Evaluation of Skid Resistance of Turf Drag Textured Concrete Pavements

Minnesota Department of Transportation

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Tim Nelson, Primary Author
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Dragging a broom or an inverted piece of AstroTurf in the longitudinal direction currently textures concrete pavements built in Minnesota. The macro-texture is specified to have a mean texture depth of 1 millimeter measured by the Sand Volumetric Technique (ASTM E 965). Newly textured pavements are usually evaluated for adequacy in providing a safe riding surface through texture measurements for acceptance and friction measurements as required. The current Federal Highway Administration (FHWA)'s Technical Advisory on texture requires that performance of non-convention textures be monitored and reported.

This report presents the Minnesota Department of Transportation's study of AstroTurf texturing practices and pavement friction. The friction numbers are collected using the ASTM E 274 standard and the values from the Minnesota Road Research Project (MnROAD) were used to create a time and loading dependent model. Friction numbers from various test sections around the state of Minnesota and the model created from the MnROAD facility were then compared using visual analysis, descriptive statistics, Chi-Squared Analysis and the Mann-Whitney Z Test.

After the completion of those tests, it was concluded that the three models created from the MnROAD facility were validated from the test sections created around the road network in Minnesota.

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Prepared By:

Tim Nelson

Minnesota Department of Transportation

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Executive Summary

This research report presents the Minnesota Department of Transportation's (Mn/DOT's) study of AstroTurf texturing practices on pavement friction. In June 2005, the Federal Highway Administration (FHWA) published a texture advisory and it was recommended that AstroTurf drag should be considered as the finishing component to any concrete pavement where the designed travel speed is 50 miles per hour or faster. In the advisory, it also declared that wet weather accidents and friction testing were two methods in which the texture could be measured to ensure adequacy. The friction results for several sections of AstroTurf textured concrete were used to study the effects of friction as time proceeded.

Prior to 1976, Minnesota's standard practice for finishing concrete pavements involved dragging a moistened, coarse piece of burlap behind the paver, which was followed with either transverse or longitudinal tining. Burlap drag alone was considered insufficient. Tining is a method that uses various wires to create straight, uniformly spaced grooves. In 1976, this standard practice was revised to replace the burlap material with an inverted piece of artificial turf and require the spacing of the tining wires to have a spacing of at least 1 inch. After that in 1983, the same method was used but the tining distance was increased to 1.5 inches. In 1995, the tining interval returned to the 1 inch standard and was specified for traffic speeds greater than 35 miles per hour.

Around 1998, a moratorium on tining was established in Minnesota because of the excess noise that the roadways created from this standard. This cessation led to the use of inverted AstroTurf drag as the finishing practice and started with a 0.8-millimeter specification for its texture depth behind the paver. This is a method that is used to ensure that adequate texture depth is being achieved but is not an actual specification of the standard. Trailing an inverted section of artificial turf from a construction bridge that spans the pavement and travels longitudinally produces the AstroTurf drag finish. Striations are typically 1.5 to 3 millimeters deep. Shortly afterwards, the texture depth specification was revised to 1 millimeter behind the paver due to the amount of texture decay after construction and specified that the Sand Patch Method (ASTM E 965) would be used to find the amount of texture depth on the surface of the pavement.

The Sand Patch Method was not adopted as a specification for construction but it has been used in most of the concrete paving projects around the state since 1999 as a special provision. Aside from the AstroTurf drag, a longitudinal broom drag is also used for finishing concrete pavements. The broom drag uses stiff bristles instead of the AstroTurf but has similar texture depths in the final pavement.

The objective of this study was to measure the friction numbers on the Minnesota Road Research Project (MnROAD) and create a skid resistance model with that information. Then the model was compared with various sections of concrete pavement around Minnesota that use the same texturing method. This comparison allowed for conclusions to be made on whether a model could be produced describing the friction numbers over time. If the model proves to be a sufficient model of the other test sections, then the model could be used to describe how the friction values change as the pavements become older and the loadings that they receive. It could also be used to identify the skid resistance of any AstroTurf dragged pavement and potentially be used to determine when various maintenance events need to happen.

In order for this study to be successful, it compiled and calculated a pavement friction degradation model for AstroTurf finished concrete from the MnROAD facility. A model of this kind was needed to show how the friction on an AstroTurf texture decays because of the age of the pavement and the loadings in which it experiences in its lifetime. This model was then compared to twelve test sections that existed around the state of Minnesota in order to validate the findings. These test sections were used because they had a reasonable amount of frictional data and had corresponding data about the construction process of the pavement. The validation process consisted of comparing the friction values from the test sections with the model and testing the comparison using various tests to investigate whether the two were similar or not.

At MnROAD, cells 32, 52 to 54 and 60 to 63 were used for the evaluation because they were the only current cells (except cell 53 was transformed into a different cell in October 2008) that had the concrete finished using the AstroTurf drag standard. The friction numbers were measured following the American Society for Testing and Materials standard (ASTM E 274) which comprises of testing friction with both a smooth and ribbed tire because each tire measures the macro- or micro-texture, respectively. The model was computed using the measured friction values and equivalent single-axle loading (ESAL) data for the corresponding cells. It was created for both the smooth and ribbed tire and shown below where F is the friction, k is the growth rate, t is the age of the concrete in years, DE is the number of ESALs calculated for when the pavement was designed and FE represents the number of ESALs forecasted for twenty years after the design year:

- Ribbed

$$F = 22.01\sin(kt) + 29.21\cos(kt)[1 + e^{-0.1t}]$$

- Mainline smooth

$$F = \left[\left(\frac{801000}{DE}\right)\left(\frac{FE}{DE}\right)\right]\left[\sin(kt) + 18.36\cos(kt)\left[1 + e^{-0.8t}\right]\right]$$

- Low-volume smooth

$$F = -4.56\sin(kt) + 15.56\cos(kt)\left[1 + e^{0.031t}\right]$$

No ribbed model was used for the Low Volume Road because the data from the research facility wasn't well represented and there wasn't a vast amount of test sections available in the state of Minnesota that could be analyzed for this tire. The smooth model was still used for the Low Volume Road because the data appeared to follow the general trend in the two test sections that could be considered to be of low volume. The ribbed equation appeared to be a straight declining model, the Mainline's smooth model declined at first and then leveled off and the low volume smooth model increased slowly and appeared as a straight line.

These three model equations were then used to calculate the model friction values for the twelve test sections that were used. Four analysis tests were conducted to find out if the models from the MnROAD facility and the twelve test sections were similar or not. Each was chosen because of a unique quality that they possessed, which allowed for better conclusions to be made about the model. The four analysis tests that were used include:

- Visual analysis
  - Charts were created of the model and the friction data from the various test sections
  - This allowed for a visual enhancement on how the data and the model were similar
- Descriptive statistics
  - Overall and within each test section, the means and standard deviations were taken from the model and the data for each of the test tires
  - Allowed for a statistical glance at how the various numbers compared
- Chi-squared analysis
  - Used various calculations to create a Chi-Squared number that could be compared to a critical value in order to determine if the model and data from the test sections were similar or not
  - Tests the goodness of fit between the model and the data for each test section to a given confidence level
- Mann-Whitney Z Test
  - Used system of equations to calculate a z-number which was compared to a table of known numbers to determine the whether or not the model and test sections were similar
  - Nonparametric test that clearly stated the results of the hypothesis to a given confidence level

After examining at the various results of the four analysis tests, it was concluded that the MnROAD friction degradation model for the AstroTurf texture could be validated for all three of the models represented. The data within each of the test sections were well modeled using those equations and could be used in design, rehabilitation considerations and the timing of various maintenance activities. The Minnesota Department of Transportation will continue its study on the AstroTurf texture to provide further analysis on how the models change throughout time and to see how the friction changes as the pavement gets older, receives more loadings and is more affected by the climate of the state.

It was also concluded that rate of friction degradation was proportional to the FN value. This resulted in a decay curve that was more evident in the smooth tire test. Turf drag provides sufficient texture particularly if the mix design, construction practice and maintenance are diligently adhered to.

Chapter 1 – Introduction

This paper presents the Minnesota Department of Transportation's (Mn/DOT's) study of AstroTurf texturing practices on pavement friction. Construction specifications for pavements are implemented to address: safety concerns, reduce noise, prevent accidents, improve ride quality, ensure durability, etc. These concerns are usually influenced by pavement texture, which is why texture is an important component into the construction of a pavement surface. In June of 2005, the Federal Highway Administration (FHWA) released a texture advisory that recommended that wet-weather crashes and friction test results should be used as evaluation factors for assessing texture methods on concrete pavements. One of the recommendations was the use of AstroTurf as a texturing finish for concrete pavements [1]. This condition lowers the sound intensity of the pavement-tire interaction and doesn't increase the wet-accident count [2]. Since this specification was published in June of 2005, an accurate degradation model in Minnesota hasn't been produced to show how the pavement friction will change with the age and loadings of the pavement. Providing such a model would enable engineers to determine the time period when various maintenance tasks should be conducted and a general idea on when the pavements should be closely watched for having low friction. By looking at this model and studying the wet weather crashes in that area, it can be determined if maintenance is needed to improve friction.

Problem Statement

The study was initiated because of the texture advisory that the FHWA published. By comparing the data collected from the Minnesota Road Research Project testing facility (MnROAD) with various test sections around the road network, the change in skid resistance for the AstroTurf texturing practice over time could be analyzed. Friction, equivalent single-axle loads (ESALs), age of the road and texturing practices were the main focuses for this study. The main objective was to provide evidence that an AstroTurf friction model could be provided by the MnROAD cells and adequately replicate the friction on other identical road surfaces. If the model accurately depicted the test sections across the state of Minnesota, then it could be concluded that the friction model could be used in ways that were described earlier.

Paper Objectives

This report:

- Provides background information about the technical advisory published by the FHWA, pavement friction, how friction is tested, current texturing procedures for Minnesota and the MnROAD testing facility.

- Describes how the AstroTurf friction model for the MnROAD cells was created.

- Gives background information on the various test sections of the road network that were used to validate the model.

- Describes how the model was fit to the various segments.

- Determines whether or not the model was an adequate model for the AstroTurf texturing method.

Literature Review

According to Izevbekhai, the use of the AstroTurf drag and the longitudinal broom drag does not increase the number of accidents or crashes caused by wet-weather when compared to the tining method [2]. This study was also conducted due to the Federal Highway Administration's Technical Advisory. Looking at wet-weather crashes was one of the ways in which the pavement friction could be analyzed to determine if the texture was effective or not in providing enough stopping power to a vehicle. The conclusion that was made in the study suggested that the AstroTurf drag and the longitudinal broom drag were sufficient by itself to provide enough skid resistance to the moving vehicle.

As stated by Bazlamit, two major components of skid resistance are adhesion and hysteresis [3]. Adhesion is the product of the actual contact area of the pavement and tire and hysteresis reflects the energy loss that occurs when the tire becomes deformed by the aggregate in the pavement. The authors felt as if the changing temperatures of the seasons would affect the skid resistance that a vehicle would experience. The main reasoning behind this was due to the fact that stiffness of the rubber and the pavement were expected to decrease when the temperature increases. This causes the deformation of the tire to change and thus changing the hysteresis portion of pavement friction. When the study was completed, it was concluded that hysteresis was a larger component of the total frictional force than the adhesion component and when the temperature increases, the skid resistance decreases and vice versa.

The "Guide for Pavement Friction," lists the four main factors that influence pavement friction: pavement surface characteristics, vehicle operational parameters, tire properties and environmental factors [4]. All of these properties impact pavement friction in a different way but pavement texture is a major contributor and there are four different types of textures on every pavement section: the overall roughness, mega, macro and micro-textures. The overall roughness and mega-textures were contributed by the deformities contributed to the paving process. The macro-texture in concrete surfaces is generally the texturing that is applied to the plastic concrete behind the paver. Finally, the micro-texture is the surface properties of the aggregate particles within the concrete.

Not only did Wu state the facts about the components of pavement friction and the different textures that existed but they also scrutinized six common practices of texturing concrete [5].

- Artificial turf drag
    - Dragging an inverted piece of artificial turf directly behind the paver

- Transverse tine
    - Mechanically-operated texturing device that controls the spacing and depth of grooves by using something similar to a metal rake and running them transversely to the direction of travel

- Longitudinal tine
    - Metal prongs are pulled parallel with the centerline of the pavement

- Transverse broom
    - Mechanically-operated stiff bristled broom operated transversely to the direction of travel

- Longitudinal broom
    - Stiff bristled broom is pulled directly behind the paver

- Transverse tine with longitudinal artificial turf drag
    - The transverse tine technique is preceded by the artificial turf drag

Other texturing methods do exist but the practices listed above are the ones currently used by the majority of transportation departments in the United States [4]. Texturing is a major factor on the skid resistance, drainage and the tire/road noise. Texture tends to erode because the wearing effects of traffic loadings and the environment.

Chapter 2 - Background Information

This chapter describes the FHWA's texture advisory on how to evaluate the pavement's surface texture, the basics of pavement friction, how the friction is tested, the various methods that are used in Minnesota to texture the concrete and general information on the Minnesota Road Research Project (MnROAD).

Federal Highway Administration's Texture Advisory

According to the advisory, "The primary purpose of adequate surface texture is to reduce wet-weather and total vehicle crashes." Texture in concrete pavements plays an important role in the safety of the roadway. To evaluate whether or not the pavement has adequate surface texture, two methods have been established. These methods look at comparing long-term safety performance data for alternate texturing methods or treatments. An example of this would be a comparison model for a pavement location that had a texture created with transverse tining but was then reconstructed with the AstroTurf drag.

- Wet weather crash performance
    - Reduction of wet-weather and/or total number of vehicle crashes at the same or similar location

- Friction test results
    - Similar or improved friction results for the new texturing style when testing in conformance with American Society for Testing and Materials (ASTM) E 274 (skid trailer) using the smooth tire (ASTM E 524), or the International Friction Index (IFI) ASTM E 1960

The advisory also recommends that the artificial turf drag finish should be used when design speeds are 50 miles per hour or greater [1].

Pavement Friction

According to the Guide for Pavement Friction, "Pavement friction is the force that resists the relative motion between a vehicle tire and a pavement surface. This resistive force is generated when the tire rolls or slides over the pavement surface," and this is shown below in figure 2.1.

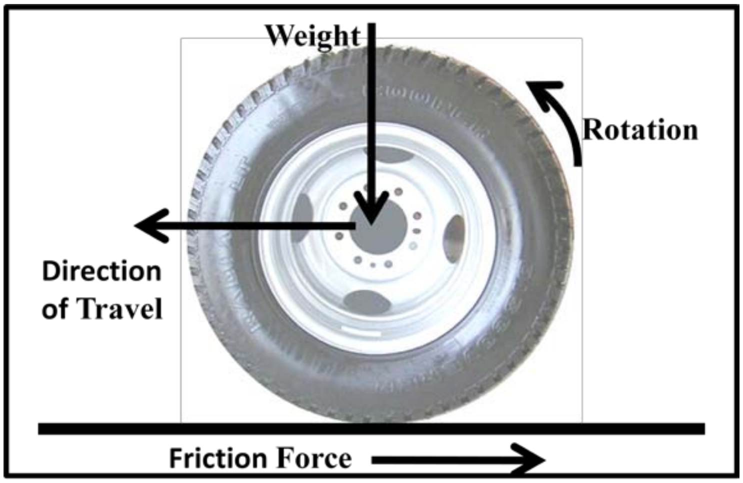

Figure 2.1: Basics on Pavement Friction

According to the Federal Highway Administration, "Pavements shall be designed to accommodate current and predicted traffic needs in a safe, durable and cost effective manner." Wet pavement friction needs to be provided, in order to maintain safe driving conditions. When the pavement becomes wet (whether it is water or some other form of fluid) the tire and the surface of the pavement become separated. In order to provide an adequate amount of friction when the pavement is wet, textures are needed in concrete pavement. Figure 2.2 shows the four main types of textures in every pavement section and how they differ in size. The roughness and mega-textures are created from imperfect construction, traffic loadings and environmentally created deformations, and rarely contribute to the pavement friction. The micro-texture of a concrete pavement represents small asperities in the aggregate particles or the mortar and will break through a small layer of water between the tire and pavement surface. Finally, the macro-texture is the measurable, deeper striations formed in the concrete from the texturing process and creates drainage for the fluid while still providing a sufficient amount of pavement surface area for the tire. The striations allow water to travel safely from the pavement surface to a drain or the shoulder of the road by the cross slope, grade or under drains of the pavement. On average, both the micro and macro-textures decay quickly for the first few months or years and then level off gradually [5].

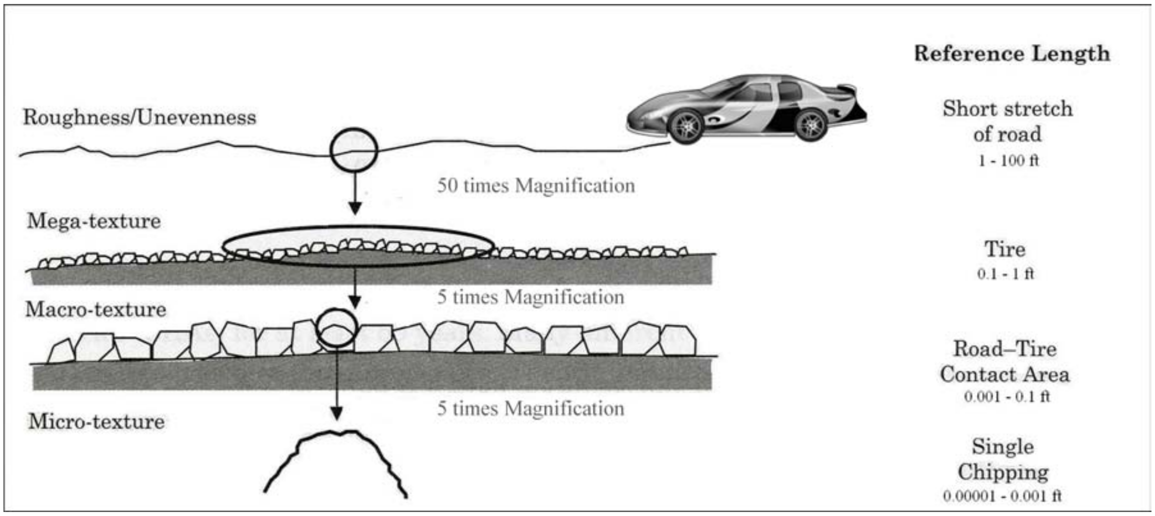

Figure 2.2: Description on Different Textures

Creating a connection between the pavement surface and the tire will allow for friction to be acquired. Friction is based mainly between two components: adhesion and hysteresis. Adhesion is a function of the interface shear strength and the contact area of the tire and hysteresis is the energy loss due to such things as the tire enveloping around the texture [3]. A high adhesion coefficient exists when shear strength and the actual contact area is high but when the pavement is wet, a trapped water film weakens the interface shear strength and lowers the amount of adhesion. Hysteresis works by compressing the tire against the pavement surface, which creates the deformation energy to be stored within the rubber and as the tire relaxes, part of the energy is lost in the form of heat. The exiting heat then leaves a frictional force, which is utilized to slow down the forward motion of the tire. Figure 2.3 shows a closer look at these two components [4].

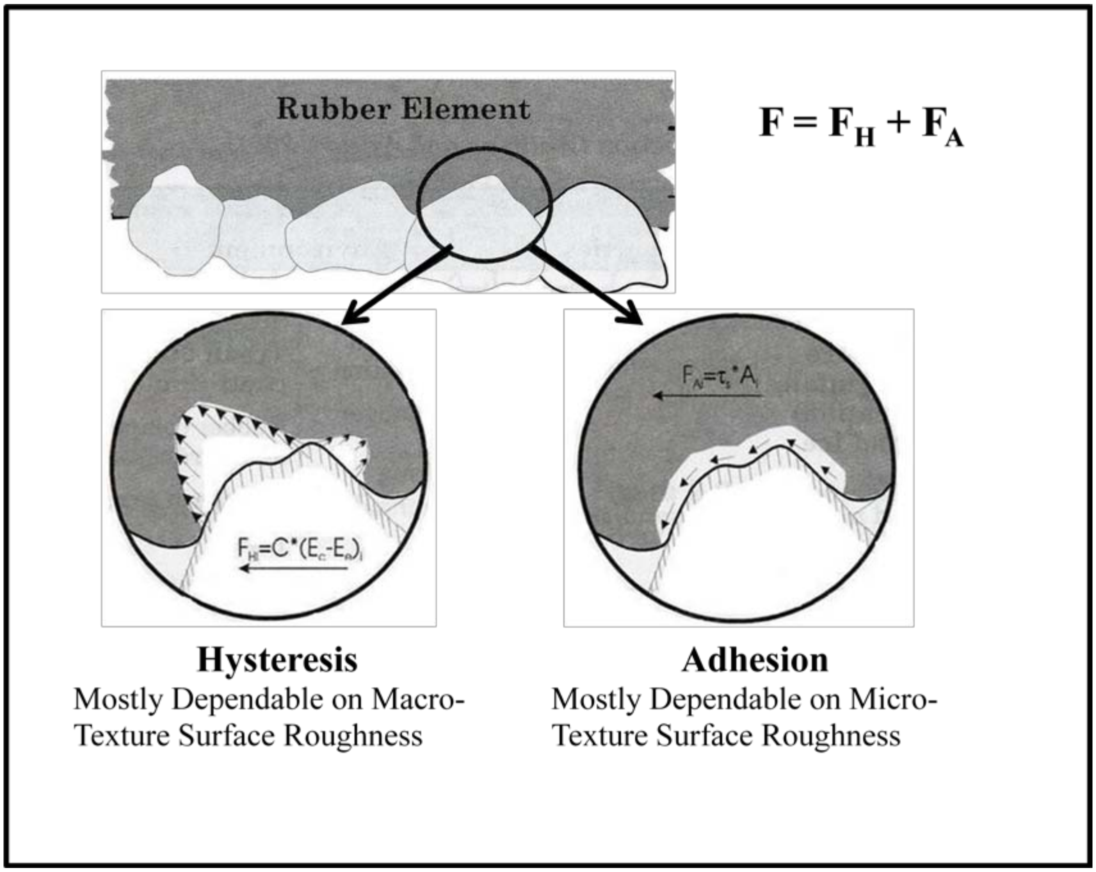

Figure 2.3: Investigative Look at Adhesion and Hysteresis

There are four main factors that influence pavement frictional forces on an average concrete pavement and each of those have corresponding key issues:

- Pavement surface characteristics
    - Micro/macro-texture
    - Material properties
- Vehicle operational parameters
    - Slip speed
- Tire properties
    - Tread design and condition
    - Inflation pressure
- Environmental factors
    - Temperature
    - Water, snow, ice, etc.

These factors are in one way or another directly connected to how adhesion and hysteresis performs. Pavement friction is primarily affected by micro and macro-texture because they are designed to limit the other constraints [4]. The tread design of the tire plays in important role into the stopping power of the vehicles when the road is wet because the ribs in the tire are designed to expel the water away from the tire, thus allowing the interaction between the pavement and the tire to exist. If a tire was severely worn out or it contained no ribs, then it would have a greater possibility of hydroplaning and receiving no friction from the pavement surface [5].

Testing of Pavement Friction

At Mn/DOT, a locked-wheel skid tester, as specified by the American Society of Testing and Materials (ASTM E 274), is used and is shown below in figure 2.4. This device is towed behind a vehicle at a speed of 40 miles per hour and measures the coefficient of friction. The vehicle also carries a supply of water that is laid down directly in front of the test tire to test the pavement when it is wet [6].

Figure 2.4: Locked-Wheel Skid Trailer and Truck

When the locked-wheel skid trailer reaches the testing area, a measured amount of water is applied to the pavement in front of the test tire; then the tire (ribbed or smooth) locks up and the wheel is pulled along for a given length. During that period of time, it measures the amount of tractive force required to pull the trailer. The measured force is then sent to a laptop, which is stored inside the tow vehicle. Finally, the skid number or coefficient of friction can be calculated by taking the tractive force divided by the known wheel load, and then multiplied by 100 (this is done automatically as the test is being conducted) [5].

Ribbed and smooth tires are both used because each tire measures the adhesion and hysteresis differently. Since the ribbed tire removes the water more efficiently, it on average examines the pavement friction on the micro-texture portion and the smooth tire is more affected by the macro-texture. If the macro-texture doesn't drain the water well enough, then the smooth tire will hydroplane and result in lower friction values.

Texturing Procedures in Minnesota

Prior to 1976, Minnesota's standard practice for finishing concrete pavements involved dragging a moistened, coarse piece of burlap behind the paver, which was followed with either transverse or longitudinal tining. Burlap drag alone was considered insufficient. Tining is a method that uses various wires to create straight, uniformly spaced grooves. Figure 2.5 shows a concrete pavement that is being finished using longitudinal tining.

Figure 2.5: Longitudinal Tining on Concrete Pavement

In 1976, this standard practice was revised to replace the burlap material with an inverted piece of artificial turf and require the spacing of the tining wires to have a spacing of at least 1 inch. After that in 1983, the same method was used but the tining distance was increased to 1.5 inches. In 1995, the tining interval returned to the 1 inch standard and was specified for traffic speeds greater than 35 miles per hour. Around 1998, a moratorium on tining was established in Minnesota because of the excess noise that the roadways created from this standard. This cessation led to the use of inverted AstroTurf drag as the finishing practice and started with a 0.8-millimeter specification for its texture depth behind the paver. This is a method that is used to ensure that adequate texture depth is being achieved. Producing the AstroTurf drag finish is accomplished by trailing an inverted section of artificial turf from a construction bridge that spans the pavement and travels longitudinally to the pavement surface. Striations are typically 1.5 to 3 millimeters deep. Figure 2.6 shows a concrete pavement that is being paved and finished using a piece of inverted AstroTurf.

Figure 2.6: Concrete Pavement Finishing with Inverted Piece of AstroTurf

Shortly afterwards, the texture depth specification was revised to 1 millimeter behind the paver due to the amount of texture decay that was experienced after construction and specified that the Sand Patch Method (ASTM E 965) would be used to determine the amount of texture depth. This method measures the macro-texture of a pavement surface by spreading a known volume of glass beads in a circle onto a cleaned surface and finding the diameter of that circle, as shown in figure 2.7. The volume of glass beads used divided by the area of the circle is recorded as the mean texture depth of the pavement [4].

Figure 2.7: Procedure for Sand Patch Method

The Sand Patch Method was not adopted as a specification for construction but has been used in most of the concrete paving projects around the state since 1999 as a special provision. Aside from the AstroTurf drag, a longitudinal broom drag is also used for finishing concrete pavements. The broom drag uses stiff bristles instead of the AstroTurf but has similar texture depths in the final pavement. Figure 2.8 shows a picture on how the longitudinal broom drag looks after the pavement was finished.

Figure 2.8: Concrete Pavement with Longitudinal Broom Drag

MnROAD Testing Facility

The Minnesota Department of Transportation (Mn/DOT) initially constructed the Minnesota Road Research Project (MnROAD) between 1990 and 1993. MnROAD is located approximately 40 miles north of Minneapolis/Saint Paul and runs along Interstate 94. This cold weather research facility features two separate roadway segments: the Mainline and the Low Volume Road (figure 2.9). Traffic can be directed from the I-94 test section back onto the original westbound I-94 section, which enables a safe environment for researchers and no traffic delays for the motorists.

There are over 50 distinct cells within the facility and each cell is approximately 500 feet long. Subgrade, aggregate base, surface materials, roadbed structure and drainage methods vary from cell to cell. The cross sections of the various cells for the Mainline and the Low Volume Road can be found in Appendix A – MnROAD Cell Maps. Thousands of sensors (frost, strain, etc) are embedded into the MnROAD test cells and collect data year-round. Various tests and observations are also conducted from the test cells throughout the year. Each MnROAD study/test cell has quality data that can be used for various types of studies. All data presented herein, as well as historical construction information, sampling and testing can be found in the MnROAD database and in various publications.

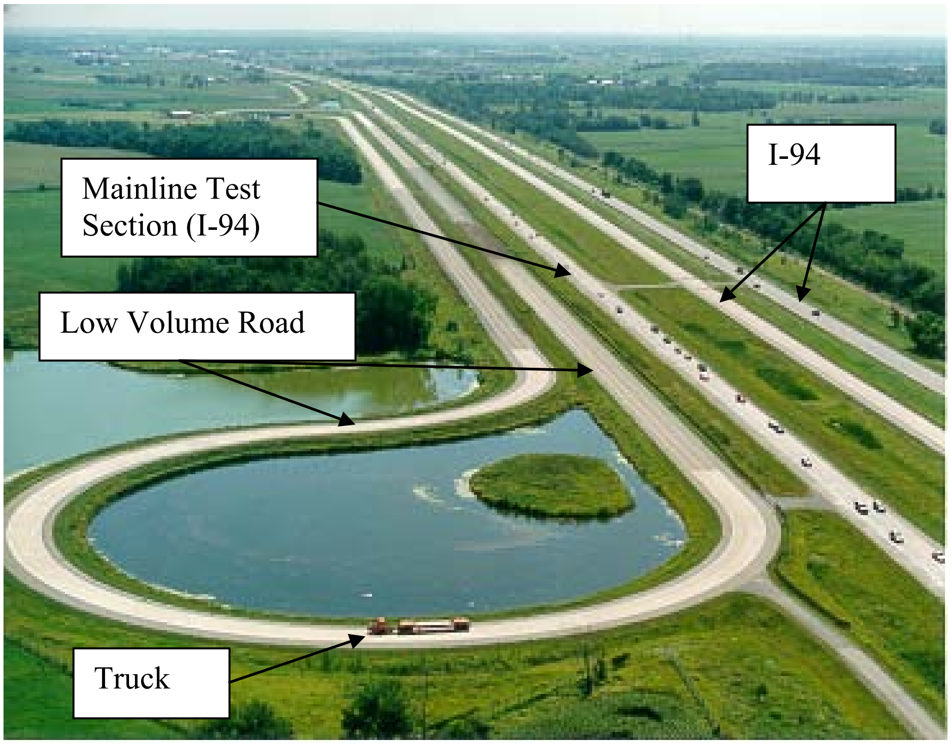

Figure 2.9: Picture of the MnROAD Facility

MnROAD's Mainline portion is a "live" road that carries two lanes of westbound Interstate 94's traffic for 3.5 miles. On the Mainline, both five and ten year designs were implemented. The five-year cells were completed in 1992 while the ten-year cells were completed in 1993. Of the original 23 cells that were constructed, 14 were hot mix asphalt (HMA) and 9 were Portland cement concrete (PCC). Superpave and whitetopping cells were added in 1997 and 2004. Typically, traffic is diverted back to the original interstate highway for three days each month to allow MnROAD researchers the ability to safely and efficiently collect data and record cell observations.

The Low Volume Road (LVR) is adjacent and parallel to Interstate 94 and the Mainline's cells. The LVR consists of a 2-lane, 2 ½-mile closed loop that contains 20 test cells. In the recent years, four of the 20 cells were equally divided into additional cells. Traffic is restricted to a 5-axle, tractor/trailer that is loaded with a gross vehicular weight of 80 kips. Currently, this vehicle travels on the inside lane of the loop for five out of the seven days in a week. The outside lane has no traffic loadings, which allows researchers to isolate the environmental effects on the pavement's performance. In figure 2.9, the Mn/DOT truck is visible at the on the west loop.

Chapter 3 - MnROAD AstroTurf Friction Model

Procedure

The first step in creating an efficient model was to select the correct cells at the MnROAD facility for this study. The only constraints to the selection process were that the pavements needed to be produced with concrete and finished with the AstroTurf drag technique. Cells on the Mainline and the Low Volume Road (LVR) were considered but the cells on the Mainline were more important in this analysis because the majority of the roads that have friction test results available in Minnesota are major highways and freeways. Thus, they are closely replicated by the cells on the mainline and not the LVR cells. Cells 60, 61, 62 and 63 were selected from the Mainline and cells 32, 52, 53 and 54 were selected from the LVR. All four of the Mainline's cells were constructed on October 15, 2004 as part of the whitetopping phase and the LVR cells were constructed between June 2000 and October 2004. All of these cells were finished using the AstroTurf drag standard, but have different cross-section thicknesses, as shown in figure 3.1.

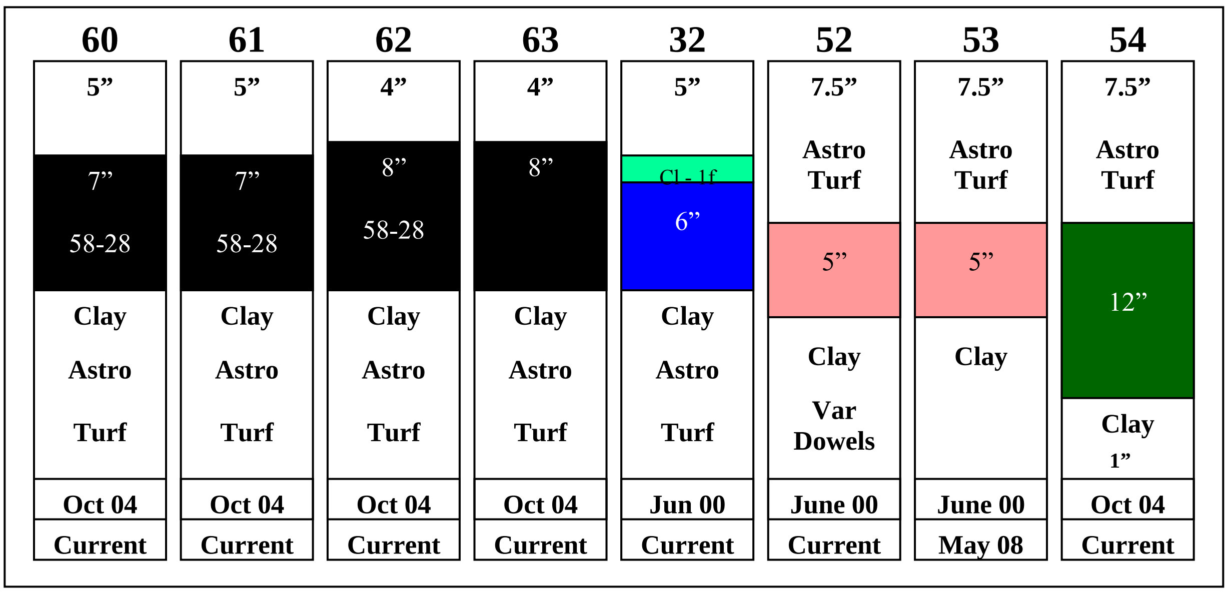

Figure 3.1: Cell Layout for Cells 32, 52-54 and 60-63

Next, all of the available pavement friction data was compiled for these cells. The friction numbers were measured following the ASTM E 274 standard as described earlier. The compiled data ranged from November 2, 2000 to June 4, 2009 for the LVR's cells and May 24, 2005 to June 16, 2009 for the Mainline's cells. For the LVR, a total of 31 and 19 data points were tabulated for the ribbed and smooth tire, respectively. The Mainline tabulated 63 data points for the ribbed tire and 48 for the smooth tire. The age (years) was also calculated for all of the conducted tests.

When constructing the model, it was noticed that the data was most likely to be decaying in a linear or exponentially pattern. An equation that could transform into those two types of models was needed but having it able to transform into others was preferred. Also, the traffic loading that a pavement receives affects the decay of the texturing because of the continuous wear from the pavement – tire interaction [5]. In order to address this condition, a connection between the amount of traffic and the age of the pavement needed to be implemented into the equation. To satisfy these stipulations, equation 3.1 was used to model the accumulated data. In the equation: *F* is the friction value, *r* is the growth rate of the traffic volume, *t* is the age of the concrete pavement in years and *C* symbolized the constants.

$$F = C_1 \sin(rt) + C_2 \cos(rt)[1 + e^{tc_3}] \qquad (Eq\ 3.1)$$

Before the equation could be used, the growth rate needed to be calculated for both sections of the facility. The growth rate is the pace in which the traffic loadings increase over the years. This was calculated by looking at the equivalent single-axle loads (ESALs) for the corresponding cells. After the data was compiled, the geometric summation formula (equation 3.2) was used to calculate the growth rate where the variable a represented the total ESALs in the first year, r is the growth rate and n is the number of years that have passed from the time the cells were constructed.

$$\sum_{k=0}^{n} ar^k = \frac{a\left(r^{(n+1)} - 1\right)}{r - 1} \qquad (Eq\ 3.2)$$

The closer the model (equation 3.1) is to the friction numbers that were measured, the smaller the error would be. Thus, the models were found by minimizing the sum of the squared errors.

Results

In following the steps of the procedure, the ESALs needed to be tabulated (table 3.1) and analyzed for the whitetopping cells. It used data from the years 1997 to 2005 because that was the only data that was available during the time this model was being created.

Table 3.1: MnROAD's Mainline Whitetopping ESALs

Year	Annual ESALs	Total ESALs
1998	801,555	801,555
1999	806,901	1,608,456
2000	911,929	2,520,385
2001	978,211	3,498,595
2002	933,997	4,432,592
2003	996,492	5,429,084
2004	893,746	6,322,830

ESALs are found by using sophisticated equations that determine how much of the loadings the pavements received. The table represented the data for the 1997-whitetopping cells (cells 92-97) because the available data only went until July 2005 and cells 60 to 63 weren't constructed until October 2004. This data was an accurate representation for cells 60 to 63 because they were all whitetopping cells and the ESALs growth rate would stay close to consistent throughout the time period that the data represents to the present. The ESALs were then looked at for the years of 1998 to 2004 (excluded 1997 and 2005) because the geometric summation equation has difficulties with fractional years of data and the growth rate wouldn't be accurately portrayed.

From equation 3.2, the summation was the total number of cumulative ESALs in 2004, n was six years and a was the annual ESALs in the first year (1998). That left the growth rate (r) as the only variable that was unknown. After solving, a growth rate of approximately four percent was found.

As stated in the general information about the MnROAD facility, the only traffic allowed on the loop is a Mn/DOT operated semi-truck and it runs approximately the same number of laps every day of the working week. This means that the ESALs during the life of the pavement should remain approximately constant and thus the growth rate for the LVR would equal one.

The three constants in each of the equations were solved for by minimizing the sum of the squared errors between the friction measurements and the friction values that the model would output. Once the sum of the squared errors was minimized, a suitable solution was found. This was completed for the Mainline and LVR models and tables 3.2 and 3.3, respectively exhibit the values for each of the constants along with the corresponding sum of squared errors. These constants are for the variables in equation 1.

Table 3.2: Constants for MnROAD's Mainline Skid Resistance Model (Equation 3.1)

Tire	**Constant 1**	**Constant 2**	**Constant 3**	**Sum of Squared Errors**	**R-Squared Value**
Ribbed	22.005	29.215	-0.1	651.76	0.242
Smooth	1.0	18.364	-0.8	298.72	0.334

Table 3.3: Constants for MnROAD's Low Volume Skid Resistance Model (Equation 3.1)

Tire	**Constant 1**	**Constant 2**	**Constant 3**	**Sum of Squared Errors**	**R-Squared Value**
Ribbed	73.77983	24.9123	0.000527	2240.24	0.040
Smooth	-4.56	15.5612	0.03126	1052.71	0.183

The models' accuracy toward the MnROAD friction data can be portrayed from the coefficient of determination (R^2) and sum of the squared errors values. The coefficient of determination measures how well the model predicts the measured friction value. As the value approaches one, the line-of-best fit becomes more exact and the model predicts the measured events better. For the sum of the squared errors, the higher the number goes, the less accurate the model would be for this data set.

From those stipulations the LVR's model is not a very good fit especially for the ribbed model and the Mainline's model provides a better fit. For both of the roadways, the smooth tire was the more accurately portrayed tire. The large differential between the model and the data could be justified by looking at the data for these MnROAD cells; there are several friction data points for each age that were presented and only one point for the modeled friction value. Since the friction measurements vary for the age of the pavement, the both the sum of the squared errors and the coefficient of determination between the model and the measurements have the opportunity to differ by a large amount. The coefficient of determination is reasonable for the ribbed model because the amount of friction measurements on a single day makes the value lower. The model can't predict the varying amounts on a single day. Coefficients of determination for the smooth tire were lower than expected but the model was created by having the smallest amount of error between all of the points.

The graphs for the Mainline and LVR (figures 3.2 and 3.3) shows an example on how the model ensures the general pattern left by the pavement friction measurements and the disparity that exists by measurements taken from the same day. The friction measurements represent the friction testing for all of the cells on the day it was tested and each cell's friction value isn't an exact match to another cell. Also, the date and the weather could affect the measurements. Seasonal variation affects the tests because of the changing effects due to the differences in temperature. Also, if the last 24 hours weather was wet and rainy, the test might be skewed because the texture can't handle the extra water that the skid trailer applies. A good weather event (examples could include a strong heavy rain or the winter months) could also remove friction-reducing contaminants from the roadway.

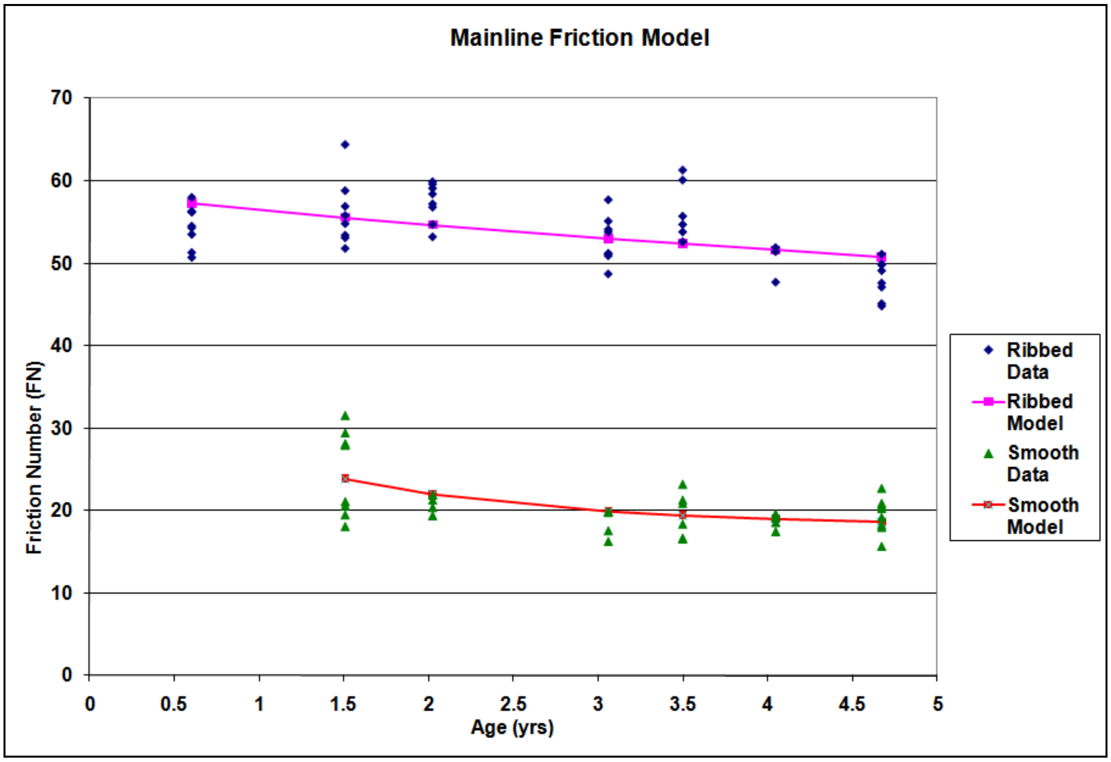

Figure 3.2: MnROAD's Mainline Friction Model Chart

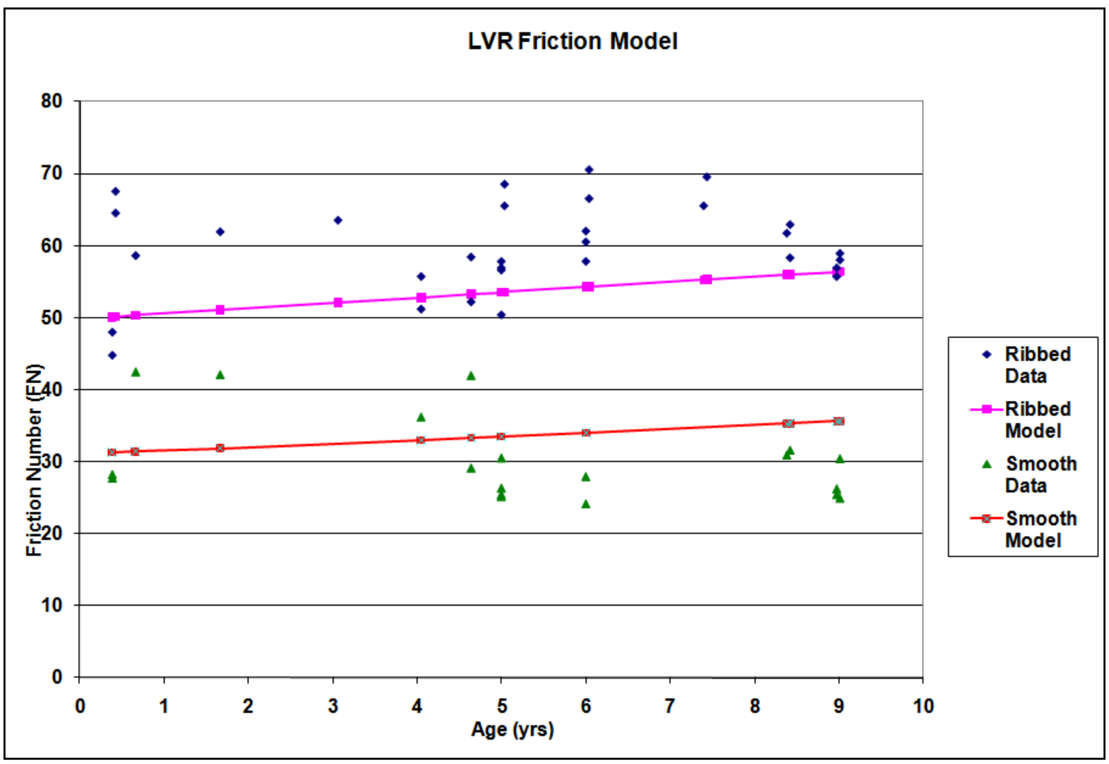

Figure 3.3: MnROAD's LVR Friction Model Chart

The models strive to represent each data point and with multiple tests per day, the model can't represent all of the data. This can't be accomplished because the data points vary by different amounts during the same day that the test was performed. This threw off the sum of squared errors and could have altered the model by some margin. Since there are numerous data points that exist, a few outliers wouldn't affect the complexion of the model itself. Each model had its own characteristics and using these characteristics would help determine whether the model was accurate in describing other roadways' friction values or not.

For the Mainline, the ribbed model was generally a declining straight line and the smooth model was a curved line that leveled out as the age of the pavement progressed. A shortcoming of the ribbed model was that: as time progressed, would the data still decline along a straight line, would it level off or would it follow another pattern. In the smooth model, no data was represented before the pavement was one and half years old and this could cause problems for the test sections where the testing occurs shortly after construction.

The LVR's model for both tires was an increasing straight line. Immediately, there are numerous problems with this model but the model could still determine friction values for roads that have lower loadings. The two models are similar in their pattern and the only difference is that the ribbed tire had friction values about 20 units higher than the smooth tire, which is very common for this test. The problem with these models was that it was highly unlikely that the friction value would continue on these paths. That is because of the wear on the pavement surfaces, the polishing of the aggregates, etc. Friction numbers for these cells at MnROAD have not seen the amount of time that a pavement would need to produce decaying friction on a road that doesn't have an excessive amount of travel on it.

Chapter 4 - Fitting Model to Test Sections

Information on Test Sections

Only test sections that followed the subsequent criterion were considered for the comparison to the MnROAD model:

- Friction data available
- Concrete with AstroTurf drag created texture
- Have ESALs data available
- ESAL and construction data available

This set of constraints lead to accurate information that could be fully examined. Twelve test sections fulfilled this criterion and were used for the examination. Table 4.1 gives basic information about these test sections including what city it is located near, the reference posts that the section corresponds with, the date in which the construction was complete and the depth in which the AstroTurf texturing was specified to be at that time.

Table 4.1: General Information on 12 Test Sections

#	Route	City	Beg. RP	End RP	Date Complete	Material Type	Surface Finish	Spec.
1	Hwy. 13	Mankato	105	107	7/23/2001	PCC	ATD	1.0
2	Hwy. 21	Jordan	32.5	36	9/1/1999	PCC	ATD	0.8
3	I-35	Elko	70	77	5/3/2004	PCC	ATD	1.0
4	I-35W	Lino Lakes	35	41	10/1/2000	PCC	ATD	0.8
5	I-90	Austin	155	166	7/1/2001	PCC	ATD	1.0
6	I-90	Eyota	222	232	8/1/1999	PCC	ATD	0.8
7	I-90	Winona	271	276.5	10/1/2000	PCC	ATD	0.8
8	I-94	Sauk Centre	115	127	6/1/1999	PCC	ATD	0.8
9	I-94	Barnesville	21	22	8/1/2000	PCC	ATD	0.8
10	Hwy. 169	Jordan	100	102	6/1/2000	PCC	ATD	0.8
11	Hwy. 169	Belle Plaine	88	90	10/1/2000	PCC	ATD	0.8
12	I-494	Golden Valley	17	22	10/1/1999	PCC	ATD	0.8

Mn/DOT collected all of the friction data for all twelve of the test sections. Since each section became an area of interest at different periods of time and the pavement friction can't be tested consistently throughout the years because of the enormity of the work that needs to be done; they all have various numbers of measurements and the range of years also differs by each section. Table 4.2 shows how many measurements were available for each test section and how the range of years is distributed.

Table 4.2: Initial Observations on Test Sections

#	Route	Number of Ribbed	Number of Smooth	First Recording	Last Recording	General Comments
1	Hwy. 13	25	13	9/5/2001	4/16/2009	Well distributed for 8 years
2	Hwy. 21	8	8	10/25/1999	4/21/2005	Well distributed for 6 years
3	I-35	5	5	10/12/2004	6/25/2008	Well distributed for 4 years
4	I-35W	9	12	4/27/2001	5/12/2009	Well distributed for first 4 years then nothing until 2009
5	I-90 (155)	13	10	11/8/2001	6/26/2008	Well distributed for 7 years
6	I-90 (222)	22	16	10/27/1999	8/20/2008	Lots of data for 7 years then nothing until 2008
7	I-90 (271)	11	4	9/11/2001	8/21/2008	Ribbed is well distributed for 8 years and smooth is weak
8	I-94 (115)	12	18	10/20/1999	9/23/2008	Well distributed for 9 years
9	I-94 (21)	6	5	5/16/2007	10/24/2008	Very weak - one year of data
10	Hwy. 169 (100)	10	13	6/8/2001	10/27/2005	Well distributed for 5 years
11	Hwy. 169 (88)	9	2	7/2/2002	10/27/2005	Ribbed has 4 different testing times and smooth has 2
12	I-494	10	5	11/2/1999	9/24/2005	Only 3 separate testing times – weak

Based upon these initial observations, the test sections that had a fair amount of data that were also well distributed for at least five years were the test sections that were more heavily scrutinized when analyzing the data rather than those sections that weren't as well represented. The sections that were very weakly distributed or only had a few testing dates wouldn't be as reliable but could still accurately represent the data. Since Highway 169 (88-90) only has two measurements for the smooth tire, which is insufficient for model fitting and wasn't used.

Calculating Growth Rate

The growth rate for each of the test sections was a function of the Equivalent Single-Axle Loads (ESALs) and was calculated using the same geometric summation formula (equation 3.2). One of the differences between this calculation and the MnROAD calculation was that the ESALs for the test sections were based upon design and forecast ESALs and not based on measured data. The growth rate was then solved for and was given as a percentage of increase. Table 4.3 shows the relevant information and the calculated growth rate.

Table 4.3: ESALs Calculations and Growth Rate for Test Sections

#	Route	Design Year	Annual Design ESALs	Annual Forecast ESALs	Forecast ESALs	Forecast Year	Growth Rate
1	Hwy. 13	2001	189,080	281,811	5,538,000	2021	3.20
2	Hwy. 21	1998	89,057	132,676	2,608,000	2018	3.19
3	I-35	2001	1,203,810	1,998,248	37,656,000	2021	3.80
4	I-35W	2001	668,267	1,043,437	20,130,000	2021	3.46
5	I-90 (155)	2002	445,439	694,497	13,406,000	2018	6.73
6	I-90 (222)	1997	569,427	844,700	16,894,000	2017	3.32
7	I-90 (271)	2001	746,947	1,136,859	22,154,000	2021	3.31
8	I-94 (115)	1999	696,238	1,075,090	20,831,000	2019	3.39
9	I-94 (21)	1998	501,247	762,153	14,858,000	2018	3.31
10	Hwy. 169 (100)	2000	874,302	1,175,274	24,103,000	2020	2.63
11	Hwy. 169 (88)	2000	874,302	1,175,274	24,103,000	2020	2.63
12	I-494	2001	737,741	1,213,519	22,947,000	2021	3.75

Calculating Friction Model Values

Since all of the data, the age of the concrete at the time of testing and all of the growth rates were calculated, the models needed to be validated for each of the test sections in order to have reasonable cause for using a particular model. When looking at the amount of annual ESALs for the test sections, it was evident that highways 13 and 21 were lower volume roads and thus would use the LVR model. Then when looking at the other test sections, it was noticed that the ESALs differ from the Mainline's model by great amounts at some times. To adjust for this, a corresponding factor was added to only the Mainline's smooth tire model. It was only added to the smooth tire's equation because the smooth tire is more sensitive to the texturing of the concrete pavement and thus has more affect to the loadings of the traffic.

A total of three equations were used to model the pavement friction values: two for the Mainline's model (equations 4.1 and 4.2) and one for the LVR (equations 4.3). The LVR's ribbed equation was not employed on the test sections because upon comparison of the number of annual ESALs and the friction data between the Mainline, LVR and the test sections showed that the ribbed equation couldn't be made with any accuracy and that the Mainline's equation would have better success. The LVR's smooth equation was still used because the texture of the concrete might have had a better representation when the ESALs are fairly close. From tables 3.2 and 3.3, equations 4.1, 4.2 and 4.3 were rewritten for analyzing the test sections. In the equations: *F* is the friction value, *k* is the growth rate, *t* is the age of the concrete in years, *FE* is the number of ESALs for the forecasted year (20 years after the design year) and *DE* is the number of ESALs for the design year.

- Mainline ribbed

$$F = 22.01\sin(kt) + 29.21\cos(kt)[1 + e^{-0.1t}] \qquad (Eq. 4.1)$$

- Mainline smooth

$$F = \left[\left(\frac{801000}{DE}\right)\left(\frac{FE}{DE}\right)\right]\left[\sin(kt) + 18.36\cos(kt)\,[1 + e^{-0.8t}]\right] \qquad (Eq. 4.2)$$

- LVR smooth

$$F = -4.56\sin(kt) + 15.56\cos(kt)\,[1 + e^{0.031t}] \qquad (Eq. 4.3)$$

After the equations were correctly entered for the data points, the modeled pavement friction values (*F*) was computed. The final step in the process was to analyze the data in order to investigate if there was sufficient evidence to validate the MnROAD model for AstroTurf drag friction or not.

Analysis of Model

Applying the MnROAD friction model for AstroTurf drag finish to the test sections was the critical portion of this study. These tests would either provide sufficient evidence to validate the model or it wouldn't. To test this model when applied to the test sections, four separate tests were conducted:

- Visual analysis
    - Visual comparison of modeled pavement friction and the actual recorded pavement friction to see if there was a trend or not.

- Descriptive statistics
    - Calculated the mean and standard deviations for all twelve of the test section's friction data and its model's data.

- This would allow a statistical analysis to notice if any general conclusions or biases could be made.

- Chi-squared analysis
  - An analysis tool that determines how much the data and the model differ from one another.
  - Creates a single number which could then be compared to a table of distributed values, which would determine whether or not the model and data were similar to a given confidence level.

- Mann-Whitney Z Test
  - A nonparametric test for analyzing whether or not the model and recorded data were similar within a given confidence level.

Visual Analysis

For each test section, a graph was created that had four different data series: ribbed data, ribbed model, smooth data and smooth model. All four of these data sets were graphed with their friction values versus the age of the concrete at the time of the test in years. Both of the model series were lined because it produced a better representation on the path that the model ensues.

Descriptive Statistics

Four means and four standard deviations were taken from each test section. These mean and standard deviation combination were taken from both the ribbed and smooth tire for the pavement friction data and the modeled friction. Also, an overall mean and standard deviation was taken for these categories. All of these numbers would allow for a quick analysis to discover if the data and modeled numbers were similar or different.

Chi-Squared Analysis

This was a practical tool to test the goodness of fit between the recorded data and the theoretical model [7]. The object of this test was to either reject or fail to reject the null hypothesis. It is inaccurate to say that a test accepts the null hypothesis because there could always be a special situation that defies the null hypothesis. For this test, the null hypothesis was that both the pavement friction data and the model were similar. So, if the test rejected the null hypothesis, then the alternative hypothesis was that the data and model were significantly different.

For each test section, the Chi-Squared test was conducted for the ribbed and smooth tires. The statistical test followed these steps:

- A corresponding number (X) was found by comparing each of the measured friction values (n) with the modeled friction value (e).

$$X = \frac{(n-e)^2}{e} \qquad (Eq. 4.4)$$

- For each test, the corresponding numbers were summed.

- The degrees-of-freedom number (d.o.f.) was calculated from the number of data sets that were represented in the summation (k).
    - The d.o.f is an estimate of the statistical parameters and calculates how much the final calculation is allowed to vary.

$$dof = k - 1 \qquad (Eq. 4.5)$$

- Finally, the critical values were found by looking in a master table for the Chi-Squared Distribution [8].
    - This is found by knowing the d.o.f. number (t) and the confidence level (α) that is being tested.

When the summation of the corresponding numbers was compared to the critical values, the hypothesis was tested. If the equation 4.6 was satisfied, then the null hypothesis was said to be failed to reject or that the null hypothesis could be followed.

$$\sum_{i=1}^{k} \frac{(n_i - e_i)^2}{e} < C_{1-\alpha,t} \qquad (Eq. 4.6)$$

If equation 4.6 was not satisfied, then the null hypothesis was rejected and the alternate hypothesis was accepted. This test allowed for the two tire types to be analyzed in all of the 12 test sections and the results to be represented with some confidence range.

Mann-Whitney Z Test

This nonparametric test allows the data two sets of data to be analyzed for possible similarity in source. It is based on a ranking process which observes intrinsically of the two sets of data by determining how they are similar [9]. That allowed for a comparison on how well the model fit with the overall data. With this test, it explicitly stated whether or not to reject the null hypothesis. The null hypothesis was that the model and the data that was collected for each test section was similar. If the test rejected the null hypothesis, then the alternative hypothesis was that the data and the model were significantly different.

Each test section had two Mann-Whitney Z Test was performed for the ribbed tire and for the smooth tire. For each test, the pavement friction values and the model friction values were combined and ranked in order from highest to lowest (one was the highest). Then, a z-number needed to be calculated. This z-number could then be compared to a table of known probabilities and state the results. The procedure and equations (4.7 through 4.10) for calculating the z-number was as follows:

- The ranking numbers for the two sets of data are summed ($t_n(data/model)$)

- The number of measurements for the data and model was counted (n and m, respectively)

- A corresponding number (U) was calculated:

$$U = nm + n\left[\frac{(m+1)}{2}\right] - t_n(data) \qquad (Eq. 4.7)$$

- Next, a factor for the total number of data points(μ_v) got calculated:

$$\mu_V = \frac{nm}{2} \qquad (Eq. 4.8)$$

- Then, a standard deviation (σ) was found:

$$\sigma = \left[\frac{nm(n+m+1)}{n}\right]^{1/2} \qquad (Eq. 4.9)$$

- Finally, the statistical value (z) that was used to evaluate the two data sets:

$$Z = \frac{(U - \mu_V)}{\sigma} \qquad (Eq. 4.10)$$

When the z-number was compared with the percentile number (z_0), it clearly stated whether the null hypothesis should be rejected or not. The percentile number was a number that came from standard normal probability tables, which could be found in numerous probability textbooks or online [8]. The z-number and percentile number were almost similar and the answer to the hypothesis test was determined by which number was bigger:

- If $Z > Z_0$, then the null hypothesis would be rejected (not accepted)
- If $Z < Z_0$, then the null hypothesis would fail to be rejected

If the null hypothesis was rejected, then it was saying that the test section’s data was similar to the friction values the MnROAD model produced.

Chapter 5 – Results

Visual Analysis

The graphs for all twelve of the test sections are shown in Appendix B – Friction Model Graphs. From these graphs, the model can be visually compared to the model results (figure 5.1). This is a subjective test but can be helpful when quickly looking at a model and its data.

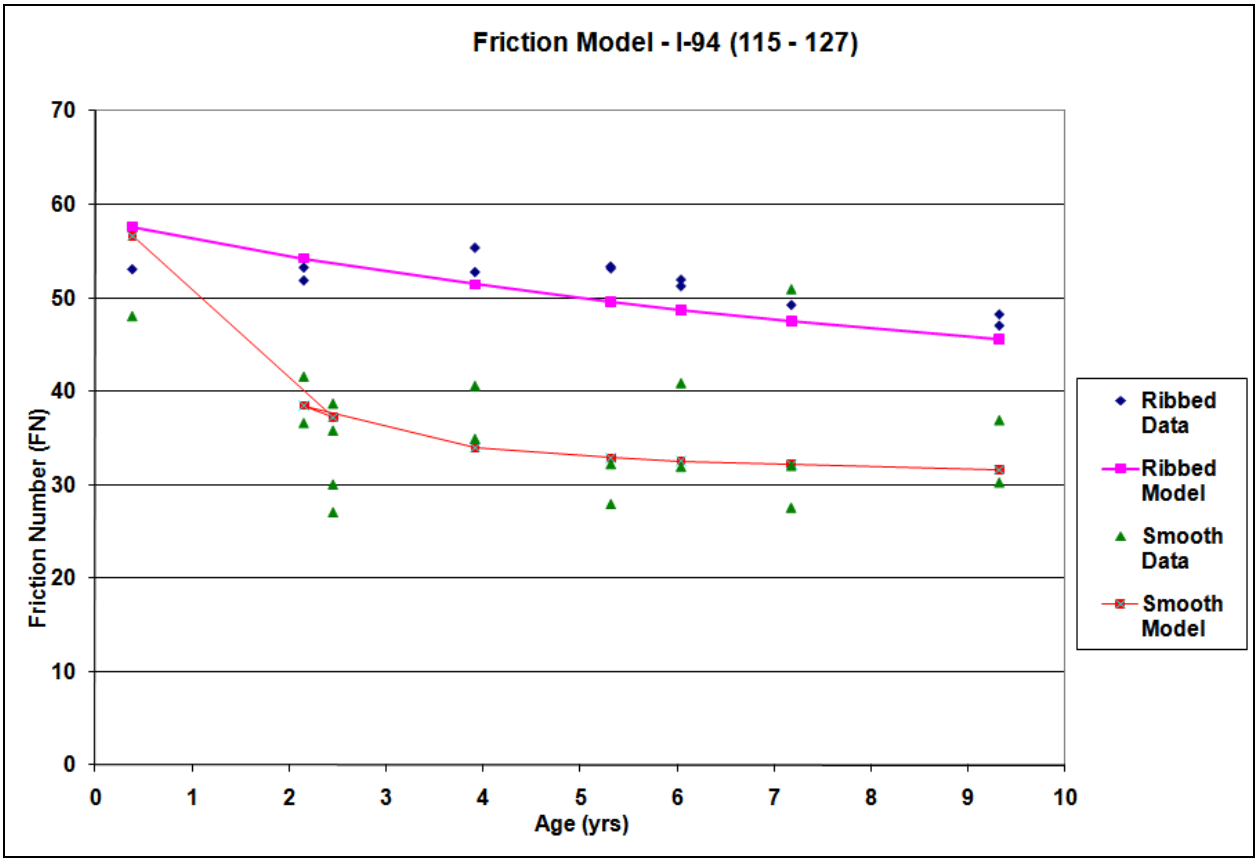

Figure 5.1: Friction Model for I-94 (115 - 127)

Descriptive Statistics

All of the standard deviations and means for the twelve test sections were found and shown below in table 5.1 and 5.2 where the ribbed and smooth tire are represented, respectively. Also, table 5.3 is the overall averages for both tires.

Table 5.1: Pavement Friction - Mean and Standard Deviations for Ribbed Tire

#	Route	Data		Calculated From Model		R-Squared Value between Model and Data
		Mean	Standard Deviation	Mean	Standard Deviation	
1	Hwy. 13	47.45	3.51	52.67	4.55	0.206
2	Hwy. 21	46.10	5.40	52.45	3.56	0.060
3	I-35	47.22	2.24	54.31	2.39	0.201
4	I-35W	51.71	1.96	52.05	3.98	0.467
5	I-90 (155)	50.00	4.98	53.39	3.50	0.484
6	I-90 (222)	49.49	5.51	52.14	3.66	0.032
7	I-90 (271)	49.22	4.09	51.35	3.46	0.020
8	I-94 (115)	51.66	2.40	50.34	3.65	0.463
9	I-94 (21)	55.17	5.00	47.31	0.65	0.249
10	Hwy. 169 (100)	48.82	3.12	51.71	2.63	0.854
11	Hwy. 169 (88)	45.82	6.93	53.70	2.07	0.088
12	I-494	44.02	6.14	52.83	4.65	0.162

Table 5.2: Pavement Friction - Mean and Standard Deviations for Smooth Tire

#	Route	Data		Calculated From Model		R-Squared Value between Model and Data
		Mean	Standard Deviation	Mean	Standard Deviation	
1	Hwy. 13	35.52	2.60	32.60	0.71	0.786
2	Hwy. 21	26.09	4.79	31.87	0.47	0.00
3	I-35	27.78	4.08	25.53	5.46	0.887
4	I-35W	24.50	4.59	43.39	8.41	0.173
5	I-90 (155)	30.04	4.04	62.04	20.48	0.200
6	I-90 (222)	33.44	6.23	44.08	8.59	0.265
7	I-90 (271)	28.60	3.88	33.27	7.21	0.166
8	I-94 (115)	35.77	6.83	35.61	5.81	0.181
9	I-94 (21)	50.34	15.25	44.10	0.22	0.011
10	Hwy. 169 (100)	27.07	4.12	27.10	3.35	0.139
11	Hwy. 169 (88)	24.25	3.75	23.27	0.44	N/A
12	I-494	27.40	4.84	57.00	13.33	0.073

Table 5.3: Pavement Friction - Average Mean and Standard Deviations

Type	Ribbed		Smooth	
	Mean	Standard Deviation	Mean	Standard Deviation
Data	48.89	4.27	30.90	5.42
Model	52.02	3.23	38.32	6.20

These results will allow for comparisons between the model and the data to be made. It will show how much the data and models differ and give statistical results for the different test sections. The coefficient of determination will measure how well the model predicted the measured values and give a rating for the best-fit-line.

Chi-Squared Analysis

A closer look at the procedure and the numbers that were involved can be found in Appendix C – Procedure and Explanation of Chi-Squared Analysis. The results of the Chi-Squared Analysis are shown below in tables 5.4 (ribbed tire) and 5.5 (smooth tire).

Table 5.4: Chi-Squared Results - Ribbed Tire

#	Route	Ribbed - Percentiles				
		99%	**97.5%**	**95%**	**90%**	**80%**
1	Hwy. 13	Similar	Similar	Similar	Similar	Different
2	Hwy. 21	Similar	Similar	Similar	Similar	Different
3	I-35	Similar	Similar	Similar	Similar	Similar
4	I-35W	Similar	Similar	Similar	Similar	Similar
5	I-90 (155)	Similar	Similar	Similar	Similar	Similar
6	I-90 (222)	Similar	Similar	Similar	Similar	Similar
7	I-90 (271)	Similar	Similar	Similar	Similar	Similar
8	I-94 (115)	Similar	Similar	Similar	Similar	Similar
9	I-94 (21)	Similar	Similar	Similar	Different	Different
10	Hwy. 169 (100)	Similar	Similar	Similar	Similar	Similar
11	Hwy. 169 (88)	Similar	Different	Different	Different	Different
12	I-494	Different	Different	Different	Different	Different

Table 5.5: Chi-Squared Results - Smooth Tire

#	Route	Smooth – Percentiles				
		99%	**97.5%**	**95%**	**90%**	**80%**
1	Hwy. 13	Similar	Similar	Similar	Similar	Similar
2	Hwy. 21	Similar	Similar	Similar	Different	Different
3	I-35	Similar	Similar	Similar	Similar	Similar
4	I-35W	Different	Different	Different	Different	Different
5	I-90 (155)	Different	Different	Different	Different	Different
6	I-90 (222)	Different	Different	Different	Different	Different
7	I-90 (271)	Similar	Similar	Different	Different	Different
8	I-94 (115)	Similar	Similar	Similar	Similar	Different
9	I-94 (21)	Different	Different	Different	Different	Different
10	Hwy. 169 (100)	Similar	Similar	Similar	Similar	Similar
11	Hwy. 169 (88)	N/A	N/A	N/A	N/A	N/A
12	I-494	Different	Different	Different	Different	Different

In these tables, the shaded cells or the ones where the model and data are different represent when the null hypothesis in that particular trial was rejected. This makes it easy to distinguish the results of this test.

Mann-Whitney Z Test

A detailed look at this test and the information that was used is located in Appendix D – Procedure and Explanation for Mann-Whitney Z Test. The findings for the Mann-Whitney Z Test are located below in the following two tables: table 5.6 is for the ribbed tire and table 5.7 is for the smooth tire.

Table 5.6: Mann-Whitney Z Test Results - Ribbed Tire

#	Route	Ribbed - Percentiles				
		99%	**95%**	**90%**	**80%**	**75%**
1	Hwy. 13	Similar	Similar	Similar	Similar	Similar
2	Hwy. 21	Similar	Similar	Similar	Similar	Similar
3	I-35	Similar	Similar	Similar	Similar	Similar
4	I-35W	Similar	Similar	Similar	Similar	Similar
5	I-90 (155)	Similar	Similar	Similar	Similar	Similar
6	I-90 (222)	Similar	Similar	Similar	Similar	Similar
7	I-90 (271)	Similar	Similar	Similar	Similar	Similar
8	I-94 (115)	Similar	Similar	Similar	Different	Different
9	I-94 (21)	Similar	Different	Different	Different	Different
10	Hwy. 169 (100)	Similar	Similar	Similar	Similar	Similar
11	Hwy. 169 (88)	Similar	Similar	Similar	Similar	Similar
12	I-494	Similar	Similar	Similar	Similar	Similar

Table 5.7: Mann-Whitney Z Test Results - Smooth Tire

#	Route	Smooth - Percentiles				
		99%	**95%**	**90%**	**80%**	**75%**
1	Hwy. 13	Different	Different	Different	Different	Different
2	Hwy. 21	Similar	Similar	Similar	Similar	Similar
3	I-35	Similar	Similar	Similar	Similar	Similar
4	I-35W	Similar	Similar	Similar	Similar	Similar
5	I-90 (155)	Similar	Similar	Similar	Similar	Similar
6	I-90 (222)	Similar	Similar	Similar	Similar	Similar
7	I-90 (271)	Similar	Similar	Similar	Similar	Similar
8	I-94 (115)	Similar	Similar	Similar	Similar	Similar
9	I-94 (21)	Similar	Similar	Similar	Similar	Similar
10	Hwy. 169 (100)	Similar	Similar	Similar	Similar	Similar
11	Hwy. 169 (88)	N/A	N/A	N/A	N/A	N/A
12	I-494	Similar	Similar	Similar	Similar	Similar

For these tables, the shaded cells are the ones where the null hypothesis was rejected (data and model are significantly different). This type of table allows for an easy reference to see how the Mann-Whitney Z Test resulted.

Recommendation

The use of Turf drag as a pavement texture yields results that are consistent with most textured surfaces. It is recommended that factors that accelerate texture loss should be minimized. These include poor, cold weather paving practice, over finishing and improper consolidation.

Limitations

The results obtained are based solely on the data obtained from some of the test sections in the network. Variabilities incurred the level of care, mix design and construction practice. The said variability and effects were not quantified in this study.

Comparison of Network Model to MnROAD models precludes the expectation that different rate of loading may cause deviation in the decay model.

Chapter 6 – Discussion of Results

Each of the four uncorrelated tests had its own advantages and disadvantages but each one gave results that were important in determining if the MnROAD model for pavement friction on AstroTurf texture was adequate in determining the friction on other similar pavements.

Visual Analysis

When visually assessing the different graphs in Appendix B – Friction Model Graphs, it was evident immediately that the graphs were not perfect but the model did follow the general trend of the data and for the most part looked reasonably represented. The modeled friction values were visually within a small proximity of the actual friction values from the test sections for the ribbed tire but had a few cases where the model would be higher than the actual values. The smooth tire's model for the first two test sections (Highways 13 and 21) were well represented because the model followed the pattern of the measurements and forecasted similar friction numbers for most of the years. When looking at the other test sections for the smooth tire, three test sections were almost perfect in modeling the pavement friction values and a few others were within a reasonable proximity of the data. On the other hand, there were also four test sections that weren't even close to the measurements.

Based solely on the various graphs, the models from the MnROAD cells were fairly accurate in modeling the friction for both tires with a few exceptions. The two worst sections for both tires were Interstate 94 (21 – 22) and Interstate 494 (17 – 22) because the models were disastrous in modeling the friction values and a main reason behind this could be that the sections didn't have a reasonable set of data. The I-94 section only had data after the pavement was over six years old and then had only one more day of measurements taken. Then the I-494 section had a lot of measurements taken a month after the construction was completed and then only two more days of testing took place, which were almost five years after the first tests were completed. Even though these test sections didn't model well, it benefited the model by showing a few flaws in the process. The biggest was that the model didn't accurately forecast the friction measurements for the first few months of the pavement's age after construction was completed. That can be explained because no two pavement sections can be produced in the same exact way but over time, the friction will most likely decay toward a similar friction value.

Looking at the graphs provides a picture of the results and allows for a better enhancement to be made between the model and the actual friction measurements. They also offer the capability for a quick glance at the graphs to determine if the model and the data follow the same general pattern. Even though the graphs were useful in those senses, they didn't provide any assurance to the conclusions of these results because it is the way in which someone portrays the graphs that determine if the two are similar or not and not by using a credited analysis tool that looks at the variability of the data.

Descriptive Statistics

By providing the means and standard deviations for all of the test sections, a statistical analysis was able to be performed that helped determine how the overall data compared to the overall model. The overall averages for the mean and standard deviations, of the ribbed tire, were within proximity of each other but the model did stand a little higher for the most part. This identifies that the overall model was higher than the overall data. When comparing the individual test sections, the majority the means of the model and the data differed by about five. Having a small differential indicates that the test sections are well represented by the model. The three that had almost identical means included: Interstate 35W (35 – 41), Interstate 90 (155 – 166) and Interstate 94 (115 – 127). There were no test sections that had a large differential between the data and the model.

Then for the smooth tire, the overall mean and standard deviations had a larger differential in each of the calculations than the data when it was compared to the ribbed tire. Even though the difference was higher than the ribbed tire, the overall calculations were still within proximity of each other and inside the range of the overall standard deviation. After looking at the individual test sections, four test sections had very similar means between the data and the model: Highway 13 (105 - 107), Interstate 35 (70 – 77), Interstate 94 (115 - 127) and Highway 169 (100 – 102). This analysis provides a comparison between statistical calculations but there were no confidence levels between these decisions, as the results that were concluded were only a view on how the statistical numbers were contrasted.

The coefficient of determination values for each of the test sections and this value relates how well the model predicted the measured values. From the ribbed tire, the highest r-squared value was 0.854 for Highway 169 (100). This number is high for this type of model because of the number of tests that could be tested on each day. Also, four other test sections had coefficients higher than 0.450. This is a reasonable number for a model like this because there is no way that a model can predict all of the various factors including two different friction measurements on the same day. For the ribbed tire, most of the measurements were around 0.200. Highway 13 (105 – 107) and Interstate 35 (70 – 77) had the highest coefficient of determination values for the smooth tire with 0.786 and 0.887, respectively.

Chi-Squared Analysis

From the results of this test, it was evident that both the ribbed and smooth tire had some test sections that concluded that the data and model were similar and some that stated they were different. The ribbed data had seven of the twelve sections that were similar throughout the different confidence intervals. Then for the sections that were rejected at some confidence, two test sections (Highway 21 (32.5 – 36) and Interstate 90 (155 – 166)) concluded that the test had a 95 percent confidence level that the model and data were significantly different and had another test section (Highway 13 (105 – 107)) that said it was 90 percent certain that the two were significantly different. The results of this test assured that the data and the model had many test sections that are, to some confidence level, similar.

For the smooth data, only three test sections were entirely similar for each of the confidence levels but three other test sections were similar to some degree. The three test sections that changed from similar to different were Highway 21 (32.5 – 36), Interstate 90 (271 – 276.5) and Interstate 94 (115 – 127). Each of these test sections concluded that the model and data were significantly different at confidence levels of 90, 95 and 80 percent, respectively. These results show that Low Volume Model for the first two test sections is fairly accurate as it failed to reject the null hypothesis for all of the different confidence levels except for two. Then the Mainline model was not as accurate according to this test. It rejected the null hypothesis at the 99 percent confidence level for five of the seven sections and that means that those sections didn't represent the data very well. From this test, it made the results clear as to which test sections had a similar model and which ones didn't, but the Chi-Squared Analysis also supplies a confidence interval, which allows for better conclusions in the end.

Mann-Whitney Z Test

The results for the Mann-Whitney Z Test provided another chance to analyze how the model and data compared within certain confidence intervals. The tables for both the ribbed and smooth tire's results (tables 5.6 and 5.7) were almost unanimous in saying that the model and data were similar. Looking at the overall picture of the two tables, the conclusion that the model and data are similar could easily be made.

For the ribbed tire, it only had two test sections that rejected the null hypothesis at some confidence. Those test sections were Interstate 94 (115 – 127) and Interstate 94 (21 – 22), which rejected the null hypothesis at confidence levels of 80 and 95 percent, respectively. For this test, having the confidence level of 80 percent isn't very good and could also be considered to be similar. According to these results, the ribbed tire model was accurately modeling the friction values from the test sections.

Then for the smooth data, being similar was once again asserted throughout the table. Only one test section out of the twelve rejected the null hypothesis. At the 99 percent confidence level, Highway 13 (105 – 107) was said to be significantly different. Since this occurred during the first test section, the Mainline model for the smooth tire never rejected the null hypothesis. This final test was one of the most known significance tests that are non-parametric and produce results that will allow final conclusions to be made about the model that also correspond with a know confidence interval and the results are thus highly creditable.

Overall

From all of the tests, a complete table of results can be found in table 6.1 for the ribbed tire and table 6.2 for the smooth tire.

Table 6.1: Summary of Results - Ribbed Tire

#	Route	Visual	Statistical	Chi-Squared	Mann-Whitney
1	Hwy. 13	Different	Similar	Different (80%)	Similar
2	Hwy. 21	Different	Similar	Different (80%)	Similar
3	I-35	Different	Different	Similar	Similar
4	I-35W	Similar	Similar	Similar	Similar
5	I-90 (155)	Different	Similar	Similar	Similar
6	I-90 (222)	Similar	Similar	Similar	Similar
7	I-90 (271)	Similar	Similar	Similar	Similar
8	I-94 (115)	Similar	Similar	Similar	Different (80%)
9	I-94 (21)	Different	Different	Different (90%)	Different (95%)
10	Hwy. 169 (100)	Similar	Similar	Similar	Similar
11	Hwy. 169 (88)	Different	Similar	Different (97.5%)	Similar
12	I-494	Different	Similar	Different (99%)	Similar

Table 6.2: Summary of Results - Smooth Tire

#	Route	Visual	Statistical	Chi-Squared	Mann-Whitney
1	Hwy. 13	Similar	Similar	Similar	Different (99%)
2	Hwy. 21	Similar	Different	Different (90%)	Similar
3	I-35	Similar	Similar	Similar	Similar
4	I-35W	Different	Different	Different (99%)	Similar
5	I-90 (155)	Different	Different	Different (99%)	Similar
6	I-90 (222)	Different	Similar	Different (99%)	Similar
7	I-90 (271)	Different	Similar	Different (95%)	Similar
8	I-94 (115)	Similar	Similar	Different (80%)	Similar
9	I-94 (21)	Different	Similar	Different (99%)	Similar
10	Hwy. 169 (100)	Similar	Similar	Similar	Similar
11	Hwy. 169 (88)	N/A	N/A	N/A	N/A
12	I-494	Different	Different	Different (99%)	Similar

The purpose of this study was to analyze the data from the MnROAD research facility and the various test sections across the state of Minnesota to evaluate the use of a time- dependent skid resistance model on AstroTurf dragged concrete pavements.

An important concept in determining the validation status of the MnROAD models was the fact that measured data could differ by large amounts even when testing was completed on the same day. This was evident when looking at the graphs for the MnROAD friction values (figures 3.2 and 3.3). The testing process is not by any means perfect, but it does give reasonable numbers that depict how much friction exists or how much it decayed in a given amount of time. Examples of these problems include: loose gravel on the roadway, potholes, bumps, cracks, or a combination of unexplained events. The main concept that needed to be considered when drawing conclusions were that error could exist and the overall picture, not every measurement, needed to be analyzed.

Based upon the results of tables 6.1 and 4.2 for the ribbed tire, it appears that the model represented the data fairly well. From looking at table 4.2, test sections 9 and 12 aren't very well distributed and thus aren't very useful in modeling the friction values. Without those two sections, the only sections that didn't fit the model were sections 1 and 2. These two sections were modeled using the Mainline model because the LVR didn't represent the data very well but an argument could be made that neither one of the models could represent that data because of the low number of ESALs and pattern of the measure friction values. After careful analysis of the data represented for the ribbed tire, it was determined that the MnROAD model for the AstroTurf drag was validated and represented the friction values within a given proximity.

Using tables 6.2 and 4.2 for the smooth tire, the model for both the LVR and the Mainline represented the data fairly well. The smooth tire was affected more by the texturing of the concrete pavement and that was the reason why the actual data in the test sections needed to be closely analyzed in order to determine if the model and data were similar or not. If the model could be concluded based solely on the Mann-Whitney Z Test then the model would pass easily but every model has its flaws and the data needs to be analyzed for the entire set of tests conducted. From the data of the test sections and table 4.2, test sections 9, 11 and 12 are not well distributed and throw off the model and weren't considered heavily in the conclusion for these models. With those exceptions, the results show that the data and the model were for the most part similar. The only exclusion to this was sections 4 and 5. Upon closer analysis of these sections, the friction for the smooth tire was lower than the model. Various causes could have resulted in this including errors in testing, type of aggregate in the pavement or errors when texturing the concrete pavement. The errors in the construction could have been caused by insufficient depth in the striations or could be caused by some unexplained event. Construction issues that lower the initial friction numbers could be adjusted in the model by increasing the age of the pavement. The only complication in this procedure is determining how much to alter the age. This needs to be accomplished by having a few measurements and finding the best possible fit of the model.

Summary of Analysis

- The ribbed tire for the LVR was the only model not to be validated because of conflicting data issues and the insufficient number of low volume roads available to test the model.

- The ribbed tire degradation model for the interstate system was repeatable for most of the twelve test sections that it was tested for. This model appeared to be a straight declining line.

- In the smooth tire's interstate degradation model, it appeared to start by declining and then easily leveling off as the age of the pavement increased. This model was also consistently providing acceptable results for the test sections used.

- For the LVR's smooth tire degradation model, it was validated from the two test sections that were available because of the low number of ESALs on those highways but it was continuously increasing as the age progressed.

- The three degradation models can depict the friction numbers on various pavements where it can be used to determine how much relative friction an AstroTurf dragged concrete pavement slab has at a given time.

- These degradation models can be applied together with wet-weather accident counts to determine if certain pavements keep motorists safe enough or if maintenance is needed to give it more friction.

After careful consideration on all of the tests and analysis for the smooth tire, it was determined that the MnROAD models for the AstroTurf drag were validated and represented the friction values for the test section within a given proximity.

The Minnesota Department of Transportation will continue to analyze these models in order to determine the degradation of pavement friction for AstroTurf finished concrete as the age of the concrete progresses.

Chapter 7 – Conclusions

This study examined AstroTurf textured concrete pavements in consideration of the Federal Highway Administration's texture advisory. Skid-resistance sustainability functions were created from the AstroTurf textured cells in the MnROAD facility and compared with similar test sections from around Minnesota. These test sections were built at various times, have different types of loadings, are located in various portions of Minnesota and have AstroTurf drag as the standard texturing technique. Four analysis tests were then performed to compare the models with the friction number from the test sections and it was concluded that the models for the three different scenarios were validated.

The examination of the sustainability functions that were produced from the MnROAD cells was found to be repeatable on most of the twelve test sections. This is evidence that the hysteresis and adhesion combined for AstroTurf drag textured concrete degrade in similar ways depending on the loadings that the pavement receives. This model doesn't distinguish the difference between the hysteresis and adhesion properties, so it is unable to determine whether the micro or macro-level of surface roughness are the contributing factors to the degradation. Further analysis is being conducted in single state surface characteristics (MPR 6021).

It is evident from the foregoing that there is a general decay in FN with time and traffic. The rate of decay, however, reduces with time.

This research does not completely answer the question but sheds light to some degrees on the degradation trend of AstroTurf drag with respect to time and traffic. In the test sections, traffic ranged from 89,000 annual ESALs to 1.2 million annual ESALs and had a calculated growth rate over 20 years of around 3.5 percent. Evidently, the friction suffers a degradation whose rate is proportional to some related variable that is positively correlated to FN. It is possible that when the mean profile depth of the AstroTurf drag is initially high, corresponding high friction numbers result. However, the rate of degradation is higher because the rate of texture loss is higher.

The ribbed tire decay pattern appears to be more rapid than the smooth tire decay pattern. In five years, the ribbed pattern generally decays from 55 – 60 to 45 – 50 and decays lower thereafter. The smooth tire pattern decays quickly from 40 to 25 – 30 in the first five years and in some cases decays to 20 – 25 in ten years.

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Appendix A - MnROAD Cell Maps

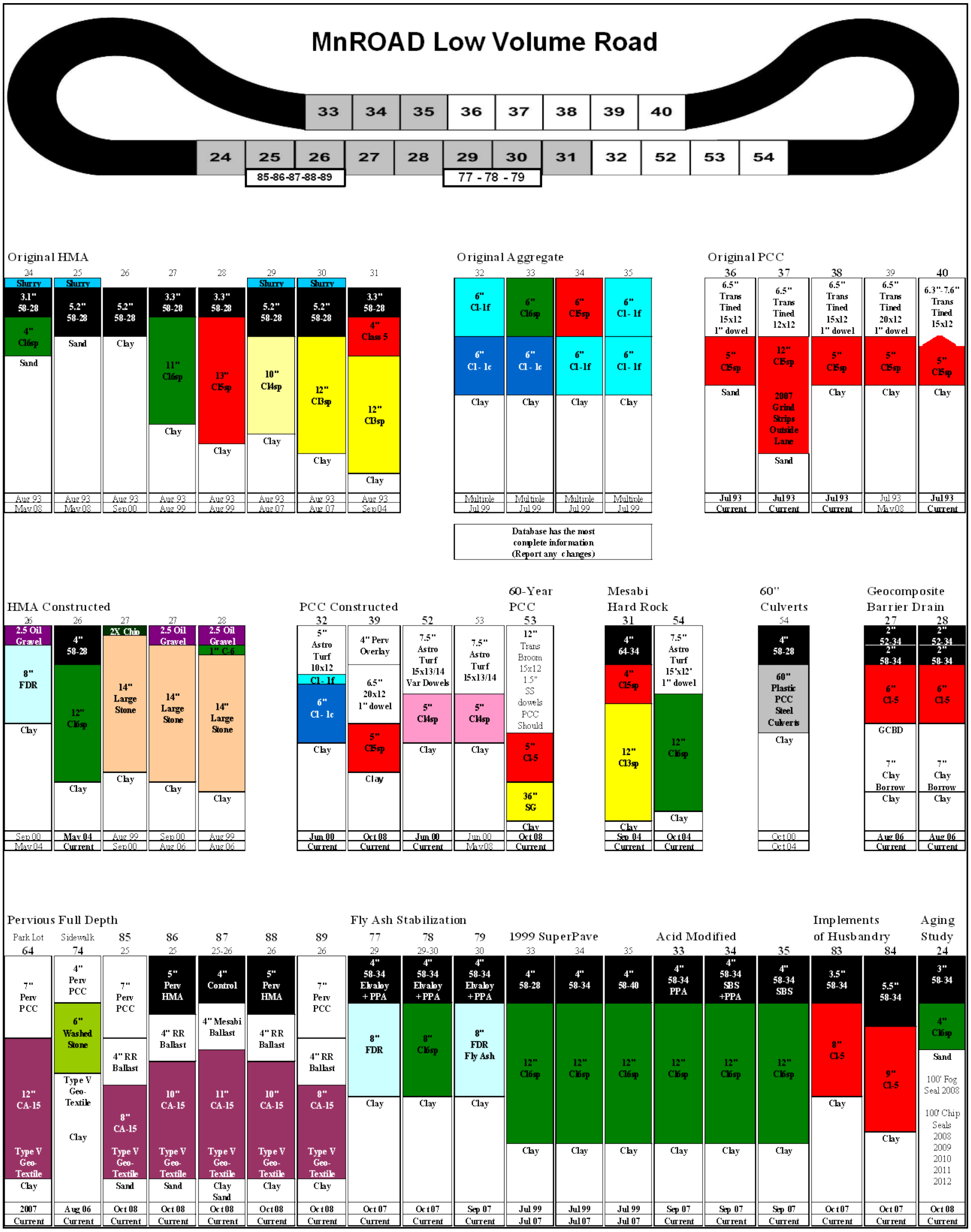

Figure A.1: Cell Cross-Section for LVR

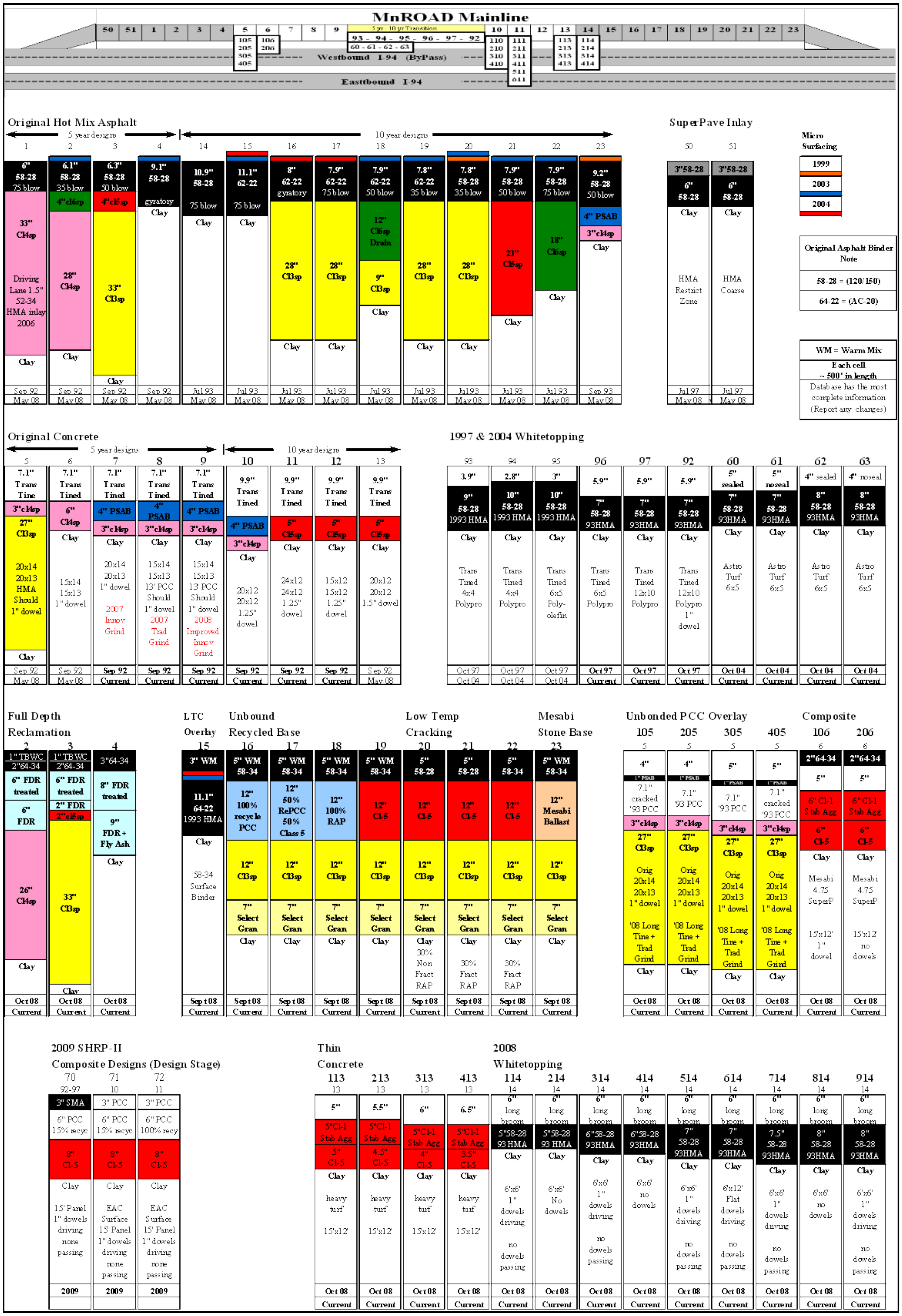

Figure A.2: Cell Cross-Section for Mainline

Appendix B - Friction Model Graphs

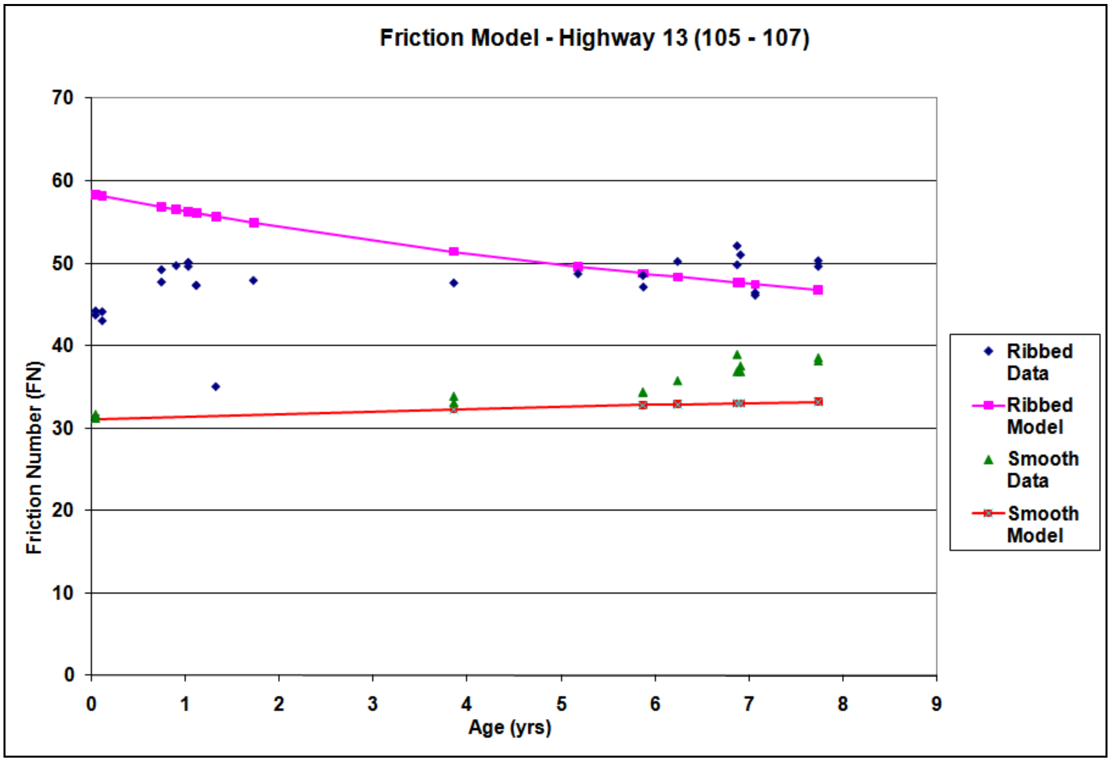

Figure B.1: Highway 13 (105 - 107) Chart

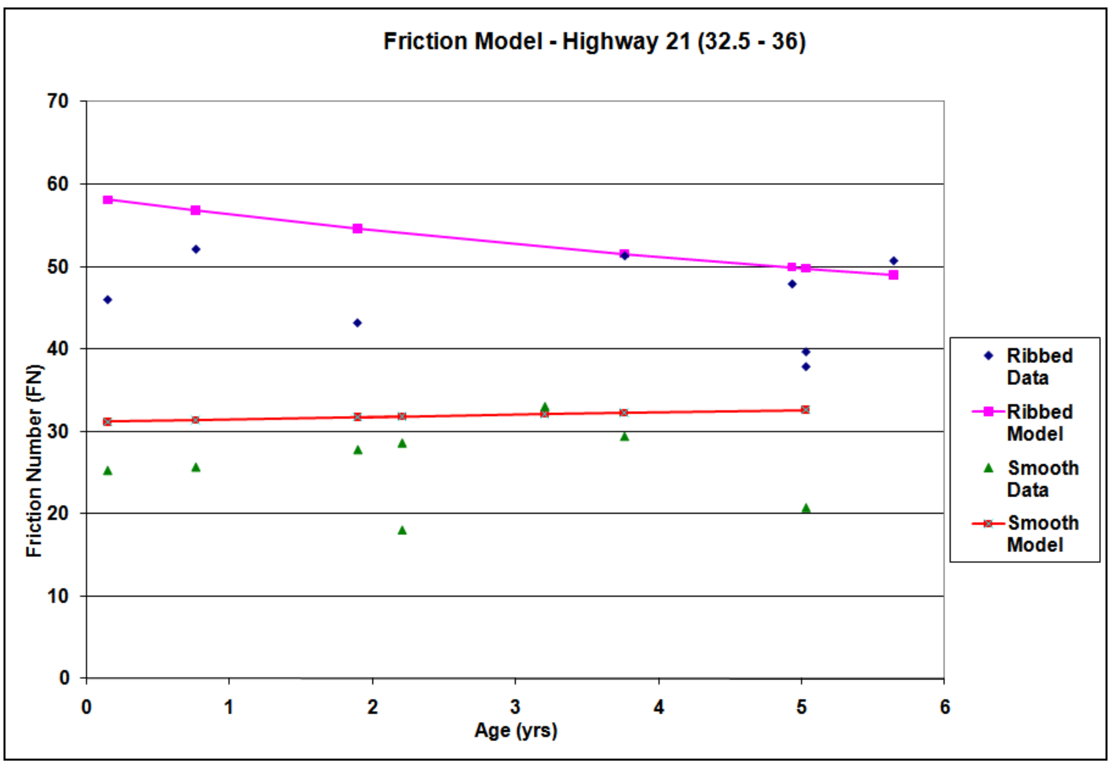

Figure B.2: Highway 21 (32.5 - 36) Chart

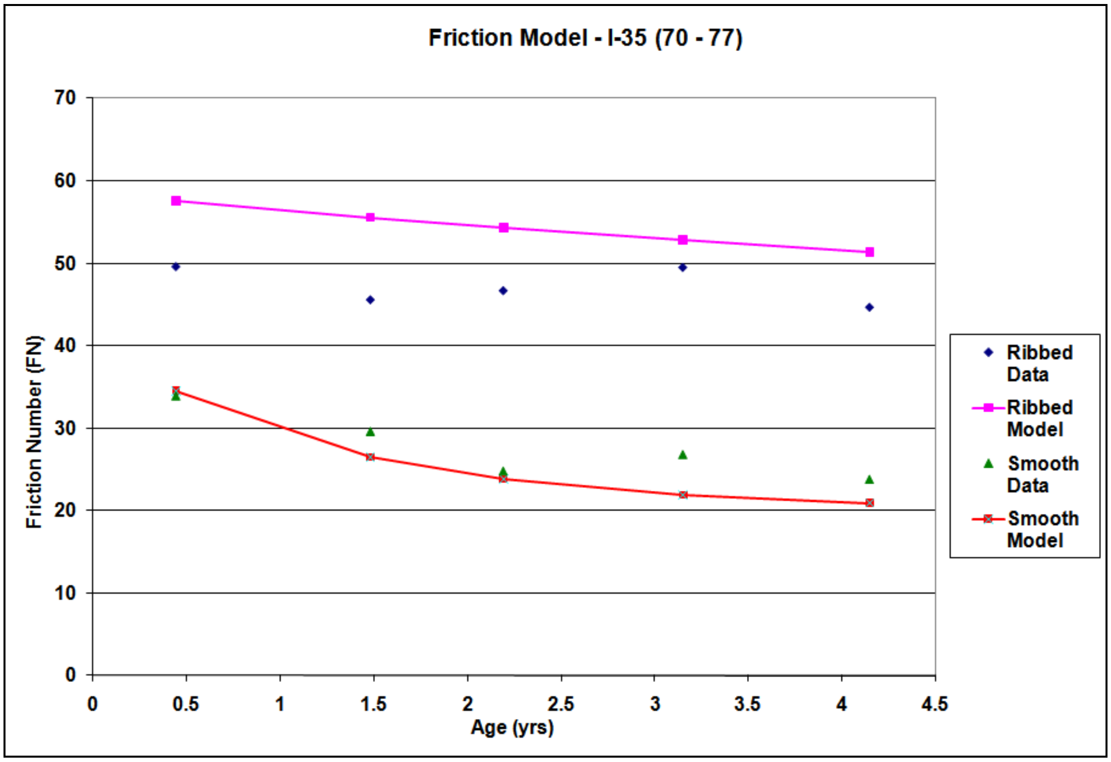

Figure B.3: I-35 (70 - 77) Chart

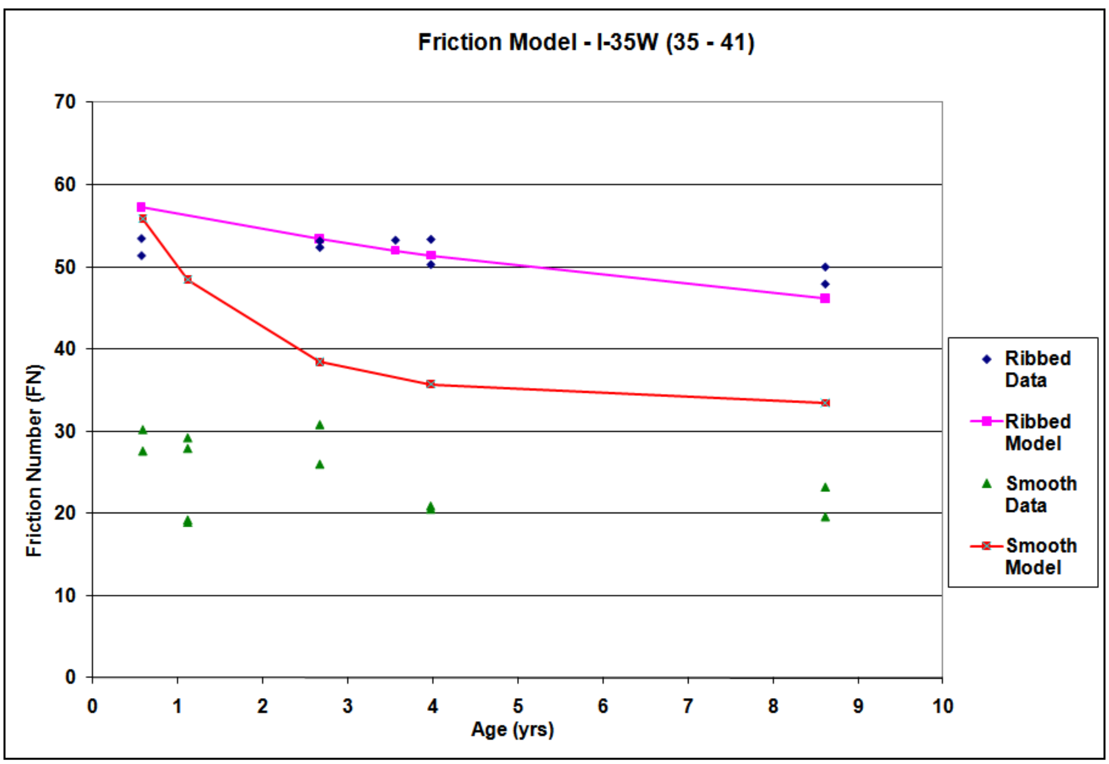

Figure B.4: I-35W (35 - 41) Chart

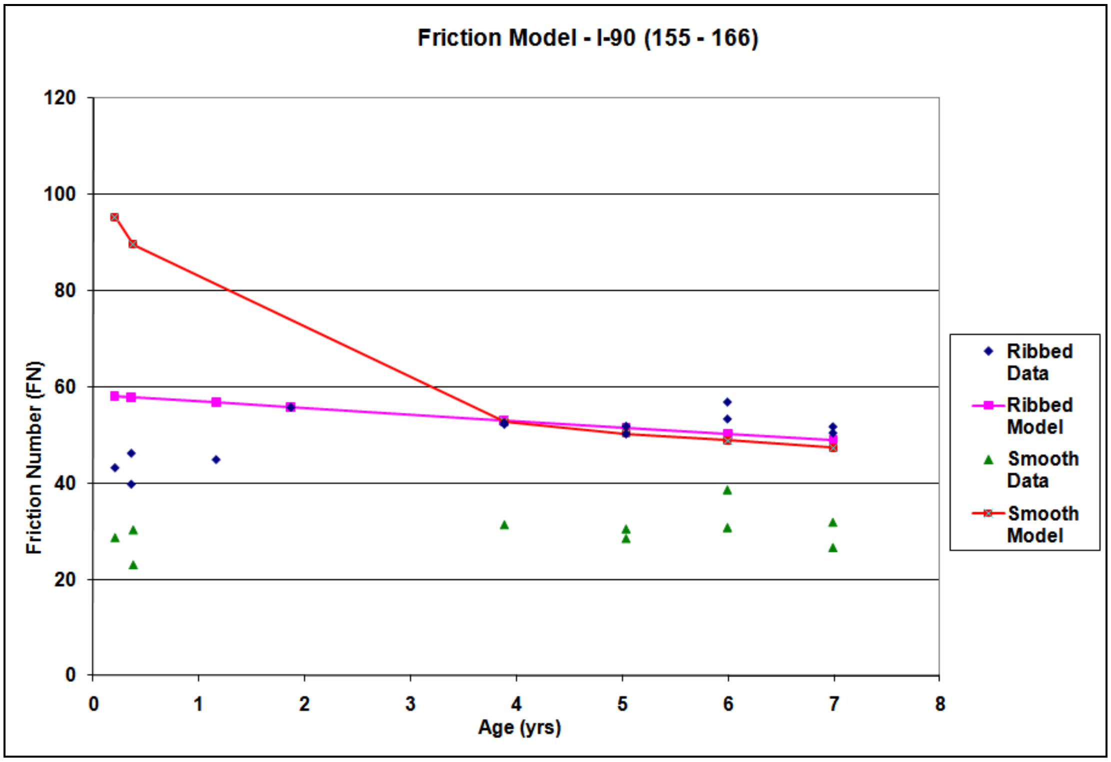

Figure B.5: I-90 (155 - 166) Chart

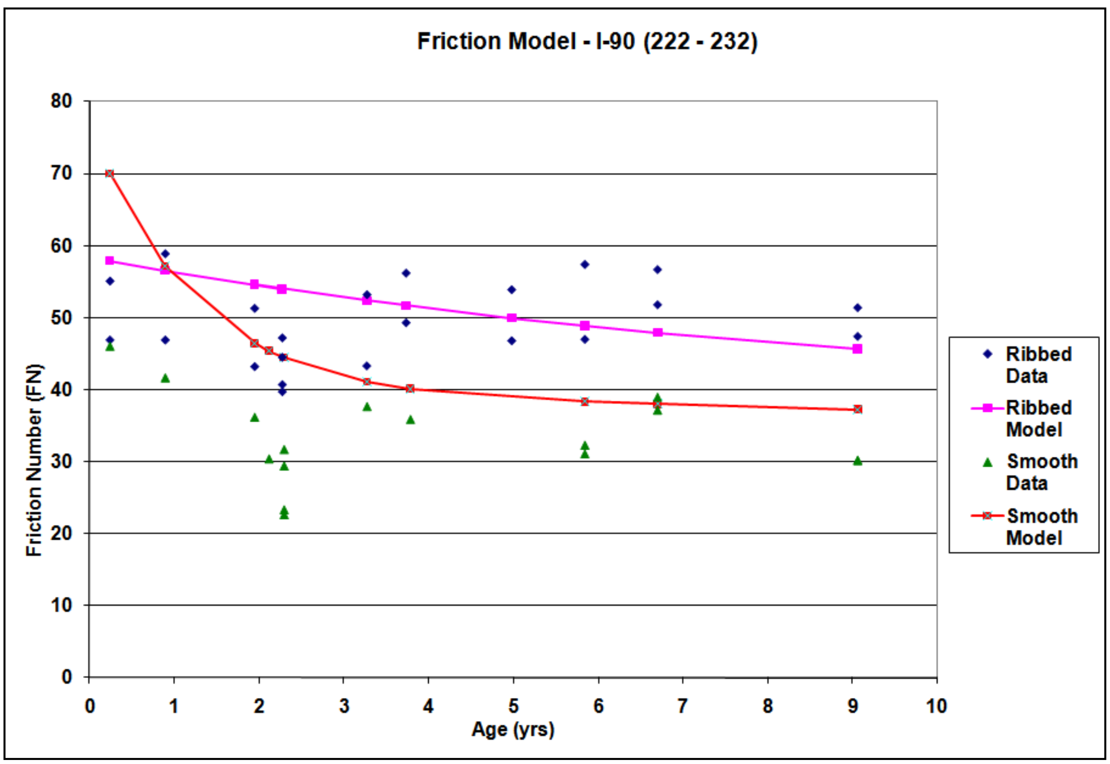

Figure B.6: I-90 (222-232) Chart

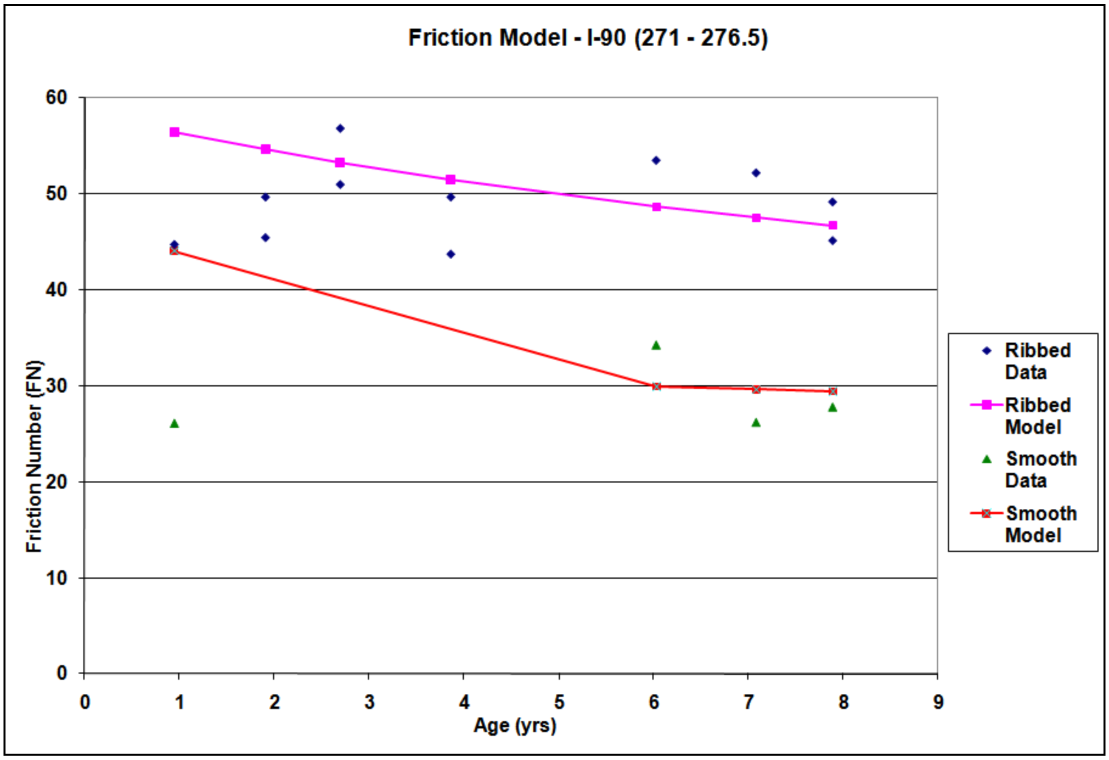

Figure B.7: I-90 (271 - 276.5) Chart

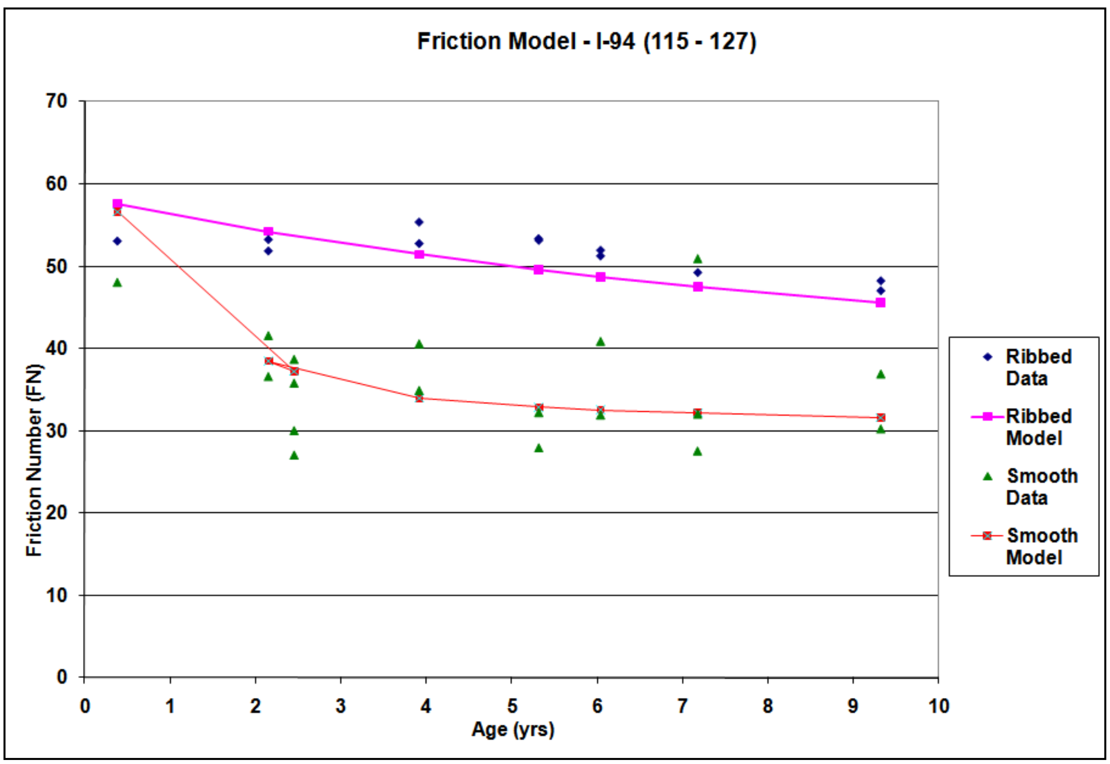

Figure B.8: I-94 (115 - 127) Chart

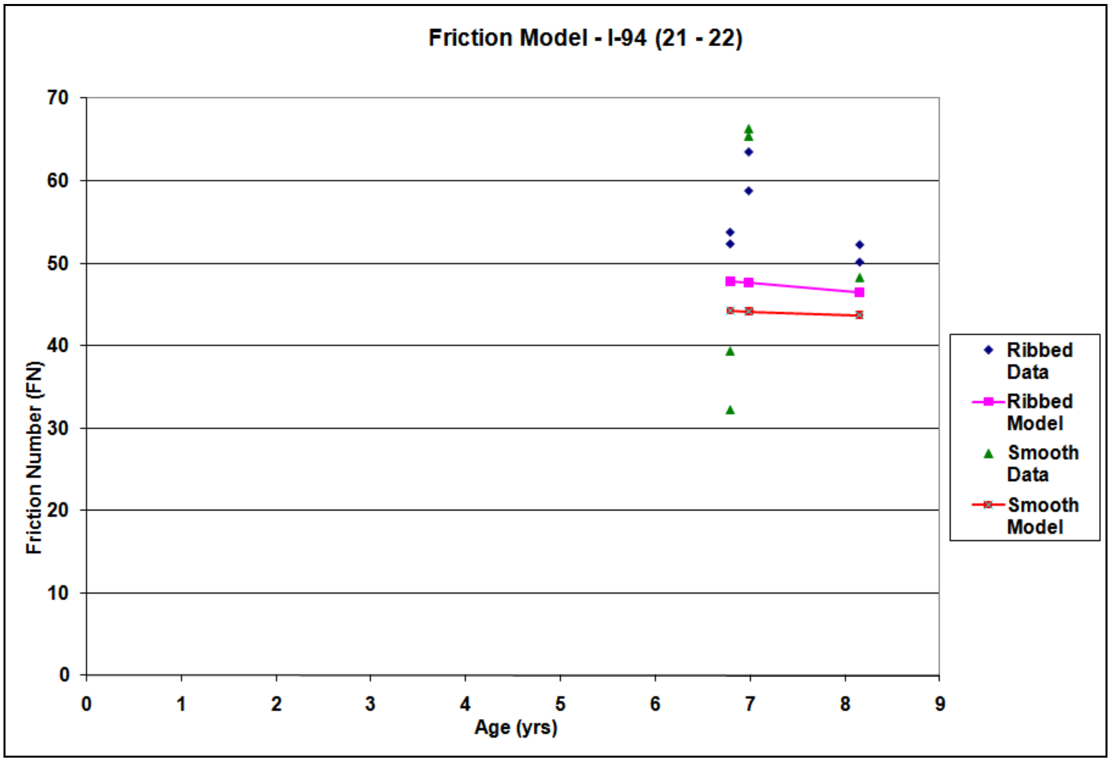

Figure B.9: I-94 (21 - 22) Chart

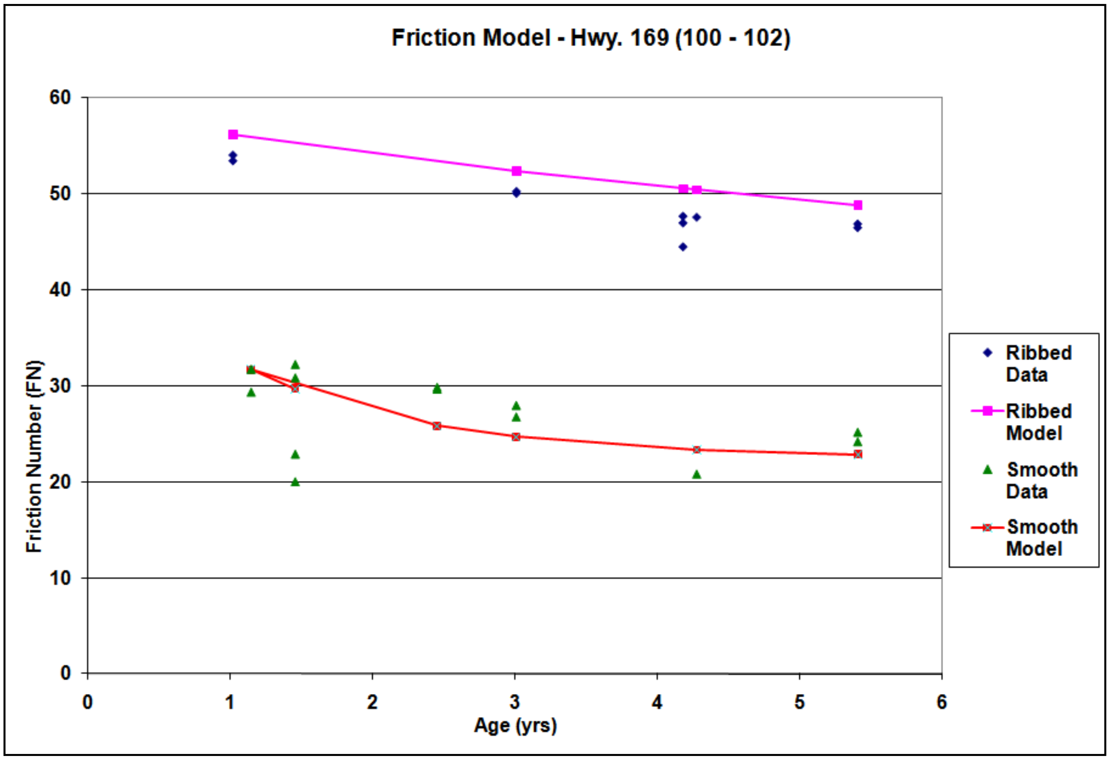

Figure B.10: Highway 169 (100 - 102) Chart

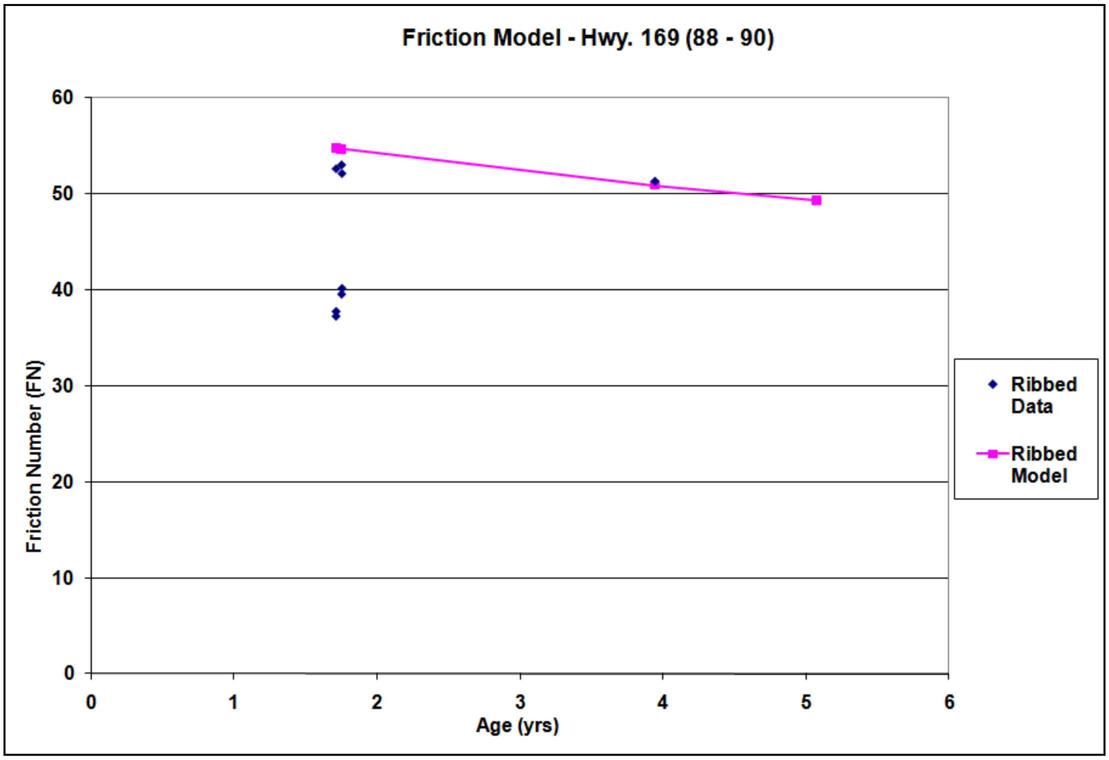

Figure B.11: Highway 169 (88 - 90) Chart

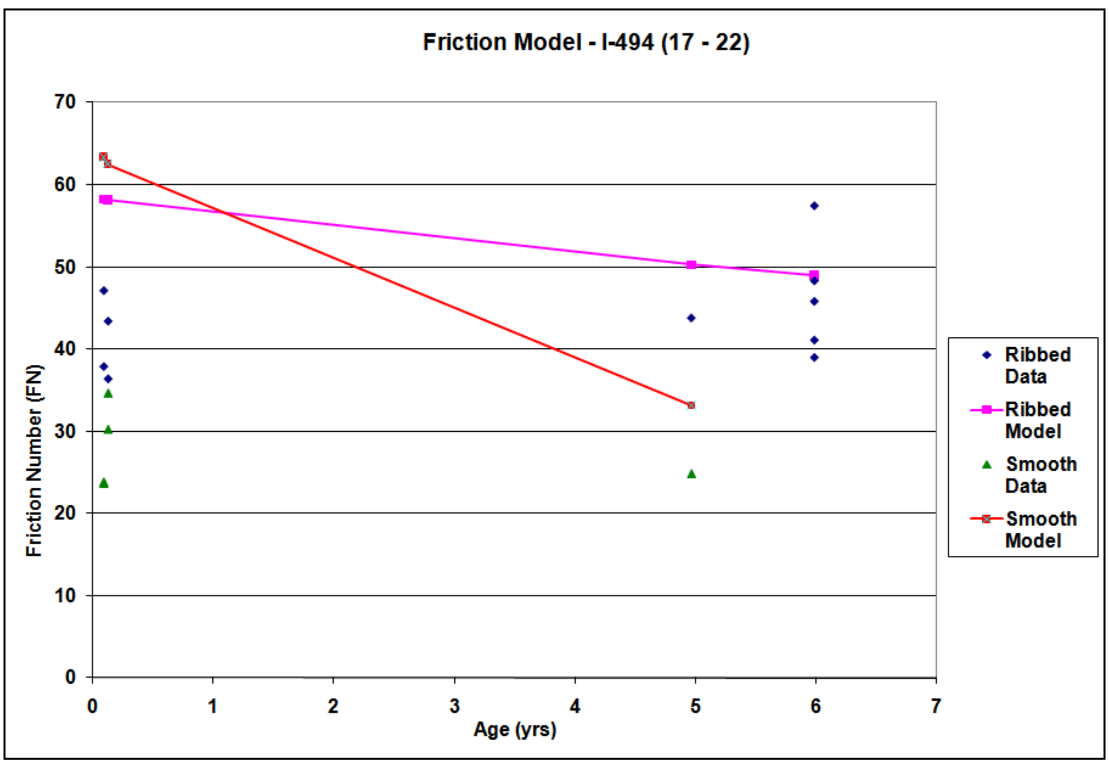

Figure B.12: I-494 (17 - 22) Chart

Appendix C - Procedure and Explanation of Chi-Squared Analysis

The object of this test was to either reject or fail to reject the null hypothesis. The null hypothesis was the statement that was trying to be proven. If the null hypothesis got rejected then the alternative hypothesis takes precedent. These two statements are explained below in table C.1.

Table C.1: Hypotheses for Chi-Squared Analysis

Chi-Squared Analysis - Hypotheses	
Null Hypothesis	The pavement friction data and the model were the same
Alternative Hypothesis	The friction data and the model were significantly different

The subsequent steps were to tabulate the average friction data, age and model friction values. Then the Chi-Squared number could be calculated by following equation 4.4. For this example, test section 2 was used and is represented below in Table C.2.

Table C.2: Chi-Squared Example Using Test Section 2

Date	Tire	Average Friction	Age	Model Friction	Chi-Square Number
10/25/1999	Ribbed	46.0	0.15	58.10	2.52
6/6/2000	Ribbed	52.1	0.76	56.80	0.39
7/23/2001	Ribbed	43.2	1.89	54.62	2.39
6/5/2003	Ribbed	51.3	3.76	51.55	0.00
8/5/2004	Ribbed	47.9	4.93	49.92	0.08
9/9/2004	Ribbed	37.9	5.03	49.80	2.84
9/9/2004	Ribbed	39.7	5.03	49.80	2.05
4/21/2005	Ribbed	50.7	5.64	49.03	0.06
10/25/1999	Smooth	25.3	0.15	31.17	1.11
6/6/2000	Smooth	25.7	0.76	31.38	1.03
11/14/2001	Smooth	18.1	2.21	31.83	5.92
11/14/2001	Smooth	28.6	2.21	31.83	0.33
7/24/2001	Smooth	27.8	1.90	31.74	0.49
11/13/2002	Smooth	33.0	3.20	32.13	0.02
6/4/2003	Smooth	29.4	3.76	32.28	0.26
9/9/2004	Smooth	20.8	5.03	32.61	4.28

Next, the sum of the Chi-Squared numbers was summed for each the ribbed and smooth tires and counted. Then the degrees-of-freedom number was calculated using equation 4.5. The information for test section 2 is given in table C.3.

Table C.3: Continuation of Chi-Squared Example of Test Section 2

	Sum of Chi-Squared Numbers	Count	d.o.f
Ribbed	10.33	8	7
Smooth	13.43	8	7

Those were the important numbers for the Chi-Squared Analysis because they represented the information that was needed to find the tabulated number in the master table of critical values and the sum is the number used for comparison. Table C.4 lists all of the sums for the Chi-Squared number along with the corresponding degrees-of-freedom number.

Table C.4: Sum of Chi-Squared Numbers and d.o.f. for all Test Sections

#	Route	Ribbed		Smooth	
		Sum of Chi	**d.o.f.**	**Sum of Chi**	**d.o.f.**
1	Hwy. 13	32.22	24	4.79	12
2	Hwy. 21	10.33	7	13.43	7
3	I-35	5.02	4	1.91	4
4	I-35W	1.37	8	105.18	11
5	I-90 (155)	15.50	12	184.21	9
6	I-90 (222)	22.99	21	54.93	15
7	I-90 (271)	7.04	10	8.45	3
8	I-94 (115)	1.95	11	22.80	17
9	I-94 (21)	10.13	5	25.56	4
10	Hwy. 169 (100)	1.89	9	7.62	12
11	Hwy. 169 (88)	19.10	8	N/A	N/A
12	I-494	26.96	9	80.98	4

The final step was to use equation 4.6 to determine if the null hypothesis was rejected or not. In equation 4.6, the summation was already found for each of the test sections and that left the critical values to be found for this test. To find the critical values, two things needed to be known: the known percentile for the test (1- α) and the d.o.f. (t). Table C.5 uses those two things to find all of the critical values needed for the test sections.

Table C.5: Critical Values for Chi-Squared Analysis

d.o.f.	Critical Values for Given Percentile				
	99%	**97.5%**	**95%**	**90%**	**80%**
3	11.34	9.35	7.81	6.25	4.64
4	13.28	11.14	9.49	7.78	5.99
5	15.09	12.83	11.07	9.24	7.29
7	18.48	16.01	14.07	12.02	9.80
8	20.09	17.53	15.51	13.36	11.03
9	21.67	19.02	16.92	14.68	12.24
10	23.21	20.48	18.31	15.99	13.44
11	24.73	21.92	19.68	17.28	14.63
12	26.22	23.34	21.03	18.55	15.81
15	30.58	27.49	25.00	22.31	19.31
17	33.41	30.19	27.59	24.77	21.61
21	38.93	35.48	32.67	29.62	26.17
24	42.98	39.36	36.41	33.20	29.55

Source: [8]

Finally, equation 4.6 could be used to determine the results of the Chi-Squared Analysis. If the critical value was lower than the summation, then the null hypothesis was said to be rejected and vice versa. Table C.6 displays the results for the ribbed tire and table C.7 has the results for the smooth tire.

Table C.6: Chi-Squared Results for Ribbed Tire

Sect #	Chi-Squared Results – Ribbed Tire				
	99%	**97.5%**	**95%**	**90%**	**80%**
1	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Reject
2	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Reject
3	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
4	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
5	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
6	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
7	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
8	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
9	Fail to Reject	Fail to Reject	Fail to Reject	Reject	Reject
10	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
11	Fail to Reject	Reject	Reject	Reject	Reject
12	Reject	Reject	Reject	Reject	Reject

Table C.7: Chi-Squared Results for Smooth Tire

Sect #	Chi-Squared Results - Smooth Tire				
	99%	**97.5%**	**95%**	**90%**	**80%**
1	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
2	Fail to Reject	Fail to Reject	Fail to Reject	Reject	Reject
3	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
4	Reject	Reject	Reject	Reject	Reject
5	Reject	Reject	Reject	Reject	Reject
6	Reject	Reject	Reject	Reject	Reject
7	Fail to Reject	Fail to Reject	Reject	Reject	Reject
8	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Reject
9	Reject	Reject	Reject	Reject	Reject
10	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
11	N/A	N/A	N/A	N/A	N/A
12	Reject	Reject	Reject	Reject	Reject

Appendix D - Procedure and Explanation for Mann-Whitney Z Test

The object of this test was to either reject or fail to reject the null hypothesis. The null hypothesis was the statement that was trying to be proven. If the null hypothesis got rejected then the alternative hypothesis takes precedent. These two statements are explained below in table D.1.

Table D.1: Hypotheses for Mann-Whitney Z Test

Mann-Whitney Z Test - Hypotheses	
Null Hypothesis	The pavement friction data and the model were the same
Alternative Hypothesis	The friction data and the model were significantly different

The first step in this test was to look at the data collected, the age at the time of when the measurement was taken and the model friction. For this example, test section 2 was looked at and is shown in Table D.2.

Table D.2: Mann-Whitney Example for Test Section 2

Date	**Tire**	**Average Friction**	**Age**	**Model Friction**
10/25/1999	Ribbed	46.0	0.15	58.10
6/6/2000	Ribbed	52.1	0.76	56.80
7/23/2001	Ribbed	43.2	1.89	54.62
6/5/2003	Ribbed	51.3	3.76	51.55
8/5/2004	Ribbed	47.9	4.93	49.92
9/9/2004	Ribbed	37.9	5.03	49.80
9/9/2004	Ribbed	39.7	5.03	49.80
4/21/2005	Ribbed	50.7	5.64	49.03
10/25/1999	Smooth	25.3	0.15	31.17
6/6/2000	Smooth	25.7	0.76	31.38
11/14/2001	Smooth	18.1	2.21	31.83
11/14/2001	Smooth	28.6	2.21	31.83
7/24/2001	Smooth	27.8	1.90	31.74
11/13/2002	Smooth	33.0	3.20	32.13
6/4/2003	Smooth	29.4	3.76	32.28
9/9/2004	Smooth	20.8	5.03	32.61

Next, the pavement friction values and the model friction values got sorted from highest to lowest. Then each number got a ranking and the values got resorted back into their original locations. For the rankings, one represented the highest value. Table D.3 shows how the numbers got ranked for test section 2.

Table D.3: Rankings of Friction Values for Test Section 2

Test Number	**Ribbed**		**Smooth**	
	Value	**Ranking**	**Value**	**Ranking**
1	46.0	13	25.3	1
2	52.1	4	25.7	14
3	43.2	14	18.1	13
4	51.3	6	28.6	16
5	47.9	12	27.8	11
6	37.9	16	33.0	12
7	39.7	15	29.4	10
8	50.7	7	20.8	15
9	57.43	1	25.88	9
10	57.01	2	25.56	8
11	56.18	3	24.78	5
12	54.66	5	24.78	5
13	63.61	8	24.96	7
14	53.52	9	24.22	4
15	53.52	9	23.89	3
16	52.93	11	23.12	2

From here through the end of the test, the rankings were the only numbers that mattered. The summation and the count for the ribbed and smooth tire (n and m, respectively) of the data and the model were then conducted. Then using equations 4.7, 4.8, 4.9 and 4.10, the rest of the variables were calculated. These calculations were completed below (table D.4) for test section 2.

Table D.4: Variable Calculations for Test Section 2

Mann-Whitney Z Test Calculations – Test Section 2: Ribbed Tire							
Sum of Data	**Sum of Model**	**n**	**m**	**u**	**μ_v**	**σ**	**z**
87	48	8	8	13	32	11.66	-1.63

The z-value was the number that was compared to the tabulated numbers. The only information needed to get the tabulated number (z_0) was the percentile in which the z-value was being compared to. Table D.5 gives the z-values for the different test sections and Table D.6 gives the tabulated numbers for the different percentiles being tested.

Table D.5: Z-Values for all Test Sections

#	**Route**	**Ribbed Z-Value**	**Smooth Z-Value**
1	Hwy. 13	-4.55	3.34
2	Hwy. 21	-1.63	-2.06
3	I-35	-1.69	0.61
4	I-35W	-0.27	-4.16
5	I-90 (155)	-1.36	-3.45
6	I-90 (222)	-2.42	-4.26
7	I-90 (271)	-1.16	-0.83
8	I-94 (115)	1.10	-0.27
9	I-94 (21)	2.04	0.34
10	Hwy. 169 (100)	-2.07	0.08
11	Hwy. 169 (88)	-2.49	N/A
12	I-494	-3.04	-1.55

Table D.6: Tabulated Numbers for Mann-Whitney Z Test

Percentile Numbers (Z_0) from Master Table					
Percentile	**99%**	**95%**	**90%**	**80%**	**75%**
Z_0	2.33	1.64	1.28	0.84	0.68

Source: [8]

Finally, the tabulated numbers and the z-values were then compared in order to find the results for the Mann-Whitney Z Test. If the z-value was higher than the tabulated number then the null hypothesis was said to be rejected and vice versa. Tables D.7 and D.8 shows the results for the ribbed and smooth tire, respectively within various confidence intervals.

Table D.7: Mann-Whitney Z Test Results for Ribbed Tire

Sect. #	Mann-Whitney Z Test Results – Ribbed Tire				
	99%	**95%**	**90%**	**80%**	**75%**
1	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
2	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
3	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
4	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
5	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
6	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
7	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
8	Fail to Reject	Fail to Reject	Fail to Reject	Reject	Reject
9	Fail to Reject	Reject	Reject	Reject	Reject
10	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
11	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
12	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject

Table D.8: Mann-Whitney Z Test Results for Smooth Tire

Sect. #	Mann-Whitney Z Test Results – Smooth Tire				
	99%	**95%**	**90%**	**80%**	**75%**
1	Reject	Reject	Reject	Reject	Reject
2	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
3	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
4	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
5	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
6	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
7	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
8	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
9	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
10	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject
11	N/A	N/A	N/A	N/A	N/A
12	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject	Fail to Reject