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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

Establish Correlation between Aggregate Properties and Pavement Friction

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16. Abstract

Over the years the Maryland State Highway Administration (SHA) has encountered issues related to aggregate quality in regards to pavement friction. Furthermore, increased variability in aggregate friction test results has prompted a review of the existing approach to aggregate friction evaluation. To address this issue SHA has recently conducted a research project (Phase I) that had an objective to evaluate existing aggregate data including laboratory test results and petrographic analysis with particular focus on the frictional properties of aggregates. It was the objective of this research project (Phase II) to i) estimate pavement friction life for mixtures with aggregates from a variety of quarries, and ii) relate pavement friction to aggregate material properties. To achieve these objectives the project included: a review of the current state of practice in aggregate quality requirements and pavement friction measurements; merging of the SHA pavement friction records and aggregate/ mixture database; comparison between pavement friction devices used by SHA; development of a methodology for predicting pavement friction life for any mixture and aggregate; and the quantification of pavement friction life (in terms of cumAADT, ESAL, friction life in years since construction, and FNdrop/10K) for common SHA mixtures and aggregates.

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Table of Contents

	Abbreviations	iii
Chapter 1	Introduction	1
Chapter 2	Literature Review	2
Chapter 3	SHA Materials Database and Pavement Friction Records	11
Chapter 4	Equipment Variability Study	22
Chapter 5	Initial Analysis on Evaluation Factors Affecting Pavement Friction	34
Chapter 6	Methodology for Predicting Pavement Friction Life & Relating Aggregates to Pavement Friction	52
Chapter 7	Conclusions & Recommendations	88
	References	91
	Appendix A	93

Abbreviations

AADT - Annual Average Daily Traffic
AASG - Allegany Aggregates Short Gap
AASHTO - American Association of State Highway and Transportation Officials
AIR - Acid Insoluble Residue
AIR - Aggregate Industries Rockville
ANOVA - Analysis of Variance
ASTM - American Society for Testing and Materials
BPN - British Pendulum Number
BPT - British Pendulum Test
CumAADT - Cumulative Average Annual Daily Traffic
CumESAL - Cumulative Equivalent Single Axle Load
CV - Coefficient of Variation
Df - Direction Factor
DumTrk - Dummy Variable used for Equipment Type in Regression
ESAL - Equivalent Single Axle Load
FHWA - Federal Highway Administration
FN - Friction Number
ICM - Independent Construction Materials
KLC - Keystone Lime Company
LAA - Los Angeles Abrasion
LCH - Lafarge Churchville
LEF - Load Equivalency Factor
LF - Lafarge Frederick
Lf - Lane Factor
LW - Lafarge Warfordsburg
MER - Multivariate Exponential Regression
MLR - Multivariate Linear Regression
MMI - Maryland Materials Incorporated
MMW - Martin Marietta Woodsboro
MP - Milepost
NYSDOT - New York State Department of Transportation
OGFC - Open Graded Friction Course
PIARC - Permanent International Association of Road Congresses (World Road Association)
PV - Polish Value
SA - Sensitivity Analysis
SER - Simple Exponential Regression
SHA - Maryland State Highway Administration
SLR - Simple Linear Regression
VMH - Vulcan Materials Hanover
VMHDG - Vulcan Materials Havre De Grace
VMW - Vulcan Materials Warrenton
YBPBv - York Building Products Belvedere

Chapter 1 - Introduction

Over the years the Maryland State Highway Administration (SHA) has encountered issues related to aggregate quality in regards to pavement friction. Furthermore, increased variability in aggregate friction test results has prompted a review of the existing approach to aggregate friction evaluation. To address this issue SHA has established on-going partnering and quarry inspections with aggregate suppliers, and has recently conducted a research project (Phase I) that had an objective to evaluate existing aggregate data including laboratory test results and petrographic analysis with particular focus on the frictional properties of aggregates. It was the objective of this research project (Phase II) to i) estimate pavement friction life for mixtures with aggregates from a variety of quarries, and ii) relate pavement friction to aggregate material properties.

Objectives

The overall goal of this research project was to develop a methodology for predicting pavement friction life for mixtures with aggregates from a variety of quarries, and eventually relate pavement friction to aggregate properties. Thus the specific objectives were:

1. Identify the major factors affecting field pavement friction.

2. Using SHA pavement friction records to examine which parameters affect pavement friction for specific mixtures and aggregates;

3. Develop a methodology for predicting pavement friction life;

4. Combine SHA pavement friction and mixture data for identifying any relationships between aggregate material properties and field pavement friction.

Methodology

To achieve these objectives, the work under this research included: i) review the current state of practice in aggregate quality requirements and pavement friction measurements; ii) examine SHA pavement friction data, and the aggregate quality database along with the aggregate quality requirements identified in the Phase I research study; iii) identify the need for any additional field and lab testing data needed to complement the existing aggregate material and friction databases; iv) develop the methodology for predicting pavement friction of selected mixtures and aggregates; and v) establish the relationships between aggregate properties and pavement friction.

Chapter 2 – Literature Review

Background on Pavement-Tire Friction (Skid Resistance)

Friction is generally defined as the resisting force created between a surface and an object, acting in the opposite direction of the intended motion. Pavement Friction (Skid resistance) can be defined as the resistance force developed at the interface of a pavement surface and the tire of a vehicle traveling on the road. The interaction between the rubber and the pavement surface can be in the form of sliding or rolling. (AASHTO Guide 2008). As in any two materials coming into contact, energy dissipation occurs when rubber from the tire interacts with surface material from the pavement. The two types of energy dissipation are hysteresis and adhesion (AASHTO Guide 2008). During contact, the tire (which is made up of a visco-elastic material) undergoes deformation while the pavement, being relatively rigid, suffers minimal or small deformation. Energy is dissipated during the interaction between the tire and the pavement surface. This phenomenon is known as hysteresis (Li, Noureldin, and Zhu 2003). The greater the energy dissipation of the tire in contacts with the pavement, the better the skid resistance of the subject pavement. On the other hand, when the tire is pressed against the pavement material, molecular bonds are formed between the tire and surface particles. The larger the number of bonds formed in such manner, the greater the energy required to break the bonds and therefore better skid resistance is achieved. The shearing of these bonds is called adhesion (Li, Noureldin, and Zhu 2003).

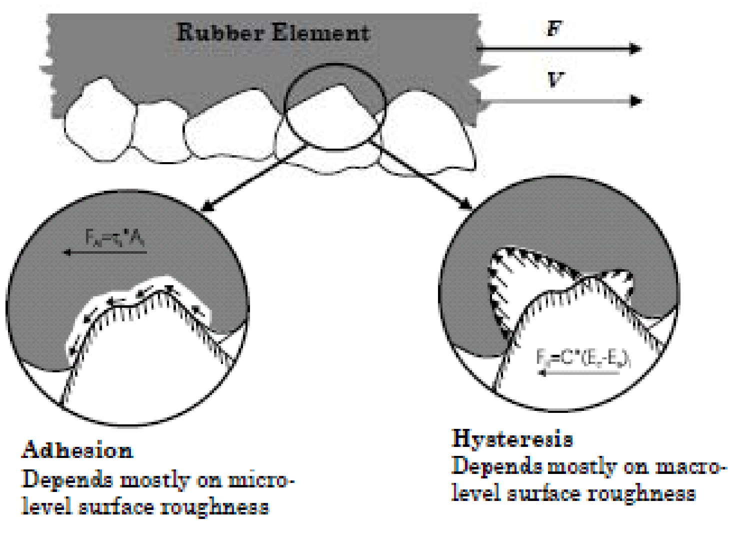


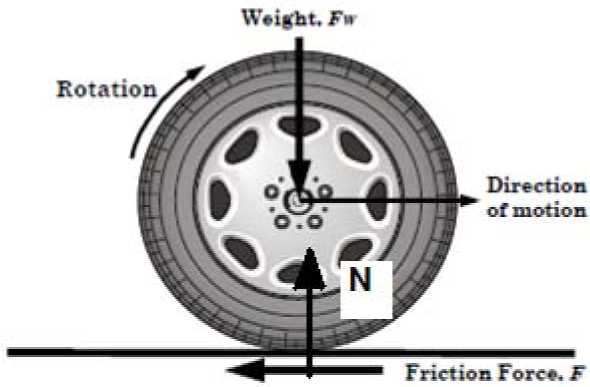
Fig 2-1. Key mechanisms of pavement–tire friction (AASHTO Guide 2008)

In terms of skid resistance, there are two kinds of friction: static and kinetic friction. Static friction is the result of the interlocking of the irregularities of two surfaces (tire and pavement) to prevent any relative motion until and up to some motion occurs. Just after the motion occurs, the two surfaces start moving against one another and static friction will give way to kinetic friction. The purpose of the kinetic friction is to keep the object in motion. Usually the kinetic friction is less in magnitude than the static friction.

Friction is often represented by a coefficient that is unitless (designated as μ). The coefficient of friction is a function of the normal (reaction) force in a direction perpendicular to the surface (and the resisting force which is parallel to the surface and acting in the opposite direction to the motion). The coefficient of friction is given as follows per the Law of Coulomb/Amonton:

$$\mu = F/N \quad (1)$$

Where μ = coefficient of friction;
F = tractive/friction force
N = normal force on tire (Equal to Weight on wheel, Fw)



<u>Fig 2-2. Simplified Diagram of Forces Acting on a Rotating Wheel (Adopted from AASHTO Guide 2008)</u>

Mechanism of Pavement Friction

For a vehicle traveling on given pavement, there are two forms of friction acting on the tire of the vehicle – longitudinal and side force friction. In Longitudinal friction, there are two modes of operation between the pneumatic tire and road surface; rolling and constant-braked. In the free rolling mode (no braking), the relative speed between the tire circumference and the pavement, also known as the slip speed is zero. In the constant-braked mode, the slip speed increases from zero to a potential maximum of the speed of the vehicle. A locked-wheel state is often referred to as a 100 percent slip ratio and the free-rolling state is a zero percent slip ratio. This relationship is depicted as follows (Meyer, 1982):

$$S = V - V_p;$$

Where: S = Slip speed, mi/hr.
V = Vehicle speed, mi/hr.

Vp = Average peripheral speed of the tire, mi/hr. Vp= (0.68 ω r)
ω = Angular velocity of the tire, radians/sec.
r = Average radius of the tire, ft.

Primary Factors Involved in Tire-Pavement Friction Interaction

The factors that determine the friction outcome of a given pavement can be summarized in four major categories, namely: Material Related, Loading/age related, environmental/site related, and Testing/Vehicle Operation related.

Material Related

Materials involved in the tire-pavement interaction are the rubber that makes up the tire, and materials that make up the pavement surface structure (aggregates and asphalt binder in the case of Flexible Pavements; aggregates and Portland cement in the case of Rigid Pavements). The tire, being a viscoelastic material, is susceptible to significant temperature and moisture changes. Pavement wetness especially has an impact on the dissipation of energy at the contact surface between the tire and the pavement. In addition, the condition and type of tire plays a significant role on how water film trapped between the rubber and the pavement can drain out, leading to an increase in the adhesion between the tire and the pavement. Draining of water out of the tire-pavement interlock is a function of the tire tread design and the level of smoothness of the tire. Macrotexture (the series of larger irregularities formed by the spaces between individual aggregate particles) provides channels through which water can be expelled out of the tire-pavement interface. At high speeds, tread depth is particularly important for vehicles driving over thick films of water. Therefore smooth tires have a significantly lower wet friction resistance compared to well-treaded tires (Henry, 1983). Moreover, deflated tires exhibit lower friction resistance on wet pavements, especially at higher speeds, because of the longer residence time of the water film between the rubber and the pavement interface (Henry, 1983; Kulakowski, 1990).

There are two basic components that make up a pavement surface: aggregates (coarse and fine aggregates graded and blended as required) and a binding agent (Asphalt or Portland Cement) that are mixed together to form a durable matrix. Depending on the type, size and proportion of aggregates used in the pavement mixture, the pavement surface will have certain texture characteristics that determine the pavement's skid resistance. Pavement texture influences both parameters of friction – hysteresis and adhesion. Pavement surface texture refers to the irregularities on the pavement as well as the various irregularities on each aggregate particle used on the pavement surface. The surface irregularity of individual particles is referred to as "Microtexture." Microtexture ranges in size from 0.0004 in. to 0.02 in. The larger irregularities formed by the spaces between individual particles on the pavement surface are called "Macrotexture." Macrotexture can range in size from 0.02 in. to 2 in. Microtexture and adhesion are the prevailing factors influencing skid resistance at speeds less than 30 mph (AASHTO Guide 2008). Other surface irregularities that are larger in size than 2 inches and less than 20 inches are called Megatexture. (PIARC 1987). Irregularities that are larger than 20 inches are considered as roughness and have minimum bearing in pavement skid resistance (Henry 2000).

Table 2-1. Factors affecting pavement friction

Material Related	Loading/Age Related	Environmental/Site Related	Testing/Vehicle Related

Tire Rubber
 	
Pavement Surface Materials
• Micro-texture
• Macro-texture
• Megatexture/Unevenness
• Binder Type and Content
• Mix Properties
  o Mix Type
  o Mix Characteristics
• Aggregate Properties
  o Gradation/Particle Size
  o Angularity/Asperity
  o Toughness
  o Carbonate/non-carbonate
  o Silica content
	Traffic Volume (AADT)
	
	Traffic Composition/truck percentage
	
	Pavement Construction year/Pavement Age
		Urban/Rural
		
		Road Geometry
		• Vertical Alignment
		• Horizontal Alignment
		• Cross Slope
		
		Temperature (Pavement and Air)
		
		Rainfall
		
		Pavement Surface cleanliness
			Vehicle Speed/Slip Speed
			
			Tire Tread (Design, smooth vs ribbed)

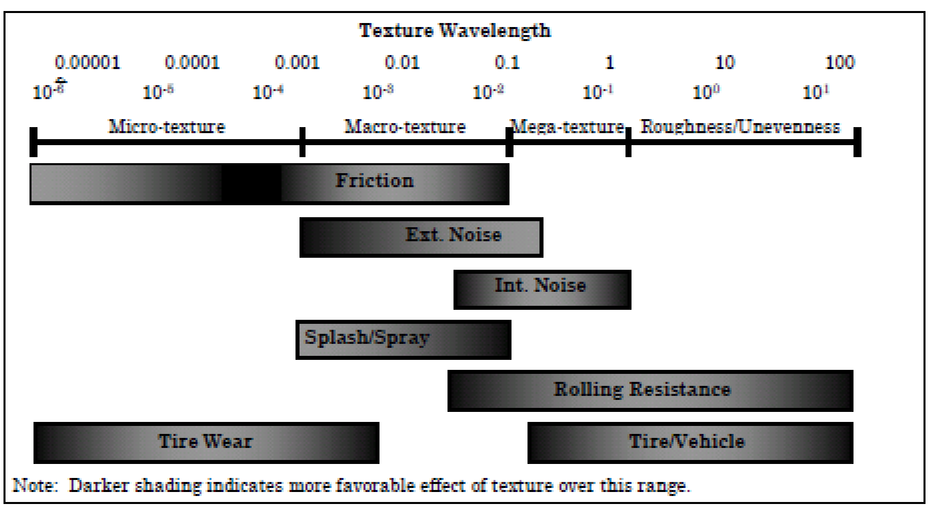


Fig 2-3. Texture wavelength influence on pavement–tire interactions (AASHTO Guide 2008)

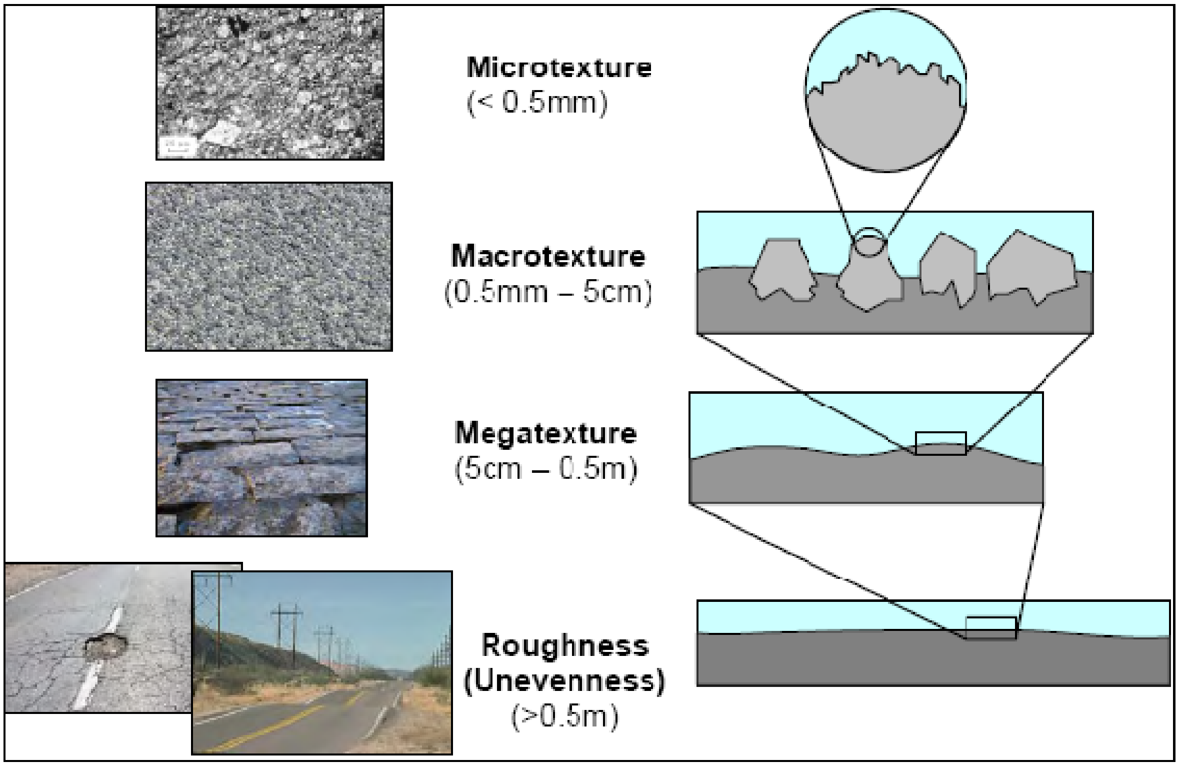


Fig 2-4. Representation and examples of surface textures (FHWA 2006)

Literature on Pavement indicates that microtexture and macrotexture ultimately determine wet-pavement friction. This is because the adhesion force component depends on the microtexture and the hysteresis force component on the macrotexture (Henry 2000). Also, surface drainage depends on the separation between individual particles which is represented by the macrotexture. A pavement with high roughness does not necessarily have large surface friction. On the other hand, an attempt to enhance pavement friction by making surface too coarse or too smooth may result in high noise, splash, or spray problems. The design of surface texture therefore requires a balance and compromise among skid resistance, internal/external noise, tire wear, and splash/spray.

Aggregate and mix characteristics, surface treatments such as tinning and other surface finishes influence both microtexture and macrotexture. Individual and grouped aggregate resistance to polishing and abrasion has direct contribution to friction resistance of the pavement surface while the type and amount of binder used in a particular mixture determines the coating on each aggregate, thereby affecting both macrotexture and microtexture. The type and composition of pavement mixture (type and grade of binder and gradation of aggregate blend) has been found to be significantly correlated to polishing resistance as exhibited in the British Pendulum Number (BPN) (Bazlamit, 2005). The following aggregate properties have correlations with the friction performance of a pavement:

- Presence of Carbonates: Skeritt discussed the various impacts of the three different types of aggregates – homogenous, sandy and blend - classified based on their polishing characteristics; one significant element of aggregates that has been found to have an impact on polishing resistance is the presence of carbonates in the mineralogical composition of the aggregates. The less percentage of carbonates available in an aggregate blend, the higher the resistance of the aggregate blend to polishing. (Skeritt 1993)
- Presence of Silica: Skeritt found out that, generally sandy rocks have a higher resistance to polishing irrespective of the traffic level. One way of quantifying this quality is by using the Acid Insoluble Residue (AIR) test. This test measures the percentage of acid insoluble residue that withstood degradation from a chemical action. New York State Department of Transportation (NYSDOT) specifies that good polishing resistant aggregates should have an AIR of 15% or more. (Skeritt 1993).
- Toughness: Toughness, as measured by the Los Angeles Abrasion or the Micro-Deval Test, is another method of quantifying how a bulk of aggregates is able to resist abrasion and degradation from mechanical and physical impacts. It is important to note that, though toughness might not directly relate to polishing resistance of aggregates on the actual pavement, it can be correlated to other more directly applicable tests such as the British Wheel (BPN). (SHA Phase I study, Massad 2008)
- Gradation and Angularity – Luce et al (2007) have investigated the impact of aggregate gradation using samples obtained from various sources and used in three different mixes.
- Chemical Reactivity /Inertness – Good aggregates are those that are inert, i.e. do not chemically interact with other compounds unless needed. One test that measures durability of aggregates against chemical action is called "Magnesium Sulphate Soundness Test," which measures the percent loss of aggregates due to chemical weathering. Since the pavement surface is exposed to various pollutants and chemicals, it is important that aggregates used on pavement surfaces be highly resistant to weathering due to chemical action.
- Clay Content/Friable Particles – It has been found that excessive clay lumps and friable particles in aggregate intended for use on pavements may interfere with the bonding between the aggregate and the binding material. This will result in spalling, raveling, or stripping and create weak points and pop-outs out of the pavement structure hence compromising its skid resistance and other qualities. (Kandhal 1998). One standard test to measure this phenomenon is AASHTO T 112 (Clay Lumps and Friable Particles in Aggregates).
- Resistance to Polishing as measured by the Accelerated Polishing Test (Using British Wheel) and the British Pendulum Test (BPT) – The resistance to polishing and abrasion is not solely dependent on one particular aggregate property. As a result, it is important to measure the actual performance of the resistance of an aggregate blend or mixture to continued physical and mechanical abrasion using the above tests (FHWA 2006).

In addition to individual and group aggregate properties, the type and composition of the pavement surface mixture also plays a significant role in determining the friction performance. Studies have shown the impact of texture and aggregate surface characteristics on the outcome of pavement friction for various Hot Mix Asphalt mixtures that were made up of aggregates obtained from various sources and with varying mineralogical compositions; (Masad 2007, 2008; Luce et al 2007; Li et al 2007). Li et al investigated friction performance of various mixes in Open Graded Friction Courses (OGFC), Stone Matrix Asphalt (SMA) and Superpave mixes that were made of steel slag, crushed gravel or naturally obtained aggregates. Luce et al also investigated quartzite, sandstone, and siliceous gravel, combined in three different mix types referred to as Superpave, CMHB-C, and Type C (Texas Specific Mixes). The type and performance of the binder used in mixes also plays a role in the friction performance as investigated by Luce et al. In addition, aggregate spacing together with gradation determines the type and size of Macrotexture of an aggregate blend. Fwa et al (2003) have shown that aggregate spacing (within a blend) and mineralogy have an impact on skid resistance of pavements. Cafiso et al demonstrated using aggregate imaging and photographic techniques that the British Pendulum Number has a significant correlation with surface smoothness/roughness of aggregate particles, by using various descriptors of the aggregate surface (Cafiso et al 2006). Moreover, petrography and rock composition of aggregates used in the preparation of a pavement mixture play a significant role in the friction performance of the pavement (Masad 2008; SHA Phase I study 2008).

Loading/Age Related

Pavement friction performance can be attributed to factors pertaining to the age of the pavement surface and the amount and type of traffic applications on the particular pavement section. The rate of polishing of a given pavement surface is a direct result of the number and type of traffic applications on the pavement. Studies have shown that friction performance increases gradually for the first year or two after construction – attributed to binder flushing – and decreases thereafter with an increasing traffic loading (Li et al 2007). It has also been shown that pavements constructed with different aggregate types exhibit varying rate of decline in friction performance (Skerritt 1993; Crouch et al 1998). Rate of friction performance as a result of repeated traffic loading is also dependent on the homogeneity of the aggregate blend.

Pavement Construction year/Pavement Age – The number of years a pavement surface has been in service determines how the surface would perform in terms of skid resistance. Studies have shown that the skid resistance of pavements decreases from an initially higher value to a somewhat constant value in a matter of a few years (Masad 2008; Li et al 2007).

Traffic Volume (AADT) and Traffic Composition (ESAL) – Pavement aging can be enhanced by the amount and type of traffic using the road on a continuous basis. It has been found out that the decline of skid resistance can be attributed to the Average Annual Daily Traffic (AADT) (Skeritt 1993) and the traffic mix as expressed in terms of

Equivalent Single Axle Loading (ESAL) (Li et al 2007).

Environmental/Site Related

The main environmental or site related factors that have an impact on pavement friction are road geometry as represented by general location of route (urban versus rural) horizontal and vertical geometry (grade, curvature, cross slope), pavement and air temperature, rainfall (frequency and severity), pavement wetness, presence of snow/ice and general pavement surface cleanliness.

Temperature - Because tires are made up of rubber which is a visco-elastic material, their characteristics are affected by higher temperature (caused by repeated and sudden braking) which causes hydroplaning as a result of melting of the rubber material. This condition causes a reduction in the hysteresis component of the friction resistance. The hysteresis component is found to comprise a larger portion of the total friction force than the adhesion component as measured with the British Pendulum Tester. The hysteresis component of friction decreases with increased temperature regardless of surface texture state. The adhesion component of friction decreases with increased temperature for a polished pavement surface. (Bazalmit et al 2005)

Smith, Chen, Song and Hedfi have found by studying the climate and friction records of the pavement network in Maryland that one degree (°F) increase of temperature leads to one unit decrease of FN. (Chen et al 2005). It has been found that skid resistance decreases with increased temperature and an approximately linear relationship exists between skid resistance and temperature with resulting models relating British Pendulum Number and skid number obtained at any arbitrary temperature to a reference temperature of 293.15 K ~68°F (Bazlamit et al 2005)

Pavement wetness - The two mechanisms by which energy is dissipated and friction force is developed through transfer of energy are hysteresis (loss of heat from the rubber) and adhesion (transfer of energy by contact). Generally adhesion is related to Microtexture while hysteresis is related to Macrotexture. When the pavement is wet, a water film is created between the two materials causing a drop in the adhesion component. The presence of water film between tire and pavement creates a condition called hydroplaning which results in an almost zero friction resistance of the pavement. It has been discovered that the effect of water film is not significant at speeds less than 25 mph while it has been found that it has a negative impact on the friction performance of the pavement at speeds higher than 40 mph (AASHTO Guide 2008).

Snow/Ice- Related to pavement wetness, snow and ice also create a film between the tire and the pavement which reduces the skid resistance of the pavement.

Testing/Vehicle Related

Many states use tractor-trailer assembly to measure the skid resistance of a pavement surface as prescribed in the ASTM E 274 testing procedures. In this test a tractor trailer combination consisting of a mid-size truck and a two-wheel trailer are driven over the pavement to record the skid resistance of the pavement surface by using a two-axis force transducer(s) mounted on the axle assembly. As a result the quality of the friction readings recorded using this equipment are dependent on the following factors:

Slip Speed - the speed at which the vehicle is traveling has a direct relationship with the slip speed. It has also been discovered that the coefficient of friction between a tire and the pavement changes with varying slip (Henry 2000). Skid Resistance increases sharply with increasing slip to a peak value that usually occurs between 10 to 20 percent slip. The friction then decreases to a value known as the coefficient of sliding which stabilizes to a 100 percent slip and a constant value of coefficient of friction which occurs at 100 percent slip. Speed also impacts the side friction resistance. The following figure shows the relationship between percentage of tire slip and coefficient of friction.

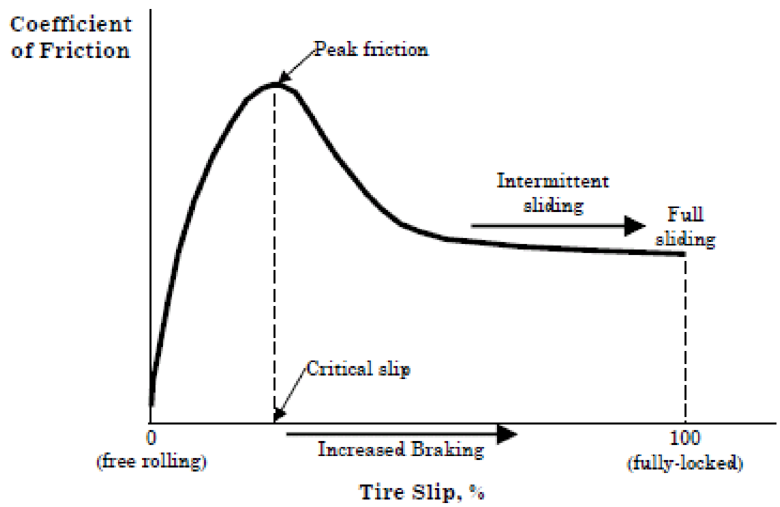


Fig 2-5. Pavement Longitudinal Friction versus Tire Slip (Henry, 2000).

Research has also shown that Friction Number varies with changes in test speed, and that there is a strong linear correlation between readings done using the ribbed tire for the ASTM E-274 test at 25 mph and 40 mph with the best relationship between these two parameters found to be to be polynomial (Jackson 2008; Li et al 2007). It has also been shown using actual friction readings in Maryland that FN values decrease at a rate of approximately 9 FN units per an increase of 5 mph in test speeds (Goulias and Awoke, 2007). At speeds less than 40 mph, the microtextue (adhesion) component contributes greatly to the skid resistance, while macrotexture governs at higher speeds (Dewey et al 2001).

Chapter 3 – SHA Materials Database and Pavement Friction Records

In order to study the relationships between pavement friction and aggregate properties the following databases and records were used.

1. Pavement Friction Records

The pavement friction records considered in this study included five years of friction data, from 2004 to 2008 with approximately 160,000 records. Overall the data are organized by Year and Route. The fields included in the database are shown in Table 3-1, while a screen shot of the Friction Database in Microsoft Access is shown in Figure 3-1. Most of the data were collected from early spring to late Fall. However there was variability in the timing of surveys at the same location from year to year. For example the data collected in 2004 were collected from March to September, while for 2006, the friction surveys were run from April to November, and so on. About 72 percent of the friction surveys represent sections with FN values between 36 and 55. The data include sections that have been surveyed for the five consecutive years, and thus include the historical change of FN in time. Any missing values and/or values outside the expected range of FN were identified and flagged in the database. About 50 percent of the sections were surveyed at the specified slip speed of 40 mph, and about 84 percent of the sections surveyed between 2004 and 2008 were evaluated at speeds between 38 and 42 mph. The reported AADT values reflect the local conditions (Rural vs Urban). About 95,000 of the surveyed sections were collected on rural conditions. Inconsistencies in AADT counts between consecutive years for the same sections were examined. In some cases there were missing AADT entries and/or very low values. These data were further examined. The SHA engineers cross referenced the contract number from the friction database to the construction database for including information on the year of rehabilitation/maintenance (ACTION_YEAR) related to the specific sections that the friction surveys were conducted, and for identifying the type of material used (Material_Type). For a certain number of sections no rehabilitation information was available, and thus the age of the existing roadway surface is unknown. In the database there are also sections that have not received any rehabilitation in the last 40 to 50 years. These data were further examined. In terms of materials, the majority of the roadway surfaces represent HMA mixtures. Thus this type of surfaces was targeted for the analysis of this study.

Table 3-1: Friction Reading Database Field name, type and description

Field Name	Data Type	Description
YEAR	Number	
CODE	Number	County Code
MUN	Number	
ROUTE	Text	
RNUM	Number	Route Number
RSUFF	Text	
Mile	Number	
DIRECTION	Text	
SPEED	Number	
FN	Number	
DATE	Date/Time	Date of Survey
AADT	Number	
UorR	Text	Urban vs. Rural
ACTION_YEAR	Number	from construction history
CONTRACT	Text	This is from Construction History
Material_Type	Text	This is type of material used
DayCompleted	Date/Time	This is maintenance date
MonthCOmpleted	Text	This is maintenance month
YearCOmpleted	Number	This is maintenance year
MaintenanceContract	Text	This is contract number in maintenance history
ProjectType	Text	Maintenance Type
Truck	Number	5: International Cybernetics; 6: Dynatest

Friction_Result

YEA	CC	ML	RO	RNU	RS	Mile	DI	SPEED	FN	DATE	AADT	U	ACTI	CONTRACT	Material_Typ	Day	MonthCo	Year	Maintena	Project	Truck
2004	11		MD	42		1.28	N	38	57	8/25/2004	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2004	11		MD	42		1.33	S	43	56	8/25/2004	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2004	11		MD	42		1.58	N	39	55	8/25/2004	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2004	11		MD	42		1.63	S	40	59	8/25/2004	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2004	11		MD	42		1.88	N	38	61	8/25/2004	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2004	11		MD	42		1.93	S	39	57	8/25/2004	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2005	11		MD	42		1.33	N	38	57	9/1/2005	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2005	11		MD	42		1.41	S	39	57	9/1/2005	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2005	11		MD	42		1.63	N	40	54	9/1/2005	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2005	11		MD	42		1.71	S	40	52	9/1/2005	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2005	11		MD	42		1.93	N	39	56	9/1/2005	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2006	11		MD	42		1.18	S	40	55	8/29/2006	3440	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2006	11		MD	42		1.18	N	40	58	8/29/2006	3440	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2006	11		MD	42		1.48	N	38	56	8/29/2006	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2006	11		MD	42		1.48	S	40	58	8/29/2006	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2006	11		MD	42		1.78	N	40	61	8/29/2006	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2006	11		MD	42		1.78	S	40	60	8/29/2006	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	5
2007	11		MD	42		1.19	N	39	63	6/6/2007	3440	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6
2007	11		MD	42		1.36	S	36	61	6/6/2007	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6
2007	11		MD	42		1.52	N	36	62	6/6/2007	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6
2007	11		MD	42		1.64	S	39	60	6/6/2007	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6
2007	11		MD	42		1.87	N	40	67	6/6/2007	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6
2008	11		MD	42		1.28	N	41	33	10/5/2008	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6
2008	11		MD	42		1.37	S	34	28	10/5/2008	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6
2008	11		MD	42		1.58	N	40	25	10/5/2008	3241	R	2008	XX9115177	HMA 12.5mm, 6	19	November	2007	XX8115177	Patching	6

<u>Fig 3-1. Screen Shot of Pavement friction Data in Access</u>

2. Materials / Mix Design Database

The SHA Mix design database provides infrormation regarding the materials and mixtures used in pavement construction, including aggregate and binder information, source of materials and proportioning (Table 3-2). Specifically for the aggregate source, often the aggregate gradation is composed of a blend of aggregates from different sources, providing a blend of different aggregate types for each mixture (Figure 3-2). This has been a limitation in the study since the effects of a single aggregate type/ source on pavement friction was to be investigated as affecting pavement friction.

3. Merged Material and Friction Database

In order to relate pavement friction to aggregates, the pavement friction records and the mixture databases were merged by using the “Contract” Column form the Friction Database with the “Project ID” column from the Mix Design Database. This resulted in about 52,000 records. The merged database (master database) was used to extract material and pavement friction related information for detailed data analysis.

4. Aggregate Bulletin Database

The Aggregate Bulletin contains a list of tests that are performed annually by SHA (except Polish Value, Soundness and Alkali-Silica Reactivity tests which are done every three years), on samples obtained from producers. Figure 3-3 provides an example of the data in the Aggregate Bulletin.
In addition to the Aggregate Bulletin data, any information related to petrographic/ texture aggregate characteristics in SHA’s records were used, when appropriate. These included among other:

- General Information
    - Supplier (Source Location), Date, sample information.
- General Classification (Carbonate or Non-Carbonate)
- Insoluble Residue Analysis
- Textural Description
- General Aggregate Testing Results:
    - Specific Gravity
    - Absorption
    - Los Angeles Abrasion
    - Sodium Sulphate Soundness
    - Polish Value
    - British Pendulum Number (BPN)

Table 3-3: Mix Design Field type and description

Column	Format
ID	Number
Mix Design	Text
Mix Size	Text
Date Approved	Text
Date Verified	Text
Current	Yes/No
Final	Yes/No
Date rescinded	Text
Traffic Level	Text
Plant	Text
Gmm	Number
Gmb	Number
Binder%	Number
Binder Source	Text
Binder Grade	Text
Gb	Number
MixTemp	Text
MoldTemp	Text
Gsb	Number
D/B	Number
50	Number
37.5	Number
25	Number
19	Number
12.5	Number
9.5	Number
4.75	Number
2.36	Number
1.18	Number
0.6	Number
0.3	Number
0.15	Number
0.075	Number

Table 3-3: Mix Design Field type and description (continued)

AS1	Text
AS1 Old	Text
AS1%	Number
PV1	Text
AS2	Text
AS2Old	Text
AS2%	Number
PV2	Text
AS3	Text
As3Old	Text
AS3%	Number
PV3	Text
AS4	Text
AS4Old	Text
AS4%	Number
PV4	Text
AS5	Text
AS5Old	Text
AS5%	Number
PV5	Text
AS6	Text
AS6Old	Text
AS6%	Number
PV6	Text
AS7	Text
AS7Old	Text
AS7%	Number
PV7	Text
RAPCA%	Number
RAP Binder%	Number
MixPV	Number
Mineral Filler Source	Text
TSR	Number
Log Number	Number
Comments	Text

Mix Design All data

ID	Mix Design #	Mix Size	Date Approved	Date Verified	Current	Final	Date Recinded	Traffic Level	Plant	Gmm	Gmb	Binder %	Binder Source
494	S16525R2C51F	25	6/3/2008		Yes	No		2 - 0.3 to < 3.0	165	2.553	2.413	0	Citgo
498	S16512R1C03F	12	6/3/2008		Yes	No		1 - < 0.3	165	2.525	2.424	5	Citgo
499	S16512R2C03F	12	6/3/2008		Yes	No		2 - 0.3 to < 3.0	165	2.533	2.432	5	Citgo
502	S16525R3C51F	25	6/3/2008		Yes	No		3 - 3.0 to < 10.0	165	2.561	2.423	2.57	Citgo
544	S01225R4C50F	25	6/12/2008		Yes	No		4 - 10 to < 30	012	2.576	2.473	4.2	Chevron
550	S01225R3C5F	25	6/12/2008		Yes	No		3 - 3.0 to < 10.0	012	2.59	2.486	4.4	Chevron
622	S15119R4C50F	19	6/16/2008		Yes	No		4 - 10 to < 30	151	2.54	2.438	4.5	Chevron
623	S15109R1C04F	09	6/16/2008		Yes	No		1 - < 0.3	151	2.492	2.39	5.7	Chevron
624	S15109R2C03F	09	6/16/2008		Yes	No		2 - 0.3 to < 3.0	151	2.49	2.39	5.7	Citgo
625	S15109R2C04F	09	6/16/2008		Yes	No		2 - 0.3 to < 3.0	151	2.5	2.4	5.5	Chevron
626	S15109R3C04F	09	6/16/2008		Yes	No		3 - 3.0 to < 10.0	151	2.51	2.41	5.3	Chevron
627	S15109R4C03F	09	6/16/2008		Yes	No		4 - 10 to < 30	151	2.5	2.4	5.4	Chevron
628	S15109V4F04F	09	6/16/2008		Yes	No		4 - 10 to < 30	151	2.482	2.383	5.2	Citgo
631	S15119R2C50F	19	6/16/2008		Yes	No		2 - 0.3 to < 3.0	151	2.614	2.509	2.72	Citgo
700	S15704V2C02F	04	6/17/2008		Yes	No		2 - 0.3 to < 3.0	157	2.469	2.37	6.4	Valero
702	S15709R2E02F	09	6/17/2008		Yes	No		2 - 0.3 to < 3.0	157	2.504	2.404	5.2	Valero

Binder Grai	Gb	MixTemp	MoldTer	Gsb	D/B	50_0	37_5	25_(	19_0	12_50	9_50	4_75	2_36	1_18	0_60	0_30	0_15
64-22	1.03			2.695	0.00	100	100	99	88.00	64	55	35	24.00	17	13	10	
64-22	1.03			2.709	0.00	100	100	100	100.00	96	85	49	33.00	23	17	12	
64-22	1.03			2.709	0.00	100	100	100	100.00	96	85	49	33.00	23	17	12	
64-22	1.03			2.695	0.00	100	100	99	88.00	64	55	35	24.00	17	13	10	
64-22	1.03			2.74	0.00	100	100	100	84.00	71	67	33	24.00	19	13	9	
64-22	1.03			2.74	0.00	100	100	97	84.00	71	67	33	24.00	19	13	9	
64-22	1.03			2.704	0.00	100	100	100	97.00	86	77	38	26.00	18	15	10	
64-22	1.03			2.683	0.00	100	100	100	100.00	100	98	59	33.00	22	18	12	
64-22	1.03			2.693	0.00	100	100	100	100.00	100	98	53	29.00	20	15	12	
64-22	1.03			2.683	0.00	100	100	100	100.00	100	98	59	33.00	22	18	12	
64-22	1.03			2.683	0.00	100	100	100	100.00	100	98	59	33.00	22	18	12	
64-22	1.03			2.683	0.00	100	100	100	100.00	100	98	59	33.00	22	18	12	
76-22	1.03			2.671	0.00	100	100	100	100.00	100	98	58	32.00	22	16	11	
64-22	1.03			2.774	0.00	100	100	99	82.00	61	53	34	17.00	10	8	6	
64-22	1.03			2.663	0.00	100	100	100	100.00	100	100	96	61.00	33	20	13	
64-22	1.03			2.665	0.00	100	100	100	100.00	100	95	56	36.00	25	18	11	

Fig 3-2: Screen Shot of Mixture database

0_075	AS1	AS1Old	AS1%	PV1	AS2	AS2Old	AS2%	PV2	AS3	AS3Old	AS3%	PV3
3.7	farge Frederick	LaFarge - Frede	40	0	Lafarge Frederi	LaFarge - Frede	20.00	0.00	:ville (Travilah)	LaFarge - Frede	15	0.00
3.7	farge Frederick	LaFarge - Frede	38	0	Lafarge Frederi	LaFarge - Frede	30.00	0.00	:ville (Travilah)	LaFarge - Texas	12	0.00
3.7	farge Frederick	LaFarge - Frede	38	0	Lafarge Frederi	LaFarge - Frede	30.00	0.00	:ville (Travilah)	LaFarge - Texas	12	0.00
3.7	farge Frederick	LaFarge - Frede	40	0	Lafarge Frederi	LaFarge - Frede	20.00	0.00	farge Frederick	LaFarge - Frede	15	0.00
3.9	farge Frederick	LaFarge - Frede	40	0	Lafarge Frederi	LaFarge - Frede	30.00	0.00	:erials Hanover	Vulcan - Hanov	5	0.00
3.9	farge Frederick	LaFarge - Frede	40	0	Lafarge Frederi	LaFarge - Frede	30.00	0.00	:erials Hanover	Vulcan - Hanov	25	0.00
4.7	farge Frederick	LaFarge - Frede	35	0	Lafarge Frederi	LaFarge - Frede	24.00	0.00		LaFarge - Frede	8	0.00
4.5	farge Frederick	LaFarge - Frede	35	0		Maryland Ston	10.00	0.00	farge Frederick	BBS PIT	15	0.00
5.5	farge Frederick	LaFarge - Frede	35	0		Maryland Ston	10.00	0.00	farge Frederick	BBT PIT	15	0.00
4.5	farge Frederick	LaFarge - Frede	35	0		Maryland Ston	10.00	0.00	farge Frederick	BBT PIT	15	0.00
4.5	farge Frederick	LaFarge - Frede	35	0		Maryland Ston	10.00	0.00	farge Frederick	BBS PIT	15	0.00
4.5	farge Frederick	LaFarge - Frede	25	0		Maryland Ston	10.00	0.00		LaFarge - Frede	35	0.00
3.9	farge Frederick	LaFarge - Frede	30	0	Lafarge Frederi	LaFarge - Frede	36.00	0.00		Maryland Ston	15	0.00
2.8	farge Frederick	LaFarge - Frede	24	0	Lafarge Frederi	LaFarge - Frede	35.00	0.00		LaFarge - Frede	8	0.00
9	farge Frederick	LaFarge - Frede	100	0			0.00	0.00			0	0.00
6	farge Frederick	LaFarge - Frede	50	0	Lafarge Frederi	LaFarge - Frede	20.00	0.00	lucts Perryville	Pareville MD	15	0.00
6	farge Frederick	LaFarge - Frede	45	0	Lafarge Frederi	LaFarge - Frede	45.00	0.00	lucts Perryville	Parville MD	10	0.00

AS4	AS4Old	AS4%	PV4	AS5	AS5Old	AS5%	PV5	AS6	AS6Old	AS6%	PV6	AS7	AS7Old
		0.00	0.00			0	0			0	0	Aggregate Indu	Aggregate Indu
		0.00	0.00			0	0			0	0	Aggregate Indu	Aggregate Indu
		0.00	0.00			0	0			0	0	Aggregate Indu	Aggregate Indu
		0.00	0.00			0	0			0	0	Aggregate Indu	Aggregate Indu
		0.00	0.00			0	0			0	0	RAP	RAP
		0.00	0.00			0	0			0	0	RAP	RAP
BBS Pit	BBS Pit	8.00	0.00			0	0			0	0	RAP	RAP
LaFarge - Frede	LaFarge - Frede	25.00	0.00			0	0			0	0	RAP	RAP
LaFarge - Frede	LaFarge - Frede	25.00	0.00			0	0			0	0	RAP	RAP
LaFarge - Frede	LaFarge - Frede	15.00	0.00			0	0			0	0	RAP	RAP
LaFarge - Frede	LaFarge - Frede	25.00	0.00			0	0			0	0	RAP	RAP
BBT PIT	BBT PIT	15.00	0.00			0	0			0	0	RAP	RAP
BBS PIT	BBS PIT	19.00	0.00			0	0			0	0		
BBS PIT	BBS PIT	8.00	0.00			0	0			0	0	RAP	RAP
		0.00	0.00			0	0			0	0		
		0.00	0.00			0	0			0	0	RAP	RAP
		0.00	0.00			0	0			0	0		

Fig 3-2: Screen Shot of Mixture database (continue)

AS7%	PV7	RAPCA%	RAP Binder	MixPV	Mineral Fille	Mineral Fille	TSR	Log Numbe	Comments
25	0	0	0	0		0	0	0	
20	0	0	0	0		0	0	0	
20	0	0	0	0		0	0	0	
25	0	0	0	0		0	0	0	
25	0	0	0	0		0	0	0	
5	0	0	0	0		0	0	0	
25	0	0	0	0		0	0	0	
15	0	0	0	0		0	0	0	
15	0	0	0	0		0	0	0	
25	0	0	0	0		0	0	0	
15	0	0	0	0		0	0	0	
15	0	0	0	0		0	0	0	
0	0	0	0	0		0	0	0	
25	0	0	0	0		0	0	0	
0	0	0	0	0		0	0	0	
15	0	0	0	0		0	0	0	
0	0	0	0	0		0	0	0	

Fig 3-2: Screen Shot of Mixture database (continue)

Maryland State Highway Administration Coarse Aggregate Properties for 2005 Test Data

Producer	SPGR	ABS	LA	UWLSE	UWROD	SOUND	BPN	PV	ASR
La Farge Churchville, MD	2.96	0.5	22	94.9	104.8	0.4	22	*	0.03
La Farge Frederick, MD	2.70	0.4	22	87.4	93.4	0.2	24	6	*
La Farge Marriotsville, MD	2.72	0.4	41	89.0	96.4	1.5	26	7	0.02
La Farge Medford, MD Nr. Westminster, MD	2.73	0.5	22	94.7	100.5	0.1	21	3	0.01
La Farge Texas, MD	2.88	0.4	21	98.2	103.2	0.3	24	6	0.02
Laurel S&G Woodsboro, MD Barrick Quarry	2.70	0.3	24	87.5	92.5	0.1	28	5	0.11
Luck Stone Corp Leesburg, VA (Leesburg Pit)	2.05	0.8	13	90.3	100.0	0.2	27	*	0.02

Page C5

Fig 3-3: Example of data in the 2005 SHA Aggregate Bulletin (Coarse Aggregates)

5. Equipment Repeatability Data

SHA is conducting repeatability pavement Friction tests annually on test sections along the I-795 corridor. The records shown in Table 3-4 were provided for the analysis of this study. These included equipment repeatability runs on both flexible and rigid pavements in 2006 and 2007 and with the SHA friction trucks, Truck #5 - International Cybernetics Corporation, and Truck #6 - Dynatest.

Table 3-4: Summary of Equipment Variability Tests

Test Date	**Equipment**	**Flexible /Rigid**
01/27/2006	Truck 5	Both
09/06/2006	Truck 5	Both
03/20/2007	Truck 5	Both
03/20/2007	Truck 6	Both
06/21/2006	Truck 5 & 6	Flexible

Chapter 4 - Equipment Variability Study

As mentioned previously, SHA is using two locked wheel friction devices, Truck #5 - International Cybernetics Corporation model, and Truck #6 the Dynatest model. These friction devices were used to collect repeatability and side by side comparison data on both flexible and rigid pavement sections of I-795 at different times. The research team has analyzed this information and the results are presented next.

Equipment Repeatability

Truck #5 - International Cybernetics Corporation model

A series of repeatability testing records collected on the same mile post and same day were examined. This included repeated testing conducted on both flexible and rigid pavement sections on the following dates:

01/27/06 (at 9:43am, and 10:07 am);
09/06/06 (at 11:41am, 11:59am, 12:54pm, and 1:14pm); and,
03/20/07 (8:47am, 9:11am, 9:43am, and 12:03pm).

The research team matched the milepost numbers of the surveyed sections so as to compare the FN values for the same sites. An example of such data is shown in Tables 4-1 and 4-2 along with the summary statistics, and based on the four repeatability records of 09/06/06. As it can be seen the average value of the coefficient of variation (CV) for this device is ranging from 2% to 3% with individual values all the way up to 7%. Figures 4-1 and 4-2 show the FN measurements in the flexible and rigid sections of I-795 in relation to the milepost. Examining the repeatability data for this device collected on other testing dates it was concluded that for flexible pavements the average CV ranged between 1% to 2%, while for rigid pavements the average CV ranged from 1% to 3%. Considering the level of FN values (average FN of 60 for the flexible and FN of 50 for the rigid pavement sections) the equipment repeatability introduce into the friction measurements, on the average, a variability of +/- 1.2FN and 1.5FN units for flexible and rigid pavements respectively.

In addition to the variability analysis, ANOVA was conducted on the repeated runs for assessing whether the measurements collected from the repeated runs can be statistically considered from the same population. The analysis are presented in Tables 4-3 and 4-4 for the FN measurements in the flexible and rigid sections of I-795 and collected on 09/06/06. As it can be concluded from the statistical analysis the null hypothesis (i.e., there is not significant variability among the means of the four different runs) is accepted since the F-calculated/Observed < F critical. The same conclusions were obtained with the data collected on other dates.

Truck #6 - Dynatest model

For this device the repeated runs collected on 03/20/07 (11:49am, 12:11pm, and 12:32pm for flexible pavements, and 11:49am, and 12:32pm for rigid pavements) were used. The research team matched the milepost numbers of the surveyed sections so as to compare the FN values. This data is shown in Tables 4-5 and 4-6 along with the summary statistics. As it can be seen the average value of the coefficient of variation (CV) for this device is ranging from 5% to 6%, with individual values all the way up to 20%. Figures 4-3 and 4-4 show the FN measurements in the flexible and rigid sections of I-795 in relation to the milepost. Considering this magnitude of variability along with the level of FN values (average FN of 60 for the flexible and FN of 55 for the rigid pavement sections) the equipment repeatability introduce into the friction measurements, on the average, a variability of +/- 3.0 FN and 3.3FN units for flexible and rigid pavements respectively.

In addition to the variability analysis, t-test and ANOVA was conducted on the repeated runs for assessing whether the measurements collected from the repeated runs can be statistically considered from the same population. While the ANOVA showed that the null hypothesis was rejected (i.e., there is significant variability among the means of the different runs), the paired t-test showed that the records collected from the repeated runs, when compared two at a time, can be considered to be from the same population. These results are further examined from the research group along with the individual values reported from the testing.

Equipment Side by Side Comparison

For the comparison of the friction measurements between these two devices the data collected on 06/21/06 were used. The research team matched the milepost numbers of the surveyed sections for the flexible test sections so as to compare the FN values for the same sections. For the rigid pavement sections the reported mileposts between the two devices did not match, thus the analysis where not included. The comparison for the flexible sections is shown in Table 4-7 along with the summary statistics. As it can be seen the average difference (CV) between the values produced by these two devices is of the order of 7%, and with individual values all the way up to 13%. Truck #6 always provided higher values than Truck #5. Figure 4-5 shows the FN measurements reported for the two friction trucks in relation to mileposts. Considering the level of FN values where these measurements were taken (average FN of 55) it is expected to observe a higher FN value of about + 6.5 FN units when truck # 6 is used in relation to #5. This is often reflected in the friction database when different devices are used, year after year, for surveying the same sections. In addition to the variability analysis, t-test and ANOVA was conducted on the data collected from the two trucks. As expected, both the t-test and ANOVA showed that neither the set of individual values (t-test) or their averages (F-test) can be statistical considered to be the same. These results are shown in Table 4-8.

Table 4-1. Repeatability of Truck #5 International Cybernetics Corporation on Flexible Pavement Sections of I-795 (09/05/06)

11:41:29 AM		11:59:21 AM		11:54:22 AM		1:14:11 PM	
MP	FN Reading	MP	FN Reading	MP	FN Reading	MP	FN Reading
0.183	62.4	0.189	64.2	0.191	63.9	0.192	62.8
0.281	60.6	0.286	59.6	0.29	61.4	0.292	58.9
0.381	60.5	0.388	62	0.39	61.7	0.391	62.6
0.482	58.7	0.486	58.7	0.49	59.4	0.491	61.3
0.581	53.2	0.587	55.6	0.589	54.2	0.591	54.6
0.682	60.3	0.686	59.3	0.69	61.3	0.69	59.6
0.782	63.5	0.787	59.6	0.791	64.2	0.791	62.3
0.882	63.6	0.887	62	0.889	63.2	0.891	61.2
0.983	63.5	0.986	62.4	0.99	64.8	0.991	61.8

Average	SD	Variance	COV
63.3	0.9	0.7	1%
60.1	1.1	1.2	2%
61.7	0.9	0.8	1%
59.5	1.2	1.5	2%
54.4	1.0	1.0	2%
60.1	0.9	0.8	1%
62.4	2.0	4.1	3%
62.5	1.1	1.2	2%
63.1	1.3	1.7	2%
	Average CV		2%

Table 4-2. Repeatability of Truck #5 International Cybernetics Corporation on Rigid Pavement Sections of I-795 (09/05/06)

11:41:29 AM		11:59:21 AM		11:54:22 AM		1:14:11 PM	
MP	FN Reading	MP	FN Reading	MP	FN Reading	MP	FN Reading
4.381	49.8	4.382	51.9	4.386	46.2	4.384	50.2
4.481	50.9	4.481	49	4.486	47	4.484	47.9
4.581	50.6	4.581	50.8	4.586	46.8	4.583	48.4
4.681	48.8	4.681	50.6	4.686	49.1	4.683	56
4.781	52.1	4.782	51.9	4.786	52.2	4.784	51
4.881	49.5	4.881	50.3	4.885	49.2	4.883	50.7
4.98	47.3	4.981	51.4	4.986	46.3	4.983	48.9
5.081	49.4	5.082	50.5	5.086	53.2	5.084	47.1
5.25	47.9	5.243	49.9	5.24	47.8	5.237	46.5
5.372	50.2	5.343	49.3	5.34	48.8	5.338	49.6

Average	SD	Variance	COV
49.5	2.4	5.7	5%
48.7	1.7	2.8	3%
49.2	1.9	3.6	4%
51.1	3.3	11.2	7%
51.8	0.5	0.3	1%
49.9	0.7	0.5	1%
48.5	2.2	4.9	5%
50.1	2.5	6.4	5%
48.0	1.4	2.0	3%
49.5	0.6	0.3	1%
	Average CV		3%

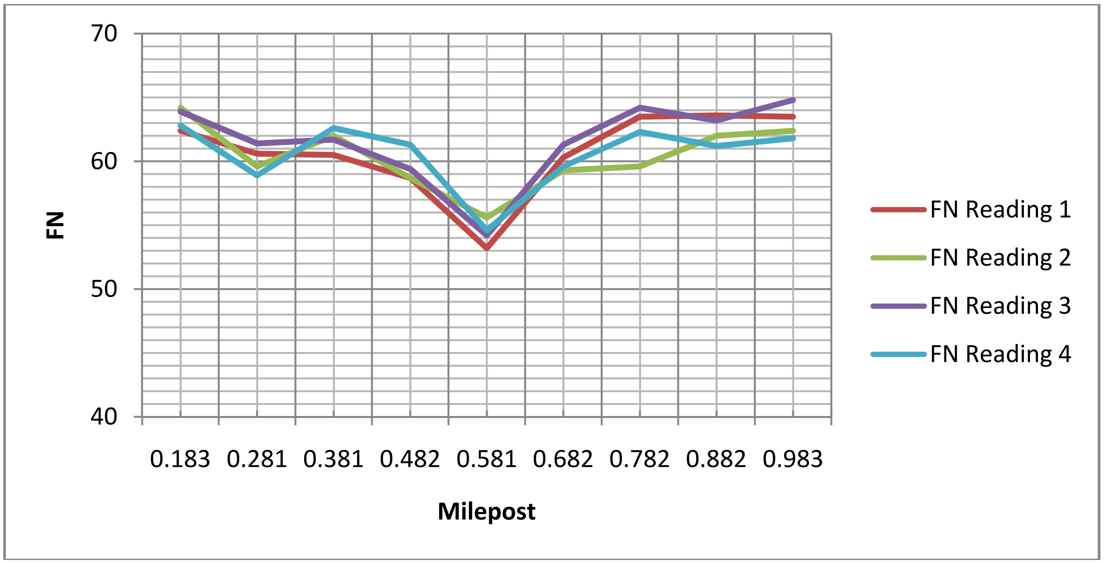


Figure 4-1. Repeatability of Truck #5 International Cybernetics Corporation on Flexible Pavement Sections of I-795 (09/05/06)

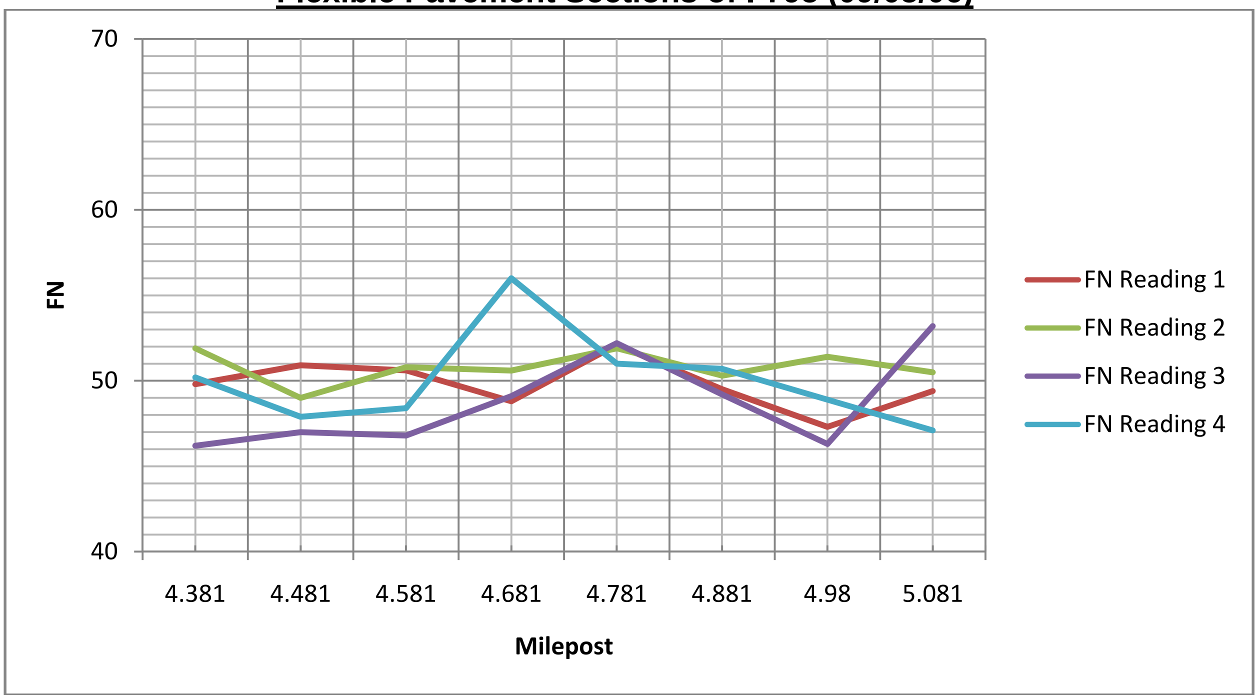


Figure 4-2. Repeatability of Truck #5 International Cybernetics Corporation on Rigid Pavement Sections of I-795 (09/05/06)

Table 4-3. ANOVA for Repeatability of Truck #5 International Cybernetics Corporation on Flexible Pavement Sections of I-795 (09/05/06)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	9	546.3	60.7	10.93
Column 2	9	543.4	60.37777778	6.496944444
Column 3	9	554.1	61.56666667	10.5725
Column 4	9	545.1	60.56666667	6.7375

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.47416667	3	2.491388889	0.28688636	0.834500554	2.90111959
Within Groups	277.895556	32	8.684236111			
Total	285.369722	35				

Table 4-4. ANOVA for Repeatability of Truck #5 International Cybernetics Corporation on Rigid Pavement Sections of I-795 (09/05/06)

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	8	398.4	49.8	2.091429
Column 2	8	406.4	50.8	0.914286
Column 3	8	390	48.75	7.342857
Column 4	8	400.2	50.025	7.730714

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	17.16375	3	5.72125	1.265813	0.305148	2.946685
Within Groups	126.555	28	4.519821			
Total	143.7188	31				

Table 4-5. Repeatability of Truck #6 Dynatest on Flexible Pavement Sections of I-795 (03/20/07)

11:49:00 AM		12:11:00 PM		12:32:00 PM	
MP	FN Reading	MP	FN Reading	MP	FN Reading
1.11	62.1	1.152	59.2	1.109	56.8
1.21	58.5	1.252	65.6	1.205	61.6
1.31	52.1	1.352	59.2	1.307	61.3
1.409	50.9	1.452	61	1.407	63.6
1.507	56.4	1.552	58.4	1.507	58
1.602	57.9	1.652	59.4	1.611	61.8
1.71	57.8	1.752	59.9	1.71	63
1.811	60.3	1.852	62.1	1.804	61.8
1.912	49	1.952	58.2	1.907	61.2
2.009	57.8	2.052	53.4	2.008	62.9

Average	SD	Variance	COV
59.4	2.7	7.0	4%
61.9	3.6	12.7	6%
57.5	4.8	23.2	8%
58.5	6.7	45.0	11%
57.6	1.1	1.1	2%
59.7	2.0	3.9	3%
60.2	2.6	6.8	4%
61.4	1.0	0.9	2%
56.1	6.4	40.4	11%
58.0	4.8	22.6	8%
	Average CV		6%

Table 4-6. Repeatability of Truck #6 Dynatest on Rigid Pavement Sections of I-795 (03/20/07)

11:49:00 AM		12:32:00 PM	
MP	FN Reading	MP	FN Reading
5.082	54.2	5.077	51.7
5.18	54.1	5.185	54.7
5.27	56.1	5.275	56.7
5.38	56.5	5.378	58.7
5.475	54.6	5.479	45.9
5.579	54.5	5.581	57.3
5.682	53.3	5.677	55.6
5.781	57.1	5.778	43.1
5.901	55.9	5.9	56.4
5.999	54.6	6.003	53.2

Average	SD	Variance	COV
53.0	1.8	3.1	3%
54.4	0.4	0.2	1%
56.4	0.4	0.2	1%
57.6	1.6	2.4	3%
50.3	6.2	37.8	12%
55.9	2.0	3.9	4%
54.5	1.6	2.6	3%
50.1	9.9	98.0	20%
56.2	0.4	0.1	1%
53.9	1.0	1.0	2%
	Average CV		5%

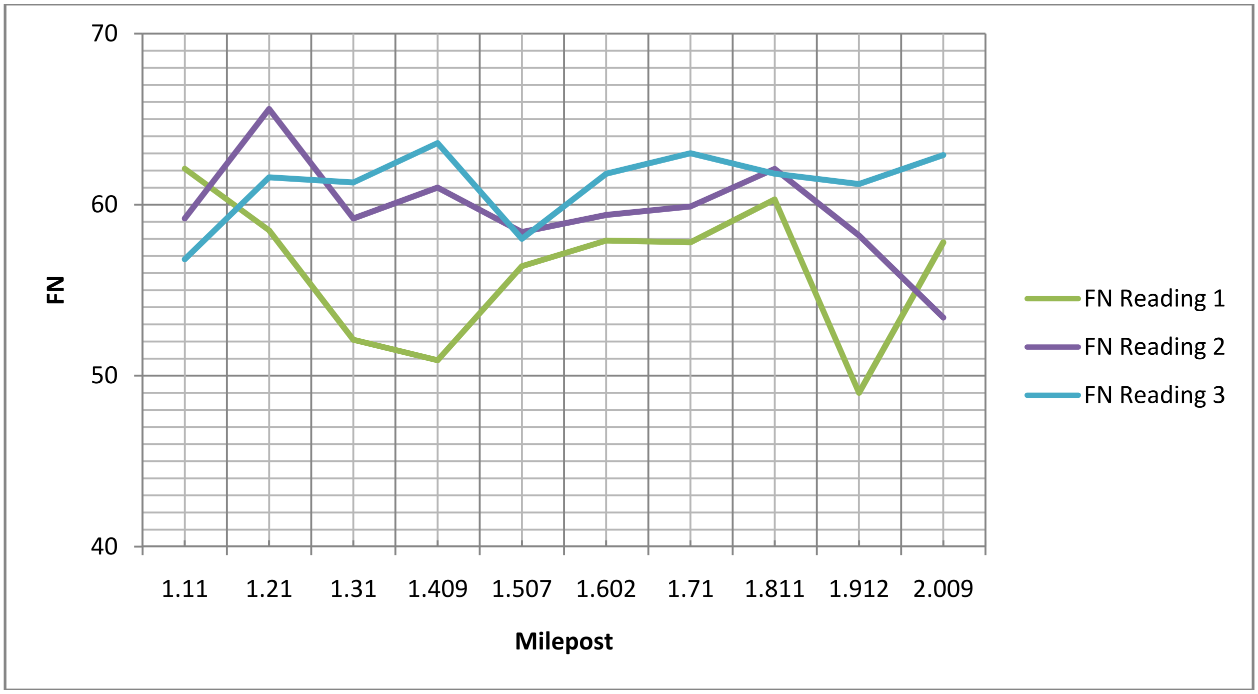


Figure 4-3. Repeatability of Truck #6 Dynatest on Flexible Pavement Sections of I-795 (03/20/07)

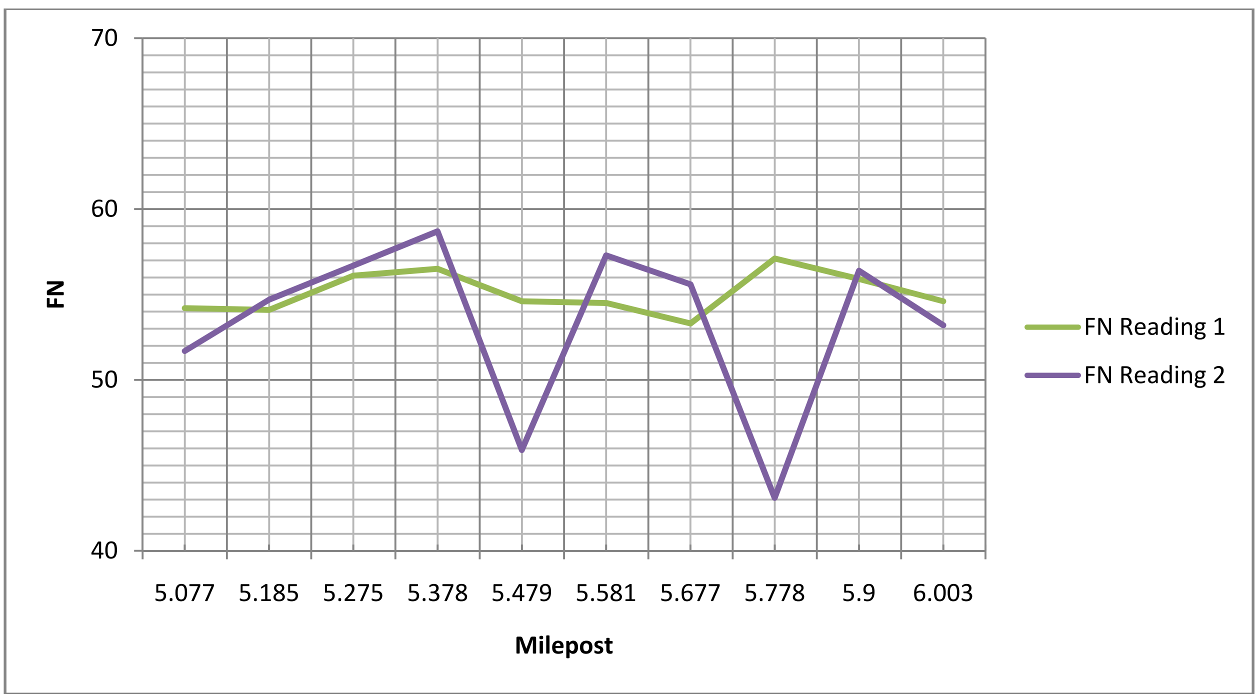


Figure 4-4. Repeatability of Truck #6 Dynatest on Rigid Pavement Sections of I-795 (03/20/07)

Table 4-7. Side by Side Comparison for Truck #5 and #6 on Flexible Pavement Sections of I-795 (06/21/06)

Truck #5		Truck #6	
MP	FN Reading	MP	FN Reading
1.144	52.9	1.155	60.9
1.243	51.9	1.255	62.2
1.342	52.1	1.355	54.5
1.443	52	1.455	60.9
1.542	49.4	1.555	53.9
1.643	52.8	1.655	56.4
1.743	53.5	1.755	60.1
1.842	53.4	1.855	57.6
1.942	54.6	1.955	57.2
2.042	53.1	2.055	58.4

Average	SD	Variance	COV
56.9	5.7	32.0	10%
57.1	7.3	53.0	13%
53.3	1.7	2.9	3%
56.5	6.3	39.6	11%
51.7	3.2	10.1	6%
54.6	2.5	6.5	5%
56.8	4.7	21.8	8%
55.5	3.0	8.8	5%
55.9	1.8	3.4	3%
55.8	3.7	14.0	7%
	Average CV		7%

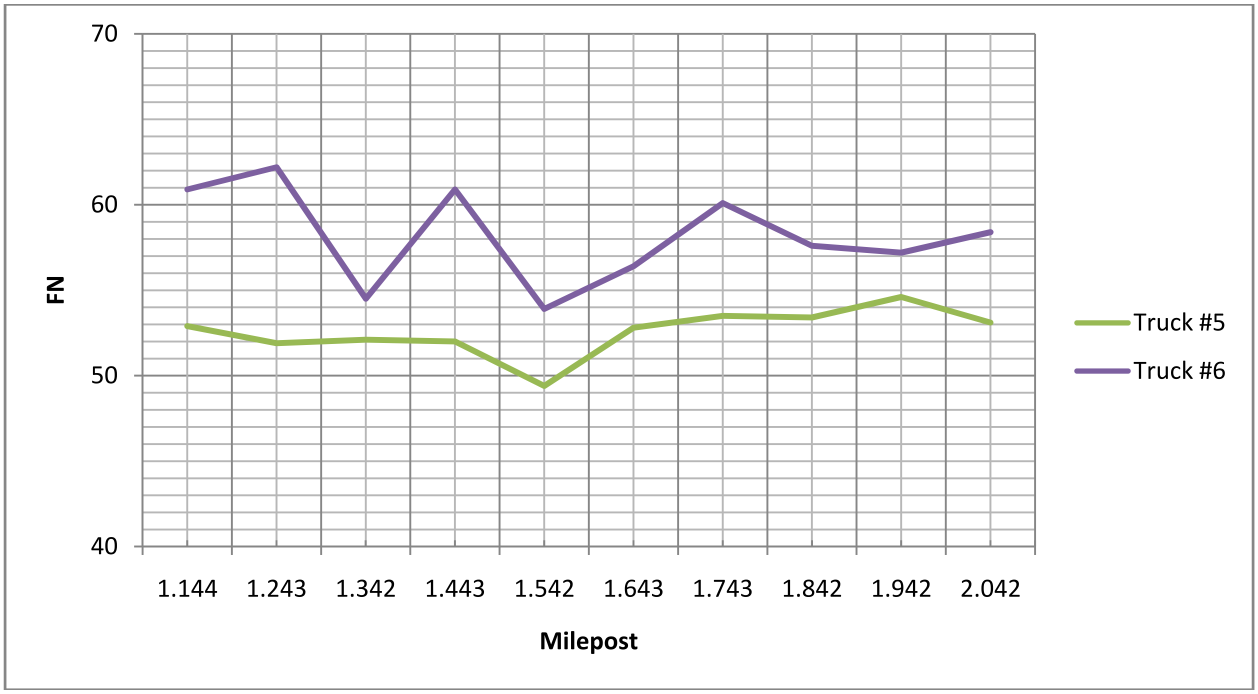


Figure 4-5. Side by Side Comparison for Truck #5 and #6 on Flexible Pavement Sections of I-795 (06/21/06)

Table 4-8. Statistical Analysis for Side by Side Comparison of Truck #5 and #6 on Flexible Pavement Sections of I-795 (06/21/06)

t-test

	Variable 1	*Variable 2*
Mean	52.57	58.21
Variance	1.906777778	7.889888889
Observations	10	10
Hypothesized Mean Difference	0	
df	13	
t Stat	-5.69822952	
P(T<=t) one-tail	3.6573E-05	
t Critical one-tail	1.770933383	
P(T<=t) two-tail	7.31459E-05	
t Critical two-tail	2.160368652	

Analysis of Variance

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10	525.7	52.57	1.906778
Column 2	10	582.1	58.21	7.889889

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	159.048	1	159.048	32.46982	2.1E-05	4.413873
Within Groups	88.17	18	4.89833333			
Total	247.218	19				

Chapter 5 – Initial Analysis on Evaluation Factors Affecting Pavement Friction

An initial set of analyses were conducted using all the friction records between 2004-2008 provided by SHA. The friction records were analyzed by grouping either by individual or group of counties, rural versus urban, or by specific route. Based on the input of SHA it was decided to eliminate any potential friction records related to data entry errors (i.e., FN<15 and FN>70) and analyze the records from Interstates separately from US and MD roads. Some of the results are shown in Figures 5-1 through 5-12. As it can be seen from the analysis the scatter/variability in relating FN to AADT, and/or years since last rehabilitation is significant thus providing insignificant relationships (poor R^2). This is true whether the data are analyzed by group of counties, by county, by roadway type, (Interstates, US and MD roads). Even in the case of analyzing the data by specific roadway and using the actual AADT values such relationships are still insignificant (Figures 5-11 and 5-12 provide the analysis for I-68 as an example). The reasons for such effects are related to the impact of several additional variables into FN, including:

- Equipment and repeatability;
- Seasonal effects on friction testing;
- Local conditions;
- Surface characteristics during testing;
- Aggregate type and abrasion resistance quality;
- Surveying speed;
- Other

The effect of survey speed on FN has been extensively studied in the past with SHA data (Goulias et. al. 2007). Those analyses conducted with approximately 1000 records per county, have reinforced the hypothesis that there is an inverse relationship between test speed and friction values. Furthermore, the analyses have shown that an increase in testing speed of 5 mph reduces friction number by about 9.1 FN units. An example of such a relationship with data from Charles County are shown in Figure 5- 13. The data selected for those analyses included friction readings taken in Charles County (CH), on the same day, on sections that have similar AADT and have received the same level of maintenance for the analysis period.

Systematic Evaluation of Variables Affecting FN

Since the objective of this study was to identify the effects of each aggregate on pavement friction there was a need to systematically examine the contribution of these parameters on FN. It is expected that different aggregates have different effects on FN, and their role might be related to the type of mixtures in which they are used. At the same time traffic level and pavement age will affect the degree of FN change. Since all remaining parameters (such as survey speed, equipment repeatability, seasonal effects, and so on) affect FN measurements their impact has to be considered as well. Thus, it was the objective of these analyses to isolate the effects of some of these variables on FN. Exploratory analysis were thus conducted by considering subgroups of the data having the same mixture type, a specific AADT level, constant survey speed and so on. According to the SHA friction data records the HMA 12.5mm mixture represents the most popular material used in Maryland. Thus, mixture specific data were used for the analysis.

Friction Analysis for HMA 12.5 mm PG 70-22 – all types

Similarly to the previous analysis, the HMA 12.5mm PG 70-22 friction data were used in examining the effects of survey speed, cummAADT and years since last rehabilitation on FN. As it can be seen from Figures 5-14 through 5-16 dealing with the friction surveys on MD and US routes the effects of the remaining parameters on FN provided significant level of variance and thus no acceptable relationship was obtained. The same was observed when the data from Interstate highways were examined, Figures 5-17 through 5-19.

Friction Analysis for HMA 12.5 mm PG 70-22 & Uniform AADT~ 10,571

In the next step, sections with the same contract number and same AADT level were included in the analysis. The AADT in the friction surveys for this and the following analyses was replaced with the actual AADT values reported in the Traffic Monitoring System web site. The selected sections are shown in Table 5-1. The effects of speed (using data from 2004), years since last rehabilitation and cummAADT are shown in Figures 5-20 to 5-22. Overall, the relationships between these variables and FN have improved however there still was a significant variability in the data due to the additional parameters affecting FN. Multivariate regression analysis was run as well on these data. The results are shown in Table 5-2. Based on the analysis the following model was obtained (F theoretical << F observed) relating FN with CumAADT, survey speed and age. However these parameters have t-observed close to the t-theoretical at 95% confidence level (significant when t-observed in absolute value is larger than t theoretical).

$$FN = 1.18\ Speed + 21.85\ Age - 0.0023\ CummAADT + 109.62$$

As expected pavement age (years since last rehabilitation) was also not significant since this variable is correlated to the CumAADT (Cumulative AADT = Age *AADT).

Friction Analysis for HMA 12.5 mm PG 70-22 with Uniform AADT= 9000 & Survey Speed of 40 mph

In the next step, the analysis included sections with the same contract number and AADT level along with a constant survey speed of 40 mph. The selected sections are shown in Table 5-3. The effects of year since last rehabilitation and CumAADT are shown in Figures 5-14 to 5-15. The relationships between these variables and FN were relatively poor due to a significant variability in the data introduced from the additional parameters affecting FN.

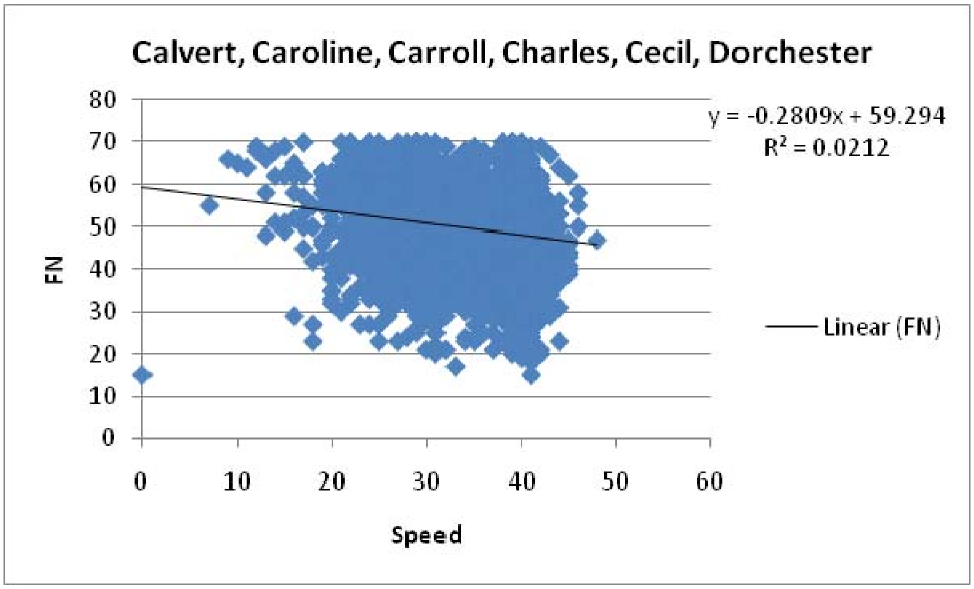


Figure 5-1 . Speed vs FN for Selected Counties (MD and US Roads, n=28,216)

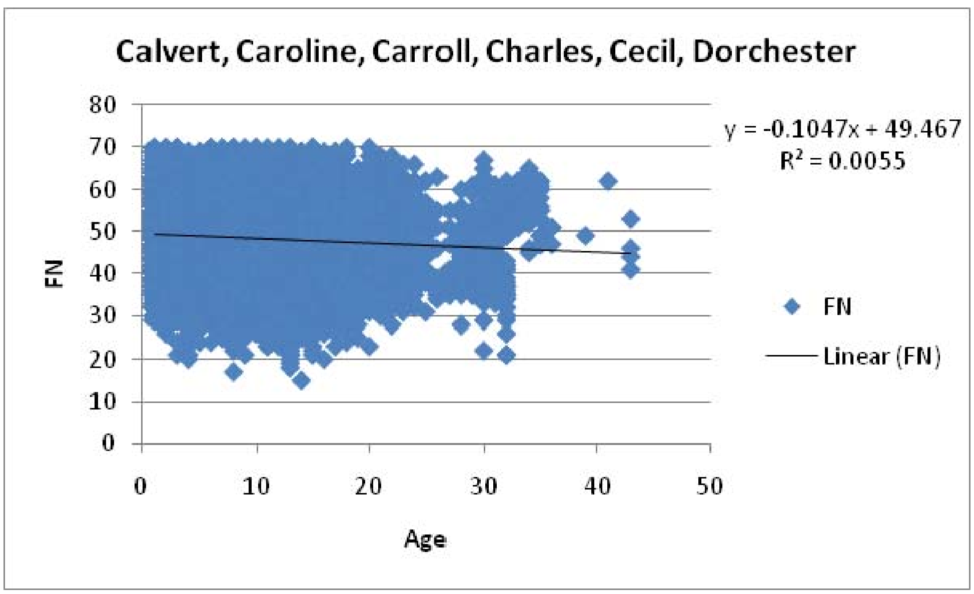


Figure 5-2. Age vs FN for Selected Counties (MD and US Roads, n=28,216)

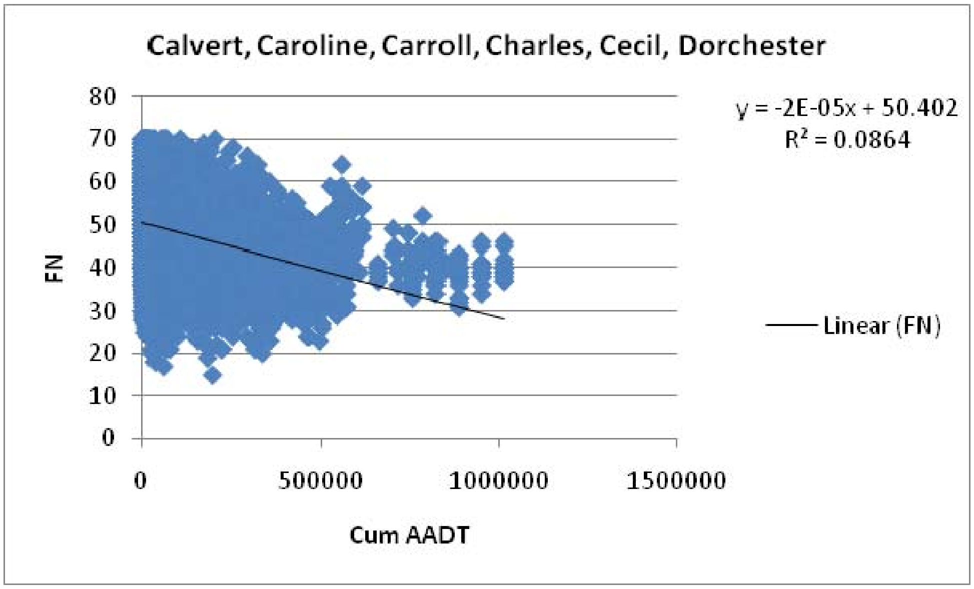


Figure 5-3. CumAADT vs FN for Selected Counties (MD and US Roads, n=28,216)

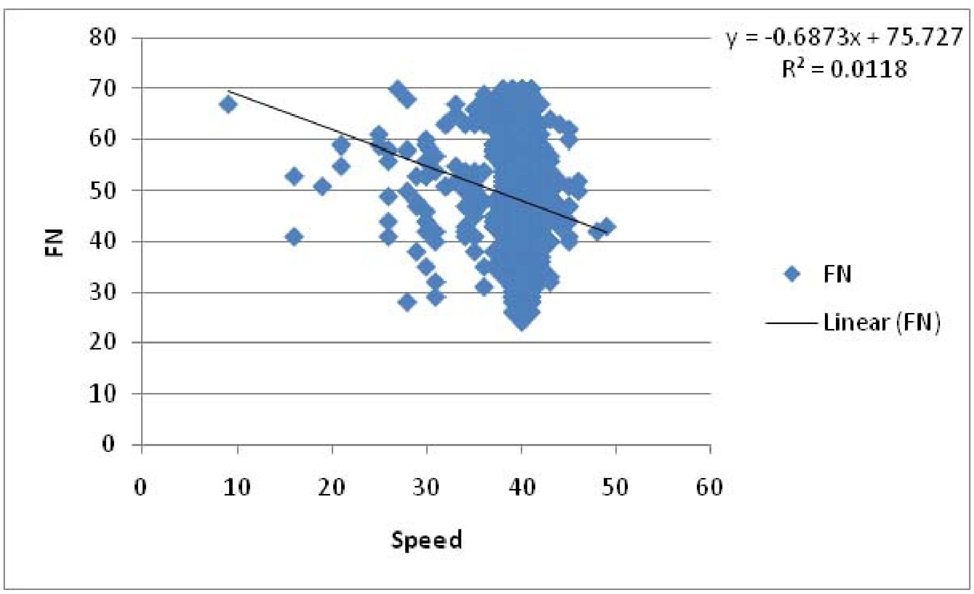


Figure 5-4. Speed vs FN for all Interstates – Statewide (n=10,828)

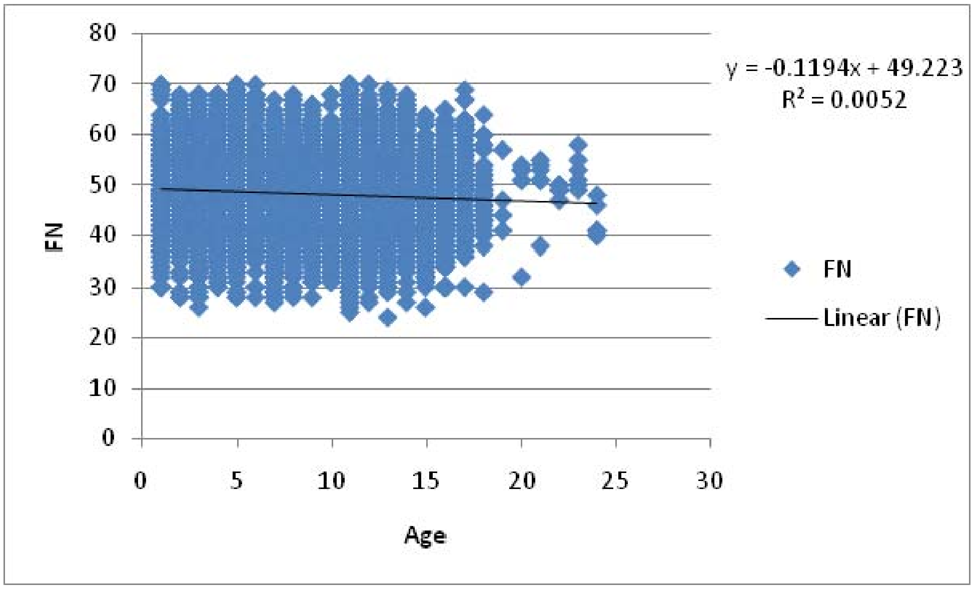


Figure 5-5. Age vs FN for all Interstates – Statewide (n=10,828)

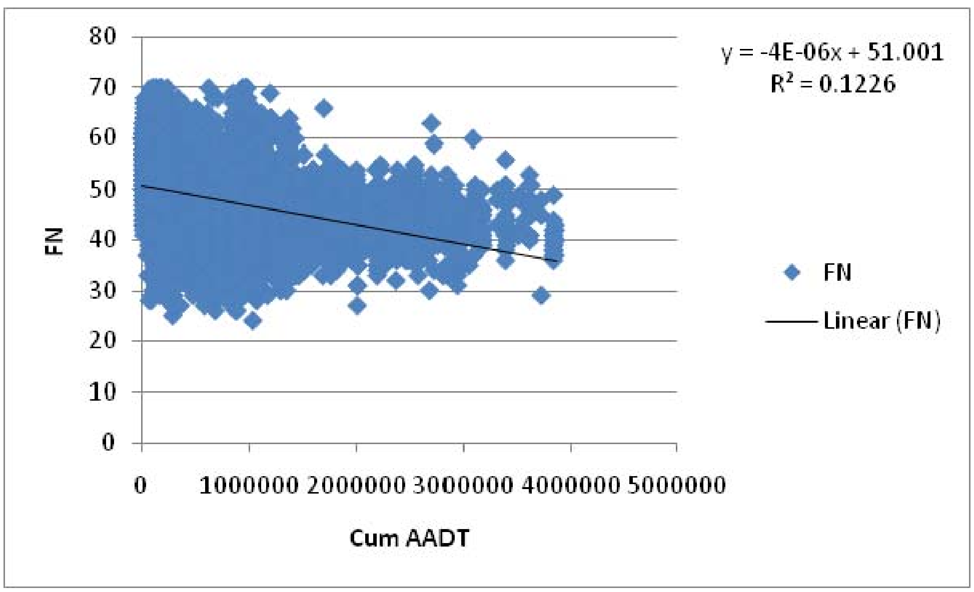


Figure 5-6. CummAADT vs FN for all Interstates – Statewide (n=10,828)

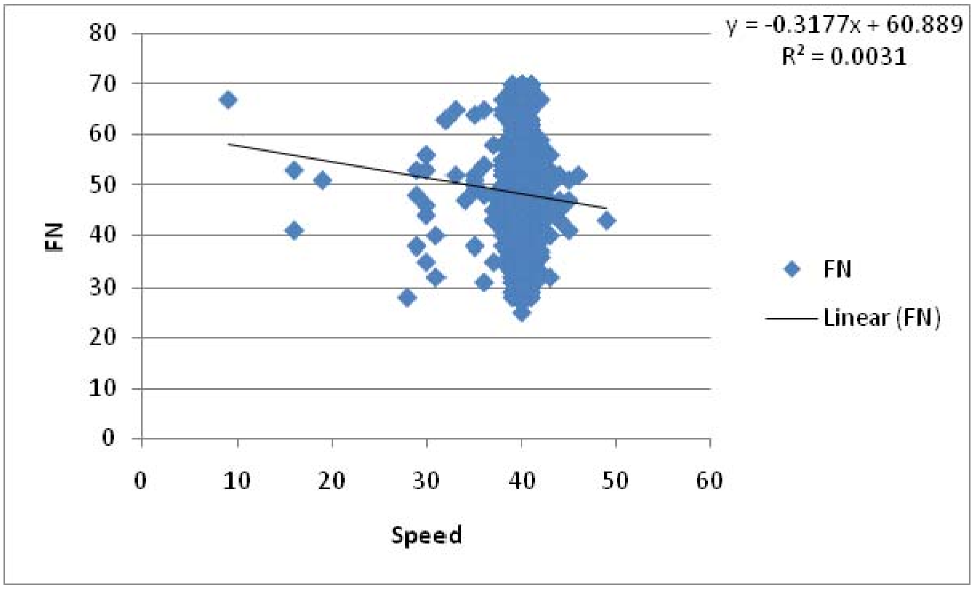


Figure 5-7. Speed vs FN for Interstates in Allegany, Anne Arundel, Baltimore, Calvert, and Charles Counties (n=3,602)

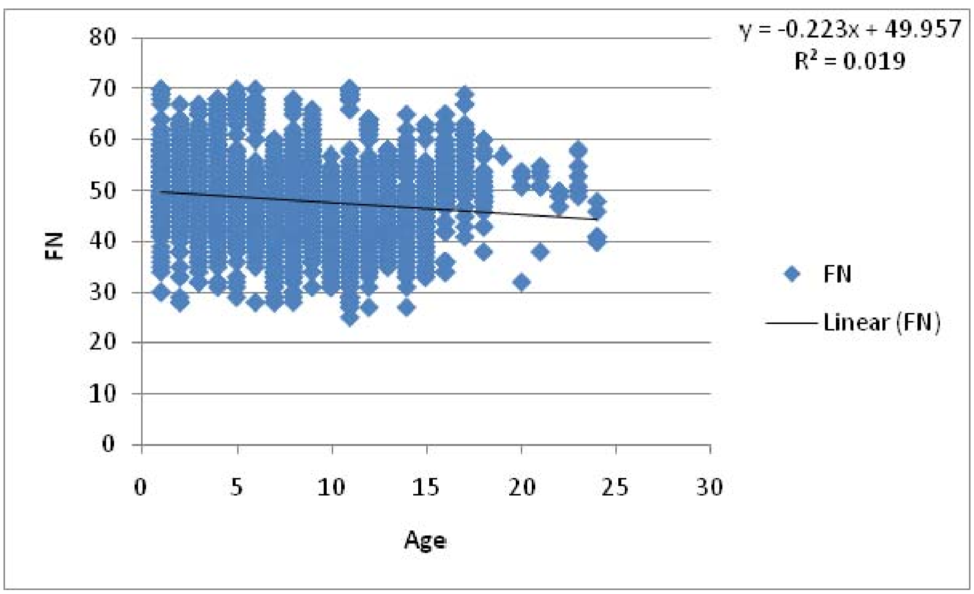


Figure 5-8. Age vs FN for Interstates in Allegany, Anne Arundel, Baltimore, Calvert, and Charles Counties (n=3,602)

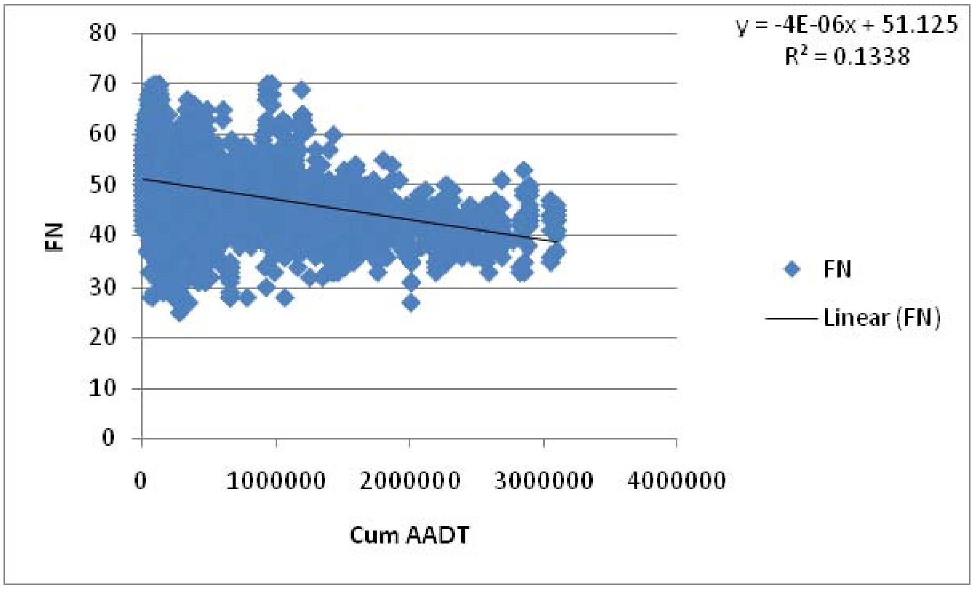


Figure 5-9. CummAADT vs FN for Interstates in Allegany, Anne Arundel, Baltimore, Calvert, and Charles Counties (n=3,602)

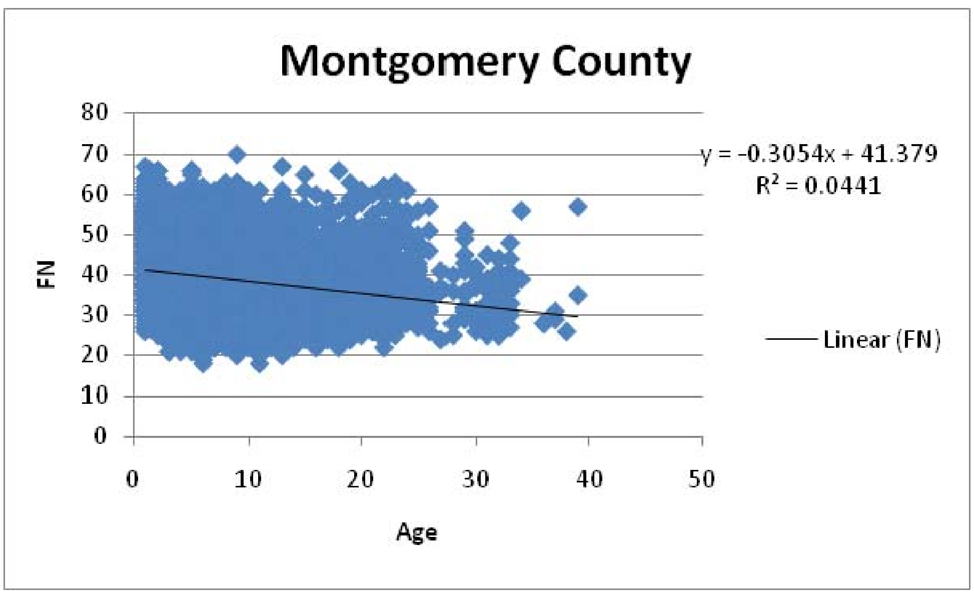


Figure 5-10. Years since Last Rehab vs. FN for MD and US routes in Montgomery County (n=7,904)

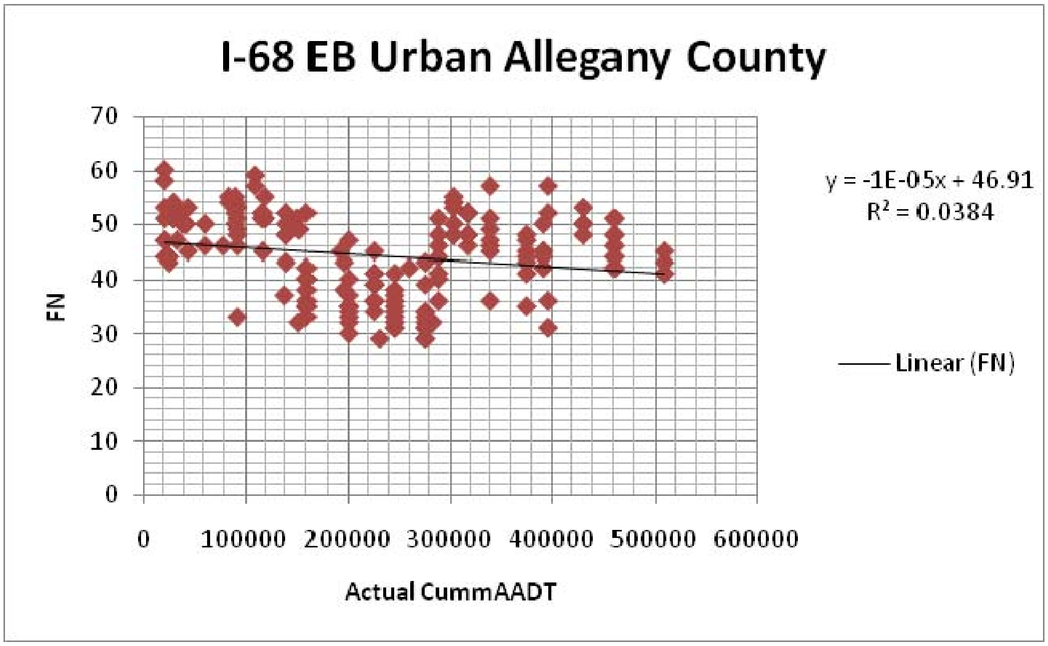


Figure 5-11.Actual CummAADT vs FN for I-68 Eastbound (n=170)

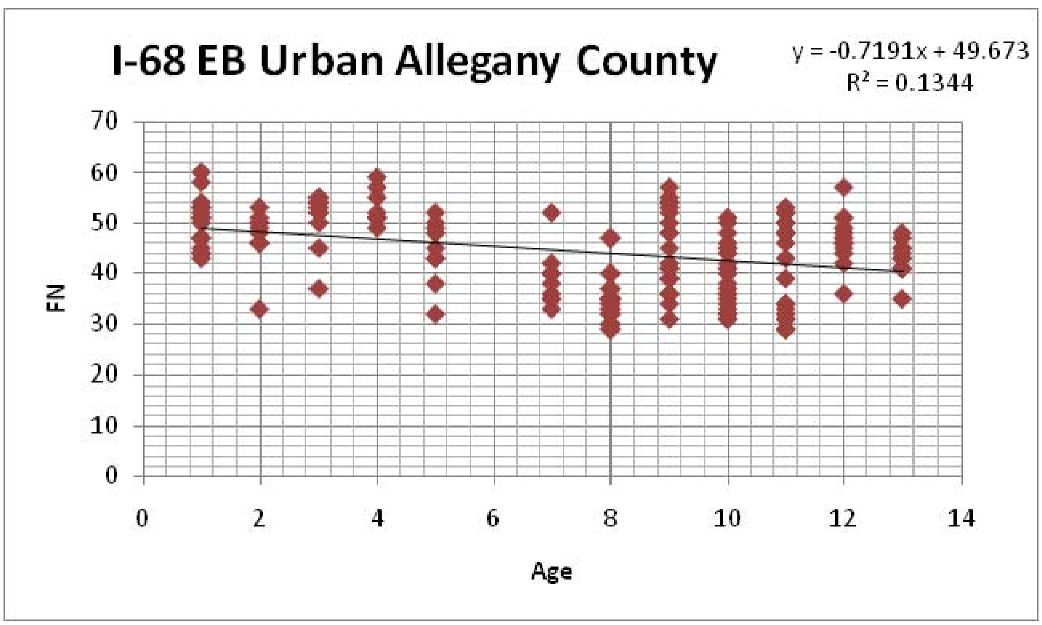


Figure 5-12 . Years since Last Rehab vs FN for I-68 Eastbound (n=170).

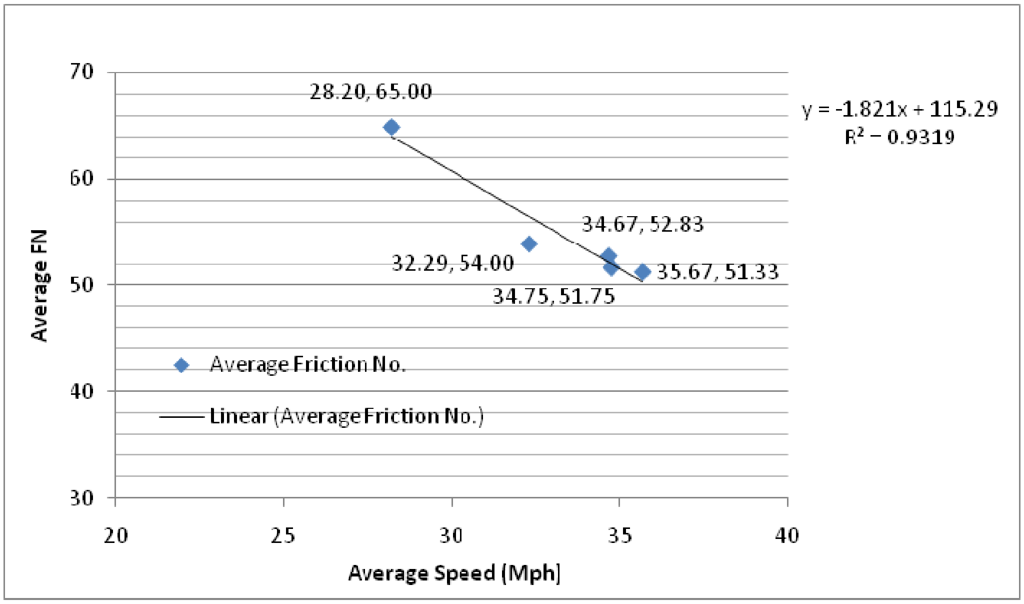


Figure 5-13. Survey Speed versus FN based on Average Values (Charles County)

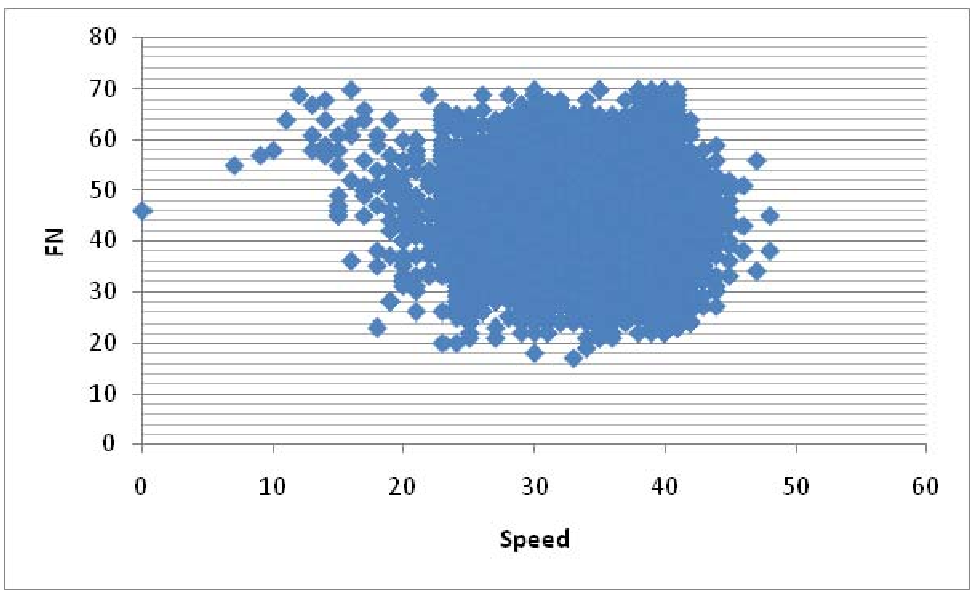


Figure 5-14. Survey Speed vs FN for HMA 12.5mm PG 70-22 in MD & US Routes (n=22,338)

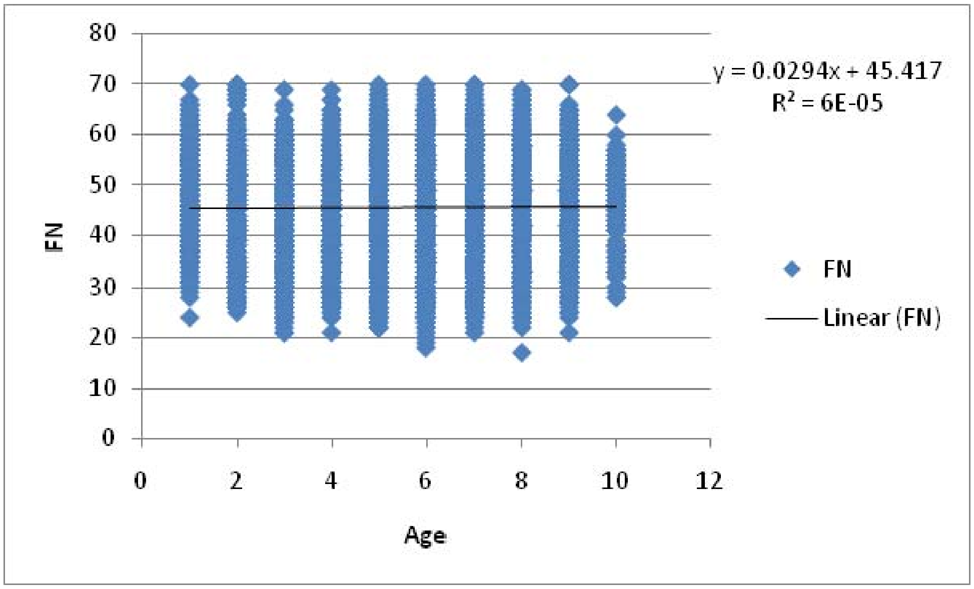


Figure 5-15. Age vs FN for HMA 12.5mm PG 70-22 in MD & US Routes (n=22,338)

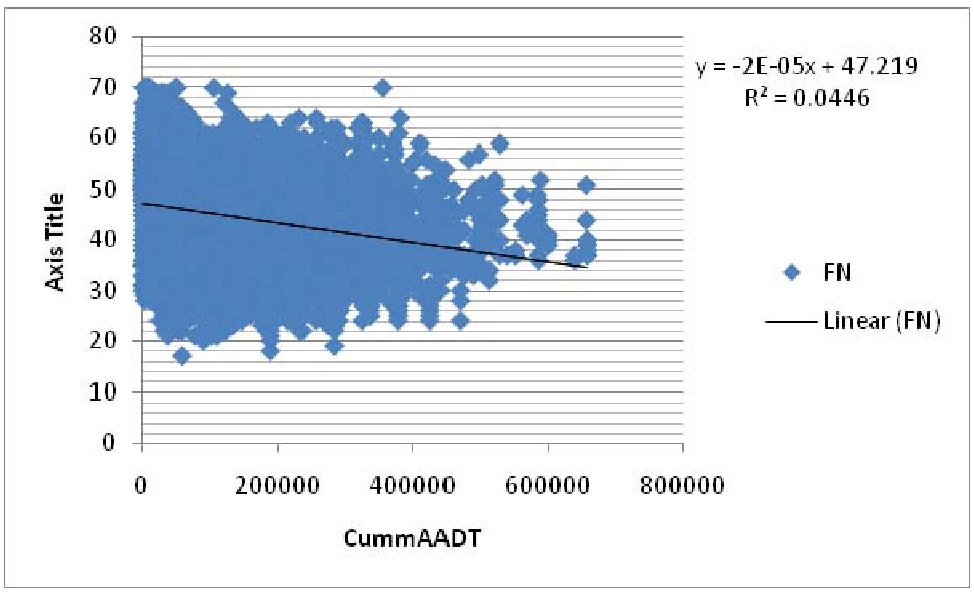


Figure 5-16. CummAADT vs FN for HMA 12.5mm PG 70-22 in MD & US Routes (n=22,338)

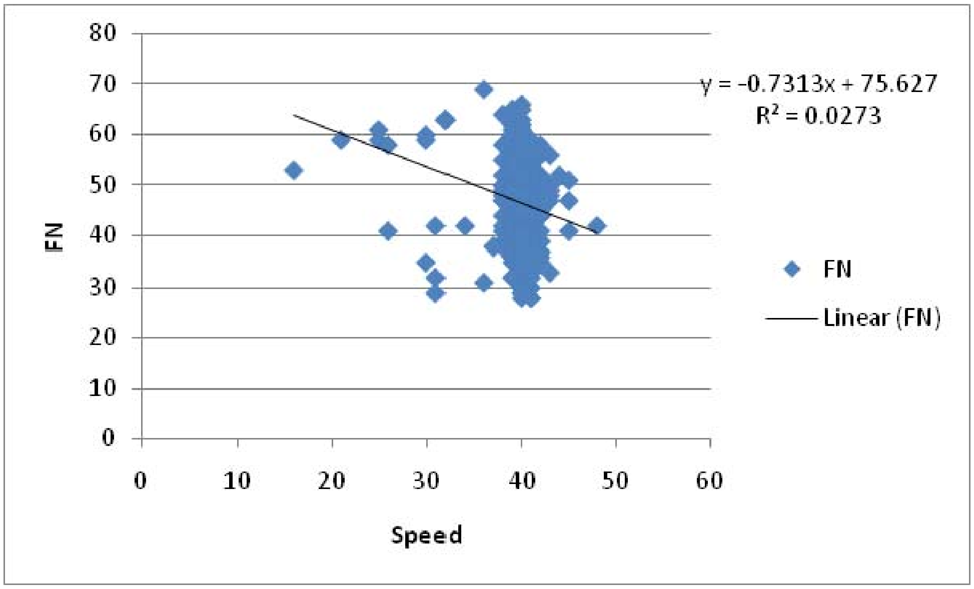


Figure 5-17. Survey Speed vs FN for HMA 12.5mm PG 70-22 in Interstates (n=2,031)

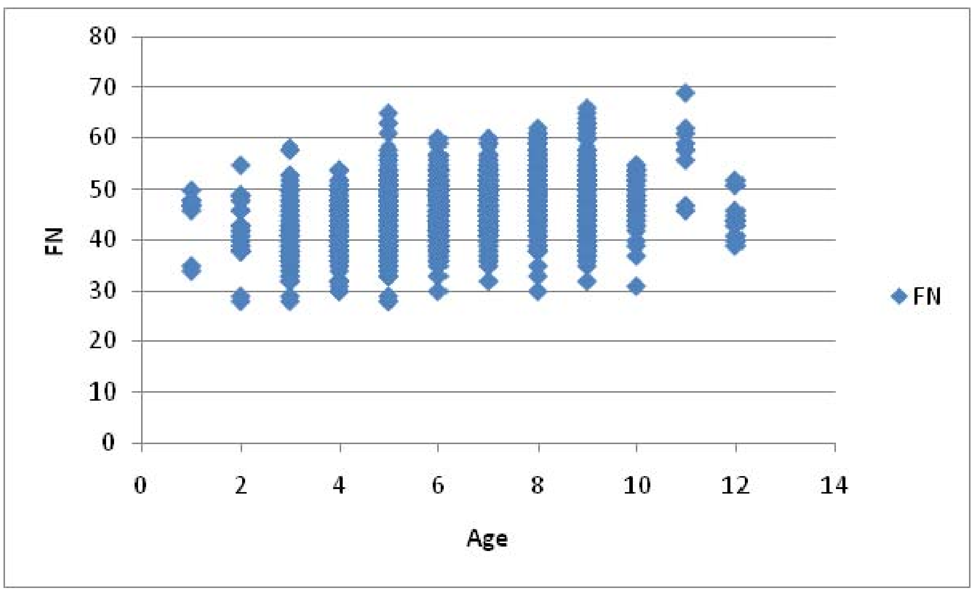


Figure 5-18. Age vs FN for HMA 12.5mm PG 70-22 in Interstates (n=2,031)

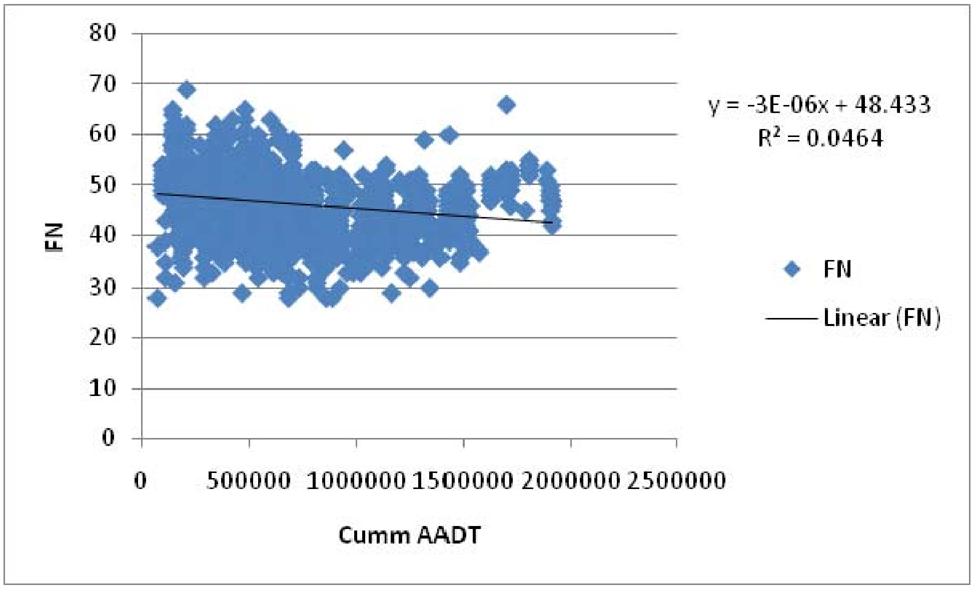


Figure 5-19. CummAADT vs FN for HMA 12.5mm PG 70-22 in Interstates (n=2,031)

Table 5-1. Selected Sections with Same AADT level and Contract Number/Mixture (12.5mm PG70-22), and Variable Speed.

year	ROUTE	RNUM	Mile	DIR	SPEED	Pav. Age	Cum AADT	FN	AADT	Actual AADT	ACTION_ YEAR	CONTRACT
2004	MD	4	0.34	S	41	3	33675	50	10571	11225	2001	SM793B5D
2004	MD	4	0.65	S	41	3	33675	52	10571	11225	2001	SM793B5D
2004	MD	4	0.95	S	38	3	33675	54	10571	11225	2001	SM793B5D
2004	MD	4	1.24	S	42	3	33675	51	10571	11225	2001	SM793B5D
2004	MD	4	1.54	S	41	3	33675	52	10571	11225	2001	SM793B5D
2004	MD	4	1.84	S	40	3	33675	51	10571	11225	2001	SM793B5D
2004	MD	4	2.15	S	39	3	33675	52	10571	11225	2001	SM793B5D
2005	MD	4	0.19	S	40	4	42700	49	10571	10675	2001	SM793B5D
2005	MD	4	0.57	S	40	4	42700	51	10571	10675	2001	SM793B5D
2005	MD	4	0.87	S	40	4	42700	49	10571	10675	2001	SM793B5D
2005	MD	4	1.17	S	41	4	42700	49	10571	10675	2001	SM793B5D
2005	MD	4	1.47	S	39	4	42700	50	10571	10675	2001	SM793B5D
2005	MD	4	1.77	S	40	4	42700	51	10571	10675	2001	SM793B5D
2005	MD	4	2.07	S	40	4	42700	51	10571	10675	2001	SM793B5D
2006	MD	4	1.16	S	39	5	52855	57	10571	10571	2001	SM793B5D
2006	MD	4	1.46	S	38	5	52855	58	10571	10571	2001	SM793B5D
2006	MD	4	1.76	S	39	5	52855	56	10571	10571	2001	SM793B5D
2006	MD	4	2.06	S	38	5	52855	55	10571	10571	2001	SM793B5D
2007	MD	4	0.20	S	43	6	62832	49	10571	10472	2001	SM793B5D
2007	MD	4	0.50	S	39	6	62832	52	10571	10472	2001	SM793B5D
2007	MD	4	0.80	S	41	6	62832	51	10571	10472	2001	SM793B5D
2007	MD	4	1.10	S	38	6	62832	56	10571	10472	2001	SM793B5D
2007	MD	4	1.40	S	41	6	62832	49	10571	10472	2001	SM793B5D
2007	MD	4	1.70	S	39	6	62832	48	10571	10472	2001	SM793B5D
2007	MD	4	2.00	S	39	6	62832	51	10571	10472	2001	SM793B5D
2007	MD	4	2.30	S	39	6	62832	49	10571	10472	2001	SM793B5D
2008	MD	4	0.30	S	40	7	75110	46	10571	10730	2001	SM793B5D
2008	MD	4	0.60	S	40	7	75110	43	10571	10730	2001	SM793B5D
2008	MD	4	0.90	S	41	7	75110	43	10571	10730	2001	SM793B5D
2008	MD	4	1.20	S	40	7	75110	42	10571	10730	2001	SM793B5D
2008	MD	4	1.50	S	40	7	75110	40	10571	10730	2001	SM793B5D
2008	MD	4	1.80	S	41	7	75110	46	10571	10730	2001	SM793B5D
2008	MD	4	2.10	S	40	7	75110	44	10571	10730	2001	SM793B5D

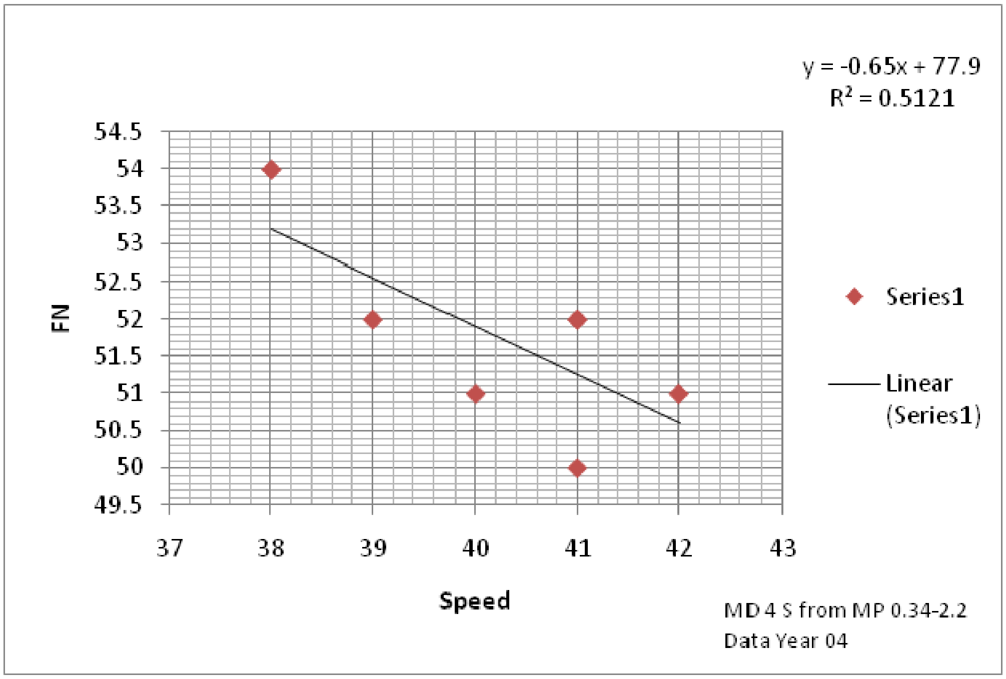


Figure 5-20. Speed vs FN for Sections with Same AADT level (~10,571) and Contract Number/ Mixture (12.5mm PG 70-22), at Variable Speed

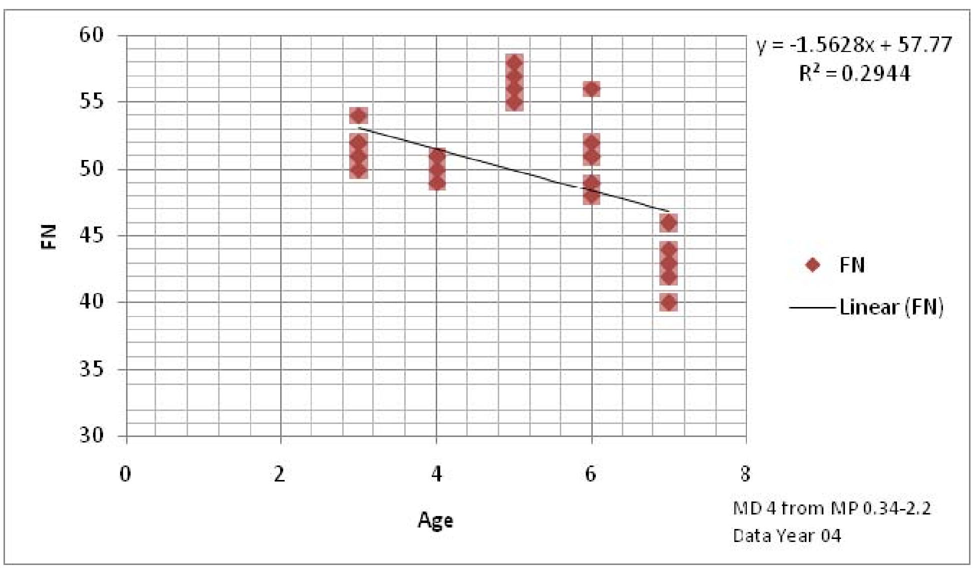


Figure 5-21. Age vs FN for Sections with Same AADT level (~10,571) and Contract Number/ Mixture (12.5mm PG 70-22), at Variable Speed

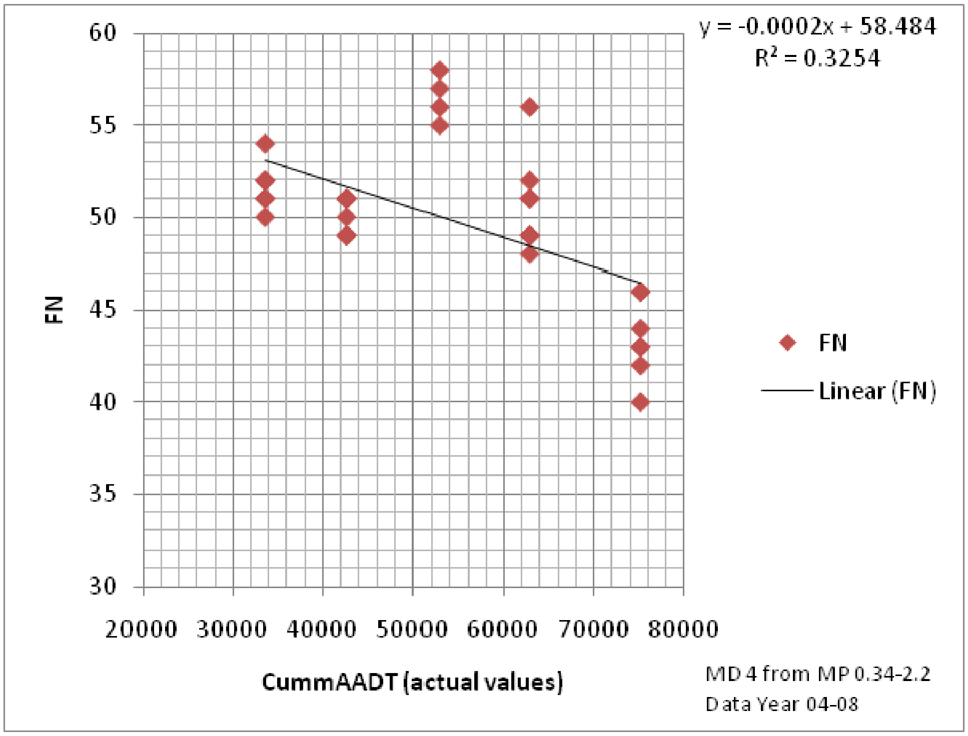


Figure 5-22. CummAADT vs FN for Sections with Same AADT level (~10,571) and Contract Number/ Mixture (12.5mm PG 70-22), at Variable Speed

Table 5-2. Multivariate Regression Analysis for Sections with Same AADT level and Contract Number/Mixture (12.5mm PG 70-22), at Variable Speed.

Coefficients

	AADT	Age	Speed	b
Coeff.	-0.00228	21.85137	-1.18182	109.6226
Std Errors	0.000568	5.85265	0.40014	15.81381
	0.671672	2.581737	#N/A	#N/A
	19.77544	29	#N/A	#N/A
	395.4316	193.2956	#N/A	#N/A

Model F Test Results

r2	0.67
df	29
n	33
v1	1
v2	29
Fdist	0.42
Fobs	19.78

t- Test Results

Variable	t-observed Value	Abs Value of t
Speed	-2.95	2.95
Age	3.734	3.73
AADT	-4.010	4.01
Tinv (95% confidence)		2.045229611

Table 5-3. Selected Sections with Same AADT level and Contract Number/Mixture (12.5mm PG70-22), at Constant Speed of 40 mph.

YEAR	ROUTE	RNUM	Mile	DIR	SPEED	Age	Cum AADT	FN	AADT	ACTUAL AADT	ACTION _YEAR	CONTRACT
2004	MD	5	14.87	S	40	5	32250	48	9000	6450	1999	SM793B53
2004	MD	5	15.17	S	40	5	32250	46	9000	6450	1999	SM793B53
2004	MD	5	15.47	S	40	5	32250	46	9000	6450	1999	SM793B53
2004	MD	5	15.77	S	40	5	32250	46	9000	6450	1999	SM793B53
2004	MD	5	16.67	S	40	5	42750	43	9000	8550	1999	SM793B53
2004	MD	5	16.97	S	40	5	42750	45	9000	8550	1999	SM793B53
2005	MD	5	14.86	S	40	6	40350	42	9000	6725	1999	SM793B53
2005	MD	5	15.17	S	40	6	40350	48	9000	6725	1999	SM793B53
2005	MD	5	16.06	S	40	6	40350	45	9000	6725	1999	SM793B53
2005	MD	5	16.36	S	40	6	53550	48	9000	8925	1999	SM793B53
2005	MD	5	16.67	S	40	6	53550	48	9000	8925	1999	SM793B53
2006	MD	5	15.69	S	40	7	49420	44	9000	7060	1999	SM793B53
2006	MD	5	16.59	S	40	7	63000	44	9000	9000	1999	SM793B53
2006	MD	5	16.89	S	40	7	63000	47	9000	9000	1999	SM793B53
2007	MD	5	14.81	S	40	8	55928	42	9000	6991	1999	SM793B53
2007	MD	5	15.11	S	40	8	55928	43	9000	6991	1999	SM793B53
2007	MD	5	16.31	S	40	8	71288	45	9000	8911	1999	SM793B53
2008	MD	5	15.48	S	40	9	59778	42	9000	6642	1999	SM793B53
2008	MD	5	15.78	S	40	9	59778	43	9000	6642	1999	SM793B53
2008	MD	5	16.38	S	40	9	76248	43	9000	8472	1999	SM793B53
2008	MD	5	16.68	S	40	9	76248	39	9000	8472	1999	SM793B53

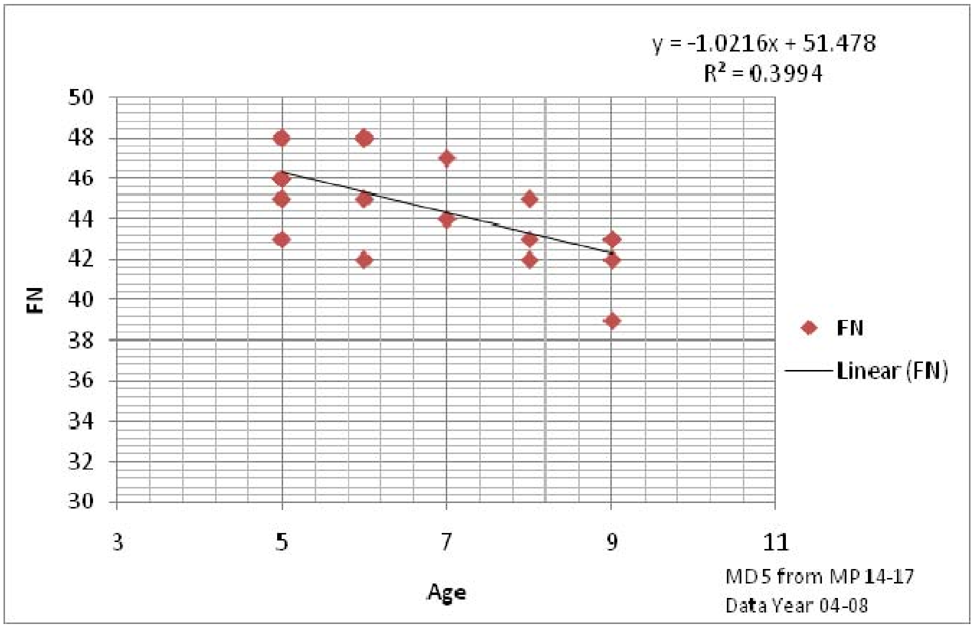


Figure 5-23. Pavement Age (Years Since last Rehab) vs FN for Sections with Same AADT level (~9000) & Contract Number/Mixture (12.5mm PG 70-22), at Constant Speed of 40 mph.

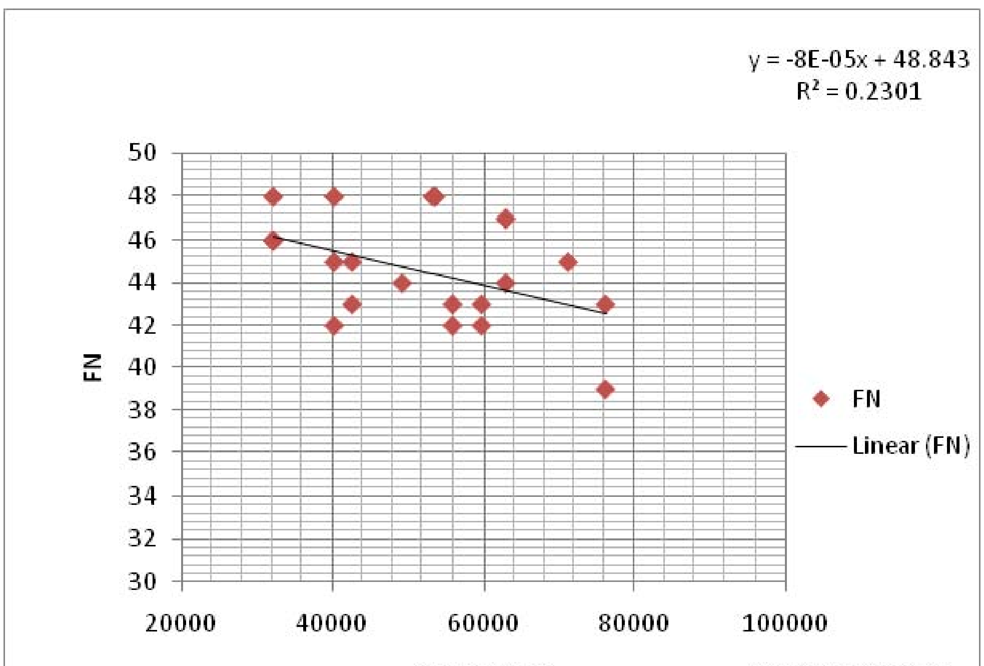


Figure 5-24. Cumulative AADT vs FN for Sections with Same AADT level (~9000) and Contract Number/Mixture (12.5mm PG 70-22), at Constant Speed of 40 mph.

Chapter 6 – Methodology for Predicting Pavement Friction Life & Relating Aggregates to Pavement Friction

Once the mixture/aggregate data and friction survey records from 2004-2008 were related using the contract/ project IDs, the analysis were directed towards identifying a methodology for predicting pavement friction life using these 5 years of friction records for each pavement section, and then relate such friction life to the aggregates used in each mixture. The merging of the friction data and the mixture design database provided about 51,000 records consisting of friction and material data for the years 2004 through 2008. Projects constructed in 2004 represent cases where 4 to 5 years of historical friction data are available. Therefore the records of these projects have been targeted as the first group to examine. As mentioned previously, the direction to follow for the analysis discussed and agreed with SHA engineers, was to consider those mixture specific data with a significant number of records. Thus, the analysis focused first on the 12.5 mm, PG 64-22, HMA mixture that has a total of 11,131 friction records. Table 6-1 shows the contract numbers for the projects constructed with this mixture in 2004 and the aggregate sources (AS1, AS2 etc) used in the mixture. Similarly Tables 6-2 and 6-3 show the records for the projects constructed in 2005 and 2006. As it can be seen from these tables, there are 385, 760 and 1,243 records in each one of these years where the project ID between friction data and mixture data matched. Furthermore it can be observed that, in many cases, different aggregate stockpiles/ sources (AS1, AS2, etc…) were used for producing the desired aggregate gradation for the mix.

***Table 6- 1. Paving Projects Constructed with* HMA 12.5mm, PG 64-22 *in 2004 with Friction Records and Aggregate Sources* . Construction Year 2004 (385 records).**

Contracts	Count
BA440B5B	77
CL821B5T	59
CL821B5Y	23
FR349B5V	74
HA250B55	22
HA250B57	111
HA250B5A	19
Grand Total	**385**

AS1	Count
Lafarge Frederick	74
Martin Marietta Woodsboro	159
Vulcan Materials Havre De Grace	152
Grand Total	**385**

As2	Count
Lafarge Frederick	74
Martin Marietta Woodsboro	159
York Building Products Belvedere Plant	152
Grand Total	**385**

AS3	Count
--------	74
Lafarge Medford	82
Martin Marietta Woodsboro	77
Vulcan Materials Havre De Grace	152
Grand Total	**385**

AS4	Count
-------	74
Arundel - Havre De Grace	152
Barricks - Woodsboro	77
LaFarge - Medford - Limestone	82
Grand Total	**385**

AS5	Count
------	385
Grand Total	**385**

S6	Count
-------	385
Grand Total	**385**

AS7	Count
-------	156
Finksburg	77
ICM	152
Grand Total	**385**

Table 6-2. Paving Projects Constructed with **HMA 12.5mm, PG 64-22** ***in 2005 with Friction Records and Aggregate Sources.***
Construction Year 2005 (760 records).

Contracts	Count
AL877B5Q	19
AL877B5S	190
BA440B5K	150
CL821A5W	86
CL821B5Z	25
WA992B5Y	38
XX6215177	252
Grand Total	**760**

AS1	Count
------	440
Allegany Aggregates Short Gap	209
Martin Marietta Woodsboro	111
Grand Total	**760**

AS2	Count
--------	440
Allegany Aggregates Short Gap	209
Martin Marietta Woodsboro	111
Grand Total	**760**

AS3	Count
------	440
Keystone Lime Company, Inc. Springs	209
Lafarge Medford	111
Grand Total	**760**

AS4	Count
-----	649
LaFarge - Medford - Limestone	111
Grand Total	**760**

AS5	Count
------	760
Grand Total	**760**

AS6	Count
------	735
Miller	25
Grand Total	**760**

AS7	Count
------	760
Grand Total	**760**

***Table 6-3. Paving Projects Constructed with* HMA 12.5mm, PG 64-22 *in 2006 with Friction Records and Aggregate Sources* .**

Construction Year 2006 (1243 records)

Contracts	Count
AL3195130	1
AL6155177	168
BA508A5X	118
BA508A5Z	24
BA508B5J	182
FR3735176	11
HA250B5S	69
HA250B5T	21
HA250B5W	95
HA250B5X	93
HA250B5Y	64
HA309B51	11
XX6015177	50
XX8015177	243
XX8135177	93
Grand Total	**1243**

AS1	Count
-------	196
Allegany Aggregates Short Gap	297
Lafarge Churchville	272
Lafarge Frederick	73
Lafarge Texas	181
Martin Marietta Woodsboro	118
Vulcan Materials Havre De Grace	106
Grand Total	**1243**

AS2	Count
-------	196
Allegany Aggregates Short Gap	297
Lafarge Churchville	272
Lafarge Frederick	254
Martin Marietta Woodsboro	118
York Building Products Belvedere Plant	106
Grand Total	**1243**

AS3	Count
---------	207
Allegany Aggregates Short Gap	81
Keystone Lime Company, Inc. Springs	216
Lafarge Frederick	62
Lafarge Texas	299
Vulcan Materials Havre De Grace	106
York Building Products Belvedere Plant	272
Grand Total	**1243**

Table 6-3. Paving Projects Constructed with **HMA 12.5mm, PG 64-22** *in 2006 with Friction Records and Aggregate Sources (continue) .*

Construction Year 2006 (1243 records)

As4	Count
------	685
Arundel - Havre De Grace	106
Barricks - Woodsboro	118
Kline	31
LaFarge - Frederick	31
York Build Prods - Belvedere	272
Grand Total	**1243**

AS5	Count
------	1125
LaFarge - Texas	118
Grand Total	**1243**

AS6	Count
------	1243
Grand Total	**1243**

AS7	Count
------	678
finksburg	118
ICM	106
LaFarge - Texas	181
MD Paving	160
Grand Total	**1243**

The 4-5 year friction records for each project were then examined to generate the data needed to study changes in FN (Friction Number) for a specific aggregate (or aggregate blend). In order to compare the friction number of a section year after year – taking into account increases in traffic - the milepost values were used. This was necessary since Annual Average Daily Traffic (AADT) may change at different mileposts. The friction readings were compared and contrasted by milepoint for the 4-5 year friction surveys which were collected on the pavement section in consideration.

Another consideration on grouping the data was related to the use of different friction equipment. The SHA operates two friction survey equipment to collect friction readings - once a year- throughout the state. In some cases truck 5 was used for readings in some years, while in the remaining years truck 6 was used. The side by side repeatability analysis included in this report indicated that for flexible sections Track 5 shows on the average a lower value of FN, by 6.5 FN units. Thus, the FN data recorded using different equipment on the same section of roadway needed to be adjusted in order to account for equipment variability.

Furthermore, studies have shown that friction survey speed affects FN readings, i.e. survey speed is indirectly proportional to friction readings (Henry 2000; Goulias et. al. 2007). As a result, Friction Number (FN) records that were collected at a speed of 38-41 mph were used during the grouping of the data so as to minimize the effect of variability due to survey speed. Finally, the grouped FN values were examined for potential outlier values. In this case the Chauvenet's criterion was used. In statistical terms this requires to first calculate the mean and standard deviation of the observed data, then use the normal distribution function to determine the probability that a given data point is an outlier, and then multiply such probability by the number of data points considered. If that value is below 0.5 then the value may be flagged as an outlier (i.e., a data point may be rejected if the probability of obtaining the particular deviation from the mean is less than 1/(2n)).

In summary, the procedure followed in the analyses includes the following steps:

- STEP 1: Identify mixtures with the higher number of friction records and available aggregate information;
- STEP 2: Merge friction records with mixture and aggregate data using Contract IDs;
- STEP 3: Identify the construction year and group friction data for the following years using milepost information;
- STEP 4: Update AADT for each milepost with the actual records from the Traffic Monitoring System web site;
- STEP 5: Include the truck type (truck # 5 and #6) used in the friction surveys;
- STEP 6: Run outlier analysis for subgroups of data representing uniform conditions;
- STEP 7: Calculate the average FN values for subgroups of data representing uniform conditions;
- STEP 8: Adjust FN values for considering the use of different friction equipment;
- STEP 9: Use average FN values and AADT records to obtain the relationship between FN and traffic for a specific aggregate/ aggregate blend;

STEP 10: Use an interpolation function to calculate: i) the “friction drop rate” (FN drop/ 10k AADT) for each aggregate/ aggregate blend, and ii) estimate “useful aggregate friction design life” (i.e., at what cum AADT a terminal FN of 32 is reached).

In addition to this 10 step methodology for relating aggregate properties to pavement friction, the research team expanded the analysis to include the following:

1) Simple Regression models using
   - Raw data – all data, both directions combined
   - Combined data - Filtered for speed, adjusted for equipment;
   - Directional Data - grouped by year of survey;

2) Multivariate Regression models
   - With adjusted data for friction equipment and considering the following Variables, Cum AADT, Speed and FN;
   - With no adjustment for equipment and considering the following variables, CumAADT, Speed, Equipment and FN;

3) Considering data with friction survey speed of 40 mph and models relating CumAADT and FN;

4) Using data from combined contracts (all directions and speed ranges) for simple and multivariate regression analysis as indicated above.

6.1. Example Analysis for a Specific Aggregate Source (Lafarge Frederick Quarry)

This section provides in summary an example of the analysis used for each pavement section/contract in the database using aggregate from a specific source and for which friction data were available. The results of the analysis from this specific supplier was selected to be included herein since: i) the aggregate gradation was designed primarily with materials from a single quarry, Table 6-4, and ii) there were sufficient number of friction records on which the analysis could be developed. The database provided records from two different contracts, FR349B5T on MD 31, and MO4335177 on MD121, that met the above listed criteria. Thus the following approach was used for analyzing the data and the outcome of the analysis is shown in Table 6-5:

1. Analysis on UNFILTERED data (any speed, equipment, etc) combining N/S or E/W RAW DATA;
2. Analysis on UNFILTERED data for each direction;
3. Analysis on filtered (for speed) and adjusted (for equipment) data for both directions combined;
4. Analysis on filtered (for speed) and adjusted (for equipment) data for each direction.

As it can be seen from the models and analysis in Table 6-5 the friction records from a single contract and on the eastbound MD 31 provided the model with the higher R^2. Overall it was observed that combining friction records from different route directions or different contracts increased the data variability, and thus reduced the coefficient of correlation for the model. Furthermore, the multivariate regression models often provided lower R^2, and or the model was reduced down to a simple linear regression form since most of the variables such as survey speed, CumAADT and/or survey track equipment were statistically insignificant.

Table 6-4: Aggregate Supplier Data

FR349B5T on MD 31

Route	RNUM	Action Yr	AS1	AS1%	AS2	AS2%	Data Count
MD	31	2004	Lafarge Frederick	50	Lafarge Frederick	50	84

Supplier Source	Year Sampled	Carbonate?	Rock Analysis	Textural Description	Rock Category	BPN	PV	SG	LAA (% Loss)	Soundness (% Loss)
Lafarge Frederick	2004	Yes	No	Very-fine grained	Limestone	28	6	2.72	23	0.2

MO4335177 on MD 121

Route	RNUM	Action Yr	AS1	AS1%	AS2	AS2%	Data Count
MD	121	2006	Lafarge Frederick	50	Lafarge Frederick	50	52

Supplier Source	Year Sampled	Carbonate?	Rock Analysis	Textural Description	Rock Category	BPN	PV	SG	LAA (% Loss)	Soundness (% Loss)
Lafarge Frederick	2005	Yes	No	Medium Gray fine to Medium grained	Carbonate-Limestone	24	6	2.70	22	0.4

Table 6-5: Summary of Analysis for Friction Records related to a Specific Aggregate Source (Lafarge Frederick Quarry)

Contract	Route	Analysis Type/ Data used for analysis	Model Type (Viable)	Equation	R^2	N	Terminal CumAADT at FN=32
FR349B5T	MD 31 (E+W)	Combined Directional Data (Filtered for Speed and Adjusted for Equipment)	SLR	FN = -0.0006 (CumAADT) + 52.66	0.41	78	34,000
		All Combined Directional Data (Un-Filtered and Un-adjusted)	MER (CumAADT, Speed and Equipment)	FN= 22.03* ((0.9999^CumAADT)*(1.001^Speed)*(1.186^DumTrk))	0.5	44	6,000(Using Eqpt 5) 8,000 (Using Eqpt 6)
	MD 31E	Directional Data (Filtered for Speed and Adjusted for Equipment)-Averages	SLR	FN = -0.0006 (CumAADT) + 52.473	0.76	40	34,200
		All Directional Data (Un-Filtered and Un-adjusted)	MLR (CumAADT and Equipment)	FN= -0.00089 (CumAADT) + 9.237 (DumTrk) + 7.75	0.49	44	24,000(Using Eqpt 5) 36,000 (Using Eqpt 6)
			MER CumAADT, Speed&Equipment)	FN= 26.102 ((0.9999^CumAADT)*(0.996^Speed)*(1.195^DumTrk))	0.52	44	6,000 (Eqpt 5) 8,000 (Eqpt 6)

Table 6-5: Summary of Analysis **for Friction Records related to a Specific Aggregate Source (Lafarge Frederick Quarry) (Continued)**

FR349B5T	MD 31W	Directional Data (Filtered for Speed and Adjusted for Equipment)-All data	SLR	FN = -0.0003 (CumAADT) + 52.907	0.08	38	81,000
		Directional Data (Filtered for Speed and Adjusted for Equipment)-Averages	SLR	FN = -0.0006 (CumAADT) + 52.966	0.73	38	35,000
		All Directional Data (Adjusted for Equipment)	MLR (CumAADT and Speed)	FN= -0.000568 (CumAADT) + 0.622 (Speed) + 27.61	0.52	40	36,000
		All Directional Data	MER (CumAADT , Speed and Equipment)	FN= 14.5*(0.9999^CumAADT)*(1.0126^Speed)*(1.1742^DumTrk))	0.45	40	5,000 (Eqpt 5) 7,000 (Eqpt 6)
MO4335177	MD 121 (N+S)	All Combined Directional Data (Un-Filtered and Un-adjusted)	MER(CumAADT , Speed and Equipment)	FN= 231.75*(0.9999^CumAADT) * (0.9962^Speed)* (0.8222^Dum-Trk)	0.29	52	6,500 (Eqpt 5)
	MD 121 N	All Directional Data (Un-Filtered and Un-adjusted)	SLR	FN= -0.0002 (CumAADT) + 55.23	0.006	26	13,000
		All Directional Data (Un-Filtered and Un-adjusted)	MER (CumAADT , Speed and Equipment)	FN= 1052.64*(0.9999^CumAADT)* (0.9920^Speed)*(0.6823^DumTrk)	0.56	26	12,000(Eqpt 5) 16,000(Eqpt 6)

Table 6-5: Summary of Analysis **for Friction Records related to a Specific Aggregate Source (Lafarge Frederick Quarry) (Continued)**

FR349B5T and MO4335177	MD 31 (E+W) and MD 121 (N+S)	All Combined/merged Data (Un-Filtered and Un-adjusted)	SLR	FN= -1E-04 (CumAADT) + 53.871	0.00 4	13 6	184,000
		Combined/merged Data (Filtered and adjusted)	SLR	FN = -0.0004 (CumAADT) + 53.328	0.06	12 8	48,000
		All Combined/merged Data (Adjusted for Equipment)	MER (CumAADT and Speed)	FN= 67.559* (0.9999^CumAADT)* (0.9940^Speed)	0.11	13 6	5,000
		All Combined/merged Data	MER (CumAADT , Speed and Equipment)	FN= 69.560* (0.9999^CumAADT)* (0.9921^Speed)*(1.0094^DumTrk)	0.08	13 6	5,000 (Eqpt 5 and 6)

Note:

SLR= Simple Linear Regression

SER= Simple Exponential Regression

MLR= Multiple Linear Regression

MER = Multiple Exponential Regression

CUMAADT= Cumulative Annual Average Daily Traffic

DumTrk = Dummy Variable used for Equipment (Dumtrk=5 for Equipment 5; Dumtrk=6 for Equipment

6.2. Analysis Relating Friction to Pavement Traffic in terms of Cumulative AADT and ESAL.

The analysis outlined in the previous sections were conducted on all projects with mixture and aggregate source data. Table 6-6 identifies the list of quarries/ suppliers considered in the study.

Table 6-6. Aggregate Quarries Considered in the Analysis

AIR	Aggregate Industries Rockville	
AASG	Allegany Aggregates Short gap	Few friction and mixture data (n=7)
KLC	Keystone Lime Company Inc. Springs	Significantly different properties than rest of aggregates
LCH	Lafarge Churchville	
LF	Lafarge Frederick	
LW	Lafarge Warfordsburg	No aggregate property data
MMI	Maryland Materials Incorporated	No aggregate property data
MMW	Martin Marietta Woodsboro	No aggregate property data
VMH	Vulcan Materials Hanover	
VMHDG	Vulcan Materials Havre De Grace	No aggregate property data
VMW	Vulcan Materials Warrenton	
YBPBv	York Building Products Belvedere	

While the merged SHA friction records and mixture material database provided records for the 12 quarries shown in Table 6-6, aggregate petrographic / polishing properties for only a subset of these were available. Furthermore, for one quarry only limited FN/ milepost records were available (AASG), while for another (KLC) the aggregate properties were significantly different than the rest of the aggregates.

The results of the regression models between pavement friction life and traffic are shown in Table 6-7. As can be seen from this table the simple linear regression analysis provided the best relationships between FN and cumAADT. For the multivariate regression analysis relating FN to cumAADT, speed and equipment type, either the models had a lower R^2 or the variables turn out to be insignificant. The details of the best models are shown in Table 6-7. Based on these models the cumAADT to a terminal FN of 32 were calculated and reported. Furthermore the cumAADT over the average AADT throughout the years was used to calculate the expected pavement friction life in years. The FN drop/10k AADT is also reported in this table. Examples of the relationships between FN and CumAADT are shown in Figures 6-1 to 6-4. As shown in Table 6-7 and these Figures, the models obtained from the 2004 to 2008 friction data where used to estimate the pavement friction life for each case, in terms of years (i.e., CumAADT over the average AADT throughout the years) and terminal cumulative AADT at a final value of FN 32. This FN value represents the minimum acceptable design value used by SHA and many other states. Furthermore the drop in FN for every 10,000 AADT is also reported.

From the comparison of the CumAADT at a terminal FN value of 32 it can be observed that there is a big difference in the order of magnitude of these values. This reflects the different traffic mix characteristics that each roadway experience during its service life. Since the AADT does not reflect the diverse truck loading conditions on each roadway, there was a need to convert AADT to ESAL considering the truck distribution factors on the projects and the mileposts considered in the analysis.

The AADT conversion into Equivalent Single Axle Loading (ESAL) can be achieved by either: i) directly converting the Cumulative AADT obtained at the FN 32 value for each case, or ii) by converting AADT data to ESAL at each milepoint. In either case, the AADT data and truck percentage factor obtained from the traffic monitoring web site of SHA were used to calculate ESAL using the equivalency load factors analysis. These two methods were used in a couple of projects for assessing whether there is a difference in the approach used. Table 6-8 to 6-9 and Figures 6-5 to 6-8 present the results from these analysis for a couple of cases (AIR and AASG). As it can be seen whether the AADT to ESAL conversion is based at the milepost level or at the CumAADT values the calculated values are similar. Thus the latter method was used for converting AADT to ESAL for all cases. The details of these calculations and analysis were also included in Table 6-7.

Table 6-7. Regression Analysis Relating Friction Life to CumAADT and Aggregate Properties

Material Source	AIR	AASG	KLC	LCH	LF
Aggregate type (If known)	Serpentine	Carbonate Dolomitic Limestone (2005 Petrography)	Carbonate-Siliceous limestone(2005 Petrography)	Hornlende Gnesiss (2005 Petrography)	Limestone
Supplier	Aggregate industries	Allegany Aggregates	Keystone Lime Company, Inc.	Lafarge	Lafarge
Quarry	Aggregate Industries Rockville	Allegany Aggregates Short Gap	Keystone Lime Company, Inc. Springs	Lafarge Churchville	Lafarge Frederick
Contract No	MO3285177	AL6165177	GA6455177	BA508B5J	FR349B5T
BPN/PV	22/5 (2004)	26/5 (2005)	34/10 (2005)	22/6 (2005)	24/6 (2005)
LAA/ Soundness	18% /4.5% (2004 tests)	15% / 2.8% (2005 tests)	18% / 1% (2005 tests)	22/0.4 (2005 tests)	22% / 0.2% (2005 tests)
Carbonate (yes/No/N/A)	N/A	Yes	N/A	No	Yes
Mix Type	HMA 12.5 70-22 8 PV	HMA 12.5mm, 64-22, Surface, L 4	HMA 12.5mm, 70-22, Surface, L 3	HMA 12.5mm, 64-22, Surface, L 2	HMA 12.5mm, 64-22, Surface, L 2
Supplier 1/% Composition	AIR/75%	AASG/100%	KLC/100%	LCH/65%	LF/100%
Supplier 2/% Composition	Plant 128 Stockpile/25%	N/A	N/A	YBPBv/25%; MD Pavng/10%	N/A
County	Montgomery	Allegany	Garrett	Baltimore	Frederick
Route	MD 190 (E+W)	US 220 (N+S)	US 219 (N+S)	MD 43 (E+W)	MD31(E+W)
MP	0-6.5	3.3-6.6	33.2-37.2	0-3.5	0-3.2
Action Year	2004	2006	2005	2006	2005
No of Lanes	2	2	3	4	2
Direction used in Analysis (Resulted in better models)	MD 190E	US 220S	US219S	MD 43E	MD 31E

Table 6-7. Regression Analysis Relating Friction Life to CumAADT and Aggregate Properties (Continued)

Material Source	AIR	AASG	KLC	LCH	LF
AADT (Averaged over Mile points and over survey years)	3,573	7,201	4,762	36,320	3,435
Truck Percentage(2005-7 Data)					
Single	11.2	7.7	8.2	3.4	8.5
Combination	2.6	4	4.6	0.8	3
Passenger/Other	86.2	88.3	87.2	95.8	88.5
Truck Percentage(2008 Data)					
Single	10.6	7.6	8.2	3.4	9.6
Combination	2.1	2.2	4.6	0.8	3
Passenger/Other	87.3	90.2	87.2	95.8	87.4
Average Percentages					
Single	10.9	7.65	8.2	3.4	9.05
Combination	2.35	3.1	4.6	0.8	3
Passenger/Other	86.75	89.25	87.2	95.8	87.95
Load Equivalency Factors, LEF (SN=5, Pt=2.5)					
Single	**1.857**	**1.857**	**1.857**	**1.857**	**1.857**
Combination	**2.714**	**2.714**	**2.714**	**2.714**	**2.714**
Passenger/Other	**0.0002**	**0.0002**	**0.0002**	**0.0002**	**0.0002**
Directional Distribution Factor	0.5	0.5	0.5	0.5	0.5
Lane Distribution Factor	1	1	0.7	0.7	1
Terminal CumAADT [CumAADT where FN=32]	**66,000**	**57,200**	**30,000**	**195,000**	**40,000**

Table 6-7. Regression Analysis Relating Friction Life to CumAADT and Aggregate Properties (Continued)

Material Source	**AIR**	**AASG**	**KLC**	**LCH**	**LF**
ESAL= Terminal CumAADT*T*Df*Lf*LEF*365					
Single	2,438,065	1,482,970	583,590	1,572,847	1,048,937
Combination	768,218	878,275	478,465	540,873	508,183
Passenger/Other	2,090	1,863	668	4,773	1,098
Total ESAL	3,208,372	2,363,108	1,062,723	2,118,493	1,558,218
Most Significant model/[Equation]	SLR/[FN = -0.0002* CumAADT + 47.75]	SLR/[FN = -0.0003*CumAADT + 49.157]	SLR/[FN= -0.0013*CumAADT + 71.011]	SLR/[FN= -1E-04*CumAADT + 51.64]	SLR/[FN= -0.0005* CumAADT+ + 52.165]
R2/n	0.17/85	0.12/20	0.65/39	0.72/18	0.75/40
FN Drop/10k AADT (in FN units)	-2	-3	-13	-1	-5
Other Models/ [R2/n/Terminal CumAADT]	MLR/[0.11/174/ 5,500]	MER/[0.78/20/ 20,000]	MER/[0.88/42 /14,000]	MER/[0.42/21/ 170,000]	MER/[0.52/44/ 14,000]
Expected Life in Years (Based on Terminal CumAADT)=CumAADT/Average AADT	*18.47*	*7.94*	*6.30*	*5.37*	*9.96*

Note:
SLR= Simple Linear Regression; Simple Exponential Regression; MLR= Multiple Linear Regression;
MER= Multiple Exponential Regression; SA= Sensitivity Analysis

Table 6-7. Regression Analysis Relating Friction Life to CumAADT and Aggregate Properties (continue)

Material Source	LW	MMI	MMW	VMH	VMHDG	VMW	YBPBv
Aggregate type (If known)	Limestone			Limestone		Diabase (2004)	
Supplier	Lafarge	Maryland Material Inc	Martin Marietta	Vulcan Materials	Vulcan Materials	Vulcan Materials	York Building Products
Quarry	Lafarge Warfordsburg	Maryland Material Inc NE	Martin Marietta Woodsboro	Vulcan Materials Hanover	Vulcan Materials Havre De Grace	Vulcan Materials Warrenton	York Building Products Belvedere Plant
Contract No	WA1005177	CE785A5N	BA440B5B	AA3285177	WO750B5O	MO9005171	CE785B5H
BPN/PV	35/6(2008)	32/HPV(2009)		21/4 (2005)	31/HPV (2008)	26/- (2005)	
LAA/ Soundness	20%/0.6% (2008 tests)	21%/0.9%(2009 tests)		25% / 0/7% (2005 tests)	14%/0.1% (2008 tests)	11/0.3 (2005 tests)	
Carbonate (yes/No/N/A)	N/A	N/A	N/A	Yes	N/A	N/A	N/A
Mix Type	HMA 12.5mm, 64-22, Surface, L 4	HMA 9.5mm, 64-22, Surface, L 2	HMA 12.5mm, 64-22, Surface, L 2	HMA 9.5mm, 70-22, Surface, L 3	HMA 9.5mm, 70-22, Surface, L 3	HMA 12.5mm, 76-22, Surface, 8 PV, L 4	HMA 9.5mm, 70-22, Surface, L 2
Supplier 1/% Composition	LW/100%	MMI/78%	MMW/75%	VMH/85%	VMHDG/68%	VMW/75%	YBPBv=72%
Supplier 2/% Composition	N/A	YBPBv/7&; Edgemoor/15%	BW/15% Finksburg/10%	Flanigan/15%	JML GT/32%	AGI-S/10%; ½ RAP=15%	SDM&S EM=18%; ICM=10%
County	Washington	Cecil	Baltimore	Anne Arundel	Worcester	Montgomery	Cecil
Route	US 40 (E+W)	MD342 (N+S)	MD 30 (N+S)	MD100W	US 113 (E+W)	MD 650 (N+S)	MD 276 (N+W)
MP	28-32	0-2.5	5-7.5	11.0-15.0	26 - 30	3.6 -- 5.3	3.5-6.5
Action Year	2005	2006	2004	2005	2005	2005	2004
No of Lanes	2	2	2	4 (in one direction-WB)	4	6	

Table 6-7. Regression Analysis Relating Friction Life to CumAADT and Aggregate Properties (continued)

Material Source	LW	MMI	MMW	VMH	VMHDG	VMW	YBPBv
Direction used in Analysis (Resulted in better models)	US 40W	MD 342N	MD 30S	MD 100W	US 113S	MD 650 N	MD 276 N
AADT (Averaged over Mile points and over survey years)	4,390	498	8,780	60,260	11,490	51,320	8,520
Truck Percentage(2005-7 Data)							
Single	6.4	0	7.5	2.2	9.8	2.9	8.3
Combination	1.9	0	4.1	0.5	8	1.5	5.7
Passenger/Other	91.7	100	88.4	97.3	82.2	95.6	86
Truck Percentage(2008 Data)							
Single	6.4	0	7.5	2.2	9.8	2.9	8.3
Combination	1.9	0	4.1	0.5	8	1.5	5.7
Passenger/Other	91.7	100	88.4	97.3	82.2	95.6	86
Average Percentages							
Single	6.4	0	7.5	2.2	9.8	2.9	8.3
Combination	1.9	0	4.1	0.5	8	1.5	5.7
Passenger/Other	91.7	100	88.4	97.3	82.2	95.6	86
Load Equivalency Factors, LEF (SN=5, Pt=2.5)							
Single	**1.857**	**1.857**	**1.857**	**1.857**	**1.857**	**1.857**	**1.857**
Combination	**2.714**	**2.714**	**2.714**	**2.714**	**2.714**	**2.714**	**2.714**
Passenger/Other	**0.0002**	**0.0002**	**0.0002**	**0.0002**	**0.0002**	**0.0002**	**0.0002**
Directional Distribution Factor	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lane Distribution Factor	**1**	**1**	**1**	**0.7**	**0.7**	**0.7**	**1**
Terminal CumAADT [CumAADT where FN=32]	**14,100**	**4,500**	**76,000**	**510,000**	**72,000**	**480,000**	**54,000**

Table 6-7. Regression Analysis Relating Friction Life to CumAADT and Aggregate Properties (continued)

Material Source	LW	MMI	MMW	VMH	VMHDG	VMW	YBPBv
ESAL= Terminal CumAADT*T*Df*Lf*LEF*365							
Single	**305,826**	**0**	**1,931,744**	**2,661,740**	**1,673,907**	**3,302,266**	**1,518,961**
Combination	**132,692**	**0**	**1,543,370**	**884,119**	**1,997,070**	**2,496,337**	**1,524,549**
Passenger/Other	**472**	**164**	**2,452**	**12,679**	**1,512**	**11,724**	**1,695**
Total ESAL	**438,990**	**164**	**3,477,567**	**3,558,538**	**3,672,489**	**5,810,328**	**3,045,205**
Most Significant model/[Equation]	SLR/[FN = -0.0018* CumAADT + 57.363]	SLR/[FN = -0.0085* CumAADT + 66.25]	SLR/[FN = -0.0085*CumAADT + 66.25]	SLR/[FN= -2E-05*CumAADT + 40.042]	SLR/[FN=-0.0003* CumAADT+ 53.192]	SLR/[FN= -3E-05* CumAADT + 47.497]	SLR/[FN=-0.0004* CumAADT + 56.283]
R2/n	**0.97/28**	**0.58/11**	**0.56/27**	**0.14/34**	**0.38/23**	**0.29/12**	**0.92/36**
FN Drop/10k AADT (in FN units)	**-18**	**-8.5**	**-2**	**-0.5**	**-0.3**	**-0.3**	**-5**
Other Models/ [R2/n/Terminal CumAADT]	**MER/[0.54/30/ 12,000]**	**MER/[0.69/21/ 4000]**	**MER/[0.09/31/ 14000]**	**MER/[0.2/39/ 28,000]**	**MER/[0.27/27/ 6000]**	**MER/[0.25/20/ 4000]**	**MLR/[0.81/37/ 56000]**
Expected Life in Years (Based on Terminal CumAADT)=CumAADT/Average AADT	*3.21*	*9.04*	*8.66*	*8.46*	*6.27*	*9.35*	*6.34*
Remark	Note: Material from both LW and LF was used in this contract			Note: This contract was used to construct MD 100 WB only			

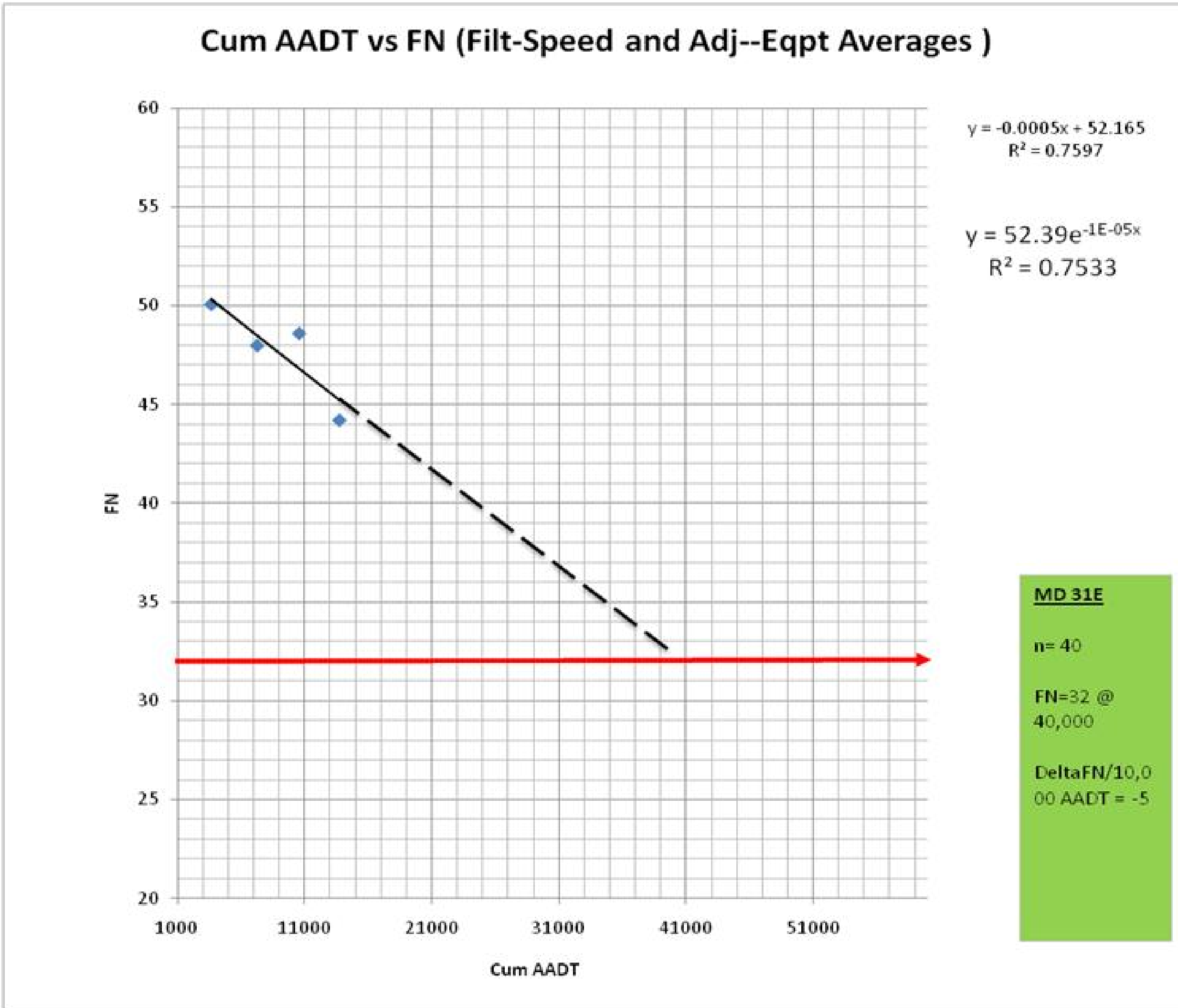


Fig 6-1. Cum AADT vs FN (filtered and adjusted Data – Averages)
N= 40, R^2= 0.76
Lafarge Frederick

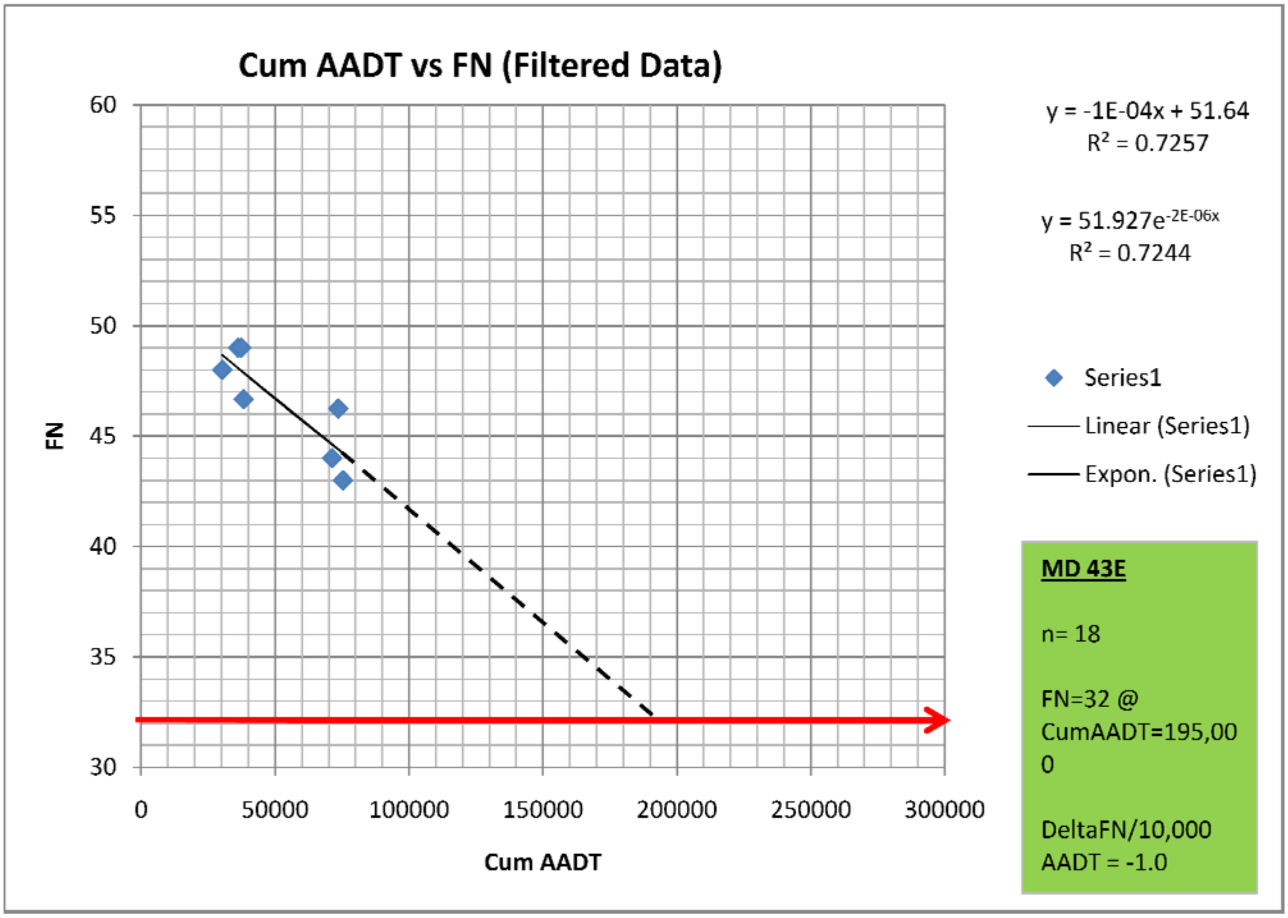


Fig 6-2. Cum AADT vs FN (filtered and adjusted Data – Averages)
N= 18, R^2= 0.73
Lafarge Churchville (Aggregate Blend)

Fig 6-3. Cum AADT vs FN (filtered and adjusted Data – Averages)
N= 23,R^2= 0.38
Vulcan Materials Havre De Grace (Aggregate Blend)

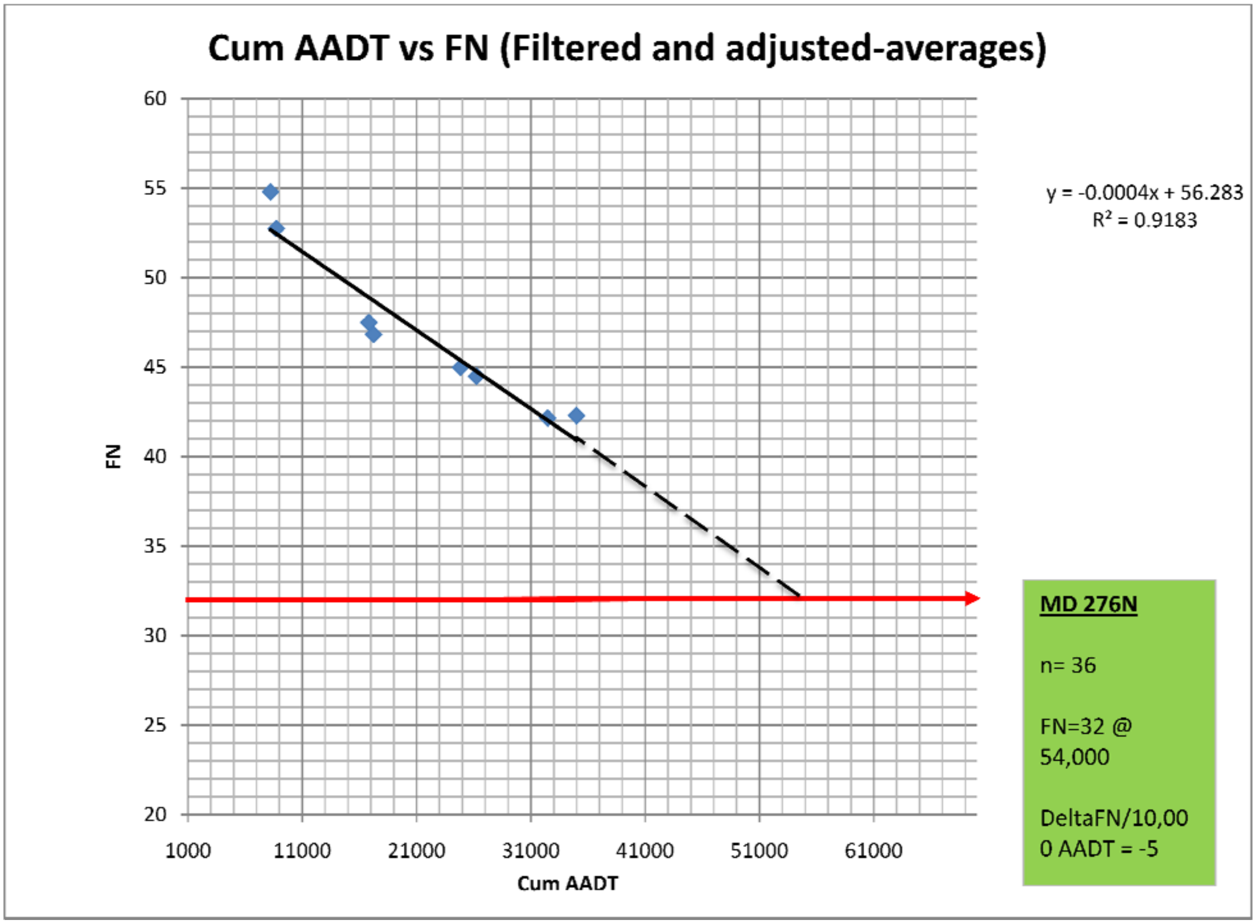


Fig 6-4. Cum AADT vs FN (filtered and adjusted Data – Averages)
N=36,R^2= 0.92
York Building Products Belvedere Plant (Aggregate Blend)

Table 6-8. Comparison of CumAADT converted to CumESAL and ESAL computed at Milepoint level
Supplier = AIR, Route= MD 190 E

Conversion of CumAADT to CumESAL

Material Source	AIR
Contract No	MO3285177
Mix Type	HMA 12.5 70-22 8 PV
County	Montgomery
Route	MD 190 (E+W)
MP	0-6.5
No of Lanes	2
AADT (Averaged over Milepoints and over survey years)	3,573
Direction used in Analysis	MD 190E
Truck Percentage(2005-7 Data)	
Single	11.2
Combination	2.6
Passenger/Other	86.2
Truck Percentage(2008 Data)	
Single	10.6
Combination	2.1
Passenger/Other	87.3
Average Percentages	
Single	10.9
Combination	2.35
Passenger/Other	86.75

Computation of ESAL at milepoint to obtain CUMESAL

Material Source	AIR
Contract No	MO3285177
Mix Type	HMA 12.5 70-22 8 PV
County	Montgomery
Route	MD 190 (E+W)
MP	0-6.5
No of Lanes	2
AADT (Averaged over Milepoints and over years)	3375
Direction used in Analysis	MD 190E
Truck Percentage(2008 Data)	
Single	10.6
Combination	2.1
Load Equivalency Factors, LEF (SN=5, Pt=2.5)	
Single	1.857
Combination	2.714
Directional Distribution Factor	0.5
Lane Distribution Factor	1
Terminal CumESAL	

Table 6-8. Comparison of CumAADT converted to CumESAL and ESAL computed at Milepoint level (Continued) Supplier = AIR, Route= MD 190 E

Conversion of CumAADT to CumESAL

Load Equivalency Factors, LEF (SN=5, Pt=2.5)	
Single	1.857
Combination	2.714
Passenger/Other	0.0002
Directional Distribution Factor	0.5
Lane Distribution Factor	1
Terminal CumAADT	**66,000**
[CumAADT where FN=32]	
ESAL= Terminal CumAADT*T*Df*Lf*LEF*365	
Single	2,438,065
Combination	768,218
Passenger/Other	2,090
Total	**3,208,372**

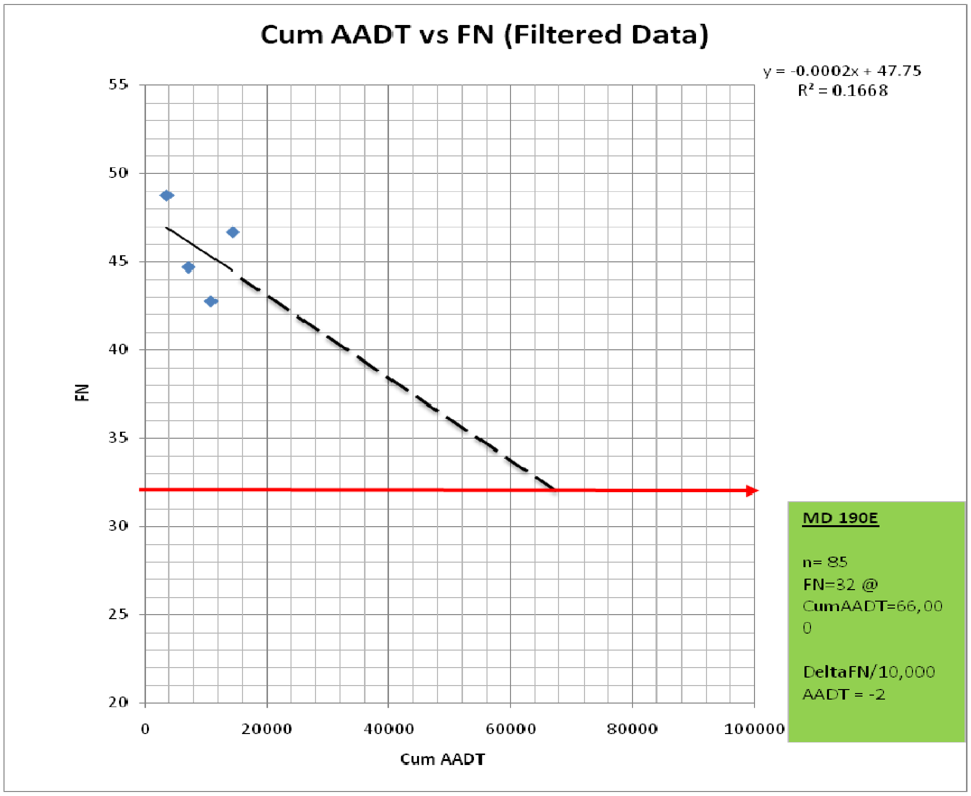


Fig 6-5. CumAADT vs FN (MD 190E

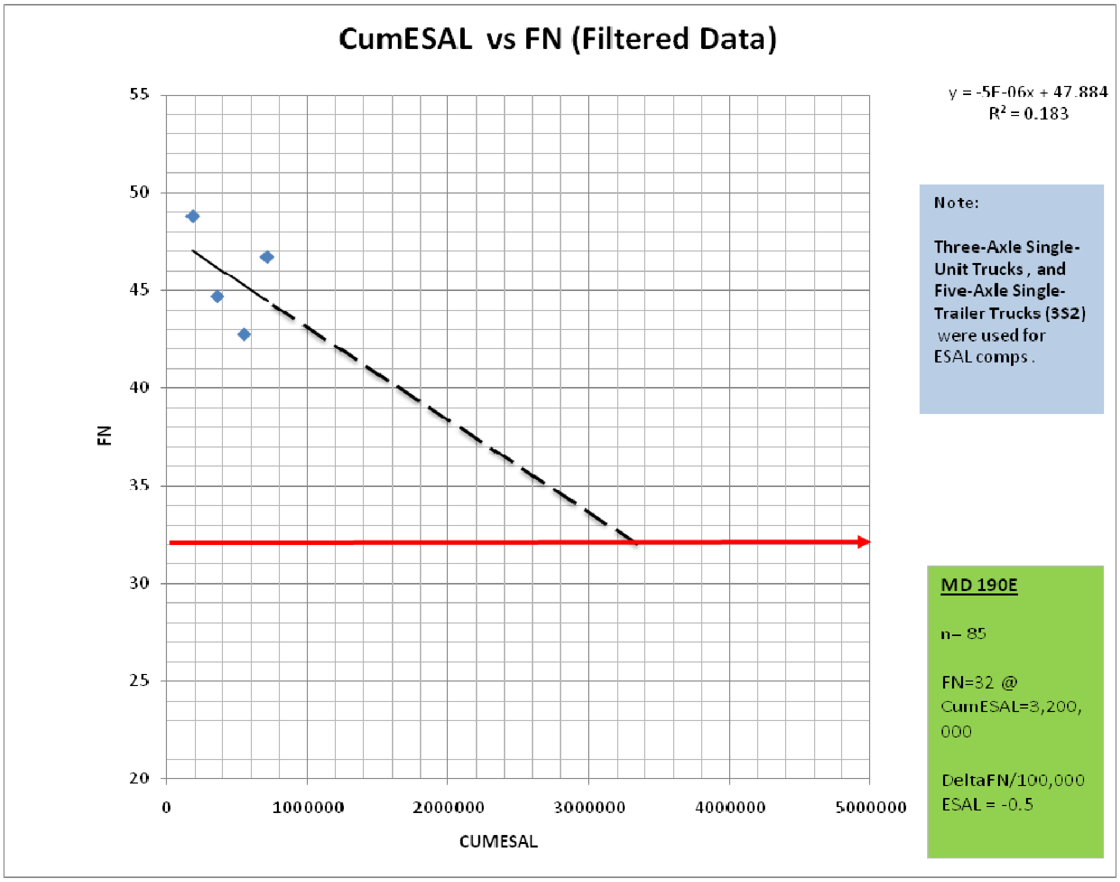


Fig. 6-6. CumESAL vs FN (MD 190E)

Table 6-9. Comparison of CumAADT converted to CumESAL and ESAL computed at Milepoint level
Supplier = AASG, Route= US 220 S

Conversion of CumAADT to CumESAL

Material Source	AASG
Contract No	AL6165177
Mix Type	HMA 12.5mm, 64-22, Surface, L 4
County	Allegany
Route	US 220 (N+S)
MP	3.3-6.6
No of Lanes	2
AADT (Averaged over Milepoints and over survey years)	7,201
Direction used in Analysis	US 220S
Truck Percentage(2005-7 Data)	
Single	7.7
Combination	4
Passenger/Other	88.3
Truck Percentage(2008 Data)	
Single	7.6
Combination	2.2
Passenger/Other	90.2

Computation of ESAL at milepoint to obtain CUMESAL

Material Source	AASG
Contract No	AL6165177
Mix Type	HMA 12.5mm, 64-22, Surface, L 4
County	Allegany
Route	US 220 (N+S)
MP	3.3-6.6
No of Lanes	2
AADT (Averaged over Milepoints and over years)	7201
Direction used in Analysis	US 220N
Truck Percentage(2008 Data)	
Single	7.7
Combination	4
Load Equivalency Factors, LEF (SN=5, Pt=2.5)	
Single	1.857
Combination	1.857
Directional Distribution Factor	0.5
Lane Distribution Factor	1
Terminal CumESAL [CumESAL where FN=32] – From Fig 4	**2,500,000**

Table 6-9. Comparison of CumAADT converted to CumESAL and ESAL computed at Milepoint level (Continued)
Supplier = AASG, Route= US 220 S

Conversion of CumAADT to CumESAL

Average Percentages	
Single	7.65
Combination	3.1
Passenger/Other	89.25
Load Equivalency Factors, LEF (SN=5, Pt=2.5)	
Single	1.857
Combination	2.714
Passenger/Other	0.0002
Directional Disribution Factor	0.5
Lane Distrcibution Factor	1
Terminal CumAADT	**57,200**
[CumAADT where FN=32]	
ESAL= Terminal CumAADT*T*Df*Lf*LEF*365	
Single	1,482,970
Combination	878,275
Passenger/Other	1,863
Total	**2,363,108**

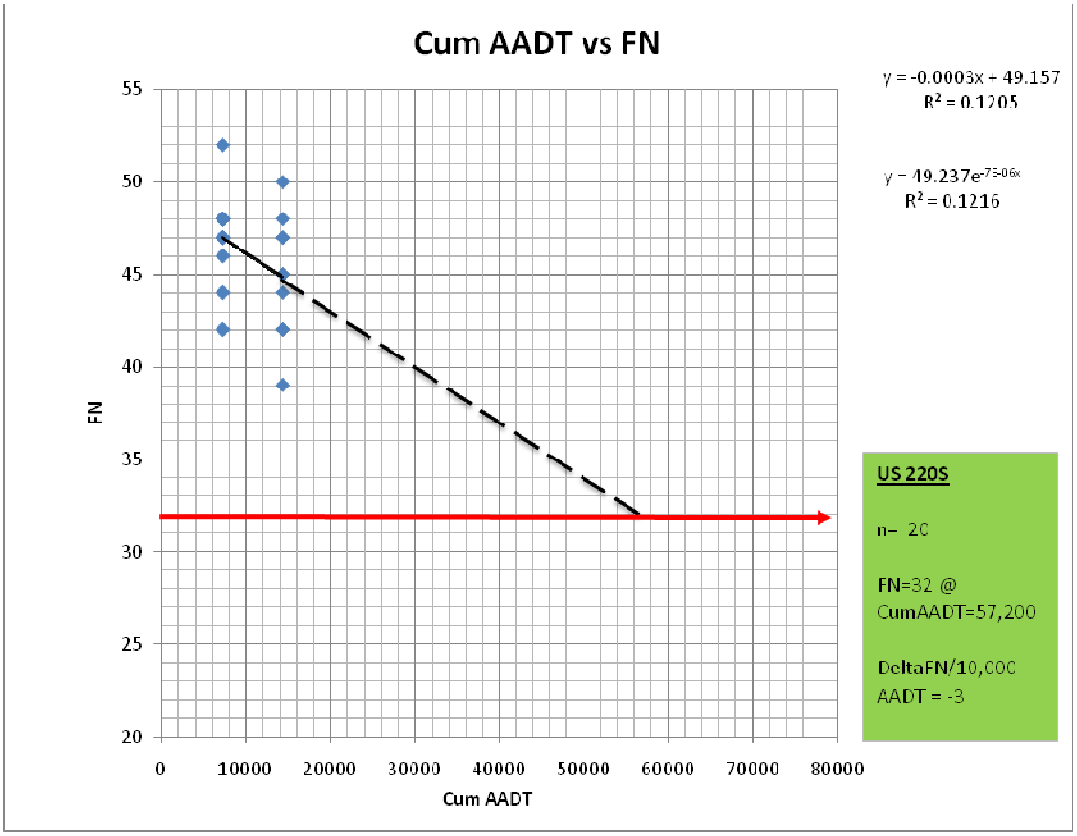


Fig. 6-7. Cum AADT vs FN (US 200S)

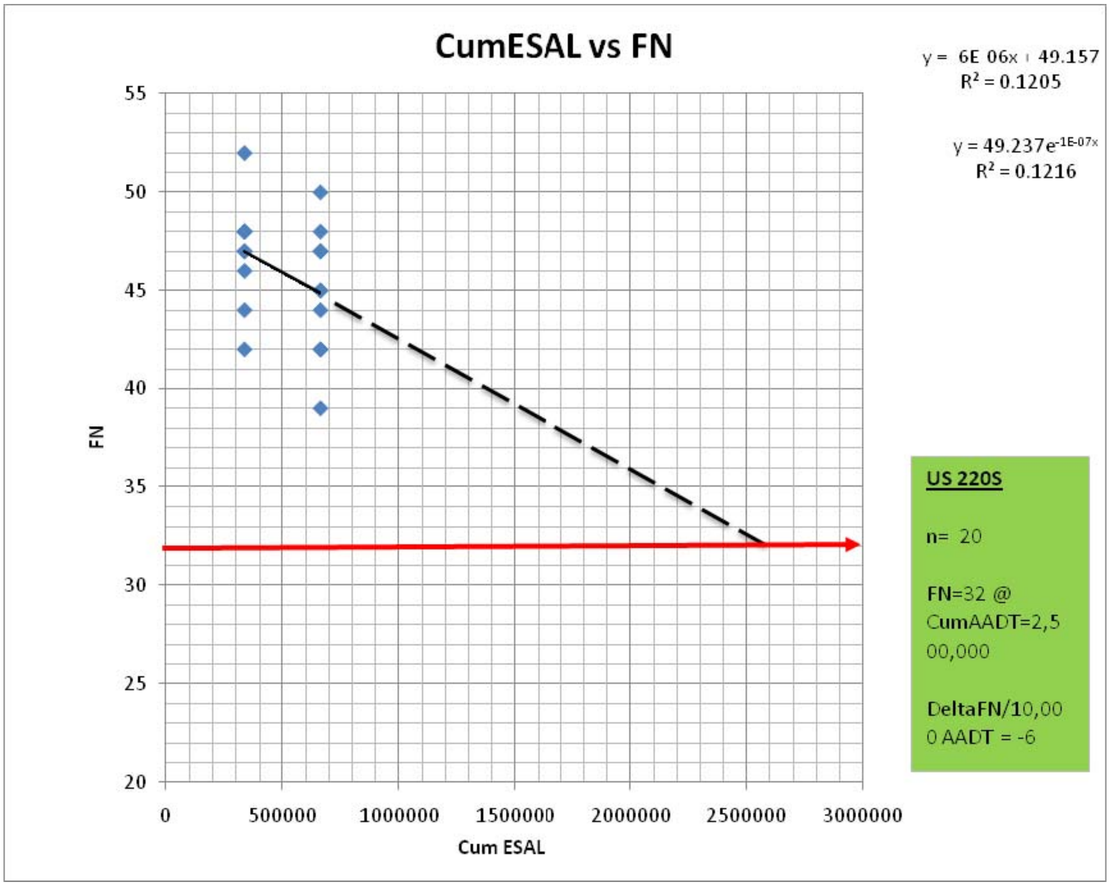


Fig. 6-8. Cum ESAL vs FN (US 220S)

6.3 Aggregate Properties and Pavement Friction

The relationships between aggregate properties, such as Los Angeles Abrasion (LAA), British Pendulum Number (BPN), Polish Value (PV) and Soundness, and the pavement friction life (in terms of total cumulative AADT, expected pavement friction life in years, FN Drop/10k AADT) were then examined even though a limited number of aggregate quality data were available as reported in section 6.2 and Table 6-6. Table 6-10 summarizes these values and Figures 6-9 and 6-10 present example plots for BPN and PV. As it can be seen from these plots these relationships were not meaningful. Similar effects were observed for the FNdrop/10k AADT, Table 6-11 and Figure 6-11, recognizing once more, the limited aggregate quality data available for these analysis, and the fact that AADT does not reflect the diverse truck loading conditions on each roadway. Similarly, the relationships between aggregate properties and total cumulative ESAL were examined. Table 6-12 summarizes these values and Figures 6-12 and 6-13 present example plots for BPN and LAA. As it can be seen from these plots while the excepted trends may be present for some of these aggregate properties, the BPN versus the total ESAL relationship is not meaningful, while the relationship between LAA and total ESAL has an R^2 of 0.36.

Table 6-10. Expected Life versus Aggregate Properties

Supplier	Exp Life (Years)	BPN	PV	LAA (%)	Soundness(%)
AASG	*7.94*	26	5	15	2.8
LCH	*5.37*	22	6	22	0.4
LF	*11.64*	24	6	22	0.2
AIR-70-22	*18.47*	22	5	18	4.5
VMH	*8.46*	21	4	25	0.7
VMW	*9.35*	26		11	0.3

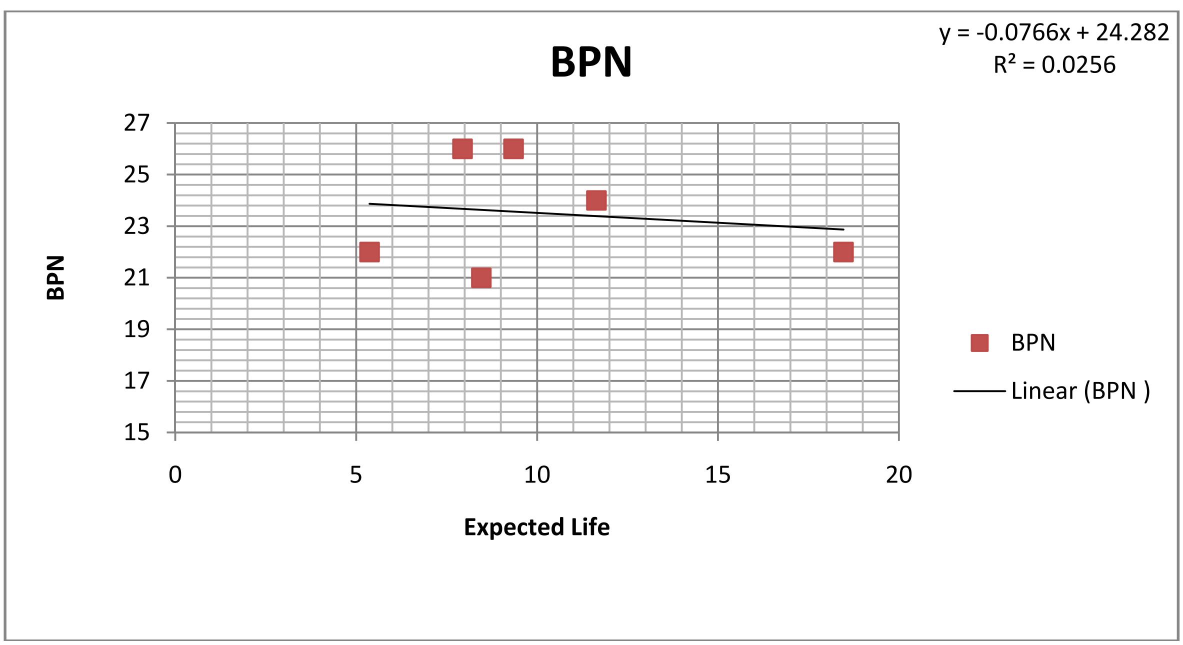


Figure 6-9. Expected FN Life vs BPN

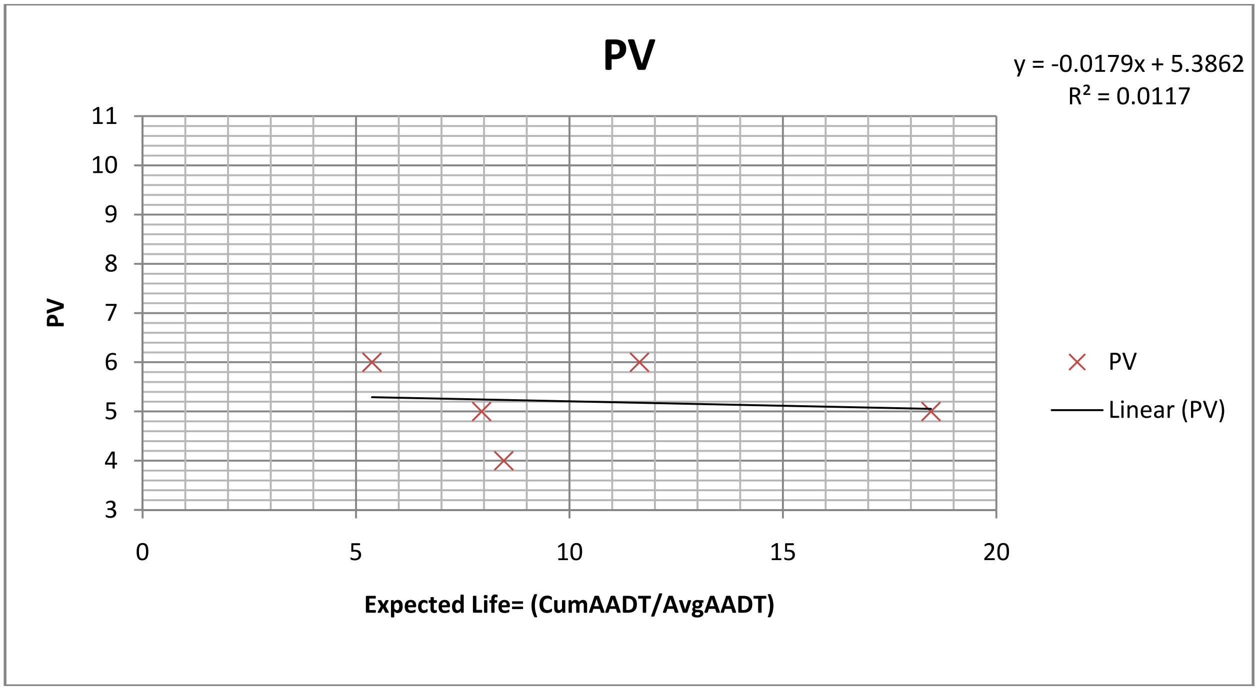


Figure 6-10. Expected FN Life vs PV

Table 6-11. FN Drop/ 10k AADT versus Aggregate Properties

Supplier	FN Drop/10k AADT (in FN units)	BPN	PV	LAA (%)	Soundness(%)
AASG	2	26	5	15	2.8
LCH	1	22	6	22	0.4
LF	5	24	6	22	0.2
AIR-70-22	2	22	5	18	4.5
VMH	1	21	4	25	0.7
VMW	0.30	26		11	0.3

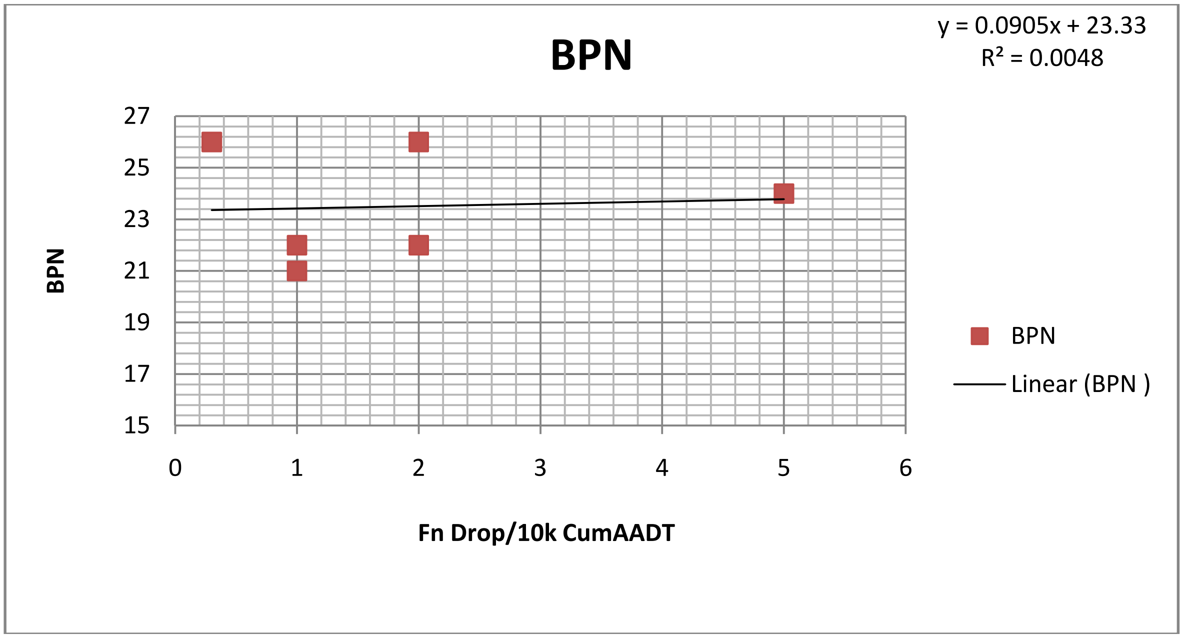


Figure 6-11. FN Drop/ 10k AADT versus BPN

Table 6-12. Total ESAL versus Aggregate Properties

Supplier	**Total ESAL**	BPN	PV	LAA (%)	Soundness(%)
AASG	2,363,108	26	5	15	2.8
LCH	2,118,493	22	6	22	0.4
LF	1,822,477	24	6	22	0.2
AIR-70-22	3,208,372	22	5	18	4.5
VMH	3,558,538	21	4	25	0.7
VMW	5,810,328	26		11	0.3

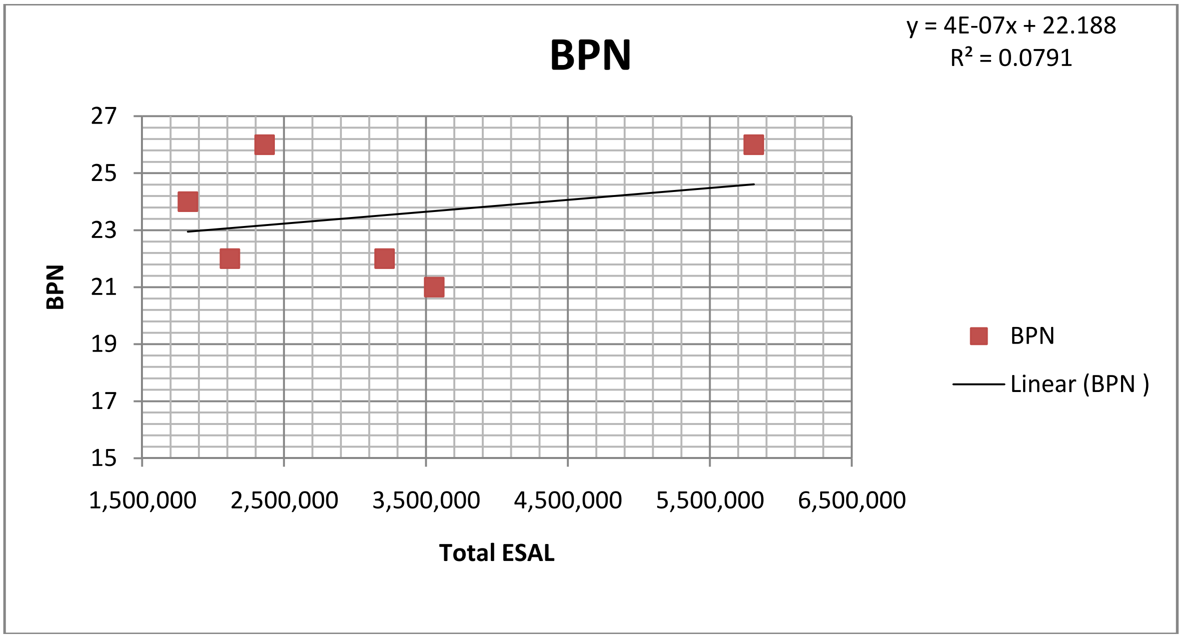


Figure 6-12. Total ESAL versus BPN

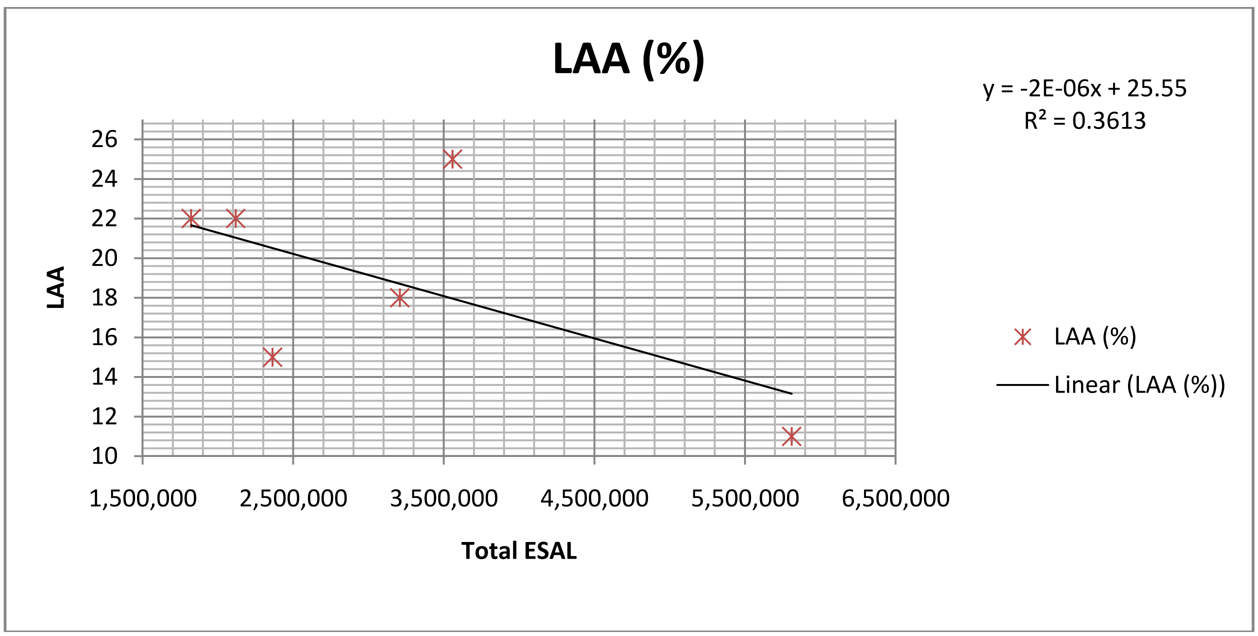


Figure 6-13. Total ESAL versus LAA

Chapter 7 Conclusions & Recommendations

Study Conclusions

The SHA friction data that were available for the analysis of this study have been collected for pavement network evaluation, and thus present significant variability. As indicated early on, pavement friction is affected from several factors, and in order to properly attribute the contribution of the specific aggregate on friction a control set of experiments is required for isolating the contribution of the remaining parameters. Furthermore, in several paving projects an aggregate blend from different sources/ quarries is used for building the desired mixture aggregate gradation, thus making it difficult to study the specific contribution of an aggregate type on pavement friction. Even though such limitations were encountered in the data and analysis of this study the direct benefits to SHA include:

i) The development of a methodology for predicting pavement friction life for any mixture and aggregate;

ii) The quantification of pavement friction life (in terms of cumAADT, ESAL, friction life in years since construction, and FNdrop/10K) for common asphalt mixtures and aggregates used by SHA;

The detailed conclusions of the study include:

- Significant *difficulties in relating friction records with mixture design records* (Contract /Project IDs);
- FN records present *significant variability* on consecutive mileposts built with same mixtures, at same action year and experiencing same traffic level;
- *Equipment repeatability* in one of the reason introducing variability in friction measurements: repeatability of Truck #5 - International Cybernetics Corporation model ranged from 2% to7% introducing a variability into friction measurements of +/- 1.2FN to 1.5FN; similarly for Truck #6 - Dynatest model repeatability ranged from 5% to 20% introducing a variability of +/- 3.0 FN to 3.3FN units;
- These friction devices provide different FN values (side by side comparison), ranging from 7% to 13%. Truck #6 always provided higher values than Truck #5. On the average such difference was about + 6.5 FN units;
- Effect of *survey speed* on FN measurement was significant;
- FN versus cumAADT & pavement age/ years since last rehabilitation *at the aggregate level* (by county, road, mixture, etc) provided no significant relations;

- A methodology for estimating i) the “friction drop rate” (FN drop/ 10k AADT) for each aggregate/ aggregate blend; and, ii) estimating “useful aggregate friction design life” (i.e., at what cum AADT a terminal FN of 32 is reached) was developed and used for predicting pavement friction life of mixtures and aggregates used by SHA;

- *Simple linear regression* of FN versus cumAADT provided the best relationships, while multivariate regression analysis of FN versus cumAADT, speed and equipment type had i) lower R^2 or ii) variables were statistically insignificant;

- The cumAADT to a terminal FN of 32; Ratio of [cumAADT / average AADT throughout years] = expected friction life in years; and FN drop /10kAADT were calculated for the various aggregates and aggregate blends;

- The possibility of relating aggregate properties (such as BPN, PV, LAA, soundness) to cumAADT was examined. However no acceptable relationship were obtained since *AADT does not reflect the diverse truck loading conditions* on the roadway that affects friction wear and pavement life. Even though the data were further divided by *pavement mixture type* no further improvement was obtained;

- The analysis considered converting AADT to ESAL to capture the traffic mixture characteristics that different pavement section experience, and thus affecting the wear and friction. Conversions at the milepost or at the cumAADT values provided similar results on predicting pavement friction life in terms of total ESAL;

- Relating aggregate properties to pavement life using ESAL analysis did not lead to a significant improvement of these relationships. Same result was obtained when the data were divided by pavement mixture type.

Study Recommendations

It was evident from the data and analysis of this study that there is a need to control and reduce variability in friction measurements due to the various parameters affecting pavement friction. Thus, it is suggested to eventually develop a study that considers and controls the following parameters:

- identify projects that use a single aggregate source in the gradation of the mixtures (i.e., AS1, AS2, AS3 etc) for each pavement section;

- consider pavement sections that use aggregates *from different sources and one type of asphalt mixture*, at a time, so as to eliminate asphalt mixture design effects (i.e., effects of binder content and other mix design volumetric parameters that may affect binder film thickness around the aggregate, and thus pavement friction values);

- conduct repeated FN friction measurement at the same test sections and at specific times of the year to measure and isolate *seasonal effects*;

- collect FN measurements for at least 5-7 years on the same sections in order to better capture potential *microtexture renewal* effects;

- consider more *accurate traffic measurements* (AADT, truck distribution factors) and traffic lane distribution.

- use *a single friction equipment*, or side by side measurements of track #5 and#6, on a wider variety of pavement friction levels;

- control *survey speed* at 40 mph during the above testing.

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Appendix A

Mineral Composition by Supplier:

Supplier	Year Sampled	Mineralogical Composition (%) Per Whole Rock Analysis				Remark
AIR	N/A					
AASG	2004	Calcite (95%)	Quartz (5%)			
ICM	2004	Dolomite (90%)	Siliceous Silt (10%)			
KLC	2006	Calcite (48%)	Quartz (50.4%)	Pyrite (+-1%)		
LCH	2005	Feldspar (35-40%)	Pyroboles (55-60%)	Opaques (<=5%)		
LF	2006	Calcite (78%)	Quartz (22%)			
LM	2006	Calcite (98%)	Pyrite (<1%)			Lafarge Medford (North Westminster MD)
LW	N/A					
LT	2005	Quartz (70-90%)	Muscovite (10-30%)	Pyrite (1%)		Lafarge Texas (Texas, MD)
MMI	N/A					
MMW	2004	Calcite (85-90%)	Quartz (3-5%)	Clays (5-8%)	Pyrite (<1%)	
VMH	2004	Carbonates (99%)	Clay (1%)			
VMHDG	2005	Quartz (+-25%)	Feldspar (30-35%)	Pyroboles (35-40%)	Opaques (<=5%)	Based on Arundel Corp Havre De Grace Quarry results
VMW	N/A					
YBPBv	N/A					
YBPRv	2004	Calcite, Dolomite (95%)	Silts, Clay (5%)			York Building Products (Roosevelt Avenue #1M)