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Sensitivity of Distress Rate to Observed Distress Levels

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Sensitivity of Distress Rate to Observed Distress Levels

By

David R. Barboza

A.S., Pre-Engineering, Central New Mexico Community College, 2005

B.S., Civil Engineering, University of New Mexico, 2010

Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Civil Engineering

The University of New Mexico

Albuquerque, New Mexico

December 2015

I dedicate this work to my wife Karin. Without her support I never would have attended college and successfully earned both my bachelor and master's degree. She was there for everything both the good and the bad. Thank you Karin and I love you very much.

Acknowledgements

I would like to take this opportunity to thank my academic advisor Dr. Susan Bogus Halter for the constant support and willingness to take me on as a master's graduate student. This cannot be overstated when it is understood that I had just started my pursuit of my master's degree without securing any sort of advisor or research. She was able to provide support to someone who obviously had no clue as to what he was getting himself into. Thank you very much Susan.

I am also going thank Dr. Vanessa Valentin who provided an immense amount of help with the Monte Carlo modeling and the @ Risk modeling software. The help I received with the software and the early problems with determining how to set up and carry out my research was invaluable. Thank you Vanessa for helping me get to a point where I could understand what to do.

During the whole process Dr. Guohui Zhang was always there to listen to the various problems and provide not only answers but encouragement when I really needed some. The power of being told that it is not as bad as you think and go get it done cannot be overestimated. Thank you Guohui very much for providing the moral support when I needed it, I consider you my friend.

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Abstract.

The New Mexico Department of Transportation (NMDOT) uses a composite pavement condition index to identify and rank roads for budgeting and scheduling repairs. NMDOT uses an index number called the Pavement Serviceability Index or PSI. A key component of this index number is the Distress Rate (DR) which is comprised of pavement distress severities and extents with a weighting factor assigned for each distress. Until 2013, NMDOT conducted pavement evaluations manually and in 2012 revised how pavement distress data were collected and evaluated. The two pavement distress collection procedures that were altered the most were for transverse cracking and alligator cracking. This research evaluates how sensitive the DR is to the revised data collection procedures. The comparison used a single milepost test section and one evaluator as ground truth data and then varied input values for a single item while holding all of the others constant to see what sort of influence the data had on the DR. The results confirmed that the DR has limited sensitivity due to the data ranges used for input to the composite DR index.

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Chapter 1. Introduction

1.1 Overview

In 2012 the New Mexico Department of Transportation (NMDOT) changed the way it conducts pavement distress evaluations. In an effort to bring the evaluation process in line with reporting requirements dictated by the Federal Highway Administration (FWHA) and the Highway Performance Monitoring System (HPMS), several changes were made to the data collection protocol for pavement surface distresses.

The previous NMDOT rating system rated the severity and extent of each distress from zero to three with zero being not present and three being a high severity or high extent. With the previous rating system only the highest severity present was reported. The new protocol records all of the severities present to get a more complete view of the condition of the pavement (Bandini, P., et.al, 2012). For distresses like alligator cracking and transverse cracking, the data collection protocol was revised to allow estimates of total crack length.

My objective is to look at the evaluation protocols that changed the most; and see what impact the new data collection procedures have on the overall distress rate (DR).

1.2 Background

Pavement evaluation surveys provide important data for a state's pavement management system (PMS) (McQueen, J. and Timm, D., 2005; Prakash, A. et al., 1994; Bianchini, A. et. al., 2010; Flintsch, G. & McGhee, K., 2009). These surveys can then be used to create a composite value to rate a road for possible maintenance (McQueen, J.

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and Timm, D., 2005; Bianchini, A. et al., 2010). Road network managers need a tool to identify and prioritize which roads in their network need attention and what the treatment should be, since our road system represents a significant investment.

A PMS program typically has two parts to it, a network level and a project level, both of which often use a composite number that represents the overall pavement condition to be used in various decision making activities(Cordova Alvidrez, A., 2007; Zimmerman, K. and Knox, R., 1998; Prakash, A. et al., 1994). The network level uses pavement condition for budgeting, planning and programing decisions while the project level uses the same information to determine repairs (Cordova Alvidrez, A., 2007; Flintsch, G. & McGhee, K., 2009).The condition of the pavement section will determine if crack sealing versus complete rehabilitation or anything in between is necessary to return the pavement back to serviceable condition.

Unfortunately manual pavement evaluation is a very subjective process and is prone to variability between different raters or even with the same rater over time (Prakashet, A., et al., 1994). There have been several studies that have looked at the variability of the ratings and used statistics to help explain and identify the effects of evaluator variability (Cordova Alvidrez, A., 2007; Bianchini, A., et al., 2010; McQueen, J. and Timm, D., 2005).They also used statistics in various ways to determine which is more accurate, automated or manual pavement condition surveys (McQueen, J. and Timm, D., 2005). Another study's goal was to look at inter-rater agreement (Cordova Alvidrez, A, 2007; Bianchini, A., et al., 2010).

The FWHA created a program and a manual to help standardize identifying pavement distresses called the Long-Term Pavement Performance program (LTPP) and

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Distress Identification Manual (DIM). Most of the states and local governments use the DIM or a modified version of it (Bianchini, A., et al., 2010). What makes the DIM such a valuable tool for the various state and local agencies are the photos and pavement distress descriptions for the entire pavement distresses commonly encountered. This allows individuals from different agencies to discuss problems and projects with a common reference. It reduces miscommunication by setting a standard for pavement distress identification. Key pavement distresses are further described in the following paragraphs.

Raveling and weathering (Figure 1) is the loss of aggregate from the pavement surface causing accelerating pavement wear. This is caused by aging and oxidation also referred to as weathering (NMDOT, 2007). Raveling and weathering can be repaired in various ways from a fog seal, slurry seal, and thin hot mix overlay to prevent further raveling if the damage is limited to the surface layers (NMDOT, 2007).

Figure 1. Raveling and weathering of flexible pavement

Bleeding (Figure 2) is the result of excess binder on the pavement surface; it often appears as a shiny surface. Excessive bleeding can lead to loss of traction during wet weather and /or foggy weather. It is often sticky to the touch, especially during warm weather and is typically found in the vehicle wheel paths. Several things can cause bleeding to take place such as excessive prime or tack coat during construction, a poor mix design or too much oil used during chip seal operations (NMDOT, 2007).

Figure 2. Pavement asphalt bleeding

Fatigue cracking (Figure 3) from repeated loads on asphalt often will develop interconnecting cracks over time which resembles the skin of an alligator, thus the name

alligator cracking is used to identify fatigue cracking. It is a result of repeated loadings from higher than normal traffic loadings, insufficient structural design, insufficient foundation support, excessive pavement flex or aged and brittle pavement (NMDOT, 2007). If alligator cracking is left unchecked it will develop cells that can eventually pop out creating a pothole, and even worse, a path for water to cause more damage to the foundation layers.

There are several ways to repair alligator cracking depending on the severity of the distress. It may consist of removing a small section and replacing the poor subgrade followed with patching the area. For very small cracks a sealing process can be used but the underlying problem of poor support remains and cracking may continue (NMDOT, 2007)

Figure 3. Pavement alligator cracking

Transverse cracking (Figure 4) is characterized as cracks that normally run perpendicular to the centerline of the roadway. It is caused by both temperature changes and shrinkage of pavement binder due to aging (NMDOT, 2007).

Figure 4. Transverse pavement cracking

Edge cracks (Figure 5) are only for roads with unpaved shoulders; the cracks must also be within two feet of the pavement edge. They can be crescent shaped cracks or long continuous cracks parallel to the pavement edge. The cause is normally the loss of foundation support by several means. Essentially the asphalt does not have a strong enough support and the pavement cracks (NMDOT, 2007).

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Figure 5. Edge cracking of flexible pavement

Patching (Figure 6) consists of removing and replacing a part of the existing pavement to repair the original pavement because of distress. According to the NMDOT Pavement Maintenance Manual a patch is considered a pavement defect regardless of how well the repair work is done (NMDOT, 2007).

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Figure 6. Pavement patching

Cracks that run parallel to the centerline are considered longitudinal cracks (Figure 7) and can appear both inside and outside the wheel paths. For this research I have defined longitudinal cracks within the wheel path to be alligator cracks with a severity rating of a one and not longitudinal cracks. This means that the definition of a longitudinal crack is a crack that runs primarily parallel and adjacent with the centerline of the road and is not in the wheel path. The cause of most longitudinal cracks is a poor asphalt seam joint during construction. The ones located in a wheel path are caused by loading and that is why they are considered alligator cracks since the cause of both cracks are the same. Repairs are to seal the crack until a mill and overlay can be accomplished.

Figure 7. Longitudinal cracking

While the different type of cracks have different causes they pose the issues from a pavement maintenance standpoint. While alligator cracking can lead to potholes if the corrective measures are not taken the other types of cracks if ignored can lead to pavement failure. The enemy for all cracks is water. Edge cracks will often lose support as water erodes the soil under the shoulder pavement. The edge of pavement loses its support pavement cracks off reducing the shoulder and eventually the lane width in extreme cases. Water in longitudinal cracks, transverse cracks and alligator cracking

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compromise the base under the pavement creating greater pavement problems as fines in the base course are washed out. When located in regions that frequently have freezing temperatures the water will freeze and expand. This causes the cracks to widen and reduces pavement's smoothness and ability to withstand heavy loads.

Most repairs revolve around sealing the cracks depending on the severity or milling and placing a new hot mix overlay (NMDOT, 2007). Normally the crack is widened using a router like tool to create a uniform width and the crack seal is poured/injected into the crack sealing it from water.

This is where the data in the form of the Pavement Serviceability Index (P.S.I.) number is used by pavement preservation managers and the District engineers for the NMDOT to help determine what roads receive what type of pavement preservation treatment. That can range anywhere from crack sealing to complete pavement reconstruction. Maintenance is typically handled with price agreements but the larger pavement rehabilitations and reconstructions must be budgeted for and typically placed in a State Transportation Improvement Plan (STIP). This is essential for participation from the FHWA. This explains why evaluating the current pavement is so important for pavement preservation.

1.3 Research Objectives

The objective of this research is to investigate the revised pavement evaluation inspection and reporting protocols enacted by NMDOT using data collected during the 2012 evaluation season. More specifically, this research investigates the two most changed evaluation and reporting pavement distress protocols. These are alligator

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cracking and transverse cracking, with both of them being reported as an amount of area or as a number of cracks. In the revised protocol all severities are reported by the field crews but only the most prevalent of the severities are used by NMDOT in the calculation of the distress rate (NMDOT, 2010). The revised protocol for alligator cracking and transverse cracking differed from protocols for the other distresses in the way the information is collected. With most of the other pavement distresses the evaluator records what they believe the severity to be as well as the extent of the pavement distress based on the written descriptions. For alligator cracking and transverse cracking, the evaluator is estimating the area of cracking or number of cracks. The first research objective was to see if there was a change in sensitivity with the revised evaluation protocols using a simple sensitivity method.

The second research objective uses more sophisticated techniques to do a sensitivity analysis using all of the pavement distresses evaluated as part of the 2012 evaluations for NMDOT. I look at how they affect the distress rate which is a component of the overall pavement condition number called the Pavement Serviceability Index (P.S.I.). A Monte Carlo sensitivity analysis was performed using software called @Risk which is produced by Palisade Corporation. The goal was to use distributions to create a thorough sensitivity analysis and get a better idea of how the new evaluation procedures work and if they are sensitive enough to truly represent what is happening with the pavement around the state of New Mexico.

1.4 Organization of Thesis

This thesis is organized such that each research objective is presented in its own chapter, including related background, the methodology and results. Chapter 2 presents the single variable sensitivity analysis, and Chapter 3 presents the multivariable sensitivity analysis. Chapter 4 presents overall conclusions for the entire research.

Chapter 2. Single Variable Sensitivity Analysis

2.1 Introduction

The objective with the simple sensitivity analysis was to see if the revised protocol for the two pavement distresses had an impact on the sensitivity of the distress rate calculation. If there appeared to be an impact then further investigation using a more sophisticated tool would follow.

Alligator cracking is one of the distresses that is now evaluated in a much different way. The new method retained the severity ratings but instead of evaluating the severity of alligator cracking on a 0-3 scale, the evaluator now collects the data on the length of the alligator cracking to be used in calculating the percent area for the section evaluated. The percent area of the alligator cracking is used for HPMS and then converted to a 0-3 scale for use in the NMDOT pavement management system (Bandini, P., et al., 2012).

Transverse cracking is the other distress that is evaluated much differently. The number of transverse cracks for each severity is counted and that value is used to calculate the total length of cracking for HPMS and then converted to a 0-3 scale for use by NMDOT. NMDOT uses the severity and extent data for individual distresses to calculate an overall DR for a pavement section.

The objective is to explore the sensitivity, if any, between the distress rate and the inputs for alligator cracking and transverse cracking under the new protocol. Both of these pavement distresses have been altered the greatest from the previous evaluation procedure making them the most interesting to look at.

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2.2 Background

A common approach to examine variability between evaluators has been statistical analysis. One group looked at the Mean, Standard Deviation (SD) and Coefficient of Variation (CV) of evaluators (Rada, G., et al, 1997). One group used a Monte Carlo analysis and regression analysis (McQueen, J. and Timm, D., 2005)

Another statistical approach is to use the chi-square distribution to test multinomial hypothesis (Bianchini, A., et al., 2010). Yet another statistical analysis method was used by Cordova to calculate the Average Deviation about the Mean or the Median (Cordova Alvidrez, A., 2007) to determine inter-rater reliability.

Up until 2013 the NMDOT used a single composite number called the Pavement Serviceability Index (PSI). This composite index number is a calculation that is supposed to provide a way to compare pavement condition among different roads. is that when the weighting factors are included to create a single number to describe the condition of the pavement, individual rater agreement improves (Rada, G., et al.,1997). For example the NMDOT weighs alligator cracking the most with a weighting factor of 25 compared to bleeding which is weighted only at 2 when calculating the distress rate, which is part of the PSI equation. That large of a numerical difference between the weighting factors tends to mask inter-rate variability on many of the pavement distresses.

There is a way to determine how the various inputs to the PSI equation affect it. Primarily this is done through a sensitivity analysis. Sensitivity analysis generally answers the question about what is an important input or factor in making a decision;

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basically what is important and what is not (Clemen, R., 1996). Clemen uses a small airline company as an example to determine if purchasing another airplane is the correct choice to expand a company. A one-way type of sensitivity analysis was used to determine if the airplane purchase was a better choice than waiting and investing the capital (Clemen, R., 1996). The example looked at the number of hours the new airplane would have to fly to provide more profit than simply investing the money (Clemen, R., 1996). The other point the author emphasized was to ask the correct question. A Type III error exists where you can get an answer that is not useful because the correct question was not asked (Clemen, R., 1996).

If you did a sensitivity analysis on how to increase motorcycle helmet usage you may come up with the answer that a helmet law is needed. The fundamental question might be, do you want to increase helmet usage to reduce head-related motorcycle deaths or do you want to reduce all motorcycle fatalities? To go back to the author's airline expansion example the question really is, does the owner want to buy an additional airplane or does he want to expand his company and profit (Clemen, R., 1996)? Sensitivity Analysis might reveal that by increasing passenger fares or increase flying time will provide the profit and expansion the owner wants.

Relating this to pavement evaluations, we pose the following question regarding the PSI equation and one of its inputs, the DR, which affects the PSI equation. Which pavement distress causes the greatest change in the DR?

The data I used for both the simple sensitivity analysis and the more complicated Monte Carlo method used later were the same. The data were collected by the 12 participants who evaluated a tenth mile long section of roadway set aside for quality

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assurance/quality control purposes. There were originally 24 milepost locations but because of road maintenance performed by the NMDOT four of the mileposts data were unusable.

The data sample size was each of the 12 raters visiting all 20 mile posts and evaluating the pavement there in the same manner they did in the field. That gave me a total sample size of 12 evaluators multiplied by 20 locations which equals 240 data points. This is the number of returned milepost data for a single round of data collection. At each of these locations all of the 7 pavement distresses evaluated would return a severity and sometimes an extent value. Take 240 multiplied by 7 which equals1680 total data points. This was done for two QA/QC rounds which gives approximately 3360 individual data points and all of that data were included in the sensitivity analysis.

For the simple simulation I picked a single evaluator out of the 12 individuals and a single milepost out of the 20 mileposts evaluated as the input data. That is only the severity and extent data for the seven different pavement distresses. For the Monte Carlo simulation I included all of the data reported back by the 12 evaluators for all mileposts.

The data consisted of the various pavement conditions, both the severities (0-3) and extents (0-3) as dictated by the new inspection protocols and the unchanged inspection protocols. The pavement distresses other than alligator cracking and transverse cracking had its severity and extent data used directly in the model to determine the DR. The raw data such as number of transverse cracks or the area of alligator cracking were converted into an extent for modeling purposes to be used for the distress rate calculations.

2.3 Methodology

The NMDOT altered their manual pavement distress data collection program in 2012. These data are used by NMDOT to calculate a composite DR, and subsequently, the PSI. The question asked here is how sensitive is the DR to the new collection procedure. I decided to look at the two pavement distresses that changed the most in the collection procedure alligator cracks and transverse cracks. These two distresses changed the most because of the need to provide data for HPMS.

Alligator cracking is now reported as a percent area value that is calculated based on the number of wheel paths, the number of paces and the evaluator's pace length (NMDOT, 2012). The new protocol for collecting transverse crack data is to count the number of cracks that are greater than half of the lane width, typically cracks six feet or longer (NMDOT, 2012).

Area of Alligator Cracking= (Pace Length) x (Number of Paces) x (One or Two Wheel Paths) x (Wheel Path Width) (Bandini, P., et al., 2012)

The wheel path width is assumed to be 2 feet wide, so the equation changes to:

Area of Alligator Cracking = (Pace Length) x (Number of Paces) x (One or Two Wheel Paths) x (2 feet)(Bandini, P., et al., 2012).

As part of this procedure it is necessary for the evaluators to pace over a known distance to determine their pace length since it is required to calculate the area of alligator cracking.

Transverse cracking is now determined by its length and width. The width of a transverse crack determines which of the possible four severities, 0-3. The length of the

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crack determines whether it is counted. A crack must cross a minimum of half the lane width. Typically the length require to be counted is 6 feet. All severities are included in the new evaluation procedure instead of only the highest severity. The evaluator identifies which cracks are 50% or greater of the lane width to determine if they are to be included and the severity of each included crack.

To keep the sensitivity analysis simple I decided to use a single evaluator's data for a single milepost section. This represents the baseline for this analysis. The evaluation section used by the NMDOT for pavement evaluation is one tenth of a mile or approximately 530 feet. The actual test site used for this sensitivity analysis is located on U.S. 0550 at milepost 3 in northern New Mexico.

To determine how sensitive the DR is to the new method of data collection we used:

$$DR = \Sigma \text{ Severity x Extent x Weighting Factor} \quad \text{(NMDOT)}$$

The DR is the summation of the product of each pavement distress severity, extent and weighting factor. For this analysis I only changed the extents of each severity.

I used Microsoft's Excel spreadsheet program to set up a table that would allow me to easily alter the inputs and provide a graphic representation of our results. I first wanted to know what the total range of possible values was so we created columns for the upper bound and lower bound in addition to the baseline data. I included all of the pavement distresses that NMDOT evaluates, but only did a sensitivity analysis for alligator and transverse cracking data. It is unknown at this point whether the other distresses create a buffering effect on the sensitivity of the DR equation.

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For alligator cracking I needed to calculate the HPMS percent area for the reason of determining the extent for each of the possible severities. The percent area calculation was rounded off to the nearest 5 percent as required for HPMS. This value is used to determine the extent for each severity. The ranges for Extent are:

Extent 0: X=0%

Extent 1: $5 < X < 10\%$

Extent 2: $15\% < X < 20\%$

Extent 3: $20\% < X$

Where X is the HPMS percent area of alligator cracking; another simpler way is to simply divide the total amount of possible area, 2112 square feet, into 30% sections (Montoya, K., 2013).

This works out to be:

Extent 1: 1-634 (sq. ft.)

Extent 2: 635-1267 (sq. ft.)

Extent 3: 1268-2112 (sq. ft.)

Transverse cracking is done slightly different from alligator cracking by calculating a total number of cracks for a given severity. Transverse cracking is much easier to work with than alligator cracking because I can divide the total number of possible cracks into four parts to identify the four extents for the DR calculation:

Extent 1: X=0

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Extent 1: $1 < X \le 17$

Extent 2: $18 < X < 34$

Extent 3: $35 < X$

Where X is the total number of cracks

As you can see transverse cracking is much simpler to deal with since there is no manipulation of the raw data to obtain an extent to use in the DR equation. For alligator cracking, the raw pace count data are used to calculate a percent area.

2.4 Results

I first used the existing data from an evaluator who went out to the sample site and actually observed and rated the pavement distresses present. This provided a baseline to compare against when I started to vary the number of transverse cracks for the sensitivity analysis. I also determined the lowest possible value and largest possible value based on perfect pavement or theoretical worse possible pavement. This provided a range of possible values that might be experienced. The theoretical number of transverse cracks comes from a NMDOT report that looked at improving the evaluation process. They determined an upper limit for transverse cracks to be 51 (Bandini, P., et al., 2012).
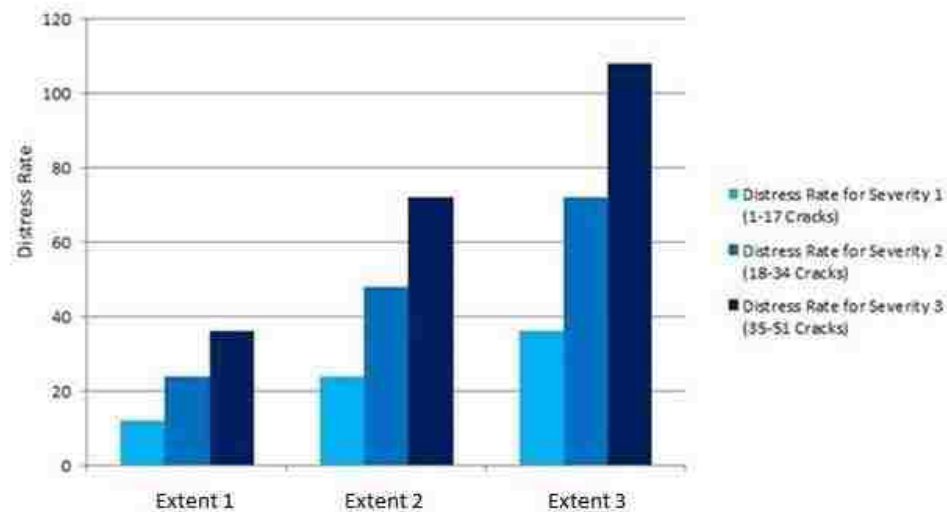
Figure 8. Comparison of transverse cracking extent and distress rate for a single milepost

It can be seen from Figure 8 that there is a range in which the number of transverse cracks can fall and not change the DR. This is because the number of cracks is converted to a 0-3 scale for use in calculating the DR. Each level of the 0-3 scale includes a range of number of cracks. This shows that an evaluator can be off by up to 17 cracks without it affecting the distress rate. This suggests that transverse cracks should not be very sensitive since there is a range of values that do no not affect the extent input into the distress rate equation.

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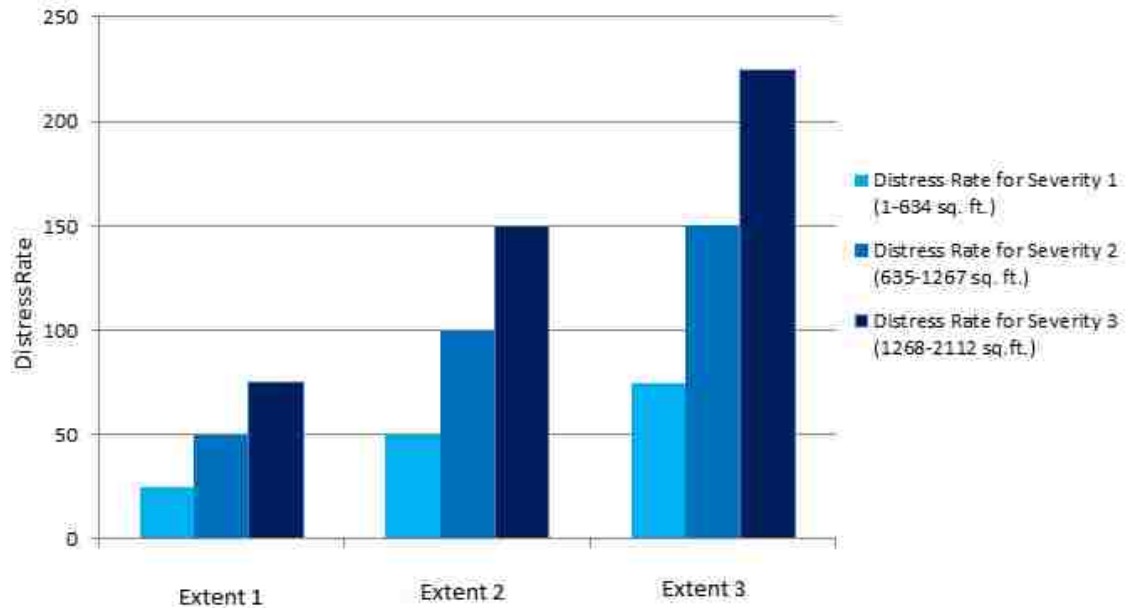
Figure 9. Comparison of alligator cracking extent and distress rate for a single milepost

Figure 9, much like figure 8, relate the distress rate to both extents and severities. There are distinct ranges for alligator cracking which allow an evaluator to be off prior to engaging the next extent to be used in the distress rate formula. This suggests that alligator cracking is not very sensitive.

Area = (Pace Length) x (Number of Paces) x (One or Two Wheel Paths) x (2 feet) (Bandini, P., et al., 2012).

Assuming a pace length of 2.5 feet and 2 wheel paths we can calculate how many steps an evaluator can take to measure out 200 sq. ft.:

200 sq. ft. = (2.5ft) x (Pace Number) x (2 wheel paths) x (2ft.)

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This calculation works out to 20 paces. Someone with a shorter or longer pace length will change the number of paces slightly but an individual can be off approximately 20 paces and that is only for an area of 200 sq. ft. When you consider the range to go from an extent 2 to an extent 3 is 686 sq. ft. an individual evaluating in the field can be off by over 60 paces before the next extent would be engaged. When you consider that alligator cracking is given the most weight, 25, in the PSI equation that could skew the PSI value in a way that may not adequately represent the pavement condition. It appears that the current method may not be sensitive enough but further research would certainly need to be done to determine how accurate the field data must be for decision makers.

2.5 Discussion

The analysis showed that the new data collection protocols do not have a large impact on the DR calculation. In fact it should be noted that the range of input values was quite large for alligator cracking before the DR showed any change. To go from an extent of zero to an extent 1 it takes additional just over 21 square feet; 633 square feet to go from extent 1 to extent 2 and 632 feet to go from extent 2 to extent 3. This would suggest that more severities with their extents should be added if more definition for alligator cracking is desired. More research is certainly required if additional sensitivity to alligator cracking is desired.

Transverse cracks seem to suffer the same problem as alligator cracking but to a lesser degree. The range to go from extent 0 to extent 1 is 17 cracks, from extent 1 to extent 2 is from 18 to 34 and anything over 34 cracks will convert to an extent 3. While

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there are still ranges, the numbers are not so great with the most number of cracks that could to be miscounted being 17 prior to another extent. That still seems a large number but considering how difficult it can be to determine if a transverse crack is of sufficient length from the shoulder of the road with traffic it does not seem unreasonable. With both alligator cracking and transverse cracking an evaluator can be off by a substantial count and it has no effect on the distress rate and the pavement serviceability index value. Like alligator cracking more study could be done to see just how sensitive the PSI equation is to variances in the input number of cracks.

Chapter 3. Multi-Variable Sensitivity Analysis

3.1 Introduction

The goal of this chapter is to answer the question of whether using a more sophisticated sensitivity analysis method provides additional value beyond the single variable analysis presented in chapter 2. A Monte Carlo analysis method uses the probability that a particular distress severity or extent is selected by the evaluator as an input instead of a discreet value.

3.2 Background

Composite numbers such as the Pavement Condition Index (PCI) or the Pavement Serviceability Index (PSI), used by the state of New Mexico, will use a weighting factor to stress the more critical pavement distresses when computing these composite pavement rating values. Interestingly when weighting factors are included, the individual rater agreement will improve (Rada, G., et. al, 1997). When looking at an equation like the PSI equation, it can be useful to determine which of the various inputs affect the output the greatest. Sensitive analysis can generally answer the question about which inputs are more influential on the output values(Clemen, R.,1996).

The PSI equation comprises several parts of which only the distress rate (DR) can be influenced by the pavements ratings. The International Roughness Index is also used but that is collected by the NMDOT directly using different methods.

DR= $\sum$ (severity) (extent) (weighting factor)

Interim Equation

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X=100-[[0.6(IRI-25) + (0.4) (DR)]/2.9]

This interim equation value is compared to a value of 60. If the interim equation value is less than or equal to 60 then:

PSI = (0.041666) (X)

If the value is greater than 60:

PSI = (0.062(X-60)) + 2.4999

In research I was unable to determine the reason the weighting factors are assigned as they are. It has not been documented by the NMDOT.

The International Roughness Index (IRI) is a measurement typically gathered with automated road profiling equipment that converts the raw data into the IRI with units of either inches per mile or meters per kilometer (Sayers, M. and Karamihas, M., 1998). For the purpose of this discussion the IRI is only used in the PSI equation and while it can vary from road section to road section, we keep it as a constant value of 151 in. /mi.. The value of 151 in./mi. equates to the roughness of new pavement (Sayers M. and Karamihas, M., 1998).

The IRI and the various pavement distresses are related. While the IRI is a measurement of peaks and valleys on the road surface the various cracks do add to the roughness of the road, at least from the viewpoint of the road user. Driving over transverse cracks which can often happen at regular intervals will certainly give the impression of a rough road surface. Alligator cracking with create the same sensation of a road that is rougher than the IRI number may convey. If alligator cracking is left untreated the fully formed cells eventually start to rock and pop out of the pavement

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leaving a pothole; possibly the worst offender to both a smooth pavement and a smooth ride while driving. Patching the pavement may have almost the same effect on pavement smoothness as a pothole. Most, if not all patches sit higher than the surrounding pavement creating a bump much like cracks.

Crack-related pavement distresses all have a negative impact on road smoothness and the distress rate. Unlike bleeding, for example, pavement cracks affect the structural integrity of the road. It allows flexing and if not maintained water can cause more damage, thus compromising the pavement's ability to support loads. This is why they are included in the distress rate equation with the highest weighting factors to increase their effect on both the DR number and eventually the P.S.I. number.

The P.S.I. equation is biased towards providing a smooth ride over the structural integrity of the pavement. A look at the interim equation; $X=100-[[0.6(IRI-25) + (0.4)(DR)]/2.9]$ shows a 60% emphasis on the IRI versus a 40% emphasis on pavement distresses that reflect the actual condition of the pavement itself.

For the purposes of my research I wanted to keep the IRI a fixed value to truly see how sensitive the new inspection protocols were to the distress rate. In IRI actually plays a large part in the overall P.S.I number used by project planners.

Conducting a more involved sensitivity analysis than simply changing a single variable requires a more complex tool such as the Monte Carlo Method. Unfortunately in a simple sensitivity analysis where you alter a single input you can miss more complex interactions between the inputs and the affects they have on the output. This is very true of a problem that involves humans inputting the data they observe. There are varied reasons why individuals can observe the same thing and interpret it differently. With

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pavement distresses this is especially true when approximating crack widths, the crack length or extent of a crack and the appropriate severities for that pavement crack or distress. There is a much randomness involved with a manual pavement evaluation process that a simple sensitivity analysis is unlikely to capture. Employing the Monte Carlo method allows one to evaluate a process with the use of random numbers and distributions.

Monte Carlo simulation, also called the Monte Carlo Method, is a mathematical technique that allows individuals to account for risk in quantitative analysis. It is very useful for obtaining numerical solutions which are too complicated to solve analytically (Weisstein, E., 2013) The Monte Carlo method "was first used by scientists working on the atom bomb; it was named for Monte Carlo, the Monaco resort town renowned for its casinos." (Weisstein, E., 2013) It can be used in decision making and allow the user to see which inputs have the greatest effect on the results (Weisstein, E., 2013).

Monte Carlo simulation uses a range of input values as a probability distribution. The simulation will then calculate the results using random values. This way it not only uses all of the possible values randomly but the ones most likely to appear bases on the probability distribution (Weisstein, E., 2013). Each calculation is called an iteration; a computer can run thousands of iterations in a fairly short time depending on the quantity of input data (Palisade Corporation, 2013). The output of the Monte Carlo simulation is a probability distribution of possible outcomes that indicates what can happen but also how likely it will happen (Weisstein, E., 2013).

The core of the Monte Carlo method is the random number generator. Monte Carlo simulation produces a graph commonly called a tornado graph that allows an

individual to easily see what inputs had the greatest effect on the output (Palisade Corporation, 2013). Unfortunately computers cannot truly generate random numbers; to do so they would have to have and infinite amount of numbers which they don't. Pseudorandom numbers are generally used in place of true random numbers but for them to be useful is they must be identically and independently distributed or i.i.d (Gentle, J., 2003). This simply means that the numbers are mutually independent from each other so the probability to select a number is the same every time. This is a key point to making the Monte Carlo process work.

3.3 Methodology

3.3.1 Original Model Development

I used slightly different approaches for the different pavement distresses; this is due to the revised data collection procedures. The pavement distresses can be classified into three broad categories based on how the data are collected and reported. Raveling and weather and bleeding can be classified in the same manner because the extent portion used to calculate the distress rate are fixed values and are not subjected to an evaluator's variability. That removes a source of variability for both of those pavement distresses. Alligator and transverse cracking use the most prevalent extent present and the associated severity of that extent in the distress rate equation. Longitudinal cracking, edge cracking and patching are treated the same since both the severity and extent are collected individually by the evaluator.

The extents of both bleeding and raveling and weathering are fixed values in the revised protocol; the result of that is the evaluator only collects the severity for those

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pavement distresses. Raveling and weathering is assumed to always have an extent of three. Bleeding is always assumed to have an extent of one. The advantage is that some of the variability with the distress number is reduced with using constants for the extents of bleeding and raveling and weathering.

The pavement distresses: longitudinal cracking severity, longitudinal cracking extent, edge cracking severity, edge cracking extent, patching severity and extent are all treated the same with both severity and extent treated individually. The pavement evaluator out in the field is evaluating both the severity and extent separately so we have the potential for variability for both in longitudinal cracking, edge cracking and patching distresses.

Alligator and transverse cracking are both analyzed using spreadsheets with similar formats. In both pavement distresses the most prevalent distress severity present is used to calculate the distress rate. The severity associated with the pavement distress that has greatest extent is used for the distress rate calculation. Using the severity with the greatest extent provides a better idea of the pavement condition. If the highest severity present has a very small extent it can alter the distress rate enough to provide a misleading condition of the pavement condition.

3.3.2 Model Development

To perform the Monte Carlo Method or Monte Carlo Simulations I used a risk analysis software tool, called @Risk produced by Palisade Corporation. It is marketed as a risk analysis tool and works with Microsoft's Excel software. @Risk will take the data inputted into an Excel spreadsheet and will run the Monte Carlo simulation. The output

from the simulation can be presented as a tornado graph (Figure 10) which allowed me to see the inputs that provided the greatest effect on the output by the length of the associated tornado graph output bar.
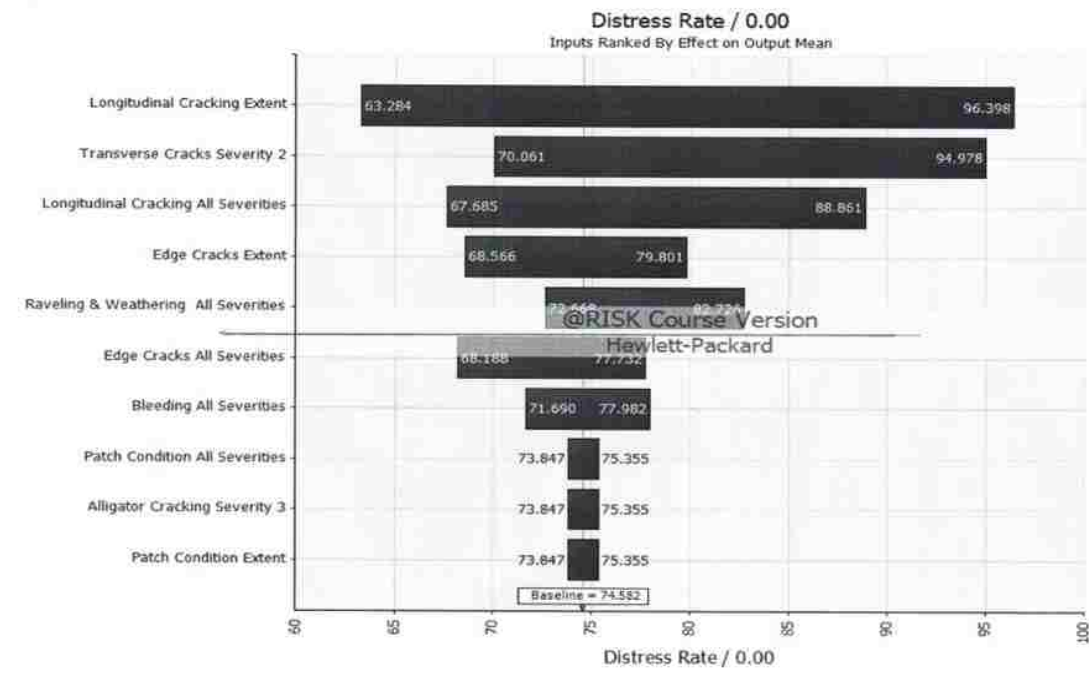
Figure 10. Example of a tornado diagram for a single milepost

The type of tornado graph used is called regression coefficients. The idea is that the longer the bar the greater its impact is on the output. The longer the bar is on the left side or more negative of the graph, the less impact it has on the output or right side of the graph. Looking at figure 10 for edge cracks, all severities; notice how the bar on the negative or left side of the graph is longer than the right side of the graph. This indicates that this input has less effect on the output. Looking at figure 10 again, for transverse cracks, severity 2 notice how the bar to the left is shorter or less negative than the previous example. This more positive (less negative) input has a much greater effect on the output for that pavement distress. The numbers on the bars are not the distress rates directly but are scaled by the standard deviation for the input and the standard deviation

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for the output. They are useful to compare to the other values on the same graph but beyond that they are unit less.

A key question prior to running a Monte Carlo model is how much iteration is necessary to achieve a high level of confidence in the simulation. Fortunately there is a process to determine the number of iterations based on the confidence interval desired. @Risk provides an online knowledge base which describes exactly how to calculate the number of iterations required based on the desired confidence level. (Palisade Corporation, 2013). For example, a 95% confidence interval would require a maximum of just over 6,500 iterations. A 99% confidence interval would require just over 11,200 iterations. Since the time it takes to run my model is short, I chose to use the default of 20,000 iterations to ensure that there are a sufficient number of iterations to satisfy either a 95% or 99% confidence interval.

I initially needed to develop a model to run on @Risk which consisted of fitting distributions to my existing data and inserting the distributions into the equation for calculating a Distress Rate value that is used to calculate a P.S.I. number. @Risk has the ability to fit distributions from its library to the actual data. In my case some of the pavement data fit the distributions quite well while other pavement data did not fit as well as I would hope. I believe this is due to the limited amount of data that I have. @Risk does allow an individual to scroll though the distributions and try to match the distribution curve to the existing data. That is what I did with my model. I tried to find the distribution curve that fit my pavement data the best and used what appeared to be the best fit.

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3.3.3 Model Validation

I ran my original model with all of the pavement data and distributions to get the upper and lower bounds represented by the tornado graph output bars. To ensure my test model was accurate I created a validation model which consisted of removing all of the distributions and substituted discreet values in place of the distributions. I used a single rater's discreet values that allowed me to check the model results against hand calculations to verify that the model was operating correctly.

I used the first rater's values taken directly from the original evaluation forms. The idea is that the distress rate values calculated from this simplified model, one rater instead of twelve, would fall in between the upper and lower bounds of the tornado diagram generated by my original model. The tornado diagram is a type of bar chart where the largest bar is listed on top with the second largest bar below it and so on in a vertical arrangement. When completed it resembles the shape of a tornado. It is often used in sensitivity analysis to compare the relative importance between the variables. The Monte Carlo simulation created the tornado diagrams from each of the runs.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Pavement Servicability Equation (P.S.I) Calculations Round #1															
2	Weighting Factors		Raveling & Weathering	3.00	Bleeding	2.00	Alligator Cracking	25.00	Transverse Cracking	12.00	Edge Cracking	3.00	Patching	2.00	Longitudinal Cracking	12.00
3	Route		NM0041				NM0041				NM0014				US 0550	
4	Milepost		0.00	1.00	2.00	3.00	29.00	30.00	31.00	32.00	0.00	1.00	2.00	3.00	0.00	1.00
5	Distress Rate		45.00	36.00	57.00	51.00					63.00	105.00	87.00	123.00	23.00	75.00
6	IRI	151.00					Do Not Use NMDOT Rehabilitated the pavement between QA/QC Rounds									
7	Interim Equation		67.72	68.97	66.07	66.90					65.24	59.45	61.93	56.97	70.76	63.59
8	P.S.I.		2.98	3.06	2.88	2.93					2.83	2.48	2.62	2.37	3.17	2.72
9	NOTE: P.S.I. can range from 0-5, larger value indicates better road condition															
10																
11	Pavement Servicability Equation (P.S.I) Calculations Round #2															

Figure 11. PSI calculation spreadsheet for all mileposts

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Shown in Figure 11 and Figure 12 are screen shots, showing the simplified model for just the single rater and for the first round of pavement evaluation. I repeated the validation for rounds 2 and 3 with the exception of the input values.

Figure 12. PSI calculation formulas, all mileposts

For the distress calculations, row 5, I summed of all of the distresses. I simplified each of the distress sheets to reflect only the first rater and replaced all of the distributions with the values obtained in the field from the original evaluation forms.

I used milepost number 2 for NM0014 and US0550 for all three evaluation rounds to test my validation model. I did a total of six hand calculations of the distress rate and compared them to the distress rates calculated by my validation model. Both of the calculations matched giving me confidence that my validation model was working correctly and that I could use those values to verify my original model was working correctly.

NM0041, Milepost 3, Round 1		
Distress	Rater	Distribution
R&W	18.00	18.00
Bleed	6.00	4.00
Alligator	25.00	0.00
Transverse	36.00	36.00
Edge	3.00	3.00
Patch	0.00	0.00
Long.	12.00	12.00
DR	100.00	73.00

Figure 13 . Single milepost and evaluation round distress rate output

Unfortunately when I compared all of the mileposts between my validation model
and actual model I found eleven mileposts where the value produced by the validation
model did not fall within the range produced by the actual model. I took a single milepost
3 from NM0041 and broke it down by each distress and calculated only that part of the
distress rate for both the validation model and Monte Carlo model to see where the two
differed (Figure 13). The problem exists with how alligator and transverse cracking is
separated into different extents and how I used an averaged sum of all the raters in the
Monte Carlo model versus using only the inputs from a single rater for the validation
model. Specifically at NM0041, milepost 3 the averaged sum of all the alligator cracking
was less than 158 square feet, the amount required to go from extent zero to extent 1,

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while rater 1 reported back 200 square feet of alligator cracking. This resulted in the validation model having a greater distress rate than the Monte Carlo model, enough of a difference that the validation model's value falls outside the range provided by the Monte Carlo model. This is certainly a limitation in how well the model represents reality.

There was another problem with some of the data that needed to be addressed. The New Mexico Department of Transportation rehabilitated a portion of the test sections we were using part way through our data collection. They used a chip seal pavement preservation technique between our first and second rounds of data collection. Therefore, mileposts 29 through 32 were highlighted in red indicating that data were not useable and to omit it.

After the Monte Carlo model was finally run I calculated the percentage of what pavement distresses appeared the most often with my interest in the most prevalent pavement distresses. To do this was quite simple with me manually counting the number of times that the pavement distress that had a range greater than 10 units. Using 10 units was slightly arbitrary; too low of a value and nearly all the pavement distresses become significant and too high of a number and none of the pavement distresses are significant. Some mileposts have a tornado bar range exceeding 100 and some that have a range less than one. Using 10 as a breakpoint to where that pavement distress has any significant variability to the distress rate was a practical choice and identified four pavement distresses that begin with nearly a 50% chance of appearance in a milepost evaluation. I simply counted the distress that exceeded a range of 10 units. To calculate the percentage I divided by 20 test sites for each of the three rounds, multiplied by 100 for a percentage.

Round # %=(number of appearances/20)*100

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For the total percentage that a pavement distress with a range greater than 10 I added the times it appears from all three rounds and applied the same formula with the exception that the total possible is 60 (Figure 14).

Total %=(number of appearances/60)*100

Percentage of total Mileposts	Round 1 %	Round 2 %	Round 3 %	Overall %
R&W	=(11/20)*100	=(13/20)*100	=(5/20)*100	=(29/60)*100
Bleed	=(0/20)*100	=(0/20)*100	=(0/20)*100	=(0/60)*100
Alligator Severity	=(6/20)*100	=(7/20)*100	=(5/20)*100	=(18/60)*100
Transverse Severity	=(16/20)*100	=(15/20)*100	=(14/20)*100	=(45/60)*100
Edge Severity	=(2/20)*100	=(2/20)*100	=(1/20)*100	=(5/60)*100
Edge Extent	=(2/20)*100	=(4/20)*100	=(0/20)*100	=(6/60)*100
Patch	=(0/20)*100	=(0/20)*100	=(0/20)*100	=(0/60)*100
Longitudinal Severity	=(14/20)*100	=(15/20)*100	=(14/20)*100	=(43/60)*100
Longitudinal Extent	=(13/20)*100	=(14/20)*100	=(13/20)*100	=(40/60)*100

Figure 14. Total pavement distress percentage calculation for all mileposts

The distress rate (DR) uses a weighting factor in addition to a severity and extent to determine the overall DR that is then used in the pavement serviceability index (PSI) equation. I decided to take a look at how the weighting factor altered the DR by changing the weighting factor in 10 percent increments until I could see a pattern emerge.

Table 1. Range of weighting factors used in sensitivity analysis using all mileposts

Pavement Distress	Baseline Run Weighting Factors	+10%	+20%	+30%	+40%	+50%
Raveling and Weathering	3	3.3	3.6	3.9	4.2	4.5
Bleeding	2	2.2	2.4	2.6	2.8	3
Alligator Cracking	25	27.5	30	32.5	35	37.5
Transverse Cracking	12	13.2	14.4	15.6	16.8	18
Edge Cracking	3	3.3	3.6	3.9	4.2	4.5
Patching	2	2.2	2.4	2.6	2.8	3
Longitudinal Cracking	12	13.2	14.4	15.6	16.8	18

The first step was to run the model using the standard weighting factors shown in Table 1. I considered this as my baseline run with changes only made to the weighting factors.

The following model run was done without any weighting factors at all; just the severity and extent information was used to calculate the distress rate. The remaining five model runs were done by increasing the original weighting factors by 10%, 20%, 30%, 40% and finally 50%. The weighting factors used are listed in table 1 for each model run.

Pavement Servicability Equation (P.S.I) Calculations Round #1

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Weighting Factors		Raveling & Weathering	3.00	Bleeding	2.00	Alligator Cracking	25.00	Transverse Cracking	12.00	Edge Cracking	3.00	Patching	2.00	Longitudinal Cracking	12.00
Route			NM0041				NM0041				NM0014				US 0	
Milepost		0.00	1.00	2.00	3.00	29.00	30.00	31.00	32.00	0.00	1.00	2.00	3.00	0.00	1.00
Distress Rate		26.00	58.00	88.00	73.00					65.00	97.00	109.00	97.00	23.00	104.00
IRI	151					Do Not Use NMDOT Rehabilitated the pavement between QA/QC Rounds										
Interim Equation		70.34	65.93	61.79	63.86					64.97	60.55	58.90	60.55	70.76	59.59
P.S.I.		3.15	2.87	2.61	2.74					2.81	2.53	2.45	2.53	3.17	2.48
NOTE: P.S.I. can range from 0-5, larger value indicates better road																

Figure 15. Spreadsheet heading with baseline weighting factors using all mileposts

Figure 16. Spreadsheet heading with +50% over baseline weighting factors using all mileposts

Figures 15 and 16 show how I altered the weighting factors for the baseline and +50% into the spreadsheet using cells along the top of the spreadsheet. I referenced within the formula calculating the distress rate. By referencing these cells within the body of the spreadsheet it allowed me to change the weighting factor values in a single place and the then run the model with the new weighting factor values. It prevented me from having to change the weighting factors throughout the spreadsheet. I did the same for all of the differing weight factors for each new run.

After completing the model run for each weighting factor. I divided each tornado graph bar representing pavement distresses into those that have a range greater than 10 units and less than 10 units. This allowed me to determine the pavement distresses that seem to have the greatest impact on the final distress rate. To separate the pavement

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distresses of interest to me from those that were not I counted the total number of times that a pavement distress appeared, divide by the total possible and multiply by 100 to get a percentage. This percentage represents the amount that a particular pavement distress appears.

Percentage of times a pavement distress with tornado graphs bar range greater than ten appears was calculated as: % of appearance = (Number of times it appears/Total number of times possible) x 100. This allows me to view the top four pavement distresses that have the greatest effect on the distress rate.

3.4 Results

One of the interesting results was observing the pavement distresses that were present at nearly half or more of the mileposts used. There is not one for the model run in which I removed all of the weighting factors; it didn't have a range for any single pavement distress greater than 10 unit; for this reason I did not include it. Figure 17 shows the results for all of the weighted factor simulation runs:

Percentage of total Mileposts	Round 1 %	Round 2 %	Round 3 %	Overall %
R&W	60.00	65.00	25.00	50.00
Bleed	0.00	0.00	0.00	0.00
Alligator Severity	30.00	35.00	25.00	30.00
Transverse Severity	80.00	75.00	75.00	76.67
Edge Severity	10.00	10.00	5.00	8.33
Edge Extent	10.00	20.00	0.00	10.00
Patch Severity	0.00	0.00	0.00	0.00
Patch Extent	0.00	0.00	0.00	0.00
Longitudinal Severity	70.00	75.00	70.00	71.67
Longitudinal Extent	65.00	70.00	65.00	66.67

Figure 17. Pavement distresses greater than 10 unit range, baseline run using all mileposts

Figure 17 highlights the top four distresses that have a range greater than 10 units at the mileposts by percentage. They are longitudinal cracks, including both severity and extent criteria, transverse cracks and raveling and weathering.

Percentage of total Mileposts	Round 1 %	Round 2 %	Round 3 %	Overall %
R&W	75.00	75.00	80.00	76.67
Bleed	0.00	0.00	0.00	0.00
Alligator Severity	30.00	35.00	25.00	30.00
Transverse Severity	75.00	80.00	85.00	80.00
Edge Severity	15.00	15.00	10.00	13.33
Edge Extent	15.00	20.00	5.00	13.33
Patch Severity	0.00	0.00	0.00	0.00
Patch Extent	0.00	0.00	0.00	0.00
Longitudinal Severity	70.00	75.00	80.00	75.00
Longitudinal Extent	65.00	75.00	70.00	70.00

Figure 18. Pavement distresses greater than 10 unit range, +10% increase using all mileposts

After getting the baseline run complete without altering the weighting factors I started increasing the weight factors to see if there was a change in the pavement distresses that appeared the most often. Figure 18 represents an increase of the weighting factors by 10% over the baseline weighting factor values.

Percentage of total Mileposts	Round 1 %	Round 2 %	Round 3 %	Overall %
R&W	80.00	80.00	75.00	78.33
Bleed	0.00	0.00	0.00	0.00
Alligator Severity	30.00	35.00	25.00	30.00
Transverse Severity	75.00	80.00	80.00	78.33
Edge Severity	10.00	20.00	15.00	15.00
Edge Extent	10.00	25.00	5.00	13.33
Patch Severity	0.00	0.00	0.00	0.00
Patch Extent	0.00	0.00	0.00	0.00
Longitudinal Severity	70.00	80.00	75.00	75.00
Longitudinal Extent	70.00	70.00	65.00	68.33

Figure 19. Pavement distresses greater than 10 unit range, +20% increase using all mileposts

Figure 19 represents when the weighting factors were increased to 20% of the baseline values. Notice that the percentage of times the distresses that have a range greater than 10 fluctuates. I believe this to be the result that the Monte Carlo method uses probability that a particular input value is selected. This results in some instances a range of 8 or 9 is outputted instead of a 10 or 11 in some instances.

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Percentage of total Mileposts	Round 1 %	Round 2 %	Round 3 %	Overall %
R&W	90.00	85.00	90.00	86.67
Bleed	0.00	0.00	0.00	0.00
Alligator Severity	30.00	35.00	25.00	30.00
Transverse Severity	80.00	80.00	80.00	80.00
Edge Severity	15.00	25.00	15.00	18.33
Edge Extent	25.00	20.00	15.00	20.00
Patch Severity	0.00	0.00	0.00	0.00
Patch Extent	0.00	0.00	0.00	0.00
Longitudinal Severity	70.00	80.00	75.00	75.00
Longitudinal Extent	70.00	70.00	65.00	51.67

Figure 20. Pavement distresses greater than 10 unit range, +30% increase using all mileposts

Figure 20 shows the results of increasing the baseline weighting factors by 30%; notice that the same pavement distress are present but their range is greater as the weighting factors exaggerate the difference between a severity 1 and a severity 3 for example.

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Percentage of total Mileposts	Round 1 %	Round 2 %	Round 3 %	Overall %
R&W	95.00	90.00	100.00	95.00
Bleed	0.00	5.00	0.00	1.67
Alligator Severity	30.00	35.00	25.00	30.00
Transverse Severity	80.00	80.00	75.00	78.33
Edge Severity	20.00	20.00	25.00	21.67
Edge Extent	25.00	30.00	15.00	23.33
Patch Severity	0.00	0.00	0.00	0.00
Patch Extent	0.00	5.00	0.00	1.67
Longitudinal Severity	70.00	80.00	80.00	76.67
Longitudinal Extent	70.00	70.00	70.00	70.00

Figure 21. Pavement distresses greater than 10 unit range, +40% increase using all mileposts

What is interesting is that raveling and weathering is showing up in the top four almost all of the time while the other distresses have increased slightly over the baseline. I believe that at lower weighting factors raveling and weathering had many more borderline simulations that the range value hovered just below 10 units. Now the higher weighting factors have exaggerated the distress rate enough for it to show up more often.

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Percentage of total Mileposts	Round 1 %	Round 2 %	Round 3 %	Overall %
R&W	90.00	95.00	100.00	95.00
Bleed	10.00	5.00	5.00	6.67
Alligator Severity	30.00	35.00	25.00	30.00
Transverse Severity	65.00	80.00	80.00	75.00
Edge Severity	15.00	20.00	25.00	20.00
Edge Extent	15.00	25.00	15.00	18.33
Patch Severity	0.00	5.00	0.00	1.67
Patch Extent	0.00	5.00	0.00	1.67
Longitudinal Severity	70.00	85.00	75.00	76.67
Longitudinal Extent	70.00	70.00	70.00	70.00

Figure 22. Pavement distresses greater than 10 unit range, +50% increase using all mileposts

Figures 17 to 22 represent the various runs from the baseline where none of the weighting factors were altered up to where the weighting factors were increased by 50%. They show that the same four pavement distresses remain the most sensitive regardless of the increase in the weighting factors. No other pavement distress was added as the weighting factors increased. The percentage of time that the four highlighted distresses appeared did increase for raveling & weathering consistently but the others moved up and down slightly.

I believe the reason the most sensitive pavement distresses did not all increase uniformly has more to do with the probability function of the Monte Carlo Simulation. At several of the mileposts when the simulation was run would be either barely above or

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below the 10 unit cutoff. The input value selected based on the probability function in the Monte Carlo simulation was most likely enough to affect the percentage of time it was above 10 units and that is reflected in the percentage of times it showed up in all of the simulations.

The weighting factor also has an effect on the final PSI value since it is part of the distress rate calculation. I ran the model for all three rounds of evaluation but I am only going to show round 2 as representative of how the weighting factors affect the final PSI number. The first graph shows illustrates how the current weighting factor affects the PSI number. It is a mirror image with the PSI number following the distress rate but at a much smaller value, 0-5, is the range for the PSI number. Looking at the graph the PSI fluctuates between a low of approximately 1.9 up to a high of 3.19. The distress rate varies between a low of 21 up to a high of 206. Figure 25 shows how the PSI and DR change when you remove the weighting factors. The differences between the high and low value almost disappear compared to the current weighting factors used. The distress rate changes by only 20 points between a low of 4 to a high of 20. The PSI is only varies between 3.16 and 3.34. Looking at the remaining graphs from +10% to +50% I get low and high values:

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Without any Weighting Factors			+30% of Baseline Weighting Factors	
PSI low	3.16		PSI low	1.54
PSI high	3.34		PSI high	3.14
DR low	4.00		DR low	27.30
DR high	20.00		DR high	267.80
PSI range	0.18		PSI range	1.60
DR range	16.00		DR range	240.50

Baseline with Original Weighting Factors			+40% of Baseline Weighting Factors	
PSI low	1.90		PSI low	1.42
PSI high	3.19		PSI high	3.12
DR low	21.00		DR low	29.40
DR high	206.00		DR high	288.40
PSI range	1.29		PSI range	1.70
DR range	185.00		DR range	259.00

+10% of Baseline Weighting Factors			+50% of Baseline Weighting Factors	
PSI low	1.78		PSI low	1.30
PSI high	3.17		PSI high	3.10
DR low	23.10		DR low	31.50
DR high	226.60		DR high	309.00
PSI range	1.39		PSI range	1.80
DR range	203.50		DR range	307.20

+20% of Baseline Weighting Factors				
PSI low	1.66			
PSI high	3.15			
DR low	25.20			
DR high	247.20			
PSI range	1.49			
DR range	222.00			

Figure 23. Changes in P.S.I. based of weighting factors using all mileposts
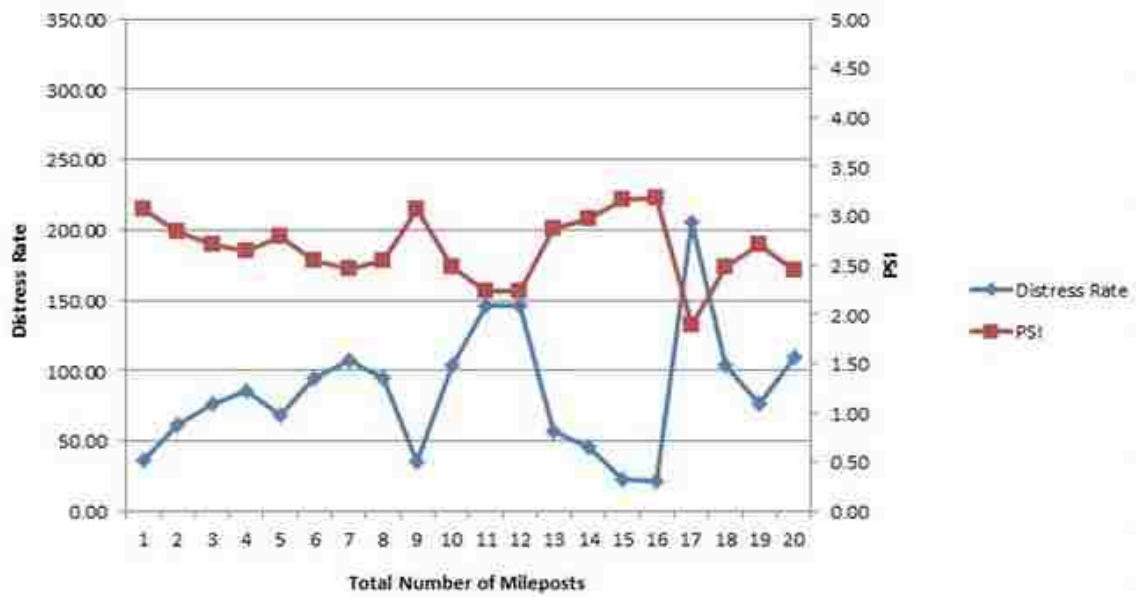
Figure 24. Baseline weighting factors, PSI vs. DR, all mileposts

Figure 25. Without weight factors, PSI vs. DR, all mileposts

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Figure 26. +10 percent increase in weight factor, PSI vs. DR, all mileposts
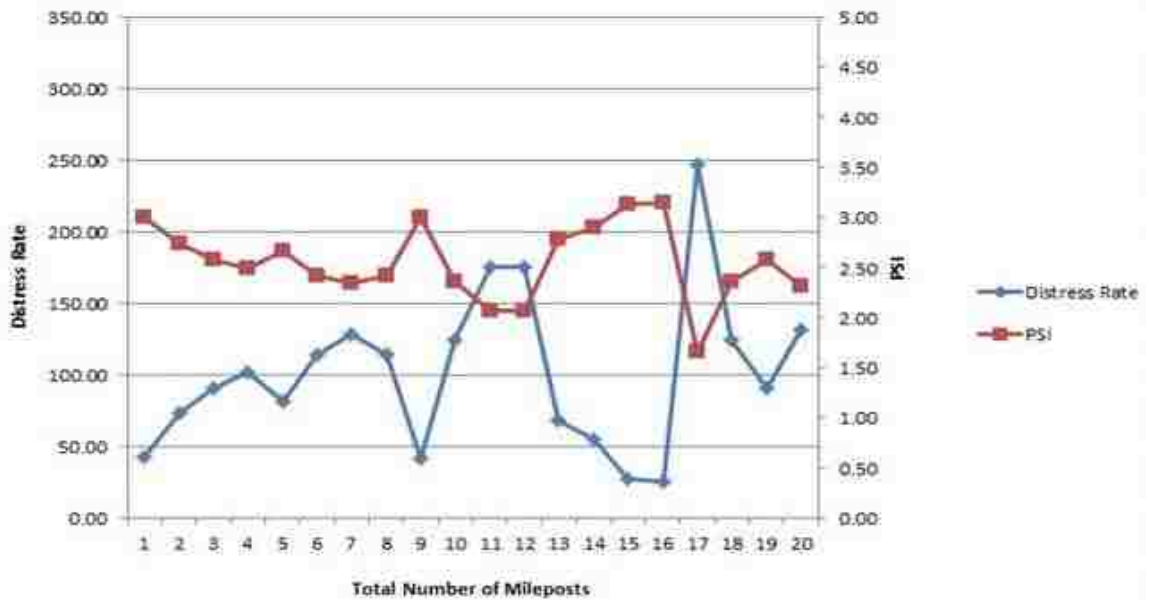
Figure 27. +20 percent increase in weight factor, PSI vs. DR, all mileposts

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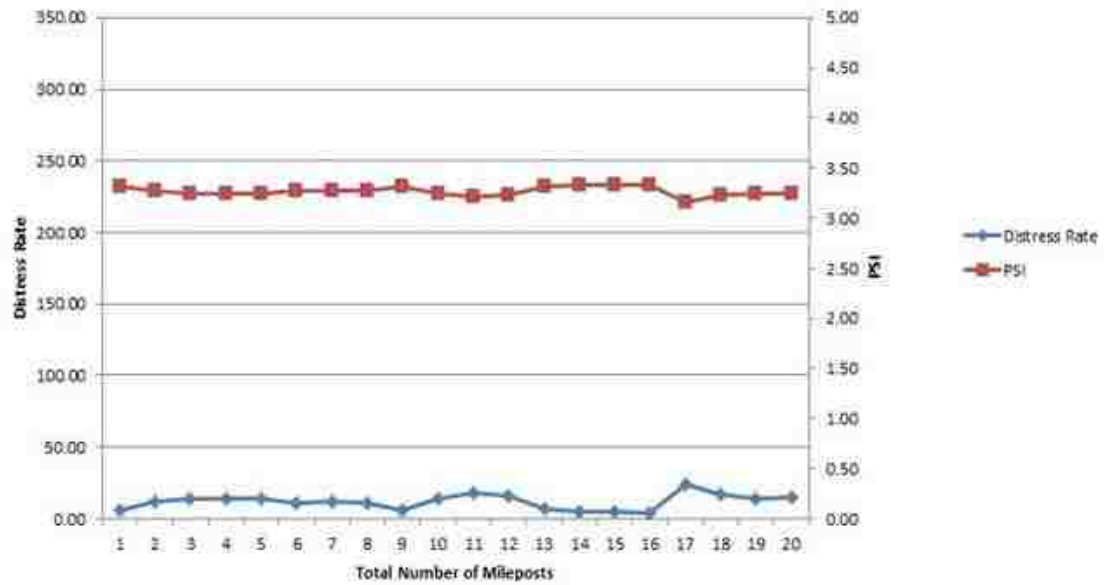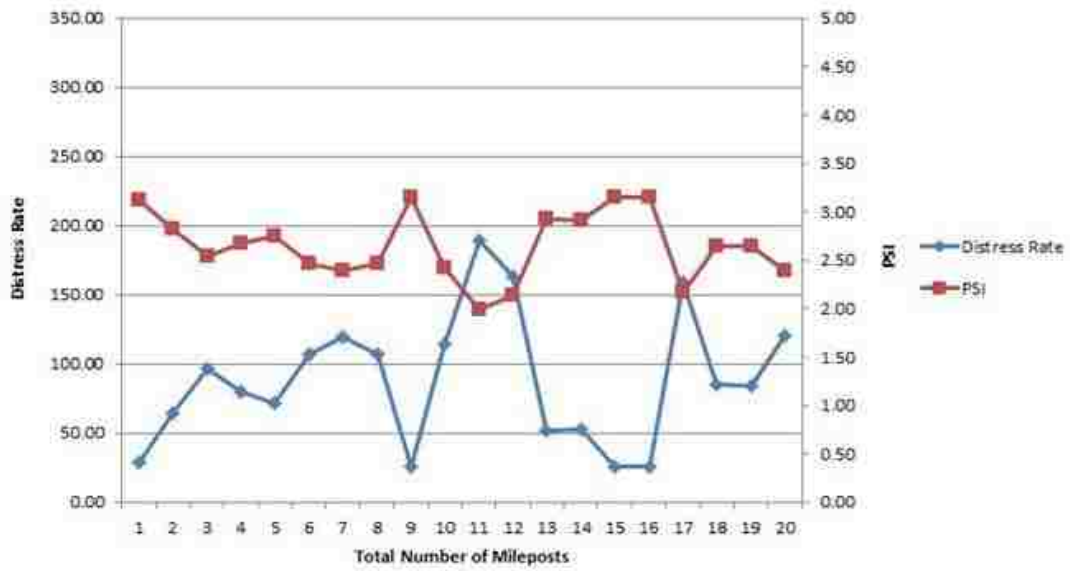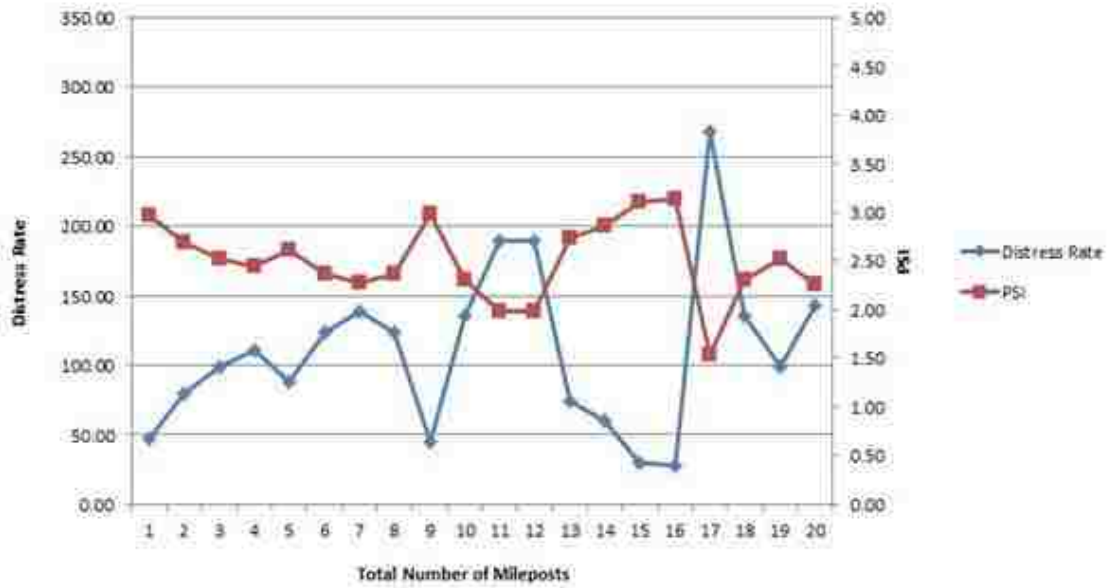**Figure 28. +30 percent increase in weight factor, PSI vs. DR, all mileposts**
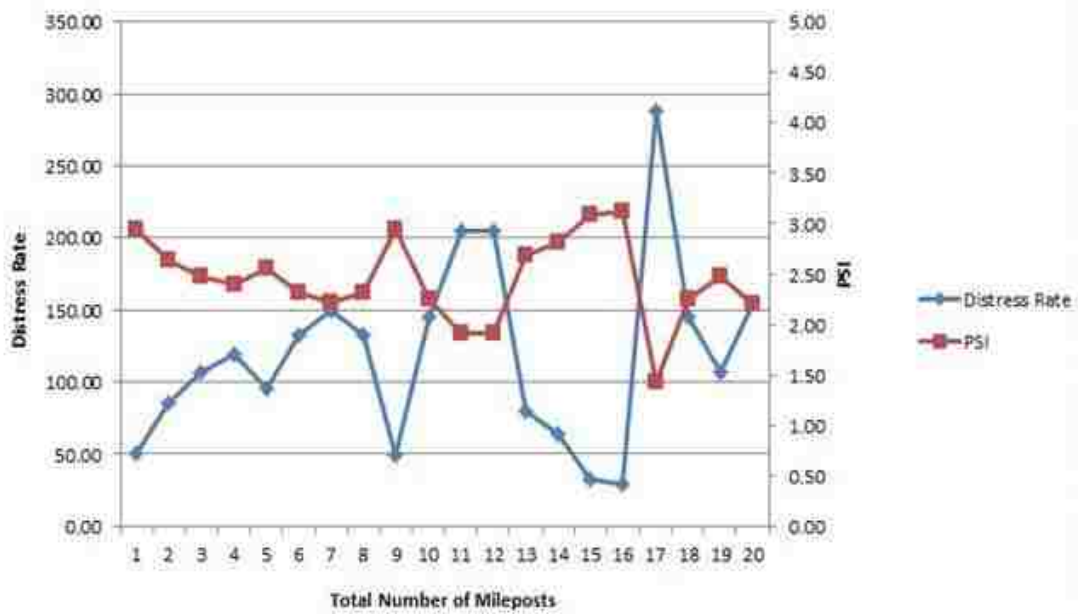
Figure 29. +40 percent increase in weight factor, PSI vs. DR, all mileposts
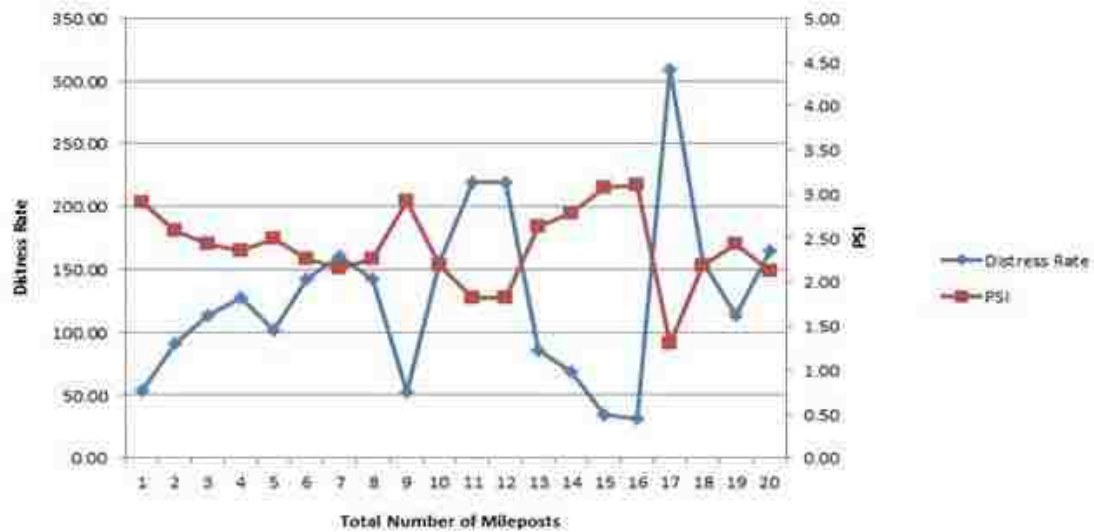
Figure 30. +50 percent increase in weight factor, PSI vs. DR, mileposts

Figures 24 through 30 take a look at how the weighting factors affect both the distress rate and the P.S.I. number using all of the data points. The baseline run is using the same weighting factors as the NMDOT uses. I took all of the weighting factors out for figure 25 and notice that both the DR and P.S.I. graph lines are nearly flat with almost no variation. Figures 26 through 30 show an exaggerating effect to both the DR and P.S.I graphs. The weighting factors do not really change the basic shapes of both graph lines but exaggerates the peaks and valleys. This makes sense when you consider that by changing the weighting factors you are simply changing the constants. The uncertainly due to the evaluator or the probability distribution within the Monte Carlo method is present.

3.5 Discussion

The same four pavement distresses, raveling and weathering, transverse crack severity, longitudinal crack severity and longitudinal crack extent, caused the most

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variation in the model runs with varying weight factors. I did not expect to see raveling and weathering on the list and transverse cracks surprised my but the inclusion of both longitudinal crack severity and extent did not surprise me. I will start with transverse cracking and work my way down the list to longitudinal cracks, both severity and extent with what I believe is causing these four pavement distresses to appear the most often and why they are the most variable pavement distress input to the distress rate number calculation.

Conditions that affect pavement evaluators are wind and temperature. Wind can easily affect how long or well a job the evaluator does, especially when mixed with blowing sand. We sent the evaluators out in the morning and had them work for 10 hours per day; the temperature is comfortable in the morning but is quite hot in the afternoon. I have no doubt that this affects early morning evaluations in a positive way and the afternoon evaluations in a negative way as people want to return to an air conditioned vehicle. The evaluators were taught to estimate the 1/10 mile section to evaluate by counting the dashed center line (NMDOT, 2012). This might be an excellent method to estimate an evaluation section but what about single land roads without a dashed centerline? This leaves the evaluator to make their best guess. This certainly has an effect of the evaluations reported back. Did the evaluator stop short and not capture some pavement distresses? Did the evaluator go too far and captured too much? Neither provides an accurate picture of what that road section actually is like.

Transverse cracks are only counted if they extend six feet or more across the lane (NMDOT, 2012). This sound simple enough until you realize that approximating the length of a crack from the shoulder is not as easy as it sounds. There is definitely a gray

area where an evaluator is trying to estimate whether the crack has reached the midpoint of the lane or not. Traffic cannot be underestimated for any of these pavement distress evaluations. A quiet rural New Mexico route is much easier to evaluate than a busy section of interstate like I40 or a U.S. route like US0550. When you have large recreational vehicles and over the road long distance trucks driving by at speeds up to 75 mile per hour. The other issue with transverse cracks is that they do not always run directly perpendicular to the centerline of the road. There are many transverse cracks that will turn to follow the road centerline before running perpendicular again. This adds greater uncertainty for the rater and increases the variability to the evaluation. The evaluators were told during training that if they believe the crack to be close to go ahead and count it but there is still an area where the judgment of each evaluator causes this variability.

The other reason I believe that there is some variability has to do with the classification of the differing extents. Depending on the number of cracks reported an extent may or may not change with until several additional cracks are reported. If the number of cracks reported by several evaluators hover near one of the values determining the difference between extents you can have only a single crack difference between raters change the extent. Have several raters do this and now it starts to appear there is more variability in the distress rate calculation than the raw data might suggest.

Both longitudinal cracking severity and extent are affected by the same situation. Unlike transverse cracking where the evaluator is reporting back the number of cracks; longitudinal cracking, for both severity and extent, are estimated by the evaluator. Essentially the evaluator on the side of the road is looking at a longitudinal crack and

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estimating the width of the crack and classifying it into a severity. After that they look at the length of that crack and estimate whether it is fewer than 30% of the section being evaluated, 30% to 60% of the section evaluated or is it over 60% of the section being evaluated. This can cause a huge variability in the reported longitudinal crack extent. Estimating the width of a crack has almost just as much variability. Not all longitudinal cracks are near the shoulder of the road where the raters are, this increases the difficulty in determining the severity of any crack. Another issue is determining if a longitudinal crack is really a longitudinal crack or does it falls within one of the two vehicle wheel paths and is now an alligator crack with a severity one?

Raveling and weathering are much more difficult to evaluate. They are both linked to the binder; incorrect binder, loss of binder, poor mix design, oxidation of the binder and the loss of aggregate (NMDOT, 2007). For someone not experienced with evaluating road surfaces this can be a challenge. The very severe cases, like many of the pavement distresses, are easy to identify but it is the less severe and more subtle road conditions that are difficult to evaluate. Unlike cracks in which you can have a ruler with you or some other sort of scale for comparison purposes when evaluating crack widths; raveling and weathering doesn't lend it to those sorts of tools. Looking at how rough the pavement surface is from aggregate loss and taking a look at the shoulder to see how much aggregate has been deposited there are a couple of indicators. These are not reliable indicators either; if a road is recently chip sealed it can give the impression that the road is severely raveled and weathered. Chip sealing can sometimes leave a rougher surface than an old pavement surface and very often a large amount of aggregate is left along the shoulder. During one of the QA/QC rounds I received multiple phones calls from my teams in the field about severely raveled road surface at one of the QA/QC test sites.

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After interviewing the teams it became obvious the maintenance crews just down the road had chip sealed the test site with in the previous day or so leaving a rough surface and a great amount of aggregate on the shoulder. Among a process that is subjective it is an extremely subjective pavement distresses distress to evaluate. Finding it is one of the pavement distresses that is quite variable is of no surprise. With a weighting factor of only a 3 compared to the weighting factors for both transverse and longitudinal cracks at 12 it is unlikely to have the same impact on the final distress rate as the other two types of cracks will.

One of the interesting observations I saw from the four pavement distresses that have the most variability on the distress rate is that the transverse and longitudinal cracks have the second highest weighted factor at 12 for each type of crack. This is only second to alligator cracking. I am not sure how much the constant weighting factor of 12 affected the distress rate but it did compel me to look at changing the distress rates and see if it altered the pavement distresses that appear more than 50% of the time in the Monte Carlo model results. Figures 53-58 are averages from each of the three evaluation rounds averaged together to provide a single percentage for each pavement distress for each weight factor. This represents the number of times a particular pavement distress had a range greater than 10 in the results for each model run. These are the pavement distresses that had the most variability on the distress rate. Altering the fixed weight factors had the tendency of increasing the percentage of times it appeared with a range greater than 10 units the same four pavement distresses still had the greatest effect on variability. I believe that the weight factors affect the final distress rate number they have no real effect on which pavement distresses are the most variable. That variability must be explained by some other means and I believe it is with the way the distress is evaluated.

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The weight factors for the distress rate certainly have an impact on the final distress rate and well as the PSI number. Looking at Figure 55 in which all of the weight factors were removed it appears that both the DR and PSI are almost a flat horizontal line with very little changes between the maximum value and the minimum value. The DR with can have a maximum of 531and a minimum of 65 using the current weighting factors. That give a range of 466 for the DR and the PSI can range from 0 up to 5 for comparison when we look at the values we obtain for each of the model runs comparing the different weight factors. With no weight factors we have a DR range of only 16 and a PSI range of 0.18 from the highest value to the lowest value. In comparison when looking at Figure 60 where the weight factors were increased by 50% of their original values we see a range of 307.20 for the DR and 1.8 for the PSI. When you take the range PSI moved of 1.8 and divides it by the range possible we see a total movement of 36%; in comparison when the weight factors are removed do the same calculation and we see a total movement from high to low of only 3.6%. While I am not investigating the appropriate values to be used for weight factors using only a spread of 3.6% doesn't seem sensitive enough to represent the condition of our roads. This is an area that could benefit from future research. The other Figures show a steady increase for both the distress rate and the PSI number as the weight factors are increased; I would expect that trend to continue as the weight factors are increased.

Chapter 4. Conclusions

4.1 Summary Conclusions

Pavement evaluations are by nature a variable process. Unlike some processes where a reasonably absolute value can be determined by repeated experiments, pavement evaluation is the result of an individual looking at a section pavement and making trying their best to compare it to a list of evaluation criteria. To improve the process, one can institute evaluation procedures and criteria in a manner that hopefully reduces the variability of the process while keeping it sensitive enough to capture the condition on the pavement.

The New Mexico Department of Transportation did incorporate new evaluation procedures and criteria for the evaluation conducted during the summer of 2012. In response to these new evaluation procedures, I researched whether the new evaluation procedures were doing a better job of capturing the condition of the pavement. Initially I looked at the two pavement distresses altered the most, alligator cracking and transverse cracking. A simple sensitivity analysis of those two pavement distresses showed that pavement could contain cracking damage while still fitting an extent of zero cracking based on the NMDOT criteria. The new evaluation procedures created ranges that are large enough to hide the true pavement condition.

Following the simple sensitivity analysis, I conducted a Monte Carlo simulation to do a more sophisticated evaluation using all of the pavement distresses to see how the distress rate compares to the final pavement serviceability index. The distress rate is an input to the PSI and this allowed me to see if the range of possible values that became evident in the early research really had any impact on the final PSI number.

I also performed a sensitivity analysis on the weighting factors used in the PSI calculation to see what sort of impact they might have on the final number. Do the weighting factors reduce the impact of the distress rate on the final PSI number? These were some of the questions I hoped to answer.

The distress rate comprises the sum of the different pavement distress severities, extents and weighting factors multiplied together. The weight factors are constants but the severities and extents are the variable part of the distress rate. The only variable to go into the PSI equation other than the severity and extents for each pavement distress is the International Roughness Index but for the purposes of this research, I used a constant value to evaluate the distress rate and its effect on the PSI.

The results of the Monte Carlo simulation showed that four pavement distress inputs to the DR repeatedly appeared as having the greatest range of passible values. This occurred with both the baseline run and with the subsequent changes to the weighting factors. Raveling and weathering, transverse cracks severity, longitudinal cracks severity and extent were the pavement distresses that showed the most sensitivity. Transverse cracks were one of the pavement evaluation procedures changed the most but the others were virtually unchanged from the old procedures. This came as a surprise to me initially but after some thought it is easy to see how they can show so much variability. Both transverse and longitudinal cracks have the second highest weight factor at 12. Any variability here is magnified compared to edge cracks with a weight factor of only 3. Estimating crack width and length for each severity while in the field adds to the variability. Raveling and weathering by the nature of how it degrades makes it difficult to evaluate accurately.

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The fact that transverse cracks were one of the pavement distresses changed but still showed the distress rate and subsequently the P.S.I. to be sensitive to it surprised me initially. With the number of cracks broken into extents that had a range of 16 cracks initially I believed the DR would not be very sensitive to inputs. I had neglected to consider the other part of the distress rate equation, severity. I believe the difficulty in judging a crack width from the shoulder of a busy roadway is what makes transverse cracks difficult to accurately classify. Take into account that a crack is not uniform along its length and an evaluator is required to record all severities makes it very easy for different evaluators to rate the severity of a pavement crack very differently.

The weighting factors seem to have a significant effect on the final distress rate and subsequent PSI value. I went from having no weighting factors up to a 50 percent increase over the existing or baseline weighting factors. Changing the weight factors had the tendency to exaggerate the distress rate and to a lesser degree the PSI. Because of the way the PSI is calculated with the distress rate only being weighted at 40 percent compared to the IRI being weighted at 60 percent it seems that the variability in the evaluation process is muted in the final PSI value. This weighting towards road smoothness minimizes the effect of any variability with regard to the evaluation process and individual bias.

While the changes made by NMDOT helped reduced some of the variability and sensitivity of the distress rate more research could be done with the weighting factors and subsequently the P.S.I. equation. One of the most sensitive pavement distresses being longitudinal cracks was not addressed when the NMDOT altered the existing inspection protocol. Research into how it can be changed to reduce the subjectivity, perhaps a

process similar to transverse cracks, could be developed bringing it in line with the other revised inspection protocols.

The weighting factors are a prime target for research into how to reduce the sensitivity of the distress and P.S.I. number. My work demonstrated then the weighting factors act to increase or decrease the distress rate. The weighting factors right now exaggerate the values of the pavement distresses they are assigned to. Why the particular weighting factors were assigned to the various pavement distresses have long been lost. The NMDOT pavement design bureau when asked about the weighting factors have no idea where they came from of the decision process used to derive them. Since they can have a significant effect on the distress rate further research into the weighting factors is beneficial.

The P.S.I equation itself is something to look at; the equation is biased towards ride or road smoothness instead if the structural soundness of the pavement. Research into a new P.S.I. number that reflects the structural condition of the NMDOT's largest and most important asset could help planners determine more accurately what pavement treatments are appropriate for actual roads conditions. This would also allow asset managers to better prioritize which roads to place into the statewide transportation improvement plan which is a schedule of projects for the next four years.

Changing the evaluation process to minimize subjectivity by the evaluators was a step in the correct direction to gain an idea of the actual pavement condition of our roads. There does not seem to be much variability among most of the various pavement distresses; the pavement distress types that consistently showed sensitivity can be

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difficult to evaluate for several reasons. Changes to weighting factors and continued research in evaluation procedures may be able to reduce some of that sensitivity.

4.2 Future Work

The model is not perfect with the various ranges for both alligator transverse cracking. This might be able to be mitigated with using something other than an averaged sum of all of the area or crack numbers. Perhaps using a weighted average will be the answer but a more accurate model may provide more information on what is influencing the distress rate calculations. The weight factors seem to have an impact on the final distress rate and PSI value; this area alone could benefit from future study. A serious limitation is the limited number of sites used. A much larger sample set may result in a different conclusion.

The type of traffic or composition of can have a tremendous impact on the pavement condition. Motorcycles do almost no damage to pavement because of their light vehicle weight. A typical motorcycle weighs somewhere between 500-700lbs. with large touring motorcycle like the Honda Goldwing weighing up to 900 lbs. The upper weight limit allowed on an interstate is 80,000 lbs. (FHWA, 2015). These are the semi or over the road trucks. That 80,000 pound load is spread out among multiple axles and wheels but is still a huge load being placed on the pavement. With the high loads being placed on roadways from large heavy trucks pavement deteriorates much quicker than if the traffic is composed of passenger vehicles. Alligator cracking is normally the result of fatigue from cycling loading. Even cracks such as transverse cracks that typically originate from internal stresses resulting from freeze and thaw conditions are negatively

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impacted from large over the road trucks as they tend to load the exposed edges of the transverse cracks causing spalling which is a way these cracks can become wider from crack edges breaking.

Traffic vehicle composition also plays a large role in the evaluation of the pavement. Light traffic with mainly passenger cars is not as intimidating as trying to evaluate a pavement section with very large and very heavy trucks speeding past.

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Appendix A

I started with a basic Excel spreadsheet and created columns across the top listing the route number and below it one row down was the milepost sections we evaluated. Down the left side of the spreadsheet I initially listed 12 raters from 1-12. These rows contained the actual data obtained from the field. Figure 31 shows the entire spreadsheet with the data inputted.

Figure 31. Finished Excel spreadsheet to calculate PSI.

Figure 32. Top portion of completed spreadsheet showing routes and mileposts.

The next four rows below that are reserved for calculating the frequency of a 0 through 3 for severity; we used the COUNTIF function from the Excel library, =COUNTIF(First cell of the rater's data : the last cell of the rater's data, this cell is the particular severity you are interested in). As an example it looks like this in the spreadsheet cell; =COUNTIF(C4:C15,$B$17). Figure 33 and Figure 34 shows the section of the spreadsheet reserved for determining the frequency of each of the possible ratings. Figure 34 shows the formula used in each of the cell

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Figure 33. Sample Frequency values

	Frequency							
	0	=COUNTIF(C4:C15,$B$17)	=COUNTIF(D4:D15,$B$17)	=COUNTIF(E4:E15,$B$17)	=COUNTIF(F4:F15,$B$17)			=COUNTIF(K4:K15,$B$17)
	1	=COUNTIF(C4:C15,$B$18)	=COUNTIF(D4:D15,$B$18)	=COUNTIF(E4:E15,$B$18)	=COUNTIF(F4:F15,$B$18)	Do Not Use NMDOT Rehabilitated the pavement between QA/QC Rounds		=COUNTIF(K4:K15,$B$18)
	2	=COUNTIF(C4:C15,$B$19)	=COUNTIF(D4:D15,$B$19)	=COUNTIF(E4:E15,$B$19)	=COUNTIF(F4:F15,$B$19)			=COUNTIF(K4:K15,$B$19)
	3	=COUNTIF(C4:C15,$B$20)	=COUNTIF(D4:D15,$B$20)	=COUNTIF(E4:E15,$B$20)	=COUNTIF(F4:F15,$B$20)			=COUNTIF(K4:K15,$B$20)

Figure 34. Frequency calculation formula

The frequency result or the number of times a particular severity or extent was inputted by the 12 evaluators was used in the following four rows. This is where the probability of those severities is calculated. We simply divided the cell for the frequency of each severity by the total number of evaluators; in this case that is 12 evaluators. The formula used to calculate the probability can be seen in figure 36, *the frequency of a particular severity/the number of raters who reported data*, we used a cell, *N1*, from the top row to hold the number of raters so we could make a single change to the number of evaluators on the spreadsheet and the computations would automatically update. Figure 35 shows how the spreadsheet returns the probabilities with Figure 36 showing the calculation formula used.

	Probability						
	0.00	0.00	0.00	0.00	0.00		0.00
	1.00	0.67	0.17	0.25	0.25	Do Not Use NMDOT Rehabilitated the pavement between QA/QC Rounds	0.83
	2.00	0.33	0.75	0.75	0.75		0.17
	3.00	0.00	0.08	0.00	0.00		0.00
	Check	1.00	1.00	1.00	1.00		1.00

Figure 35. Sample probability values.

	Probability						
	0	=C17/$N$1	=D17/$N$1	=E17/$N$1	=F17/$N$1		=K17/$N$1
	1	=C18/$N$1	=D18/$N$1	=E18/$N$1	=F18/$N$1	Do Not Use NMDOT Rehabilitated the pavement between QA/QC Rounds	=K18/$N$1
	2	=C19/$N$1	=D19/$N$1	=E19/$N$1	=F19/$N$1		=K19/$N$1
	3	=C20/$N$1	=D20/$N$1	=E20/$N$1	=F20/$N$1		=K20/$N$1
	Check	=SUM(C22:C25)	=SUM(D22:D25)	=SUM(E22:E25)	=SUM(F22:F25)		=SUM(K22:K25)

Figure 36. Probability calculation formulas

As a check to ensure that we get a maximum probability of 1.00 I reserved the row below the probability rows for a check. I simply summed the previous four rows or in this case rows C22 though C25 for the first column of evaluation probabilities. These rows are just the sum of the probabilities for the four possible severities; *=sum(probability of 0+probability of 1+probability of 2+probability of 3).* They should always sum to one, if they do not then check to ensure the raters did not miss a milepost. Figures 37 and 38 how to setup the row to check you don't have a probability greater than 1.00

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	Check	1.00	1.00	1.00	1.00

Figure 37. Probability check

	Check	=SUM(C22:C25)	=SUM(D22:D25)	=SUM(E22:E25)	=SUM(F22:F25)

Figure 38. Probability calculation formulas

The final row was reserved for the distribution:

=RiskOutput("RW1")+RiskDiscrete({0,1,2,3},probability of 0 : probability of 3, RiskName(route number+milepost number)) This was the basic format for all of the pavement distresses with some alterations made for alligator cracking and transverse cracking which I will go into detail later. The final row is reserved for the distribution created to deal with the number of data input. Figure 40 shows the final row with the distribution inputted, *=RiskOutput("RW1")+RiskDiscrete({0,1,2,3},C22:C25, RiskName(C2+C3))*.

	Distribution					
		1.00	2.00	2.00	2.00	1.00

Figure 39. Distribution format with sample values

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Figure 40. Distribution formulas

When developing the spreadsheet for alligator cracking I started with the same spreadsheet format as all of the other spreadsheets with the route names and mileposts listed across the top and the raters down the left side with the area for the milepost in each cell.

Figure 41. Alligator cracking input with evaluator's values

A major difference from the other pavement distress spreadsheets is that I list all three severities on the same spreadsheet since I would need to determine the severity of the most prevalent extent. I just placed them severity 1 with severity 2 and severity 3 spreadsheets underneath in numerical order. Unlike the other pavement distresses I added several rows so identifying extents and severities could be accomplished. At the top I added cells for the number of evaluators to for the probability calculation and the

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boundary values for each extent. The boundary values are the points where the extent will change from zero to one, one to two and from two to three. These are needed for calculations at the bottom of the worksheet.

Alligator Cracking Round 1, Severity 1 , Severity 2, and Severity 3				Evaluators	12.00	Extent Boundaries	158.00	791.00	1425.00
Severity 1									
Route	NM0041	NM0041		NM0014			US 0550		

Figure 42. Heading with extent value thresholds entered

To go from extent zero up to extent one a value of 159 square feet is needed. Extent tow requires 791 square feet and extent three is anything greater than 1425 square feet.

One of the other major changes from the sheets for the other pavement distresses is the inclusion of twelve rows, one for each rater, that uses nested IF commands to determine the extent for each milepost by rater. The formula in the cell looks like this, ***=IF (C7>1425,"3.00", IF (C7>791,"2.00", IF (C7>158,"1.00", IF (C7<158,"0.00")))).*** To put it in a way easier to understand I substitute names for cell designations; ***=IF (rater data input>1425,"3.00", IF (rater data input>791,"2.00", IF (rater data input>158,"1.00", IF (rater data input<158,"0.00")))).*** Cell C7 just happens to be the first rater and first milepost and the data input for alligator cracking is an area. If this was the transverse cracks sheet then the input would be numbers of cracks. I chose not to use the cells where the boundaries are located at top of the spreadsheet to make it easier for me to understand but there is no reason that instead of using values such as 791 you referenced the cell the value is stored.

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Figure 43 (Alligator cracking extents):

Extent					Do not Use NMDOT Rehabilitated the Test Section between QA/QC Rounds														
1.00	0.00	0.00	0.00	1.00		0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00		0.00	0.00	1.00	1.00	0.00	0.00	2.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00
3.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00
4.00	0.00	0.00	0.00	0.00		0.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00		0.00	0.00	1.00	0.00	0.00	0.00	2.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00		0.00	0.00	1.00	0.00	0.00	0.00	2.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
8.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
9.00	0.00	0.00	0.00	1.00		1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	2.00
10.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00
11.00	0.00	0.00	0.00	1.00		0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	1.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00

Figure 43. Alligator cracking extents

Figure 44 (Alligator cracking extent calculation formulas):

Extent				
1	=IF(C7>1425,"3.00",IF(C7>791,"2.00",IF(C7>158,"1.00",IF(C7<158,"0.00"))))	=IF(D7>1425,"3.00",IF(	=IF(E7>1425,"3.00",IF(	=IF(F7>1425,"3.00",IF(
2	=IF(C8>1425,"3.00",IF(C8>791,"2.00",IF(C8>158,"1.00",IF(C8<158,"0.00"))))	=IF(D8>1425,"3.00",IF(	=IF(E8>1425,"3.00",IF(	=IF(F8>1425,"3.00",IF(
3	=IF(C9>1425,"3.00",IF(C9>791,"2.00",IF(C9>158,"1.00",IF(C9<158,"0.00"))))	=IF(D9>1425,"3.00",IF(	=IF(E9>1425,"3.00",IF(	=IF(F9>1425,"3.00",IF(
4	=IF(C10>1425,"3.00",IF(C10>791,"2.00",IF(C10>158,"1.00",IF(C10<158,"0.00"))))	=IF(D10>1425,"3.00",IF	=IF(E10>1425,"3.00",IF	=IF(F10>1425,"3.00",IF
5	=IF(C11>1425,"3.00",IF(C11>791,"2.00",IF(C11>158,"1.00",IF(C11<158,"0.00"))))	=IF(D11>1425,"3.00",IF	=IF(E11>1425,"3.00",IF	=IF(F11>1425,"3.00",IF
6	=IF(C12>1425,"3.00",IF(C12>791,"2.00",IF(C12>158,"1.00",IF(C12<158,"0.00"))))	=IF(D12>1425,"3.00",IF	=IF(E12>1425,"3.00",IF	=IF(F12>1425,"3.00",IF
7	=IF(C13>1425,"3.00",IF(C13>791,"2.00",IF(C13>158,"1.00",IF(C13<158,"0.00"))))	=IF(D13>1425,"3.00",IF	=IF(E13>1425,"3.00",IF	=IF(F13>1425,"3.00",IF
8	=IF(C14>1425,"3.00",IF(C14>791,"2.00",IF(C14>158,"1.00",IF(C14<158,"0.00"))))	=IF(D14>1425,"3.00",IF	=IF(E14>1425,"3.00",IF	=IF(F14>1425,"3.00",IF

Figure 44. Alligator cracking extent calculation formulas

The frequency, probability and check rows remain the same as for the other pavement distresses. The frequency is calculated with the **COUNTIF** function: *=COUNTIF (C19:C30, $B$32)* referencing the extent instead of the raw data inputted by raters. To put names to cell references; *=COUNTIF (extent of that milepost for first rater: extent of that milepost for last rater, the severity of interest)*

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Frequency

0.00	12.00	12.00	12.00	8.00			11.00	12.00	8.00	11.00	12.00	12.00	2.00	12.00	7.00
1.00	0.00	0.00	0.00	4.00			1.00	0.00	4.00	1.00	0.00	0.00	6.00	0.00	5.00
2.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	4.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Probability

0.00	1.00	1.00	1.00	0.67			0.92	1.00	0.67	0.92	1.00	1.00	0.17	1.00	0.58
1.00	0.00	0.00	0.00	0.33			0.08	0.00	0.33	0.08	0.00	0.00	0.50	0.00	0.42
2.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00
3.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 45. Frequency and probability results

Frequency

0	=COUNTIF(C31:C42,$B	=COUNTIF(D31:D42,$B	=COUNTIF(E31:E42,$B	=COUNTIF(F31:F42,$B
1	=COUNTIF(C31:C42,$B	=COUNTIF(D31:D42,$B	=COUNTIF(E31:E42,$B	=COUNTIF(F31:F42,$B
2	=COUNTIF(C31:C42,$B	=COUNTIF(D31:D42,$B	=COUNTIF(E31:E42,$B	=COUNTIF(F31:F42,$B
3	=COUNTIF(C31:C42,$B	=COUNTIF(D31:D42,$B	=COUNTIF(E31:E42,$B	=COUNTIF(F31:F42,$B

Probability

0	=C44/$N$1	=D44/$N$1	=E44/$N$1	=F44/$N$1
1	=C45/$N$1	=D45/$N$1	=E45/$N$1	=F45/$N$1
2	=C46/$N$1	=D46/$N$1	=E46/$N$1	=F46/$N$1
3	=C47/$N$1	=D47/$N$1	=E47/$N$1	=F47/$N$1

Figure 46. Frequency and probability formulas

The rows following the frequency calculation is reserved for calculating the probability of the four possible severities, 0-3. I simply divide the frequency by the total number of raters that rated that milepost for that distress. I say this because some mileposts and distresses were not reported. If the cell used to check that the probabilities sum to one show something less than one then review the data and adjust the number of raters in the probability calculation to the actual number of raters that reported. The

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probability calculation is the same as the other pavement distresses; *=frequency/number of raters who reported*. The check row ensures the probability totals to one by summing all four of the probabilities, *=SUM (probability of a 0 + probability of a 1 + probability of a 2 + probability of a 3).*

For each sheet the distribution row is still used *=RiskOutput("AG1")+RiskDiscrete({0,1,2,3},probability of a 0:probability of a 3, RiskName(route number+milepost number)),* but an additional row is included to sum and average the square footage for each milepost from all the raters. This is used to determine the average area for each milepost. This is done for all three of the severities so at the end they can be compared and the most prevalent extent and severity determined.

3.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Check	1.00	1.00	1.00	1.00			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Distribution															
	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
Summed															
	13.80	18.40	84.40	1639.40			1428.00	731.40	1465.40	1535.00	0.00	711.80	6042.80	541.70	2533.60
							Severity #2								

Figure 47. Greatest extent and severity results

	Extent Distribution	=RiskOutput("AG1")+RiskDiscrete({0,1,2,3},C37:C40, RiskName("Alligator Cracking Round 1, Severity 1"))		=RiskOutput("AG1")+	=RiskOutput("AG1")+
	Averaged Sum	=SUM(C7:C18)/12		=SUM(D7:D18)/12	=SUM(E7:E18)/12
Route			NM0041		
Milepost					

Figure 48. Greatest extent and severity calculation formulas

At the bottom of the severity 3 calculations, the bottom of the sheet, five additional rows were added to determine the greatest extent and severity. It also determines which of the three severity distributions to use in the distress rate portion of the P.S.I. equation. To determine the most prevalent extent two rows are used with the IF command to find which of the three different "summed" rows, one for each severity, is the greatest,

"Severity Used in Distress Rate", *=IF(Severity #1 averaged area sum>Severity #2 averaged area sum,Severity#1 averaged area sum, Severity #2 averaged area sum)* and

"Distribution Used for Extent in Distress Rate", *=IF (Previous extent calculation-row 135>Severity #3 averaged area sum, previous extent calculation, Severity #3 averaged area sum)*.

With the cell designations in place the formulas looks like this:

"Severity Used in Distress Rate", *=IF (C133>C89, "3.00", IF(C89>C45,"2.00",IF(C45>158,"1.00","0.00")))*

"Distribution Used for Extent in Distress Rate", *=IF(C133>C89,C131,IF(C89>C45,C87,IF(C45>158,C43,"0.00")))*

Row 135 is the severity to be used when calculating the distress rate and row 136 is the distribution to be used for the extent in the distress rate calculations.

To put it another way each of the three severities has a row that returns the average area for each milepost. I then need to identify which of those areas are the greatest; this is the most prevalent area or extent. Once that is accomplished I needed to identify from which severity the most prevalent area or extent is from; I did this with a

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series of **IF** commands to identify everything. After identifying the most prevalent extent and severity I used the **IF** command a final time to identify the distribution associated with the most prevalent extent and severity.

Extent Calculations	13.80	18.40	84.40	1639.40			1428.00	731.40	1465.40	1535.00	11.40	711.80	6042.80	541.70	2533.60
	13.80	18.40	84.40	1639.40			1428.00	731.40	1465.40	1535.00	11.40	711.80	6042.80	541.70	2533.60
Extent	0.00	0.00	0.00	3.00			3.00	1.00	3.00	3.00	0.00	1.00	3.00	1.00	3.00
Severity	1.00	1.00	1.00	1.00			1.00	1.00	1.00	1.00	2.00	1.00	1.00	1.00	1.00
Distribution Used for PSI	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00

Figure 49. Severity results

Extent Calculations	=IF(C57>C113,C57,C113)		=IF(D57>D113,D57,D1	=IF(E57>E113,E57,E11:	=IF(F57>F113,F57,F1:
	=IF(C171>C169,C171,C169)		=IF(D171>D169,D171,(	=IF(E171>E169,E171,E	=IF(F171>F169,F171,(
Extent	=IF(C172>1425,"3.00",IF(C172>791,"2.00",IF(C172>158,"1.00","0.00")))		=IF(D172>1425,"3.00",	=IF(E172>1425,"3.00",	=IF(F172>1425,"3.00"
Severity	=IF(C169>C113, "3.00", IF(C113>C57,"2.00","1.00"))		=IF(D169>D113, "3.00"	=IF(E169>E113, "3.00"	=IF(F169>F113, "3.00
Distribution Used for PSI	=IF(C174=3,C167,IF(C174=2,C111,C55))		=IF(D174=3,D167,IF(D	=IF(E174=3,E167,IF(E1	=IF(F174=3,F167,IF(F

Figure 50. Most prevalent severity and extent calculation formulas

The spreadsheet for transverse cracks is almost the same. There are some slight differences such as the extent boundaries but the form and equations used are virtually identical. I still used the same format as the other sheets with the route numbers and mileposts along the top rows. The raters are listed on the left side vertically oriented. Instead of area inside each cell I have the total number of cracks based on severity for each milepost. Each severity has its own sheet that is arranged vertically from severity 1 to severity 2 and at the bottom is severity 3. This is the same format as used with alligator cracking.

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Figure 51. Example of transverse cracking spreadsheet

Moving downward along the right side of the sheet the next 12 rows calculate the extent of each milepost by rater. The basic formula uses the IF command to determine the extent based on the number of cracks present.

=IF (C7>16,"3.00",IF(C7>8,"2.00",IF(C7>0,"1.00",IF(C7=0,0))))

When I added names to the formula it becomes easier to understand.

=IF (rater's data input>16,"3.00",IF(rater's data input>8,"2.00",IF(rater's data input>0,"1.00",IF(rater's data input=0,0))))

Figure 52. Extent calculation formulas

As I move downward along the sheet the next calculation is to determine the frequency of the different extents with a **COUNTIF** command. This count how many times a certain extent appeared. We have a cell for each of the extents 1 through 3.

=COUNTIF (C19:C30,$B$32)

After I add names:

=COUNTIF (Extent of rater first rater: Extent Rater of last rater, extent of interest form 0-3)

After I have calculated the frequency of each extent, zero through three, I needed to determine the probability of each extent appearing. This is done by dividing each extent by the total number of evaluators who reported for that milepost.

Frequency				
0	=COUNTIF(C19:C30,$B$32)	=COUNTIF(D19:D30,$B$3	=COUNTIF(E19:E30,$B$3	=COUNTIF(F19:F30,$B$3
1	=COUNTIF(C19:C30,$B$33)	=COUNTIF(D19:D30,$B$3	=COUNTIF(E19:E30,$B$3	=COUNTIF(F19:F30,$B$3
2	=COUNTIF(C19:C30,$B$34)	=COUNTIF(D19:D30,$B$3	=COUNTIF(E19:E30,$B$3	=COUNTIF(F19:F30,$B$3
3	=COUNTIF(C19:C30,$B$35)	=COUNTIF(D19:D30,$B$3	=COUNTIF(E19:E30,$B$3	=COUNTIF(F19:F30,$B$3
Probability				

Figure 53. Frequency calculations formulas

Probability calculations:

=C32/$N$1

=Frequency of extent/total number of raters who reported transverse cracks for that milepost

Probability														
0.00	1.00	1.00	1.00	1.00		0.58	1.00	1.00	1.00	1.00	0.00	0.00	0.33	1.00
1.00	0.00	0.00	0.00	0.00		0.42	0.00	0.00	0.00	0.00	0.83	0.17	0.58	0.00
2.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.17	0.33	0.08	0.00
3.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00
Check	1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Distribution	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	1.00	2.00	1.00	0.00

Figure 54. Probability results

Figure 55. Probability calculation formulas

The same as the sheet for alligator cracking I summed the probabilities to ensure they add to one and put that on its own row.

Figure 56. Extent distribution formula

Following that is the row with the distribution:

=RiskOutput("TC1")+RiskDiscrete({0,1,2,3},C37:C40, RiskName(C3+C4))

With names substituted for cell references we get:

=RiskOutput("TC1")+RiskDiscrete({0,1,2,3},probability of extent 0:probability of extent 3, RiskName(TC Round 1 Severity 3))

Figure 57. Averaged of totaled number of cracks formulas

Following these calculations is the averaged of the total number of cracks for each milepost. *=SUM(C7:C18)/12*

With names I get: *=SUM(number of cracks for first rater: number of cracks for final rater)/the number of raters that reported back for that milepost*

Figure 58. Extent calculation formulas

After the Severity 3 sheet I added additional rows to determine the most prevalent extent, the severity of the most prevalent extent and its distribution. The calculations are virtually the same as for alligator cracking worksheets. There are two rows dedicated to determining the greatest extent:

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Row 135 *"Severity used in Distress Rate", =IF(C45>C89,C45,C89)*

Row 136 *"Distribution Used for Extent in Distress Rate", =IF (C135>C133, C135, C133)*

Then replace the cell designations with names it looks like this:

Row 135 *"Severity used in Distress Rate", =IF(Severity 1 Averaged Sum>Severity 2 Averaged Sum, return Severity 1 Averaged Sum, otherwise return Severity 2 Averaged Sum)*

Row 136 *"Distribution Used for Extent in Distress Rate", =IF (Previous extent calculation>Severity 3 Averaged Sum, return Severity 3 Averaged Sum, Otherwise return Severity 2 Averaged Sum)*

Figure 59. Extent distribution formulas

When I took a look at the distresses of edge cracking, patching and longitudinal cracking I saw that all the distresses were can be treated the same way for both the severity and the extent since both are reported individually. What I mean by that is the severity and extent of those three pavement distresses are subjected to evaluation variability unlike alligator or transverse cracking which are dependent on the quantity of the distress. This actually simplifies creating the spreadsheets. I am going to use

longitudinal cracking as an example but both edge cracking and patch condition are arranged exactly the same.

The spreadsheet is set up along the heading the same as all of the other sheets with the routes and mileposts evaluated. The values entered here are direct from the evaluator's evaluation sheets and indicated the severity of any longitudinal cracks found. If this was a sheet for extent then the extent values from the evaluation forms would be inputted instead.

Figure 60. Sample heading for longitudinal cracks

Following the input of the raw data, whether it is severity or extent, I need to determine the frequency of either the severity of cracks present or the extent of those cracks. Like the other sheets up until now I used a COUNTIF command to count the presence of crack severities or extents.

=COUNTIF(C4:C15,$B$17)

=COUNTIF(First rater's evaluation: final rater's evaluation, the severity or extent we are counting)

With names to replace the cell identifications:

16		Frequency			
17		0	=COUNTIF(C4:C15,$B$17)	=COUNTIF(D4:D15,$E	=COUNTIF(E4:E15,$B	=COUNTIF(F4:F15,$B
18		1	=COUNTIF(C4:C15,$B$18)	=COUNTIF(D4:D15,$E	=COUNTIF(E4:E15,$B	=COUNTIF(F4:F15,$B
19		2	=COUNTIF(C4:C15,$B$19)	=COUNTIF(D4:D15,$E	=COUNTIF(E4:E15,$B	=COUNTIF(F4:F15,$B
20		3	=COUNTIF(C4:C15,$B$20)	=COUNTIF(D4:D15,$E	=COUNTIF(E4:E15,$B	=COUNTIF(F4:F15,$B
21		Probability			
22		0	=C17/$N$1	=D17/$N$1	=E17/$N$1	=F17/$N$1
23		1	=C18/$N$1	=D18/$N$1	=E18/$N$1	=F18/$N$1

Figure 61. Frequency and probability formulas

The probability that any given severity or extent may be found along that milepost test section I take the frequency of the various severities and extents and divide it by the number of raters who reported.

21	Probability																
22	0.00	0.00	0.00	0.17	0.00		0.00	0.00	0.00	0.00	0.83	0.00	0.00	0.00	0.17	0.58
23	1.00	0.83	1.00	0.83	1.00	Do Not Use, NMDOT Rehabilitated the test section between QA/QC Rounds	0.67	0.33	0.00	0.00	0.17	0.33	0.17	0.00	0.83	0.42
24	2.00	0.17	0.00	0.00	0.00		0.33	0.67	1.00	0.83	0.00	0.67	0.75	0.25	0.00	0.00
25	3.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.17	0.00	0.00	0.08	0.75	0.00	0.00
26	Check	1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure 62. Probability and check with values shown

21		Probability			
22		0	=C17/$N$1	=D17/$N$1	=E17/$N$1	=F17/$N$1
23		1	=C18/$N$1	=D18/$N$1	=E18/$N$1	=F18/$N$1
24		2	=C19/$N$1	=D19/$N$1	=E19/$N$1	=F19/$N$1
25		3	=C20/$N$1	=D20/$N$1	=E20/$N$1	=F20/$N$1
26		Check	=SUM(C22:C25)	=SUM(D22:D25)	=SUM(E22:E25)	=SUM(F22:F25)

Figure 63. Probability and check formulas

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=C17/$N$1

Let's add names to the formula.

=Extent or severity frequency/number of raters

This is followed with a row that checks to ensure the probability does not exceed one. I simply summed all of the probabilities.

Figure 64. Distribution formula

Following the check to ensure I have a sum of the entire probabilities equal to one, then I have the actual distribution for the values we obtained from the field. This can be seen in figure 64 on row 28. It is this distribution that is used for the inputs to the distress rate.

Remember that this last section starting with figure 45 is applicable for both the severity and extent. The format is the same for severity and extent for all three pavement distresses, edge cracking, patching and longitudinal cracking, primarily because these are all collected using the old evaluation protocol. Under the old evaluation protocol the evaluator in the field is making a judgment decision on both the severity of the pavement distress and independently making a judgment decision concerning the severity's extent. This allows for individual's variability for both and extent and that is why these distresses can be treated in the model the same way using the same format.

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