.000	-1.274E-02	-9.991E-03
DAYS2	4.235E-06	.000	8.986	.000	3.311E-06	5.158E-06
TRF_LANE	-2.674	.176	-15.154	.000	-3.019	-2.328

The first column '*Source*' in Table 4.1 lists the various factors to use in accounting for the variation in observed friction within the data. There are eight interrelated factors in this listing. These factors will be discussed not in their listed order for purposes of conceptual clarity beginning with *Total*. 'Total' presents the total sum of the 7778 friction values after squaring each value. It represents the total 'statistical accounting' task of the model very much as if it represented a total sum of money which must be financially accounted for within particular accounts. A large part of accounting for that total will be attributed to a shift in the datum owing to the fact that the mean friction value is well above zero.

This naturally leads to discussing the *Corrected Total* within the enumerated list. In developing the sum of squares for the corrected total, the mean friction value is subtracted from each friction observation to arrive at a deviation that is then squared and totaled. The total is corrected for the mean, thus the name 'Corrected Total'. In making this adjustment the positions of each observation is not changed relative to each other only the collective reference point is changed, which is now the mean value while before each observation was referenced to zero.

The third source factor discussed is the *Intercept*. This factor partitions the influence on the sum-of-squares of the shift from a zero to a mean 'friction value' datum. Numerically, it is the correction factor between the *Total* and *Corrected Total* sum-of-squares as illustrated using values from Table 4.1

Total Sum-of-Squares = 13988596.0

less	Intercept Sum-of-Squares	= 13675237.2
Equal	Corrected Total Sum-of-Squares	= 313358.8 (with rounding).

The fourth 'source' factor is *Corrected Model.* This factor accounts for the magnitude of the sum-of-squared deviations that may be explained by the fitted mathematical model. Its relative magnitude compared to the Corrected Total suggests the amount of 'order' that is brought to the observed data by the collection of parameters used in the model. This 'order' is quantified as a ratio termed R-squared which is given in this particular output table as 0.123. This number is developed from partitioning the underlying sum-of-squared as illustrated below.

	Corrected Model Sum-of-squares	= 38575.687
divided by	Corrected Total Sum-of-squares	= 313358.787
equals	R-Squared	= 0.123

This R-squared value of 0.123 indicates that 12.3 percent of the observed variation in the friction value is accounted for by the parameters within the mathematical model.

Obviously, the absolute limit to R-squared is 1.00 where all the variation in the data is ordered by the model. This would be the case if a straight-line model of two parameters, an intercept and slope, were fit to two data points. The model would naturally pass through each data point resulting in a 'perfectly' descriptive model. This concept will be dealt with more fully in the discussion of degrees-of-freedom (df) below.

The fifth source factor discussed is the *Error*. This factor partitions the remainder sum-of-squares that is not accounted for in the model. Numerically, it is the difference between the *Corrected Total* sum-of-squares and the *Corrected Model* sum-of-squares as illustrated using values from Table 4.1

	Corrected Total Sum-of-Squares	= 313,358.787
less	Corrected Model Sum-of-Squares	= 38,575.687
Equal	Error Sum-of-Squares	= 274,783.100.

The remaining three source factors – days, days2, and trf_lane – represent days-in-service, days-in-service squared, and traffic lane. These factors are those in the model and cumulatively account for the *Corrected Model* sum-of-squares as illustrated using the numbers from Table 4.1:

	Days-in-service Sum-of-squares	= 28,257.272
plus	Days-in-service Squared Sum-of-squares	= 2,201.169
plus	Traffic Lane Sum-of-squares	= 8,117.245
equals	Corrected Model Sum-of-squares	= 38,575.687 (w/ rounding).

The sum-of-squares attributable to each factor is allocated in consecutive order. Days-in-service is fit first as if it were the only variable in the model. Days-in-service squared is fit second. The sum-of-squares allocated to this second variable is that which is added to the model by the inclusion of this second variable. Traffic Lane is fit third; the sum-of-squares added by this third variable is shown next to that factor.

The second column in the upper table provides the Type I Sum of Squares associated with each source factor as discussed above.

The third column represents the degrees-of-freedom (df). As a statistical concept, degrees-of-freedom describes data in the same manner as degrees-of-motion may be used in describing the range of motions available to a mechanical robot. If a robot is limited to moving only in one direction – frontward or backward – then the robot has one degree-of-motion. If independent two-directional movement is designed into a robot then it's said to have two degrees-of-motion.

So it is with degrees-of-freedom and data. If there are 7778 separate data points then the data is said to have a total of 7778 degrees-of-freedom as is the case in using the present data set. The degrees-of-freedom would fall by one to 7777 if the mean friction values was calculated and used in describing this particular data set, since knowing the mean and the value of 7777 data points allows the remaining point to be deduced.

Describing the data as it departs from a mathematical model would limit the unrestricted degrees-of-freedom by the number of terms used in the model. If a straight line were fit there would be a corresponding reduction in the unrestricted degrees-of-freedom by two, the number of terms in the model.

In the present situation, if the data were modeled by a 7778-term equation then the R-squared would be 1.00 regardless of the terms used. The equation would perfectly describe all the data points but would have no 'predictive' or 'ordering' power.

Explaining a large amount of data with relatively few terms develops the power or effectiveness of a 'regression equation'.

With this in mind, there is a balance struck in statistical modeling between the number of terms included in the model and the ability of the model to account for the sum-of-squares in the data. This requirement to balance model sum-of-squares gives rise to the fourth 'sample output' column – *Mean Square*. This column provides ratios of the source factor sum-of-squares divided by their degrees-of-freedom. For example, the mean square for the *Corrected Model* is 12,858.562 – which is developed by dividing 38,575.687 by 3. The *Error* mean square is 35.346 -- which takes the error sum-of-squares of 274,783.1 divided by 7774. This 'Error Mean Square' is an estimate of the statistical variance remaining within the data about the fitted mathematical model.

This statistical variance estimate is used in developing the F-statistics that are recorded in the fifth column of the output. For the corrected model, the F-statistic is 363.787 arrived at by dividing the Mean Square of the Corrected Model (12,858.562) by the Error Mean Square (35.346) with rounding.

The sixth and last column in the upper output table is Significance (abbreviated Sig.) or p-value, the likelihood of observing this particular F-statistic value if the fitted model actually contributed no ordering to the data. Based on the low p-values, each source factor contributes to establishing order and is not simply a reflection of randomness.

The lower output table presents the parameter estimates of the variables within the model. The first column lists the equation parameters and the second column provides their fitted estimates. Using these parameters to fit the unknowns of Equation 4.1 provides the following equation,

$$\text{Skid Number} = 48.9 - 0.011(\text{days\_in\_service}) + 0.0000042(\text{days\_in\_service})^2 - 2.67(\text{traffic\_lane}) + \varepsilon \quad \ldots\ldots(4.2)$$

The third column provides the standard error of the 'regression coefficient' estimate. The standard error of the estimate is the unresolved residuals of the fitted regression as a multiple of the sample variance of the independent variable adjusted for colinearity with the other independent variables. The small value here indicates that what is left un-described between predicted and observed friction values in the fitted model is small relative to the dispersion of the independent variable used in predicting skid number, such as days-in-service.

The fourth column provides the t-statistic for considering the hypothesis that the individual coefficient of the particular independent variable is actually zero. The fifth column provides the statistical significance or p-value for the t-statistic, which in each case is 0.000 meaning in all likelihood the coefficient is not zero. The sixth and seventh column indicates the 95% upper and lower bound showing the relative range of the parameter estimate given the underlying standard error (+/- 1.96 σ).

SUMMARY

In summary, scientific inquiry is all about observing and explaining. However, the specific order in which these elements of scientific inquiry are accomplished differ.

The experimental method regimen explains then observes under carefully controlled conditions, while the observational method approach provides observation of natural-state data then explains what is observed. In this case, friction performance observations are relatively easy to perform, while the explanations are involved and complicated.

5. EXPLORATORY ANALYSIS

Exploratory analysis, as used here, refers to investigating a small data sample to determine from the observed relationship what concepts might be inferred and what conventional wisdom might be true within the larger data population.

FACTOR EXPLORATION

Factor exploration is the task of incrementally reviewing the joint behavior of observational data to determine if there is in fact an existing order within the data. In this context, each observed data point represents not only a single skid test result but also a singular record of 29 other factor measurements. Ultimately, having the friction-performance information mapped onto only 3, 4, or perhaps 5 of these factors or combination of factors will be evidence of the 'existing order' that is sought.

The 29 factors are described in Table 5.1 and are further categorized into four groups: pavement, polishing, polishing/response, and response. The 'pavement' grouping contains 14 factors related to the design and material properties of the pavement. 'Polishing' has 4 factors that represent the wearing actions imposed on the roadway. 'Polishing/Response' has 4 factors that might influence both polishing wear

Table 5.1 Factor Descriptions (Page 1 of 2)

---	Factor	Description
Pavement	BPN(9)	Measures the residual friction characteristics of limestone coarse aggregate after 9-hours of polishing
	Percent Limestone	Quantifies the amount of limestone used in the coarse aggregate fraction of the pavement.
	Percent Sand	Quantifies the amount of natural sand making up the fine aggregate fraction of the pavement.
	Sand Quality	Ordinal ranking of sand types into subjective performance categories of poor (1), medium (2), and good (3).
	LA Abrasion	Indicates the percent of coarse aggregate material passing through a No. 12 sieve after being subjected to impact and abrasive wearing conditions in a revolving cylinder containing steel balls.
	Tensile Strength Ratio (TSR)	Measure comparing the tensile strength bond between the asphalt and aggregate for a moisture-conditioned specimen versus that of a dry specimen for a given HMA design mixture.
	Unit Mass	Coarse aggregate measure dividing the dry weight of aggregate particles filling the volume of a calibrated container.
	Stability	Indicates the cohesive strength and internal friction within an asphalt mixture as measured by the maximum compressive force (lbs) resisted under a loading rate of 2-inches per minute for a Marshall specimen.
	Percent Asphalt	Measurement of the asphalt weight as a percentage of the overall mixture weight.
	Mix Number	Specification Index indicating both the aggregate mixture gradation and criteria for design test specimen. Mix Numbers 4-6 use a 75-blow Marshall Criteria in developing pavement specimens reflecting a higher compactive effort, while the standard 50-blows is used in Mix Numbers 1-3. Mixes 1 and 4 have the same aggregate gradation criteria, as does Numbers 2 and 5, and 3 and 6.
	Percent Absorption	Measure of the weight of saturated water in the permeable pores as a percent of the dry aggregate weight.
	Apparent Specific Gravity	Measure of the aggregate weight as a multiple of the weight of water displaced by the volume excluding the permeable pores.
	Bulk Specific Gravity	Measure of the aggregate weight as a multiple of the weight of water displaced if the permeable and impermeable pores were included in the volume of the aggregate.
	Bulk Specific Gravity (SSD)	Ratio of the aggregate weight with the permeable voids saturated with water to the weight of water equal in volume to the aggregate and saturated voids.

Table 5.1 Cont'd (Page 2 of 2)

Polishing	Cumulative Traffic	Lane estimate of the total number of vehicles over the location during the time period between pavement construction and skid test date.
	Average Traffic/Lane	Lane estimate of the daily vehicle volume on the pavement surface.
	Truck Volume	Lane estimate of the total truck volume on the pavement surface during the time period between construction and skid test.
	Days-In-Service	Total number of elapsed calendar days between pavement construction and skid test.
Polishing/ Response	Degree of Curvature	Measure of the change in vehicular heading at the pavement location being tested representing the subtended angle at the center of the curve along a 100-foot pavement length.
	Cleansing Gradient	Measure (angular cosine) of the geometric configuration of the pavement surface with a horizontal plane combining both pavement grade and cross-slope.
	Pavement Grade	Slope of the pavement surface in the direction of travel relating the vertical rise (+) or fall (-) as a percentage of the horizontal distance.
	Pavement Cross Slope	Percentage rise (+) or fall (-) of the pavement surface in the direction perpendicular to travel when facing the median.
Response	Rainfall on Day of Test	Likely amount of area rainfall on the skid test date.
	Three-Day Rainfall	Likely cumulative area rainfall three-days prior to and including the day of the skid test.
	Seven-Day Rainfall	Likely cumulative area rainfall seven-days prior to and including the day of the skid test.
	Twenty-One Day Rainfall	Likely cumulative area rainfall twenty-one days prior to and including the day of the skid test.
	Month of Skid Test	Numerical reference to the month the skid test was performed; Jan = 1, Feb = 2, etc.
	Maximum Temperature	Highest area temperature on the skid test date.
	Minimum Temperature	Lowest area temperature on the skid test date.

and response. 'Response' contains 7 factors that impact variations in the field-measured skid resistance.

A total of 399 separate factor pairings were individually explored and reported earlier in a two-volume set forwarded with the Quarterly Report of November 1999. Figure 5.1 displays the index of 'factor pairing' figures for these volumes with the factors blocked into the four groupings. Within these volumes, each pairing was documented with a contour map and a one-page discussion of the relevant information gleaned from this data display. A sample of these factor maps and accompanying discussion is provided in Figures 5.2(a) and 5.2(b).

Each of the 399 factor pairings demonstrates a joint observation of the data along three dimensions – the two plotted factors and the skid test result. Each pairing also fits into one of 10 possible regions of joint group effect. Figure 5.3 identifies these 10 joint regions with a numerical index displayed on an affinity chart. Table 5.2 describes each of these 10 regions.

Figure 5.4 identifies factor pairings that were subjectively judged by the researcher to have significant potential in demonstrating important 'ordering' concepts. Also, there is a distinction in this figure reflected in shading. The two rows not shaded represent the two factors central to this study, BPN (9) and percent limestone. All other factors are subsidiary to these two in the context of this targeted research. Consider what factors coupled with BPN(9) result in a contour maps judged most significant. There are only five significant couplings. Two are with other pavement-related factors, percent limestone and percent sand; one is a factor grouped into polishing, which is days-in-service; and two are in the polishing/response group, pavement grade and cross slope.

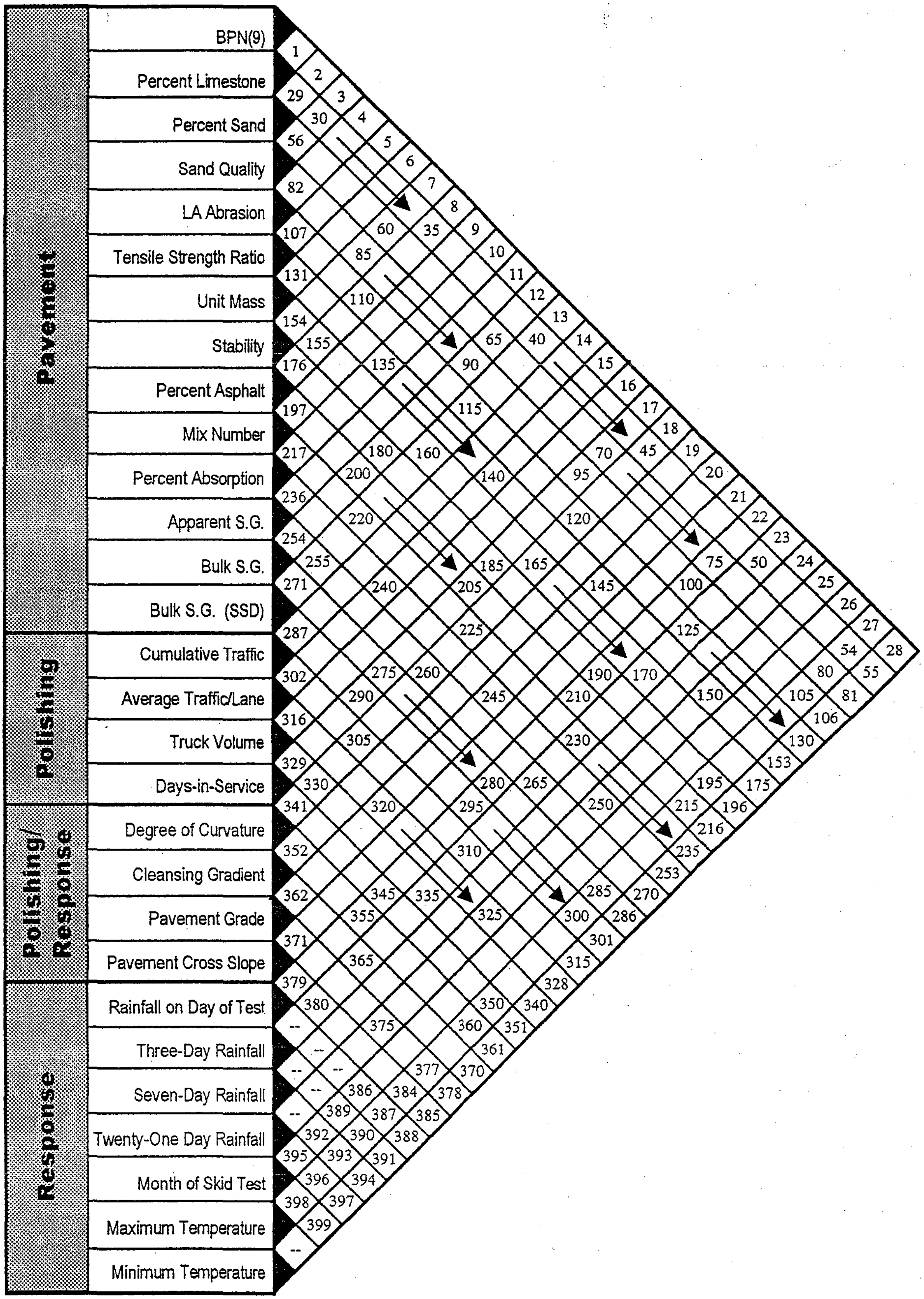
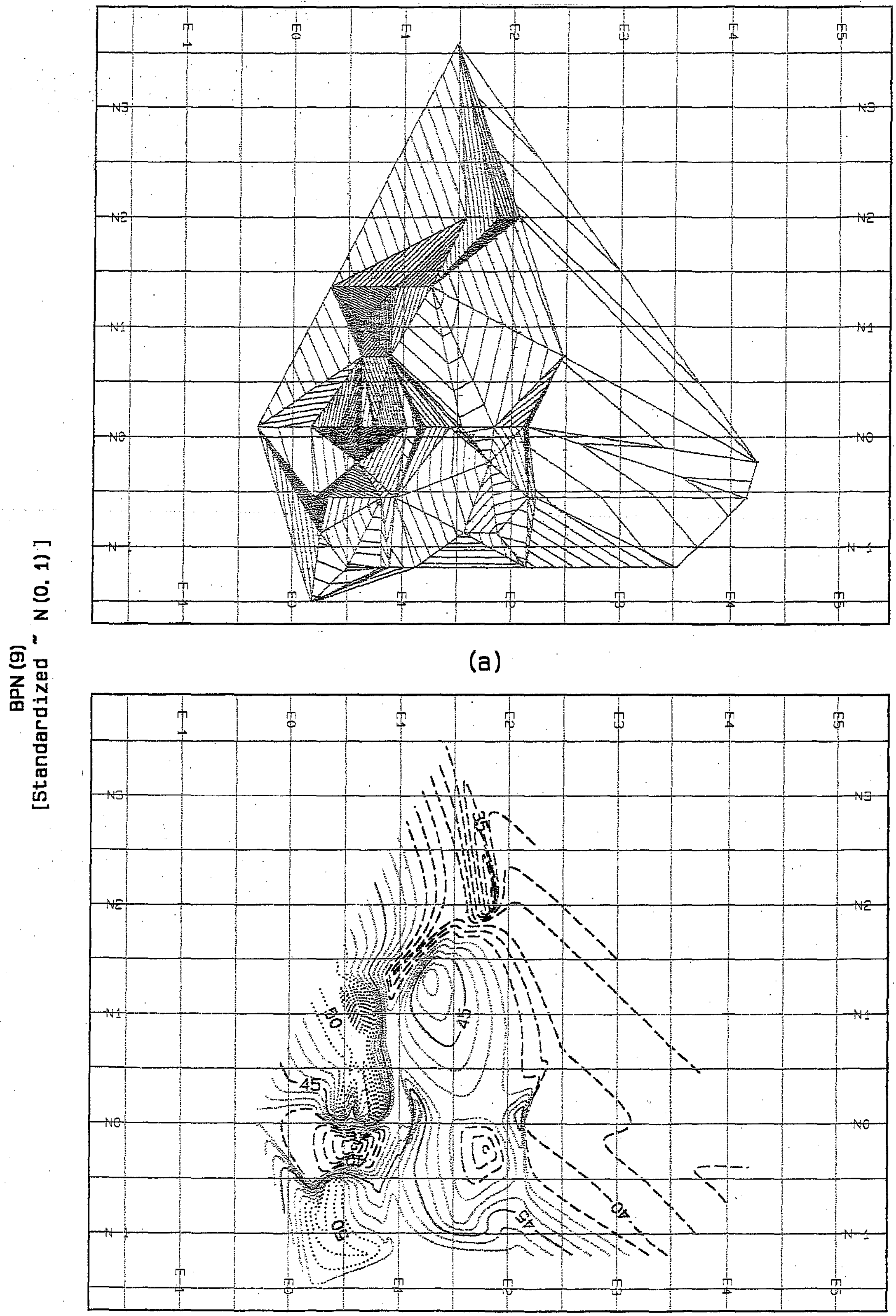


FIG. 5.1 Plot Index of Two-Volume Exploratory Investigation



(a)

(b)

(Days in Service) * 100

FIG. 5.2 (a) Exploratory Contour Map illustrating Friction Numbers (FN) ~~as~~ a Function of BPN ~~(9)~~ ~~and~~ Days-in-Service (Copy FIG. 17 from November 1999 Quarterly Report)

DESCRIPTION

Factors: **BPN(9)** measures the residual friction characteristics of limestone coarse aggregate after 9 hours of polishing. **Days-in-Service** is the total number of elapsed calendar days between pavement construction and skid test.

Concept: BPN(9) measures the residual texture on the exposed surface of the limestone aggregate after extended wear. Days-in-service measures the number of days the pavement surface has been exposed to service loads and the relative age of pavement materials.

Data: There are 49 interaction points between BPN (9) and Days In Service, each point representing from 2 to 69 test observations with average friction values from 31.5 to 59.33. BPN (9) ranges from 19 to 35 (plotted from -1.51to 3.67) and Days In Service from -33 (error) to 424. BPN(9) plotted as a standardized value.

RESULTS

Main Effects: Plotted friction values associated with BPN(9) exhibit no single distinctive trend but rather reflect banded performance characteristics around certain BPN(9) values. In relation to days in service, pavement friction performance is best after a being inservice a short period and then generally decreases as the pavement ages although the pattern is somewhat inconsistent.

Joint Effects: Pavements made with high BPN(9) aggregates have generally lower friction performance while pavements from extremely low BPN(9) aggregate perform adequately even after significant service.

Anomalies: No atypical friction values exist.

INTERPRETATION

Significance: This plot reflects the commonly-held belief that pavements perform better after being in service for a short time period. Also, notice the significant performance bands evident around certain BPN(9) values and the relatively good friction performance obtained with low BPN(9) value pavements relative to pavement age.

Future Action: More observations need to be captured relating pavement age to BPN(9) value, especially at high BPN(9) values where there is currently only one days-in-service value is reflected. The performance banding at certain BPN(9) values should be investigated further.

FIG. 5.2(b) Example of Plot Description

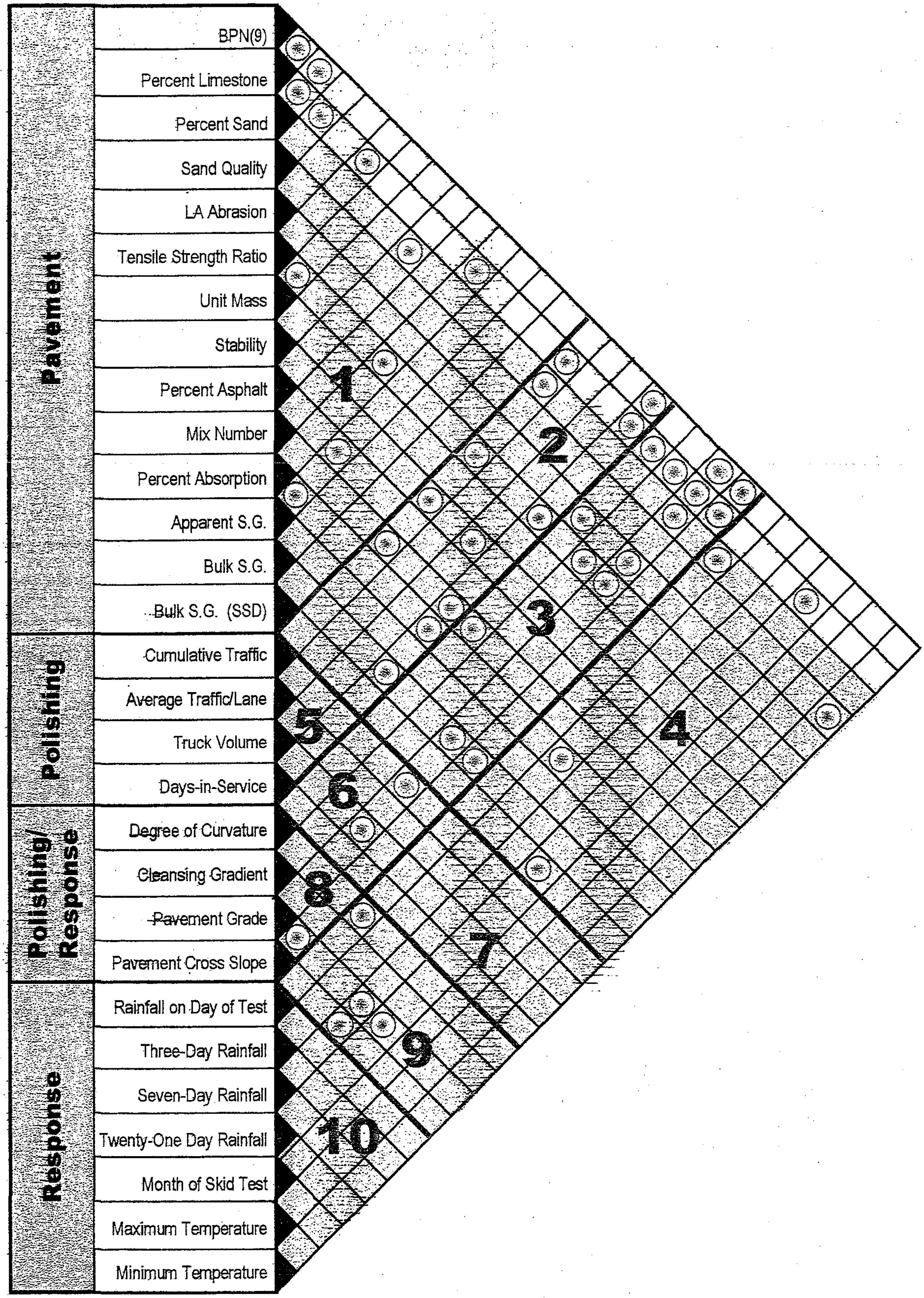


FIG. 5.3 Segmental Regions of Joint Factor Effect

Table 5.2 Significance of Factor 'Joint Effect' Zones (Page 1 of 2)

Index	Zone	Joint Effect	Significance	Example
1	Component Interaction	Pavement X Pavement	Factor combinations where two pavement elements may affect friction performance by working in concert with each other.	Poor friction performance may develop when large coarse aggregates (Mix No.) are coupled with poor limestone quality (BPN(9)).
2	Component Wear Resistance	Pavement X Polishing	Factors reflecting potentially resistant-to-wear pavement components contrasted with factors describing type and amount of pavement wear.	Good friction may be present even after extensive use (Days-in-Service) if high surface energy particles are exposed in contact patch (Natural Sand Content).
3	Component Geometry	Pavement X Polishing/ Response	Factors reflecting pavement components in conjunction with geometric orientation influencing characteristics of loading, wearing, and contaminate cleansing.	Poor friction may be reflected in flat pavements (cleansing gradient) designed using small-aggregate 'micro-texture' dominate features (Mix No.).
4	Component Environment	Pavement X Response	Factors describing pavement components associated with factors demonstrating temporary environmental effects.	Poor friction performance may occur with certain aggregates (Percent Absorption) when used in high humidity/moisture environments (Three-Day Rainfall).
5	Polishing Interaction	Polishing X Polishing	Coupling wear types may discriminate between situations resulting in different levels of damage to the long-term friction performance of a wearing surface.	Good friction performance may occur on long-service life pavements (Days-in-Service) experiencing little cumulative truck volume (Truck Volume).
6	Polishing Geometry	Polishing X Polishing/ Response	Factors reflecting wear in association with those that provide the geometric orientation demonstrates the joint influences of transverse shear and normal loads.	Good relative friction performance occurs where trucks (Truck Volume) traverse pavements without tire slippage on slight downhill grades (Pavement Grade), a condition known as coasting or free-rolling.

Table 5.2 Cont'd (Page 2 of 2)

7	Wear Affected Environment	Polishing X Response	Factors reflecting type and level of pavement wear exposure in conjunction with the presenting 'temporary environmental' effects at the time of skid test.	Well-worn pavements (Days-in-Service) may demonstrate poor friction performance on pavements with significant surface contamination (Twenty-One Day Rainfall).
8	Geometric Interaction	Polishing/ Response X Polishing/ Response	Combining geometric orientation factors may isolate particularly damaging pavement wear-scenarios.	Highway pavements on sharp curves (Degree of Curve) with inadequate super elevation (Cross Slope) may experience heavy wear from high transverse shear forces.
9	Geometric Affected Environment	Polishing/ Response X Response	Factors combining geometric orientation of the pavement in conjunction with the presenting 'temporary environmental' effects at the time of skid test.	Pavements on slight uphill grades (Pavement Grade) have better friction performance after even modest rainfall during the preceding seven days (Seven-Day Rainfall) likely due to improved contaminate cleansing from the scrubbing effect of slippage in the contact patch.
10	Environmental Interaction	Response X Response	Combining rainfall and temperature environmental effects demonstrate the degree to which these two temporary conditions combine in affecting friction performance.	Pavements with potentially high surface contaminates (Twenty-One Day Rainfall) might be less forgiving when combined with high ambient temperatures (Maximum Temperatures).

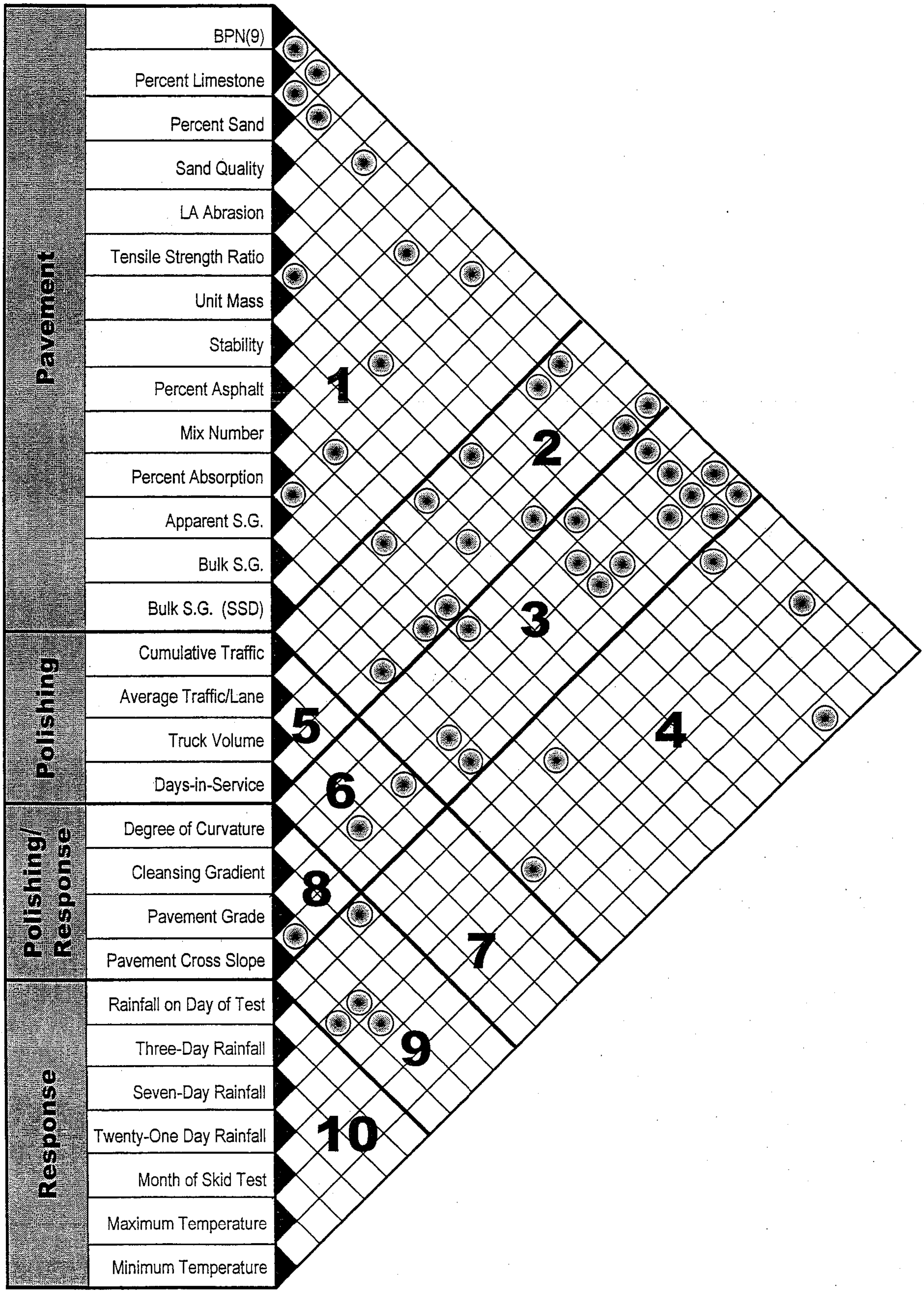


FIG. 5.4 Highly Significant Factor Pairings

These five contour maps and their accompanying one-page discussion reports are included in Appendix C.

Percent limestone has more significant factor couplings than does BPN(9) in developing ordered relationships relative to observed roadway friction performance. Along with its pairing with BPN(9), there are 11 other significant factor pairings. Four are with other pavement-related factors -- percent sand, sand quality, tensile strength ratio, and percent absorption. Two are within the factor group associated with polishing; these are cumulative traffic and days-in-service. There were four judged to be significant pairings with factors related to polishing/response -- degree-of-curvature, cleansing gradient, pavement grade, and pavement cross slope. One significant pairing is associated with response; this is twenty-one day rainfall. These eleven contour maps and accompanying discussion are included in Appendix D.

In terms of factor pairings judged most significant, Region 3 is the most heavily populated with 25% of those pairings included as highly significant. This particular region considers the interaction between pavement-related factors and the geometric alignment of the roadway. Regions 5, 7, and 10 had no significant factor pairings at all.

Appendix E contains affinity charts that provide the subjective ranking of the factor pairing significance from a high of 10 to a low of 1. On reviewing these charts it's obvious that not all pairings proved to be significant.

CONCEPTUAL DEVELOPMENT

Numerous concepts were developed in the process of exploring the contour maps of factor pairings produced by the underlying data. These concepts are laid out without discussion in Table 5.3. Detailed discussion will be provided on only a few of these within this listing beginning with wear.

Vehicle-Load Surface Wear

Arriving at a simple lifecycle measure of wear on pavement surfaces is important. This measure would mark the expected phases that the pavement surface goes through as it is used up or worn away. Four possible measures were considered: (1) Cumulative Traffic, (2) Cumulative Vehicle (Cars-Only) Traffic, (3) Cumulative Truck Traffic, and (4) Days-In-Service. There were some interesting and unexpected results.

The natural expectation is that the best predictor of 'wearing out' the frictional characteristic of a pavement surface would be related to a function of wear such as Cumulative Traffic. However with the 699 skid tests used in arriving at an appropriate measure, the best linear predictor of frictional characteristic is Days-In-Service, which alone accounts for 29% of variability in the observed friction numbers within this small data set.

Figure 5.5 shows the fitted linear regression function with the four demonstrated life-cycle phases identified as: Phase I – Enhancement, Phase II – Plateau, Phase III -- Decline, and Phase IV – Terminal State.

The other measures that were considered are addressed briefly here. Cumulative Traffic shown as a fitted linear regression function on Figure 5.6 accounts for only 17% of the observed variability. This increased to match that of Days-In-Service when a decay-type function was fit (R-square = 0.286). Cumulative Vehicle Traffic (Cars-Only) shown on Figure 5.7 accounts for 17% with a linear function and 30% with a decay

Table 5.3 Potential *Pavement Friction* Concepts (Page 1 of 3)

- Pavement
  - Design Components
    - Macro Texture Dominate
      - Mix Number
    - Micro Texture Dominate
      - Sand Content
      - Asphalt Content
  - Pavement Performance and Distress
    - Structural Distress
      - Densification
      - Rutting
    - Surface Performance
      - Micro-rotation as function of asphalt viscosity
      - Surface Roughening under Traffic
      - Rainfall storage (valley storage)
      - Volumetric Expansion of Asphalt
      - Recoverable Texture
      - Asphalt bleeding
  - Aggregate Properties
    - Limestone
      - Clay Seams and other Deleterious Material
      - Specific Gravity Stratification
      - Limestone Formation
      - Aggregate Quality
    - Surface Characteristics
      - Chemical (wetted)
        - Adhesion (Surface)
        - Surface Energy and Potential
        - Hydrophobic Properties
        - Anti-Stripping Agent "Acid Wash"
      - Mechanical
        - Texture
        - Angularity
      - Wear Characteristics
        - Polishing
        - BPN Distortions, Accelerated Polishing during Test
    - Miscellaneous
      - Sand Characteristics
      - Slag Content
      - Limestone Fines (Manufactured Sand)

Table 5.3 Potential *Pavement Friction* Concepts – Cont'd (Page 2 of 3)

- Wear
  - Material Loss
    - Small Scale
      - Polishing
    - Large Scale
      - New Edge Formation (sacrificial loss)
      - Stripping and Raveling
  - Grade Associated Wear (work transmission concept)
    - Uphill Grade
    - Free-rolling wear
    - Downhill Braking Wear
  - Load Associated Wear
    - Shear Interaction
      - Transverse
      - Polishing
      - Abrading
    - Normal Forces
  - Contact Associated Wear
    - Higher Contact Pressures with Coarse Aggregate Protruding
    - Isolated Contact on Limestone
    - Localized Tire Wear with polishing
  - Time Dependent Wear
    - Asphalt Film Removal
    - Days in Service
    - Wear Rate
  - Wear Intensity
    - Traffic
      - Truck Volume
      - Cumulative Traffic
      - Number of Lanes
    - Abrasive Contaminates

Table 5.3 Potential *Pavement Friction* Concepts – Cont'd (Page 3 of 3)

- Response
  - Surface Contamination
    - Cleansing
      - Traffic Volume Daily Cleansing
      - Rainfall
    - Contamination
      - Residual Contamination
      - Lubricating Slurry
      - Fine particle dusting
      - Bound surface contaminates and traffic oils
      - High contaminate potential for high surface energy aggregates
      - Limestone polish dust present
  - Environmental Effects
    - Rainfall dependent performance
    - Temperature dependent performance
  - Skid Trailer Resistance
    - Friction Reading
      - Skid Number
      - Speed
    - Possible Test Bias
      - Geometric Effect on Skid Trailer
      - Groove closure on test tire on certain types of surfaces
      - Test Tire Compositions – Suited for hysteresis than adhesion
      - Locked wheel bias is skid tests
      - Tire Stress distribution
      - Torque measurement versus normal load
  - Experimental or Residual Error

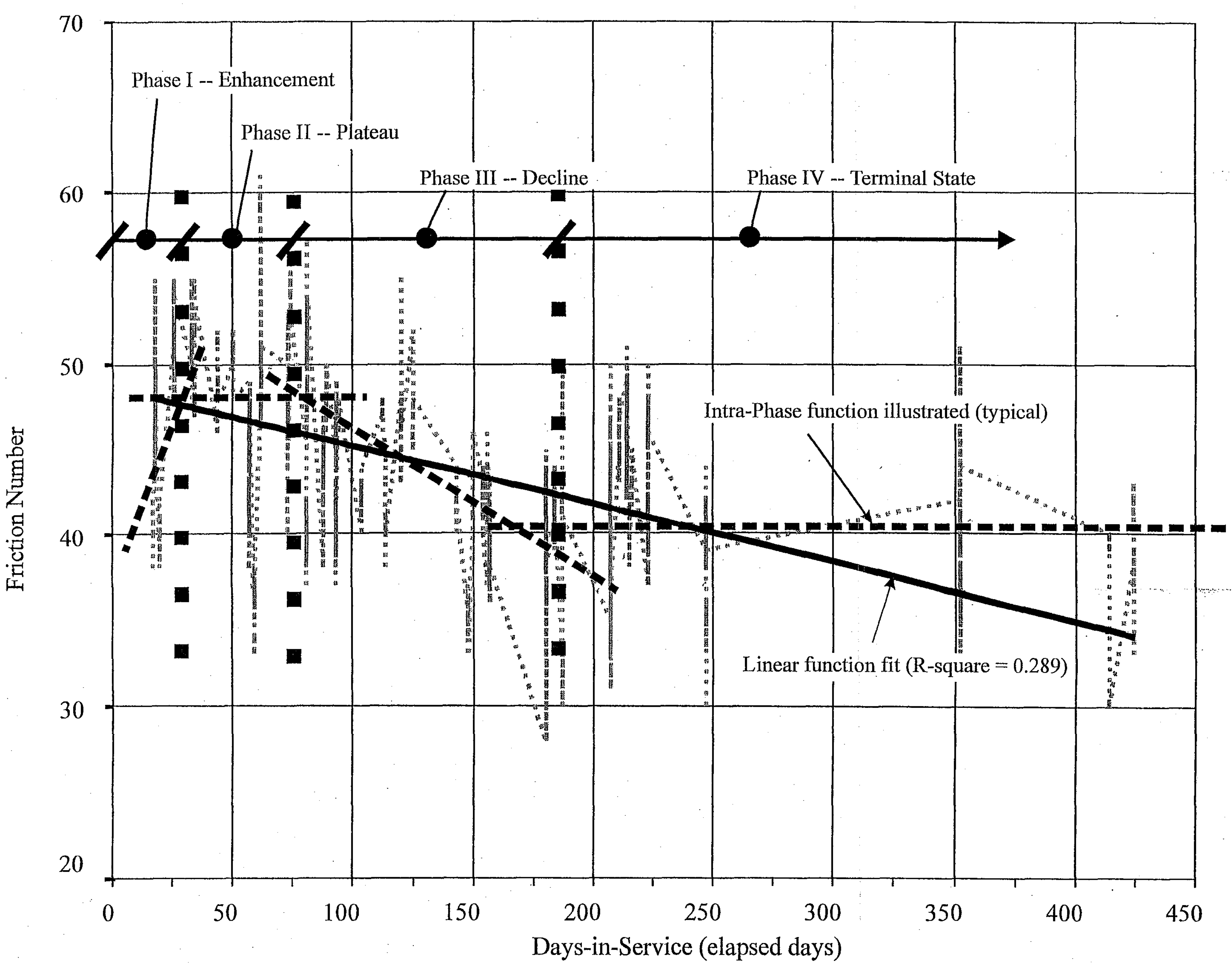


FIG. 5.5 Pavement Friction Lifecycle Phases

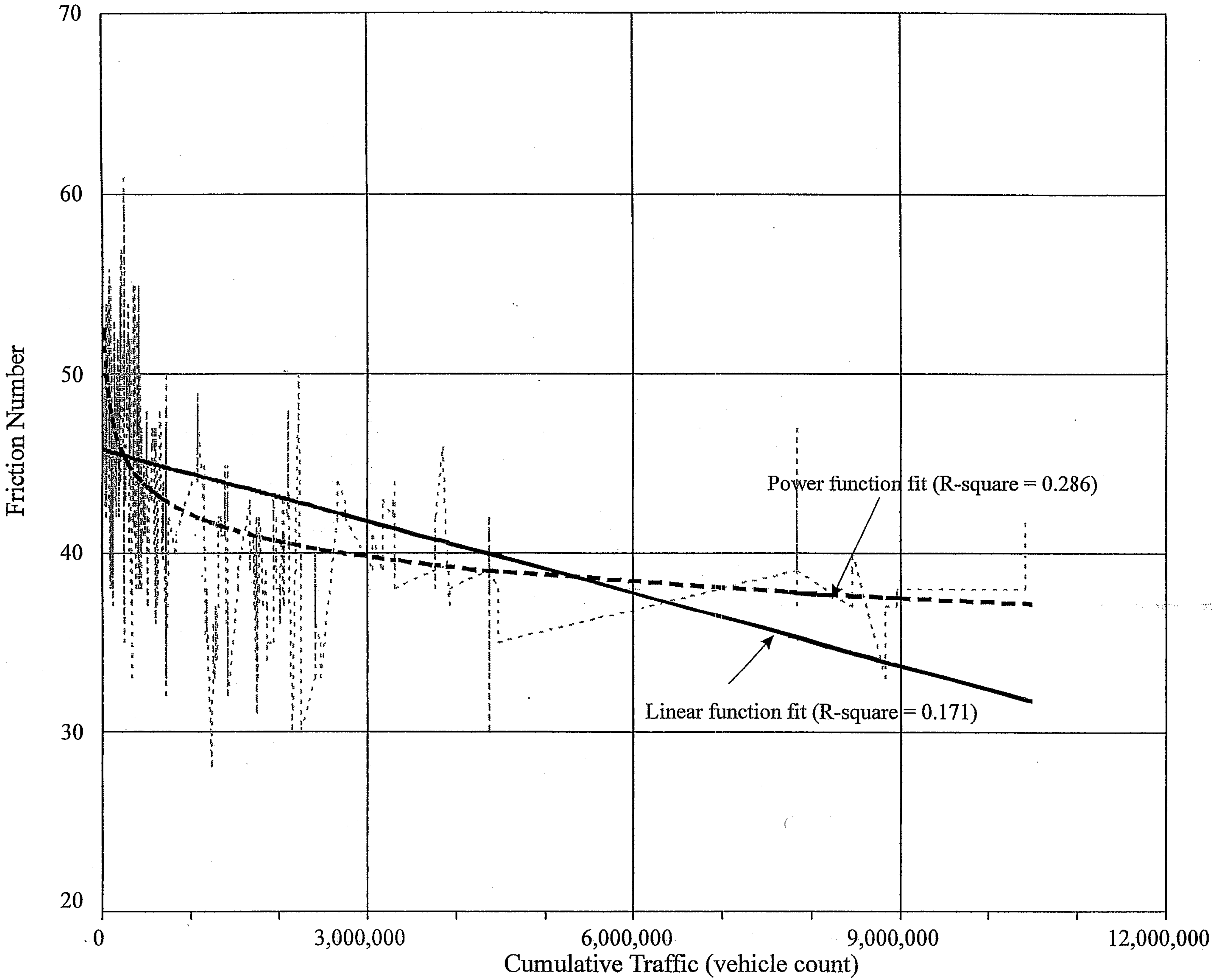


FIG. 5.6 Description of Skid Number as function of Cumulative Traffic (699 tests)

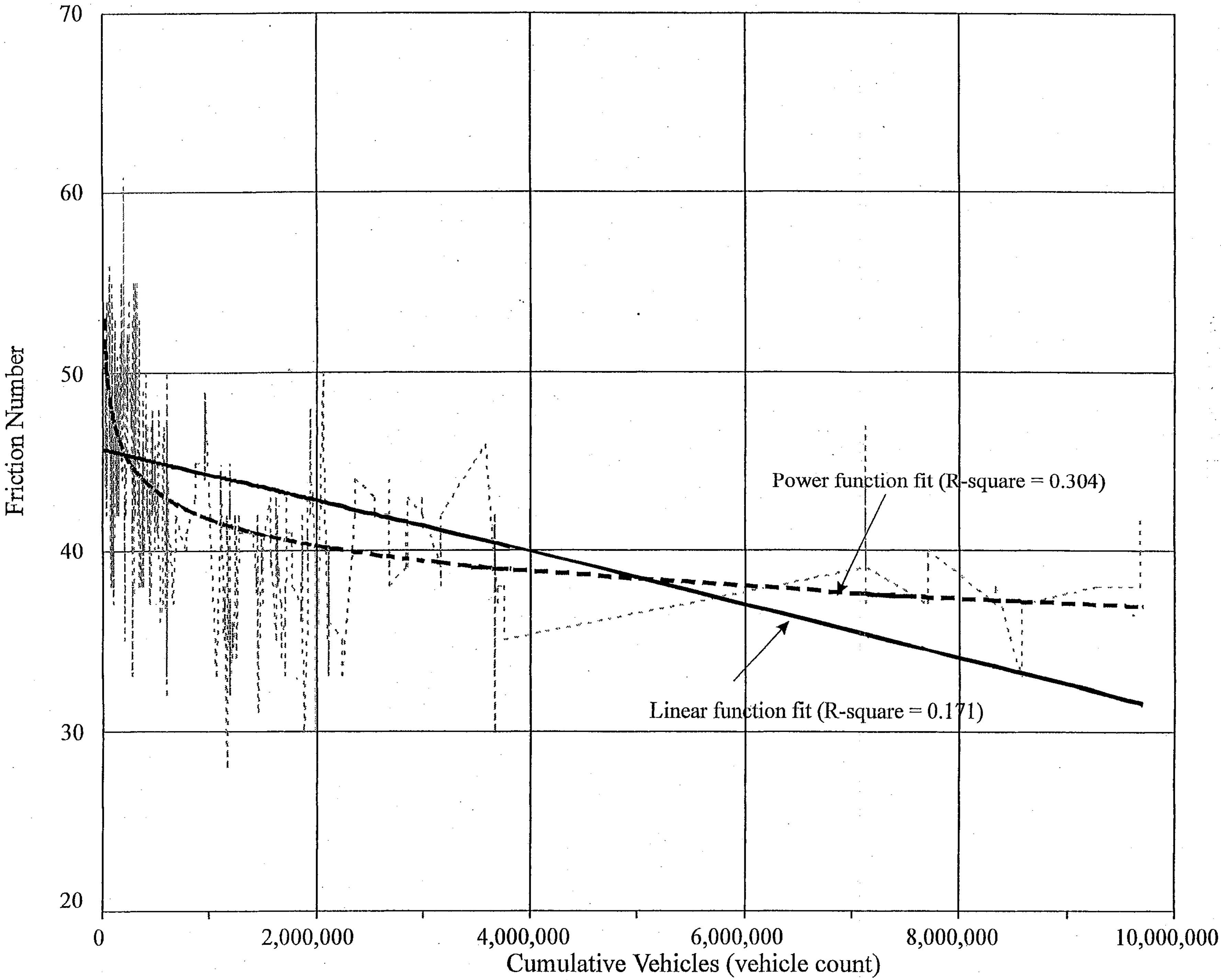


FIG. 5.7 Description of Skid Number as function of Cumulative 'Car-Only' Vehicles (699 skid tests)

function.

Cumulative Truck Traffic shown on Figure 5.8 accounts for only 13% of the variability in friction performance with a linear function and 15% with a decay function.

Each of these potential 'wear-style' measure of pavement surface lifecycle can only match that provided by a simple linear measure using Days-In-Service. This fact requires a major rethinking of the chief contributing mechanisms to pavement surface decline.

The four lifecycle phases using Days-In-Service are further illustrated by looking at some of the contour plots in the following figures. Shown earlier, Figure 5.2 plots BPN(9) vs. Days-In-Service. Figure 5.9 plots Percent Limestone vs. Days-In-Service. Figure 5.10 plots Percent Sand vs. Days-In-Service. In these plots, the top frame indicates the coverage of data used in developing the contours. The bottom frame provides the contour maps. Contours shown in blue indicate friction values greater than 49 and those shown in red indicate friction values less than 41-- blue contours are good and red contours are bad.

The four phases are prevalently displayed in the observations of each of these figures. Moving from left to right along the 'Days-In-Service' axis, the frictional performance increases rapidly for a short period of time (Phase I – Enhancement) reaching a peak level of performance (Phase II – Plateau). Notice this region as the blue contours on the plots. Then performance declines from this peak (Phase III – Decline) to an area of poor overall performance with little change in friction numbers (Phase IV – Terminal State).

The most interesting phase of the four is Phase III – Decline. It appears that the

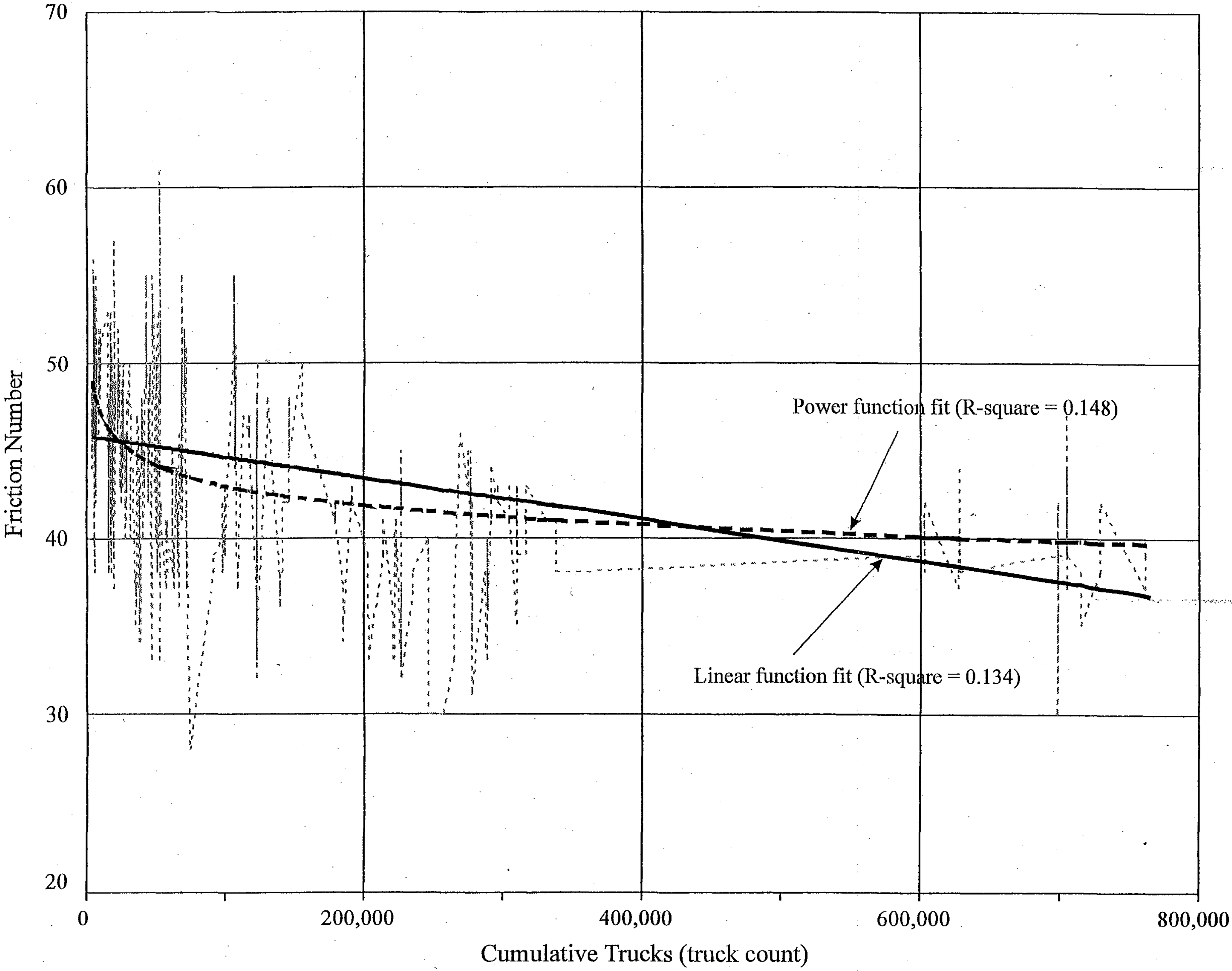


FIG. 5.8 Description of Skid Number as function of Cumulative Trucks (699 Skid tests)

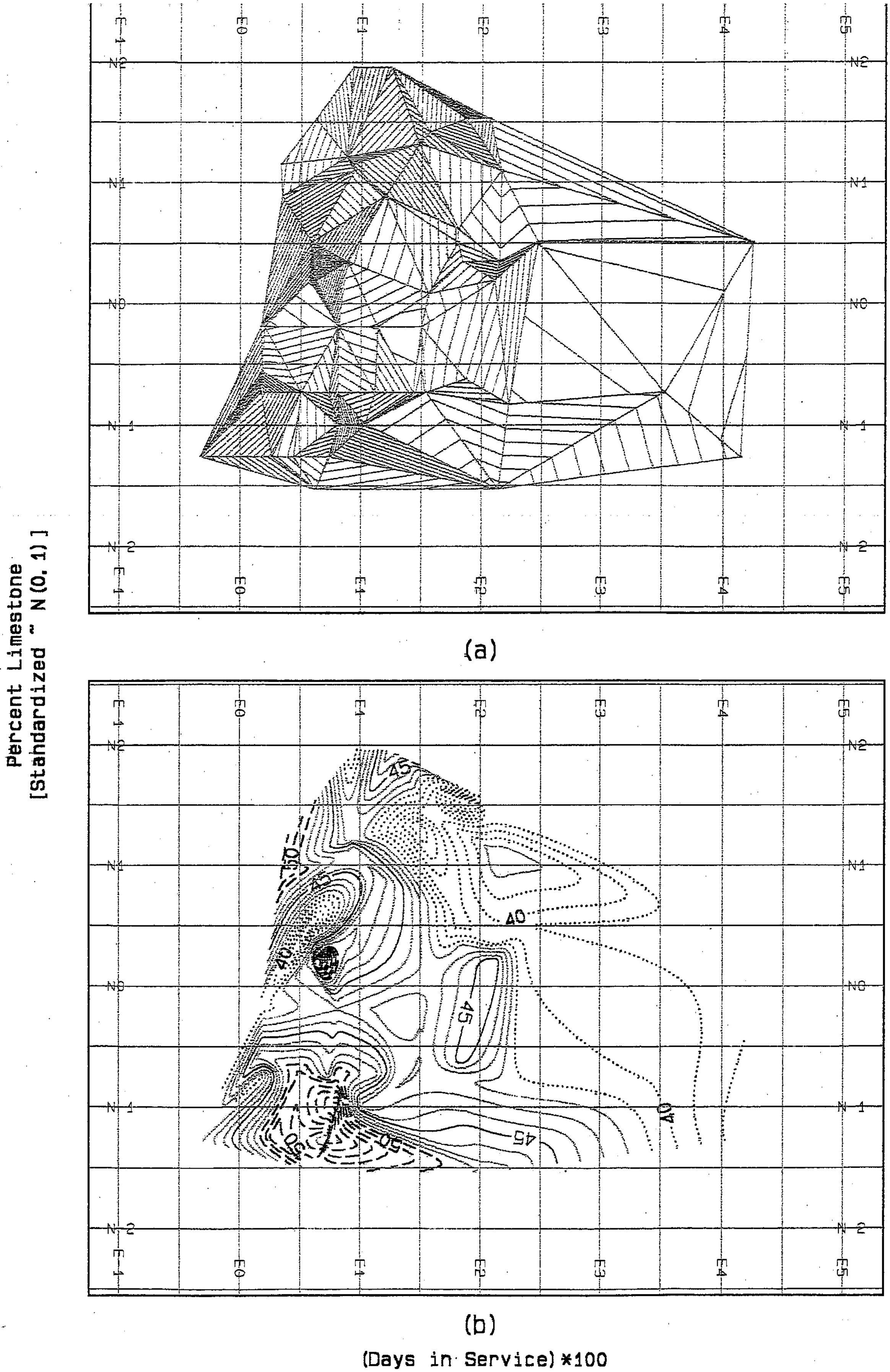


FIG. 5.9 Skid Number Contours as a Function of Percent Limestone and Days in Service (a) Triangulation of Initial Data (53 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (704 obs run on 10/16/98) (Copy of FIG. 44 from November 99 Report)

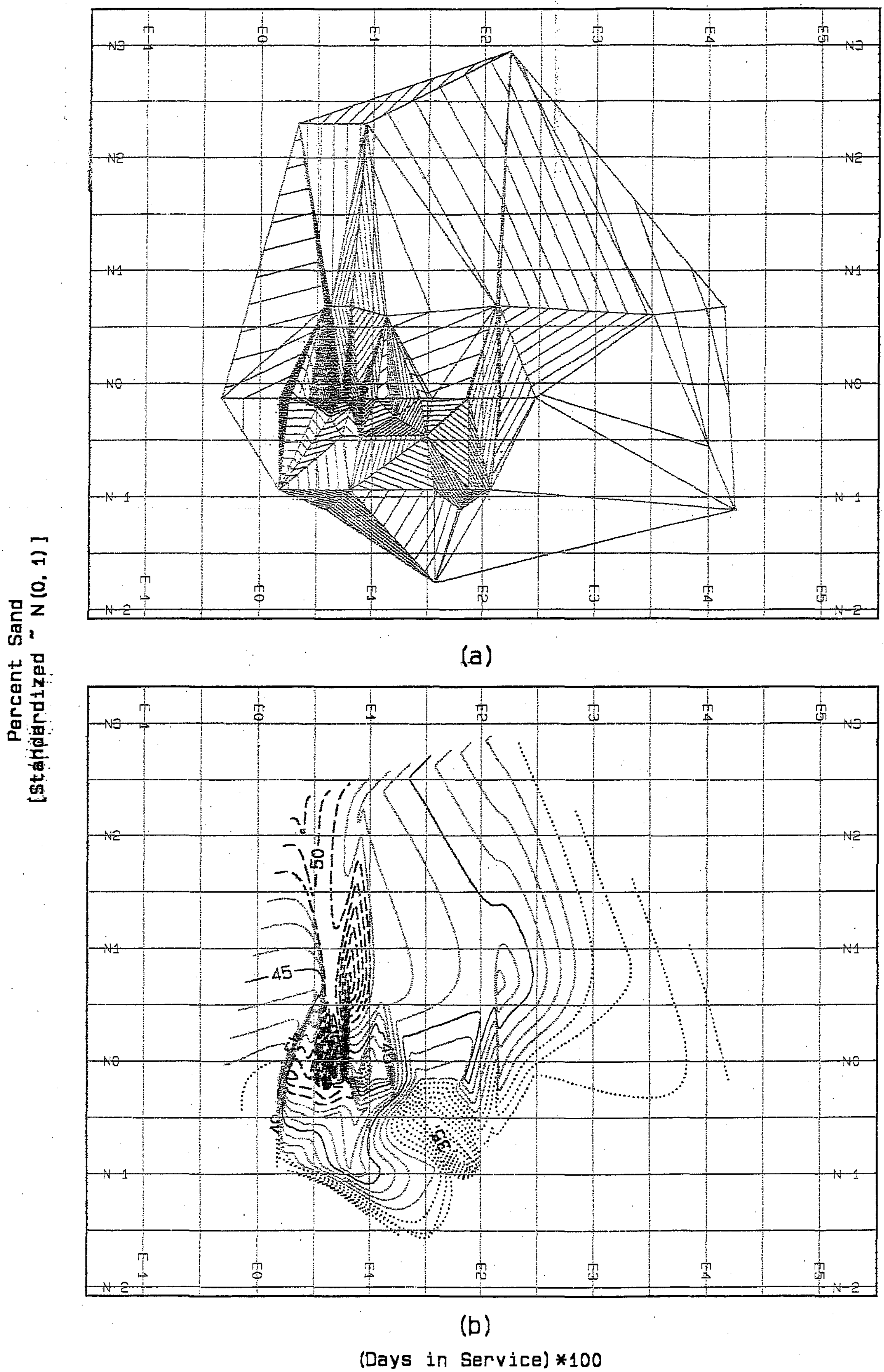


FIG. 5.10 Skid Number Contours ~~as~~ a Function of Percent Sand ~~and~~ Days in Service (a) Triangulation of Initial Data (52 pts) (b) Contours with ~~Dotted Lines~~ ~~Indicating~~ FN < ~~41~~ and Dashed Lines Indicating FN > ~~49~~ ~~(704~~ obs run on ~~10/19~~/98).
(Copy FIG. 70 ~~from November~~ ~~1999 Report)~~

steepness of the decline during this phase is the smoking gun that will pinpoint the principles that are in play for frictional decline of wearing surfaces. Let me draw your attention to what would constitute Phase III (Decline) on Figure 5.9 – Percent Limestone vs. Days-In-Service. As anticipated from the outset of this study, limestone content does play a prominent role in the frictional decline of pavement surfaces. There are three different rates of decline during Phase III as measured by the closeness of the contours to one another. When limestone content is low the decline in friction performance is gradual, at moderate levels of limestone the decline is accelerated, and with high limestone content the decline is rapid.

Now look at the observed friction numbers during Phase III on Figure 5.2 – BPN(9) vs. Days-In-Service. The plot does not display the original expectations of the study effort, which was that higher BPN(9) aggregates would slow the frictional decline of the wearing surface. Just the opposite is observed. The decline is more moderate with lower BPN(9) aggregates, which would suggest our original premise is inaccurate. Although, it must be noted that there is a positive correlation within the observed data between high BPN(9) values and high limestone content which may bias this conclusions.

One plot stood out when considering the different Days-In-Service plots for 'Phase III – Decline' and that plot is shown here as Figure 5.11, which contours friction performance as a function of Percent Absorption vs. Days-In-Service. The frictional decline appears to be slow with low absorptive aggregates and rapid with high absorptive aggregates. It is a very real possibility that what is being observed is not a function of the aggregates underlying absorptiveness, but rather the 'percent absorption' factor

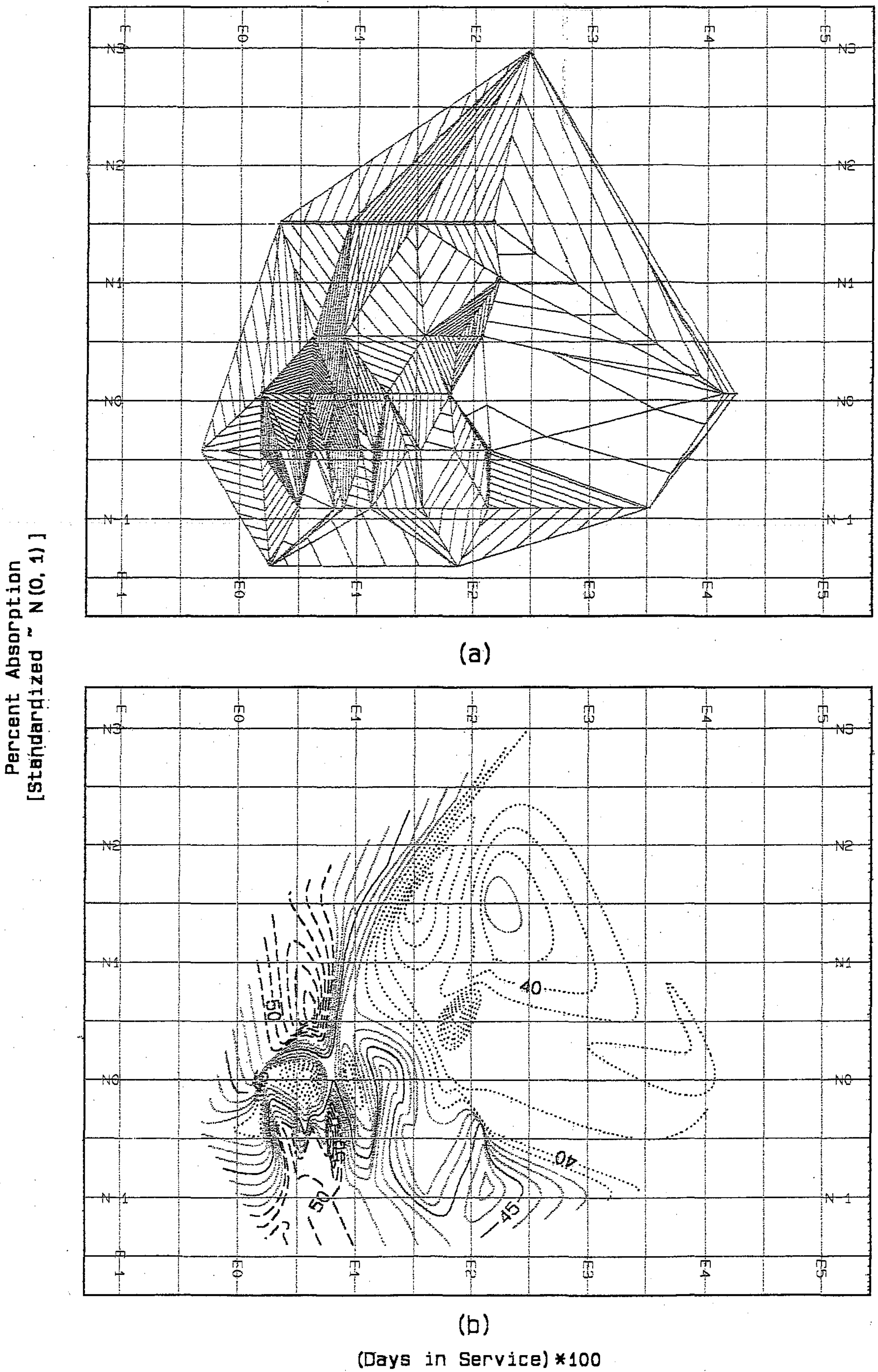


FIG. 5.11 Skid Numbers as a Function of Percent Absorption and Days in Service (a) Triangulation of Initial Data (47 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > ~~49~~ (~~704 obs~~ run ~~on 9/22/96~~)
(Copy FIG. 242 from November 1999 Report)

discriminates between limestones on the basis of different materials, different sedimentary environments, and different digenesis. Limestones are different and it is natural to assume these different limestones will have different transfer-rates of kinetic energy, which is commonly termed 'friction'.

Geometric-Load Surface Wear

Geometric loading of pavement surfaces affect the degree of surface wear due to the relative amount of 'work' transmission between pavement and tire in the contact patch. Two types of work are performed at the surface. One 'work' type moves a vehicle-mass up or downhill, thus moving the vehicle to one of higher or lower potential energy. Even though the engine supplies the necessary power to accomplish the move, the pavement/tire contact patch provides the surface through which the work is transmitted. This work-type is a function of the pavement grade. The grade corresponds with the different wearing actions caused by the tire-pavement interface. Moving the vehicle uphill is the most severe work-transmission and results in the highest slippage in the contact patch thus the most wear on the pavement surface. During coasting or 'free-rolling' on slight downhill grades there is little, if any, slippage in the contact patch and thus no wear on the pavement surface. If the downhill grades become too severe, then brakes will be engaged or 'pumped' to slow the vehicle resulting in significant tire/pavement slippage especially with heavy loads. This downhill-condition can result in devastating pavement surface wear as well.

The second 'work' type is that done in changing the direction of a vehicle that is traversing a curve in the roadway. On a flat roadway, this change in momentum is accomplished in the tire/pavement contact patch through a transverse shearing action on the pavement surface. With roadway super-elevation, the 'transverse' shearing action is redirected to an increase in 'normal' pavement loading. This increase in normal loading has potentially devastating affects on rutting or other consolidating issues.

Macro/Micro-Texture Dominate Design

Certain pavements are designed to rely more on the macro-texture of the pavement surface and other pavements use more micro-textural features. This trade-off between micro- and macro-texture can be observed in the friction performance. For example, high asphalt content allows more surface area contact within the pavement/tire interface and consequently more friction-performance dependence on the sand content rather than the coarse aggregate. With moderately low asphalt contents, natural sand does not rise to contact the tire and therefore plays no role in friction performance. At low asphalt contents, macro-texture predominates and friction performance is dependent on the coarse aggregate contributions of the pavement surface.

In these pavements, the frictional performances of pavements containing limestone aggregates will prove to be a function of aggregate gradation and the relative nested position of the limestone within that gradation.

Limestone polishing.

Conventional wisdom suggests that long-term friction performance is dominated by the polish-resistance of limestone aggregates used in the pavement surface layer. BPN(9) quantifies this quality where high BPN(9) values indicate more resistance.

Figure 5.12 displays the three factors considered most relevant to this speculative 'cause-and-effect' explanation: BPN(9), Days-in-Service, and Friction Number.

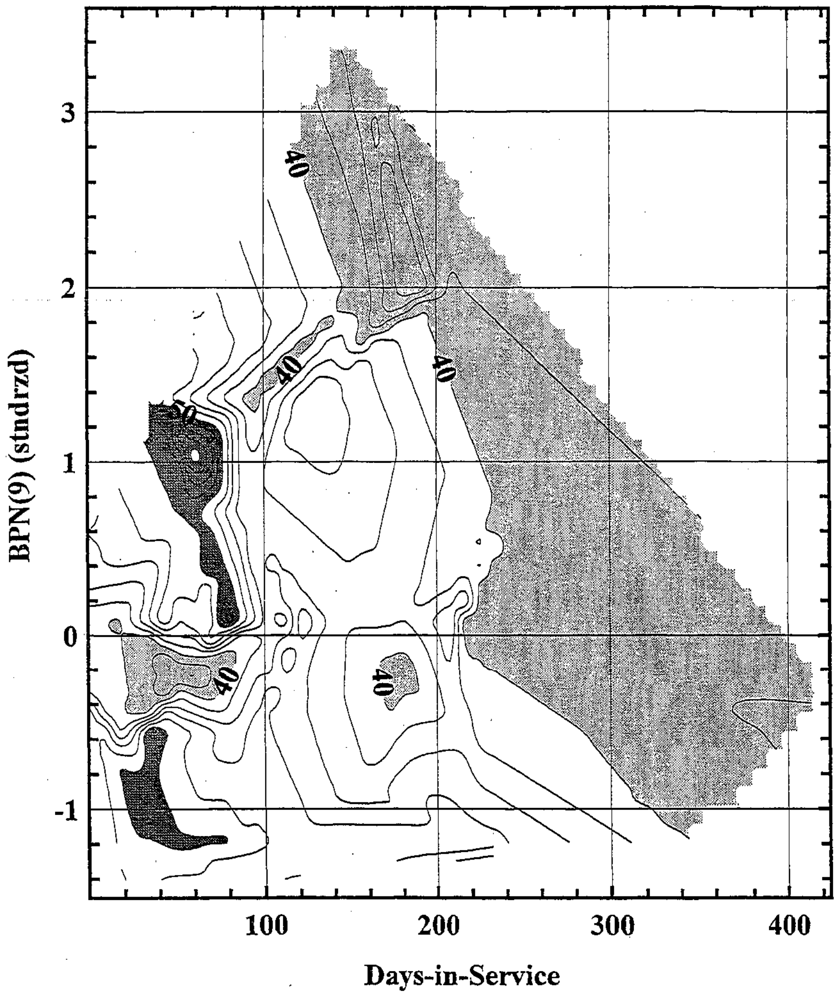


Figure 5.12. Friction Numbers (FN) as a function of BPN(9) and Days-in-Service

Contrary to the expected relationship, poor friction performance occurs earlier in pavements using better quality limestone. While this may possibly reflect a joint incident of other factors that may actually be driving the observation; none-the-less, these observations strongly suggest that limestone polishing does not play a singularly dominant role in diminished friction performance.

Natural sand content

Another point of conventional wisdom suggests that fine aggregate angularity (crushed stone) is preferred for enhanced friction performance over that of more rounded natural sands. As one can see from Figure 5.13, extremely low sand content tends to diminish the friction performance of pavements across all service lives. The need for natural sand within the pavement becomes more prevalent as the pavement ages. This observation implies that above average natural sand content helps maintain long-term pavement friction.

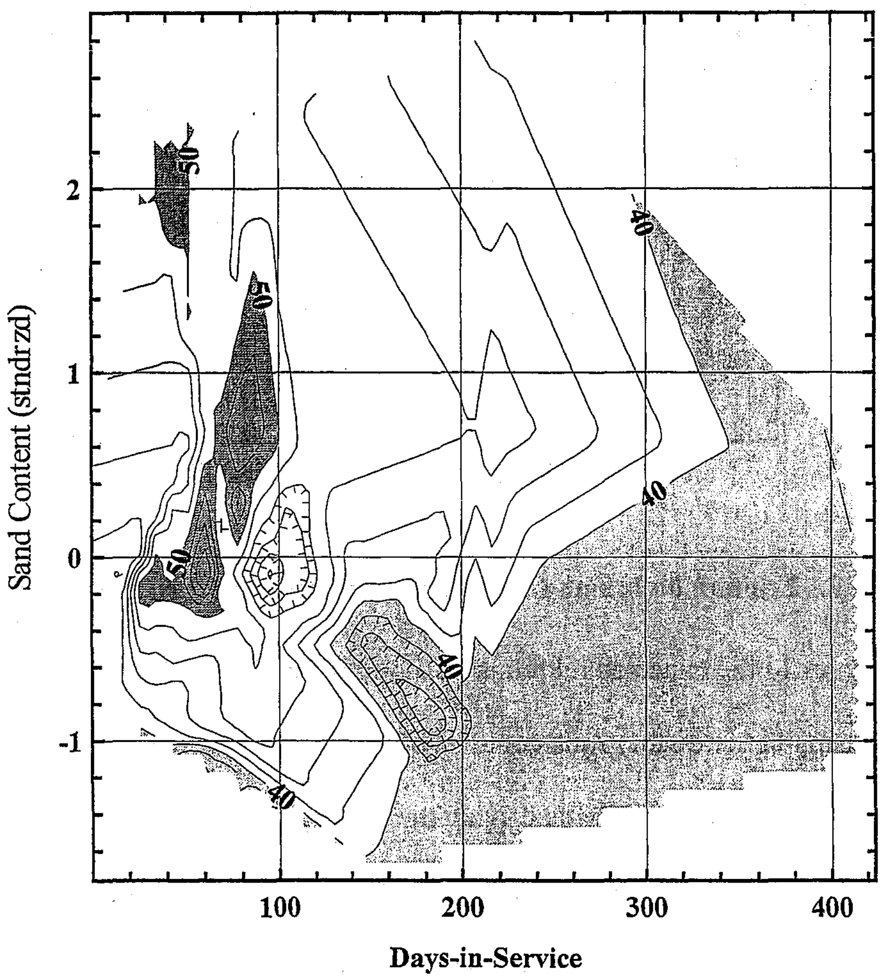


Figure 5.13 Friction Numbers (FN) as a function of Sand Content and Days-in-Service

Surface contamination

Conventional wisdom suggests that pavements are slickest after light rainfall combines with surface contamination and traffic-oils to form sludge. A natural corollary to this would be that increased, sustained rainfall would contribute to the removal of surface contaminates and therefore improve measured skid resistance. This corollary was tested when Hurricane Georges stalled for several days just inland off the coast. From area rainfall records, approximately two inches of rainfall fell on Alabama's Highway 13 one day, followed by fifteen inches the next, 6 inches the following day, and then a light trace amount the fourth day.

This rainfall provided a good scrubbing of the countryside and most likely the roadways as well. Skid tests were performed on Highway 13 just under thirty days after Hurricane Georges to determine the surface skid resistance. The results were impressive. Figure 5.14 illustrates that each roadway section had presumably reached its terminal

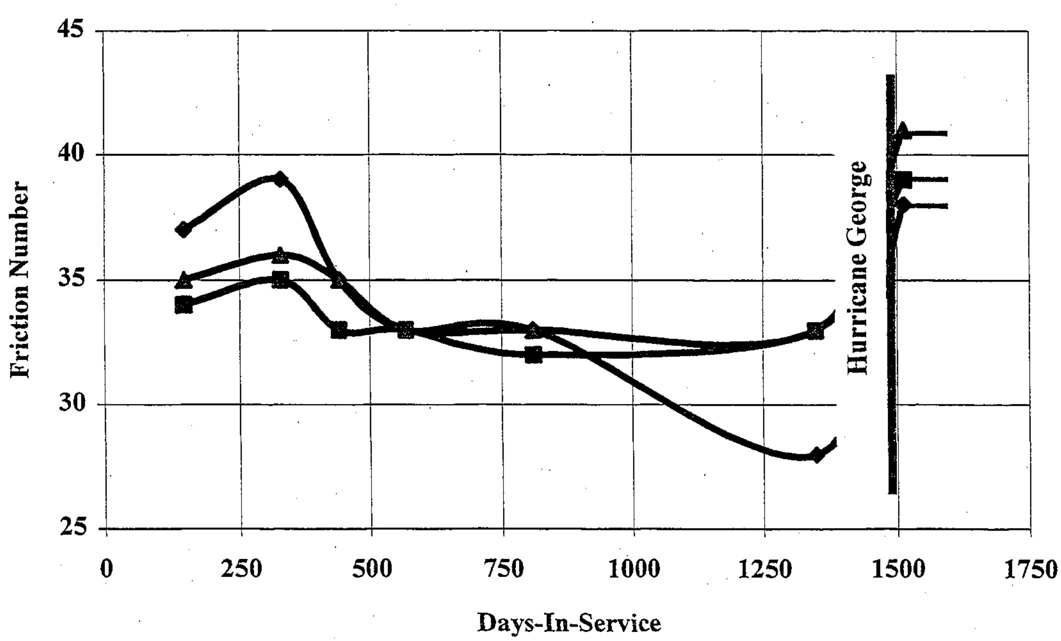


Figure 5.14 Friction Numbers on Al. No. 13 before and after Hurricane Georges

skid values before the hurricane. However, the intense, sustained rainfall recovered significant texture as observed by the improved skid numbers. This observation implies that pavements have significant recoverable surface texture even at assumed terminal skid numbers.

In addition to removing surface contaminates, high rainfall may also accelerate surface raveling which would expose fresh aggregate surfaces.

Surface Energy

Limestone aggregates polish faster than other aggregates. This statement means that limestone aggregates give-off both more and smaller wear particles than do other aggregates. In coming to grips with this known characteristic, most researchers attribute the poor friction performance of limestone pavements to the smooth physical surface that results when small particles are worn away. This condition is known as low micro-texture. The rationale for the implied causal relationship between smooth surface and low friction is that the micro-texture will serve to penetrate the last few microns of surface water to provide intimate surface contact between aggregate and tire. What is left unresolved with this explanation is … what then?! How does friction take place once contact is made? Why is it logical to reason that contact is both necessary and sufficient for friction to take place? Its not!

What this researcher has come to believe about friction and limestone polishing is that they are both a function of low-surface energy. Limestones polish and have low frictional properties due to low surface energy. Differences in polish resistance is simply an indicator of marginally different surface energies within the limestone.)

Relational Modeling

With concepts and modeling elements, Figure 5.15 lays out a relational model for studying the effects that the polish-resistance of limestone aggregates might have on pavement friction.

At the core of this model is pavement surface friction – a latent factor. Here, a necessary distinction is made between surface friction and the generated skid-trailer effect. Friction is not a single attribute like mass or height, but is an observed phenomenon describing the transfer-rate of energy, a rate that is heavily dependent on a myriad of variable factors. To describe friction as the measured results of a single simulated event is simplistic and misleading, but to admit that friction influences the observed skid results is in keeping with the underlying physics and potential errors within the observations.

As can be seen from the directed arrow, pavement friction is considered to influence the observed field skid measurement with a modeled allowance for error in the observed results represented by epsilon. While keeping with the construct that friction is not directly observable, then what influences the latent 'pavement friction' element will also be observed by its affect on field-tested friction measurement as well.

Considering what might influence pavement friction requires stepping one-layer back from pavement friction. At first the number of possible influences appear limitless; however, the exploratory analysis searches the boundaries of these influences pointing to four possible categories of direct influences affecting pavement friction.

(1) 'Pavement Surface Wear' represents a class of factors that act to wear away the pavement surface. This category is further broken into four subcategories: vehicle

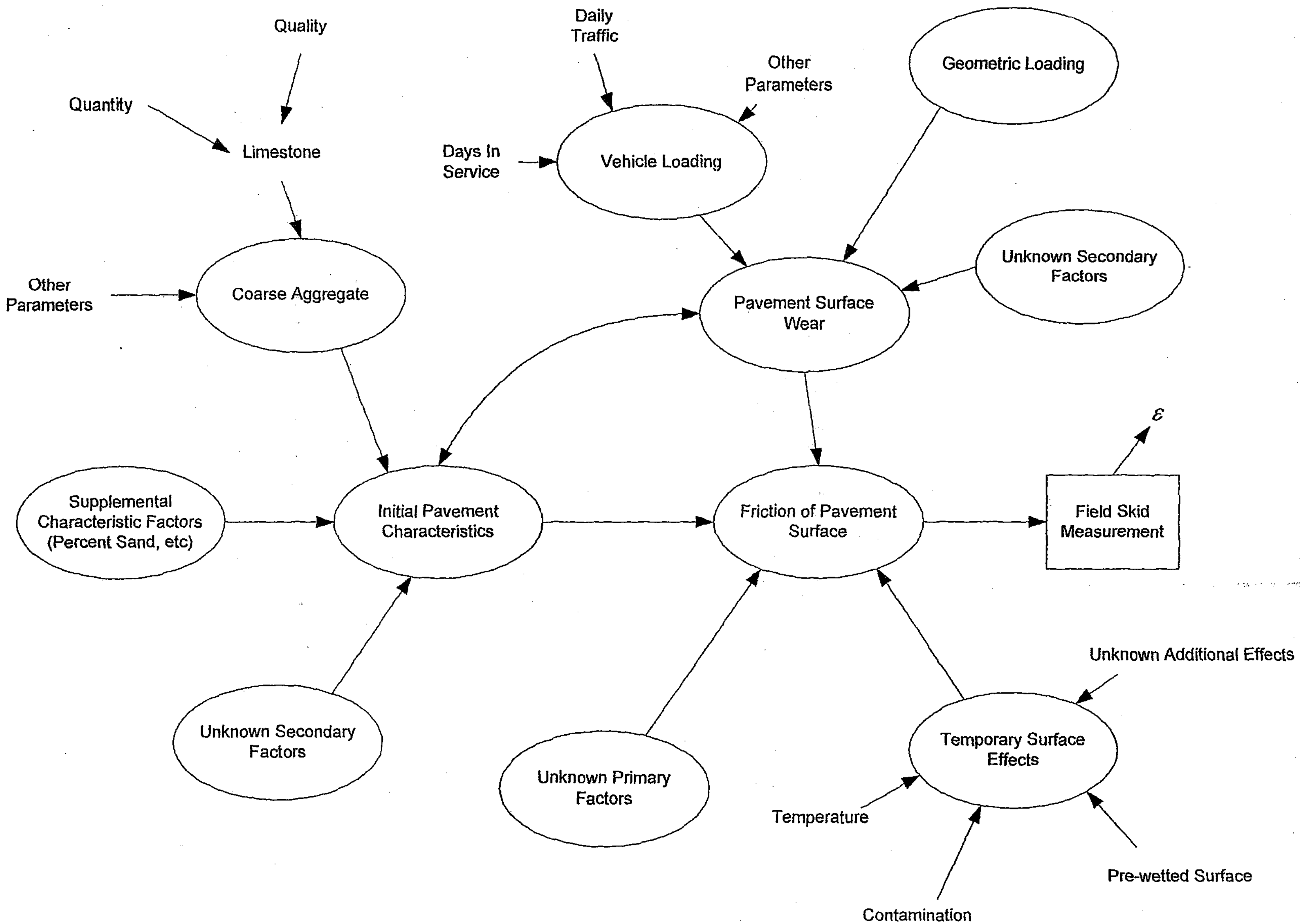


FIG. 5.15 Pavement Friction Relational Model

loading, aging, geometric loading, and a place-keeper for, as yet, unknown factor(s). 'Vehicle loading' is at the center of surface wear since it's the differential slip in the interplay between vehicle tires and pavements that wear away surface texture much like sandpaper grinds surface imperfections from wood. On pavements, these imperfections are currently seen as contributing to pavement friction through macro- and micro-texture.

'Aging' accounts for those elements that deteriorate pavement surfaces through time, which would include the cumulative wear associated with vehicles. 'Geometric loading' reflects the possibility of differential wear associated with pavement geometry and the vehicle maneuvers suggested by that geometry. For example, super-elevation is placed on pavement surfaces so that vehicles maneuvering around a curve would translate transverse shear to increased normal load on the pavement. A curve without corresponding super-elevation should exhibit increased wear due to this unresolved shearing action. A vehicle moving uphill is converting kinetic energy into potential energy through a transfer made at the tire/pavement interface, which increases the wear rate. Moving downhill, a vehicle may free-roll thus inducing no differential slip in traversing that pavement section and minimizing the resulting wear. 'Unknown factors' is the fourth subcategory. There are many facets of pavement wear that are not known as yet. This factor recognizes that probability and the corresponding unresolved and unexplained variance component associated with surface wear.

(2) 'Initial Pavement Characteristics' reflect the friction and wear resistant performance of the composite pavement mixture attributable to the chosen components in terms of quality and quantity. Coarse aggregates, fine aggregates, asphalt content, latex additives – as a composite -- form the exposed surface that generates friction through

coupling with vehicle tires and withstands the wearing conditions on pavements. The relative quality and quantity of these underlying components differentiate good friction and good wearing pavements from bad.

While it is indisputably true there is some link between pavement components and friction performance; however, can this linkage be demonstrated within the observed data? It is likely that each pavement component plays some role in that performance. But, does coarse aggregate play the dominant role? More particularly, how does limestone coarse aggregate contribute to the friction and wear performance associated with the initial pavement characteristics? Is there some measurable characteristic of limestone indicating its relative friction performance? If one exists, is this unnamed limestone quality a function of its wear resistance; perhaps measured by the BPN(9) results?

Limestone tends to polish, an extremely detrimental form of wear in terms of residual friction performance. Under polishing, the aggregate wears away through giving up small surface particles leaving exposed an apparently smooth surface. Is this wearing away of surface irregularities the cause of poor friction performance or is it itself an exhibited effect of the factor which causes both polishing wear and poor friction performance? Many indicators point to low surface energy within the aggregate itself that allows small bits to wear away and poor coupling potential with traversing tires.

(3) 'Temporary Surface Effects' represent those frictional influences that are a function of things external to the pavement itself and thus only temporary -- subject to change in its influence on friction with changing circumstances. The model reflects three subcategories of temporary effects: Temperature, Contamination, and additional

unknown effects. Temperature is a complex element in terms of friction. Friction vents kinetic energy through 'waste' heat. Thus, the available heat sink or differential temperature of the pavement will affect the rate at which heat can be vented and kinetic energy be dissipated. From this perspective, the ambient temperature influences the friction potential of pavements with lower demonstrated friction at higher temperatures. This statement seems counter to the common knowledge that heat in tires is beneficial for traction, a companion to friction. Increasing traction is why dragster-racing teams will 'smoke' their tires in order to heat them. A cold tire has a compact footprint with few active coupling receptors in the contact patch. Warming the tire makes the rubber more supple thus flexing the sidewalls and activates surface receptors in the contact patch.

Surface contamination reduces the frictional interface between tire and pavement. This contamination accumulates over time and then is periodically removed by intense rain events in combination with the scrubbing action of concurrent traffic.

A third category represents all those possible temporary surface effects that are not mentioned. While none of these temporary effects are included in the current statistical analysis, the fact that they influence observed friction reflects the limits on what we should expect in terms of accounting for the variation in friction performance.

(4) 'Unknown Primary Factors' serves as a place to partition all those myriad of factors that influence friction performance. The fact that it is included in the representation of the relational model does not diminish the value, but only serves to remind us of the following: (1) This is an uncontrolled environment. (2) We know very little about the phenomenon that is being explored within this research. (3) It

demonstrates what is to be expected in terms of accounting for observed variation within the data.

6. STATISTICAL RESULTS

Overview

In general, the objective of statistical results is to demonstrate the potential of organizing 'study data' through mathematical modeling. In arriving at these results, researchers divide the 'study data' into a minimum of two groups. One data group represents the measured 'effect' being studied and the other describes the speculated 'cause' or 'causes' that precede and influence that 'effect'. These two groups are then related through best-fit mathematical equations that collect the independent 'causes' on one side of the equation with the dependent 'effects' on the other.

In this process, 'study data' is considered organized to the extent that observed variances in the 'causes' will result in the anticipated influences on the 'effects'. Data that is sufficiently organized in this manner supports the validity of the underlying 'cause-and-effect' hypothesis. Insufficient organization suggests the absence of the modeled 'cause-and-effect' relationship within the study data. Given this objective, what level of organization is considered 'sufficient' to provide validation?

'Sufficiency' for validation varies in reference to what organization appears possible in the data. For example, within highly controlled, single variable scientific experiments sufficiency is set at a high level, say ninety percent. This high level of organization within the data is possible because the researcher achieves most of it through his external control and influence of the study problem. However, this same 'ninety-percent' level is seldom attainable in uncontrolled observational studies. In fact, statistical benchmarks for significance in an observational study are not rigidly defined. Therefore, 'sufficiency' must be judged on the level of organization found possible within the study data itself.

In the present study, the 'skid number' represents the 'effect' group, which is a field-tested measure of local pavement friction. The ultimate 'cause' group is specified by the study objective to be two 'limestone coarse aggregate' variables – one its BPN(9) value and the other its relative percentage in the skidded surface pavement. These two variables seek to represent the underlying wear-resistance of the pavement surface. Additional variables are incorporated into the model to portray the relative wear on these same pavements.

While the 'causes' are dictated by the study objectives, the required level of organization within the data that is necessary to sufficiently and persuasively validate the tested hypothesis is not. The required level is somewhat of a variable benchmark based on how much organization seems achievable through mathematical modeling. This task is accomplished by considering comprehensive variables reflecting wear and pavement performance. Here, wear is measured by a combination of days-in-service as discussed earlier and an intensity factor. Pavement performance is initially addressed through a 'project number' surrogate factor. In this manner as will be discussed shortly, these surrogates mathematically model sixty-eight percent of the variability in observed friction performance. How much of this descriptive order is traceable to differences in limestone

BPN(9) quality and content determines the persuasiveness of this specific 'cause-and-effect' hypothesis.

Rather than making a single increment from comprehensive surrogate to the variables of ultimate interest, the statistical analysis took an intermediate step. Between these two endpoints, 'limestone sources' is considered as a potential 'cause'. In this way some indication can be garnered as to whether or not limestone quality, without regard to how it is measured, is important in friction performance.

The discussion of results that follow will be divided into two segments. First, the discussion will focus on establishing a 'wear influence' baseline to use in identifying accelerated wear conditions. Three separate models are considering in establishing this baseline: a straight-line model, a declining rate model, and a service exposure-intensity model.

Second, the discussion progresses to evaluating pavement influences that affect friction performance relative to the wear baseline. This evaluation process begins with considering a comprehensive surrogate that simultaneously represents all potential, although undifferentiated, factors that may influence the observed pavement performance. This surrogate variable is the project number. Its ability to organize the skid data serves to establish a benchmark in judging the relative performance of other causal factors put forward in the statistical analysis.

Next in this evaluation process, limestone sources are considered as surrogates representative of all potential, yet undifferentiated, measures of limestone quality. This surrogate naturally includes, but is not limited to, quality as defined by BPN(9) measurements. Following this, the results of limestone content in ordering skid data is evaluated independently of limestone quality. Then, limestone source and content are considered simultaneously in a model. Finally, limestone quality as defined by its BPN(9) measurements are considered first alone and then in concert with the content measures.

As the discussion unfolds, consider how well the initial ordering of the data is maintained as the 'causes' more specifically target limestone quality and content. This is the key in testing the notion that limestone quality as defined by BPN(9) along with its relative content is the major determinate of long-term friction performance. Is the 'effects' data persuasively organized around these speculated, but specifically defined, 'causes'?

Establishing a Wear Influence Baseline

At the most fundamental level, pavements wear out and become slick due to use. This fact is self-evident. It is also self-evident that there is many underlying determinates of 'use'. And, many pavements are 'used' more than others. Some factors that are associated with use include traffic exposure, hostile environments, temperature extremes, severe localized vehicle maneuvers, abrasive surface contaminates, and the like.

While it is true these factors of 'use' will not be consistently applied to all pavement surfaces alike; however, there exists a typical 'use' condition if only by construct. This typical 'use' condition describes how a 'typical' pavement has its friction surface worn away.

It is this typical 'wear' baseline that helps to isolate and identify instances of accelerated wear within the data. These specific instances may potentially be associated with elements of pavement wear-resistance such as low polish-resistant limestone aggregates.

Three alternative 'wear' models are considered as follows: (1) Straight-line model, (2) Declining-rate model, and (3) Service exposure-intensity model.

(1) Considering a Straight-Line Model

Pavement 'wear' may be quantified using many different measures. Many of these measures were explored and reported on in an earlier exploratory analysis section. None of these measures are perfect, each carrying its own built-in bias favoring one condition of 'use' or another. However, the measure of wear chosen for purposes of this research effort is the length of service exposure as quantified by the days-in-service.

In support of this choice, considering Figure 6.1 that demonstrates an undeniable tendency for older pavements to exhibit lower skid numbers. A straight-line model that summarizes this effect would have the trend line begin with an initial skid value of 45.05. Thereafter, friction would decline at the rate of 0.5 skid numbers every 100 service days. This simple model of the data describes only 9 percent of the variability in the observed skid values. (Statistical ANOVA results are provided as Table A1 in Appendix A.)

(2) Considering a Declining-Rate Model

A second regression equation that includes a squared 'days-in-service' term was fit to the data. This modeled relationship more closely conforms to the decreasing rate of friction-loss observed as the pavement ages.

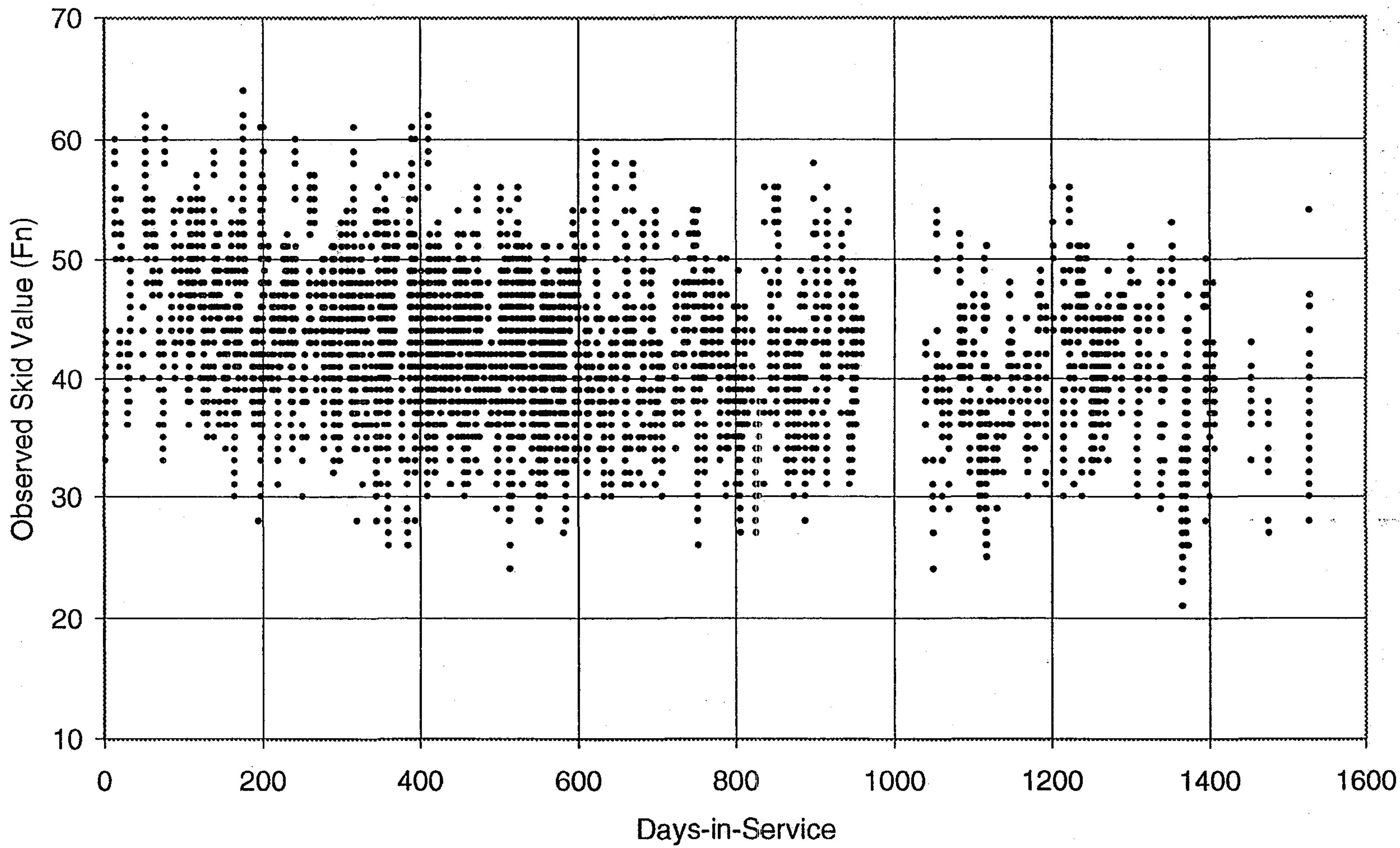


FIG. 6.1 Scatter Plot of Observed Skid Values as a function of Service

There was an overall modest shift in the estimated parameters from those of the straight-line model. The initial skid value is slightly higher at 46.41 rather than 45.05 as the pavement is put in service. Also, the initial rate of decline was steeper with 1.0 skid value lost every 100 days of service rather than 0.5 indicated in the previous model. However, that decline becomes less steep through time. At 100 days, the modified decline rate is 0.98 per 100 days and at 500 days the rate is 0.68 per 100 days.

Based on the fitted equation, the minimum estimated friction value of 39.0 would be reached after 1415 days (3 years 10 months). This calculated minimum is an indication of the time required to reach a steady-state condition.

Figure 6.2 illustrates the fitted equation within a scatter plot of the data. This equation describes a modest 9.7 percent of the observed variation in the skid data. (Statistical ANOVA results are provided as Table A2 in Appendix A.)

This more complex fit is more appealing than the earlier model for three reasons. (1) Many researchers note the decreasing rate of performance decline with time. This model reflects that expectation. (2) Selecting to gain even the slight increase of 0.7 in descriptive power while allocating only 1 additional degree-of-freedom from among a total of 7778 is well advised.

(3) The third reason for its appeal is that the anticipated pattern of an 'ideal' mathematical model would likely be even more complex given the underlying physics. For example, consider the apparent complexity within the data for the few projects tested during the initial service period (say 0-150 days) as shown on Figure 6.3. This data indicates a complex pattern of a slight initial friction increase followed by a somewhat

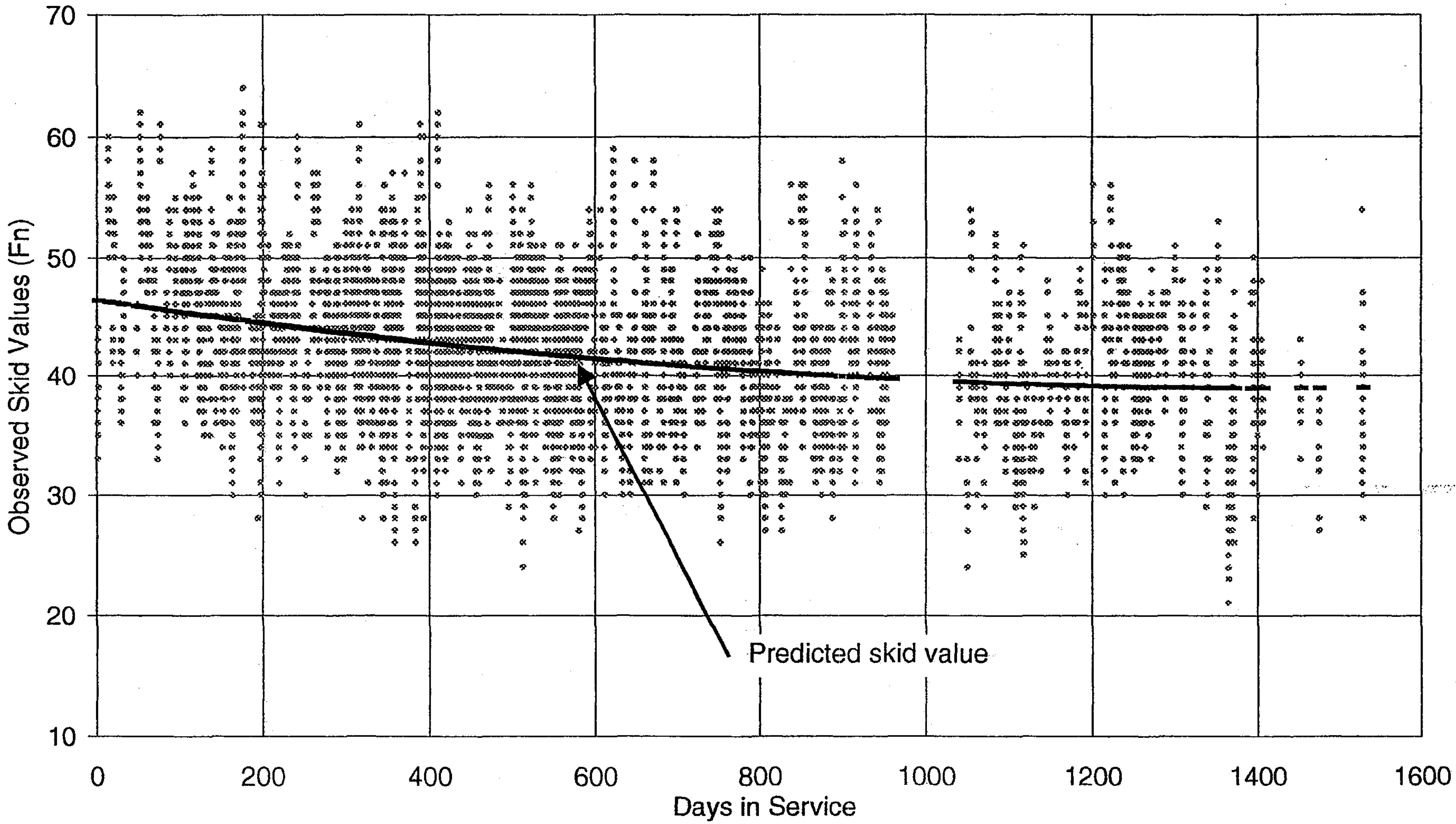


FIG. 6.2 Fitted 'Days-In-Service' Model

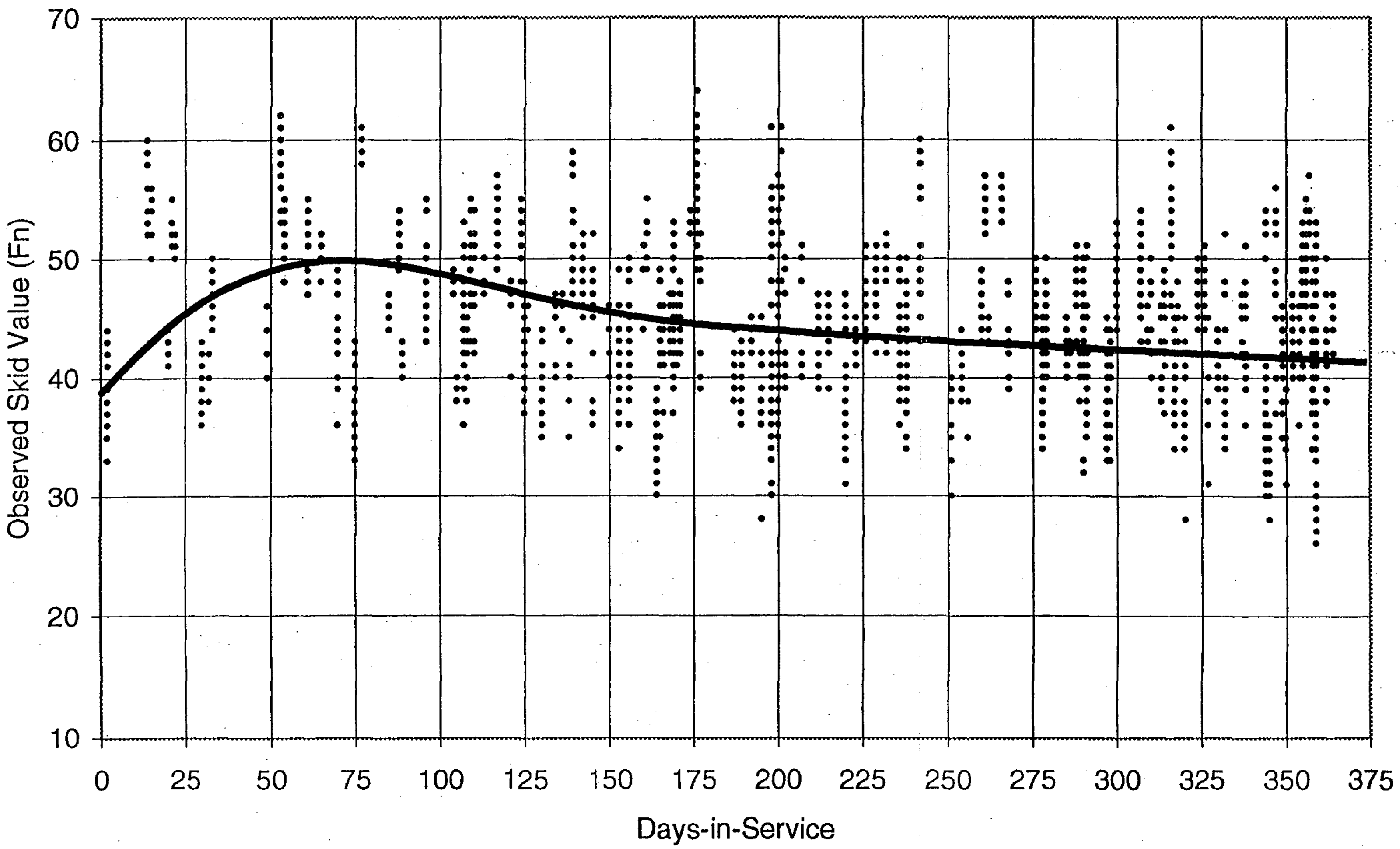


FIG. 6.3 Project Performance during First Service Year

rapid decline, which moderates into a slowly decreasing decline toward a steady-state baseline.

(3) Considering a Service Exposure-Intensity Model

A third model was fit that couples 'days-in-service' with an 'exposure intensity' variable. This additional exposure variable indicates whether or not the test was conducted on the more lightly traveled inner-lane of a multi-lane highway. The initial friction performance expectations for the less-traveled lanes are that it would closely mirror that of its parallel traffic-lane. Over time the non-traffic lane should reflect better relative performance as differences in total traffic volumes accumulate.

Modeling these diverging expectations within the equation is not worthwhile for two reasons. One, the resulting equation would be an order-of-magnitude more complex with only modest gains in descriptive power. And two, this complex equation would require difficult, abstract interpretation of the fitted parameters. To avoid these complexities a more straightforward model was crafted using a 'fixed' shift in the intercept term for pavement experiencing less intense exposure. This simplification does produce a slight bias in the fit of the less traveled pavements, overestimating performance for young pavement and underestimating it for old. However, the gain in interpretation of the fitted parameters is considered worth incurring this slight bias.

The fitted parameters of this combined 'service exposure-intensity' model suggests an initial 'traffic-lane' friction of 46.2 when placed in service. This friction performance initially declines at a rate of 1.1 every 100 days, which is modified over time such that after 100 service-days the decline rate would be 0.97 every 100 days and after 500 days 0.71 every 100 days.

By the design of this model, the non-traffic lanes have the same decline rates as the high traffic lanes, but use a higher initial value of 48.9. Figure 6.4 illustrates how this mathematical model summarizes the description of friction performance among the scatter of actual observations.

This 'service exposure-intensity' model accounts for 12.3 percent of the observed variability in the friction performance. (Statistical ANOVA results are provided as Table A3 in Appendix A.) In giving scale to this measure consider that 90-percent of the variability must be explained during controlled experiments for the results to be regarded as statistically significant. In observational studies, the 90-percent significance level is simply not attainable largely due to the lack of a controlled environment where outside influences can be strictly limited.

While this statistical 'wear' model did not bring significant explanatory order to the data; however, the influence of service exposure and intensity within the data is undeniable. This descriptive model will serve as the 'baseline wear' condition to use in evaluating the effects of pavement material properties.

Evaluating Pavement Influences

With a baseline wear-equation established, attention is directed toward elements of pavement design, materials, or construction that may influence friction performance. These pavement-related factors are considered within the following seven models:

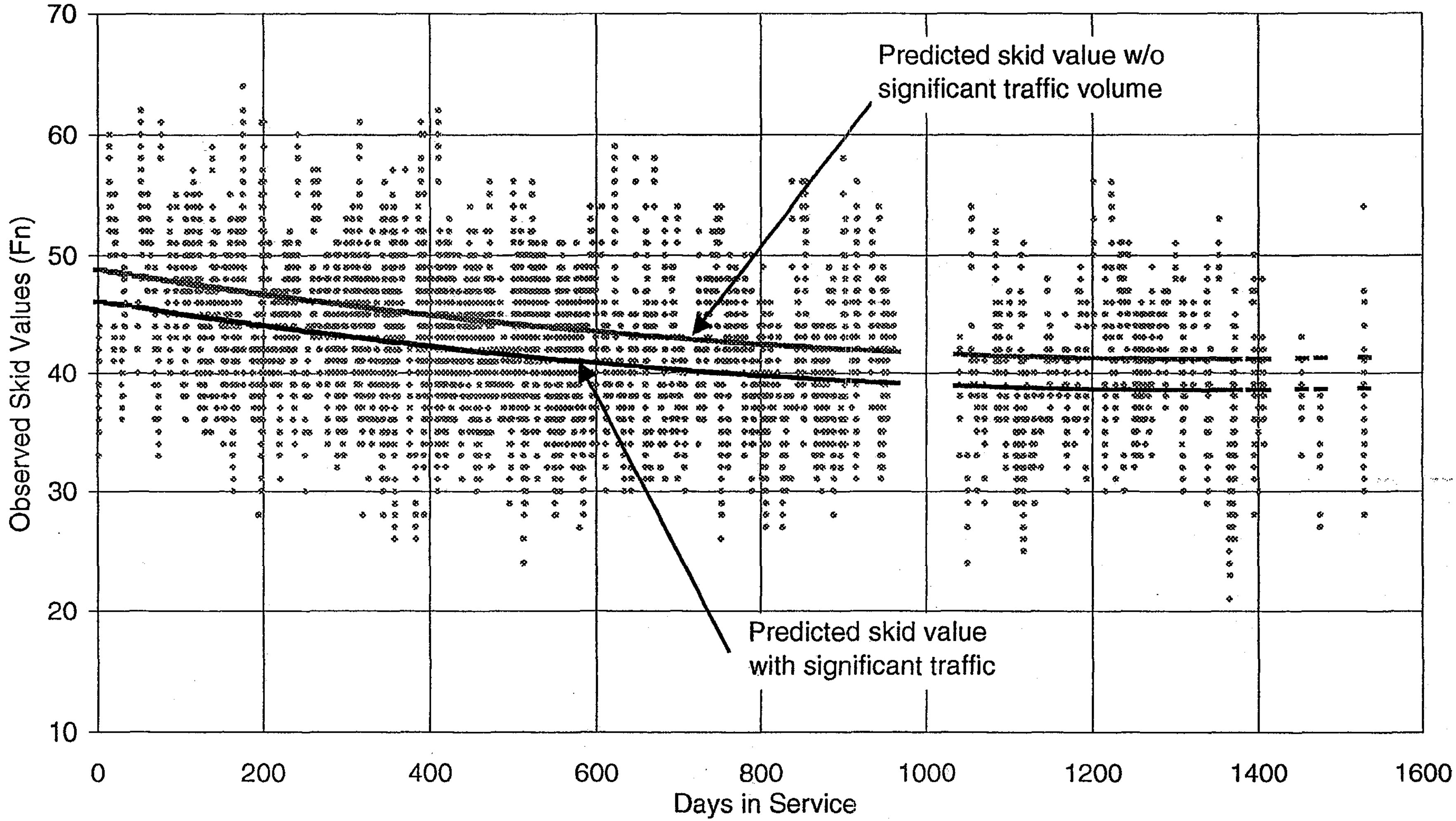


FIG. 6.4 Fitted 'Service Exposure-Intensity' Model

(1) projects, (2) Limestone sources, (3) Limestone content, (4) Limestone source and content in concert, (5) Limestone BPN(9), (6) Limestone BPN(9) and content in concert, and (7) Percent Natural Sand.

(1) Considering a 'Project' Model

A unique project code is assigned to every ALDOT highway project. This code is used to associate the project with various pieces of detailed project information. This project code indexes its location within the state associating it with information providing the highway mileposts that delineate its boundary. This code is associated with the project contractor. Codes are associated with the pavement mix designs that contain information on the pavement surface materials -- the aggregate sources, gradations, compaction requirements, and asphalt, sand, and limestone contents.

Along with these direct uses, other influencing factors can be associated through these project numbers. Similar traffic volumes and car/truck composition are shared for roadways constructed during a single project. Lifecycle exposures to harsh environments, seasonal extremes, and service lengths are shared for project pavements. Weather conditions just prior to the skid test such as ambient temperature and recent rainfall events are shared. Skid trailer equipment malfunction or differences in operator performance will have similar influences during the skidding of a single project around a common date.

This multitude of factors shared within a single project will allow a robust substitution to be made. This project code can serve as a surrogate to 'stand-in' for some as yet unidentified, but significant causal factor naturally shared within individual projects. And, while we may not yet know what that factor is we can observe its organizing affect on the skid performance data.

Table 6.1 provides the ALDOT project codes along with the number of field skid tests included for each project within the study data. In the present instance, project codes partition skid test results into associated groups with similar underlying, but undifferentiated causal factors. It is the goal of this Analysis-of-Variance (ANOVA) statistical technique to account for the considerable variation in the observed friction performance of the 7778 skid tests by these project groupings.

Table 6.2 provides the analysis of variance using projects as a class variable. The parameter estimates are provided in the lower portion of the table. This project-surrogate model assumes each project and traffic lane will experience the same time-dependent decay of friction performance as expressed in wear baseline model. Estimates indicate an initial decline rate of 1.27 in skid-test results for every 100 days of service exposure. This initial decline is modified over time through the 'days-in-service-squared' term such that after 100 days the rate is 1.16 lost every 100 days and after 500 days 0.73 lost every 100 days. From the mathematical fit of the data, a hypothetical minimum friction value is expected after 1170 days (3 years 2 months) with a cumulative loss of 7.43 below the initial friction observations for each project. The same 'friction performance' decline function will be utilized in fitting each project.

Frictional differences between traffic lanes and between projects are modeled using the intercept term. The heavily trafficked outer lanes are accounted for by a downward 3.39 adjustment in the intercept relative to their lighter traveled companion

Table 6.1 Projects Included within Study Data

		Number of Skid Tests
Project No.	99-301-224-003-401	108
	99-301-224-157-401	227
	99-301-253-035-401	54
	99-301-363-002-401	70
	99-301-363-117-401	36
	99-301-421-002-401	72
	99-301-452-001-401	84
	99-301-452-002-402	48
	99-302-171-002-303	108
	99-302-171-002-401	141
	99-302-171-002-403	84
	99-302-171-002-501	36
	99-302-171-013-405	198
	99-302-171-020-302	100
	99-302-171-157-402	132
	99-302-171-157-404	121
	99-302-302-005-501	15
	99-302-302-024-401	30
	99-302-391-064-401	60
	99-302-391-157-402	42
	99-302-402-033-401	36
	99-302-473-118-401	144
	99-302-473-118-402	132
	99-302-673-074-401	36
	99-303-052-075-401	180
	99-303-052-079-601	3
	99-303-052-160-401	42
	99-303-103-009-401	54
	99-303-103-273-401	66
	99-303-283-001-401	96
	99-303-283-007-401	36
	99-303-371-004-401	156
	99-303-371-079-401	144
	99-303-371-150-401	42
	99-303-371-150-402	25
	99-303-371-151-401	120
	99-303-582-007-401	41
	99-303-582-053-401	48
	99-303-595-038-707	6
	99-303-644-004-402	150
	99-304-082-021-402	198
	99-304-082-021-403	110

		Number of Skid Tests
Project No.	99-304-144-009-401	102
	99-304-154-009-301	80
	99-304-413-015-401	30
	99-304-564-022-401	53
	99-304-576-165-401	45
	99-305-044-000-402	169
	99-305-044-005-401	53
	99-305-335-014-401	84
	99-305-335-014-402	42
	99-305-535-219-303	102
	99-305-543-006-406	72
	99-305-632-006-301	108
	99-306-062-015-401	48
	99-306-062-239-401	72
	99-306-261-009-401	284
	99-306-434-021-401	143
	99-306-513-094-401	102
	99-307-162-167-401	73
	99-307-203-055-401	11
	99-307-351-052-401	36
	99-307-555-167-401	30
	99-308-121-010-418	102
	99-308-121-010-428	30
	99-308-462-008-414	36
	99-308-462-025-413	30
	99-308-654-017-408	54
	99-308-663-010-405	48
	99-308-663-010-510	39
	99-308-663-164-406	42
	99-308-663-265-407	18
	99-309-022-016-403	90
	99-309-022-059-406	50
	99-309-022-059-407	72
	99-309-491-013-402	360
	99-309-491-016-404	96
	BR-4601(105)(112)(	30
	BR-4601(111)	30
	BR-461(16)	30
	BRS-4601(106)	30
	BRS-4601(110)	4
	IA-050-021-001	30
	IM-59-1(187)	60
	IM-59-2(97)	258
	IM-59-2(98)	311

		Number of Skid Tests
Project No.	IM-85-1(116)	200
	MAAA-6616(101)	31
	NH-398(42)	36
	ST-552-21	93
	STPNU-2908(104)	72
	STPOA-1627(7)	96
	STPSA-000S(3)	30

Table 6.2 ANOVA of 'Project Surrogate' Model (Page 1 of 3)

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	215561.999[a]	95	2269.074	178.237	.000
Intercept	13675237.2	1	13675237.213	1074198.59	.000
DAYS	28257.272	1	28257.272	2219.627	.000
DAYS2	2201.169	1	2201.169	172.903	.000
TRF_LANE	8117.245	1	8117.245	637.615	.000
PROJECT	176986.312	92	1923.764	151.113	.000
Error	97796.788	7682	12.731		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .688 (Adjusted R Squared = .684)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	47.755	.678	70.447	.000	46.426	49.083
DAYS	-1.271E-02	.000	-29.316	.000	-1.356E-02	-1.186E-02
DAYS2	5.427E-06	.000	18.735	.000	4.859E-06	5.995E-06
TRF_LANE	-3.394	.131	-25.883	.000	-3.651	-3.137
[99-301-224-003-401]	-3.541	.736	-4.808	.000	-4.985	-2.097
[99-301-224-157-401]	-.906	.696	-1.301	.193	-2.271	.459
[99-301-253-035-401]	1.546	.813	1.903	.057	-4.675E-02	3.139
[99-301-363-002-401]	1.490	.779	1.914	.056	-3.621E-02	3.016
[99-301-363-117-401]	7.478	.882	8.478	.000	5.749	9.207
[99-301-421-002-401]	-4.083	.775	-5.266	.000	-5.603	-2.563
[99-301-452-001-401]	-2.039	.759	-2.686	.007	-3.526	-.551
[99-301-452-002-402]	-5.339	.831	-6.428	.000	-6.967	-3.711
[99-302-171-002-303]	-.959	.736	-1.302	.193	-2.403	.484
[99-302-171-002-401]	.153	.718	.213	.831	-1.254	1.560
[99-302-171-002-403]	-2.901	.759	-3.822	.000	-4.390	-1.413
[99-302-171-002-501]	-4.415	.882	-5.003	.000	-6.145	-2.685
[99-302-171-013-405]	9.992E-02	.699	.143	.886	-1.270	1.470
[99-302-171-020-302]	-.397	.743	-.534	.593	-1.853	1.059
[99-302-171-157-402]	8.373	.724	11.560	.000	6.954	9.793
[99-302-171-157-404]	6.732	.730	9.220	.000	5.301	8.164
[99-302-302-005-501]	2.596	1.129	2.301	.021	.384	4.809
[99-302-302-024-401]	2.470	.921	2.681	.007	.664	4.276
[99-302-391-064-401]	9.620	.798	12.054	.000	8.056	11.184

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
[99-302-391-157-402]	13.363	.853	15.666	.000	11.691	15.036
[99-302-402-033-401]	4.727	.882	5.358	.000	2.998	6.457
[99-302-473-118-401]	-2.450	.719	-3.410	.001	-3.859	-1.041
[99-302-473-118-402]	-5.897	.724	-8.143	.000	-7.316	-4.477
[99-302-673-074-401]	-2.985	.882	-3.384	.001	-4.714	-1.256
[99-303-052-075-401]	9.963	.707	14.088	.000	8.577	11.350
[99-303-052-079-601]	1.163	2.161	.538	.590	-3.072	5.399
[99-303-052-160-401]	9.591	.853	11.244	.000	7.919	11.263
[99-303-103-009-401]	3.158	.813	3.887	.000	1.566	4.751
[99-303-103-273-401]	7.130	.786	9.073	.000	5.589	8.670
[99-303-283-001-401]	5.272	.746	7.063	.000	3.809	6.735
[99-303-283-007-401]	3.323	.882	3.767	.000	1.594	5.052
[99-303-371-004-401]	-3.110	.714	-4.354	.000	-4.511	-1.710
[99-303-371-079-401]	.554	.719	.770	.441	-.856	1.964
[99-303-371-150-401]	3.005	.853	3.522	.000	1.333	4.677
[99-303-371-150-402]	1.172	.966	1.213	.225	-.722	3.067
[99-303-371-151-401]	-.795	.731	-1.087	.277	-2.229	.639
[99-303-582-007-401]	2.928	.857	3.415	.001	1.247	4.608
[99-303-582-053-401]	3.216	.831	3.872	.000	1.588	4.844
[99-303-595-038-707]	-4.747	1.596	-2.974	.003	-7.876	-1.618
[99-303-644-004-402]	.403	.716	.563	.574	-1.001	1.807
[99-304-082-021-402]	-7.015	.702	-9.998	.000	-8.390	-5.639
[99-304-082-021-403]	-3.486	.737	-4.728	.000	-4.931	-2.041
[99-304-144-009-401]	.822	.741	1.109	.267	-.631	2.275
[99-304-154-009-301]	4.784	.764	6.263	.000	3.287	6.282
[99-304-413-015-401]	-1.568	.921	-1.702	.089	-3.374	.238
[99-304-564-022-401]	1.984	.815	2.434	.015	.386	3.582
[99-304-576-165-401]	3.871	.841	4.601	.000	2.222	5.521
[99-305-044-000-402]	-.669	.708	-.945	.345	-2.056	.719
[99-305-044-005-401]	-.460	.815	-.564	.573	-2.058	1.138
[99-305-335-014-401]	2.887	.759	3.803	.000	1.399	4.375
[99-305-335-014-402]	5.345	.853	6.266	.000	3.673	7.017
[99-305-535-219-303]	8.111	.741	10.943	.000	6.658	9.564
[99-305-543-006-406]	12.560	.775	16.198	.000	11.040	14.080
[99-305-632-006-301]	4.866	.737	6.606	.000	3.422	6.310
[99-306-062-015-401]	7.110	.830	8.561	.000	5.482	8.738
[99-306-062-239-401]	8.170	.775	10.537	.000	6.650	9.690
[99-306-261-009-401]	-2.969	.687	-4.320	.000	-4.316	-1.622
[99-306-434-021-401]	6.072	.717	8.472	.000	4.667	7.477
[99-306-513-094-401]	4.519	.741	6.097	.000	3.067	5.972
[99-307-162-167-401]	2.893	.774	3.739	.000	1.376	4.410

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	Upper Bound
[99-307-203-055-401]	-3.114	1.258	-2.476	.013	-5.580	-.649
[99-307-351-052-401]	1.783	.882	2.021	.043	5.380E-02	3.512
[99-307-555-167-401]	2.592	.921	2.814	.005	.786	4.398
[99-308-121-010-418]	4.832	.741	6.521	.000	3.380	6.285
[99-308-121-010-428]	3.238	.921	3.515	.000	1.432	5.044
[99-308-462-008-414]	2.301	.882	2.608	.009	.572	4.030
[99-308-462-025-413]	5.718	.921	6.206	.000	3.912	7.524
[99-308-654-017-408]	5.039	.812	6.201	.000	3.446	6.631
[99-308-663-010-405]	2.792	.830	3.362	.001	1.164	4.420
[99-308-663-010-510]	3.780	.867	4.362	.000	2.081	5.478
[99-308-663-164-406]	4.232	.853	4.961	.000	2.560	5.904
[99-308-663-265-407]	3.190	1.064	2.998	.003	1.104	5.275
[99-309-022-016-403]	.257	.752	.341	.733	-1.218	1.731
[99-309-022-059-406]	4.715E-02	.824	.057	.954	-1.569	1.663
[99-309-022-059-407]	4.404	.775	5.679	.000	2.884	5.924
[99-309-491-013-402]	-5.688	.679	-8.380	.000	-7.019	-4.358
[99-309-491-016-404]	.830	.746	1.112	.266	-.633	2.293
[BR-4601(105)(112)( ]	11.961	.921	12.983	.000	10.155	13.767
[BR-4601(111)]	12.939	.921	14.044	.000	11.133	14.745
[BR-461(16)]	8.826	.921	9.580	.000	7.020	10.632
[BRS-4601(106)]	13.037	.921	14.148	.000	11.231	14.843
[BRS-4601(110)]	10.501	1.899	5.529	.000	6.778	14.225
[IA-050-021-001]	6.421	.921	6.969	.000	4.615	8.227
[IM-59-1(187)]	3.823	.798	4.791	.000	2.259	5.387
[IM-59-2(97)]	5.898	.691	8.534	.000	4.543	7.252
[IM-59-2(98)]	5.580	.685	8.147	.000	4.238	6.923
[IM-85-1(116)]	5.318	.702	7.574	.000	3.942	6.695
[MAAA-6616(101)]	9.738	.914	10.657	.000	7.947	11.530
[NH-398(42)]	1.543	.882	1.749	.080	-.186	3.272
[ST-552-21]	10.133	.749	13.522	.000	8.664	11.602
[STPNU-2908(104)]	2.464	.776	3.175	.002	.943	3.985
[STPOA-1627(7)]	-1.828	.746	-2.449	.014	-3.291	-.365
[STPSA-000S(3)]	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

lanes. This adjustment is equivalent to adding roughly +300 service-days to these more heavily traveled lanes as illustrated in Figure 6.5.

Differences in the intercept term also reflect differences in observed friction performance between projects. The baseline model is referenced to project number STPSA-000S(3) having an intercept term of 47.755. All other projects are modeled relative to this baseline intercept; some having higher intercepts and others lower. The highest estimated project intercept is 61.118 and reflects the observed friction performance associated with the 42 skid-test observations on project number 99-302-391-157-402. This intercept is 13.363 above that of the baseline. The lowest project intercept is 42.067 and describes the 360 friction observations of project 99-309-491-013-402. This intercept is 5.688 below that of the baseline.

As fitted, this model accounts for 68.4 percent of the variability in observed friction within the data. Of that total, the 'wear' parameters of days-in-service and traffic lane accounts for 12.3 percent with the project-surrogate describing the remaining 56.1 percent. This leaves 31.6 percent of the variation as unallocated by the model. Figure 6.6 illustrates the allocation of observed variability within the data to model components.

Using projects to describe 68.4 percent of the variation begs the question, "What underlying project component(s) drives the descriptive power of this model?". Is it simply joint association? For example, could high traffic volumes occur on certain projects resulting in significantly different skid performances than projects with lighter volumes? Or perhaps, the descriptive power may reflect a more intriguing possibility of a cause-and-effect dynamic. While not dismissing the likelihood of some joint association, a closer look at the underlying project components is merited in exploring the

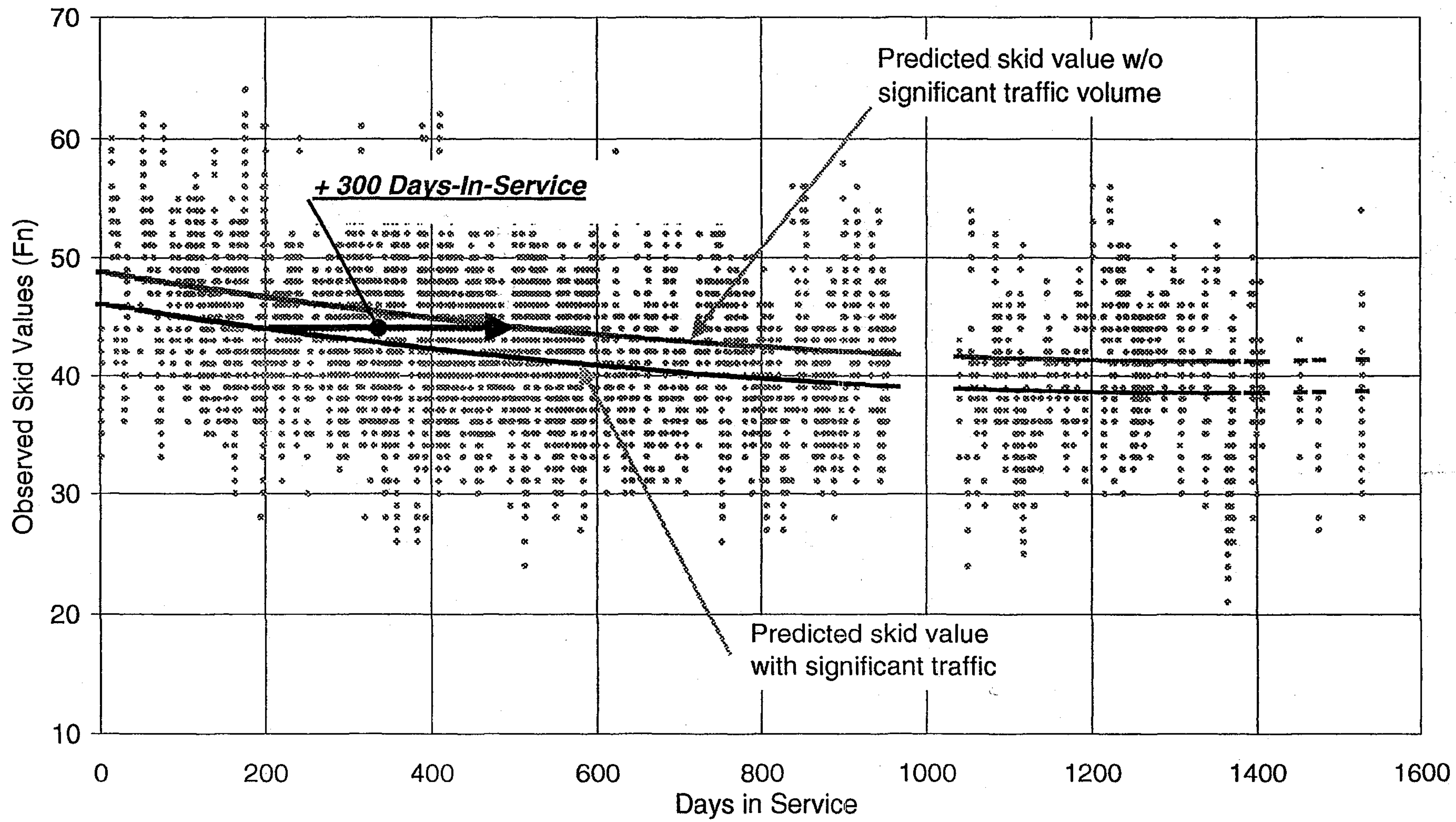


FIG. 6.5 Illustration of Traffic Lane Effect

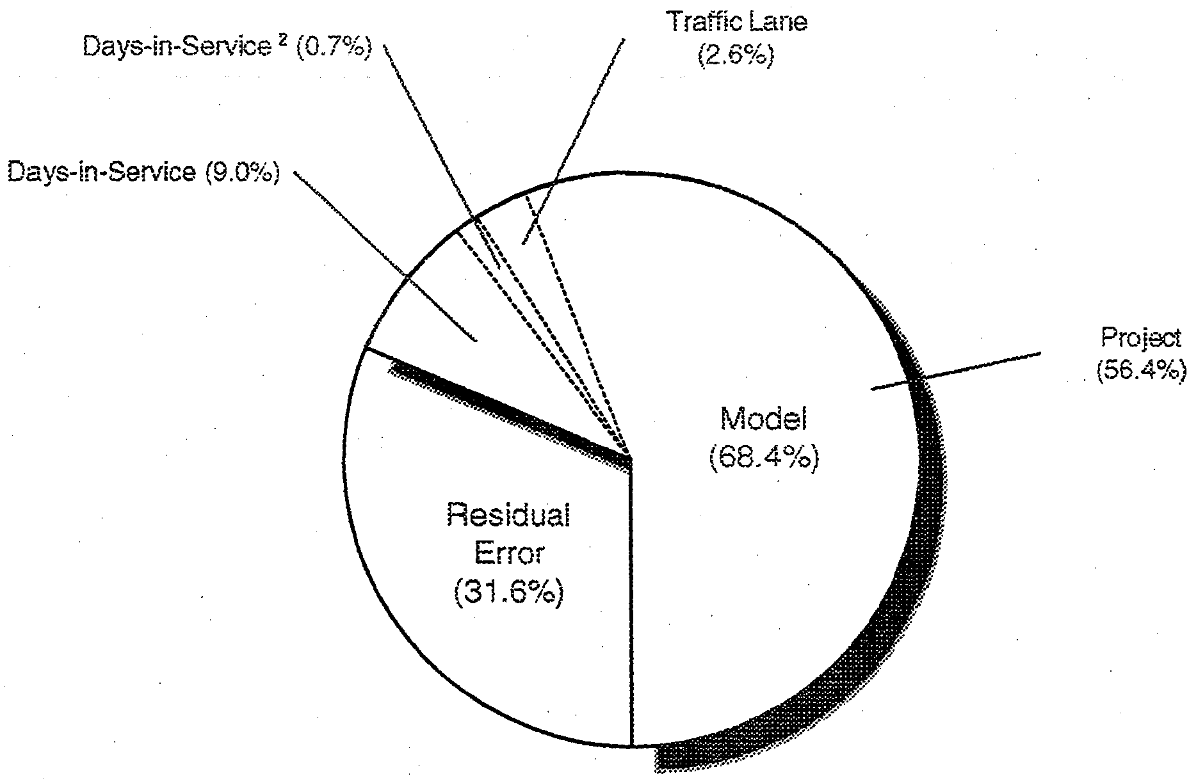


FIG. 6.6 Allocated Variance in Project Model

potential cause-and-effect relationships. The guiding premise is to determine how much of this 68.4 percent descriptive power can be replicated by underlying factors considered below.

In taking a closer look it is necessary to decompose the general 'project' variable into a more targeted array of underlying factors as displayed in Figure 6.7. This 'project' decomposition proceeds from general to specific and highlights the deductive reasoning at the foundation of this observational approach. Next in this line of progressive reasoning is whether or not 'any' potentially relevant characteristics of limestone aggregates can come close to matching the 68.4 percent described by the projects. In doing this, limestone sources are used as a surrogate measure of limestone quality that would include but is not necessarily limited to its BPN(9) performance.

(2) Considering a 'Limestone Aggregate Source' Model

The surrogate 'limestone source' variable describes a distinct, but undesignated, set of limestone coarse aggregate characteristics. The rationale is that each source will produce aggregates over a short time period that have similar characteristics of porosity, surface energy, polish resistance, and the like. These aggregates will also be similar in terms of the level of silicate and other interspersed contaminates. Using limestone source as a variable in describing the observed friction performance allows the aggregate 'quality' characteristics into the model without limiting it to the BPN(9).

Twenty-five limestone quarries produced coarse aggregates for the 93 projects within the observational sample. Considering averages, each quarry would have contributed aggregates to 3.7 projects and would be reflected in 311 separate skid-test

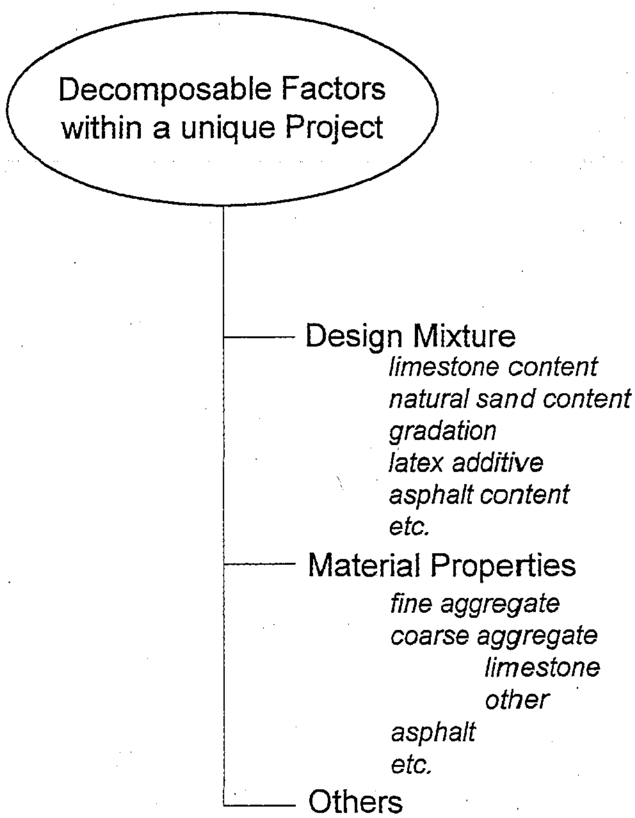


FIG. 6.7 Project Surrogate Decomposition

observations. But, averages do not accurately represent the individual contributions of each quarry. For example, one quarry contributed aggregates to 15 separate projects while half of the twenty-five quarries had aggregates used in only one project. In these twelve cases the results would be identical to those of the project-surrogate variable. Table 6.3 provides limestone source numbers along with the project numbers these quarries supplied.

The model includes 27 variables to use in fitting the wear, intensity and limestone quarry parameters. Twenty-four of these variables are used in representing the 25 potential limestone quarries. The model can account for 49.6 percent of the observed friction variability. Of this amount, the model attributes 12.3 percent of the descriptive power to pavement 'wear' exposure and 'use' with the remaining 37.3 percent to the 24 limestone quarry sources. (Statistical ANOVA results are provided as Table A4 in Appendix A.)

Now consider the fitted parameters. The intercept term of 52.8 is high relative to earlier models; but in this instance, it reflects an initial service situation along with the influence of the specific quarry identified by code as 1414. Similar to earlier models, the initial service-exposure decline rate is 1.1 lost in measured skid number value in 100 days. This rate is moderated so that after 100 days the rate of decline is reduced to losing 1.0 skid value every 100 days, then after 500 days the decline is 0.6 lost every 100 days. By mathematical estimates the minimum friction value would be reached after 1217 days (3 years 4 months) reflecting a skid value of 46.08 for pavements using limestone source '1414' on the non-trafficked inner lane.

Table 6.3 Limestone Sources within Sample Data (Page 1 of 3)

Limestone Source	Project Numbers Supplied	Number of Skid Tests
48	99-304-413-015-401	30
	99-304-564-022-401	53
	99-304-576-165-401	45
134	99-303-371-004-401	156
	99-303-371-079-401	144
	99-303-582-007-401	41
	99-303-644-004-402	150
137	99-304-082-021-402	198
	99-304-082-021-402	110
	99-304-144-009-401	102
141	99-301-253-035-401	54
142	99-302-171-013-405	198
	99-302-171-157-402	132
	99-302-171-157-404	121
	99-302-302-024-401	30
	NH-398(42)	36
147	99-306-264-009-401	284
	99-307-203-055-401	11
	99-308-462-008-414	36
	99-308-462-025-413	30
	99-308-663-010-405	48
	99-308-663-164-406	42
151	99-301-224-003-401	108
	99-301-224-157-401	227
	99-302-673-074-401	36
152	99-302-391-064-401	60
	99-302-402-033-401	36
	99-308-121-010-418	102
	99-308-121-010-428	30
155	99-305-044-005-401	53
	99-305-632-006-301	108
	99-309-022-016-403	90
	99-309-022-059-406	50
158	99-303-103-009-401	54
	99-303-103-273-401	66
	99-303-283-001-401	96
	99-303-283-007-401	36
	99-303-582-053-401	48
	IM-59-2(98)	311

Table 6.3 Cont'd (Page 2 of 3)

159	99-303-371-150-402	25
	99-305-044-000-402	169
	99-306-434-021-401	143
165	99-302-473-118-401	144
	99-302-473-118-402	132
	STPNU-2908(104)	72
168	99-301-363-002-401	70
169	99-302-171-002-303	108
	99-302-171-002-401	141
	99-302-171-002-403	84
	99-302-171-002-501	36
	99-302-171-020-302	100
	99-302-3021-005-501	15
	99-302-391-157-402	42
170	99-303-371-150-401	42
	99-303-371-151-401	120
315	99-305-335-014-401	84
	99-305-335-014-402	42
	IM-59-1(187)	60
414	99-303-595-038-707	6
	99-307-162-167-401	73
	99-307-351-052-401	36
	99-307-555-167-401	30
	99-308-663-010-510	39
	STPSA-000S(3)	30
497	99-301-363-117-401	36
	99-301-421-002-401	72
	99-301-452-001-401	84
	99-301-452-002-402	48
783	99-303-052-075-401	180
	99-303-052-079-601	3
	99-303-052-160-401	42
	ST-552-21	93
911	99-305-535-219-303	102
	99-306-062-015-401	48
	99-306-062-239-401	72
	99-306-513-094-401	102
	99-308-663-265-407	18
	BR-4601(105)(112)(	30
	BR-461(16)	30
	MAAA-6616(101)	31
912	99-305-543-006-406	72

Table 6.3 Cont'd (Page 3 of 3)

924	99-308-654-017-408	54
	99-309-022-059-407	72
	99-309-491-013-402	360
927	BR-4601(111)	30
	BRS-4601(106)	30
	BRS-4601(110)	4
	IA-050-021-001	30
928	99-309-491-016-404	96
1414	99-304-154-009-301	80
	IM-59-2(97)	258

Heavily trafficked lanes are reflected in a 3.3 downward shift of the friction curve relative to its less trafficked companion. This shift is larger than in earlier models suggesting it's better able to capture wear-related friction performance differences than earlier models.

The estimated parameters of limestone sources represent a relative shift in the friction performance curve compared to the fit of the limestone source '1414'. The initial intercept terms ranged from a low of 45.0 with limestone quarry '0137' to a high of 61.7 with quarry '912'. It must be noted that these results may ultimately be found as an effect of some factor other than the limestone source, itself.

Looking at the actual data is a good exercise in self-proving the analysis. An overall minimum in friction is projected by the 'wear-intensity' decline function to occur after approximately 1217 days of service. For aggregate source '1414' the closest data observation was at day 1243 on a trafficked lane. The analysis suggests an expected value of 42.78. The average of the 12 observations taken on day 1243 for that pavement indicates a measured average skid value of 44.50, slightly higher than expected.

There were 39 skid observation taken after 1253 days in service on a I-59 project that also used limestone aggregates from source '1414'. Within this data, 19 tests were taken on trafficked lanes and 20 on non-trafficked lanes. The average on the trafficked lane was 37.89 and on the non-trafficked 42.35. These were slightly lower than expected by the analysis as well.

For aggregate source '0137', which was the lowest-ranking source, the closest to the expected friction minimums were taken after 1273 days-in-service. The average of these 20 observations was 41.47 on the trafficked lane. Data was also recorded on a different pavement made from these aggregates with 1118 days of service exposure. The average of these 20 observations was 33.30. The analysis indicates an expected minimum after 1217 days of 32.98. This was close to what was observed on the 1118-day pavement but not on the 1273-day pavement, which was significantly higher.

One must consider on this seemingly poor performing aggregate source that each pavement tested had only 14 percent natural sand content. This lack of sand could be what drives down the observed friction performance. Further, there is a sharp division of friction performance for pavements made from this aggregate source based on aggregate gradation. The sixty observations made on Mix No. 1 pavements performed fairly well with an overall skid number averaging 42.52. The 350 other observations consisting of pavements using gradations of Mix No. 3 and 6 have a much lower overall average of 35.55. This may indicate that aggregate gradation plays a significant role in pavement wear and friction performance and/or the pavement surface components that are engaged during skidding. Figure 6.8 illustrates the percent passing for each Mix Number.

For aggregate source '0912', which was the highest-ranking source, there were 72 total observations made with 12 observations being recorded after 1186 days of service. These 12 had an average skid number of 47.00, not much different than the expected value of 49.67 given by the mathematical model.

A note of caution is appropriate at this time. If a great many of the quarries contributed to only one project, then what is statistical modeled may simply be the cast shadow of some other project characteristic that through the absence of alternatives is associated with the quarry source as well.

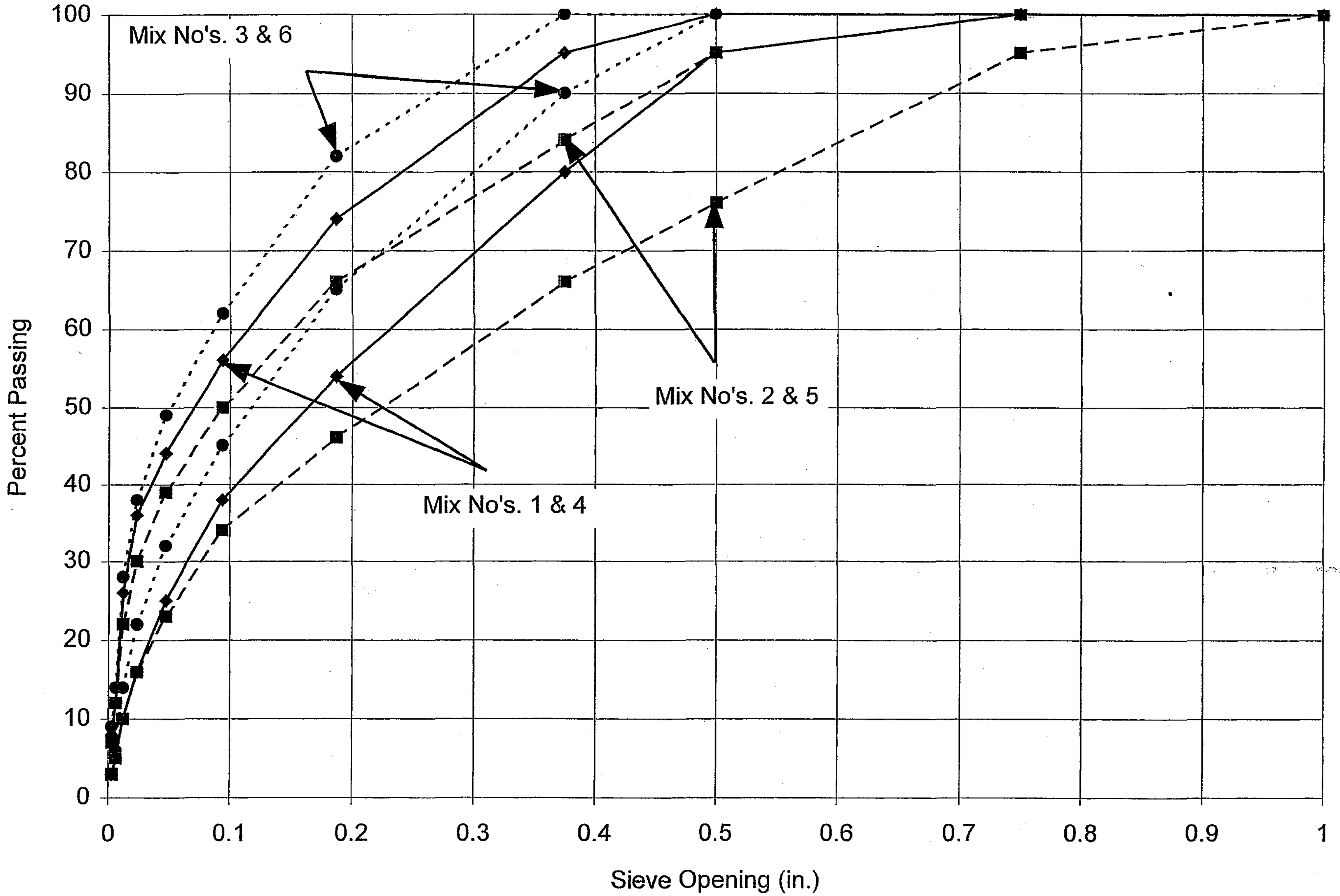


FIG. 6.8 Gradation Limits for Mix Numbers

Limestone sources play a significantly descriptive role in observed frictional performance. Aggregates from particular sources perform well, while others sources perform poorly. Some questions come to mind such as: Can the simulated BPN(9) polish performance successfully discriminate between the aggregate characteristics which lead to good or poor friction performance? Is good limestone performance as measured by an upward shift in intercept term of the model also reflected in a high BPN(9) value?

These questions led to Figure 6.9 that illustrates the association between ANOVA intercept shifts, sources, and polishing characteristics. The highest intercept is 56.4 associated with limestone source '912' having a moderate BPN(9) value of 27. The lowest performance is modeled with an intercept of 39.7 delivered by limestone source '137' having a moderate BPN(9) of 23. The second lowest performance is 40.8 from source '924'; this source has the highest simulated polish resistance in the sample, a BPN(9) of 35.

The observed crossing patterns between high 'limestone source' performance and the matching BPN(9) values tend to dispute the original premise. High performance sources tend toward lower relative BPN(9) values while low performance sources have relatively higher BPN(9) values. Perhaps, these observations reflect that high BPN(9) aggregates also have higher limestone content as well. Therefore, in progressing the analysis further the limestone content is considered next.

(3) Considering a 'Limestone Content' Model

Limestone content quantifies the amount of limestone used in the coarse aggregate fraction of the surface pavement. This variable, which reflects a percentage,

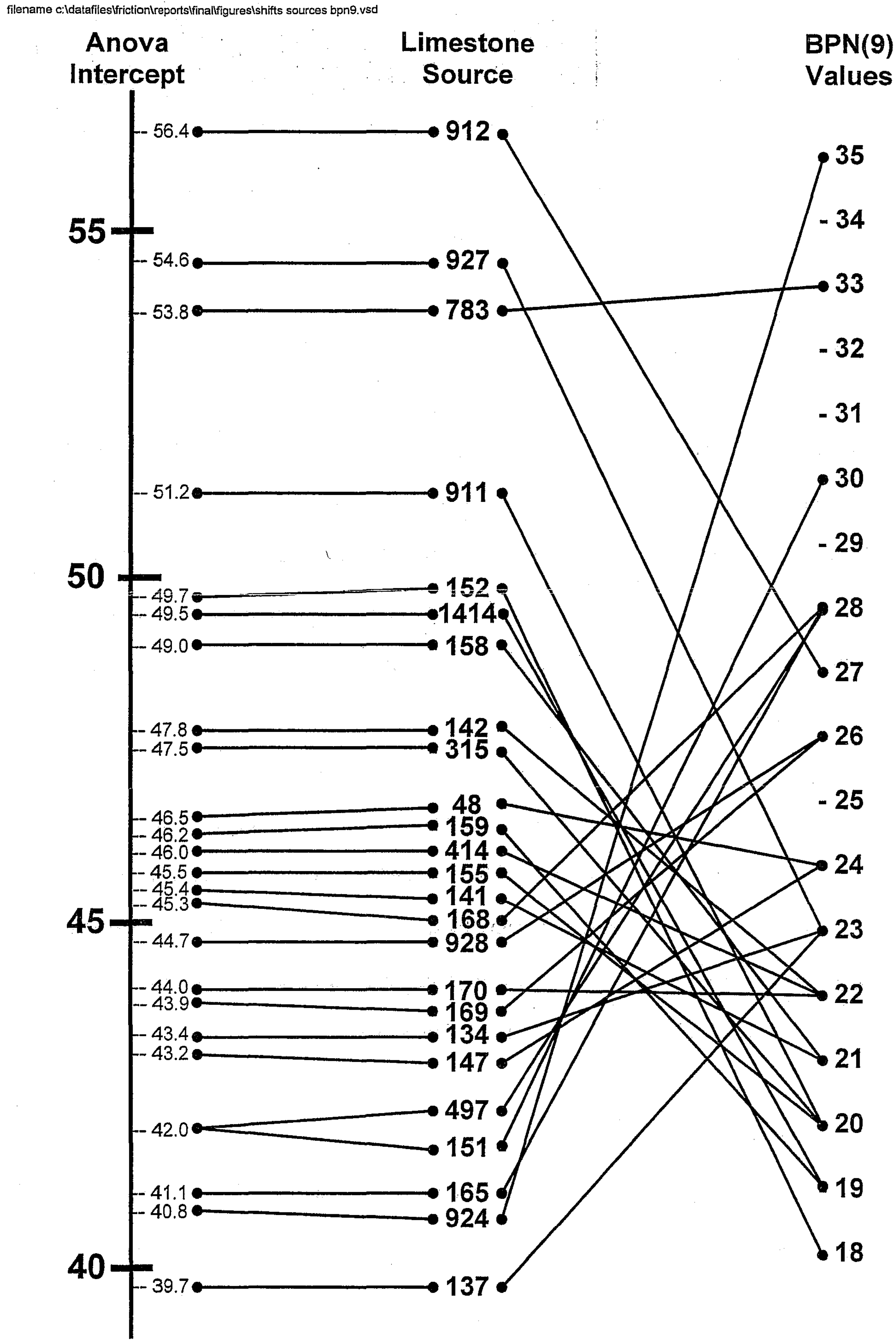


FIG. 6.9 ANOVA Intercepts with Limestone Sources and BPN(9) Values

can be utilized within a statistical model in two ways. First, the variable can reflect a continuous value where 80% limestone would be considered as twice the potential influence as 40% limestone content. Or second, the limestone content variable can represent a class variable where there are expectations of an orderly increase in influence, but not necessarily in terms of the order of magnitude such that 80% limestone would reflect worse performance but not necessarily twice as bad as 40% content. Both of these analyzes are performed here in turn.

The underlying premise is that limestone aggregates tend to polish overtime, thus losing micro-texture and impeding the surface friction characteristics. The original research objective was to determine a limit, if possible, of surface course limestone contents in the surface mix based on the BPN(9) polish-resistance of the limestone.

Contents ranged from a low of 14% to a high of 80%. The most frequently observed content was 30% with slightly over 1100 of the 7778 observations having this amount.

Limestone content used as a continuous variable can describe 23.1% of the observed skid value variability when combined with wear and intensity variables in a statistical model. Wear and intensity variables again account for 12.3% of the variation while limestone content accounted for the remaining 10.8% of the descriptive power. (Statistical ANOVA results are provided as Table A5 in Appendix A.)

The fitted parameters of this statistical model include an intercept term estimated at 54.2, which is somewhat higher than earlier models. The initial rate of decline had pavements losing 1.08 in skid number value during the first 100 days. After 100 days of service the model forecasts a modified decline of 1.0 lost every 100 days and after 500 days the decline is 0.7 every 100 days. The decline will bottom out after 1333 days (3 years 8 months) of service exposure at a skid value of 40.7 on the more heavily trafficked lane when pavements contain 30 percent limestone coarse aggregate. Friction values predicted for the traffic lane is 2.5 less than for the non-trafficked companion lane. Increasing limestone content decreases performance at the rate of 0.122 in skid value per percentage increase in limestone.

Consider the range of limestone contents and their influence. After 1333 days of service on pavements with 14% limestone the friction value is estimated to be 42.7 while with 80% limestone the estimate is for pavements to test at a 34.6 skid number.

Comparing actual data within the days-in-service range associated with the estimated minimum friction performances will give some indication of the ballpark accuracy of these estimates. There are 33 skid test observations for pavements using the most common level of limestone content (30 percent) at approximately 1333 days of service. The average skid number of these observations is 41.0, which is close to the predicted value of 42.7 from the model.

Pavements with only 14 percent limestone, the minimum in the study population, had an average skid number of 43.9 on the 8 recorded skid tests in this service range. This is close to the model estimate of performance at 42.7. While pavements with 80% limestone, the maximum, had an average skid number of 38.2 for the 20 observations in the +1130 day range. This average is slightly higher than the predicted 34.6.

The 20 observations of the 80% limestone pavements could be divided into two classes based on Mix Numbers. Mix No. 3 pavements had 6 observations taken after 1147 days of service exposure averaging 45.5 skid number. Mix No. 6 pavements had 14 observations taken at 1131 days-in-service averaging 35.1 skid number. Together these averaged the 38.2 indicated above. What caused the difference in skid performance at this high limestone content? The two mix numbers have the same aggregate source, gradation, and sand content. But, the two have different compaction efforts and expected traffic volumes. While the cause is in doubt, its relevance here is to demonstrate that limestone content alone does not define friction performance.

This model that combines limestone content as a continuous variable along with wear and intensity factors describes only 23.1 percent of the observed 'friction performance' variation.

Limestone content used as a class variable within an alternative statistical model along with a wear and intensity variables describes a significant 47.6 percent of the observed variability is skid performance. Limestone content accounted for 35.3% of the variation while wear and intensity variables accounted for the remaining 12.3% of the descriptive power. (Statistical ANOVA results are provided as Table A6 in Appendix A.)

The intercept term of 44.57 describes the fit to an 80% limestone content class of pavements with limited to no service exposure. The fitted parameters of decline are roughly the same as in previous models. Initially, pavement performance declines at 1.1 skid numbers per 100 days. This rate is modified after 100 days to 1.0 lost per 100 days, then after 500 days only 0.66 in skid value is lost every 100 days. Decline is estimated to continue until a mathematical minimum is reached in the fitted function after 1217 days (3 years 4 months) with an estimated minimum friction of 35.17 for traffic-lane pavements containing 80% limestone. Pavement with only 14% limestone content has a minimum friction estimate of 45.71 and with 30% limestone the minimum is estimated at 41.15.

The true value of this contrast between continuous versus class treatment can be seen in Figure 6.10. The data represents ANOVA intercepts of limestone content classes plotted on the vertical axis and the underlying limestone content of these classes plotted on the horizontal axis. The annotated line at a slope of -0.122 in skid number per percent increase in limestone represents the best fit through the data when considering limestone content as a continuous variable. While the overall trend is most definitely toward declining values, there are noticeable exceptions within the class variable.

(4) Considering a 'Limestone Source and Content' Model

Combining limestone source and content in one model along with wear and intensity variables poses the question: "Can observed friction performance be largely describe as some measure of limestone aggregate quality and its relative content?".

Before discussing the statistical models, consider the underlying data within the sampled projects. Table 6.4 provides a cross-tabulation of the 25 limestone sources by the various contents utilized in a surface pavement. The number of skid test observations for each unique pairing is indicated. For nearly a third of the sources (7 of the 25), only one limestone content was used within the tested pavements. For another third of the sources (8 of the 25), the limestone contents used in the tested pavements were very nearly the same, only a 1 to 8 percent difference. The remaining 10 sources had larger variation in the limestone content, from 10 to 35 percent difference.

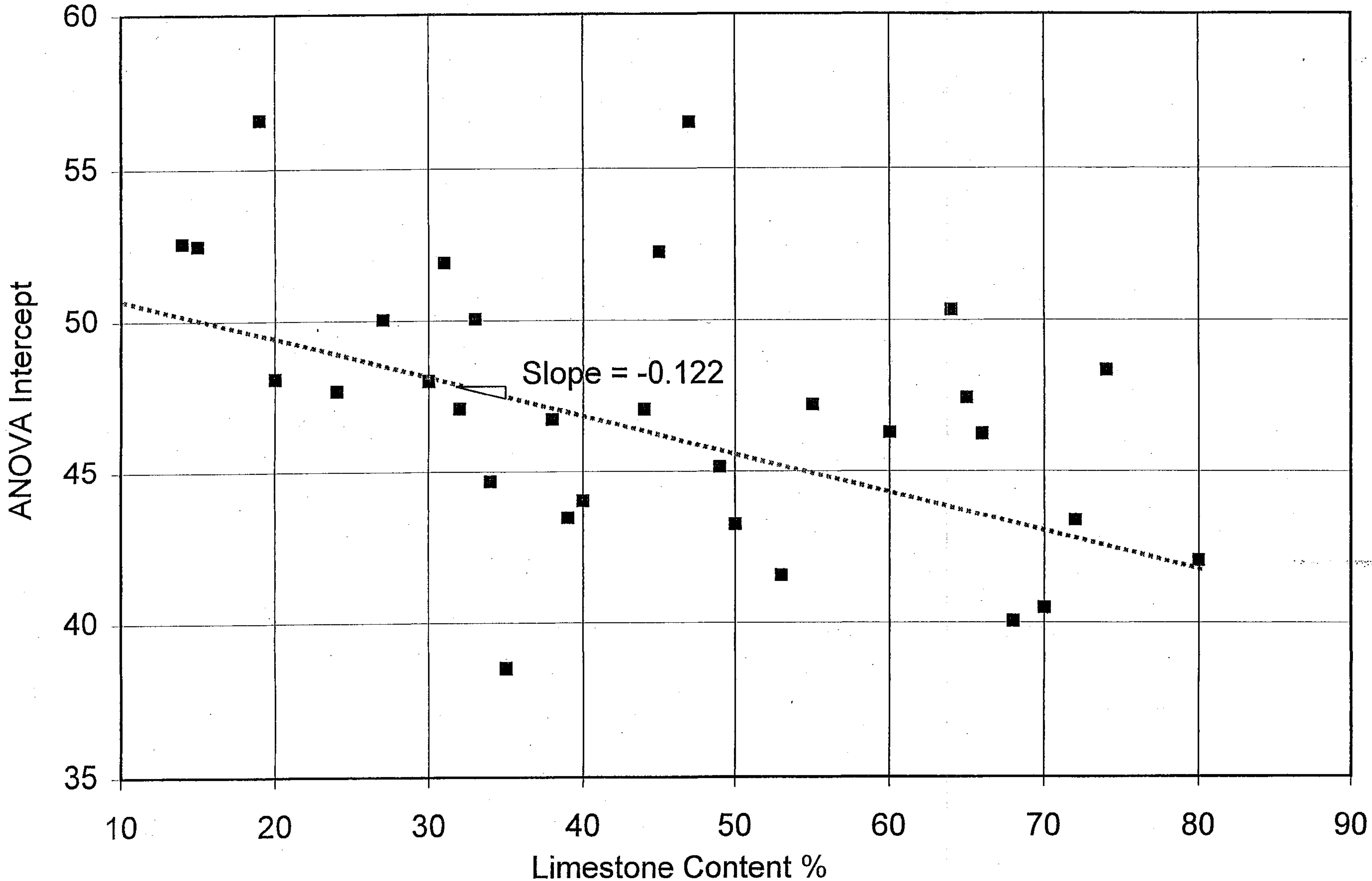


FIG. 6.10 Contrasting Class vs. Continuous Limestone Content Model

Table 6.4 Cross-Tabulation of Limestone Source and Content

Count

		Limestone Source									
		48.00	134.00	137.00	141.00	142.00	147.00	151.00	152.00	155.00	158.00
Lime%	14.00										
	15.00										
	19.00										
	20.00										
	24.00										
	27.00										473
	30.00	35					96		228	108	
	31.00										
	32.00										90
	33.00										
	34.00										
	35.00										
	38.00										
	39.00									53	
	40.00						355			140	
	44.00										48
	45.00				54						
	47.00										
	49.00		191								
	50.00		300								
	53.00			350							
	55.00			60							
	60.00	389									
	64.00					198					
	65.00					319					
	66.00										
	68.00										
	70.00							144			
	72.00							227			
	74.00										
	80.00										
Total		424	491	410	54	517	451	371	228	301	611

Table 6.4 Cross-Tabulation of Limestone Source and Content

Count

		Limestone Source									
		159.00	165.00	168.00	169.00	170.00	315.00	414.00	497.00	783.00	911.00
Lime%	14.00										48
	15.00							6			102
	19.00										
	20.00		72					30			30
	24.00						60				
	27.00										
	30.00	109	144					39		93	253
	31.00	30									
	32.00										
	33.00	143									
	34.00	55									
	35.00		132							3	
	38.00						84				
	39.00										
	40.00						42	139			
	44.00										
	45.00									180	
	47.00										
	49.00										
	50.00				51	162					
	53.00				267						
	55.00										
	60.00			70							
	64.00										
	65.00									42	
	66.00										
	68.00				208						
	70.00										
	72.00										
	74.00										
	80.00								240		
Total		337	348	70	526	162	186	214	240	318	433

Table 6.4 Cross-Tabulation of Limestone Source and Content

Count

		Limestone Source					
		912.00	924.00	927.00	928.00	1414.00	Total
Lime%	14.00						48
	15.00			30			138
	19.00			34			34
	20.00			30		80	242
	24.00						60
	27.00					258	731
	30.00						1105
	31.00						30
	32.00						90
	33.00						143
	34.00						55
	35.00						135
	38.00						84
	39.00						53
	40.00						676
	44.00						48
	45.00						234
	47.00	72					72
	49.00						191
	50.00						513
	53.00						617
	55.00						60
	60.00						459
	64.00						198
	65.00						361
	66.00		54		96		150
	68.00		360				568
	70.00						144
	72.00						227
	74.00		72				72
	80.00						240
Total		72	486	94	96	338	7778

An initial model included only main effect terms for limestone source and the continuous variable representation of limestone content. This allows the independent fit of content and source, indicating the descriptive power of the model if the joint effect between limestone quality and quantity was not considered. This main effect model including wear and intensity terms accounted for 49.9% of the observed frictional variability within the data. The limestone content fitted parameter was -0.088 suggesting that the modeled friction curve shifted downward 0.88 skid number for every 10-percent increase in limestone content. (Statistical ANOVA results are provided as Table A7 in Appendix A.)

A second model including both main and joint effect terms of source and content was fit to the data. This model design allows the mathematical fit of the data to conform not only to limestone source and content as individual terms but to reflect the interaction between the terms as well. This model describes 55.7 percent of the friction variation within the data. However, the main effect parameter for limestone content becomes statistically insignificant in the model when interaction is modeled between quality (source) and quantity. This suggests that all of the descriptive power attributable to limestone content is determined in conjunction with its quality. When limestone quality is included along with the potential to combine the effect of limestone quality and quantity, then quantity alone proves to be of no real value in the equation. (Statistical ANOVA results are provided as Table A8 in Appendix A.)

A third model was fit including the standard wear and intensity terms along with main effect limestone source and the joint effect between source and limestone content. This model contains 45 terms and can describe 55.7 percent of the observed friction performance in the 7778 field trials. The fitted parameters of the initial decline rate and adjustments to that decline are roughly the same as earlier models, although, the traffic lane downward shift is somewhat larger at 3.7 (Statistical ANOVA results are provided as Table A9 in Appendix A.)

Some interesting insight is provided by closer inspection of the fitted parameters for the joint effect terms, most particularly the sign of the parameter estimates. Seven of the twenty-five joint terms were not fit because only one content was observed for the particular limestone source. Of the 18 joint terms that were fit, 8 were limestone sources with small content differences. The joint effect parameters had evenly divided signs, three were negative, one neutral, and four positive. The negative sign indicates increasing limestone content is associated with decreasing friction performance; the opposite is true for a positive sign.

The 10 joint effect parameters of limestone sources with larger content differences had seven negative signs, 2 neutral, and 1 positive. This finding suggests that with only minor difference in limestone content the relative skid performance will be determined by other factors than content. With larger differences, limestone content will prove to be the larger influence on skid performance over that of other factors.

(5) Considering a 'Limestone BPN(9') Model

BPN(9) is short-hand for the resulting number obtained from a British Pendulum device on a wetted sample after nine-hours of abrasive-induced 'accelerated polishing'. The British Pendulum device uses a swinging pendulum that slides across the wetted sample with a natural rubber slider. The friction performance of the polished sample is indicated by the amount of kinetic energy in a swinging pendulum that can be converted to internal kinetic energy (heat) within the slider while traversing the contact patch.

It is assumed that a polished sample will have diminished frictional performance. Under field conditions, polishing is a certain type of wear where small particles are plucked from the surface matrix of the material being polished. There is some doubt in this researcher's mind as to whether or not the accelerated wear under the abrasives used in the BPN(9) test will parallel the polishing effects on pavement aggregates over an extended period of service exposure. The BPN(9) abrasives may tend to scour the aggregates rather than polish them leading to inaccurate simulation of the polishing action over time.

Being a limestone aggregate characteristic, BPN(9) is included within the assortment of undifferentiated factors contained in the 'project' and 'limestone source' models. The analysis discussed in the following sections will consider the descriptive power of the 'limestone source' model that can be traceable to the BPN(9) characteristics.

BPN(9) aggregates that are included in the field skid data ranged from a low of 18 to a high of 35. The most frequently observed BPN(9) value is 23 with slightly less than 1000 of the 7778 observations having this value.

This variable, like that of limestone content, can be treated as either a continuous or class variable. A statistical model using an assumed continuous 'BPN(9)' value combined with wear and intensity variables describe 17.1% of the observed variation in field-tested friction values obtained using a skid trailer. (Statistical ANOVA results are provided as Table A10 in Appendix A.)

The fitted parameters to the model for intercept, initial decline rates, changes to that rate, and intensity differences are similar to earlier models. This is to be expected since most of the descriptive power remains in the wear and intensity factors. Only 4.8 percent of the variability can be traced to the BPN(9) aggregate characteristic, but perhaps most troubling is that the fitted coefficient of this characteristic is negative with an estimated value of -0.307. Friction performance actually appears to get marginally worse with more polish-resistant aggregates. Perhaps one reason for this is that higher BPN(9) aggregates have higher limestone content within the data as well. This possibility of a joint effect between BPN(9) value and limestone content will be taken up in the next section.

An alternative statistical model uses BPN(9) values as a class variable. This model describes 39.7% of the data, a significant improvement over that of the single continuous variable. (Statistical ANOVA results are provided as Table A11 in Appendix A.) Again, measures of wear and intensity are fitted very close to earlier models. The effect of BPN(9) characteristics is represented as a shift in the intercept term under the ANOVA model and the same troubling display of decreasing friction performance with increasing BPN(9) values is evident within the fitted parameters. This runs contrary to expectations.

Figure 6.11 illustrates the downward trend in both the continuous and class variable versions of this model. The class variables are shown as the individually plotted data on the figure with the continuous variable represented in an annotated trend line with a downward slope of -0.307. Perhaps the most telling information comes from the two anomalies at BPN(9) values of 27 and 33 within the composite data. First, the increase of

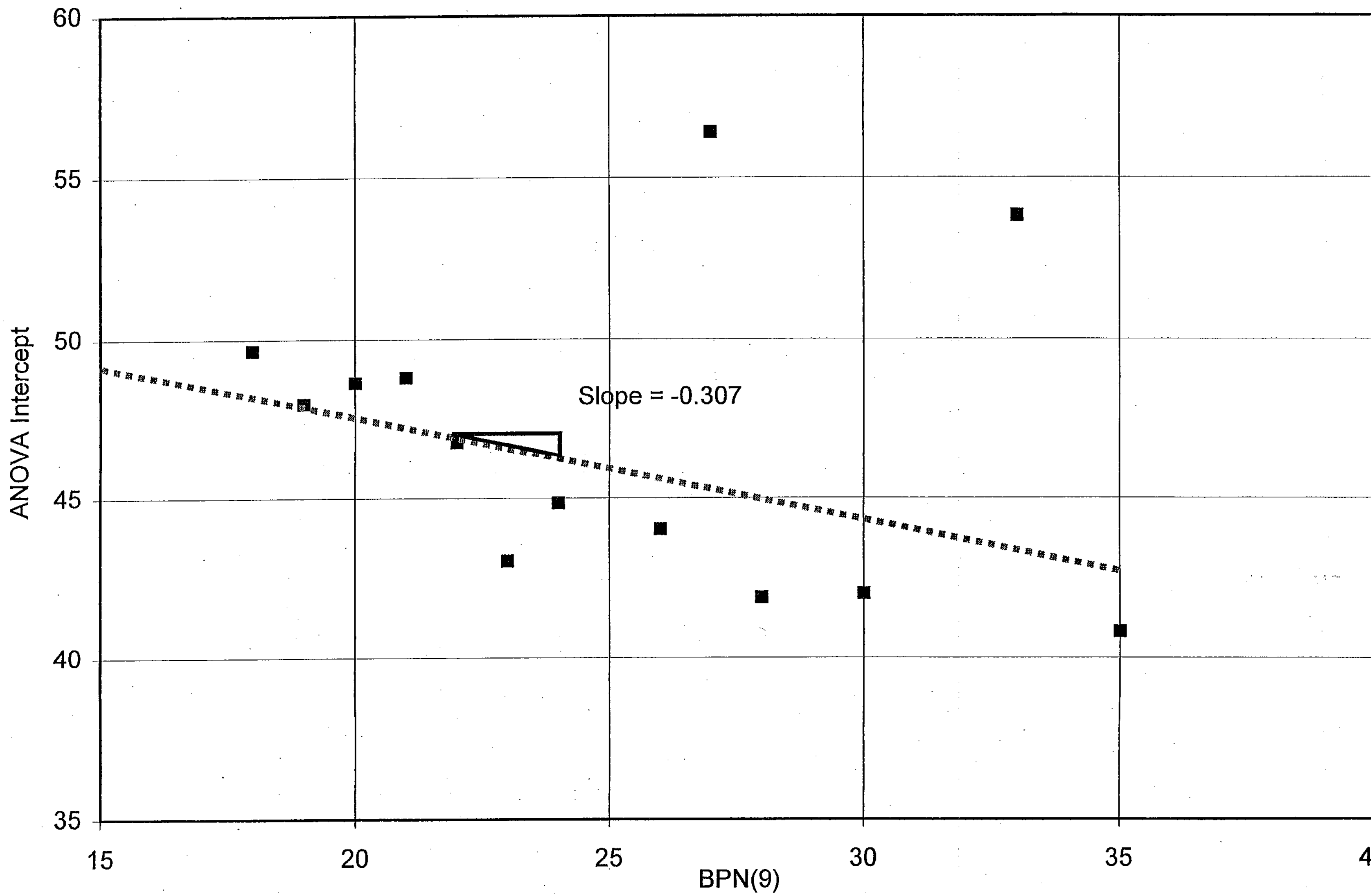


FIG. 6.11 Contrasting Class vs. Continuous BPN(9) Model

predictive power from 17.1 in the continuous variable version to 39.7 in the class variable version is attributable to the class model being able to isolate the frictional behavior of these two outliers.

Second, there are some distinguishing characteristics about the pavement that exhibited these outlying friction performances over time. The pavements indexed under the BPN(9) value of 27 all came from a single source, limestone source '912'. It is important to note that there is some difference in the recorded data concerning the BPN(9) value of this source. The ALDOT "Sources of Coarse and Fine Aggregates" list as revised on 02/28/94 and included in Appendix B indicates this source produces aggregates with a BPN(9) value of 27. However, the master's thesis of Auburn student E.A. Bishara (Bishara 1992) that led to the final report "Evaluation of Limestone Aggregates in Asphalt Wearing Courses – Phase II" submitted by Kandhal and Bishara (1992) to ALDOT identified this aggregate source under the code A-25 with a BPN(9) value of 35. Even at a higher BPN(9) value of 35, the results are out of line with what the other close cohort data suggests.

It is the limestone composition of aggregates produced by source '912' that probably influences its high friction performance. Bishara (1992) indicates this source produces aggregate with 13% silica and has an acid insoluble residue of 29.132%, the highest residue value within the data by almost a factor of 2.

The pavements indexed under the BPN(9) value of 33 also came from a single source, coded as '783'. Bishara (1992) provides a BPN(9) value of 35 for aggregates produced by this source, which is coded 'A-9' under that author's reference system. Its composition cannot be what distinguishes its performance from those of other close cohort aggregates. The percent silica is only 1% and the acid insoluble residue is a modest 6.33%. And, its performance does not stem from the limestone content within the pavement surface mixture. Limestone contents were tested at 4 levels -- 30%, 35%, 45%, and 65%. The pavements at each content level performed well. The pavement performance difference is most likely associated with the natural sand content in the pavement mixture at 3 levels – 35%, 40%, and 57%. No other pavements included this high of a sand content.

Both of these outlying observations indicate a silica-based determinate in long-term friction performance rather than the aggregates performance based on BPN(9) tests.

(6) Considering a 'Limestone BPN(9) and Content' Model

The ability of limestone to resist polishing wear is simulated with the BPN(9) results, while the extent that the pavement surface depends upon this aggregate is reflected to a certain extent by the limestone content within the pavement mix.

Table 6.5 provides a cross-tabulation of BPN(9) and limestone content revealing a bias within the data. Higher BPN(9) aggregates have higher limestone content and lower BPN(9) aggregates have lower content. While this is not an ideal composition of the data, some mid-range aggregates have good content coverage that will allow some comparisons.

The statistical model targets the combined influence of polish resistance and limestone content on observed friction performance through an interaction term. Wear and intensity terms are also included within the model as discussed earlier, as are the main effects of polish resistance and limestone content. What is new to this model is the

Table 6.5 Cross-Tabulation of BPN(9) and Limestone Content

Count

		BPN(9)								
		18.0	19.0	20.0	21.0	22.0	23.0	24.0	26.0	27.0
Lime%	14.00			48						
	15.00			102		6	30			
	19.00						34			
	20.00		80	30		30	30			
	24.00			60						
	27.00		258		473					
	30.00	228	109	361		39		131		
	31.00		30							
	32.00				90					
	33.00		143							
	34.00		55							
	35.00									
	38.00			84						
	39.00			53						
	40.00			182		139		355		
	44.00				48					
	45.00				54					
	47.00									72
	49.00						191			
	50.00					162	300		51	
	53.00						350		267	
	55.00						60			
	60.00							389		
	64.00					198				
	65.00					319				
	66.00								96	
	68.00								208	
	70.00									
	72.00									
	74.00									
	80.00									
Total		228	675	920	665	893	995	875	622	72

Table 6.5 Cross-Tabulation of BPN(9) and Limestone Content

Count

		BPN(9)				
		28.0	30.0	33.0	35.0	Total
Lime%	14.00					48
	15.00					138
	19.00					34
	20.00	72				242
	24.00					60
	27.00					731
	30.00	144		93		1105
	31.00					30
	32.00					90
	33.00					143
	34.00					55
	35.00	132		3		135
	38.00					84
	39.00					53
	40.00					676
	44.00					48
	45.00			180		234
	47.00					72
	49.00					191
	50.00					513
	53.00					617
	55.00					60
	60.00	70				459
	64.00					198
	65.00			42		361
	66.00				54	150
	68.00				360	568
	70.00		144			144
	72.00		227			227
	74.00				72	72
	80.00	240				240
Total		658	371	318	486	7778

opportunity to demonstrate the interaction between limestone quality -- as measured by its simulated resistance to polishing -- and limestone content on the observed friction performance.

The first fitted statistical model represents BPN(9) and limestone content as continuous variables and include only their main effect terms for now. Along with wear and intensity, the model fitting BPN(9) and limestone content accounts for only 23.2% of the observed friction variability. This is within 0.1% of a model including limestone content without any reference to its BPN(9) value. It is not surprising to learn that wear, intensity, and limestone content parameters are essentially identical to that provided by a model without a BPN(9) term. (Statistical ANOVA results are provided as Table A12 in Appendix A.)

The second fitted statistical model includes an interaction terms along with the main effect terms. This model indicates that there is no statistically significant influence on friction values from BPN(9) or its interaction with limestone content. This model is able to account for only 23.2% of the variability within the data, an amount similar to the model above. (Statistical ANOVA results are provided as Table A13 in Appendix A.) The parameter estimate for limestone content is -0.101, suggesting friction values tend to decrease 1.01 in value from every 10% increase in limestone content. Parameter fits for BPN(9) and the interaction term are inconclusive.

The third model again fits only the main effects but used a class variable to represent BPN(9). The real benefit in using class variables here is separate treatments allowed for BPN(9) values of 27 and 33. These pavements performed much better than expected given the slight increase in BPN(9) values relative to their neighboring data.

This model describes 40.3% of the frictional variation in the observed data. (Statistical ANOVA results are provided as Table A14 in Appendix A.) The fitted parameter for limestone content showed an expected decline in friction performance by 0.46 for every 10% increase in content. BPN(9) influences were captured in difference for the intercept term with a net range of 14.58 between highest and lowest effects.

A fourth model includes the main effects as in model three but also includes an interaction term. This model accounts for nearly half of the observed variation in the friction data (48.1%). (Statistical ANOVA results are provided as Table A15 in Appendix A.) In this model, limestone content has a parameter estimate of +0.902 suggesting the overall effect of content is that friction values actually improve as limestone content increases.

At first blush this estimate seems contrary to the general expectation within the research; however, it reflects only observational data for aggregates with BPN(9) values equal to 35. As fitted, this model allows different limestone content influences to be fit to each BPN(9)-valued aggregate as a combination of main and interaction parameter estimates. For example, the limestone content influence of aggregates with a BPN(9) value of 19 would be -0.16, combining an interaction estimate -1.062 with a main effect of +0.902 to net the -0.16 value. This suggests that with these aggregates a 1.6 decrease in observed friction is associated with every 10% increase in limestone content.

Figure 6.12 illustrates these differences in the influence of limestone content by the aggregate categories as distinguished by their BPN(9) values. The observed friction performance can be influenced by limestone content in one of three ways within the BPN(9)-categorized pavements. First, increasing limestone content can decrease

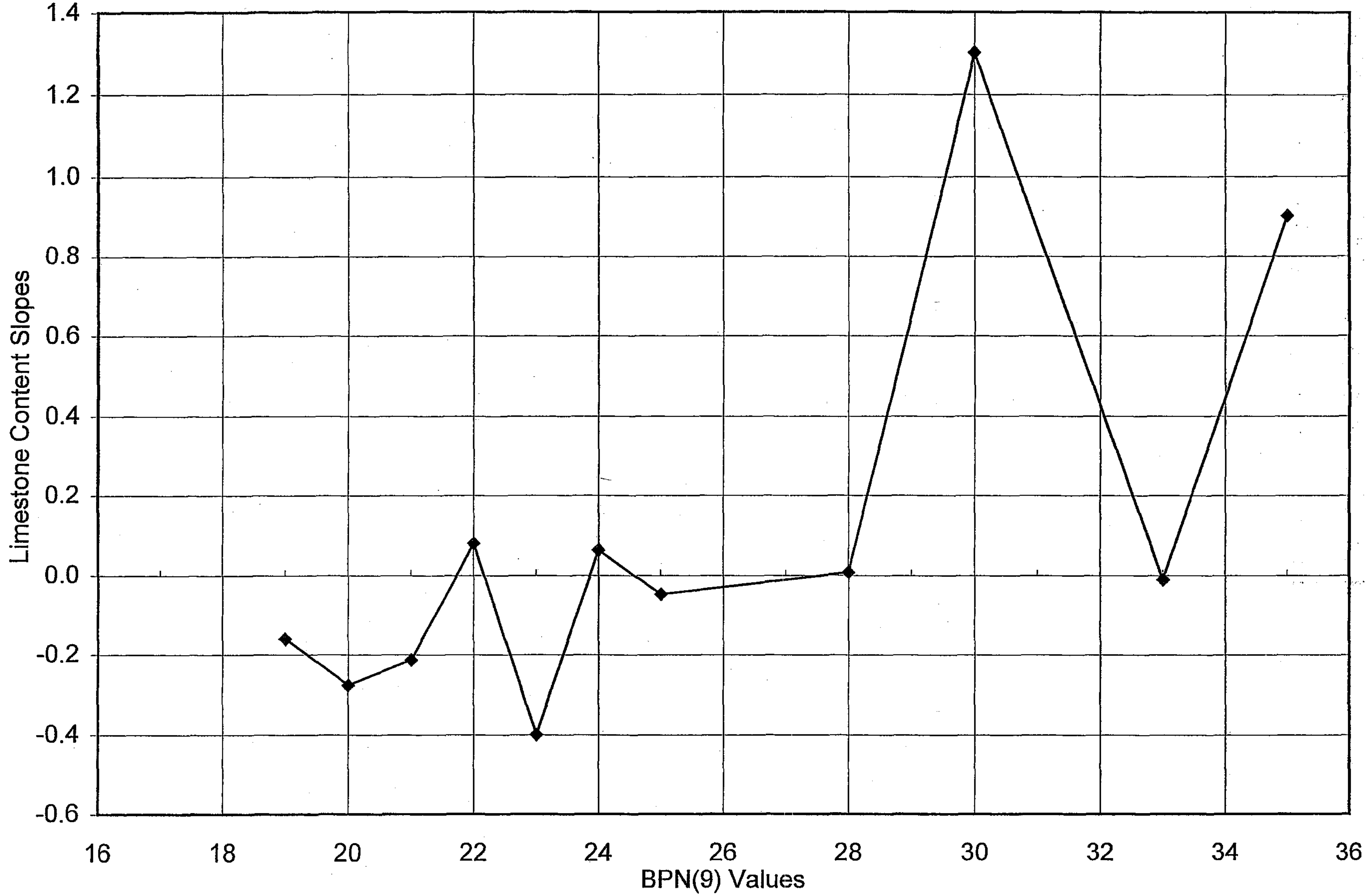


FIG. 6.12 BPN(9) Influences on Limestone Content Effect

performance. Only in four categories does a distinct downward trend in limestone content show up in the data. These BPN(9) values are for 19, 20, 21, and 23.

Second, changing limestone content can by neutral on its effect on friction performance. Five of the 13 BPN(9) aggregate categories fall into this type -- BPN(9) values of 22, 24, 25, 28, and 33. Statistically, there is no discernable trend traced to limestone content within these categories of values.

Third, increasing limestone content can improve friction performance levels. Positive slopes are associated with 2 BPN(9) aggregate categories, BPN(9) values of 30 and 35. However, in these categories there is not a large differences in limestone content and thus estimated parameters are more a reflection of the assigned intercept term.

For other BPN(9) data there is insufficient data to estimate the limestone content influence since only one content value is utilized. This is true for BPN(9) values of 18 and 27.

(7) Considering a 'Natural Sand Content' Model

Natural Sand Content quantifies the amount of natural sand making up the fine aggregate fraction of the surface pavement. This particular component contributes a high surface-energy element to the micro-texture of the pavement surface.

Two statistical models were considered. The first model uses Natural Sand Content as a continuous variable and when combined with wear and intensity variables describe 22.9 percent of the observed variability in skid performance. Natural Sand accounted for 10.6% of the variation while wear and intensity variables accounted for the remaining 12.3% of the descriptive power. (Statistical ANOVA results are provided as Table A16 in Appendix A.)

The intercept term of 42.53 describes the fit of a hypothetical pavement containing no natural sand content (smallest actual sand content is 10%) and having experienced no service exposure. The fitted parameters of decline are roughly the same as in previous models. Initially, pavement performance declines at 1.2 skid numbers per 100 days.

The second statistical model uses Natural Sand Content as a class variable which when used in conjunction with wear and intensity variables describe a relatively modest 39.0 percent of the observed variability in skid performance. Natural Sand Content accounted for 26.7% of the variation while wear and intensity variables accounted for the remaining 12.3% of the descriptive power. (Statistical ANOVA results are provided as Table A17 in Appendix A.)

The intercept term of 57.70 describes the fit to a 57% natural sand content class of pavements with limited to no service exposure. The fitted parameters of decline are roughly the same as in previous models. Initially, pavement performance declines at 1.2 skid numbers per 100 days.

The true value of this contrast between continuous versus class treatment of the 'natural sand content' variable can be seen in Figure 6.13. The data represents ANOVA intercepts of sand content classes plotted on the vertical axis and the underlying sand content of these classes plotted on the horizontal axis. The annotated line shown with a slope of +0.295 in skid number per percent increase in natural sand content represents the best fit through the data when considering natural sand as a continuous variable.

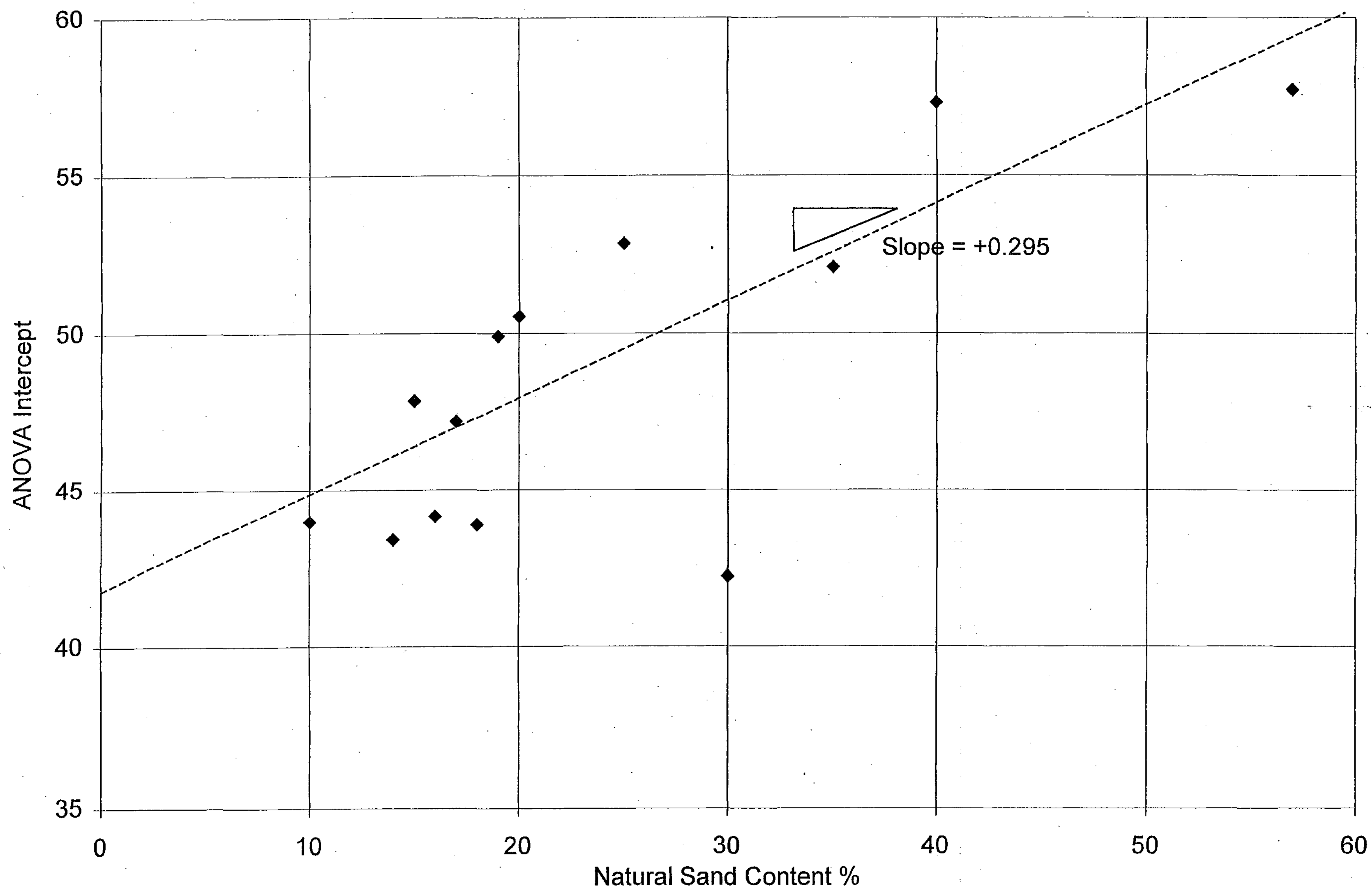


FIG. 6.13 Contrasting Class vs. Continuous Natural Sand Content Model

While the overall trend on this figure is most definitely toward increasing values, there are noticeable exceptions within the class variables allowing for the difference in descriptive power between the two models, 22.9% for the continuous model and 39.0% for the class model. The most extreme exception, where natural sand content is equal to 30%, merits a more in-depth consideration. On closer inspection of these '30% sand content' pavements an interesting fact is revealed that may be what drives this unexpected low friction performance. These surface pavements were constructed with limestones from two different quarries – source '0151' and '0165'. From information obtained from the Masters Thesis of Emad Atta Bishara entitled <u>Evaluation of Limestone Aggregates in Asphalt Wearing Courses – Phase II</u>, both of these sources produce limestones containing 100% calcite and were the only two such sources within that researcher's database. As a consequence, limestones from these sources contained miniscule amounts of acid irreducible residue and absolutely no silica content. Could this be further evidence that cumulative silica content dominates the resulting skid performance of surface pavements? Perhaps!

One other note concerning why silica content is vital in obtaining good skid performance, even with the moderate descriptive power of the natural sand content models. The 'skid performance' data itself subscribes to the notion that on-average skid performance improves with increasing sand content. This agreement can be viewed from the strict order brought to the data as indicated by the ANOVA class intercepts for natural sand content shown on Figure 6.13. These intercepts reflect average skid performances for each class. Observed skid performance variation remains about these class averages. This fact leads to why this 'natural sand content' model lacks significant descriptive power. Its lack is not due to a miss assigned dominant cause, but in the lack of control for various secondary causes of skid variation about these class averages.

SUMMARY DISCUSSION

BPN(9) in combination with limestone content can not sufficiently order the skid data so as to validate a 'cause-and-effect' relationship. Any relationship that may exist is dominated by other factors that more forcefully influences the observed skid results obtained. However, there is promise that a cause-and-effect relationship including limestone quality, but not as measured by BPN(9), will prove out. Most likely this quality term is associated with the silica content in the limestone in combination with natural sand content in the surface mix.

7. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In this study, evaluations of field gathered skid data was conducted to determine if a relationship existed between the skid resistance of dense-graded HMA pavement surfaces and the limestone aggregate content and its BPN(9)-measured polish/frictional characteristics. Based on the observational data and its evaluations the following conclusions are drawn and recommendations made:

1) No apparent relationship exists in the observational data between long-term friction performance and limestone aggregate BPN(9) values and the pavement surface contents of these aggregates. Expectations prior to this research suggests higher BPN(9)-valued aggregates and the lower 'polish' susceptibility inferred by these results will contribute to better pavement friction. This was not found to be true within the observational data. In fact, with the exception of BPN(9) values of 27 and 33 there appears to be a strong downward trend in frictional performance with increasing BPN(9) values.

The limestone content of these aggregates indicated a mixed effect on friction performance. Largely neutral in its influence, increasing limestone content is detrimental only in low valued BPN(9) aggregates and even then not to a significant level.

2) Friction is not well characterized in pavement-oriented research. A basic question that needs to be resolved is whether friction is a *force* or *energy dissipated.* Many researchers consider friction to be a resistive force and conduct their experiments to maximize the transfer of this force between pavement and tire. Other researchers agree with Kummer (1966) that the two interpretations are equivalent. While the two may be equivalent in terms of effect, they are not equivalent in terms of a guiding principle of research. On one hand, forces are seen as a function of how well the pavement can grip the normal load of a moving object. This view leads to piecemeal optimization efforts, with little comprehensive understanding of the mechanism at work. On the other hand, energy is seen within a bounded system where energy conversion can be measured, accounted, and tracked. Even the verbs used to describe them are indicative of the differences with which they are viewed, Forces *are* … and Energy *is*…!

For pavement friction research, friction can best be defined and treated as an observed 'energy transfer' phenomenon that is inherently rate-based. Vehicular kinetic energy is converted to some alternative, non-recoverable form of energy; slowing a vehicle of known mass by 5-mph represents a sum-specific conversion of energy. The quicker this conversion takes place the more 'friction' is believed to be present.

The real power in this representation stems from the general law of energy conservation. This law dictates that any lost kinetic energy must remain in the system as some other form of energy in as much as a *closed* system can neither gain nor lose energy. We can speculate that the converted energy has been principally converted to waste heat, a form of internal kinetic energy, in the vicinity of the tire/pavement contact patch.

One can see the clarity and discipline this conceptualization brings to friction research when considering micro-texture. The basic question that must be addressed if micro-texture alone impacts friction is as follows: "Where is the store of energy made available simply because an aggregate has microscopic textural features?". The 'touch-ability' of the aggregate surface is not explanation enough; there must be something more.

3) The standard 40-mph skid-trailer tests does not accurately replicate coarse-aggregate dependent friction performance. The skid numbers these tests produce represent measured surface performance during a fabricated situation where a well-treaded tire skids across a thinly wetted pavement while traveling at moderate speeds. The manner in which these tests are performed influence how the roadway is engaged and thus defines how and what components of the surface are tested.

For any likely relationship to be identified between BPN(9), limestone content, and skid resistance it is necessary to create a field test scenario where adhesion is essentially limited to the coarse aggregate fraction. The severity of the event necessary to create this condition is not known. But from the observed data, it is obvious that the sand/binder mix continues to contribute the most significant adhesion element in the skid-trailer field test results.

4) Limestones polish most likely as a result -- not a cause -- of the aggregate characteristic that lead to poor friction performance. Polishing wear of limestone aggregates reflects the loss of microscopic material from the surface by adhesive forces

greater than those binding the aggregate material together. Thus, small particles are 'plucked' from the matrix where they are situated. The size of the particles lost in the polishing action is directly related to the surface energy of the material being polished (Rabinowicz 1963). Limestone is a soft material and has extremely low surface energy as it approaches pure calcite.

Surface energy is a dominant element in the adhering of two substances to each other, in this case limestone coarse aggregate pavement to tire. By adhering, stretching, and then rupturing this connective junction the internal vibrations set up in the bulk material generates the waste heat to vent the kinetic energy of the vehicle. An intervening substance – most often water -- negatively affects the adhesion element of friction by limiting the proximity of mating surfaces. (Remember friction is not considered a problem on dry pavements.) Whether the proximity provided by the micro-textural asperities or the residual surface energy of the material itself dominates adhesive friction is a matter not taken up in this research.

5) Observed friction performance is a composite effect of a multi-dimensional phenomenon. This research effort pointed to four categories of direct influences affecting pavement friction. First, 'pavement surface wear' represents a class of factors that act to wear away the pavement surface. This category can be further broken into vehicle loading, aging, geometric loading, and a place-keeper for, as yet, unknown factor(s).

Second, 'initial pavement characteristics' reflect the friction and wear resistant performance of the composite pavement mixture attributable to the chosen components in terms of quality and quantity. Coarse aggregates, fine aggregates, asphalt content, latex additives – as a composite -- form the exposed surface that generates friction through coupling with vehicle tires and withstands the wearing conditions on pavements. The relative quality and quantity of these underlying components differentiate good friction and good wearing pavements from bad.

Third, 'temporary surface effects' represent those frictional influences that are a function of things external to the pavement itself and thus only temporary -- subject to change in its influence on friction with the changing circumstances. The most relevant of these temporary effects are temperature and contamination. Temperature is a complex element in terms of friction. Friction after all vents kinetic energy through 'waste' heat. Thus, the available heat sink or differential temperature of the pavement will affect the rate at which heat can be vented and kinetic energy be dissipated. Surface contamination reduces the frictional interface between tire and pavement. This contamination accumulates over time and then is periodically removed by intense rain events in combination with the scrubbing action of concurrent traffic.

Fourth, as yet 'unknown primary factors' serves as a place to partition out into all those myriad of factors that influence friction performance. The fact that it is included in the representation of the relational model serves to remind us how little we know of the observed phenomenon and how little we can control the observational data.

6) BPN evaluation of limestone aggregates is an imperfect reflection of the characteristics being studied. Most researchers use the BPN test as a measure of the micro-texture contribution of aggregates. The 9-hours of 'polishing' is done in the

presence of silicon-carbide grit abrasive that is used to 'accelerate' the wearing process. This tends toward an abrasive wearing action – the surface 'plowing' of softer material by harder material. Abrasive wear tends to leave gouges in the surface and accelerates the loss of large wear fragments. This gouging leaves the surface in a more roughened condition than if the wear were by polishing only. Later when the BPN pendulum is swung over the 'polished/abraded' surface the loss mechanism is not limited to micro-textural (adhesion) features.

7) Frictional contribution of siliceous material is misrepresented and underrated. Limestones containing interspersed contaminates of hard siliceous material is seen by many to play a significant part in skid resistance by differential wear of these hard/soft composite limestones. In this scenario, friction is seen as strictly a mechanical process thus leading to the assignment of physically defined attributes as accounting for the differences in observed performance. This reasoning treats the presence of micro-texture as the cause for available friction rather than a coincident condition of low (or high) surface energy measuring the potential for low or high adhesion. Friction is not simply a physical phenomenon; rather it is a thermodynamic one. Most likely, the presence of micro-texture of any substantial scale reflects the higher composite surface energy of the composite hard/soft material.

Siliceous material is also underrated in its contribution in frictional performance that is measured by the 40-mph skid-trailer. It is obvious from the collected data that the sand/binder mix contributes the most significant adhesion element to the skid-trailer field trials.

RECOMMENDATIONS

The results, conclusions, and opportunity for further study warrant the following recommendations for consideration:

1) There should be a continued collection and evaluation of skid-test data on Alabama highways.

2) The skid performance data should be analyzed on the basis of the silica content of limestone coarse aggregates as measured with insoluble residue, total mix aggregate insoluble residue and mix natural sand content. The insoluble residue of limestone aggregates could be collected as part of routine source testing. Total mix aggregate insoluble residue should be measured on surface mixes with limestone course (+ #4) aggregate and siliceous fine (-#4) aggregate.

3) The many findings of this research effort should be focused on individually and progressively so as to craft a foundation on which to attempt to resolve the roadway friction problem. This should start with a review of friction itself.

4) A study of the coincident conditions associated with skid accidents should be performed in order to better reflect actual critical conditions in our performance testing and evaluation methods.

5) Skid testing parameters should be modified to more closely match the identified critical conditions found in accomplishing the recommendation above.

6) A finite element model of pavement surfaces should be created to reflect surface response, chemistry, geometry, and antecedent temporal conditions. This model could then be tuned by observational and test track data.

7) Trial mixes should be developed for test track implementation.

REFERENCES

Bishara, E.A. (1992). Evaluation of Limestone Aggregates in Asphalt Wearing Courses Phase II, Masters Thesis, Auburn University, Auburn, AL.

Cooley, W.W. (1979). "Introduction: Structural Equations and Explanatory Observational Studies," Advances in Factor Analysis and Structural Equations Models. Editor Magidson, J., Abt Books, Cambridge, Mass., pp. xv-xxviii.

Kandhal and Bishara (1992) "Evaluation of Limestone Aggregates in Asphalt Wearing Courses – Phase II" A report submitted to ALDOT

Kummer, Harwig W. (1966). Unified Theory of Rubber and Tire Friction. Engineering Research Bulletin B-94, The Pennsylvania State University, College of Engineering, University Park, Pennsylvania.

Rabinowicz, E. (1961). "Influence of Surface Energy on Friction and Wear Phenomena," Journal of Applied Physics, Volume 32, No. 8, pp. 1440-1444.

APPENDIX A – ANOVA TABLES

Table A.1 ANOVA of Linear 'Days-in-Service' Model

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	28257.272[a]	1	28257.272	770.703	.000
Intercept	13675237.2	1	13675237.213	372985.197	.000
DAYS	28257.272	1	28257.272	770.703	.000
Error	285101.514	7776	36.664		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .090 (Adjusted R Squared = .090)

Parameter Estimates

Dependent Variable: Skid Number

					95% Confidence Interval	
Parameter	B	Std. Error	t	Sig.	Lower Bound	Upper Bound
Intercept	45.054	.132	341.846	.000	44.796	45.312
DAYS	-5.178E-03	.000	-27.762	.000	-5.543E-03	-4.812E-03

Table A.2 ANOVA of 'Days-in-Service' Model

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	30458.442[a]	2	15229.221	418.547	.000
Intercept	13675237.2	1	13675237.213	375838.952	.000
DAYS	28257.272	1	28257.272	776.600	.000
DAYS2	2201.169	1	2201.169	60.495	.000
Error	282900.345	7775	36.386		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .097 (Adjusted R Squared = .097)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	46.413	.219	212.339	.000	45.985	46.842
DAYS	-1.050E-02	.001	-14.807	.000	-1.189E-02	-9.111E-03
DAYS2	3.709E-06	.000	7.778	.000	2.774E-06	4.644E-06

Table A.3 ANOVA of 'Service Exposure-Intensity' Model

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	38575.687[a]	3	12858.562	363.787	.000
Intercept	13675237.2	1	13675237.213	386891.676	.000
DAYS	28257.272	1	28257.272	799.438	.000
DAYS2	2201.169	1	2201.169	62.274	.000
TRF_LANE	8117.245	1	8117.245	229.648	.000
Error	274783.100	7774	35.346		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .123 (Adjusted R Squared = .123)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Intercept	48.867	.269	181.333	.000	48.338	49.395
DAYS	-1.137E-02	.001	-16.205	.000	-1.274E-02	-9.991E-03
DAYS2	4.235E-06	.000	8.986	.000	3.311E-06	5.158E-06
TRF_LANE	-2.674	.176	-15.154	.000	-3.019	-2.328

Table A.4 ANOVA of 'Limestone Source' Model

Between-Subjects Factors

		Number Skid Tests
Lmstn Source	48.00	424
	134.00	491
	137.00	410
	141.00	54
	142.00	517
	147.00	451
	151.00	371
	152.00	228
	155.00	301
	158.00	611
	159.00	337
	165.00	348
	168.00	70
	169.00	526
	170.00	162
	315.00	186
	414.00	214
	497.00	240
	783.00	318
	911.00	433
	912.00	72
	924.00	486
	927.00	94
	928.00	96
	1414.00	338

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	155586.631[a]	27	5762.468	283.061	.000
Intercept	13675237.2	1	13675237.213	671747.737	.000
Days-In-Service	28257.272	1	28257.272	1388.039	.000
Days-In-Srvc^2	2201.169	1	2201.169	108.125	.000
Traffic Lane	8117.245	1	8117.245	398.731	.000
Lmstn Source	117010.945	24	4875.456	239.490	.000
Error	157772.155	7750	20.358		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .497 (Adjusted R Squared = .495)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Intercept	52.844	.304	173.648	.000	52.247	53.440
Days-In-Service	-1.111E-02	.001	-20.564	.000	-1.217E-02	-1.005E-02
Days-In-Srvc^2	4.563E-06	.000	12.587	.000	3.852E-06	5.273E-06
Traffic Lane	-3.303	.146	-22.552	.000	-3.590	-3.016
[Source=48.00]	-3.085	.330	-9.337	.000	-3.733	-2.438
[Source=134.00]	-6.158	.320	-19.251	.000	-6.785	-5.531
[Source=137.00]	-9.795	.332	-29.525	.000	-10.445	-9.145
[Source=141.00]	-4.190	.664	-6.313	.000	-5.491	-2.889
[Source=142.00]	-1.709	.317	-5.391	.000	-2.330	-1.087
[Source=147.00]	-6.325	.325	-19.460	.000	-6.962	-5.688
[Source=151.00]	-7.591	.340	-22.312	.000	-8.258	-6.924
[Source=152.00]	.130	.391	.332	.740	-.637	.896
[Source=155.00]	-3.996	.362	-11.029	.000	-4.707	-3.286
[Source=158.00]	-.501	.306	-1.635	.102	-1.102	9.975E-02
[Source=159.00]	-3.320	.349	-9.521	.000	-4.003	-2.636
[Source=165.00]	-8.468	.346	-24.500	.000	-9.145	-7.790
[Source=168.00]	-4.208	.595	-7.073	.000	-5.374	-3.042
[Source=169.00]	-5.612	.320	-17.525	.000	-6.240	-4.985
[Source=170.00]	-5.533	.432	-12.805	.000	-6.380	-4.686
[Source=315.00]	-1.993	.416	-4.793	.000	-2.809	-1.178
[Source=414.00]	-3.482	.398	-8.755	.000	-4.262	-2.702
[Source=497.00]	-7.573	.385	-19.689	.000	-8.327	-6.819
[Source=783.00]	4.215	.353	11.943	.000	3.523	4.906
[Source=911.00]	1.708	.332	5.148	.000	1.057	2.358
[Source=912.00]	6.890	.588	11.719	.000	5.738	8.043
[Source=924.00]	-8.695	.325	-26.762	.000	-9.332	-8.058
[Source=927.00]	5.055	.529	9.554	.000	4.018	6.093
[Source=928.00]	-4.874	.525	-9.290	.000	-5.902	-3.845
[Source=1414.00]	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Table A.5 ANOVA of Limestone Content (Continuous) Model

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	72447.538[a]	4	18111.885	584.380	.000
Intercept	13675237.2	1	13675237.213	441231.447	.000
Days-In-Service	28257.272	1	28257.272	911.721	.000
Days-In-Srvc^2	2201.169	1	2201.169	71.021	.000
Traffic Lane	8117.245	1	8117.245	261.903	.000
Lmstn Content	33871.851	1	33871.851	1092.875	.000
Error	240911.249	7773	30.993		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .231 (Adjusted R Squared = .231)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	54.180	.299	181.091	.000	53.594	54.767
Days-In-Srv	-1.082E-02	.001	-16.465	.000	-1.210E-02	-9.529E-03
D-N-Srv^2	4.057E-06	.000	9.193	.000	3.192E-06	4.922E-06
Traffic Lane	-2.564	.165	-15.514	.000	-2.887	-2.240
Lmstn Cntnt	-.122	.004	-33.059	.000	-.129	-.115

Table A.6 ANOVA of Limestone Content (Class) Model

Between-Subjects Factors

		Number of Skid Tests
Lmstn Content	14.00	48
	15.00	138
	19.00	34
	20.00	242
	24.00	60
	27.00	731
	30.00	1105
	31.00	30
	32.00	90
	33.00	143
	34.00	55
	35.00	135
	38.00	84
	39.00	53
	40.00	676
	44.00	48
	45.00	234
	47.00	72
	49.00	191
	50.00	513
	53.00	617
	55.00	60
	60.00	459
	64.00	198
	65.00	361
	66.00	150
	68.00	568
	70.00	144
	72.00	227
	74.00	72
	80.00	240

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	149734.692[a]	33	4537.415	214.747	.000
Intercept	13675237.2	1	13675237.213	647221.530	.000
Days-In-Srvc	28257.272	1	28257.272	1337.360	.000
D-N-Srvc^2	2201.169	1	2201.169	104.177	.000
Traffic Lane	8117.245	1	8117.245	384.173	.000
Lime%	111159.005	30	3705.300	175.364	.000
Error	163624.095	7744	21.129		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .478 (Adjusted R Squared = .476)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	44.572	.372	119.968	.000	43.844	45.301
Days-In-Srvc	-1.126E-02	.001	-20.500	.000	-1.234E-02	-1.018E-02
D-N-Srvc^2	4.623E-06	.000	12.545	.000	3.900E-06	5.345E-06
Traffic Lane	-2.549	.149	-17.120	.000	-2.840	-2.257
[Lime%=14.0]	10.539	.727	14.498	.000	9.114	11.963
[Lime%=15.0]	10.444	.491	21.254	.000	9.481	11.407
[Lime%=19.0]	14.562	.843	17.281	.000	12.910	16.214
[Lime%=20.0]	6.053	.419	14.442	.000	5.231	6.874
[Lime%=24.0]	5.658	.664	8.524	.000	4.357	6.959
[Lime%=27.0]	8.003	.346	23.099	.000	7.324	8.683
[Lime%=30.0]	5.977	.328	18.222	.000	5.334	6.620
[Lime%=31.0]	9.874	.890	11.092	.000	8.129	11.619
[Lime%=32.0]	5.078	.568	8.934	.000	3.964	6.192
[Lime%=33.0]	8.026	.486	16.509	.000	7.073	8.979
[Lime%=34.0]	2.641	.687	3.843	.000	1.294	3.988
[Lime%=35.0]	-3.516	.499	-7.047	.000	-4.494	-2.538
[Lime%=38.0]	4.717	.583	8.088	.000	3.574	5.860
[Lime%=39.0]	1.423	.698	2.040	.041	5.535E-02	2.791
[Lime%=40.0]	1.993	.346	5.754	.000	1.314	2.672
[Lime%=44.0]	5.041	.727	6.931	.000	3.615	6.467
[Lime%=45.0]	10.217	.427	23.936	.000	9.380	11.053
[Lime%=47.0]	14.462	.618	23.412	.000	13.251	15.673
[Lime%=49.0]	3.126	.449	6.956	.000	2.245	4.007
[Lime%=50.0]	1.207	.365	3.305	.001	.491	1.923
[Lime%=53.0]	-.477	.352	-1.358	.175	-1.166	.212
[Lime%=55.0]	5.184	.664	7.811	.000	3.883	6.485
[Lime%=60.0]	4.268	.367	11.617	.000	3.548	4.988
[Lime%=64.0]	8.310	.444	18.713	.000	7.439	9.180
[Lime%=65.0]	5.422	.384	14.137	.000	4.670	6.174
[Lime%=66.0]	4.218	.478	8.815	.000	3.280	5.156
[Lime%=68.0]	-1.980	.355	-5.575	.000	-2.676	-1.284
[Lime%=70.0]	-1.544	.485	-3.186	.001	-2.495	-.594
[Lime%=72.0]	1.333	.432	3.082	.002	.485	2.180
[Lime%=74.0]	6.300	.618	10.197	.000	5.089	7.511
[Lime%=80.0]	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Table A.7 ANOVA of Limestone Source and Content Main Effect Model

Between-Subjects Factors

		Number of Skid Tests
Lmstn Source	48.00	424
	134.00	491
	137.00	410
	141.00	54
	142.00	517
	147.00	451
	151.00	371
	152.00	228
	155.00	301
	158.00	611
	159.00	337
	165.00	348
	168.00	70
	169.00	526
	170.00	162
	315.00	186
	414.00	214
	497.00	240
	783.00	318
	911.00	433
	912.00	72
	924.00	486
	927.00	94
	928.00	96
	1414.00	338

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	157041.422[a]	28	5608.622	278.032	.000
Intercept	13675237.2	1	13675237.213	677911.971	.000
Days-In-Service	28257.272	1	28257.272	1400.776	.000
Days-In-Srvc^2	2201.169	1	2201.169	109.117	.000
Traffic Lane	8117.245	1	8117.245	402.390	.000
Lime%	33871.851	1	33871.851	1679.103	.000
Lmstn Source	84593.883	24	3524.745	174.729	.000
Error	156317.365	7749	20.173		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .501 (Adjusted R Squared = .499)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.
Intercept	55.144	.406	135.699	.000
Days-In-Service	-1.124E-02	.001	-20.884	.000
Days-In-Service^2	4.610E-06	.000	12.774	.000
Traffic Lane	-3.328	.146	-22.820	.000
Lime%	-8.828E-02	.010	-8.492	.000
[Source=48]	-.232	.470	-.494	.621
[Source=134]	-4.009	.407	-9.858	.000
[Source=137]	-7.324	.440	-16.639	.000
[Source=141]	-2.440	.692	-3.525	.000
[Source=142]	1.768	.517	3.420	.001
[Source=147]	-5.218	.349	-14.960	.000
[Source=151]	-3.529	.586	-6.022	.000
[Source=152]	.557	.392	1.420	.156
[Source=155]	-3.016	.379	-7.964	.000
[Source=158]	-.166	.308	-.540	.589
[Source=159]	-2.727	.354	-7.703	.000
[Source=165]	-8.062	.347	-23.210	.000
[Source=168]	-1.137	.694	-1.639	.101
[Source=169]	-2.655	.472	-5.623	.000
[Source=170]	-3.344	.501	-6.670	.000
[Source=315]	-1.218	.424	-2.873	.004
[Source=414]	-2.649	.408	-6.493	.000
[Source=497]	-2.739	.686	-3.992	.000
[Source=783]	5.790	.397	14.575	.000
[Source=911]	1.600	.330	4.841	.000
[Source=912]	8.811	.627	14.042	.000
[Source=924]	-4.854	.556	-8.730	.000
[Source=927]	4.427	.532	8.323	.000
[Source=928]	-1.273	.673	-1.892	.059
[Source=1414]	0[a]	.	.	.

Parameter Estimates

Dependent Variable: Skid Number

Parameter	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	54.347	55.941
Days-In-Service	-1.229E-02	-1.018E-02
Days-In-Service^2	3.903E-06	5.318E-06
Traffic Lane	-3.614	-3.042
Lime%	-.109	-6.790E-02
[Source=48]	-1.154	.690
[Source=134]	-4.806	-3.212
[Source=137]	-8.187	-6.461
[Source=141]	-3.797	-1.083
[Source=142]	.754	2.781
[Source=147]	-5.902	-4.534
[Source=151]	-4.678	-2.381
[Source=152]	-.212	1.326
[Source=155]	-3.759	-2.274
[Source=158]	-.769	.437
[Source=159]	-3.421	-2.033
[Source=165]	-8.743	-7.381
[Source=168]	-2.498	.223
[Source=169]	-3.581	-1.729
[Source=170]	-4.327	-2.361
[Source=315]	-2.049	-.387
[Source=414]	-3.448	-1.849
[Source=497]	-4.083	-1.394
[Source=783]	5.011	6.568
[Source=911]	.952	2.247
[Source=912]	7.581	10.041
[Source=924]	-5.944	-3.764
[Source=927]	3.384	5.470
[Source=928]	-2.591	4.599E-02
[Source=1414]	.	.

a. This parameter is set to zero because it is redundant.

Table A.8 ANOVA of 'Limestone Source and Content' Main and Joint Effects Model

Between-Subjects Factors

		Number of Skid Tests
Lmstn Source	48.00	424
	134.00	491
	137.00	410
	141.00	54
	142.00	517
	147.00	451
	151.00	371
	152.00	228
	155.00	301
	158.00	611
	159.00	337
	165.00	348
	168.00	70
	169.00	526
	170.00	162
	315.00	186
	414.00	214
	497.00	240
	783.00	318
	911.00	433
	912.00	72
	924.00	486
	927.00	94
	928.00	96
	1414.00	338

Tests of Between-Subjects Effects

Dependent Variable: Friction

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	175419.664[a]	45	3898.215	218.509	.000
Intercept	8826.029	1	8826.029	494.732	.000
Days-In-Service	9022.490	1	9022.490	505.744	.000
Days-In-Srvc^2	3369.739	1	3369.739	188.886	.000
Traffic Lane	12250.967	1	12250.967	686.712	.000
Lime%	3.187	1	3.187	.179	.673
Lmstn Source	17103.886	17	1006.111	56.396	.000
Lmstn Source * Lime%	18378.243	17	1081.073	60.598	.000
Error	137939.123	7732	17.840		
Total	13988596.000	7778			
Corrected Total	313358.787	7777			

a. R Squared = .560 (Adjusted R Squared = .557)

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	49.686	2.013	24.689	.000	45.741	53.631
Days-In-Service	-1.144E-02	.001	-22.489	.000	-1.244E-02	-1.044E-02
Days-In-Service^2	4.681E-06	.000	13.744	.000	4.013E-06	5.348E-06
Traffic Lane	-3.770	.144	-26.205	.000	-4.052	-3.488
Lime%	.141	.078	1.816	.069	-1.123E-02	.294
[Source=48.00]	5.454	2.465	2.213	.027	.622	10.285
[Source=134.00]	114.900	19.516	5.887	.000	76.643	153.158
[Source=137.00]	-242.442	15.955	-15.195	.000	-273.719	-211.166
[Source=141.00]	-6.787	1.659	-4.091	.000	-10.040	-3.535
[Source=142.00]	230.290	24.829	9.275	.000	181.617	278.962
[Source=147.00]	16.916	2.704	6.256	.000	11.615	22.217
[Source=151.00]	-85.625	16.304	-5.252	.000	-117.587	-53.664
[Source=152.00]	-.343	.521	-.658	.510	-1.363	.678
[Source=155.00]	17.574	2.745	6.402	.000	12.193	22.955
[Source=158.00]	8.324	2.269	3.669	.000	3.876	12.771
[Source=159.00]	-56.693	5.157	-10.993	.000	-66.803	-46.583
[Source=165.00]	12.007	2.338	5.137	.000	7.425	16.589
[Source=168.00]	-8.938	2.763	-3.235	.001	-14.354	-3.522
[Source=169.00]	2.244	2.442	.919	.358	-2.543	7.031
[Source=170.00]	-8.994	1.963	-4.581	.000	-12.843	-5.146
[Source=315.00]	1.485	2.518	.590	.555	-3.450	6.420
[Source=414.00]	-4.183	2.364	-1.769	.077	-8.818	.451
[Source=497.00]	-15.137	4.279	-3.537	.000	-23.525	-6.749
[Source=783.00]	8.394	2.212	3.794	.000	4.057	12.730
[Source=911.00]	8.035	2.101	3.824	.000	3.916	12.155
[Source=912.00]	3.992	1.781	2.242	.025	.502	7.483
[Source=924.00]	-66.711	6.038	-11.049	.000	-78.546	-54.875
[Source=927.00]	25.391	4.221	6.016	.000	17.117	33.665
[Source=928.00]	-10.450	3.211	-3.254	.001	-16.745	-4.155
[Source=1414.00]	0[a]	.	.	.	.	.
[Source=48.00] * Lime%	-.226	.082	-2.760	.006	-.387	-6.551E-02
[Source=134.00] * Lime%	-2.510	.399	-6.292	.000	-3.292	-1.728
[Source=137.00] * Lime%	4.292	.308	13.953	.000	3.689	4.895
[Source=141.00] * Lime%	0[a]	.	.	.	.	.
[Source=142.00] * Lime%	-3.675	.391	-9.398	.000	-4.442	-2.909
[Source=147.00] * Lime%	-.659	.091	-7.213	.000	-.838	-.480
[Source=151.00] * Lime%	1.005	.239	4.201	.000	.536	1.474
[Source=152.00] * Lime%	0[a]	.	.	.	.	.
[Source=155.00] * Lime%	-.632	.094	-6.754	.000	-.816	-.449
[Source=158.00] * Lime%	-.320	.086	-3.696	.000	-.489	-.150
[Source=159.00] * Lime%	1.641	.168	9.766	.000	1.311	1.970
[Source=165.00] * Lime%	-.707	.088	-8.056	.000	-.879	-.535
[Source=168.00] * Lime%	0[a]	.	.	.	.	.
[Source=169.00] * Lime%	-.211	.082	-2.589	.010	-.371	-5.126E-02

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
[Source=170.00] * Lime%	0[a]	.	.	.	.	.
[Source=315.00] * Lime%	-.133	.090	-1.477	.140	-.309	4.340E-02
[Source=414.00] * Lime%	-1.297E-02	.086	-.151	.880	-.181	.155
[Source=497.00] * Lime%	0[a]	.	.	.	.	.
[Source=783.00] * Lime%	-.155	.081	-1.911	.056	-.313	3.961E-03
[Source=911.00] * Lime%	-.249	.083	-3.005	.003	-.411	-8.645E-02
[Source=912.00] * Lime%	0[a]	.	.	.	.	.
[Source=924.00] * Lime%	.758	.114	6.663	.000	.535	.981
[Source=927.00] * Lime%	-1.060	.219	-4.828	.000	-1.490	-.629
[Source=928.00] * Lime%	0[a]	.	.	.	.	.
[Source=1414.00] * Lime%	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Table A.9 ANOVA of Limestone Source Main Effect and Content Interaction Model

Between-Subjects Factors

		Number of Skid Tests
Lmstn Source	48.00	424
	134.00	491
	137.00	410
	141.00	54
	142.00	517
	147.00	451
	151.00	371
	152.00	228
	155.00	301
	158.00	611
	159.00	337
	165.00	348
	168.00	70
	169.00	526
	170.00	162
	315.00	186
	414.00	214
	497.00	240
	783.00	318
	911.00	433
	912.00	72
	924.00	486
	927.00	94
	928.00	96
	1414.00	338

Tests of Between-Subjects Effects

Dependent Variable: Friction

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	175419.664[a]	45	3898.215	218.509	.000
Intercept	13675237.2	1	13675237.213	766547.823	.000
Days-In-Service	28257.272	1	28257.272	1583.925	.000
Days-In-Srvc^2	2201.169	1	2201.169	123.384	.000
Traffic Lane	8117.245	1	8117.245	455.002	.000
Lmstn Source	117010.945	24	4875.456	273.287	.000
Lmstn Source * Lime%	19833.033	18	1101.835	61.762	.000
Error	137939.123	7732	17.840		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .560 (Adjusted R Squared = .557)

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	49.686	2.013	24.689	.000	45.741	53.631
Days-In-Service	-1.144E-02	.001	-22.489	.000	-1.244E-02	-1.044E-02
Days-In-Srvc^2	4.681E-06	.000	13.744	.000	4.013E-06	5.348E-06
Traffic Lane	-3.770	.144	-26.205	.000	-4.052	-3.488
[Source=48.00]	5.454	2.465	2.213	.027	.622	10.285
[Source=134.00]	114.900	19.516	5.887	.000	76.643	153.158
[Source=137.00]	-242.442	15.955	-15.195	.000	-273.719	-211.166
[Source=141.00]	-.422	2.062	-.205	.838	-4.465	3.621
[Source=142.00]	230.290	24.829	9.275	.000	181.617	278.962
[Source=147.00]	16.916	2.704	6.256	.000	11.615	22.217
[Source=151.00]	-85.625	16.304	-5.252	.000	-117.587	-53.664
[Source=152.00]	3.901	2.000	1.950	.051	-2.044E-02	7.822
[Source=155.00]	17.574	2.745	6.402	.000	12.193	22.955
[Source=158.00]	8.324	2.269	3.669	.000	3.876	12.771
[Source=159.00]	-56.693	5.157	-10.993	.000	-66.803	-46.583
[Source=165.00]	12.007	2.338	5.137	.000	7.425	16.589
[Source=168.00]	-.451	2.044	-.221	.825	-4.459	3.557
[Source=169.00]	2.244	2.442	.919	.358	-2.543	7.031
[Source=170.00]	-1.922	2.014	-.954	.340	-5.870	2.027
[Source=315.00]	1.485	2.518	.590	.555	-3.450	6.420
[Source=414.00]	-4.183	2.364	-1.769	.077	-8.818	.451
[Source=497.00]	-3.820	2.000	-1.910	.056	-7.741	9.975E-02
[Source=783.00]	8.394	2.212	3.794	.000	4.057	12.730
[Source=911.00]	8.035	2.101	3.824	.000	3.916	12.155
[Source=912.00]	10.641	2.043	5.208	.000	6.636	14.645
[Source=924.00]	-66.711	6.038	-11.049	.000	-78.546	-54.875
[Source=927.00]	25.391	4.221	6.016	.000	17.117	33.665
[Source=928.00]	-1.115	2.027	-.550	.583	-5.089	2.860
[Source=1414.00]	0[a]	.	.	.	.	.
[Source=48.00] * Lime%	-8.471E-02	.025	-3.400	.001	-.134	-3.587E-02
[Source=134.00] * Lime%	-2.368	.392	-6.049	.000	-3.136	-1.601
[Source=137.00] * Lime%	4.433	.297	14.948	.000	3.852	5.014
[Source=141.00] * Lime%	0[a]	.	.	.	.	.
[Source=142.00] * Lime%	-3.534	.383	-9.229	.000	-4.284	-2.783
[Source=147.00] * Lime%	-.518	.049	-10.604	.000	-.614	-.422
[Source=151.00] * Lime%	1.147	.228	5.036	.000	.700	1.593
[Source=152.00] * Lime%	0[a]	.	.	.	.	.
[Source=155.00] * Lime%	-.491	.052	-9.435	.000	-.593	-.389
[Source=158.00] * Lime%	-.178	.037	-4.873	.000	-.250	-.106
[Source=159.00] * Lime%	1.782	.148	12.052	.000	1.492	2.072
[Source=165.00] * Lime%	-.565	.042	-13.613	.000	-.647	-.484
[Source=168.00] * Lime%	0[a]	.	.	.	.	.
[Source=169.00] * Lime%	-6.959E-02	.024	-2.875	.004	-.117	-2.214E-02
[Source=170.00] * Lime%	0[a]	.	.	.	.	.

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	Upper Bound
[Source=315.00] * Lime%	8.665E-03	.045	.193	.847	-7.932E-02	9.665E-02
[Source=414.00] * Lime%	.128	.036	3.544	.000	5.742E-02	.200
[Source=497.00] * Lime%	0[a]	.	.	.	.	.
[Source=783.00] * Lime%	-1.315E-02	.022	-.598	.550	-5.628E-02	2.997E-02
[Source=911.00] * Lime%	-.107	.028	-3.813	.000	-.162	-5.209E-02
[Source=912.00] * Lime%	0[a]	.	.	.	.	.
[Source=924.00] * Lime%	.900	.083	10.841	.000	.737	1.063
[Source=927.00] * Lime%	-.918	.205	-4.475	.000	-1.320	-.516
[Source=928.00] * Lime%	0[a]	.	.	.	.	.
[Source=1414.00] * Lime%	.141	.078	1.816	.069	-1.123E-02	.294

a. This parameter is set to zero because it is redundant.

Table A.10 ANOVA of BPN(9) (Continuous) Model

Tests of Between-Subjects Effects

Dependent Variable: Friction

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	53787.195[a]	4	13446.799	402.671	.000
Intercept	13675237.2	1	13675237.213	409511.757	.000
Days-In-Service	28257.272	1	28257.272	846.178	.000
Days-In-Srvc^2	2201.169	1	2201.169	65.915	.000
Traffic Lane	8117.245	1	8117.245	243.075	.000
BPN(9)	15211.508	1	15211.508	455.516	.000
Error	259571.592	7773	33.394		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .172 (Adjusted R Squared = .171)

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	56.235	.433	129.769	.000	55.385	57.084
D-N-Srvc	-1.159E-02	.001	-16.997	.000	-1.292E-02	-1.025E-02
D-N-Srv^2	4.534E-06	.000	9.893	.000	3.636E-06	5.432E-06
Traffic Lane	-2.618	.172	-15.266	.000	-2.954	-2.282
BPN(9)	-.307	.014	-21.343	.000	-.336	-.279

Table A.11 ANOVA of BPN(9) (Class) Model

Between-Subjects Factors

		Number of Skid Tests
BPN(9)	18.0	228
	19.0	675
	20.0	920
	21.0	665
	22.0	893
	23.0	995
	24.0	875
	26.0	622
	27.0	72
	28.0	658
	30.0	371
	33.0	318
	35.0	486

Tests of Between-Subjects Effects

Dependent Variable: Friction

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	124731.010[a]	15	8315.401	342.177	.000
Intercept	13675237.2	1	13675237.213	562733.619	.000
Days-In-Service	28257.272	1	28257.272	1162.782	.000
Days-In-Srvc^2	2201.169	1	2201.169	90.578	.000
Traffic Lane	8117.245	1	8117.245	334.023	.000
BPN(9)	86155.324	12	7179.610	295.440	.000
Error	188627.776	7762	24.301		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .398 (Adjusted R Squared = .397)

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	43.792	.324	135.334	.000	43.158	44.426
Days-In-Srvc	-1.100E-02	.001	-18.727	.000	-1.216E-02	-9.853E-03
D-In-Srvc^2	4.500E-06	.000	11.393	.000	3.726E-06	5.275E-06
Traffic Lane	-2.976	.155	-19.170	.000	-3.281	-2.672
[BPN9=18.0]	8.821	.397	22.217	.000	8.043	9.599
[BPN9=19.0]	7.120	.298	23.925	.000	6.537	7.704
[BPN9=20.0]	7.786	.278	28.023	.000	7.241	8.330
[BPN9=21.0]	7.964	.297	26.788	.000	7.381	8.547
[BPN9=22.0]	5.928	.281	21.066	.000	5.377	6.480
[BPN9=23.0]	2.214	.280	7.905	.000	1.665	2.762
[BPN9=24.0]	4.017	.283	14.200	.000	3.462	4.571
[BPN9=26.0]	3.192	.301	10.613	.000	2.602	3.782
[BPN9=27.0]	15.585	.623	25.004	.000	14.364	16.807
[BPN9=28.0]	1.066	.298	3.572	.000	.481	1.650
[BPN9=30.0]	1.197	.344	3.484	.000	.524	1.871
[BPN9=33.0]	13.006	.361	36.039	.000	12.299	13.714
[BPN9=35.0]	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Table A.12 ANOVA of BPN(9) and Limestone Content (Continuous) Main Effect Model

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	72865.405[a]	5	14573.081	470.957	.000
Intercept	13675237.2	1	13675237.213	441941.241	.000
Days-In-Service	28257.272	1	28257.272	913.187	.000
Days-In-Srvc^2	2201.169	1	2201.169	71.135	.000
Traffic Lane	8117.245	1	8117.245	262.324	.000
BPN(9)	15211.508	1	15211.508	491.589	.000
Lime%	19078.210	1	19078.210	616.549	.000
Error	240493.382	7772	30.944		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .233 (Adjusted R Squared = .232)

Parameter Estimates

Dependent Variable: Skid Number

					95% Confidence Interval	
Parameter	B	Std. Error	t	Sig.	Lower Bound	Upper Bound
Intercept	55.259	.419	131.887	.000	54.438	56.080
Day-In-Srvc	-1.091E-02	.001	-16.602	.000	-1.219E-02	-9.618E-03
D-N-Srv^2	4.132E-06	.000	9.360	.000	3.267E-06	4.997E-06
Traffic Lane	-2.561	.165	-15.511	.000	-2.885	-2.237
BPN(9)	-6.251E-02	.017	-3.675	.000	-9.586E-02	-2.917E-02
Lime%	-.112	.005	-24.830	.000	-.121	-.103

Table A.13 ANOVA of 'BPN(9) and Limestone Content (Continuous)' Main and Joint Effects Model

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	72874.541[a]	6	12145.757	392.478	.000
Intercept	13675237.2	1	13675237.213	441901.165	.000
Days-In-Service	28257.272	1	28257.272	913.105	.000
Days-In-Srvc^2	2201.169	1	2201.169	71.129	.000
Traffic Lane	8117.245	1	8117.245	262.300	.000
BPN(9)	15211.508	1	15211.508	491.544	.000
Lime%	19078.210	1	19078.210	616.493	.000
BPN(9) * Lime%	9.136	1	9.136	.295	.587
Error	240484.246	7771	30.946		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .233 (Adjusted R Squared = .232)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	54.694	1.120	48.830	.000	52.499	56.890
Days-In-Srvc	-1.093E-02	.001	-16.593	.000	-1.223E-02	-9.642E-03
Days-In-Srv^2	4.153E-06	.000	9.371	.000	3.284E-06	5.022E-06
Traffic Lane	-2.547	.167	-15.239	.000	-2.875	-2.219
BPN(9)	-3.869E-02	.047	-.823	.411	-.131	5.349E-02
Lime%	-.101	.022	-4.670	.000	-.143	-5.850E-02
BPN(9) * Lime%	-4.702E-04	.001	-.543	.587	-2.167E-03	1.226E-03

Table A14 ANOVA of BPN(9) (Class) and Limestone Content (Continuous) Main Effect Model

Between-Subjects Factors

		Number of Skid Tests
BPN(9)	18.0	228
	19.0	675
	20.0	920
	21.0	665
	22.0	893
	23.0	995
	24.0	875
	26.0	622
	27.0	72
	28.0	658
	30.0	371
	33.0	318
	35.0	486

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	126688.614[a]	16	7918.038	329.200	.000
Intercept	13675237.2	1	13675237.213	568561.728	.000
Days-In-Service	28257.272	1	28257.272	1174.824	.000
Days-In-Srvc^2	2201.169	1	2201.169	91.516	.000
Traffic Lane	8117.245	1	8117.245	337.483	.000
BPN(9)	86155.324	12	7179.610	298.500	.000
Lime%	1957.604	1	1957.604	81.389	.000
Error	186670.173	7761	24.052		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .404 (Adjusted R Squared = .403)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	46.910	.472	99.312	.000	45.985	47.836
Days-In-Srvc	-1.098E-02	.001	-18.776	.000	-1.212E-02	-9.831E-03
Day-In-Srv^2	4.463E-06	.000	11.356	.000	3.692E-06	5.233E-06
Traffic Lane	-2.930	.155	-18.958	.000	-3.233	-2.627
[BPN9=18.0]	7.038	.442	15.935	.000	6.172	7.904
[BPN9=19.0]	5.286	.359	14.720	.000	4.582	5.990
[BPN9=20.0]	6.003	.340	17.670	.000	5.337	6.669
[BPN9=21.0]	6.208	.354	17.531	.000	5.513	6.902
[BPN9=22.0]	5.294	.289	18.339	.000	4.728	5.860
[BPN9=23.0]	1.282	.297	4.315	.000	.700	1.864
[BPN9=24.0]	3.044	.301	10.102	.000	2.454	3.635
[BPN9=26.0]	2.778	.303	9.177	.000	2.185	3.371
[BPN9=27.0]	14.583	.630	23.147	.000	13.348	15.818
[BPN9=28.0]	.272	.310	.878	.380	-.335	.878
[BPN9=30.0]	1.326	.342	3.875	.000	.655	1.997
[BPN9=33.0]	11.840	.382	31.025	.000	11.092	12.588
[BPN9=35.0]	0[a]	.	.	.	.	.
Lime%	-4.599E-02	.005	-9.022	.000	-5.598E-02	-3.600E-02

a. This parameter is set to zero because it is redundant.

Table A15 ANOVA of 'BPN(9) (Class) and Limestone Content (Continuous)' Main and Joint Effects Model

Between-Subjects Factors

		Number of Skid Tests
BPN(9)	18.0	228
	19.0	675
	20.0	920
	21.0	665
	22.0	893
	23.0	995
	24.0	875
	26.0	622
	27.0	72
	28.0	658
	30.0	371
	33.0	318
	35.0	486

Tests of Between-Subjects Effects

Dependent Variable: Skid Number

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	151184.059[a]	26	5814.772	277.912	.000
Intercept	13675237.2	1	13675237.213	653596.064	.000
Days-In-Service	28257.272	1	28257.272	1350.532	.000
Days-In-Srvc^2	2201.169	1	2201.169	105.203	.000
Traffic Lane	8117.245	1	8117.245	387.957	.000
BPN(9)	86155.324	12	7179.610	343.143	.000
Lime%	1957.604	1	1957.604	93.562	.000
BPN(9) * Lime%	24495.445	10	2449.544	117.074	.000
Error	162174.728	7751	20.923		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .482 (Adjusted R Squared = .481)

Parameter Estimates

Dependent Variable: Skid Number

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	-17.925	6.181	-2.900	.004	-30.042	-5.809
Days-In-Service	-1.131E-02	.001	-20.648	.000	-1.239E-02	-1.024E-02
Days-In-Service^2	4.682E-06	.000	12.735	.000	3.961E-06	5.402E-06
Traffic Lane	-3.115	.149	-20.957	.000	-3.406	-2.823
[BPN9=18.0]	43.713	3.496	12.504	.000	36.860	50.566
[BPN9=19.0]	73.602	6.301	11.681	.000	61.251	85.954
[BPN9=20.0]	78.055	6.201	12.588	.000	65.900	90.211
[BPN9=21.0]	76.355	6.240	12.236	.000	64.123	88.588
[BPN9=22.0]	63.555	6.212	10.232	.000	51.379	75.732
[BPN9=23.0]	83.301	6.218	13.396	.000	71.112	95.491
[BPN9=24.0]	62.976	6.211	10.140	.000	50.801	75.151
[BPN9=26.0]	67.986	6.350	10.706	.000	55.538	80.433
[BPN9=27.0]	35.131	2.033	17.284	.000	31.146	39.115
[BPN9=28.0]	62.653	6.191	10.119	.000	50.516	74.789
[BPN9=30.0]	-29.484	18.599	-1.585	.113	-65.943	6.974
[BPN9=33.0]	75.367	6.267	12.025	.000	63.081	87.653
[BPN9=35.0]	0[a]	.	.	.	.	.
Lime%	.902	.090	10.036	.000	.726	1.078
[BPN9=18.0] * Lime%	0[a]	.	.	.	.	.
[BPN9=19.0] * Lime%	-1.062	.100	-10.655	.000	-1.257	-.866
[BPN9=20.0] * Lime%	-1.179	.092	-12.877	.000	-1.359	-1.000
[BPN9=21.0] * Lime%	-1.115	.094	-11.826	.000	-1.300	-.930
[BPN9=22.0] * Lime%	-.824	.091	-9.086	.000	-1.001	-.646
[BPN9=23.0] * Lime%	-1.301	.091	-14.279	.000	-1.479	-1.122
[BPN9=24.0] * Lime%	-.840	.091	-9.242	.000	-1.018	-.662
[BPN9=26.0] * Lime%	-.950	.093	-10.193	.000	-1.132	-.767
[BPN9=27.0] * Lime%	0[a]	.	.	.	.	.
[BPN9=28.0] * Lime%	-.895	.090	-9.928	.000	-1.072	-.719
[BPN9=30.0] * Lime%	.398	.262	1.517	.129	-.116	.912
[BPN9=33.0] * Lime%	-.913	.093	-9.813	.000	-1.095	-.730
[BPN9=35.0] * Lime%	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Table A16 ANOVA of 'Sand (Continuous)' Main Effect Model

Tests of Between-Subjects Effects

Dependent Variable: Friction

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	71734.426[a]	4	17933.607	576.920	.000
Intercept	13675237.2	1	13675237.213	439929.230	.000
DAYS	28257.272	1	28257.272	909.030	.000
DAYS2	2201.169	1	2201.169	70.811	.000
TRF_LANE	8117.245	1	8117.245	261.130	.000
SAND	33158.739	1	33158.739	1066.709	.000
Error	241624.361	7773	31.085		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .229 (Adjusted R Squared = .229)

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	42.533	.319	133.522	.000	41.909	43.158
DAYS	-1.162E-02	.001	-17.659	.000	-1.290E-02	-1.033E-02
DAYS2	4.629E-06	.000	10.471	.000	3.763E-06	5.496E-06
TRF_LANE	-2.684	.165	-16.224	.000	-3.009	-2.360
SAND	.295	.009	32.661	.000	.277	.313

Table A17 ANOVA of Sand (Class) Main Effect Model

Between-Subjects Factors

		N
SAND	10.0	108
	14.0	410
	15.0	432
	16.0	109
	17.0	546
	18.0	582
	19.0	389
	20.0	3617
	25.0	618
	30.0	168
	35.0	523
	40.0	183
	57.0	93

Tests of Between-Subjects Effects

Dependent Variable: Friction

Source	Type I Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	122452.779[a]	15	8163.519	331.918	.000
Intercept	13675237.2	1	13675237.213	556018.075	.000
DAYS	28257.272	1	28257.272	1148.905	.000
DAYS2	2201.169	1	2201.169	89.497	.000
TRF_LANE	8117.245	1	8117.245	330.037	.000
SAND	83877.092	12	6989.758	284.195	.000
Error	190906.008	7762	24.595		
Total	13988596.0	7778			
Corrected Total	313358.787	7777			

a. R Squared = .391 (Adjusted R Squared = .390)

Parameter Estimates

Dependent Variable: Friction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	57.697	.559	103.260	.000	56.602	58.793
DAYS	-1.181E-02	.001	-20.099	.000	-1.297E-02	-1.066E-02
DAYS2	4.983E-06	.000	12.604	.000	4.208E-06	5.758E-06
TRF_LANE	-3.470	.155	-22.435	.000	-3.773	-3.166
[SAND=10.0]	-13.735	.702	-19.559	.000	-15.111	-12.358
[SAND=14.0]	-14.324	.573	-25.019	.000	-15.446	-13.202
[SAND=15.0]	-9.833	.569	-17.284	.000	-10.948	-8.718
[SAND=16.0]	-13.559	.704	-19.255	.000	-14.939	-12.179
[SAND=17.0]	-10.485	.561	-18.700	.000	-11.585	-9.386
[SAND=18.0]	-13.844	.555	-24.945	.000	-14.932	-12.756
[SAND=19.0]	-7.802	.574	-13.584	.000	-8.928	-6.676
[SAND=20.0]	-7.166	.522	-13.736	.000	-8.189	-6.143
[SAND=25.0]	-4.834	.552	-8.756	.000	-5.916	-3.752
[SAND=30.0]	-15.493	.644	-24.052	.000	-16.755	-14.230
[SAND=35.0]	-5.591	.560	-9.982	.000	-6.689	-4.493
[SAND=40.0]	-.403	.638	-.632	.528	-1.653	.847
[SAND=57.0]	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

APPENDIX B – OMITTED

APPENDIX C – BPN(9) SIGNIFICANT FACTOR PAIRINGS

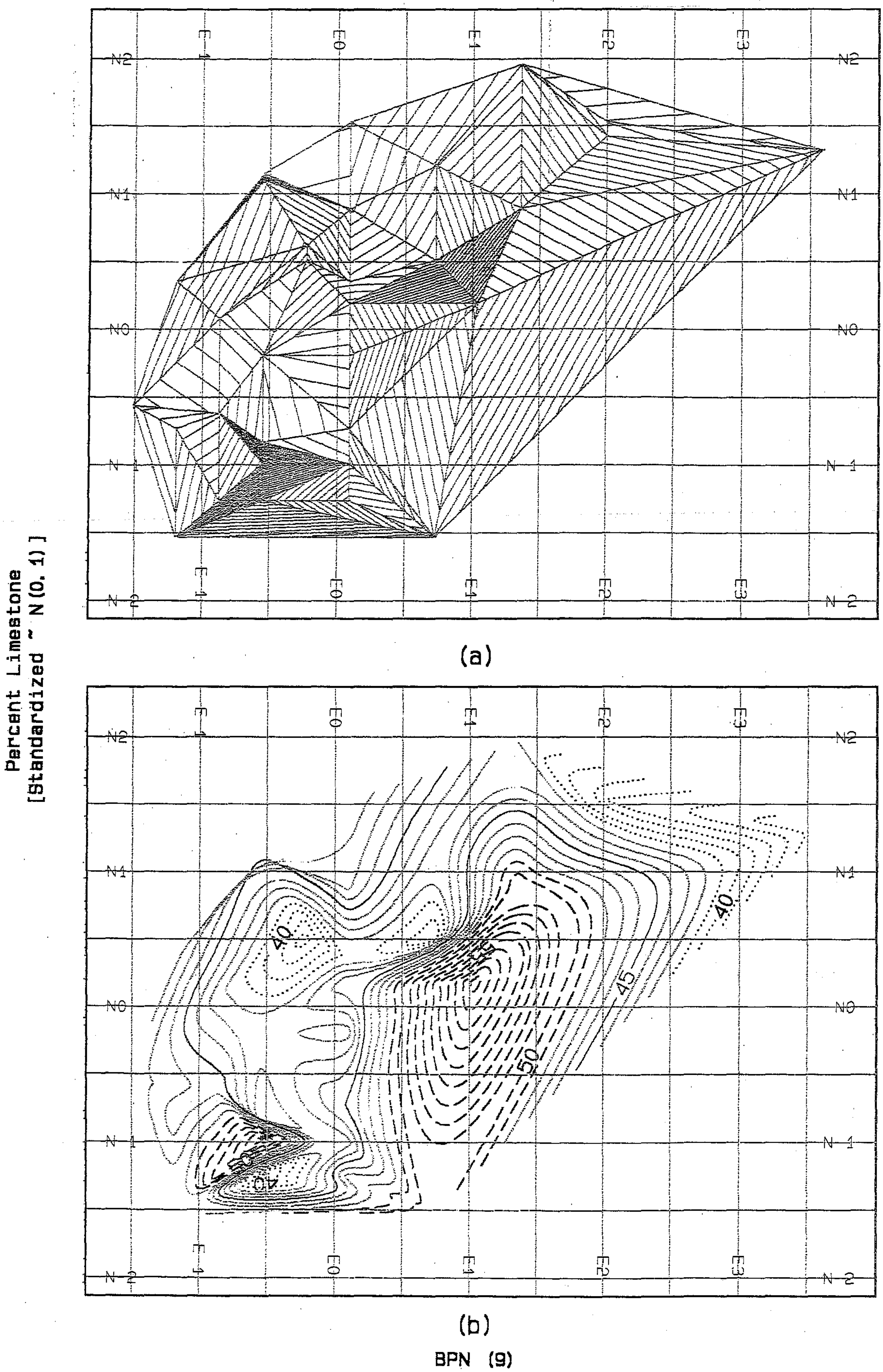


FIG C.1 Skid Number Contours as a Function of Percent Limestone and BPN (9) (a) Triangulation of Initial Data (32 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating ~~FN~~ > ~~49~~ (704 obs ~~run on 9~~/22/96).
(Copy FIG. 1 from ~~November 1999 Report)~~

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **BPN(9)** measures the residual friction characteristics of limestone coarse aggregate after 9 hours of polishing.

Concept: This plot contrasts limestone content with the wear resistant characteristics of limestone. Limestone is an aggregate known to lose surface texture when placed under wearing conditions that polish exposed surfaces. BPN(9) represents the ability of limestone to withstand surface polishing actions.

Data: There are 47 plotted interaction points between Percent Limestone and BPN(9) values, each point representing from 3 to 74 friction test observations with average friction numbers from 34.9 to 59.3. Percent Limestone ranges from 14.0 to 80.0 and BPN(9) ranges from 18 to 35. Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values show no general relationship to changes in Percent Limestone or BPN(9) values.

Joint Effects: When pavements have higher limestone content the observed friction performance is generally higher with higher BPN(9) values. However, the friction performance of the pavement is poor when both Limestone content and BPN(9) are pushed to the extreme highregions. In the extreme low regions of both factors, the friction performance is observed to be both excellent and poor with nearly identical values for the two factors.

Anomalies: Atypical friction values labeled as <Percent Limestone (stdzd), BPN(9) (stdzd), and Friction Number> exist at <-1.63, 0.57, 50.89>; <-1.34, -0.80, 51.60>; <-1.34, -0.52, 37.40>; <-0.88, -0.52, 40.5>; <-0.76, 1.12, 40.71>; <-0.19, -1.07, 40.3>; <0.56, -0.25, 37.5>; <0.56, 0.57, 39.09>; and <0.67, -0.25, 38.9>.

INTERPRETATION

Significance: Generally, pavement friction values remain high with high limestone content when there is a correspondingly high BPN(9) value. However, this doesn't hold true in the most extreme case of high limestone content.

Future Action: The area of low friction that exists with high limestone and high BPN(9) values should be investigated further to see what other factor may be contributing to these low numbers. Very likely the reason for this may be due to low sand content in these pavements.

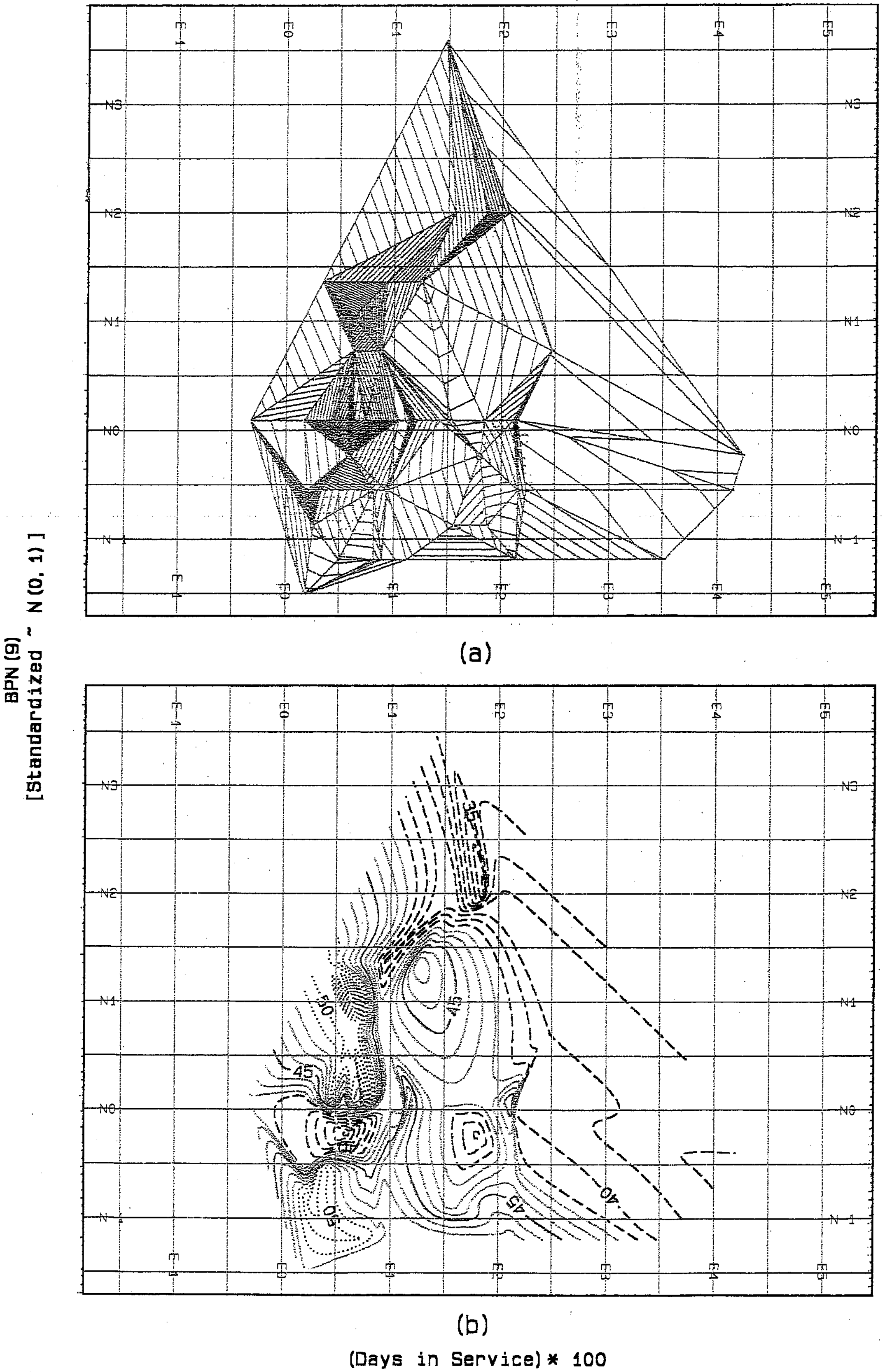


FIG. C.2 ~~Skid Number Contours as a Function of BPN (9) and~~ Days in Service (a) Triangulation of Initial Data (48 pts) (b) Contours ~~with Dotted Lines Indicating FN < 41 and Dashed~~ Lines Indicating ~~FN > 42~~ (704 obs ~~run on~~ 10/16/98).
(Copy FIG. 17 ~~from November 1999 Report.)~~

DESCRIPTION

Factors: **BPN(9)** measures the residual friction characteristics of limestone coarse aggregate after 9 hours of polishing. **Days-in-Service** is the total number of elapsed calendar days between pavement construction and skid test.

Concept: BPN(9) measures the residual texture on the exposed surface of the limestone aggregate after extended wear. Days-in-service measures the number of days the pavement surface has been exposed to service loads and the relative age of pavement materials.

Data: There are 49 interaction points between BPN (9) and Days In Service, each point representing from 2 to 69 test observations with average friction values from 31.5 to 59.33. BPN (9) ranges from 19 to 35 (plotted from -1.51to 3.67) and Days In Service from -33 (error) to 424. BPN(9) plotted as a standardized value.

RESULTS

Main Effects: Plotted friction values associated with BPN(9) exhibit no single distinctive trend but rather reflect banded performance characteristics around certain BPN(9) values. In relation to days in service, pavement friction performance is best after a being inservice a short period and then generally decreases as the pavement ages although the pattern is somewhat inconsistent.

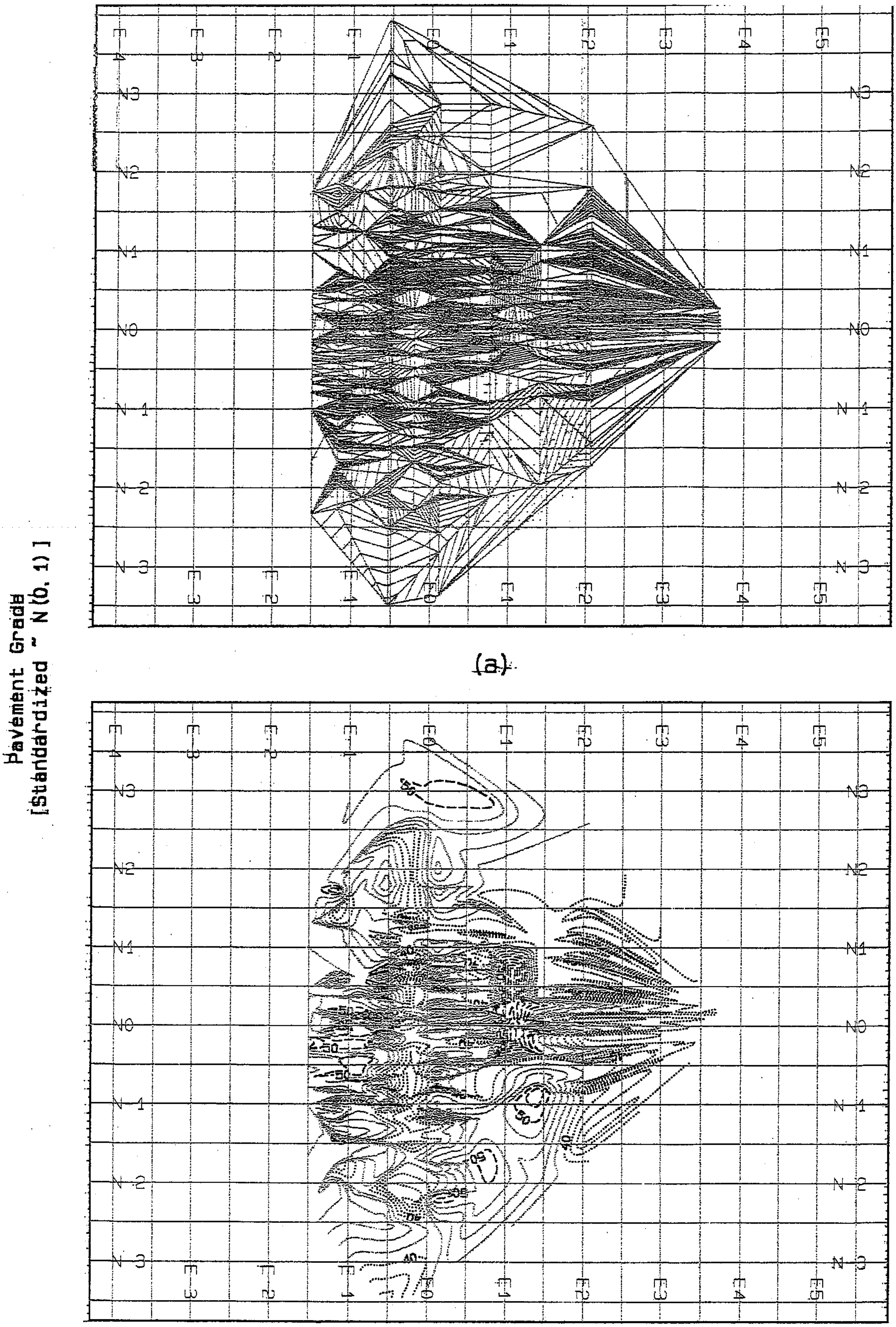
Joint Effects: Pavements made with high BPN(9) aggregates have generally lower friction performance while pavements from extremely low BPN(9) aggregate perform adequately even after significant service.

Anomalies: No atypical friction values exist.

INTERPRETATION

Significance: This plot reflects the commonly-held belief that pavements perform better after being in service for a short time period. Also, notice the significant performance bands evident around certain BPN(9) values and the relatively good friction performance obtained with low BPN(9) value pavements relative to pavement age.

Future Action: More observations need to be captured relating pavement age to BPN(9) value, especially at high BPN(9) values where there is currently only one days-in-service value is reflected. The performance banding at certain BPN(9) values should be investigated further.



BPN (9)
[Standardized ~ N(0, 1)]

FIG. C.3 Skid Number Contours as a Function of BPN(9) and Pavement Grade (a) Triangulation of Initial Data (554 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (743 obs run on 9/22/96).
(Copy FIG. 20 for November 1999 Report)

DESCRIPTION

Factors: **Pavement Grade** is the slope of the pavement surface in the direction of travel relating the vertical rise (+) or fall (-) as a percentage of horizontal distance. **BPN(9)** measures the residual friction characteristics of limestone coarse aggregate after 9 hours of polishing.

Concept: Grade corresponds with the different wearing actions caused by the tire-pavement interaction in moving the vehicle uphill, coasting (free rolling), or braking on downhill grades. BPN(9) measures the residual texture on the exposed surface of the limestone aggregate after extended wear.

Data: There are 573 interaction points between Pavement Grade and BPN(9), each point representing from 1 to 9 test observations with average friction values from 28 to 61. Pavement Grade ranges from -7.82 to 9.1 and BPN(9) from 19 to 35. Both factors are plotted as stanardized values.

RESULTS

Main Effects: Plotted friction values tend to be highest within typical regions of grade and have noticeable bands of poor friction performance at plotted values of BPN(9) from -0.5 to 0.00 and above 2.00 (actual BPN(9) values from 22 to 23 and above 30).

Joint Effects: The is no apparent joint effect between these two factors.

Anomalies: Atypical friction values plotted as standardized values for <Pavement Grade (stdzd), BPN (9) (stdzd), Friction Number> exist at <-3.48, -0.53, 35>; <2.16, 0.11, 54>; <-2.05, -0.53, 35>; <-1.76, -1.18, 36>; <-1.67, -0.21, 41>; <-1.24, -1.18, 37>; <-0.81,2.06, 30>; <-0.77, 0.11, 56>; <-0.26, -0.53, 40>; <-0.05, 0.11, 55>; <-0.004, 0.11, 53>; <0.45, 0.11, 56>; <0.50, -0.53, 57>; <0.59, -1.18, 33>; <0.62, -0.21, 28>; <0.75, 0.11, 55>; <1.32, -0.21, 45>; <1.49, -1.18, 35>; and <2.45, -0.53, 35.5>.

INTERPRETATION

Significance: The noticable bands of good and poor friction performance suggest an external factor to this plot is controlling the observed values.

Future Action: The relatively large, undisturbed area of good friction performance at flat grades when associated with BPN(9) values that are plotted from approximately 0.9 to 1.3 should be investigated more closely. Also, some observations should be made with high BPN(9) values and high grades.

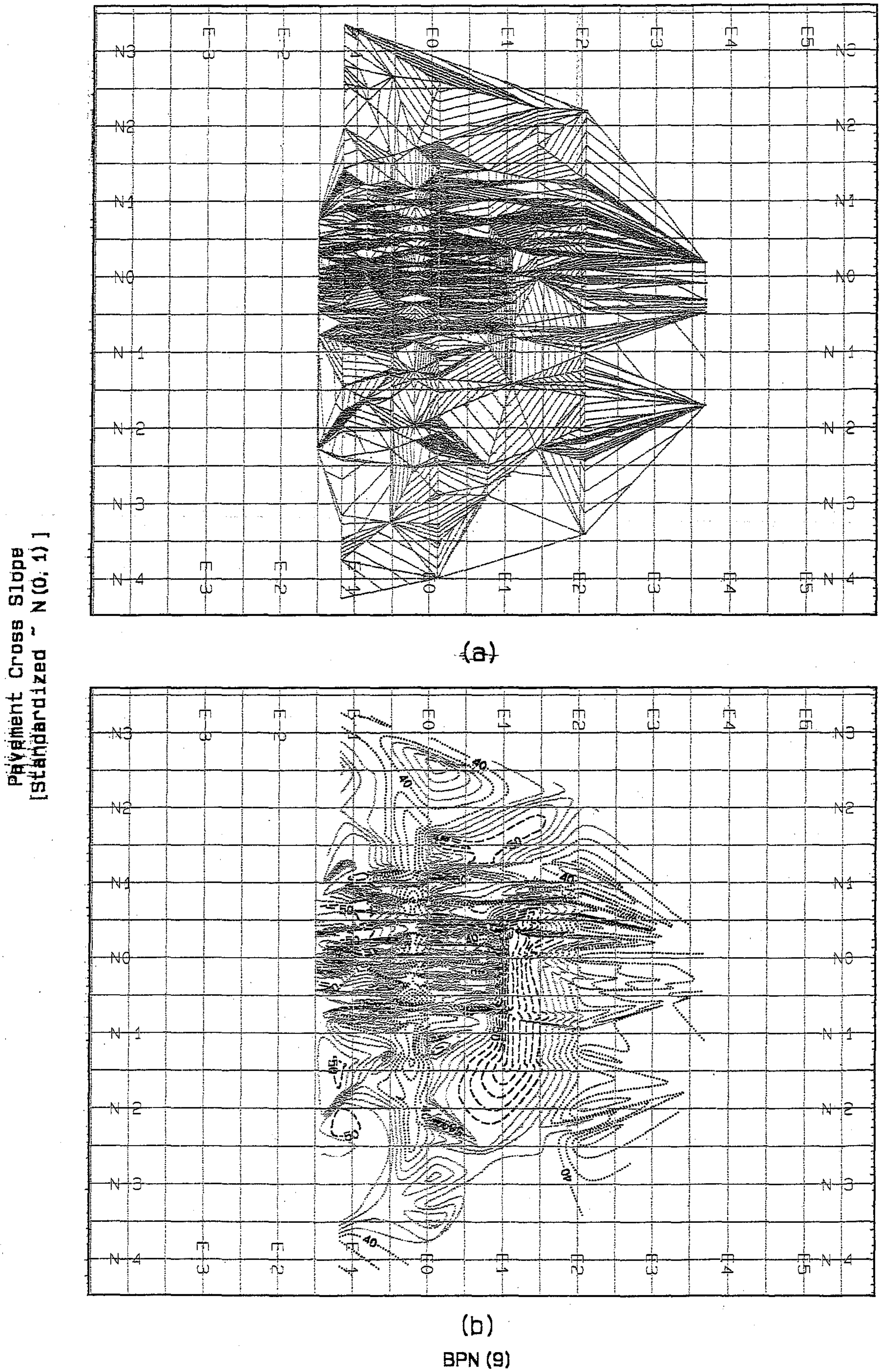


FIG. C.4 Skid Number Contours as a Function of Pavement Cross Slope and BPN(9) (a) Triangulation of Initial Data (553 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (734 obs run on 9/22/96).
(Copy FIG. 21 from November 1999 Report.)

Contour Plot

Pavement Cross Slope X BPN(9)

DESCRIPTION

Factors: **Pavement Cross Slope** is the percentage rise (+) or fall (-) of the pavement surface in the direction perpendicular to travel when facing the median. **BPN(9)** measures the residual friction characteristics of limestone coarse aggregate after 9 hours of polishing.

Concept: Cross Slope reflects the pavement surface orientation tangential to travel, indicates the amount of superelevation present, and facilitates surface drainage and contaminate cleansing. BPN(9) measures the residual texture on the exposed surface of the limestone aggregate after extended wear.

Data: There are 574 interaction points between Cross Slope and BPN(9), each point representing from 1 to 7 test observations with average friction values from 28 to 61. Cross Slope ranges from -4.6 to 7.09 (plotted from -4.25 to 3.35) and BPN(9) from 19 to 35(plotted from -1.51 to 3.67). Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values tend to be highest within typical regions of cross slope and have noticeable bands of poor friction performance at plotted values of BPN(9) from -0.5 to 0.00 and above 2.00 (actual BPN(9) values from 22 to 23 and above 30).

Joint Effects: There is no apparent joint effects on plotted friction values between Pavement Cross Slope and BPN(9).

Anomalies: Atypical friction values plotted as standardized values for <Cross Slope (stdzd), BPN(9) (stdzd), Friction Number> exist at <-4.25, -1.18, 35>; <-2.16, 0.11, 56>; < -1.29, 0.11, 53>; < -1.09, 0.11, 54>; < -0.67, -1.18, 36>; < -0.60, -0.21, 28>; < -0.42, -0.53, 54.5>; < -0.35, 1.08, 60>; < -0.28, 0.11, 50>; < -0.24, 0.11, 51>; < 0.00, -1.18, 37>; < 0.36,0.11,53>; < 0.23, -0.53, 57>; < 0.39, -1.18, 38>; < 0.48, -0.53, 35.5>; < 0.59, 0.11, 55>; < 0.59, -0.53, 35>; < 1.07, 0.11, 56>; < 1.15,0.53, 30>; < 1.27, -1.18, 33>; < 1.59, 0.11, 55>; and < 1.80, 0.11, 38>.

INTERPRETATION

Significance: Bands of poorly performing pavements plotted at certain BPN(9) values may indicate a potentially flawed limestone aggregate or pavement mixture.

Future Action: Investigate associated pavement values within BPN(9) banding of poor and good friction performance of pavements.

Figure No. 21|| Table No. 21

SIG. INDEX = 10

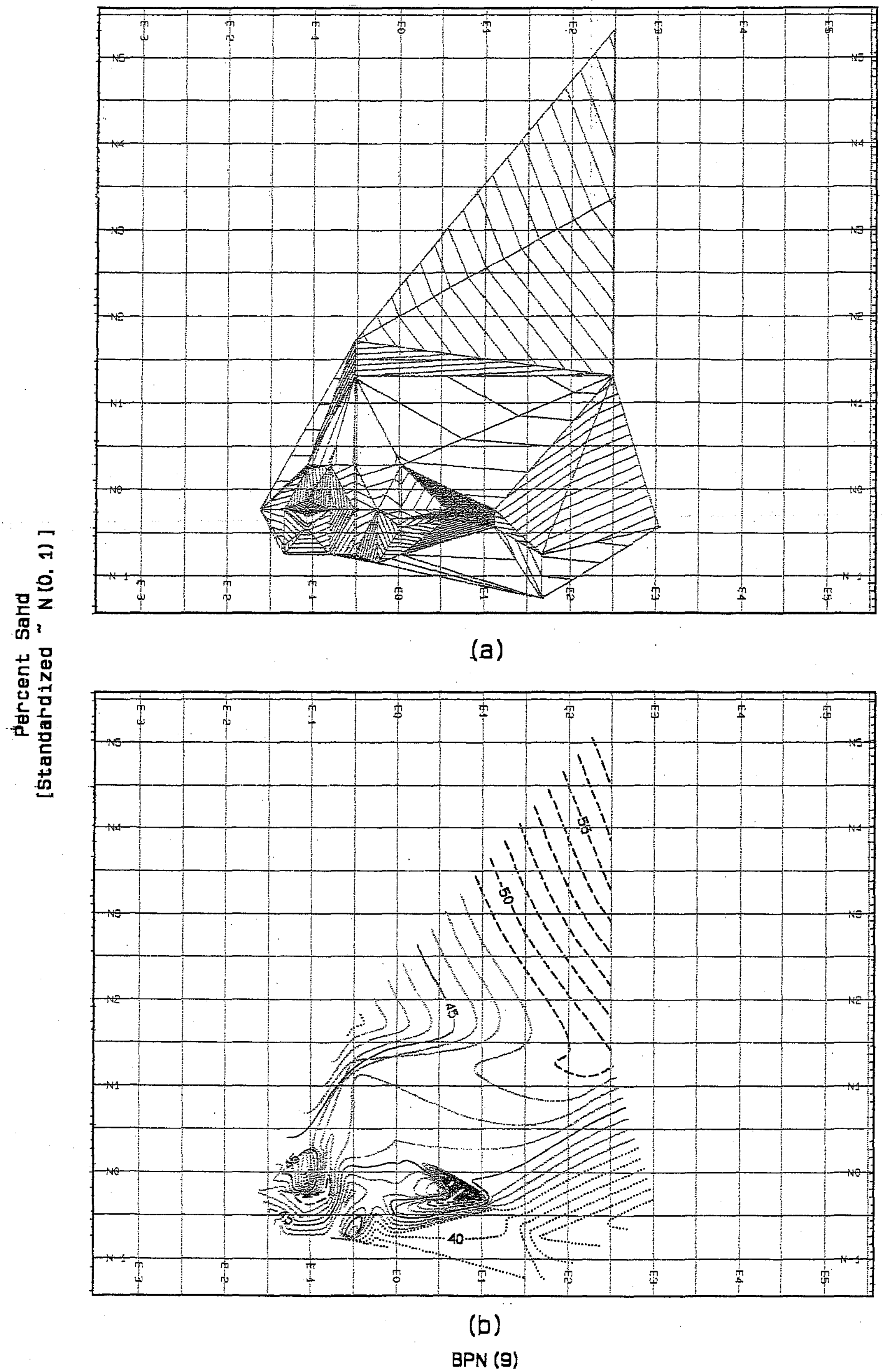


FIG. C.5 Skid Number Contours as a Function of BPN (9) and Percent Sand (a) Triangulation of Initial Data (36 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (f138 obs run on 9/22/96). (Copy FIG 2 from November 1999 Report)

DESCRIPTION

Factors: **Percent Sand** quantifies the amount of sand making up the fine aggregate fraction of the pavement. **BPN(9)** measures the residual friction characteristics of limestone coarse aggregate after 9 hours of polishing.

Concept: Both factors influence the pavement surface microtexture. Percent sand influences the pavement surface roughness which contributes to the pavement microtexture surface. BPN(9) measures the residual texture on the exposed surface of the limestone aggregate after extended wear.

Data: There are 36 plotted interaction points between Percent Sand and BPN(9) values, each point representing from 4 to 144 friction test observations with average friction numbers from 34.9 to 58.4. Percent Sand ranges from 10 to 74 percent and BPN(9) rangesfrom 18 to 35. Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values increase with sand content and show no general relationship to changes in BPN(9) values.

Joint Effects: When considering pavements with high BPN(9) values, there is a distinct linear relationship between friction and sand content where friction numbers increase from 36 to 58 with increasing sand content of 17 to 74 percent (plotted values of -0.5 and 5.3).Relatively low friction numbers (below 41) are observed within a range of BPN(9) values from 23 to 35 when the sand content of pavement is less than average.

Anomalies: Atypical friction values labeled as <Percent Sand (stdzd), BPN(9) (stdzd), and Friction Number> exist at <-0.23,0.85, 59.33>; <-0.34,0.57, 50.89>; <-0.29,-1.07, 50.25>; and <-0.13, -1.07, 40.33>.

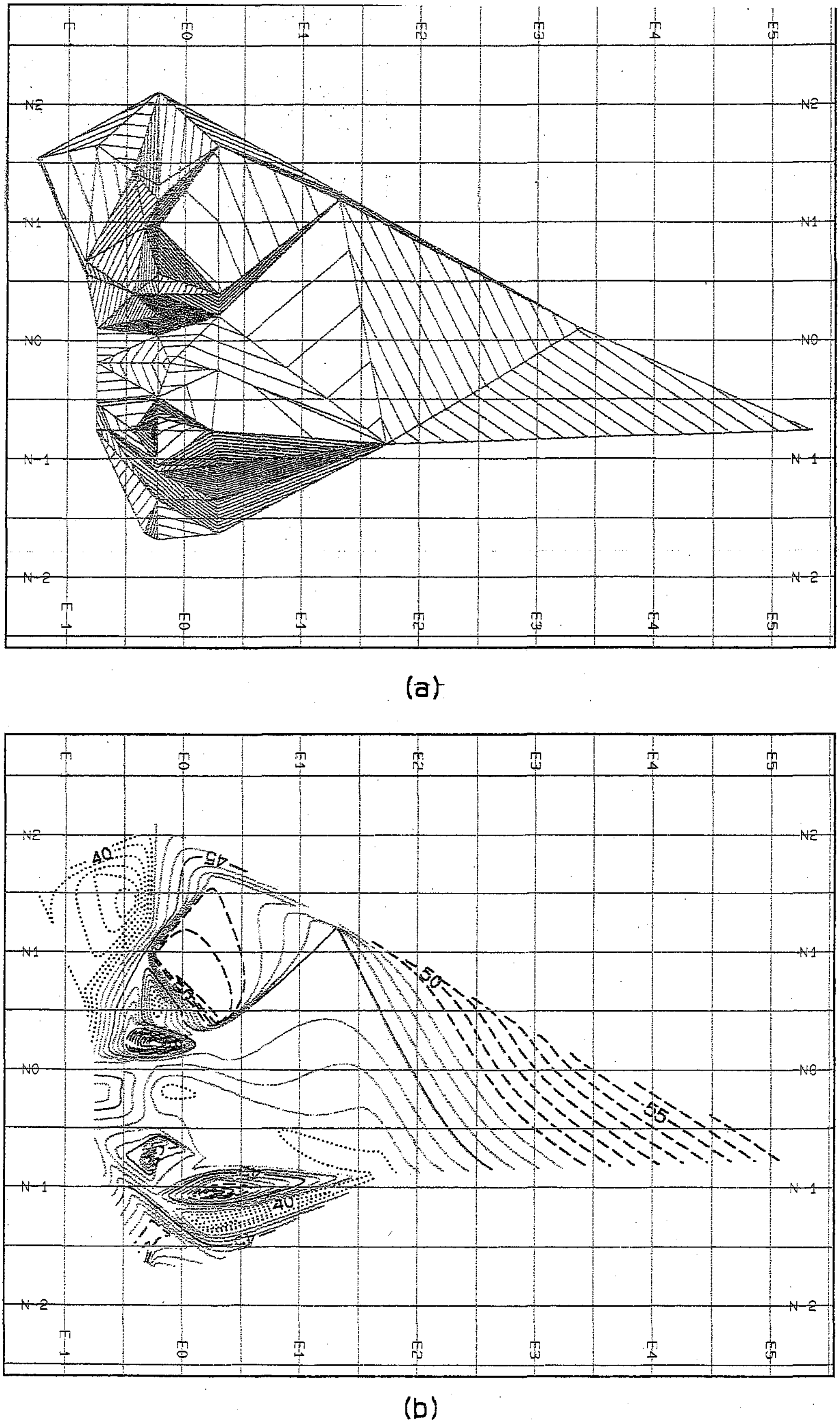
INTERPRETATION

Significance: The relationship between friction numbers and sand content at high BPN(9) values is extremely interesting; but, the contours are developed using only 142 separate skid tests or about 12 percent of the total observations.

Future Action: Check the data for input accuracy in the high percent sand region. If accurate, more friction skid data is needed on pavements with high sand content at varying levels of BPN(9) values.

APPENDIX D – LIMESTONE CONTENT SIGNIFICANT FACTOR PAIRINGS

Percent Limestone
[Standardized ~ N(0, 1)]



Percent Sand
[Standardized ~ N(0, 1)]

FIG. D.1 Skid Number Contours as a Function of Percent Limestone and Percent Sand (a) Triangulation of Initial Data 47 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (1138 obs run on 5/22/96). (Copy FIG. 29 from November 1999 Report.)

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Percent Sand** quantifies the amount of sand making up the fine aggregate fraction of the pavement.

Concept: Both factors influence the contact surface microtexture of the pavement. Limestone is an aggregate known to lose surface texture when placed under wearing conditions that polish exposed surfaces. Sand contributes to the pavement surface roughness.

Data: There are 47 plotted interaction points between Percent Limestone and Percent Sand, each point representing from 3 to 125 friction test observations with average friction numbers from 34.9 to 59.3. Percent Limestone ranges from 14.0 to 80.0 and PercentSand ranges from 10 to 74 percent. Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values increase with Percent Sand and show no general relationship to changes in Percent Limestone.

Joint Effects: Low friction is observed in pavement with high limestone and low sand content. With nearly the same limestone content, significantly higher friction values are observed when sand is slightly higher than average. Interestingly, both high and low friction is observed under nearly identical conditions when limestone is near or below average levels and sand content is near or above average. The high friction numbers observed in the high regions of sand content is a function of the sand, not limestone.

Anomalies: Atypical friction values labeled as <Percent Limestone (stdzd), Percent Sand (stdzd), and Friction Number> exist at <-0.19,-0.13, 40.3>; <-1.05,0.28,52.9>; <-0.76,5.33,58.4>; <-0.88,1.72,40.5>; <-1.34,0.28, 37.4>; and <-1.34,-0.23,49.8>.

INTERPRETATION

Significance: What is most interesting about this plot is the compensating effect that increasing sand content has on friction values of pavements with high limestone content. The high skid values observed in the extremely high ranges of sand content are also interesting but may be due to an input error.

Future Action: Check the data for the high sand content to insure no input error was made. Also, determine factors that may be responsible for the anomalies that are observed in the plot.

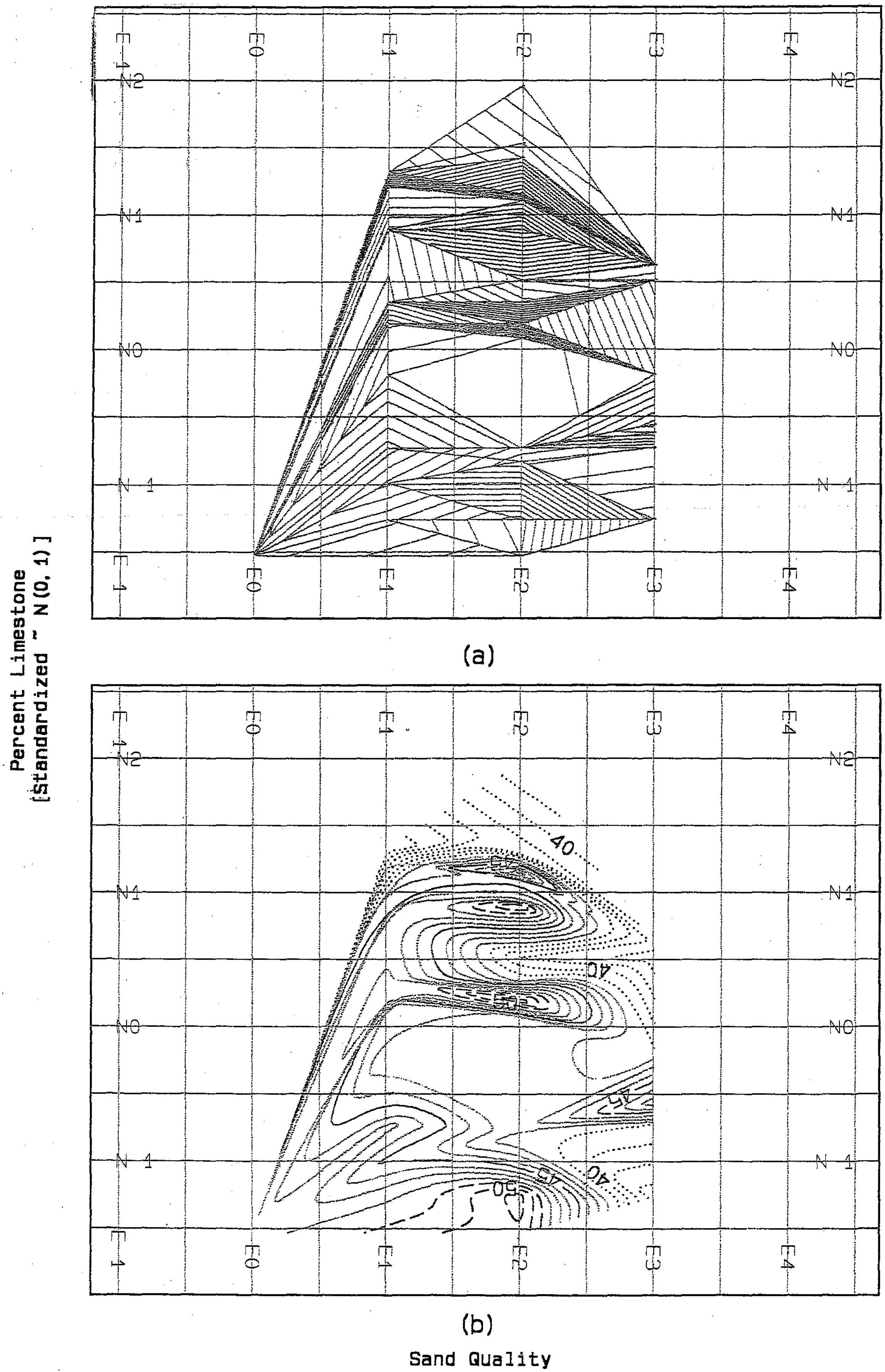


FIG. D.2 Skid Number Contours as a Function of Percent Limestone and Sand Quality (a) Triangulation of Initial Data (31 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (704 obs run on 9/22/96).
(Copy FIG. 30 from November 1999 Report.)

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Sand Quality** is an ordinal ranking of sand types into subjective performance categories of poor (1), medium (2), or good (3).

Concept: Limestone is an aggregate known to lose surface texture when placed under wearing conditions that polish exposed surfaces. Sand Quality is a subjective evaluation of the contribution that the sand makes toward the durability of pavement surface roughness.

Data: There are 32 interaction points between Percent Limestone and Sand Quality, each point representing from 1 to 69 test observations with average friction values from 35 to 52.83. Percent Limestone ranges from 14 to 80 (plotted from -1.68 to 2.11) and Sand Quality from 0 to 3 (plotted from 0 to 3). Percent Limestone is plotted as standardized values.

RESULTS

Main Effects: Plotted friction values indicate no predominate main effect trend with respect to Limestone content and peaks when pavement sand has been subjectively graded as 'fair'.

Joint Effects: Plotted friction values indicate good performance is observed at nearly all levels of limestone content when associated with sands subjectively graded as 'fair'. Poor performance is most noticeable with pavements using 'good' sand or having extremely high Limestone content.

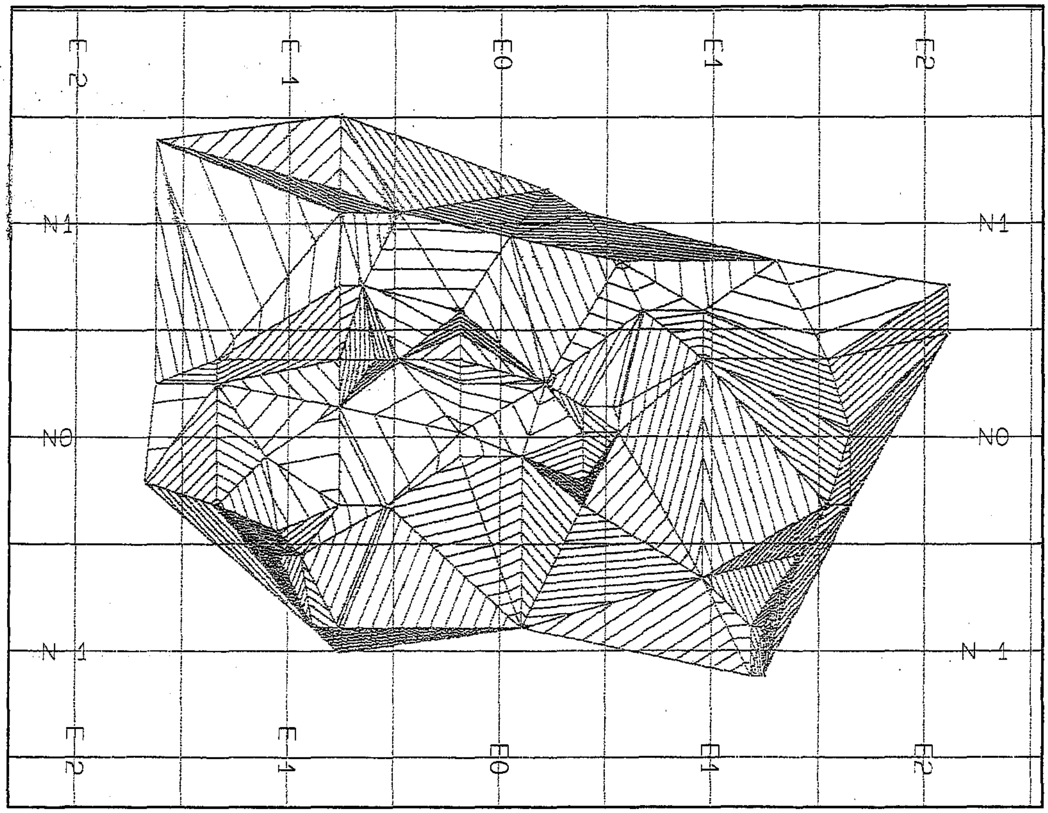
Anomalies: No computations were performed to indentify anomalies when using ordinal data.

INTERPRETATION

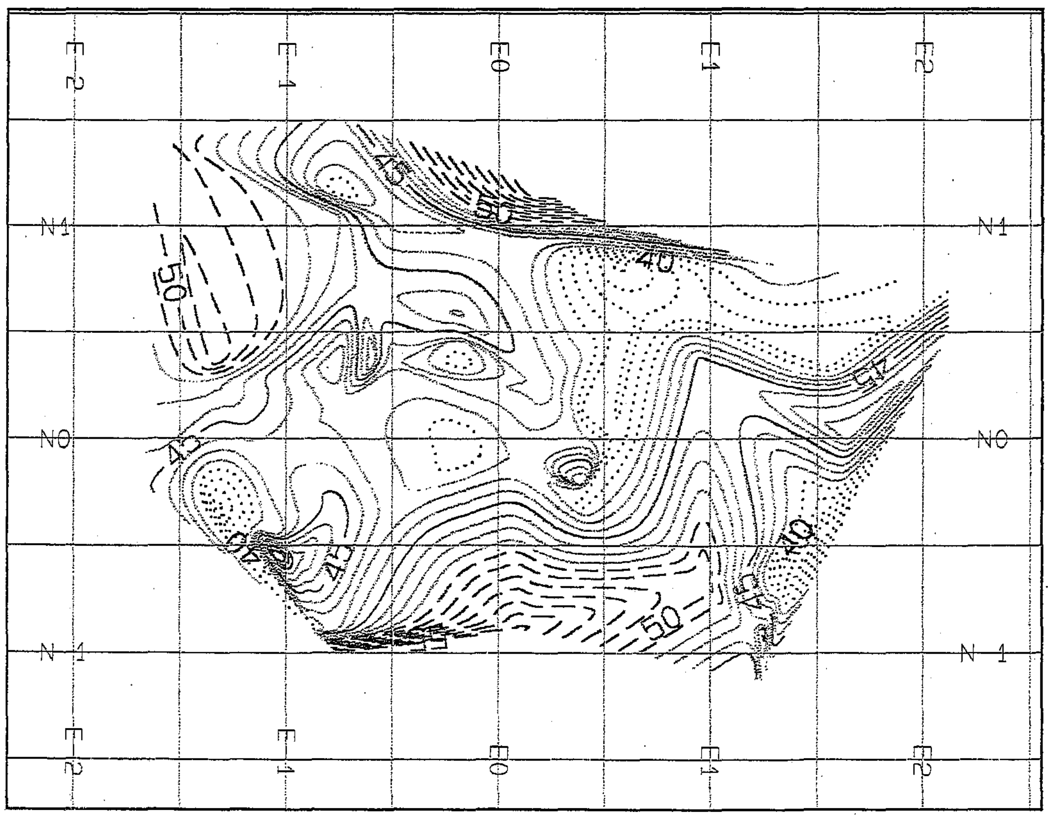
Significance: The relationship between sand grading and performance is counter-intuitive. One would expect better performance with 'good' sands but some of the worst friction observations are made with these sands. Using 'poor' sands the performance is poor only when extremely high limestone contents are used.

Future Action: More thought needs to be given for the reason why sand quality and performance do no align as expected.

TSR
[Standardized ~ N(0, 1)]



(a)



(b)

Percent Limestone
[Standardized ~ N(0, 1)]

FIG. D.3 Skid Number Contours as a Function of Percent Limestone and TSR (a) Triangulation of Initial Data (61 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (1138 ~~obs run on~~ 9/22/96).
(Copy FIG. 32 from ~~November~~ 1999 ~~Report.~~)

DESCRIPTION

Factors: **Tensile Strength Ratio (TSR)** is a measure comparing the tensile strength bond between the asphalt and aggregate for a moisture-conditioned specimen versus that of a dry specimen for a given HMA design mixture. **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement.

Concept: TSR measures the general decline in aggregate/asphalt bond due to the presence of moisture within the aggregate. Limestone is an aggregate known to lose surface texture when placed under wearing conditions that polish exposed surfaces.tions that polish exposed surfaces. There is no expected interaction effect between these two factors.

Data: There are 60 interaction points between TSR and Percent Limestone, each point representing from 3 to 72 test observations with average friction values from 34.9 to 59.33. TSR ranges from 0.75 to 0.98 (plotted from -1.12 to 1.51) and Percent Limestone from 14 to 80 (plotted from -1.68 to 2.11). Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values indicate good performance with both extremely high and low TSR values while showing no general trend with Limestone content.

Joint Effects: There is no readily apparent joint effect between these two factors.

Anomalies: No atypical friction values exist.

INTERPRETATION

Significance: Good friction performance is observed at both high and low values of TSR. At high TSR values, the pavement mix may have some intrinsic property that promotes good friction performance. Low TSR values most likely reflects an association with high sand content pavements which may account for the observed performance.

Future Action: Check the low TSR values to determine to what extent high natural or manufactured sand content has on producing the observed friction performance.

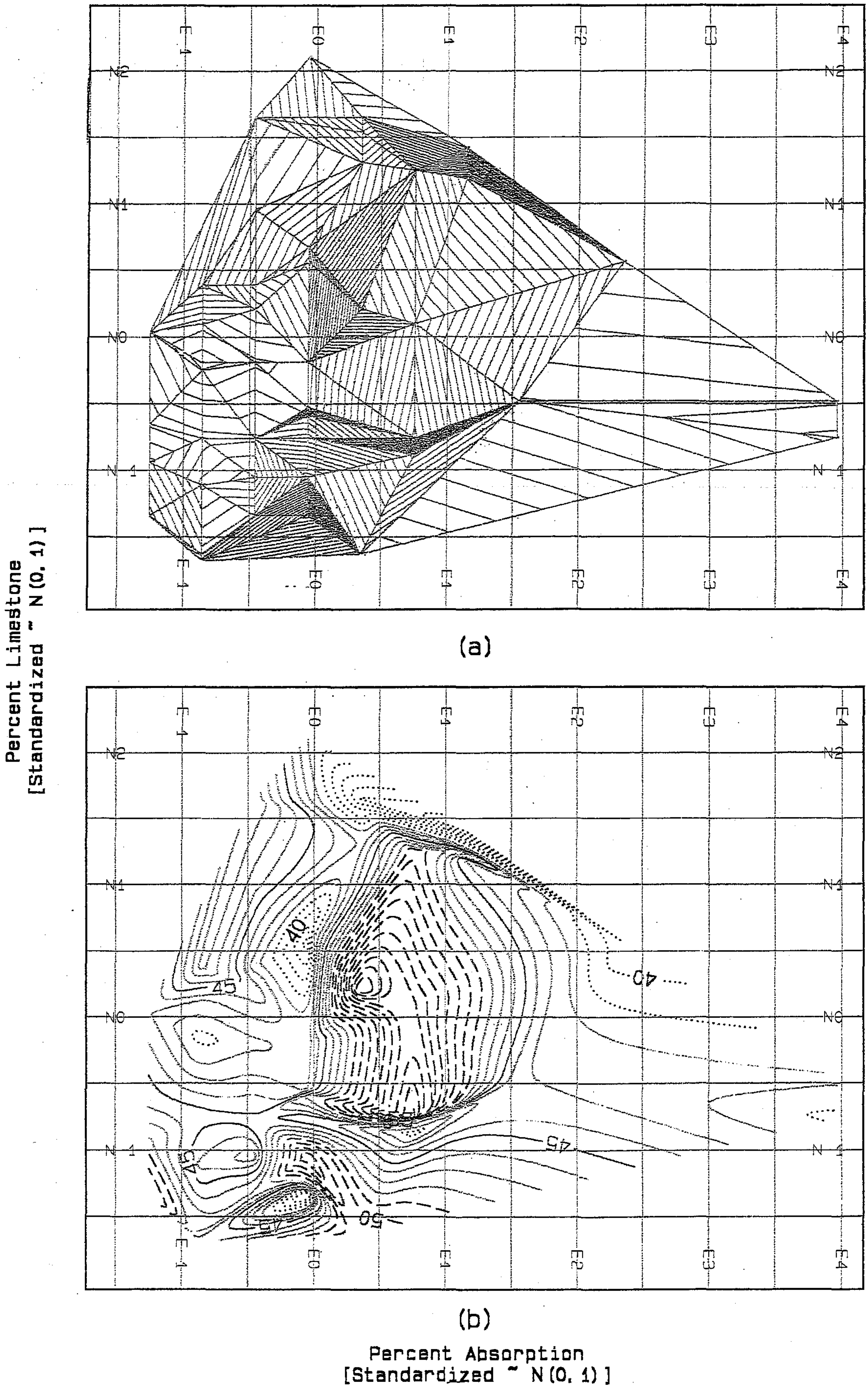


FIG. D.4 Skid Number Contours as a Function of Percent Limestone and Percent Absorption (a) Triangulation of Initial Data (45 pts) (b) Contours with ~~Dotted~~ Lines In~~dicating~~ FN < 41 and Dashed (Copy obtained from November 1989 Report on 9/22/96).

Contour Plot

Percent Limestone X Percent Absorption

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Percent Absorption** is a measure of the weight of saturated water in the permeable pores as a percent of the dry aggregate weight.

Concept: Limestone loses surface texture when placed polished. Absorptive aggregates have significant microtexture due to high porosity, as well as, significant construction problems due to difficulty in drying which results in inadequate asphalt coating.face texture, as well as, significant construction problems due to difficulty in drying which results in inadequate asphalt coating. There is no expected interaction effect between these two factors.

Data: There are 45 interaction points between Percent Limestone and Percent Absorption, each point representing from 3 to 80 test observations with average friction values from 34.9 to 59.33. Percent Limestone ranges from 14 to 80 (plotted from -1.68 to 2.11) and Percent Absorption from 0.03 to1.6 (plotted from -1.26 to 3.96). Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values indicate no general trend in relation to limestone content and friction values peak at slightly above average absorption then decline as absorption increases.

Joint Effects: There is no apparent joint effect between these factors.

Anomalies: Atypical friction values plotted as standardized values for <Percent Limestone (stdzd), Percent Absorption (stdzd), Friction Number> exists at <-1.34,-1.26,51.6>.

INTERPRETATION

Significance: Friction performance of the pavement is good except for extremely high limestone contents when the aggregate has slightly above average absorption levels. The signficance of this trait is not readily apparent at this time.

Future Action: Consider the significance of above average absorption levels and limestone content on friction performance. The type of limestone deposit may be indicated by the absorptive characteristics of the aggregate and may be a valuable clue.

Figure No. 37|| Table No. 37

SIG. INDEX = 10

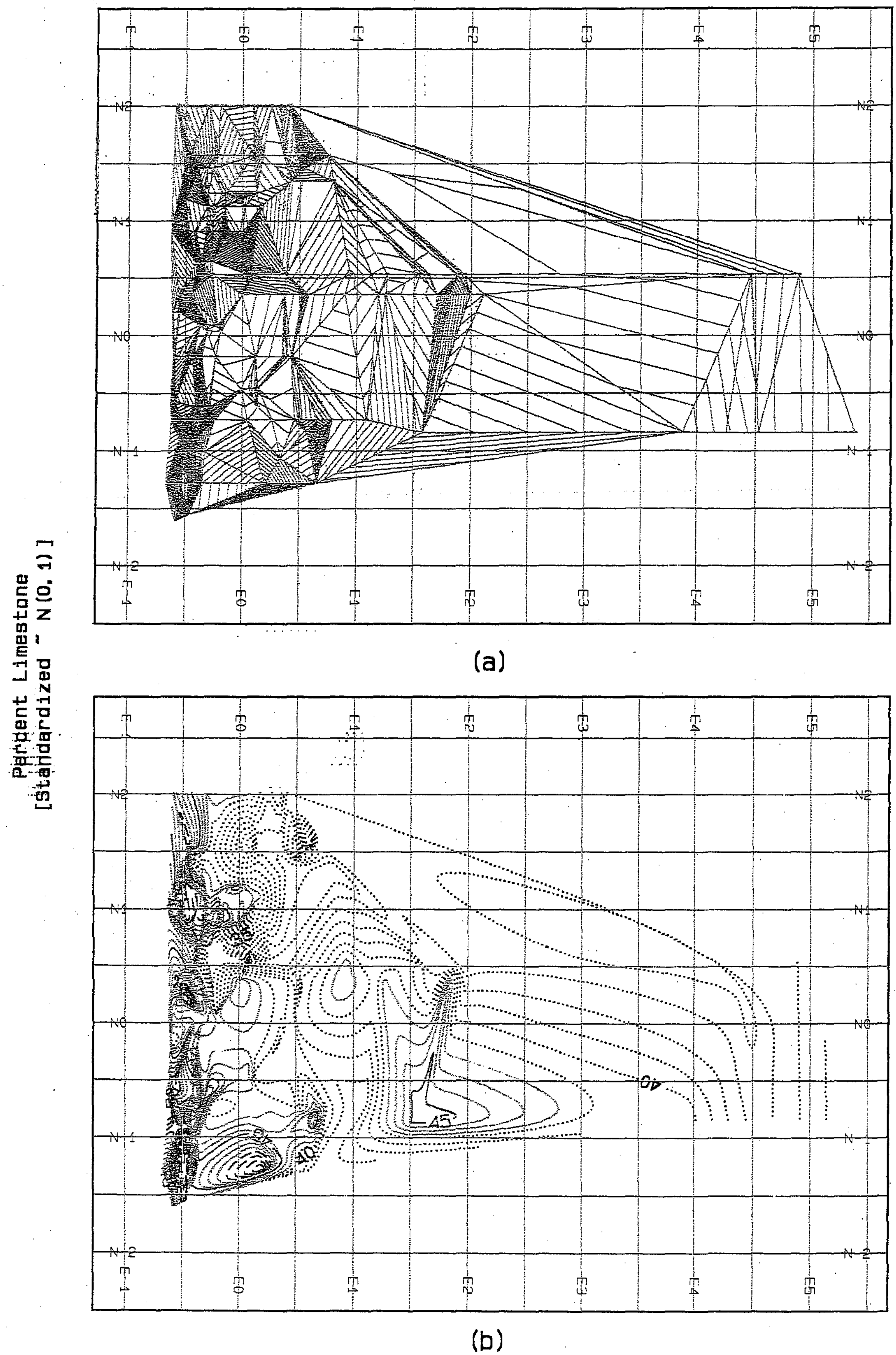


FIG. D.5 Skid Number Contours as a Function of Percent Limestone and Cumulative Traffic (a) Triangulation of Initial Data (148 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (540 obs run on 9/22/96).
(Copy FIG 41 from November 1999 Report.)

Contour Plot

Percent Limestone X Cumulative Traffic

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Cumulative Traffic** is a lane estimate of the total number of vehicles over the location during the time period between pavement construction and skid test date.

Concept: Limestone is an aggregate known to lose surface texture when placed under wearing conditions that polish exposed surfaces. Cumulative traffic is a measure of the wear applied to the pavement. An interaction effect is expected between these two factors.

Data: There are 182 interaction points between Percent Limestone and Cumulative Traffic, each point representing from 1 to 66 test observations with average friction values from 28 to 59.33. Percent Limestone ranges from 14 to 80 (plotted from -1.75 to 2.09)and Cumulative Traffic from -56760 (error) to 10,400,000 (plotted from -0.65 to 5.35). Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values indicate no general trend with Limestone content while generally decreasing with increasing Cumulative Traffic.

Joint Effects: Some joint effect is evident between these factors. Low limestone pavements seem to maintain higher friction performance at the lower Cumulative Traffic levels than does higher limestone content pavements.

Anomalies: Atypical friction values plotted as standardized values for <Percent Limestone(stdzd), Cumulative Traffic (stdzd), Friction Number> exists at <-0.99,-0.49,57> ; <-0.72,-0.43,36> ; <0.2,-0.47,59.33> ; <1.56,0.56,30>

INTERPRETATION

Significance: The predominate trend observed within this plot is the obvious loss of skid resistance with increasing wear that is attributable to higher Cumulative Traffic over the pavement surface. Only moderate gains are made in pavement performance life when low limestone content pavement is used, although, noticable outliers do exist within the performance data.

Future Action: Interesting outlier observations with low limestone content is worth investigating for external factors.

Figure No. 41|| Table No. 41

SIG. INDEX = 10

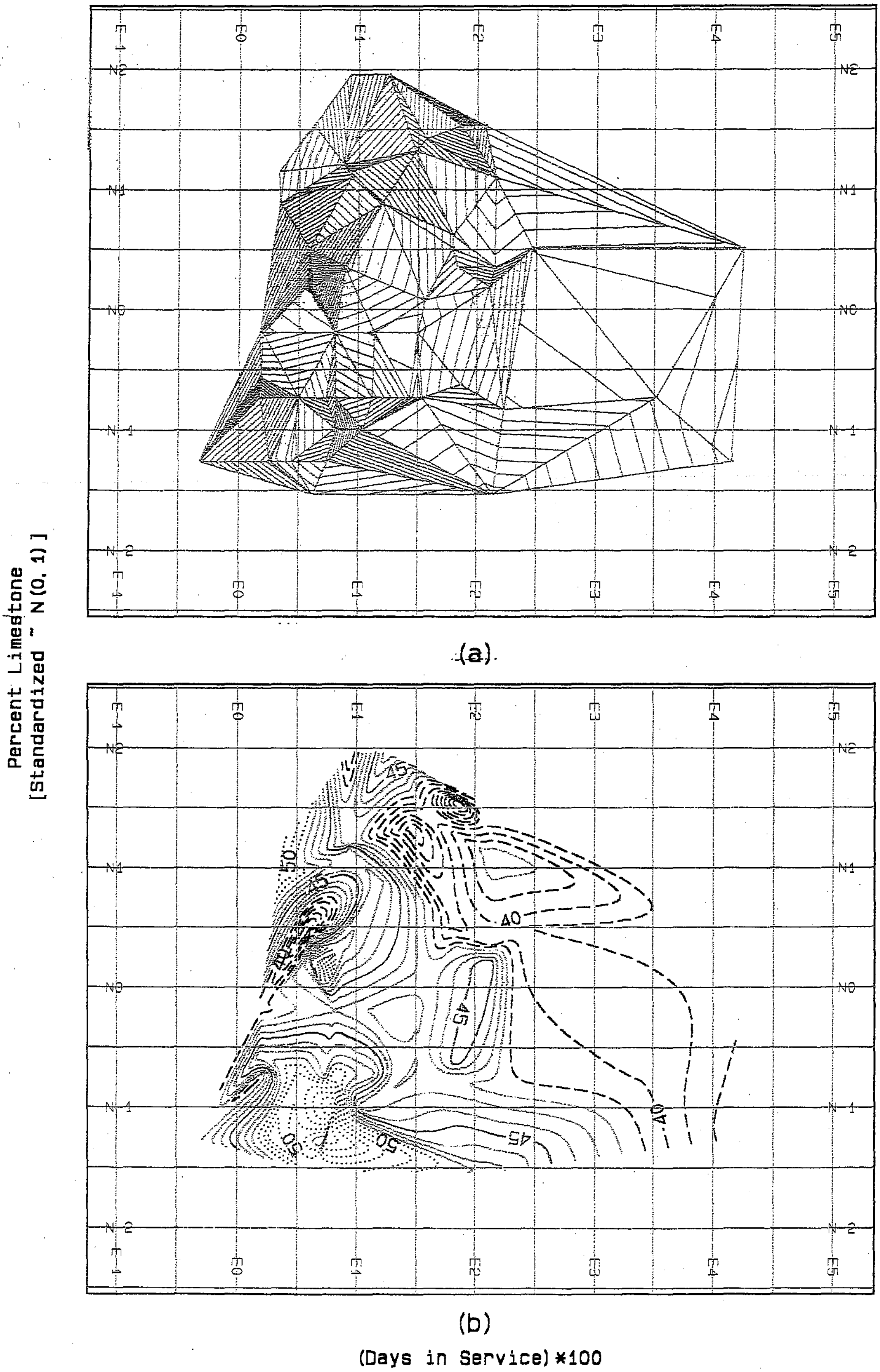


FIG. D.6 Skid Number Contours as a Function of Percent Limestone and Days in Service (a) Triangulation of Initial Data (53 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 45 (704 obs run on 10/16/98).
(Copy FIG 44 from November 1999 Report.)

Contour Plot — *Percent Limestone X Days-in-Service*

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Days-in-Service** is the total number of elapsed calendar days between pavement construction and skid test.

Concept: This plot contrasts the limestone amount with the pavement age. Limestone is known to lose surface texture when polished from wear. Days-in-Service indicates the cumulative day count for pavement exposure to service loads and the relative age of pavement materials.

Data: There are 68 plotted interaction points between Percent Limestone and Days-in-Service, each point representing from 1 to 69 friction test observations with average friction numbers from 31.5 to 59.3. Percent Limestone ranges from 14.0 and 80.0 Days-in-Service ranges from 17 to 424.

RESULTS

Main Effects: Plotted friction values show no general relationship to changes in Percent Limestone and tends to decrease with increases in Days-in-Service.

Joint Effects: Pavements with high limestone content is observed to have lower friction values even when the number of Days-in-Service are relatively short. Friction performance of pavements with low limestone content is more favorably than with higher limestone content as the Days-in-Service increase.

Anomalies: Atypical friction values labeled as <Percent Limestone (stdzd), Days-in-Service, and Friction Number> exist at <-1.59,112,44.0>; <-0.72,17,40.0>; <-0.18,17,40.0>; <-0.18, 20, 40.6>; <0.53,59, 35.6>; <1.13,216,43.1>; <1.18,33,51.64>; and <2.00, 125, 47.8>.

INTERPRETATION

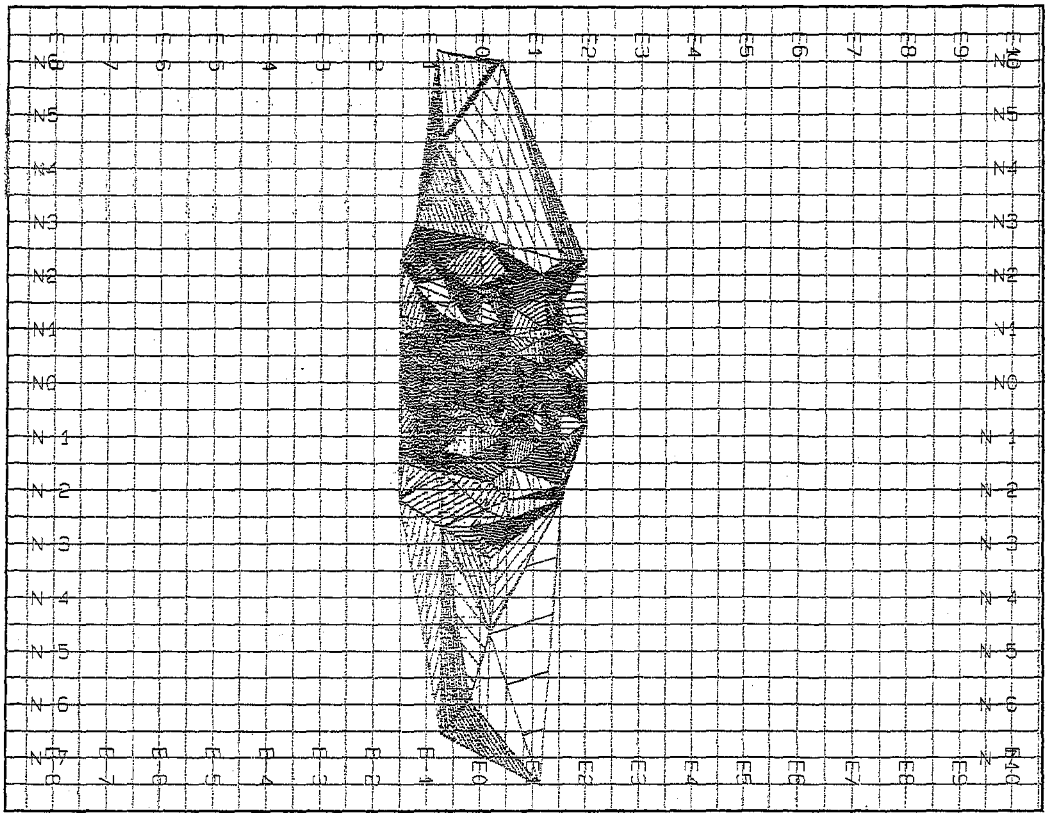
Significance: There are two interesting aspects to this plot. 1) Pavements with low limestone content seem to exhibit relatively stable friction numbers over extended periods of service time. 2) High friction numbers are observed over a limited time period even with high limestone content; however, the values quickly decrease as the pavement is used.

Future Action: The anomaly generating high friction numbers with high limestone content should be investigated to determine if another factor is contributing to these high observed values.

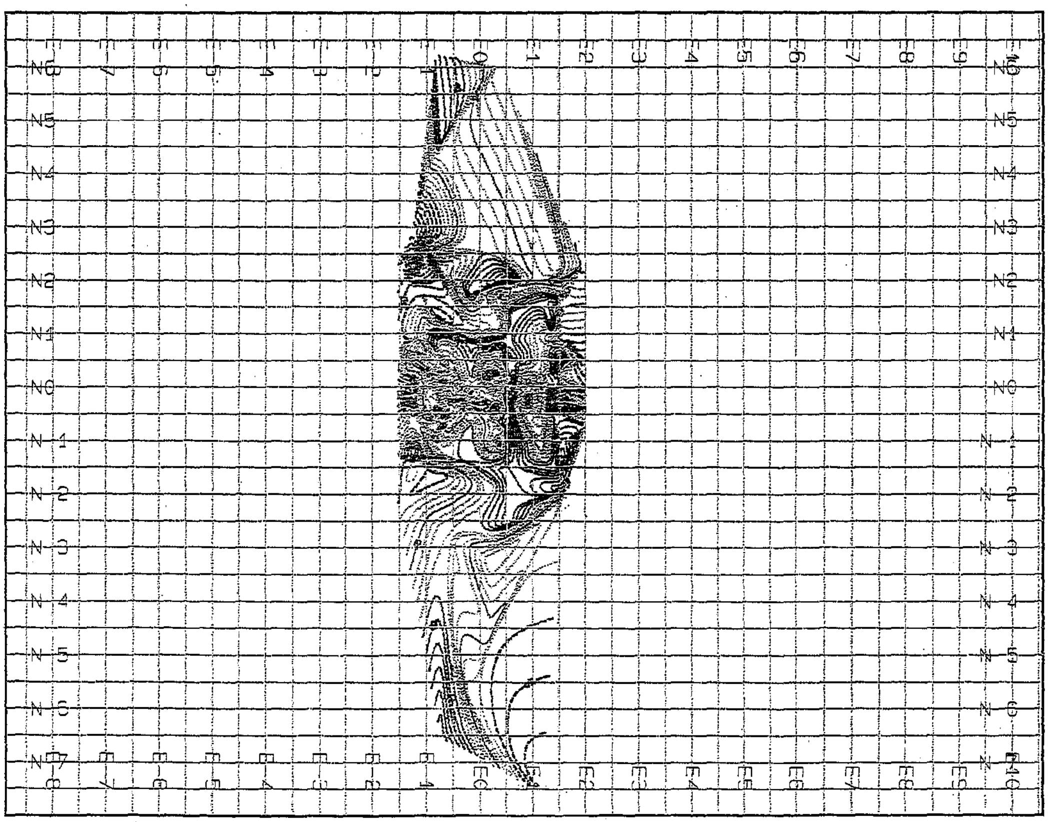
Figure No. 44|| Table No. 44

SIG. INDEX = 10

Degree of Curve
[Standardized ~ N(0, 1)]



(a)



(b)

Percent Limestone
[Standardized ~ N(0, 1)]

FIG. D.7 Skid Number Contours as a Function of Degree of Curve and Percent Limestone (a) Triangulation of Initial Data (380 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (704 obs run on 9/22/96).
(Copy FIG 45 from November 1999 Report.)

Contour Plot — *Degree-of-Curve X Percent Limestone*

DESCRIPTION

Factors: **Degree-of-Curve** is a measure of the change in vehicular heading at the pavement location being tested as quantified by the subtended angle along a 100 foot pavement length. **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement.

Concept: Degree-of-Curve reflects the transverse wear caused by the centrifugal force transferred to the pavement by the tires. Limestone loses surface texture when polished. Higher wearing conditions coupled with higher limestone content should interact to provide lower friction performance.

Data: There are 456 interaction points between Degree-of-Curve and Percent Limestone, each point representing from 1 to 31 test observations with average friction values from 30 to 61. Degree-of-Curve ranges from -10.98 to 9.18 (plotted from -7.43 to 6.29) and Percent Limestone from 14 to 80 (plotted from -1.59 to 1.98). Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values appear marginally higher on left-hand (negative) curves while seeming to decline with increasing Percent Limestone; although, signficant performance banding appears at certain limestone levels.

Joint Effects: There appears to be some joint effect. Slight left-hand curves seem to perform better over a broad range of limestone contents.

Anomalies: Atypical friction values plotted as standardized values for <Degree-of-Curve(stdzd), Percent Limestone(stdzd), Friction Number> exist at < -0.67, 0.9, 54>; < -0.64, 0.9, 54>; < -0.62, -0.56, 55>; < -0.62, -1.26, 56>; < -0.62, 0.19, 59>; < -0.57, -0.83, 35>; < -0.57, 0.19, 61>; < -0.57, 0.52, 30>; < -0.57, -0.56, 54>; < -0.44, -0.72, 54>; < -0.29, -0.72, 33>; < 1.58, -0.18, 48>; < 1.81, 0.19, 60>; <1.81, 1.17, 53>; and < 1.81, 0.52, 33>.

INTERPRETATION

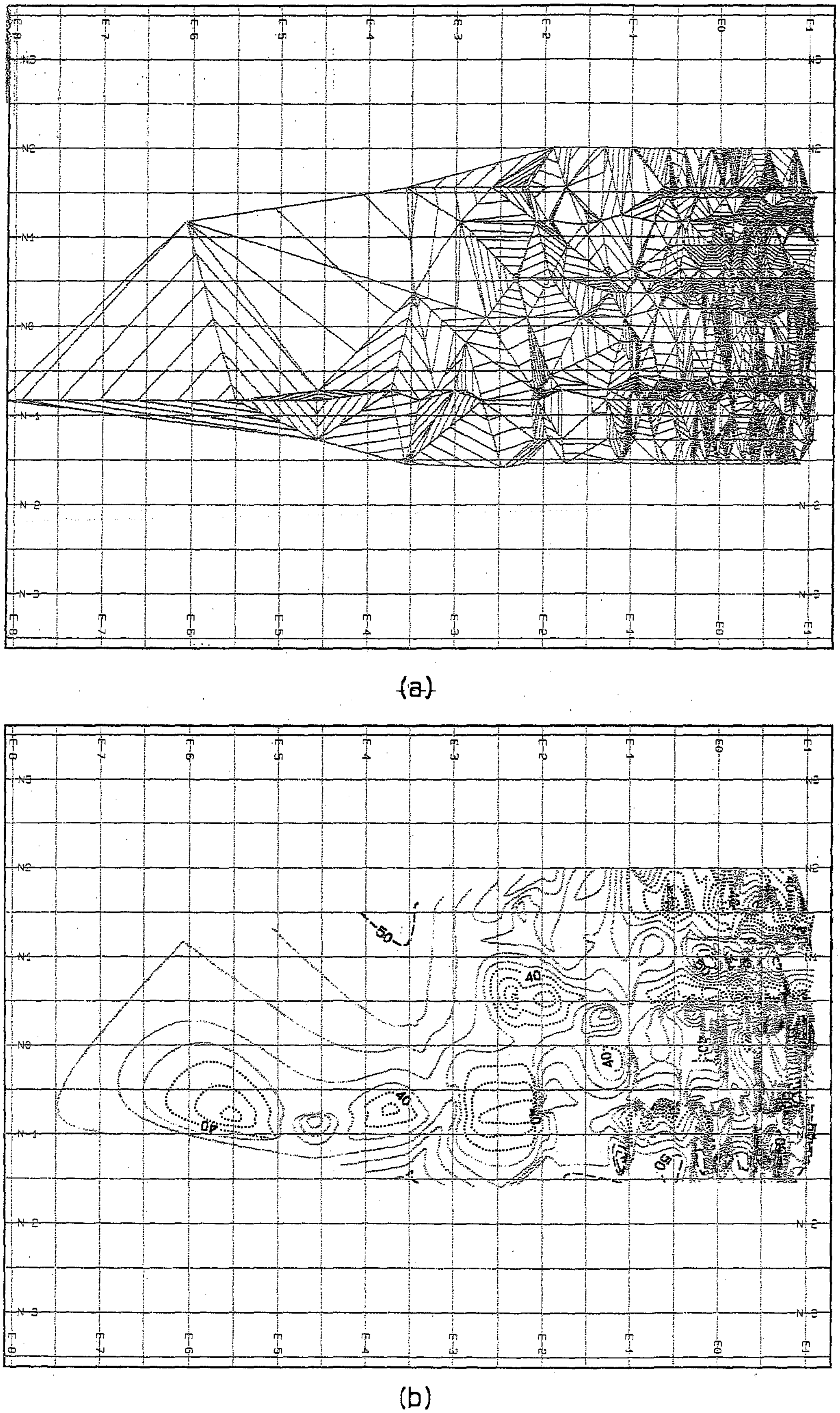
Significance: Focusing on high Limestone content pavements with slight left-hand curves offers a good contrast between transverse wear and vehicular weight as a leading contributor to Limestone aggregate polishing. Assuming no adjustment for superelevation the effective 'pavement normal' weight of vehicles would be reduced while the transverse wear component would be increased. Another interesting observation is the performance banding at certain limestone levels which reflect an external factor at work.

Future Action: Further investigate limestone content, degree-of-curve, and cross-slope/superelevation to more conclusively support this weight/transverse wear contrast.

Figure No. 45|| Table No. 45

SIG. INDEX = 10

Percent Limestone
[Standardized ~ N(0, 1)]



Cleansing Gradient
[Standardized ~ N(0, 1)]

FIG. D.8 Skid Number Contours as a Function of Percent Limestone and Cleansing Gradient (a) Triangulation of Initial Data (636 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (733 obs run on 9/22/96).
(Copy FIG 46 from November 1999 Report.)

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Cleansing Gradient** is a measure (angular cosine) of the geometric configuration of the pavement surface with a horizontal plane combining both pavement grade and cross slope.

Concept: This plot contrasts the limestone amount with the pavement geometry. Limestone loses surface texture when polished. Cleansing Gradient reflects the surface cleansing potential of rainfall associated with steeper gradients and a pavement configuration that induces certain adverse wearing conditions.

Data: There are 659 interaction points between Percent Limestone and Cleansing Gradient. Each point represents from 1 to 6 test observations with an average friction value of 44.1 which ranges from 28 to 60. Percent Limestone ranges from 14 to 80 (plotted from -1.59 to 2.00) and Cleansing Gradient from 0.99518 to 1.00000 (plotted from -8.14 to 1.07). Both factors are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values tend to decrease with increasing Percent Limestone and increase with Cleansing Gradient as it approaches 1 or flat.

Joint Effects: Plotted friction values indicate a joint effect where higher friction values are associated with low Percent Limestone on relatively flat pavement surfaces.

Anomalies: Atypical friction values plotted as standardized values for <Percent Limestone, Cleansing Gradient, and Friction Number> exist at <-1.27, -0.27, 56>; <-1.27, -0.26, 30>; <-1.27, 0.64, 56>; <-0.99, 0.42, 57>; <-0.72, -0.57, 33>; <-0.72, -0.55, 54>; <-0.72, 0.65, 55>; <-0.56, 0.81, 54>; <-0.56, 0.90, 55>; <-0.18, 0.95, 48>; <0.20, 0.51, 59>; <0.20, 0.53, 60>; <0.37, -1.25, 50>; <0.37, -0.33, 50>; <0.37, 0.30, 49>; <0.37, 0.55, 50>; <0.53, 0.76, 28>; <0.53, 0.99, 30>; <0.64, 0.76, 28>; <0.91, -0.11, 55>; <.91, 0.31, 55>; <1.18, 0.84, 54>; <1.56, 0.03, 30>; and <2.00, -0.96, 52>

INTERPRETATION

Significance: Notice the gathering of the high friction numbers into the lower right quadrant of the plot indicating a combination of low limestone content on flat pavement surfaces tends to result in high friction values.

Future Action: The observed relationship between Percent Limestone and Cleansing Gradient should be statistically compared along with other influencing factors that may contribute to this pattern. Also, the noticable bands of friction performance tied to Percent Limestone should be explored more

closely to identify the potential contributions of other factors.

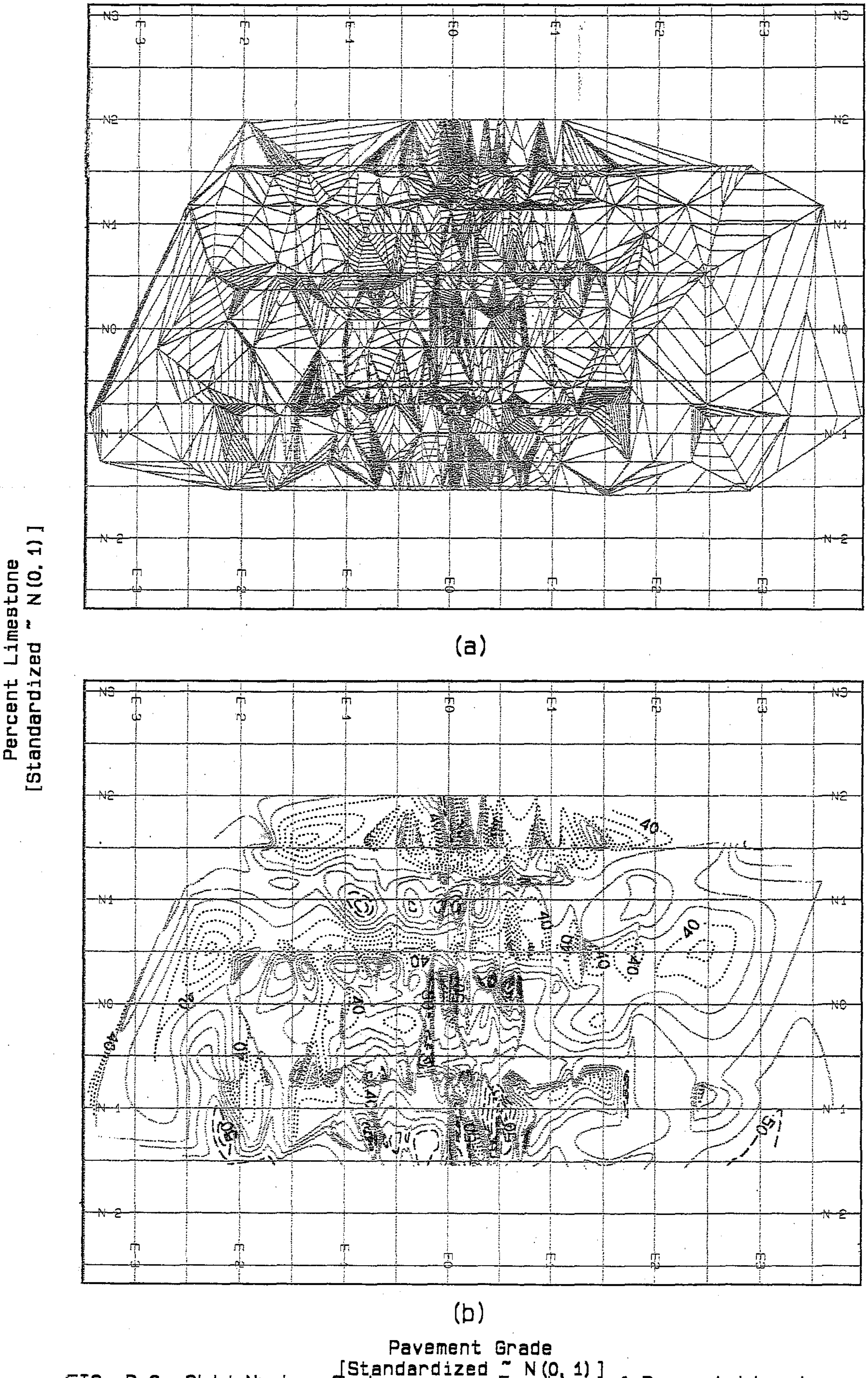


FIG. D.9 Skid Number Contours as a Function of Percent Limestone and Pavement Grade (a) Triangulation of Initial Data (612 pts) (b) Contours with ~~Dotted~~ Lines ~~Indicating~~ FN < 41 and Dashed Lines Indicating ~~FN > 49 (748~~ obs ~~run on 9/22/96~~).
(Copy FIG 47 from ~~November~~ 1999 ~~Report~~.)

Contour Plot

Percent Limestone X Pavement Grade

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Pavement Grade** is the slope of the pavement surface in the direction of travel relating the vertical rise (+) or fall (-) as a percentage of horizontal distance.

Concept: Limestone is an aggregate known to lose surface texture when placed under wearing conditions that polish exposed surfaces. Grade corresponds with the different wearing actions caused by the tire-pavement interaction in moving the vehicle uphill, coasting (free rolling), or braking on downhill grades.

Data: There are 627 interaction points between Percent Limestone and Grade, each representing from 1 to 9 observations with average friction from 28 to 61. Percent Limestone ranges from 14 to 80 (plotted from -1.74 to 1.94) and Grade from -7.82 to 9.10 (plotted from -3.42 to 3.81). Both are plotted as standardized values.

RESULTS

Main Effects: Plotted friction values generally increase with Percent Limestone; however, bands of particularly good performance occur at plotted Limestone content values of 1.53, 0.88, and 0.18. Friction values peak at moderate grades.

Joint Effects: Pavements with low Limestone content exhibit good friction performance while appearing less sensitive to grade differences. With increasing Limestone content, flat graded pavements generally perform best with slight moderations attributable to Limestonecontent. Average Limestone content pavements perform best at slightly uphill grades while higher Limestone pavements perform best with slightly downhill grades.

Anomalies: Atypical friction for <Percent Limestone (stdzd), Grade (stdzd), Friction Number> exist at <-1.27,-0.77,56>; <-1.27,0.22,30>; <-1.27,0.45,56>; <-1.27,0.75,55>; <-0.99,0.50,57>; <-0.83,-3.48,35>; <-0.83,-2.05,35>; <-0.83,2.45,35.50>; <-0.72,0.59,33>; <-0.72,1.49,35>; <-0.56,-0.28,54>; <-0.56,-0.20,55>; <-0.18,-1.05,46>; <-0.18,-0.21,49>; <-0.18,0.07,48>; <-0.18,0.44,45>; <-0.18,0.74,37>; <0.09,-1.00,37>; <0.20,-0.004,61>; <0.53,0.62,28>; <0.64,0.62,28>; <0.91,-0.05,55>; <0.91,0.06,55>; <1.18,0.69,54>; <156,-0.81,30>.

INTERPRETATION

Significance: Low limestone pavements have high friction regardless of grade while high limestone has low friction. Good friction is limited at moderate Limestone to relatively flat grades with banding at certain Limestone levels. Poor friction on steep downhill grades could reflect higher wear due to severe braking.

Figure No. 47|| Table No. 47

SIG. INDEX = 10

Future Action: Investigate the factors influencing the Limestone performance banding.

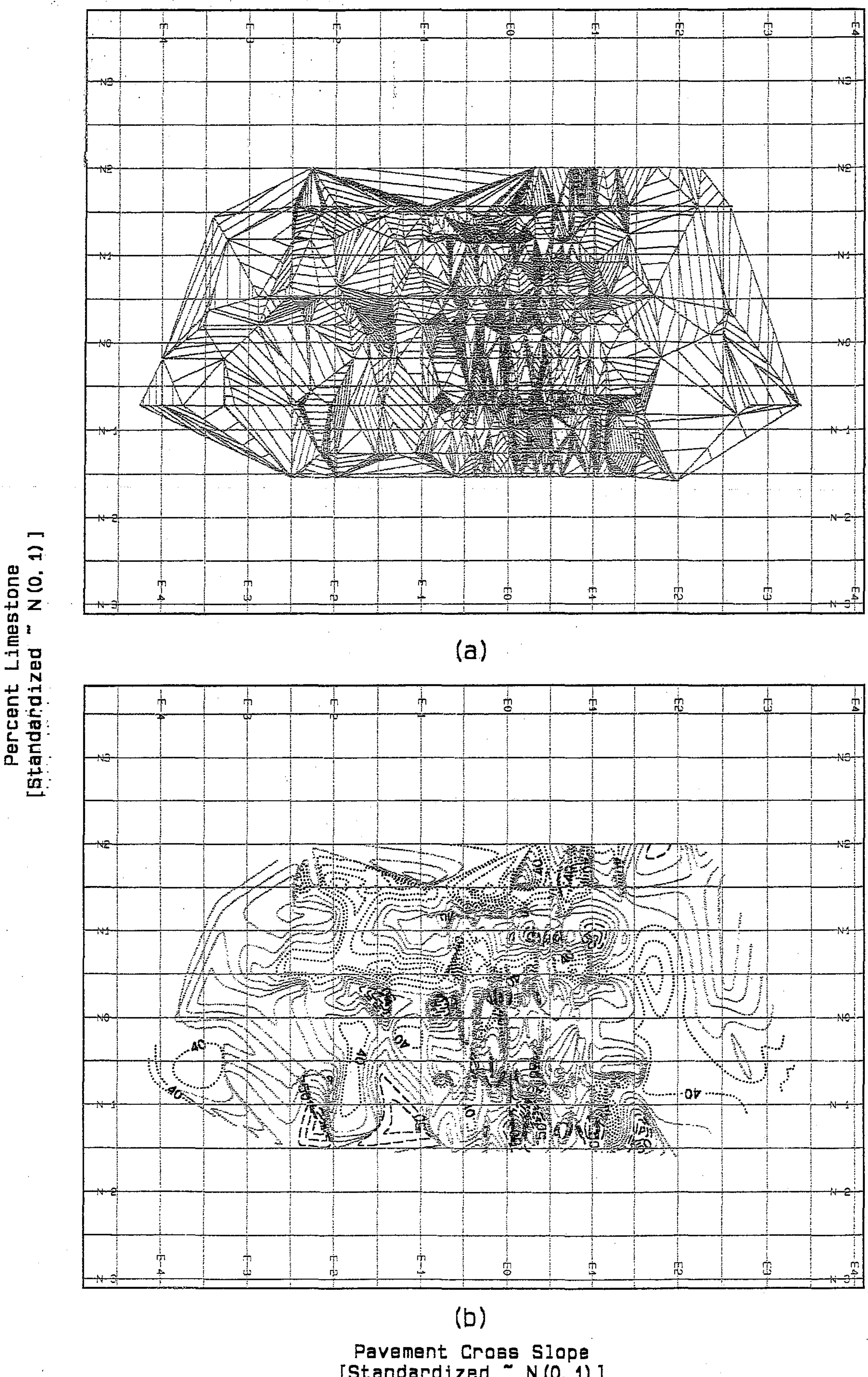


FIG. D.10 Skid Number Contours as a Function of Percent Limestone and Pavement Cross Slope (a) Triangulation of Initial Data (615 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (747 obs run on 9/22/96).
(Copy FIG 48 from November 1999 Report.)

Contour Plot — *Percent Limestone X Pavement Cross Slope*

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Pavement Cross Slope** is the percentage rise (+) or fall (-) of the pavement surface in the direction perpendicular travel when facing the median.

Concept: Limestone loses surface texture when polished. Cross Slope reflects surface orientation, superelevation, and cleansing potential. No interaction effect is expected.

Data: There are 627 interaction points between Percent Limestone and Slope, each representing from 1 to 7 observations with average friction from 28 to 60. Percent Limestone ranges from 14 to 80 (plotted from -1.61 to 1.96) and Cross Slope from -4.6 to 7.1 (plotted from -4.24 to 3.27). Both are plotted as standardized values.

RESULTS

Main Effects: Plotted values indicate banded friction performance although it generally declines as Limestone increases and peaks with average Cross Slopes.

Joint Effects: There appears to be a joint effect between these factors. Low Limestone pavements perform well irrespective of cross slope. Moderate limestone pavements achieve best performance at slightly lower than average cross slopes, a flatter cross-section. Moderately high limestone pavements perform best with slightly steeper cross slopes than average. High limestone pavements are generally poor performers irrespective of cross slope.

Anomalies: Atypical friction for <Percent Limestone (stdzd), Cross Slope (stdzd), Friction> exists at <-1.27,-2.16,56>; <-1.27,-1.09,54>; <-1.27,1.15,30>; <-0.99,0.23,57>; <-0.83,0.48,35.5>; <-0.93,0.59,35>; <-0.83,1.08,35>; <-0.72,-0.67,54>; <-0.72,1.27,33>; <-0.56,-0.41,55>; <-0.56,0.32,54>; <0.20,0.04,59>; <0.20,0.37,54>; <0.37,-2.39,50>; <0.37,-1.78,50>; <0.37,-0.15,48>; <0.37,-0.13,48>; <0.53,-0.60,28>; <0.64,-0.60,28>; <0.91,0.06,53>; <1.18,-0.68,53>; <1.18,-0.42,54.5>; <1.18,-0.31,51>; and <1.56,0.58,30>.30>.

INTERPRETATION

Significance: Banding at certain limestone contents suggests an external factor. Observed differences with varying limestone and slopes may represent different wearing conditions. Limestone pavements are best with relative flat cross sections that potentially reducetangential wear. Good 'high limestone' friction at steeper cross-sections may represent a balance between superelevation and roadway alignment.

Figure No. 48|| Table No. 48

SIG. INDEX = 10

Future Action: Investigate superelevation balance and banding effect.

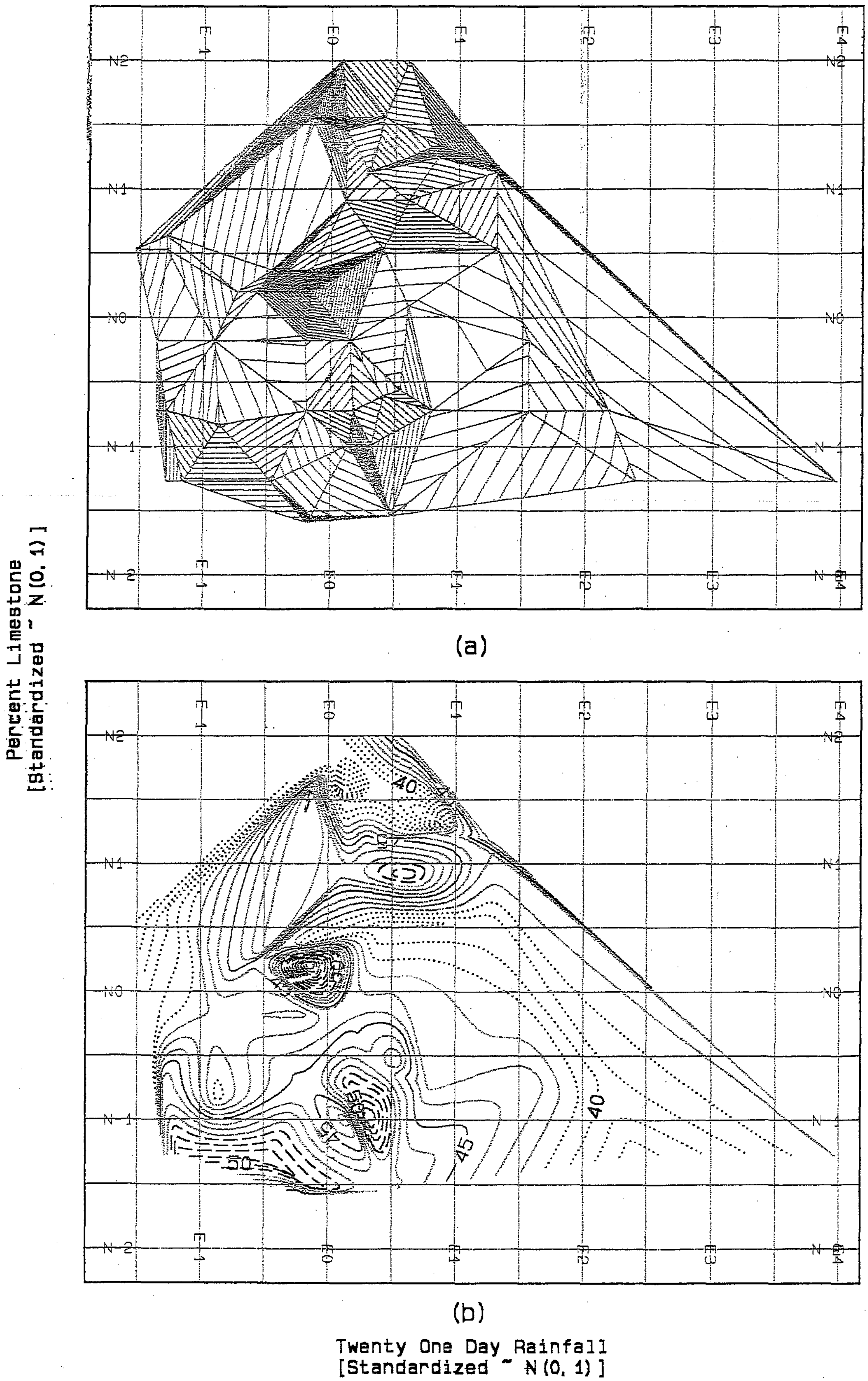


FIG. D.11 Skid Number Contours as a Function of Percent Limestone and Twenty-One Day Rainfall (a) Triangulation of Initial Data (50 pts) (b) Contours with Dotted Lines Indicating FN < 41 and Dashed Lines Indicating FN > 49 (763 obs run on 9/22/96)
[Copy FIG 52 from November 1999 Report]

DESCRIPTION

Factors: **Percent Limestone** quantifies the amount of limestone used in the coarse aggregate fraction of the pavement. **Twenty-One Day Rainfall** is the likely cumulative rainfall in the area twenty-one days prior to and including the day of the skid test.

Concept: Limestone is known to lose surface texture when polished. Pavements with little or no rainfall in the previously 21 days should have poor skid resistance because of the lack of cleansing.eansing. There is no interaction expected between these two factors.

Data: There are 50 interaction points between Percent Limestone and Twenty One Day Rainfall, each point representing from 1 to 69 test observations with average friction values from 31.5 to 59.33. Percent Limestone ranges from 14 to 80 (plotted from -1.595 to1.931) and Twenty One Day Rainfall from 1.02 to 8.87 (plotted from -1.572 to 3.544). Both factors are plotted as standardized values.

RESULTS

Main Effects: Friction performance generally declines as Percent Limestone is increased and peaks with near average twenty-one day Rainfall levels.

Joint Effects: Some joint effect is evident between these factors. Pavements with low limestone contents are not as dependent upon rainfall levels to maintain good friction performance as are higher limestone content pavements. At higher limestone contents, pavementperformance is improved with average rainfall levels while little or no rainfall generally results in poor friction performance.

Anomalies: No atypical friction values exist.

INTERPRETATION

Significance: This plot reflects the trade-off between the cleansing effect of rainfall in conjunction with the recoverable surface texture of the surface aggregates. The poor performance associated with moderately high twenty-one day rainfall while having low limestone content is a product of high day-of-test rainfall. Also, poor friction performance with high Limestone content and low rainfall may indicate the presence of pavement contamination from Limestone dust.

Future Action: The bunching up of pavement performance with twenty-one day rainfall indicates the values are from a single stretch of pavement or pavement within a single locale. This could be used as a clue in tracking down the performance banding observed on other plots.

APPENDIX E – RELATIVE SIGNIFICANT RANKINGS OF FACTOR PAIRINGS

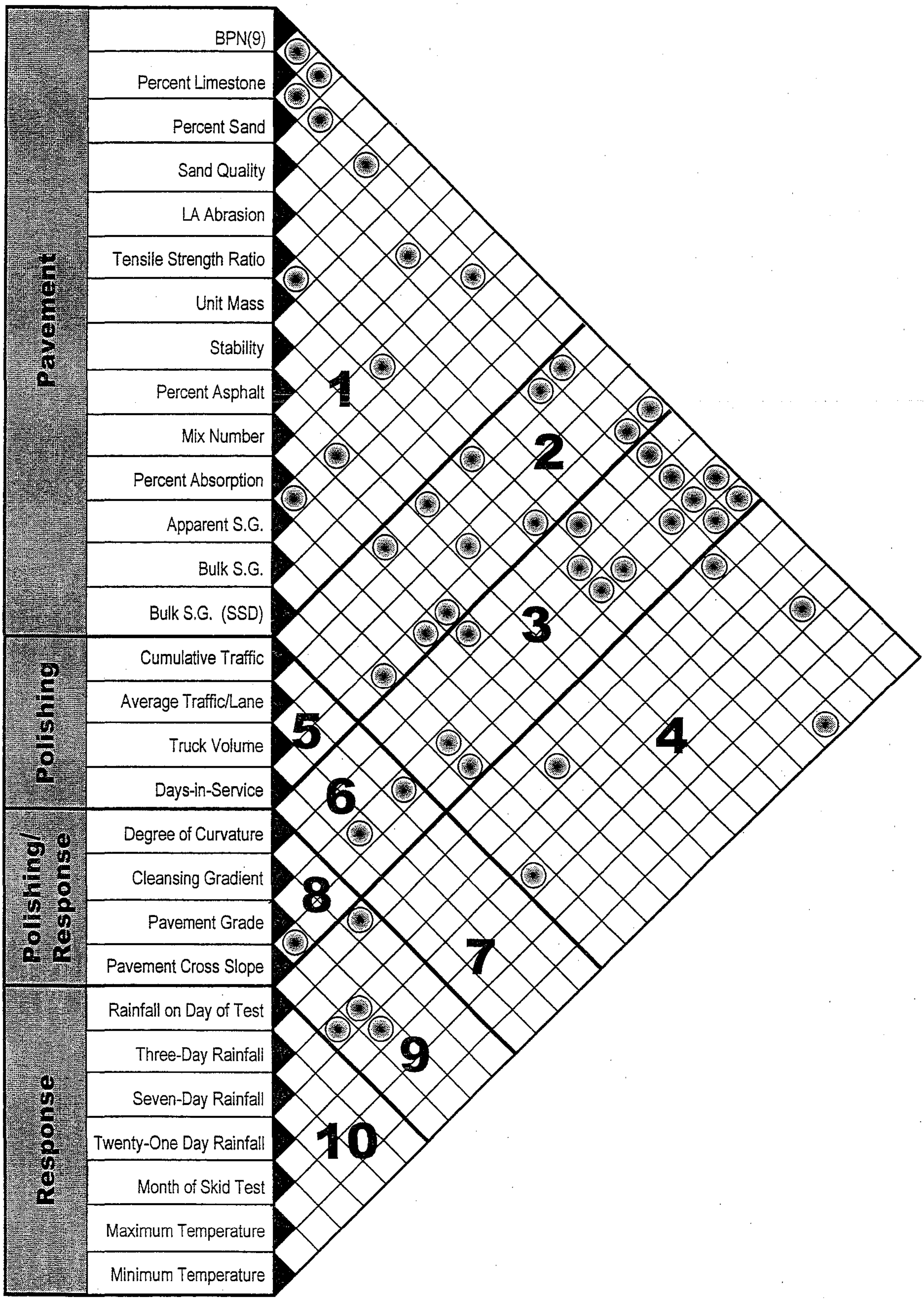


FIG. E.1 Factor Pairings with Significance Rank of 10 (Highest)

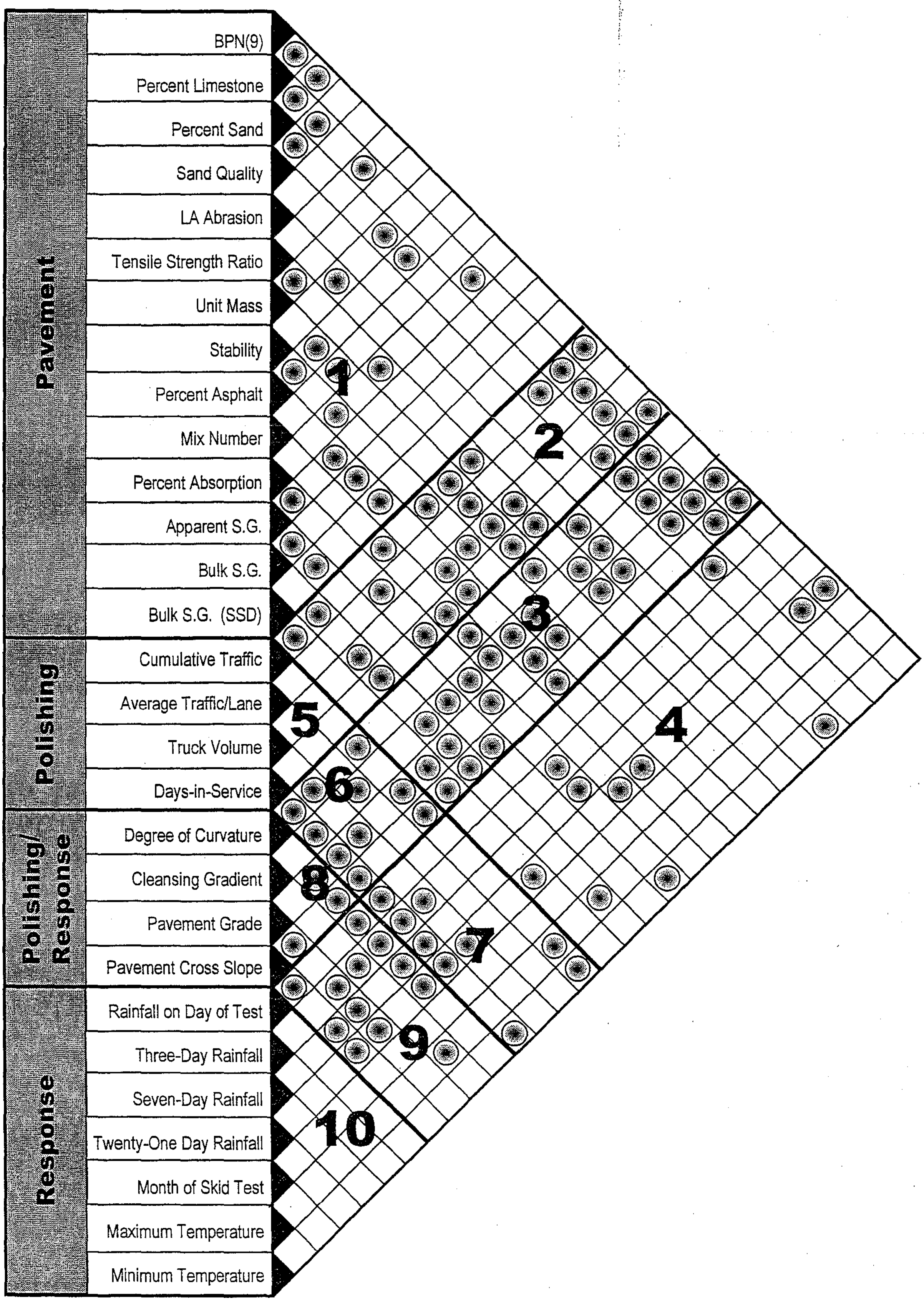


FIG. E.2 Factor Pairings with Significance Rank of 9

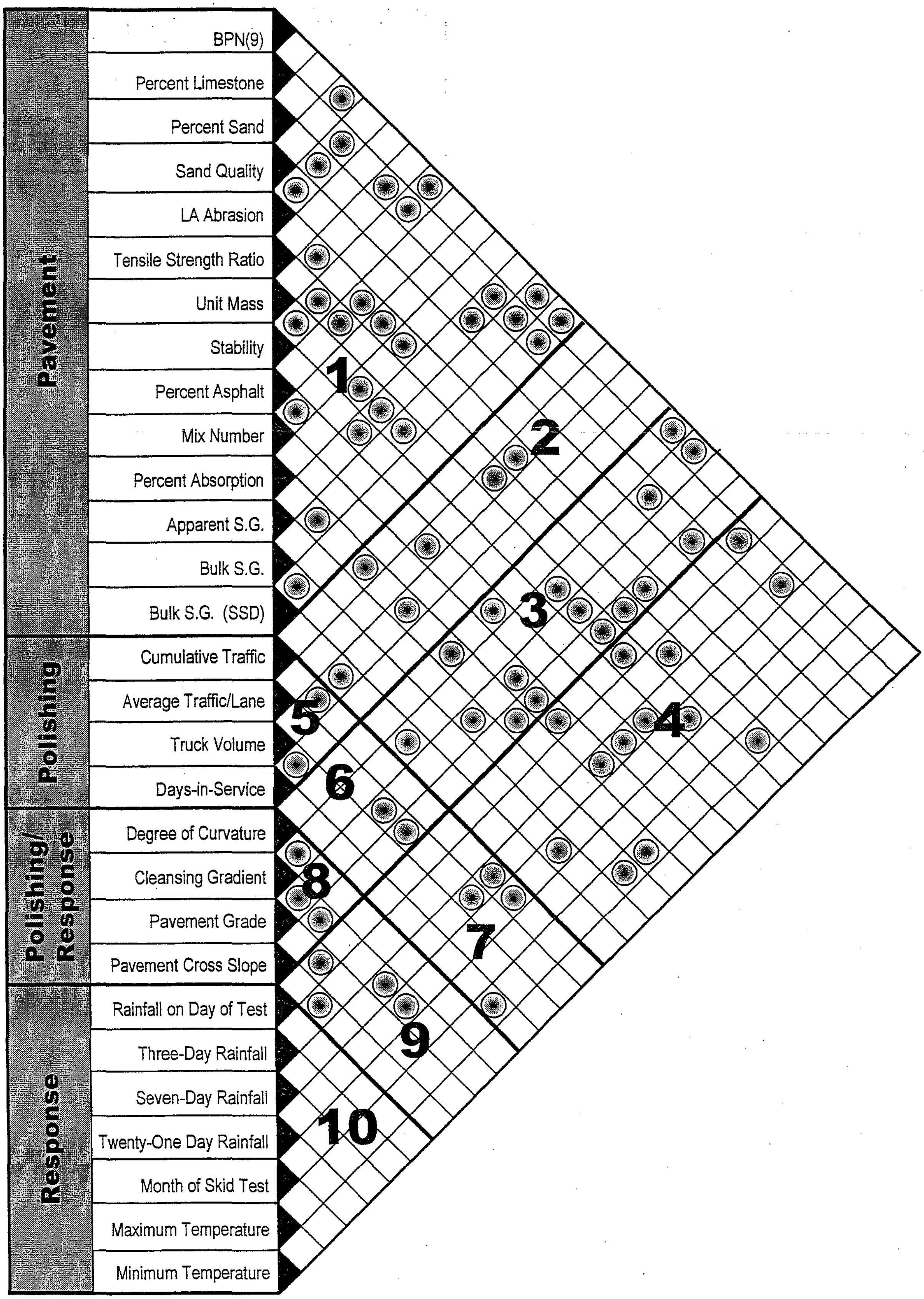


FIG. E.3 Factor Pairings with Significance Rank of 8

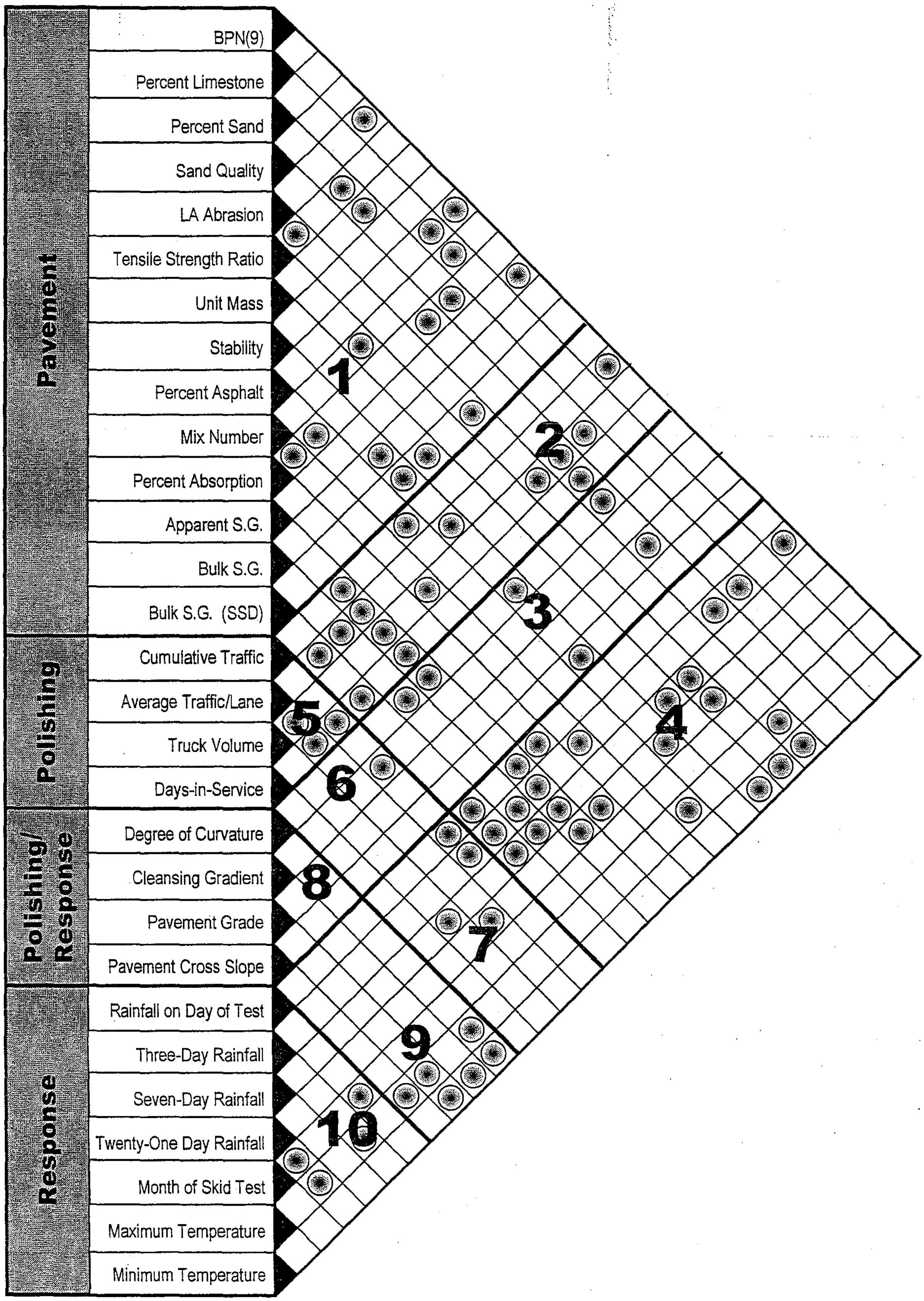


FIG. E.4 Factor Pairings with Significance Rank of 7

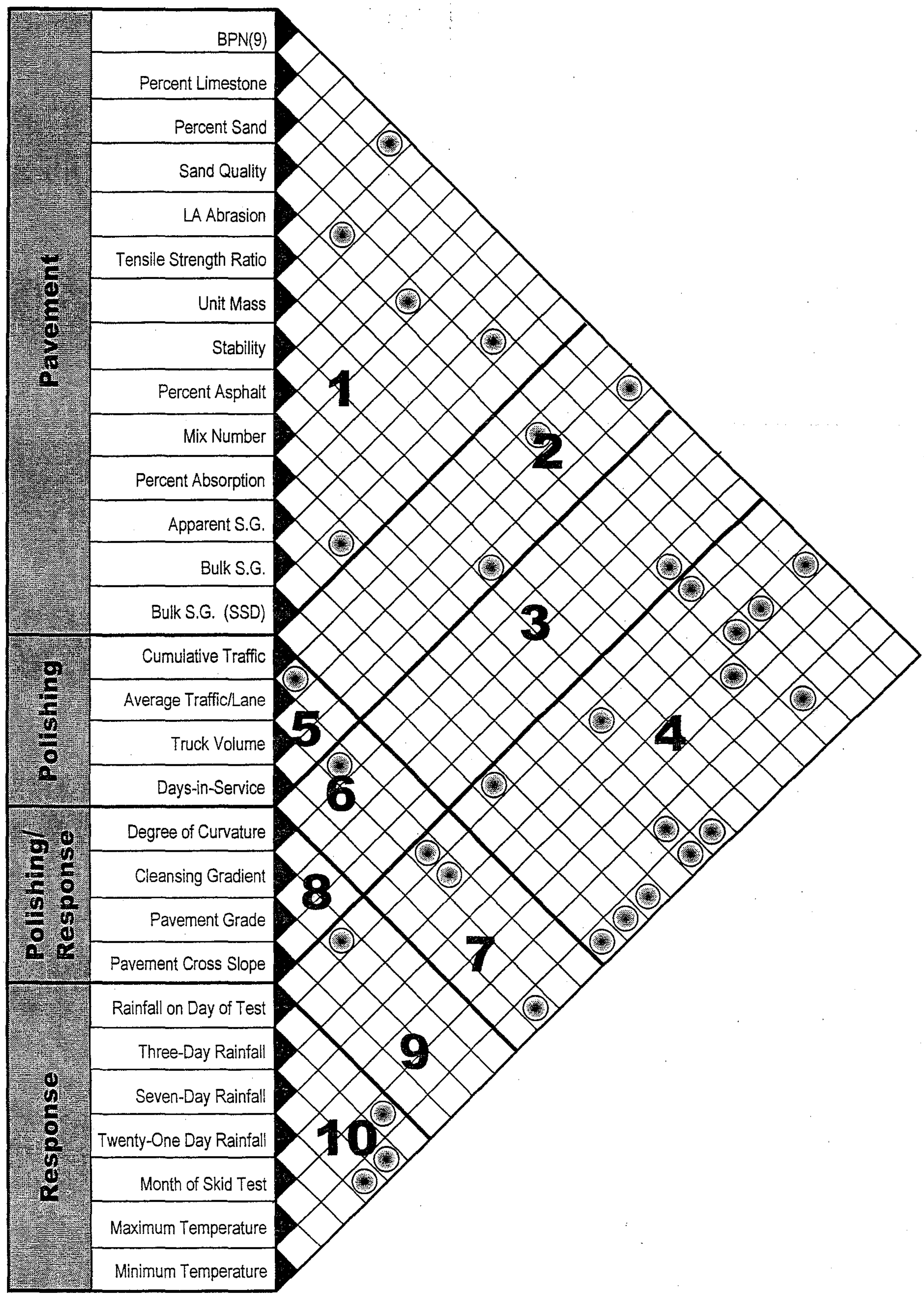


FIG. E.5 Factor Pairings with Significance Rank of 6

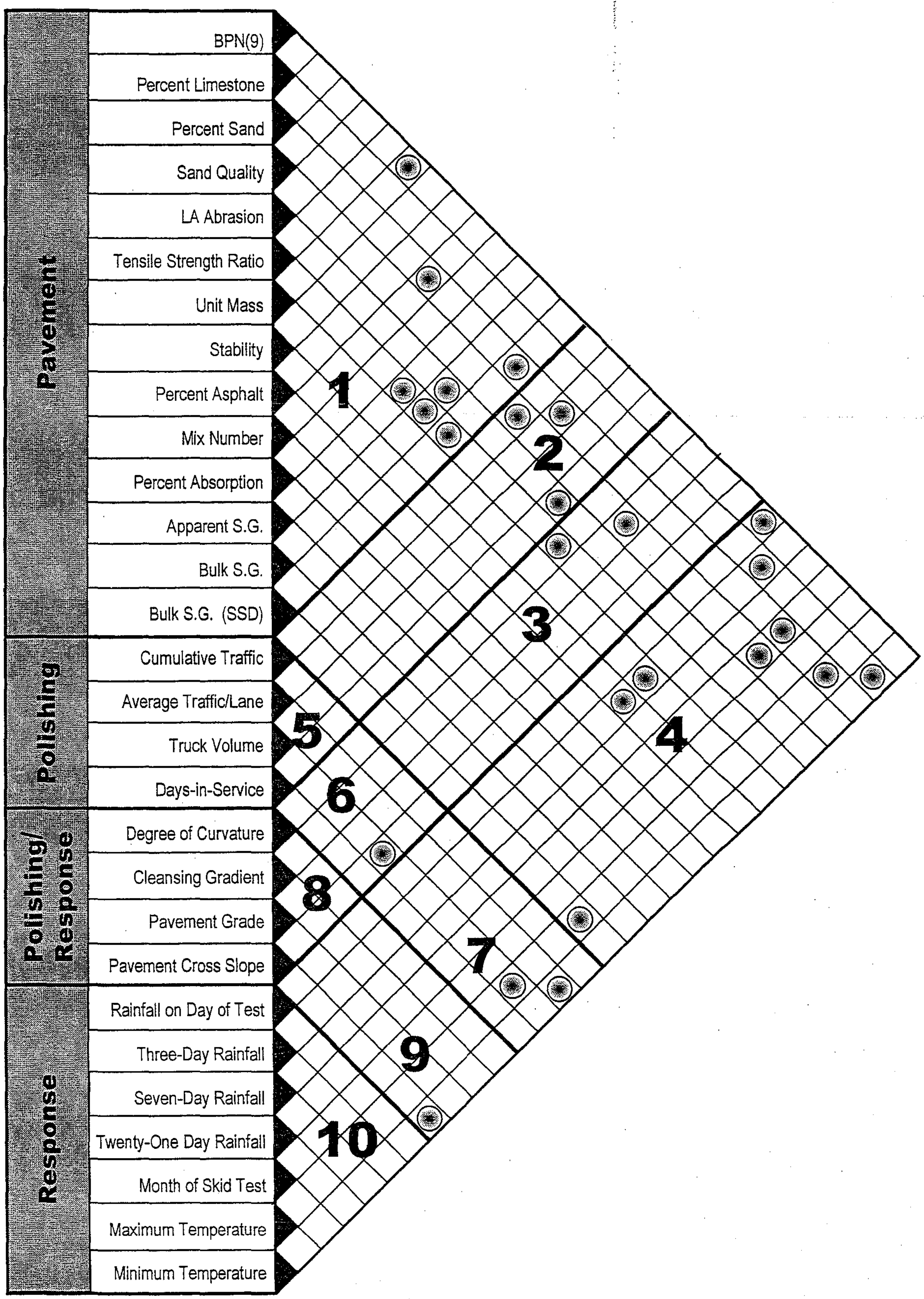


FIG. E.6 Factor Pairings with Significance Rank of 5

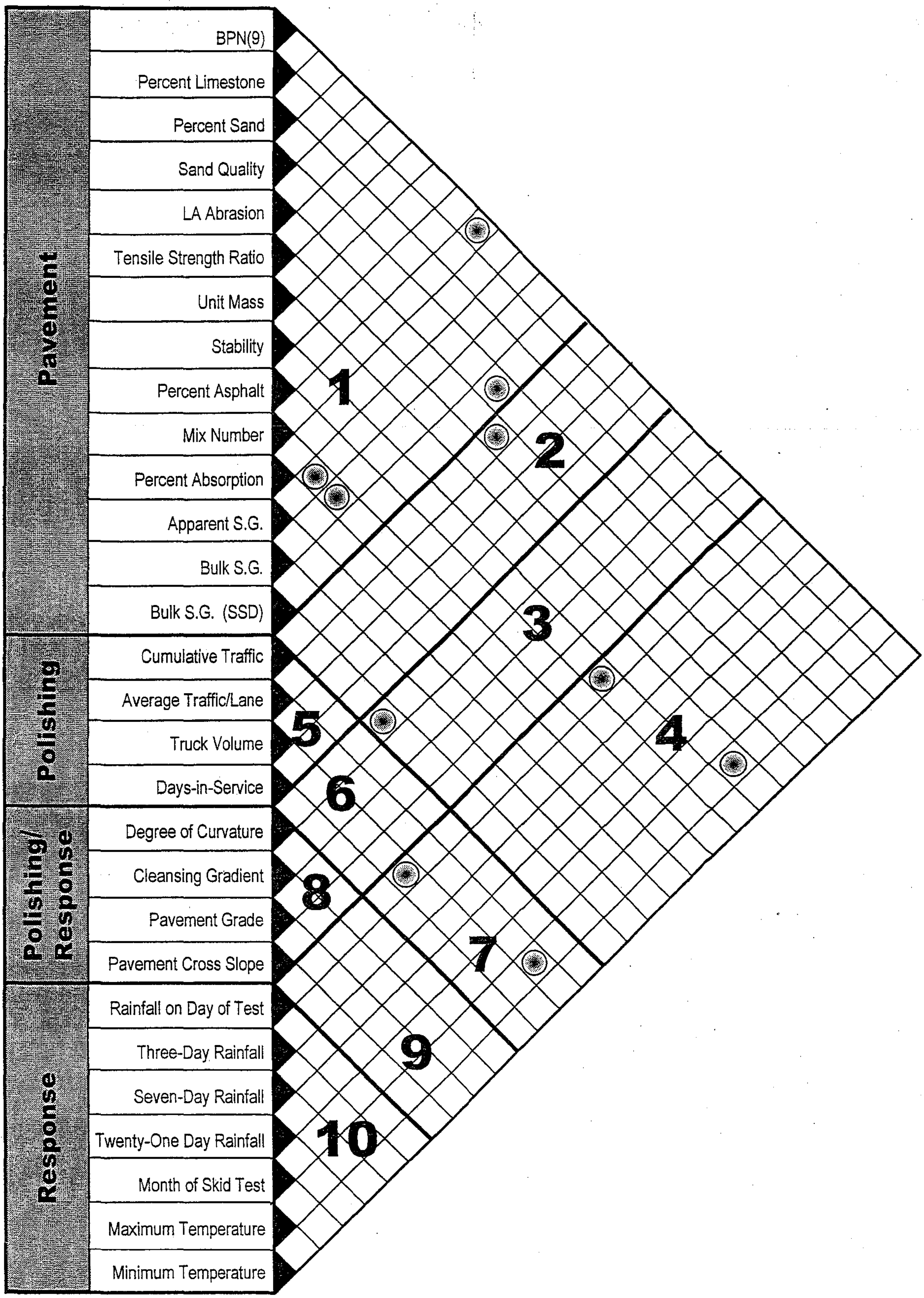


FIG. E.7 Factor Pairings with Significance Rank of 4

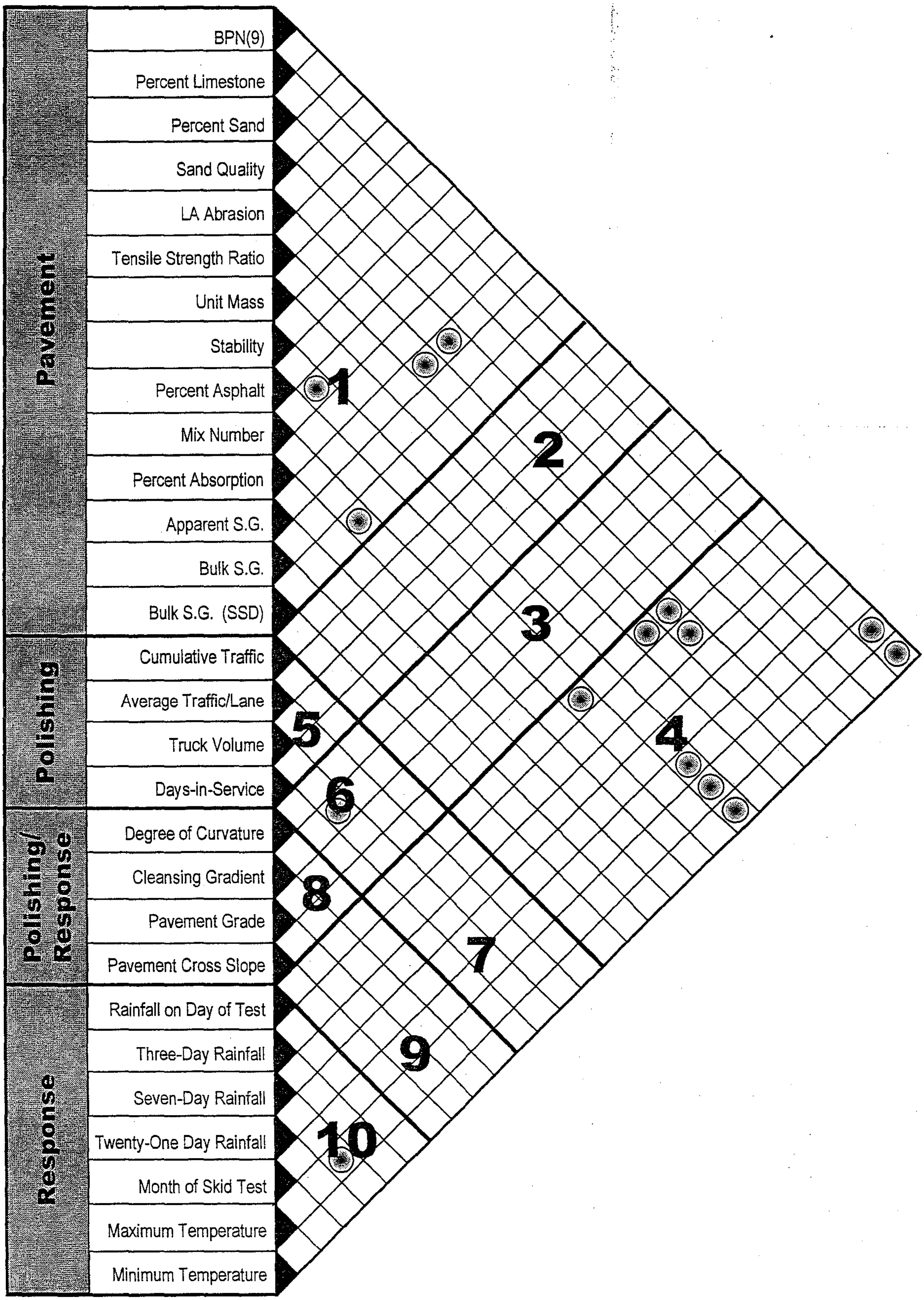


FIG. E.8 Factor Pairings with Significance Rank of 3

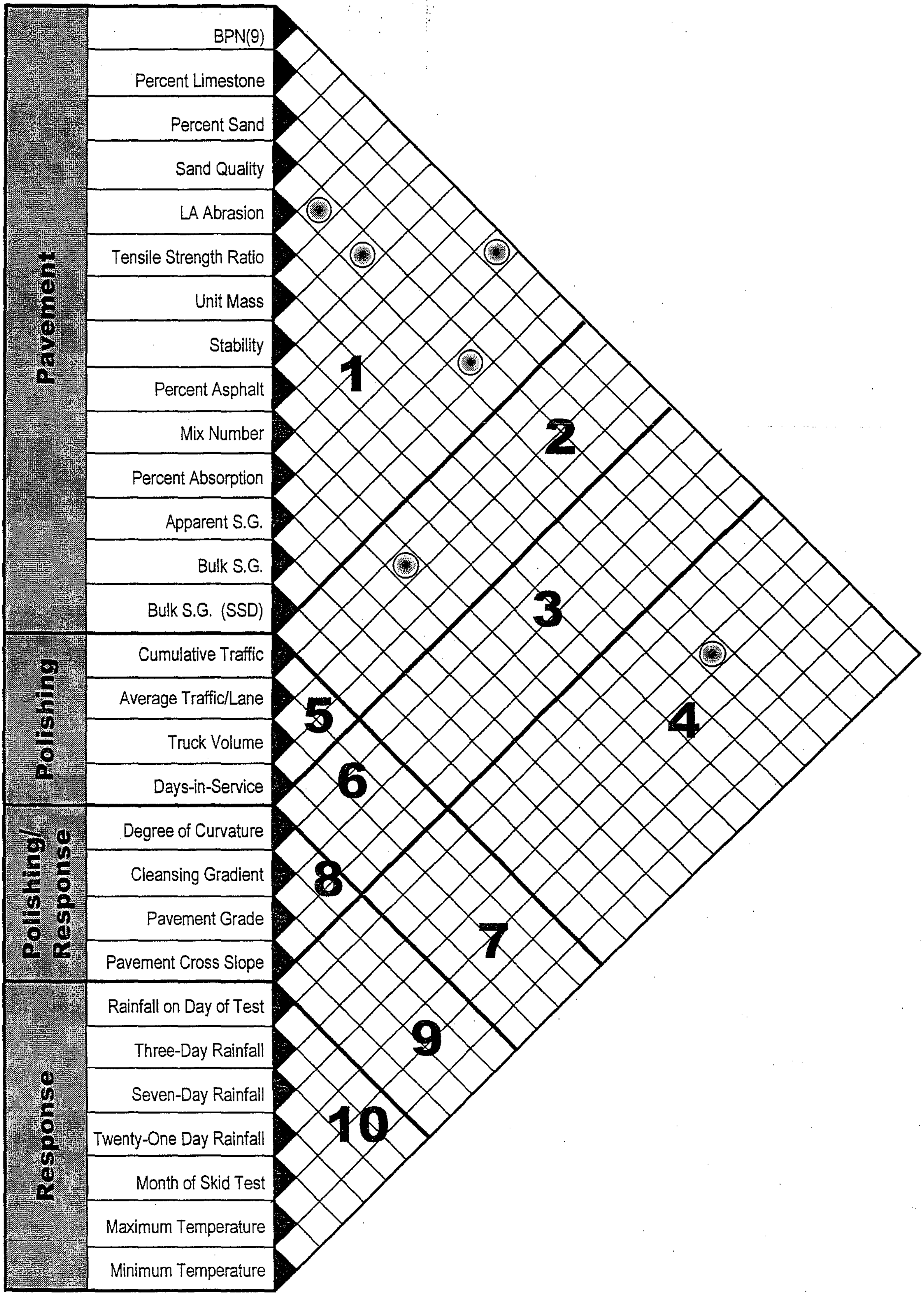


FIG. E.9 Factor Pairings with Significance Rank of 2

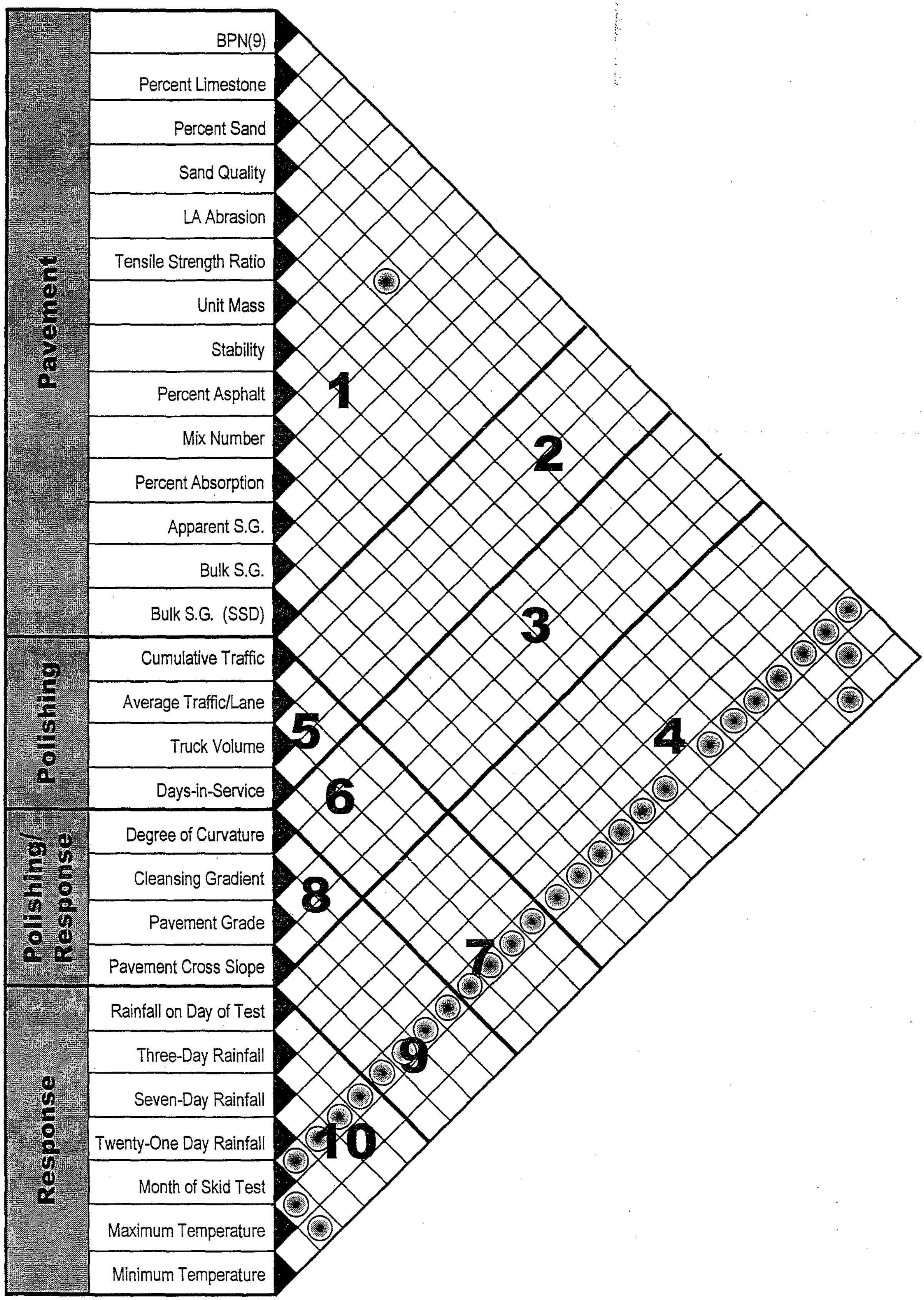


FIG. E.10 Factor Pairings with Significance Rank of 1 (Lowest)