ABSTRACT

HARRIS, ELIZABETH ALLISON. Sign Maintenance Strategies for Agencies to Comply with the FHWA Minimum Retroreflectivity Standards. (Under the direction of William J. Rasdorf and Joseph E. Hummer.)

A new highway sign management and minimum retroreflectivity standard issued by the Federal Highway Administration (FHWA) is compelling highway agencies to re-evaluate how they manage their signs and determine how to comply with the standard while remaining within their budgets. To demonstrate compliance with these standards, agencies will need to have a traffic sign management method in place. This research created models for sign deterioration and sign management that agencies can use to determine how to modify their traffic sign management practices to maintain a high level of safety on the road in a cost-effective manner.

Sign management methods rely upon knowledge of how retroreflectivity decreases as signs weather and age. To provide this knowledge, data collected for a North Carolina Department of Transportation (NCDOT) sign study and data from five similar US efforts were analyzed using regression to identify the best available deterioration models. Initial results indicated that the best-fitting relationships between retroreflectivity and age were generally linear and that these models were significant despite having low R^2 values. Because age did not explain some of the variance, a re-evaluation of the data including NCDOT divisions as a factor found that sign deterioration differed significantly by division.

Currently, there is limited information about the long-term deterioration of ASTM Type III and IX signs. One way of achieving a better understanding of long-term sign deterioration is to establish an experimental sign retroreflectivity measurement facility (ESRMF). An ESRMF is an arrangement of signs in a controlled area that have their retroreflectivity measured at regular intervals to determine how it deteriorates as a function of time. This

thesis describes how such a facility should look and why. A template is presented that can be used by agencies nationwide for collecting critical sign data to inform policy decisions.

Next, a unique microscopic sign system simulation was developed to quantitatively evaluate the effectiveness of various sign management practices for a wide variety of agencies. Using the Arena simulation software, the author built and validated a simulation model where each sign was represented as a separate entity and moved through a network of sub-models replicating the management and environmental processes experienced annually. The simulation includes sub-models for sign damage, inspection, replacement, and deterioration that are modifiable by key input parameters. The simulation model produces several key estimates on an annual basis for the purpose of comparing different sign management scenarios. The analysis focused on three management methods - nighttime visual inspection, blanket replacement, and expected sign life - and two key sign maintenance functions, sign damage and replacement.

The scenarios comparative analysis found that sign damage is a contributor to sign condition and that sign managers should make prompt replacement of damaged signs a priority. The *blanket replacement* method was found to be less cost-effective than the *nighttime visual inspection* method. The *expected sign life* method was competitive on costs with the visual inspection method. Training inspectors to be more accurate when judging retroreflectivity can realize further savings. Skipping inspection or replacement one year, or having an insufficient sign budget, can lead to degraded sign condition levels. Based on these findings, the author offers five *best practices* that agencies can consider when making sign management decisions.

Sign Maintenance Strategies for Agencies to Comply with the FHWA Minimum Retroreflectivity Standards

by
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DEDICATION

To Jon

BIOGRAPHY

Elizabeth Allison (Graf Peters) Harris is originally from Poughkeepsie, New York and graduated in 1998 from Franklin D. Roosevelt High School in Hyde Park, NY. She then attended The Cooper Union for the Advancement of Science and Art in New York, NY and graduated with a Bachelor of Engineering in Civil Engineering in 2002. Elizabeth earned a Master of Civil Engineering degree from North Carolina State University in 2005. As part of her Ph.D. research in transportation engineering, Elizabeth worked on an evaluation of the North Carolina Department of Transportation's nighttime sign inspection procedure and sign management practices under the direction of Dr. William Rasdorf and Dr. Joseph Hummer.

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1.0 INTRODUCTION

Traffic sign asset management is becoming an important issue for transportation agencies both because the Federal Highway Administration (FHWA) has enacted minimum retroreflectivity standards for traffic signs and because agencies are looking to better asset management to reduce sign costs. To demonstrate compliance with these standards, agencies will need to have some form of traffic sign management in place. Smaller agencies that have a smaller sign population may find creating a sign inventory and regularly updating this inventory with field changes and observations to be a feasible sign asset management strategy. However, larger agencies can have a large sign population, which makes it difficult to inventory and track the condition of every sign in the field.

Traffic signs are an essential component of the transportation system. During the day and night traffic signs provide vital guidance to motorists regarding traffic regulations, destinations, safe speeds, and unexpected road conditions. Minimum sign retroreflectivity standards issued by the FHWA for inclusion in the Manual on Uniform Traffic Control Devices (MUTCD) have focused the attention of administrators and sign managers on improving the nighttime performance of roadway signs (FHWA 2007a). Retroreflectivity can be defined as the ratio of the light that the sign reflects to a driver (cd) to the light that illuminates the sign (lx) per unit area (m^2). In straightforward terms it is a measure of how well the sign can be seen at night.

As a result of the minimum retroreflectivity standards issued by the FHWA, transportation agencies will need to assess whether their current sign management practices will ensure compliance with the standards. Compliance with the standards will involve establishing an agency-wide sign management strategy and ensuring that there is proof of compliance to protect against lawsuits. Sign management strategies generally involve manually evaluating the retroreflectivity of all signs or a sample of signs in a jurisdiction or predicting when signs should be replaced based on information in a comprehensive sign inventory database.

1.1 Problem Statement

The dissertation research will focus on improving traffic sign asset management for both local and state agencies. The implementation of minimum retroreflectivity standards in the MUTCD will present several issues to all local and state agencies responsible for traffic sign replacement and maintenance.

Agencies will need to evaluate whether their current sign asset management practices will ensure compliance with the standards. If not, they will need to develop an improved sign asset management system and adjust their budget accordingly. Although the FHWA has provided guidance on what sign management methods will ensure compliance with the standards, there is limited guidance available to agencies on the costs associated with each management method.

By January 2012, all highway agencies will have to create and put into practice a sign asset management program that includes addressing the minimum retroreflectivity standards (FHWA 2007a). Highway agencies have until January 2015 to have most of their red, white, yellow, and green ground-mounted signs comply with the new retroreflectivity standards. When January 2015 arrives, both compliance (for the safety and well being of the public) and proof of compliance (to protect against lawsuits) will be necessary. An effective management strategy can support both, while keeping costs down. This dissertation seeks to provide guidance to agencies on which traffic sign asset management strategies will enable them to maintain the highest level of safety on the road in the most cost-effective manner.

1.2 Research Objectives

The primary objective of this research is to improve traffic sign management, and in turn, road safety. This objective is met by creating a sign management simulation tool that will assist agencies in determining the management strategy or strategies that will ensure compliance with the FHWA minimum retroreflectivity standards while minimizing costs. To provide a tool that agencies can fully utilize and that best represents real-world conditions, the following tasks are necessary:

1. Gather data on sign deterioration, inspection, and replacement.
2. Design a sign experimental facility that will enable transportation agencies to test signs in a controlled (no damage) environment and determine how their retroreflectivity deteriorates with time.
3. Design, test, execute, and validate a sign asset management simulation that uses the sign asset parameters and agency budget procedures as input parameters and output measures including the resulting sign conditions and costs associated with implementing scenarios.
4. Calculate and compare the total costs of compliance with the proposed FHWA standards for each sign asset management scenario using the sign asset management simulation.
5. Determine what percentage compliance agencies can reasonably achieve.
6. Develop recommended sign management practices from the simulation results.

2.0 BACKGROUND

Traffic sign asset management relies on information about the condition of signs in order to determine the maintenance method and budget necessary to ensure all traffic signs are visible to motorists. The goal of traffic sign asset management is to use information about traffic signs and maintenance practices to determine a cost-effective strategy for maintaining a high level of safety on the roads.

This chapter provides a summary of existing traffic sign asset management knowledge in the areas of condition standards, sign deterioration, condition assessment, asset management, budgeting, and simulation techniques. Traffic sign condition can be determined by evaluating field sign conditions against a common minimum condition standard. The FHWA has added a minimum sign retroreflectivity standard to the MUTCD, and transportation agencies need to decide how to assess traffic sign condition in a cost-effective manner. A better understanding of how traffic signs deteriorate can help agencies determine a traffic sign condition assessment method. Condition assessment is just one component of a traffic sign asset management program. These programs often include sign inventories and budgeting tools to better predict what resources are required to maintain signs at a desired performance level. Simulations of different traffic sign asset management scenarios can be used to compare scenario costs and resulting field conditions.

2.1 FHWA Minimum Retroreflectivity Standards

Beginning in the early 1990's, the FHWA sponsored several studies to develop recommendations for minimum traffic sign retroreflectivity levels. This effort was motivated by a congressional directive to create a minimum sign retroreflectivity standard in response to the aging U.S. population (1992). These studies represent various attempts to define and refine the concept of minimum sign retroreflectivity. Initial minimum retroreflectivity levels were developed through research in the early 1990's (Paniati and Mace 1993). In 1998 a report revised these levels (McGee and Paniati 1998). Further updated minimum levels were proposed in 2003 (Carlson and Hawkins 2003) and these are the ones that FHWA proposed for use. Carlson et al. then wrote a paper that describes the evolution of the research to develop minimum levels of sign retroreflectivity (2003).

Before the final minimum retroreflectivity standards were included in the MUTCD, several refinements and updates were incorporated into the 2003 levels (Carlson and Hawkins 2003):

- An improved computer model was used to develop the minimum levels.
- Additional sheeting types were incorporated into the minimum levels.
- Headlamp (headlight) performance was updated to represent the model year 2000 vehicle fleet.
- Vehicle size was increased to represent the greater prevalence of sport utility vehicles and pickup trucks.
- The luminance level needed for legibility was increased to better accommodate older drivers.
- Minimum retroreflectivity levels were consolidated across more sheeting types to reduce the number of minimum levels.

Table 2.1 shows the minimum retroreflectivity standard that a sign must meet to be compliant. The minimums vary based on sign type and color. They represent the most current research recommendations, and the recommendations of the FHWA. This table is referenced in the Revision 2 to the 2003 MUTCD (FHWA 2007a). The revision also includes methods that agencies can use to maintain traffic sign retroreflectivity. The Condition Assessment Methods section of this chapter discusses these methods.

Table 2.1. Federal Highway Administration Retroreflectivity Minimums (FHWA 2007a)

*Table 2A-3. Minimum Maintained Retroreflectivity Levels*①

Sign Color	Sheeting Type (ASTM D4956-04)				Additional Criteria
	Beaded Sheeting			Prismatic Sheeting	
	I	II	III	III, IV, VI, VII, VIII, IX, X	
White on Green	W*; G ≥ 7	W*; G ≥ 15	W*; G ≥ 25	W ≥ 250; G ≥ 25	Overhead
	W*; G ≥ 7	W ≥ 120; G ≥ 15			Ground-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			②
	Y*; O*	Y ≥ 75; O ≥ 75			③
White on Red	W ≥ 35; R ≥ 7				④
Black on White	W ≥ 50				–

① The minimum maintained retroreflectivity levels shown in this table are in units of cd/lx/m² measured at an observation angle of 0.2° and an entrance angle of -4.0°.
② For text and fine symbol signs measuring at least 1200 mm (48 in) and for all sizes of bold symbol signs
③ For text and fine symbol signs measuring less than 1200 mm (48 in)
④ Minimum Sign Contrast Ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity)
* This sheeting type should not be used for this color for this application.

Bold Symbol Signs

- W1-1, -2 – Turn and Curve
- W1-3, -4 – Reverse Turn and Curve
- W1-5 – Winding Road
- W1-6, -7 – Large Arrow
- W1-8 – Chevron
- W1-10 – Intersection in Curve
- W1-11 – Hairpin Curve
- W1-15 – 270 Degree Loop
- W2-1 – Cross Road
- W2-2, -3 – Side Road
- W2-4, -5 – T and Y Intersection
- W2-6 – Circular Intersection
- W3-1 – Stop Ahead
- W3-2 – Yield Ahead
- W3-3 – Signal Ahead
- W4-1 – Merge
- W4-2 – Lane Ends
- W4-3 – Added Lane
- W4-5 – Entering Roadway Merge
- W4-6 – Entering Roadway Added Lane
- W6-1, -2 – Divided Highway Begins and Ends
- W6-3 – Two-Way Traffic
- W10-1, -2, -3, -4, -11, -12 – Highway-Railroad Advance Warning
- W11-2 – Pedestrian Crossing
- W11-3 – Deer Crossing
- W11-4 – Cattle Crossing
- W11-5 – Farm Equipment
- W11-6 – Snowmobile Crossing
- W11-7 – Equestrian Crossing
- W11-8 – Fire Station
- W11-10 – Truck Crossing
- W12-1 – Double Arrow
- W16-5p, -6p, -7p – Pointing Arrow Plaques
- W20-7a – Flagger
- W21-1a – Worker

Fine Symbol Signs – Symbol signs not listed as Bold Symbol Signs.

Special Cases

- W3-1 – Stop Ahead: Red retroreflectivity ≥ 7
- W3-2 – Yield Ahead: Red retroreflectivity ≥ 7; White retroreflectivity ≥ 35
- W3-3 – Signal Ahead: Red retroreflectivity ≥ 7; Green retroreflectivity ≥ 7
- W3-5 – Speed Reduction: White retroreflectivity ≥ 50
- For non-diamond shaped signs such W14-3 (No Passing Zone), W4-4p (Cross Traffic Does Not Stop), or W13-1, -2, -3, -5 (Speed Advisory Plaques), use largest sign dimension to determine proper minimum retroreflectivity level.

Retroreflective sheeting is generally classified into one of ten categories defined by the American Society for Testing and Materials (ASTM 2004). Table 2.2 shows the ASTM requirements for new sheeting for sign colors and sheeting types typically used for permanent traffic signs. The difference between the two tables is that Table 2.1 shows the minimum retroreflectivity standards and Table 2.2 shows the retroreflectivity requirements for a brand new sign. Note that the minimum retroreflectivity standards only cover white, yellow, orange, red, and green sheeting.

Table 2.2. ASTM Retroreflectivity Requirements for New Sheeting (ASTM 2004)

	Color	Sheeting Type						
		I	II	III	VII	VIII	IX	X
ASTM D4956-04	White	70	140	250	750	700	380	560
	Yellow	50	100	170	560	525	285	420
	Orange	25	60	100	280	265	145	210
	Green	9	30	45	75	70	38	56
	Red	14	30	45	150	105	76	84
	Blue	4	10	20	34	42	17	28
	Brown	1	5	12	N/A	21	N/A	17

All table values in $cd/lx/m^2$, observation angle of 0.2°, entrance angle of -4°

2.2 Sign Deterioration

To predict when a sign will need replacement, an agency will need to know when the retroreflectivity of signs with similar characteristics deteriorate to the minimum level established by the FHWA. Signs with the same color and ASTM sign sheeting type tend to deteriorate similarly. The ASTM sheeting types typically used in the US for roadway signs include Type I (Engineering Grade), Type III (High Intensity), and Type IX. Type I sheeting is less retroreflective than Types III and IX, and is therefore no longer being used for new installations in many areas. However, the retroreflectivity deterioration behavior of Type I is the most well defined because it has been in use and researched for several decades. Currently in the literature there is limited information about the long-term deterioration behavior of ASTM Type III High Intensity (encapsulated lens), Type III Prismatic, and IX signs.

Sign deterioration has been studied under controlled or uncontrolled conditions. Controlled conditions means that the signs examined by the research study were installed in a regulated area where the signs were separate from traffic flows. As a result, signs in controlled studies only deteriorate because of natural weathering. Signs studied in uncontrolled conditions are in service along the roads, exposed to traffic and vandalism as well as natural weathering. This section will examine both controlled and uncontrolled sign deterioration studies.

2.2.1 Controlled Studies

The main source for controlled sign deterioration data is the National Transportation Product Evaluation Program (NTPEP) of the American Association of State Highway and Transportation Officials (AASHTO). Manufacturers who want their new sign sheeting product to be used in the US submit it to the NTPEP for testing. Signs tested by NTPEP generally include most sign sheetings used in permanently-installed traffic signs, including Type I, III, and IX. The NTPEP currently tests signs for three years in four states (Minnesota, Arizona, Louisiana, and Virginia) (AASHTO 2005). NTPEP tests two 4" x 12" sign panels for each sheeting type to be tested, and places them on southern-facing test decks angled 45° from horizontal. Placing the signs at this orientation causes the test panels to deteriorate at double the rate of a vertically mounted sign (Carlson et al. 2003). Therefore the NTPEP test panels effectively deteriorate for six years, although they are only placed outdoors for three years. One sign panel for each sheeting type remains indoors to serve as a control. As a result of the NTPEP tests being conducted in a controlled setting, there is less variability in the results than for uncontrolled tests. Generally, R^2 values for deterioration curves (of retroreflectivity versus time) generated from the NTPEP data are greater than 0.8, however, the sample size is small since there are only two weathered samples per sheeting type.

2.2.2 Uncontrolled Studies

Five uncontrolled sign deterioration studies have been conducted in the US in recent years in addition to the tests conducted as a part of the NTPEP. These studies were conducted by the FHWA (Black et al. 1991), the State of Oregon (Kirk et al. 2001), Louisiana State University (Wolshon et al. 2002), Purdue University (Bischoff and Bullock 2002), and North Carolina State University (NCSU) (Rasdorf et al. 2006). These studies measured the retroreflectivity and ages of hundreds of traffic signs in the field and created deterioration models from this data. Nearly all of the deterioration models had R^2 values less than 0.5, indicating that age could not explain much of the variability in the deterioration data.

The Purdue, Louisiana, and FHWA studies investigated whether cleaning signs prior to measurement would improve retroreflectivity. Each of the studies found that although there is a slight improvement in retroreflectivity with cleaning, it is not statistically significant, and higher-intensity sheetings are less likely to show an improvement with cleaning (Bischoff and Bullock 2002; Black et al. 1991; Wolshon et al. 2002). Another cause of variability in retroreflectivity data is the damage and vandalism signs are subject to in an uncontrolled roadside environment. Further discussion and quantification of sign damage rates can be found in Immaneni et al. (2007).

There are very few Type III encapsulated lens sheeting signs in the field older than 15 years. Therefore, the studies cited above could only make limited conclusions about how these signs deteriorate to the point where they are below the FHWA minimums (Rasdorf et al. 2006). Type III signs, as well as Type IX signs, are also available as prismatic sheetings. Encapsulated lens sheetings use glass beads to reflect light back to the driver, while prismatic sheetings use micro prisms to reflect light. These prismatic sheetings have not been studied because there are very few in the field, although many transportation agencies are currently installing or planning to install prismatic sheeting types.

2.2.3 Significance

A previous study of 1057 signs from five NCDOT divisions found only 265 Type III (encapsulated lens) signs and 10 Type IX prismatic signs (Rasdorf et al. 2006). The maximum ages of these signs were 15 and 5 years, respectively. While Type I signs exist in abundance (and their field age varies from new installations to typically 20 years), this is not the case for Types III and IX. In essence, while there are some Type III and IX signs installed in the field their numbers are low and, except for guide signs (which themselves are hard to measure), their locations are generally not recorded in any NCDOT database. Thus, targeted field studies of these signs are not generally feasible. However, by installing a facility like that presented herein it will be possible to begin to collect these critically-needed data that are not otherwise available and for which not other mechanism exists. These data will allow state DOTs to develop efficient and cost effective sign management strategies.

2.3 Condition Assessment Methods

Condition assessment is a critical function of sign asset management systems. Without knowledge of asset conditions, an agency cannot determine which signs have failed and need to be replaced for the safety of the public. Sign failure is indicated by insufficient retroreflectivity or by the sign message being obscured due to sign damage or an object. Sign condition and retroreflectivity assessments can be performed visually, using optical instruments, or by using management methods that attempt to predict when signs will be deficient.

2.3.1 Visual Nighttime Inspection

Visual inspection is the most commonly used condition assessment method for signs. Most agencies use visual inspection as the primary method for determining if a sign needs replacement. Some agencies only observe signs during the daytime, while others observe during the daytime and nighttime.

The advantage of nighttime inspections is that the retroreflective performance of the sign can be clearly viewed by those inspecting the sign. During the daytime most vandalism, mower damage, and sign knockdowns can be identified, however nighttime inspection is necessary to evaluate retroreflective performance and identify nighttime-only visible damage. In NC, the NCSU research group found that approximately 75% of signs needing replacement were identified through nighttime inspections while 25% of replaced signs were identified during the daytime (Rasdorf et al. 2006). It follows from this research that by only inspecting signs during the daytime, an agency could miss up to 75% of the signs needing replacement. Conversely, nighttime inspections are an essential part of visual inspections because most signs needing replacement are identified at night.

2.3.1.1 Inspector Accuracy

Over the last 20 years, several researchers have sought to quantify the accuracy of nighttime visual inspections. In these studies sign inspectors typically view a set of signs and are asked to record whether they pass or fail according to a standard. The standard can be an arbitrary visual standard decided upon by the inspector or it could be an agency-wide minimum standard, such as the FHWA minimum retroreflectivity standard. The qualitative visual judgments of the sign inspectors are compared to quantitative sign retroreflectivity measurements made using a retroreflectometer.

Washington State examined the nighttime performance of 17 sign observers with limited training in 1987 (Lagergren 1987). The observers rated Type I warning and stop signs in laboratory, controlled highway, and uncontrolled highway settings. The uncontrolled highway was a segment of a rural highway with 76 signs and an urban highway with 54 signs. Each sign was rated on a scale of zero to four, with ratings of zero or one indicating that the observers felt the sign needed replacement. Stop signs with a measured white R_A less than 80 and warning signs with a yellow R_A less than 19 were considered to need replacement. The study found that the observers accurately classified warning signs 74% of the time and stop signs 75% of the time. Table 2.3 presents the findings of the Washington

State study. The percent correct are the signs that the observers correctly identified as either passing or failing. Type I errors occur when observers fail the sign but the sign actually passes inspection when it is measured by a retroreflectometer. Type II errors happen when observers pass the sign but when it is measured by a retroreflectometer, the sign fails inspection. It is desirable to minimize Type II errors because they result in deficient signs remaining in service, jeopardizing motorist safety.

Table 2.3. Washington State Study Inspector Accuracy

Sign Type	% Correct	% Type I Error	%Type II Error
Warning	74	20	6
Stop	75	7	18

Texas DOT and the Texas Transportation Institute conducted another study of sign inspector performance in 2001 (Hawkins and Carlson 2001). Approximately 50 field sign inspection personnel participated in rating 49 signs removed from the field on a 5 mile closed course. The inspectors were given no additional training. The inspectors rated each sign acceptable, marginal, or unacceptable, and the researchers also measured vehicle headlamp luminance. The visual inspection results were compared to retroreflectivity measurements using the FHWA minimum retroreflectivity standards. The sign inspectors identified 26 signs as being unacceptable, however only one of these signs was actually unacceptable according to the FHWA standards. The researchers concluded that visual nighttime inspections result in a higher failing rate than does the application of the FHWA minimum standard. This conclusion is based on having only one failing sign in the sample of 49 signs. If there were more failing signs in the study sample then the results could have been different. In other words, one sign below the standard does not provide an adequate sample size to determine overall inspector accuracy. The Texas study emphasized that retroreflectivity is only one factor of sign nighttime performance. Overall variations in retroreflectivity across the face of the sign can be seen during a visual inspection but not through retroreflectometer measurements because only small portions of the sign are measured by the retroreflectometer.

Looking to update the Washington State research, NCSU studied the inspector accuracy of NCDOT sign inspectors in five locations across the state (Rasdorf et al. 2006). The NCSU research team accompanied sign inspection crews as they performed their annual nighttime visual sign inspections and recorded whether the inspectors passed or failed a sign. The following day the research team measured the retroreflectivity of the signs inspected the night before. A total of 1057 signs were both visually inspected and measured by a retroreflectometer in this study. Due to a lack of Type III signs found to be visually or measured deficient, inspector accuracy conclusions could only be drawn for white, yellow, red, and green Type I signs. Table 2.4 gives the inspector accuracy results found by the NCSU study.

Table 2.4. NCSU Study Type I Sign Inspector Accuracy

Sign Color	% Correct	% Type I Error	% Type II Error
White	67	0	33
Yellow	51	2	47
Red	74	4	22
Green	63	5	32

The NC inspectors were found to have greater Type II error percentages than the Washington State inspectors. The research team believed that some of this discrepancy might be due to sign inspectors only failing signs they have the budget to replace. In NC, red stop signs have the highest priority for replacement. Also, the NC inspectors did not participate in a special training session before going out into the field to inspect signs. The NCSU study found that the percent of signs inspected correctly ranged from 54% to 83% for different NCDOT divisions. This observation, along with the red (stop) sheeting color inspector accuracy results being very similar for the NC and WA studies, demonstrates the effect budget has on the real-world inspection decisions of the NC inspectors. The red stop signs best approximate a "budgetless" condition for the NC sign inspectors. The NCSU research team also found that inspector accuracy is generally more critical for Type I signs than Type III because Type I tend to have more issues with retroreflectivity deterioration, insufficient contrast ratio, and damage.

Recently, a nighttime sign inspection accuracy study was conducted in Indiana using university students briefly trained as sign inspectors (Kilgour et al. 2007). A team of two students in a van inspected a total of 1,743 signs, with both students contributing to the nighttime inspection decision. The signs inspected at night were later measured using a retroreflectometer and the retroreflectivity values were compared to the FHWA minimum retroreflectivity standard. Overall, the Indiana study found that 88% of the signs were inspected accurately by the student team and that nighttime visual inspection was completed in approximately half of the time it took to measure retroreflectivity (Kilgour et al. 2007). Table 2.5 presents the inspector accuracy results for the Indiana study.

Table 2.5. Indiana Inspector Accuracy Study Results

Sign Group	Signs Surveyed	Type I Error	% Type I	Type II Error	% Type II	Correct Rating	% Correct Rating
1	681	9	1.3	56	8.2	616	90.5
2	505	1	0.2	65	12.9	439	86.9
3	391	6	1.5	44	11.3	341	87.2
4	162	5	3.1	21	13.0	136	84.0
5	4	0	0.0	3	75.0	1	25.0
All Signs	1743	21	1.2	189	10.8	1533	88.0

Notes:
- Sign Group 1 represents signs with white legend and red background. (Stop, Yield, Do Not Enter, 4-way, 3-way, All-way, etc.)
- Sign Group 2 represents signs with black legend on white background. (Speed Limit, One Way, Guide Arrows, Truck Route, Weight Limit, etc.)
- Sign Group 3 represents signs with black legend on yellow background considered bold symbol signs. (Caution, Road Direction signs, School Signs, RR Crossing Ahead, etc.)
- Sign Group 4 represents signs with black legend on yellow background considered fine symbol signs. (Lettered signs, Playground signs, etc.)
- Sign Group 5 represents all other signs not included in Groups 1-3.

By examining the inspector accuracy results from the Washington State, NCSU, and Indiana, some generalization about inspector accuracy under ideal (no budget influence) conditions can be made. For any color of Type I sheeting, it seems that the expected accuracy (percent correct) will lie between 75 to 85%. The Type I error typically is between 0 and 5%, and the Type II error can be expected to be between 10-20%.

2.3.2 Retroreflectometer Measurement

Retroreflectometer measurement can be used as either an alternative or supplement to visual nighttime inspection. The main advantage of using portable retroreflectometers to assess sign condition is that retroreflectometers provide a quantitative determination of the sign's retroreflectivity that can be directly compared with the FHWA minimum retroreflectivity standards. An agency could use retroreflectometers to measure all signs in their jurisdiction or only signs that a visual nighttime inspection has identified as being questionable. Agencies, such as the Virginia DOT, have measured a random sample of signs using a retroreflectometer instead of measuring all signs, which is very time-consuming and costly relative to visual nighttime inspection (Virginia DOT 2006). Virginia DOT collects data on 10,700 tenth-mile roadway sections and then uses the data to determine the percent of sign assets requiring maintenance by road type (interstate, primary, secondary). In 2005, the overall percent of sign assets "needing work" in Virginia was estimated to be 15.8% from their Random Condition Assessment program (Virginia DOT 2006).

Retroreflectometer measurement has also been used by the State of Louisiana and Hillsborough County, FL. In Louisiana, an 830-sign inventory of logo signs included a retroreflectometer measurement of the blue background sheeting (Smalius et al. 1996). The blue sheeting was measured once in its field condition and then the sign was wiped clean in that spot and measured again. Instead of measuring the retroreflectivity of all signs in an inventory, the Hillsborough County study measured a 95% confidence level sample of 1,423 signs from an inventory of 45,851 signs (Rogoff et al. 2005). The existing inventory did not contain sign retroreflectivity information, just sign type and location. The study measured the retroreflectivity of the sign legend and background and found that approximately 35% of the signs sampled were below the FHWA minimum standard.

ASTM has provided a standard measurement procedure for using portable retroreflectometers to measure sign retroreflectivity (ASTM 2001). Using this procedure, the retroreflectometer readings should correspond to the sign brightness as seen by a driver at a distance of 200 m (656 ft) distance. The procedure requires that retroreflectivity readings be taken at a minimum of four different locations on both the sign background and legend (if retroreflective) and averaged for each retroreflective color. Often in sign retroreflectivity studies and inventories less than four retroreflectivity readings are taken because each measurement results in the inspection time per sign to increase, increasing the cost to measure each sign. This practice is rationalized because often after two or three retroreflectivity measurements the sign retroreflectivity appears to be approximately constant.

Sign retroreflectivity can also be measured using automated mobile measurement units that are able to operate at or near highway speeds, increasing the data collection speed. Automation tends to be very expensive, because mobile units containing integrated instruments, video recorders, and computer hardware need to be either purchased or leased. For example, it cost $210,000 for the FHWA to construct its Sign Management and Retroreflectivity Tracking System (SMARTS) van that automated sign inventory and condition data collection (Smith and Fletcher 2001).

A study of this van’s performance, as compared to a portable handheld retroreflectometer, found its retroreflectivity readings to be unacceptable due to the high variation in readings, a low percentage of signs captured by the van on a single pass, and no correlation between the van retroreflectivity readings and the more accurate handheld retroreflectometer (Smith and Fletcher 2001). Other automated data collection systems have had more success. The mobile pavement marking retroreflectivity measurement vehicle developed by PrecisionScan, LLC has accurately measured pavement markings over the last five years for the NCDOT (Sitzabee 2006).

Mandli Communication Inc. and Facet Technology Corporation have also developed a mobile retroreflectivity measurement system called RetroView™. A vehicle that collects data using the RetroView™ system is illustrated in Figure 2.1. This instrumented vehicle has the ability to collect traffic sign retroreflectivity in a single pass at posted road speeds. The companies announced that over 5,000 signs per day could be measured with its RetroView™ mobile system at the 2005 Transportation Research Board Annual Meeting (Mandli Communications Inc. 2005). The RetroView™ system has been tested versus hand-held retroreflectometer measurements at the Texas Transportation Institute's research facilities, but there is little information available about how well the RetroView™ system performed (Facet Technology Corp. 2009). There is no information in the literature concerning the cost-effectiveness of using the RetroView™ system.

Figure 2.1. RetroView™ vehicle (Mandli Communications Inc. 2005)

The RetroView™ vehicle can collect not only retroreflectivity data at several observation angles but also digital roadway imagery and GPS data with its Roadview6 software, high resolution color digital camera, high definition black and white digital camera, and GPS unit (Mandli Communications Inc. 2005).

2.3.3 Sign Inventory

Vehicles like the RetroView™ are of interest to agencies not only because they can perform sign retroreflectivity condition assessment but they can also create a sophisticated sign inventory containing sign images, position, and attribute data. Not all sign inventories are created using mobile data collection. A sign inventory is a collection of records or a database containing information about sign attributes (age, message, sheeting type), location, and sometimes condition. Most condition assessments begin as part of a sign inventory project. Traditional inventory collection methods such as paper records, sign identification labels, and ambulatory field data collection do not require sophisticated information technology systems. Digital technologies such as voice recognition software and hand-held computers have been used to automate sign inventory data collection. Emerging mobile sign locating, imaging and recognition technologies have sought to automate sign inventory creation.

2.3.3.1 Manual Inventory Methods

The term *manual inventory methods* encompasses all inventory methods that require the person(s) collecting the inventory to physically approach each sign and collect attribute data. The most basic manual inventory method is paper records. These paper records can record sign purchasing and installation, condition assessment, replacement, and location information. Paper records are also used to communicate sign changes in the field to office data entry workers in order to update an existing inventory. This ongoing data updating process has been termed “data-currency” by Larson and Skrypczuk (2004).

The emergence of personal computers and digital databases have facilitated sign inventory creation and data-currency. The need for unique record identifiers for individual sign database entries have led many agencies to assign each sign a unique identification (ID) number, which is also placed on a label on the sign in the field (Jones 2004). The unique ID number can also be encoded in a bar code so that the ID number can be quickly input into a database using a barcode reader (Menezes et al. 1997). A barcode reader often interfaces with a portable computer used to collect sign data for the inventory.

Portable computers, such as personal data assistants (PDAs), have been used by many agencies to aid sign inventory efforts. In Virginia, computer backpacks with voice recognition software technology were field tested to determine if they were an effective for populating a sign inventory (Larson and Skrypczuk 2004). The voice recognition system enabled inspectors to accurately collect data hands-free, but the system was found to be more expensive and time-consuming than other inventory methods.

Because of the desire to include precise positional information about each sign asset, portable computers equipped with global positioning system (GPS) receivers have been used by several agencies to collect sign positional and attribute data using the same unit (Jones 2004). These GPS-equipped units collect point data for each sign and allow the inspector to collect sign attributes defined by the data dictionary (data collection items) pre-loaded onto the device. GPS-collected positional sign data have been found to have an accuracy near vendor-provided specifications (typically within 1-3 meters) and to have less positional error than positions determined using a route-milepost system (Hawkins et al. 2007). Once the GPS positional data and corresponding sign attribute data have been collected, the inventory can be imported into a geodatabase that can use geographic information system (GIS) software to display sign locations and sign attributes (Kruse and Simmer 2003).

For sign inventories created in a GIS, data-currency can be performed in several ways. In the Virginia inventory study, paper forms filled out by sign maintenance crews equipped with GPS devices were used to update the GIS sign inventory. These forms were then sent to a central office where the GIS inventory was modified (Larson and Skrypczuk 2004). New Mexico updates inventory data when a work order is completed for the sign (Haas and Hensing 2005).

2.3.3.2 Mobile and Automated Inventory Methods

Instead of physically approaching each sign to conduct manual inventory data collection, inventories can be populated by sensors and instruments recording sign assets as they pass by the signs at highway speeds. Mobile inventory data collection typically involves a vehicle equipped with video and photographic cameras recording images of signs along the road. These vehicles also may have a GPS unit that can attach GPS coordinates to (georeference) an image, essentially locating the sign. Limitations of mobile inventories for sign applications include the intervals between photographic images being too large to capture the sign well and the inability to completely assess sign condition and attributes such as age. The Virginia inventory study identified these limitations of mobile inventories while using a combination of right of way image collection and voice recognition software to collect inventory data on overhead signs, which could not be reached with manual data collection (Larson and Skrypczuk 2004). Mobile data collection can make it easier and safer to collect inventory data along high-speed roads because inspectors do not need to leave the vehicle.

Mobile inventory data collection can be automated not only through the use of images/video and GPS but through emerging technologies. Algorithms have been developed and field tested that can recognize the image of a sign within a larger image taken by a mobile inventory van (Wang et al. 2007). A system known as Geo-3D combines inventory image data with laser technology enabling the laser to aid in asset recognition (Laflamme et al. 2006). In Michigan and Missouri, there have been efforts to also assess sign visibility condition during mobile inventory data collection. The Mobile Evaluation of Traffic Signs (METS) van was developed in Michigan and uses image analysis software to determine sign retroreflectivity from a black and white sign image taken during the daytime (Long 1997). The METS van also takes a color image of the sign for identification and inventory purposes.

The Missouri system used digital video analysis of color sign images taken at night by a camera in a moving vehicle to determine sign visibility (Maerz and Niu 2003). Mobile/automated sign inventories can be kept current by scheduling data collection passes at regular intervals through the jurisdiction. If inventory runs are not repeated on a regular basis the inventory collected using the mobile technology will become outdated shortly.

2.3.4 Management Condition Assessment Methods

Sign condition assessment traditionally was performed through qualitative daytime and nighttime visual inspection. With the introduction of retroreflectometers, quantitative sign condition assessments became possible. The FHWA has also put forward several "management methods" for agencies to use in place of the visual and retroreflectometer methods (Chappell and Schertz 2005). Management methods do not involve evaluating every sign in place on the roadways. Instead, management methods predict how long signs with similar characteristics (such as sign color and sheeting type) will maintain an above-standard retroreflectivity, also known as the sign life. When the end of the sign's lifetime has been reached, it should be replaced.

The expected sign life method calculates a sign life from known sign retroreflectivity deterioration rates for combinations of sign sheeting color and sheeting type. The expected sign life method requires tracking the age of signs either by using sign installation date labels on the back of each sign or maintaining a sign asset management system that can identify the age of every sign in the jurisdiction. When an individual sign's retroreflectivity is predicted to fall below the minimum it should be replaced. As a part of their asset management analysis, Michigan DOT uses expected sign life based on retroreflectivity deterioration research to determine when a sign should be replaced (Cambridge Systematics and Meyer 2007).

The blanket replacement method replaces all signs along a corridor, within an area, or of the same sign and sheeting type at intervals based on the expected sign life of the signs. For blanket replacement, the replacement interval can be selected by DOTs based on previous sign deterioration experience or the sign sheeting manufacturer's warranty period. Once the time interval has elapsed, all signs within the corridor/area/type are replaced, regardless of age.

The control sign method uses signs either in a controlled study yard or a sample of signs from the field to determine sign life. The control sample of signs is used to represent all of the signs in an agency's jurisdiction. The sampling plan should ensure that the quantity and diversity of signs sampled represents the agency's sign population and that there is monitoring of sign retroreflectivity at regular intervals. When a control sign's retroreflectivity is measured by a retroreflectometer and is found to fall below the minimum level, all similar signs in the field should be replaced. All three of these management methods require basic knowledge of the age and performance characteristics of the signs on the roadways. A database of signs by type, sheeting type, and age needs to be updated at regular intervals (at least every five years) to ensure that the management condition assessment methods reflect actual conditions. Random sampling of sign assets can be used to update sign database data.

2.4 Traffic Signs Asset Management

Condition assessment is just one element of a comprehensive traffic sign asset management system. A traffic sign asset management system is "a coordinated program of policies and procedures which ensure that the highway agency provides a sign system that meets the needs of the user most cost-effectively within available budgets and constraints" (McGee and Paniati 1998). Sign asset management encompasses all of the activities that take place during a sign's lifecycle from sign material selection to replacement. Figure 2.2 illustrates the activities within the lifetime of a sign that a highway sign asset management system includes.

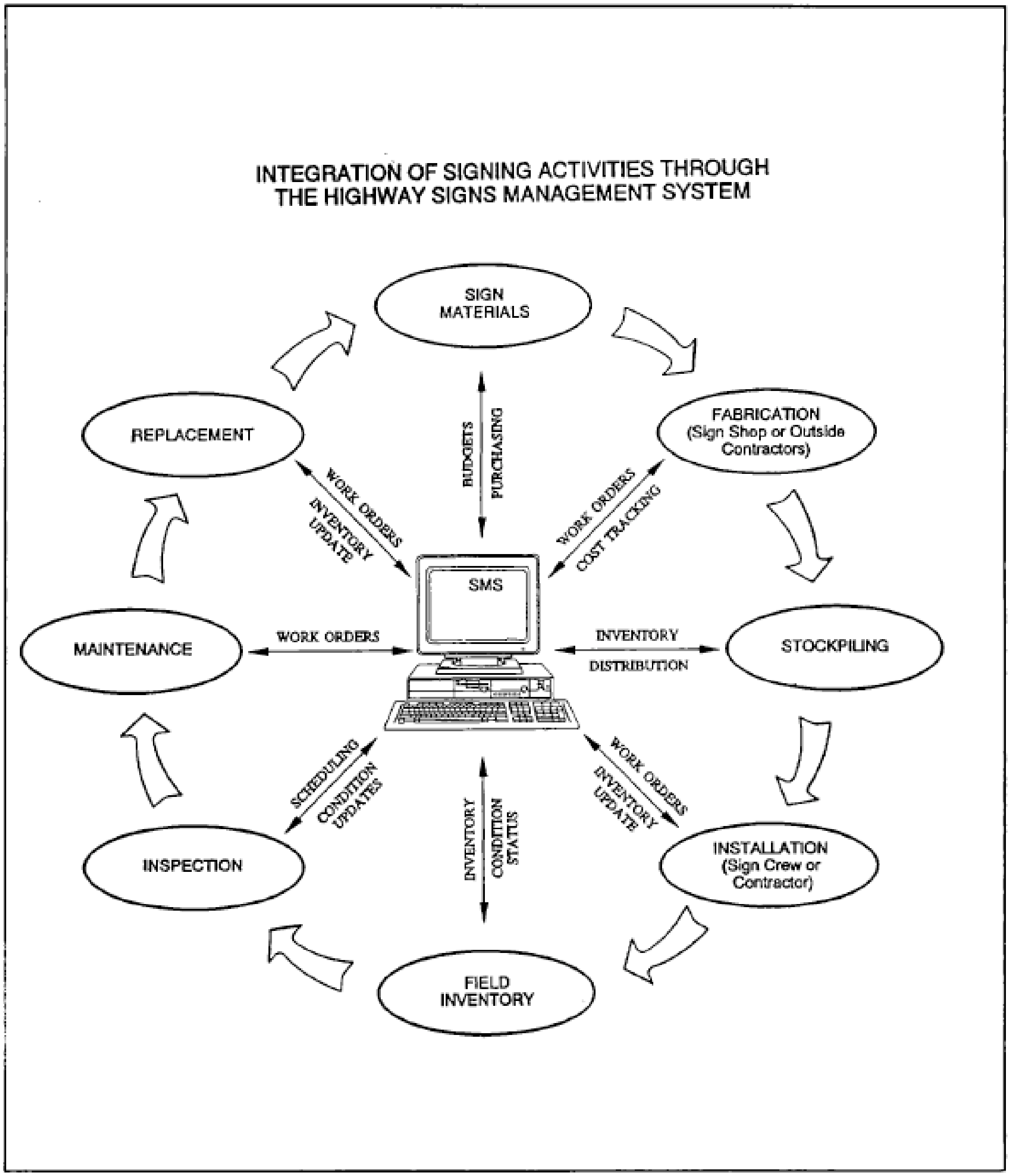


Figure 2.2. Highway Sign Lifecycle and Management Elements (McGee and Paniati 1998)

McGee and Paniati (1998) outlined the following steps in a sign lifecycle and how asset management can potentially play a role. The sign lifecycle begins with the agency selecting sign materials on the basis of performance (service life), cost, and motorist visibility needs. A sign asset management system (SMS in Figure 2.2) can track the cost and service life of signs currently in the field so that the most cost-effective sign materials can be chosen and then fabricated or ordered. A sign asset management system ideally can anticipate the agency's new sign needs and place the necessary orders and incorporate these costs into the agency's budget.

Once signs have been purchased, the sign asset management system can keep track of the signs stockpiled in the agency's inventory and order additional signs when the inventory is low. Using already existing sign condition and work schedule data, the sign asset management system could suggest locations where new sign installations are needed. Once the new signs are installed, the updated status of the signs would be entered into the sign asset management system via completed agency work orders. The inventory of signs in the field would include data about sign attributes, location, and condition. The sign asset management system can use the sign inventory data to schedule condition assessment of the signs most likely to need replacing or maintenance. The necessary maintenance work can be prioritized, scheduled, and documented through the sign asset management system. The cycle begins again when replacement of deficient sings requires that new signs be fabricated and installed in the field (McGee and Paniati 1998).

The sign asset management system proposed by McGee and Paniati would be fully integrated; however, most existing sign asset management systems are not integrated to this extent. Agencies have instead focused on better managing sign assets through sign **inventories**, **performance**/condition assessment, improving sign maintenance **budgeting**, and **integrating** sign asset management efforts with overall agency asset management efforts.

Sign asset management inventories have been developed using the methods outlined in Section 2.3.3. Agencies that have developed a sign inventory generally also conduct some form of condition assessment, although the assessment may not include nighttime retroreflectivity, just a daytime assessment of the sign's condition. The developers of the FHWA minimum retroreflectivity standards give some leeway to agencies on how they can determine the nighttime performance of signs in their jurisdiction. They state, "the existence of minimum retroreflectivity levels is not intended to imply that agencies need to measure the retroreflectivity of **every sign** in their jurisdictions. Instead, these methods provide agencies with options that will help to improve nighttime sign visibility" (Carlson and Hawkins 2005). In other words, the standard is meant to give agencies flexibility in developing methods to assess sign condition.

Another sign asset management step that some agencies have taken is improving how they record financial transactions related to signs to develop smarter sign budgets. Sign-related financial transactions include sign purchasing, installation, condition assessment, and administrative costs. By recording at greater level of detail what money is spent on these financial transactions the agency can better predict future sign budget needs. Sign budgets can be developed based on the projected sign maintenance needs (also known as zero-based budgeting) and not by increasing the previous year's allotted budget by a growth factor (Haas and Hensing 2005).

A few agencies in the U.S. have begun to integrate their existing sign asset management system (a sign inventory, for example) with other agency asset management systems, such as a maintenance management system (MMS) that tracks what maintenance work is being done in the field. For example, the integration of a sign inventory and an MMS enables sign maintenance work done through the MMS to be automatically reflected in the sign inventory database. Benefits of integrated asset management systems include the ability to share data and improve interdepartmental communication, reduce data discrepancies, improve data collection and reliability, and support strategic decision making (Haas and Hensing 2005). Integration can also result in increased available funding for preventive sign maintenance and a corresponding enhancement of highway safety (Hensing and Rowshan 2005).

Because all agencies manage their sign assets in some way and the amount of funds available for sign asset management in proportion to the number of signs that need to be maintained differs from agency to agency, there is no one size fits all solution to sign asset management. Instead agencies across the U.S. have developed different asset management approaches. Table 2.6 compares sign asset management practices at state and local agencies across the U.S. The year when the program began, a description, the management method(s) used, the condition assessment method(s) used, and the current program status are given. More information about each sign asset management system can be found at the reference cited in the *Agency* column. The four agencies with integrated sign asset management systems are shaded in Table 2.6. This table is not intended to be a comprehensive list of all sign asset management efforts across the U.S. but a summary of the information available in the literature.

Most agencies listed in Table 2.6 began their sign asset management efforts within the last decade, with the exception of Florida DOT, which has had a program since 1975. In Table 2.6, nearly all of the agencies are at the state level, with the exception of Hillsborough County, Florida and the City of Portland, Oregon. The most commonly-used management method is sign inventory, followed by budgeting. In their Sign Inventory Management System (SIMS), the Wisconsin DOT uses sign performance in addition to the inventory and budgeting methods. The SIMS uses a system that records the life span of signs to allow for better financial planning and to prevent signs from being prematurely replaced or remaining in the field in a poor condition (Hensing and Rowshan 2005). Among the agencies listed in Table 2.6, the condition assessment methods used include no assessment, simple daytime visual inspection, nighttime visual inspection, retroreflectometer measurement, and expected sign life. Some larger DOTs, such as Virginia and Florida, only assess the condition of a random sample of their signs and then estimate the condition of their entire sign population.

Table 2.6. Comparison of Sign Asset Management Efforts Across the U.S.

Agency	State	Year	Description	Management Method	Condition Assessment Method	Status
South Carolina DOT (Menezes et al. 1997)	SC	1997	Proposed sign management system using barcodes	Inventory	Nighttime Visual	500,000 signs
North Dakota DOT (Kruse and Simmer 2003)	ND	2003	GPS/GIS based sign inventory	Inventory	Visual	Unknown (Proposed)
New Mexico State Highway and Transportation Department (Haas and Hensing 2005)	NM	2003	New Mexico Road Feature Inventory, Highway Maintenance Management System	Inventory (van video-image), Budgeting	Visual daytime (virtual drive)	Full deployment
Virginia DOT (Haas and Hensing 2005)	VA	2003	Random Condition Assessment	Inventory, Budgeting	Visual Daytime (sampling)	Pilot Deployment
Florida DOT (Haas and Hensing 2005)	FL	1975	Roadway Characteristics Inventory	Inventory (continuous updating)	Visual night and day sampling	Fully Deployed
Tennessee DOT (Haas and Hensing 2005)	TN	2005	Road Information Management System, MMS	Inventory (continuous updating), Budgeting	Visual (nighttime) sampling	Deployed 2005
Georgia DOT (Hensing and Rowshan 2005)	GA	2005	Highway Sign Management System	Inventory (barcoding, stock, roadside)	none	Fully Developed, not deployed
North Carolina DOT (Hensing and Rowshan 2005)	NC	2005	Maintenance Management System	Budgeting	Visual (sampling)	Deployed
Oregon DOT (Hensing and Rowshan 2005)	OR	1994	Sign Management System	Inventory, Budgeting	none	Partially Deployed
Wisconsin DOT (Hensing and Rowshan 2005)	WI	2003	Sign Inventory Management System	Inventory, Performance, Budgeting	Visual	Partially Deployed (365,000 signs)
Michigan DOT (Cambridge Systematics and Meyer 2007)	MI	2006	Safety Program	Inventory, Budgeting	Expected Sign Life	450,000 signs
Ohio DOT (Cambridge Systematics and Meyer 2007)	OH	1997	Maintenance Program	Budgeting	Visual (using laptop)	Fully Deployed
Utah DOT (Cambridge Systematics and Meyer 2007)	UT	1997	Maintenance Management System	Inventory	Visual Night and Day	18,000 Signs
Hillsborough County (Cambridge Systematics and Meyer 2007)	FL	2000	Hillsborough Co. Asset Management System	Inventory	Measured	86,574 signs
City of Portland (Cambridge Systematics and Meyer 2007)	OR	2003	Sign Library	Inventory	none/limited	Deployed

Some agencies have developed program goals that expand upon sign inventories and visual nighttime inspection. Florida DOT has set a statewide goal that a minimum of 80% of road signs should meet performance standards (Cambridge Systematics and Meyer 2007). This goal was based on what would be economically feasible in the state. As an alternative to nighttime visual inspection or retroreflectometer measurement, Michigan DOT chose to implement the expected sign life method described by the FHWA. Michigan calculated a sign lifetime of 15 years based on existing sign deterioration research and warranties and aims to replace signs every 15 years. Overall, 42 states have been found to have some kind of sign asset management program, with most states using manual collection of condition data and unintegrated sign inventory databases (Cambridge Systematics and Meyer 2007).

2.5 Sign Maintenance Costs

Assuming that an agency has determined from sign inventories and condition assessments how many signs need replacing within their jurisdiction, defining and minimizing replacement and ongoing maintenance costs can be a challenge. By determining the lifecycle costs of various signs, agencies can choose the most cost-effective sign materials. Agencies also need to budget for the upcoming implementation of the FHWA minimum retroreflectivity standards, which will require them to demonstrate compliance with the standards.

2.5.1 Lifecycle Costs

The lifecycle cost of a sign is determined by dividing the initial cost to install and purchase a sign by the length of time the sign is expected to perform above a retroreflectivity standard. The units for lifecycle cost are typically dollars per year. The calculated lifecycle cost can be used to compare signs made of different sheeting types and determine which would yield the lowest lifecycle cost, and therefore be the most cost-effective to the agency. The lifecycle cost can also be used to plan an agency's sign budget for future years.

A study conducted for Minnesota DOT in 2000 sought to better define the lifecycle costs of signs in Minnesota (Montebello and Schroeder 2000). The Minnesota study considered initial material costs and installation costs (labor and equipment) when generating their lifecycle costs. The cost of the sign sheeting material was found to be only a small percentage of the total installation cost. Type I and II sign sheeting was assumed to last on average 5 to 7 years, Type III 14 years, and Type VIII and IX 15 to 20 years.

The study calculated a total lifecycle cost over an 18-year period rather than a cost per year. Generally, calculating a cost per year instead of a lifecycle cost over a period of years is better for comparison because a lifecycle cost over a period of years could distort the results. For example, the results of the Minnesota study lifecycle cost analysis for sheeting types I to IX are given in Table 2.7. From this table, it appears that although the Type IX sheeting had the longest projected lifetime, Type III sheeting had the lowest lifecycle cost over 18 years ($78). However, the Minnesota study concluded that Type IX sheeting had a lower lifecycle cost. Dividing the "Initial Sign Face Costs" column by the "Expected Life" column in Table 2.7 yields a cost per year of $5.24 for Type III and $4.66 for Type IX (in 1999 dollars). Although Type IX sheeting had the highest initial sign costs in 2000, its longer visible lifetime resulted in the lowest lifecycle cost. As a result of this analysis, Minnesota DOT decided to switch to all Type IX sheeting (Montebello and Schroeder 2000).

The Minnesota study did not factor into their lifecycle cost analysis the additional safety benefits of more visible signs and of fewer sign replacements lowering the exposure of sign crews to traffic (Montebello and Schroeder 2000). The study found that purchasing signs in bulk could sometimes help to lower the price of signs over bidding for signs by project. As a part of the study, the researchers found from financial records that 60% of the signs ordered by rural local agencies in Minnesota were of Type I sheeting, 30% of Type III, and 10% of Type IX. Looking towards the future, the study emphasized that as more Type III and Type

IX sheeting signs were purchased by agencies, the cost per sign should drop over time, making these sheetings even more cost-effective.

Table 2.7. 18-Year Lifecycle Cost by Sheeting Type (Montebello and Schroeder 2000)

Material Type	Initial Sheeting Material Costs(2)	Initial Sign Face Costs(3)	Initial Sign Costs(4)	Expected Life (Years)	Replacement Costs(5)	Total Costs	Material as a percentage of initial sign face costs	Material as a percentage of initial sign costs
Type I	$5.31	$20.31	$58.31	5-7	$49.92	$108.23	26%	9%
Type II	Not Available	Not Available	Not Available	5-7	Not Available	Not Available	Not Available	Not Available
Type III	$21.94	$35.31	$73.31	14	$4.78	$78.09	62%	30%
Type IV	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available
Proposed Type VII	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available
Proposed Type VIII	$26.56	$45.94	$83.94	18	$0	$83.94	58%	32%
Proposed Type IX	$26.56	$45.94	$83.94	18	$0	$83.94	58%	32%

(1) Based on a 18-year sign life for a 30" X 30" sign.
(2) Sheeting material cost were calculated by multiplying the cost of the material per square foot by 6.25 feet, the size of a 30" X 30" sign.
(3) Initial sign face costs include the sheeting material and the aluminum sign backing. Costs were calculated by using the midpoint of the price ranges listed in Table 1 and multiplying by 6.25 square feet – the size of a 30" X 30" sign.
(4) Initial sign costs include the sign face, the posts, staff time and equipment costs. Estimated costs for posts and hardware are $20 per sign and cost for staff and equipment is estimated at $18 per sign.
(5) Additional replacement costs incurred due to shorter sheeting life. Items calculated in replacement costs included the sign face and labor and equipment costs. In performing the lifecycle analysis a 5 percent discount rate was used. Replacement costs were based on an 18-year life.

2.5.2 Cost of Regulations

Ever since the FHWA began to study implementing minimum retroreflectivity standards, agencies have been interested in what their additional cost would be to comply with the standards. In response to this, the FHWA conducted an economic impacts analysis to determine the cost of the standards to state and local agencies across the U.S. This analysis found that the costs would be about $51 million per year (Federal Highway Administration 2007). The analysis assumed a worst-case scenario with all overhead guide and street name signs needing to be replaced with Type III sheeting over a 10 year period and regulatory, warning, and other ground-mounted signs needing replacement with Type III over 7 years. If the signs were instead replaced with Type VII sheeting, the cost per year would be about $73 million. The FHWA allowed for the 7 and 10 year implementation periods so agencies could divide the total costs of compliance over many years, incorporate the costs into their regular maintenance programs, and allow existing signs to remain in the field to finish their lifetimes (approximately 7 years for a Type I sign).

One agency, the Indiana DOT, conducted research to determine the cost of the standards for Indiana (Kilgour et al. 2007). Using an average replacement cost per sign of $64.58 (includes labor, overhead, Type III sign sheeting, and post) and a knowledge of the average number of deficient signs per mile by road type, the researchers were able to calculate that it would cost $621 in towns and $75 in counties per mile to upgrade signs to meet the FHWA standard. Combining these costs with statewide mileage figures resulted in an estimated total (7-year) compliance cost of $14.2 million for Indiana (Kilgour et al. 2007). This total was calculated assuming that no jurisdictions had an active sign replacement program, whose budget could offset the total cost.

2.6 Asset Management Maintenance Optimization Models

Several researchers have used various optimization models to determine optimal infrastructure management policies. These models attempt to address and account for the uncertainties present in several aspects of asset management. These uncertainties include:

- Uncertainty in **asset deterioration** prediction or forecasting
- Uncertainty in condition assessment **measurement**
- Uncertainty in condition assessment **inspection interval**/decision making
- Uncertainty in maintenance/rehabilitation **application**/policies

Over time as the field of asset management optimization modeling progressed, the models became more complex, progressing from Markov chains to simulation to account for greater uncertainty. All of the optimization models seek to maximize asset condition or performance while minimizing the costs to agencies (inspection and maintenance/rehabilitation costs) and users. Table 2.8 lists these asset management optimization models.

Table 2.8. Asset Management Maintenance Optimization Models

Paper/Model	Author(s) and Year	Model(s) Used	Optimization Goal	Uncertainties Considered
Arizona Statewide Pavement Management System (PMS)	Golabi, Kulkarni, and Way, (1982)	Markov/ Linear Programming	Min. total agency cost	asset deterioration
Optimal Inspection and Repair Policies for Infrastructure Facilities	Madanat, and Ben-Akiva (1994)	Latent Markov Decision Process	Min. lifecycle inspection and maint/ rehabilitation costs	asset deterioration, measurement, inspection int
Singapore PMS	Chan, Fwa (1994)	Non-linear int. prog./GA	min cost	
	Li and Madanat (2002)	Markov	robust policies that can sustain error in deterioration models	deterministic deterioration
	Ouyang and Madanat (2004)	Mixed-integer non-linear prog.	n/a	deterministic deterioration
Simulating Highway Infr. Maint. Policies	de la Garza, (1998)	Simulation (macroscopic)	Min. total agency cost	n/a
Modeling interdependencies in infr. mgt using complex systems	Sandford-Bernhardt, and McNeil, S. (2004)	Simulation (microscopic)	n/a	n/a
Analysis of Maint. Policies for Inductive Loop Detection Systems	Yao, Teng, and Hoel, (2007)	Simulation (microscopic)	min. cost	asset deterioration, inspection int

The first asset management maintenance optimization models used a variation of Markov decision processes to minimize agency cost or maximize condition. All of these models are interested in determining which maintenance policies will lead to lower costs while maintaining some level of asset performance. All of the Markov models seek to optimize pavement management. The first Markov model to appear was the Arizona Pavement Management System in 1982. The Markov process was used to model probabilistic pavement deterioration over time (Golabi, et. al, 1982). A linear programming model was then used to minimize the total agency cost for maintaining the statewide pavement to a desired condition level for a multi-year time span. Further development of the Markov model by Madanat and Ben-Akiva included uncertainty in condition assessment interval and condition assessment measurement in addition to pavement deterioration uncertainty (Madanat and Ben-Akiva, 1994). A simple Markov decision process model was used by Madanat and Li to determine how errors in modeling pavement deterioration affect the selection of optimal maintenance policies. They used a deterministic pavement deterioration model that could be varied to test the sensitivity of the optimal maintenance policies to deterioration modeling uncertainty.

The next stochastic modeling method applied to the maintenance optimization problem was non-linear integer programming. The Singapore PMS developed by Chan and Fwa applied non-linear models to individual roadway segments in a in a network. To solve the non-linear models, a genetic algorithm (PAVENET-R) was developed. Ouyang and Madanat (2004) used a mixed-integer nonlinear programming model with a nonlinear deterministic pavement deterioration model. This study found that non-linear programming incurs unaffordable computational cost when the problem scale increases.

Because of the inability of Markov decision process and non-linear integer programming models to model all of the uncertainties and variables in asset management, simulation models have been developed to tackle the complexities caused by the interactions between asset deterioration and maintenance policies. Simulation has been used as a tool to estimate asset condition and costs over time to choose scenarios that are cost-effective. Because signs are a relatively low-cost asset as compared to bridges and pavements, there has been limited development of sign asset management simulations.

A macroscopic simulation of different sign asset management scenarios was developed by NCSU using a spreadsheet (Microsoft Excel) program (Rasdorf et al. 2006; Vereen et al. 2002). This macroscopic sign simulation divided signs into groups based on their retroreflectivity and modeled how the signs would deteriorate deterministically, become damaged, be inspected, and replaced over time. The simulation was carried out to 120 years to achieve a steady state. Based on the cost per sign and number of signs compliant with the FHWA standard, the simulation found that regular nighttime visual inspection and replacing all signs with Type III sheeting (high intensity or prismatic) would be the most ideal maintenance scenario (Harris et al. 2007). In the area of pavement and bridge management, de la Garza et al. developed a macroscopic simulation to facilitate the decision-making process for one of the nine DOT districts in Virginia. The simulation was based on the number of miles of highway in the system, not on the behavior of individual highway segments.

Currently there are no existing microscopic sign asset management simulations described in the literature. However, microscopic simulations have been developed for pavement and inductive loop detection (ILD) maintenance systems. A microscopic simulation using a spreadsheet program was developed for pavements by Sanford-Bernhardt and McNeil (2006). The simulation modeled the pavement condition and rehabilitation costs over time for a network of 1000 pavement segments. Four different pavement management scenarios were evaluated that varied environmental conditions, maintenance, and rehabilitation strategies. Once the simulation reached a steady-state condition, the user costs (based on actual pavement condition) and the agency costs (based on reported pavement condition) were calculated. The researchers found that inaccurate condition assessment leads to statistically significant differences in actual pavement condition over time. Yao, et al. used microscopic simulation to model how varying maintenance policies affected ILD system condition and costs. The components of each inductive loop were modeled over time in the simulation using a Weibull distribution-based deterioration model, a service crew model, and a maintenance policy model. The simulation was run to a fixed time of 20 years with 30 runs per policy scenario and evaluated system availability, annual maintenance cost per station, number of crews employed, working load, annual maintenance delay time, and cost to availability ratio for the system.

2.7 Research Gaps

Based on the previous sections of this chapter, there are several gaps in the literature in certain areas. There is a lack of Type III (encapsulated lens and prismatic) and Type IX long-term sign deterioration data. Because of this deficiency, it is difficult to estimate with certainty how long these sheetings will perform above the standard. Without a strong estimate of their lifetime, their lifecycle costs cannot be determined with much confidence. Another gap exists in inspector accuracy during nighttime visual inspections research. Only three of the inspector accuracy studies described in Section 2.3.1.1 were able to estimate what percentage of signs would be incorrectly inspected, and each study used a different method to determine inspector accuracy. More research into inspector accuracy would help agencies make more informed decisions about condition assessment.

The largest research gaps occur in the area of sign asset management. Most agencies have approached sign asset management by creating a sign inventory, but only a few have attempted to integrate a sign inventory with other asset management systems. Further research into best practices for integration is needed. There are no existing microscopic sign asset management simulations. A microscopic simulation would be able to model sign deterioration, damage, inspection, and replacement with more variation than a macroscopic simulation. Better simulation methods could help agencies more easily determine what level of compliance with the standards they could reasonably achieve and the cost of that compliance. Simulation results could lead to a better understanding of the tradeoffs between different condition assessment methods and replacement practices.

3.0 RESEARCH METHODOLOGY

The primary objective of this dissertation is to improve traffic sign management and maintenance, and in turn, road safety. To meet this objective, guidance on which traffic sign management practices will enable agencies to maintain a high level of safety on the road in a cost-effective manner are provided. The following research tasks were necessary to provide this guidance and to address the research gaps:

1. Gather data on sign deterioration, inspection, and replacement.
2. Articulate the data collection and management issues involved in traffic sign management and recommend techniques to improve management.
3. Design a sign experimental facility that will enable transportation agencies to test signs in a controlled (no damage) environment and determine how their retroreflectivity deteriorates with time.
4. Evaluate existing sign deterioration models and data and develop a sign deterioration model that can be used in a sign management simulation.
5. Develop models for the processes involved in sign management.
6. Develop a set of sign asset management scenarios.
7. Design, test, execute, and validate a sign management simulation that uses the sign parameters and agency practices as input data and outputs data reflecting the resulting sign conditions and costs associated with management scenarios.
8. Develop recommended sign management practices from the simulation results.

The following sections of this chapter describe in further detail how the author approached these research tasks.

3.1 Data Collection

Most of the sign retroreflectivity, damage, inspector performance, and replacement data available were collected during the winters of 2005 and 2006 in North Carolina by a team of three graduate research assistants led by Elizabeth Harris. Sign retroreflectivity and age data were collected from the North Carolina fieldwork and from data available in the literature and used to determine the best available sign retroreflectivity deterioration models. Please see Section 5.0 for a discussion of the sign deterioration models developed from this data collection effort.

Section 2.3.1.1 describes the data collection and analysis of the inspector accuracy data collected in 2005 as a part of the NCSU study. Further information on sign damage and replacement findings can be found in Rasdorf, et al. (2006).

To gather data on sign deterioration, inspection, and replacement, the following data collection tasks were completed:

- Selection of data collection sites
- Nighttime sign inspector observation and data collection
- Daytime sign retroreflectivity data collection
- Development of sign retroreflectivity deterioration models
- Follow-up data collection

A team of graduate research assistants from NCSU collected retroreflectivity and nighttime sign inspection data in five locations across NC from January to April 2005 as part of an NCDOT research project (Rasdorf et al. 2006). The five locations selected in NC are shown in Figure 3.1. These locations were chosen so that the western, central, and eastern portions of the state were represented in the data set.

At each location, the research team accompanied a local NCDOT sign maintenance crew as they performed a nighttime visual condition assessment of each sign along a predetermined route. The nighttime visual condition assessment was conducted using a typical NCDOT sign maintenance pickup truck. The research team noted the message, rejection reason, and location of each rejected sign, and used GPS tracking software to record the route followed by the inspectors.

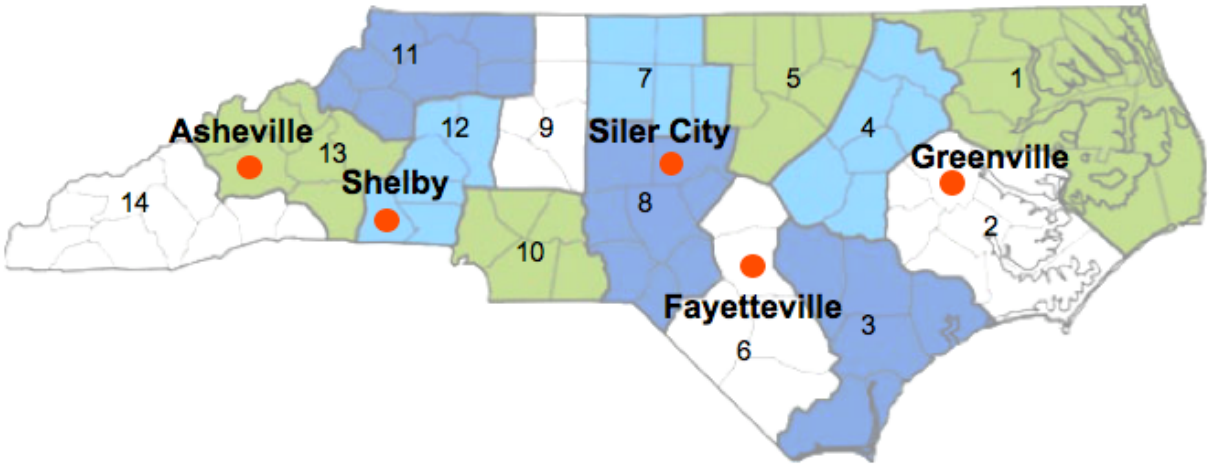


Figure 3.1. Locations Visited for Data Collection

The following morning, the research team measured the retroreflectivity of all signs rejected during inspection by the sign crew and signs not rejected by the sign crew. During retroreflectivity data collection the NCSU research team collected data on white, yellow, red, and green signs and on Types I and III sheeting using a RetroSign® 4500 retroreflectometer that was calibrated (ASTM 2001) each time it was turned on. For each sign, three to five retroreflectivity readings were taken and the sign's color(s), sheeting type, installation date, road type, location, and GPS coordinates were recorded. These data were entered into a Microsoft Excel spreadsheet to serve as a database for analyzing inspector accuracy and retroreflectivity performance over time.

The data gathered from the NCDOT field study were combined with and compared to retroreflectivity deterioration data present in the literature (Bischoff and Bullock 2002; Black et al. 1991; Kirk et al. 2001; Wolshon et al. 2002). The collected and existing data in the literature were analyzed to determine the best available sign retroreflectivity deterioration models for each sign sheeting color-type combination (Immaneni et al. 2009). The NCSU research team found that there was a lack of deterioration data for Type III (high intensity) and Type IX signs because most of these signs had been installed recently. This is the case even for Texas DOT, which changed its retroreflective sheeting policy in 1993 to use Type III sheeting for all new non-white signs. Because Texas DOT did not replace all of their existing signs with new Type III signs in 1993, research found that Type III signs with low retroreflectivity were very rare in Texas (Hawkins and Carlson 2001).

A follow-up sign data collection in Winter 2006 measured the retroreflectivity of the same signs measured in 2005 and noted any new or replaced signs during the one-year period. As of Summer 2006, the data collection research task was completed.

3.2 IT Issues for the Management of High Quantity, Low Cost Assets (Rasdorf et al. 2009)

Transportation infrastructure asset management efforts normally focus on collecting data on items with low volumes and higher capital costs, such as bridges. Road signs and pavement markings, on the other hand, are high volume, low capital cost items but are critical elements of the transportation infrastructure. These high volume assets serve a critical function, safety, and thus they are receiving attention. In particular, the Federal Highway Administration (FHWA) has been working to establish minimum retroreflectivity standards for signs.

The paper attached to this thesis in Section 14.1 addresses information technology (IT) problems that emerge when developing an overall asset management system for high volume assets and to identify their unique characteristics. For low capital cost assets, several IT problems arise related to collecting, managing, and analyzing asset data. These include: asset identification, asset location, unavailable critical data, fragmented existing data, data collection automation, software choice, and system size and resources.

Several IT challenges exist when developing asset management systems for low capital cost, high volume assets. Because these assets cost less and there are so many of them, agencies are initially inclined to exclude them from their asset management efforts, instead focusing on higher value assets. However, when the economic value of the high volume assets is totaled agency-wide, these assets represent a significant part of the investment in highway infrastructure. More importantly, low capital cost, high volume assets are critical to highway safety and motorist navigation. This criticality has been emphasized on the national level by mandates for improved performance and management of assets such as traffic signs and pavement markings. It is hoped that by discussing the issues related to these IT problems, the development of more comprehensive systems to address low capital cost, high volume asset management will be enabled, enhancing motorist safety.

3.3 Sign Experimental Facility (Harris et al. 2009)

Minimum sign retroreflectivity standards enacted by the Federal Highway Administration (FHWA) have focused the attention of administrators and sign managers on improving the nighttime performance of traffic signs. To predict when a sign will need replacement, an agency will need to know when the retroreflectivity of signs with similar characteristics deteriorate to the minimum level established by the FHWA. Currently in the literature there is limited information about the long-term deterioration behavior of ASTM Type III and IX signs and as stated above our field data collection was of little help in this regard.

One way of achieving a better understanding of long-term sign deterioration is to establish an experimental sign retroreflectivity measurement facility (ESRMF). An ESRMF is an arrangement of signs in a controlled area that have their retroreflectivity measured at regular intervals to determine how their retroreflectivity deteriorates as a function of time and other factors. While field measurement of in-place signs affords valuable data, as demonstrated by the five previous retroreflectivity deterioration studies, there are uncontrollable factors that are faced when using only in-place signs. Vandalism, such as gunshots and paintballs, can cause a sign to deteriorate prematurely. Natural deposits of tree sap and dust can also cause premature deterioration and damage. Because of these uncontrollable factors, there is a need to design and build an ESRMF in which a wide range of variables of interest to traffic sign managers can be controlled.

A better understanding of sign sheeting performance will help transportation agencies manage their sign assets because they will be able to predict when signs will deteriorate to the point where they require replacement. Improved knowledge about the deterioration of certain sheetings will also improve sign specification and purchasing decisions. For example, the North Carolina DOT owns over one million signs (Palmquist and Rasdorf 2002) with a replacement value of around $140 million; effective management of this asset can save the agency and its stakeholders millions per year. The findings from the ESRMF will also be helpful to agencies and researchers across the United States because currently there are no ESRMFs designed to evaluate the long-term performance of Type III and higher sign sheetings that are known. The National Transportation Product Evaluation Program (NTPEP) does monitor the deterioration of retroreflectivity over time in a controlled setting. However, the NTPEP experiments only last for three years, yielding no data as to when signs are expected to deteriorate below the FHWA minimum retroreflectivity standards.

A design for an experimental sign retroreflectivity measurement facility needs to ensure that the following objectives are met:

- Measure sign retroreflectivity over time to model sign deterioration.
- Determine when signs will fall below the FHWA minimum retroreflectivity standards.
- Evaluate sign sheeting types and colors most used by transportation agencies, both now and in the future.
- Minimize the costs and space requirements associated with the ESRMF.

To illustrate how an ESRMF can be designed according to these objectives, a ESRMF design for the North Carolina Department of Transportation (NCDOT) is to be presented as a case study in Chapter 4.0 of this dissertation. The case study design includes a base ESRMF design and suggested optional modifications to show how the design can be customized.

The ESRMF design process involves the following four steps:

- Sign Selection
- Sign Layout and Installation
- Data Collection
- Cost Analysis

Sign selection entails determining the sign sheeting types and colors to be studied and the required sample size. Signs are selected based on their sheeting type, color(s), cost, and criticality to safety. Once the signs are selected, the necessary sign layout and installation parameters can be determined in order for the signs to all be subject to the appropriate exposure to the sun and weather. Once the ESRMF has been installed, a data collection program to measure sign retroreflectivity and monitor its deterioration over time must be designed and implemented. The ESRMF design outlined here can be viewed as a base configuration that can be modified depending on the unique needs and requirements of any transportation agency. This template can be used by agencies nationwide for collecting critical sign data. The costs associated with the installation and maintenance of the ESRMF are included with the design.

3.4 Sign Deterioration Model

To be able to predict the useful lifetime of a sign, sign deterioration models are necessary. A total of six sign retroreflectivity studies and tests were examined in the process of collecting sign retroreflectivity data for use in a deterioration model. These studies were conducted by the FHWA (Black et al. 1991), the State of Oregon (Kirk et al. 2001), Louisiana State University, (Wolshon et al. 2002), Purdue University (Bischoff and Bullock 2002), and

NCSU (Rasdorf et al. 2006). The retroreflectivity and age data from the NCSU study were further evaluated to determine if any sign location effects were present. The sign deterioration model developed as a part of this dissertation also needs to attempt to capture the scattered nature of retroreflectivity versus age data.

3.5 Sign Asset Management Simulation

Sign management strategies generally involve manually evaluating the retroreflectivity of all signs or of a sample of signs in a jurisdiction. Alternatively they may consist of predicting when signs should be replaced based on information in a comprehensive sign inventory database. Although the FHWA has provided guidance on what sign management methods will ensure compliance with the standards, there is limited guidance available to agencies on the tradeoffs between the sign retroreflectivity performance and the maintenance costs associated with each management method. These tradeoffs can be explored by creating a model of the sign system that is implemented using simulation software and techniques. The main objective of this effort is to improve upon the modeling of the sign asset management process in the original simulation (Hummer et al. 2007). The steps necessary to develop the simulation are as follows:

- Determine simulation framework and platform
- Conceptualize simulation submodels
- Define simulation input values and scenarios
- Define simulation output values
- Build simulation model
- Test and validate simulation
- Evaluate scenarios

3.5.1 Model Selection

To be able to model signs as they are installed, deteriorate, inspected, and replaced, a system model that can best represent how signs are managed in the field over time needs to be selected. The selected model should be able to schedule when signs are installed, inspected, and replaced and the rate at which they deteriorate over several years. The model also needs to calculate system sign condition (retroreflectivity) and yearly sign costs for both short-term (transient) and long-term (steady state) time periods using different sign management scenarios. These scenarios would vary parameters such as inspection frequency and replacement policies. Finally, the selected model should be able to find optimal sign management scenarios for different sign management situations. In the following sections, different types of models that can determine optimal solutions are investigated for their suitability for the sign management problem.

3.5.1.1 Deterministic Processes

Deterministic process modeling techniques progress from a given initial state of a system to a single final state to find optimal solutions. In deterministic processes, no randomness is involved in the development of future states of the system. In other words, repeated analysis of a deterministic process will always yield the same output as long as the initial system state is the same.

The first step in modeling is to determine the decision variables for the problem. The decision variables fully describe the decisions to be made within the model. These are the variables that you wish to vary to find an optimal solution. For example, decision variables could be the number of signs to purchase each year or sign inspection interval. The objective function describes the relationship between the decision variables that need to be maximized or minimized to find the model's optimal solution. In other words, the objective function defines the analytical goal of the model, be it to minimize costs or materials used, or to maximize profit or sign conditions. Theoretically, one could just increase or decrease the decision variables continuously to maximize or minimize the objective function. Constraints are used in the model to restrict the decision variables so that they correspond with real-world conditions. For example, it would be ridiculous to expect to inspect all signs in a region every day or to be able to purchase new signs for an entire state every year, due to budget limitations. Sign limitations are used similarly to constraints to restrict decision variables to nonnegative values or to permit both negative and positive values.

Table 3.1 lists three common deterministic processes used to find optimum conditions for systems, *linear/integer programming*, *nonlinear programming*, and *deterministic dynamic programming*. Linear and integer programming use a linear objective function and linear constraints. Linear and integer programming models are relatively simple to solve because only linear relationships are used. Integer programming differs from linear programming in that some or all of the decision variables are required to be nonnegative integers, which makes them more difficult to solve than linear programming models. For a linear or integer program to appropriately model a real-life situation, the decision variables must satisfy the proportionality, additivity, and certainty assumptions. The proportionality assumption requires that the contribution of the objective function from each decision variable is proportional to the value of the decision variable, and the additivity assumption requires that the contribution to the objective function for any variable is independent of the values of the other decision variables. The certainty assumption requires that each parameter used in the objective function is known with certainty. For example, if one were unsure of the exact number of laborer hours required to install a sign, the certainty assumption would be violated.

Nonlinear programming differs from linear programming in that the objective function and/or the constraints are not a linear function or relationship. The removal of the linear restriction allows nonlinear programming to be able to model more complex relationships, but in turn the solution is harder to obtain. Also, nonlinear programming models may not satisfy the proportionality and additivity assumptions.

Table 3.1. Comparison of System Modeling Methods

Method	Description	Advantages	Disadvantages	Applications
Deterministic Processes				
Linear/Integer Programming	Tool for solving optimization problems using a linear objective function, constraints, and variable sign restrictions.	• Relatively simple and straightforward	• Cannot use non-linear objective function • Decision variables must satisfy the proportionality. additivity, divisibility (LP only), and certainty assumptions	• Linear behavior
Nonlinear Programming	Non-linear objective function and constraints	• Can use non-linear objective function and constraints	• May not satisfy proportionality and additivity assumptions	• Nonlinear behavior
Deterministic Dynamic Programming	Works backward from the end of a problem toward the beginning using stages	• Breaks large problem into smaller, more solvable parts	• Need to know end result first	• Shortest path • Inventory
Stochastic Processes				
Probabilistic Dynamic Programming	Next period state and/or decision are unknown	• Do not need to know with certainty future states	• Finite horizon	• Networks • Resource allocation
Markov Chains	Probability distribution of the state at time t+1 depends on the state at time t (i_t) and does not depend on the states the chain passed through on the way to i_t at time t.	• Analytical • Can model transient and steady-state behavior (infinite horizon)	• Probability distribution of the state at time t+1 depends on the state at time t (i_t) and does not depend on the states the chain passed through on the way to i_t at time t.	• Education • Marketing • Health services • Finance • Accounting • Production
Monte-Carlo (Static) Simulation	Static simulation model, representation of a system at a particular point in time	• Easier to apply than analytical methods	• Does not evolve over time • Simulation results dependent on the sequence of random numbers generated	Sensitivity analysis Risk analysis
Dynamic, Discrete-event, Steady-state Simulation	Modeling of a stochastic system as it evolves over time by a representation in which state variables change only at discrete points in time	• Evolves over time • Relatively straightforward • Allow greater flexibility in representing the real system • Once built, model can be used repeatedly to analyze different polices, parameters, or designs	• Need to account for transient behavior when simulation "warms up." • Not an optimizing technique • Optimization is possible, but a slow process	• "What if" types of questions
Genetic Algorithm Simulation	Simulation in which a population of abstract representations of candidate solutions to an optimization problem evolves toward better solutions	• Can rapidly locate good solutions • Useful in problem domains that have a complex fitness landscape	• May have a tendency to converge towards local optima instead of the global optimum • Operating on dynamic data sets is difficult	• Scheduling • Global optimization • Fitting Quantitative Models

Deterministic dynamic programming differs from linear and nonlinear programming because it obtains solutions by working backwards from the end of a problem to the beginning instead of determining the optimal solution from a calculated solution set. This requires knowledge of the final result of the model before beginning analysis. Problems well suited for deterministic dynamic programming can be divided into stages with a decision required at each stage and the decision chosen at any stage describes how the state at the current stage is transformed into the state at the next stage. Deterministic dynamic programming models must obey the principle of optimality, which requires that given the current state, the optimal decision for each of the remaining stages must not depend on previously reached states or previously chosen decisions.

None of the deterministic processes can fully model the sign management problem because they require knowledge of either the final model result (deterministic dynamic programming) or certainty in the parameter values used (linear and nonlinear programming). In reality, signs are installed, inspected, and replaced at an uncertain and varying frequency depending on factors such as available materials, personnel, and funds. These frequencies may be uncertain, but they can be described using models that take random variations into account, also known as stochastic processes.

3.5.1.2 Stochastic Processes

Stochastic processes enable one to model how a random variable changes over time. Random variables are functions that associate a number with each point in an experiment's sample space. Essentially, the value of a random variable is not known until the current time (t) is reached. This introduces randomness into the development of future states of the system, so that repeated analysis of a stochastic process will yield output dependent on the random values used. A major advantage of stochastic processes is that they do not require certainty, enabling parameter values to be uncertain, or random.

Table 3.1 lists five common stochastic processes used to find optimum conditions for systems, *probabilistic dynamic programming, Markov chains, Monte-Carlo simulation, dynamic simulation*, and *genetic algorithm simulation*. Probabilistic dynamic programming is similar to deterministic dynamic programming in that they both obtain solutions by working backward from the end of a problem to the beginning. Probabilistic dynamic programming differs because the specification of the current state and current decision is not enough to determine with certainty the new state and the costs during the current stage. This is because a randomized model determines either the current period's cost or the next period's state. Common probabilistic dynamic programming applications include network, inventory, and resource allocation problems. The goal is to minimize expected cost incurred or maximize the expected reward earned over a fixed time horizon.

A Markov chain process is just a probabilistic dynamic programming problem in which the decision maker faces an infinite horizon, instead of a finite horizon (Winston 2004). Markov chains are interested in modeling how a random variable changes over time. In a Markov chain process, the state of the system is observed at discrete points in time, resulting in a finite number of system states. Markov chains are stochastic because the likelihood of transitioning from one state to another is determined by a matrix of transition probabilities. In a Markov chain, the probability distribution of a state at time t+1 only depends on the state at time t, and does not depend on the states the chain passed through on the way to time t.

Because of complexity and stochastic relations, not all real-world problems can be represented adequately by analytical methods such as Markov chains and probabilistic dynamic programming. Attempts to use analytical models for such systems usually require so many simplifying assumptions that the solutions are likely to be inferior or inadequate for implementation. Often, in such instances, the only alternative form of modeling available to the decision maker is simulation.

Simulation can be defined as a technique that imitates the operation of a real-world system as it evolves over time. A simulation model is comprised of a set of assumptions about system operations, expressed as mathematical or logical relations between the objects of interest, known as entities, in the system. In contrast to the exact mathematical solutions possible with most analytical models, the simulation process involves executing or running the model through time, usually on a computer, to generate representative samples of performance measures. Simulations use state variables to describe the status of the system at any given time. As entities progress through the simulation model, their properties, or attributes can change and be tracked.

There are several advantages of simulation over analytical methods. Simulation theory is relatively straightforward and is therefore easier to apply than analytical methods. Simulation models have fewer restrictions on how the system can operate, reducing the need for simplifying assumptions and allowing the simulation model to have greater flexibility in representing the real system using stochastic, empirical, or any other distribution that can be modeled. Once a simulation model is built, it can be used repeatedly to analyze different policies, parameters, or designs. However, simulation does have some limitations. Simulation is not an optimizing technique. Optimization with simulation is possible, but it is usually a slow process because it requires multiple runs of the simulation to estimate the location of maximum or minimum values. Also, simulation can be costly because of the complex calculations and multiple runs involved, but with developing technology, the problem of cost is becoming less important.

Simulations can be divided into different types based on how they model the passage of time and entity behavior. Simulations can be deterministic, but are most commonly stochastic so they can model one or more random variables. In a discrete simulation, the state variables change only at discrete points in time, while in a continuous system the state variables change continuously over time, which is tracked by the clock time system variable. A situation that causes the state of the system to change instantaneously is known as an event. A static simulation, also known as a Monte-Carlo simulation, represents a system at a particular point in time. Dynamic simulations model systems as they evolve over time. Dynamic simulations typically increment the simulation clock time based on when the next event will take place. Sampling the simulation's probability distributions using random number generation creates the schedule of events. A terminating simulation runs for a duration of time T (the time until an event happens to stop the simulation), while a steady-state simulation runs over a long period of time, effectively to "infinity."

Simulation applications vary depending on the type of simulation used. For example, a Monte-Carlo (or static) simulation is useful for modeling phenomena with significant uncertainty in inputs, such as the calculation of risk in business. Monte-Carlo simulations are also useful for situations where each day is an independent simulation and the system does not evolve over time. Discrete, dynamic simulation can efficiently model both transient (short-term simulation start-up period) and steady-state behavior, and is ideal for answering "what if" types of problems that evolve over time.

Another type of simulation is a genetic algorithm, which is a problem-solving method that uses genetics as its model of problem solving (Buckles 1992). Genetic algorithms apply the rules of reproduction, gene crossover, and mutation to pseudo-organisms so those organisms can pass beneficial and survival-enhancing traits to new generations. Genetic algorithms are implemented as a computer simulation in which a population of abstract representations (called chromosomes or the genotype or the genome) of candidate solutions (called individuals, creatures, or phenotypes) to an optimization problem evolves toward better solutions. Random mutations are introduced into the model by changing a randomly determined variable in the genotype. The mutation occurs according to a pre-determined percentage chance. Genetic algorithm simulations are only of value where it is possible to test, often many hundreds of thousands of times, the efficacy of a suggested solution.

Applications of genetic algorithms include optimizing or improving the performance of operating systems and testing and fitting quantitative models. Genetic algorithms are not ideal for models that are time event dependent.

For the sign management problem, dynamic, discrete simulation is the best choice from among the stochastic processes. Because the sign management problem evolves over time, the finite time horizon of the probabilistic dynamic programming and Monte-Carlo simulation method would fail to model this characteristic. The Markov chains requirement that the probability distribution of the next state depends only on the immediately preceding state would limit the ability to model different inspection and replacement frequencies for different road classes. Genetic algorithms also have difficulty operating on dynamic datasets. Dynamic, discrete simulation can model how signs (entities) move through installation, deterioration, inspection, and replacement processes that occur at varying frequencies that can be stochastically modeled. The greater flexibility and ability to analyze different sign management scenarios using the same model make dynamic, discrete simulation the process of choice for the sign management problem.

3.5.2 Simulation Model Development

Sign management parameters are rates and distributions that describe the current state of sign management in a jurisdiction and enable prediction of future conditions. These parameters can be input into a model or simulation to predict future sign management costs and sign condition. Sign management parameters include:

- Deterioration rates
- Damage rates
- Replacement rates
- Inspection frequency
- Base sign condition and distribution

Sign deterioration rates are one of the sign parameters needed as inputs into a sign asset management simulation. An agency could choose to use sign deterioration rates developed from the studies mentioned in Section 2.2 and Chapter 5.0 or could develop their own through a field data collection program similar to the NCSU study or by constructing an ESRMF.

The other major sign asset management parameters that agencies need to consider are damage rates, replacement rates, and inspection frequency. Damage rates can be found through a field study similar to the NCSU study or through the budget analysis method also used in the NCSU study (Rasdorf et al. 2006). Replacement rates can be found by conducting a field study in two or three consecutive years and tracking which signs are replaced when. Theoretically, replacement rates could also be found through a sign inventory or by analyzing budget items if the necessary inventory or budget items are set up to track replacement. Agency sign inspection frequency can be determined by examining the agency's current sign inspection policy and surveying the maintenance units to ascertain actual practice. This method can also be used to get an idea of likely agency replacement rates because many agencies prioritize replacement of critical signs (such as stop signs) over signs viewed as less critical (guide signs).

In addition sign deterioration, damage, and replacement rates, a sign asset management simulation will need a base sign condition or distribution to begin with. This base condition includes a general knowledge of the sheeting types, sheeting colors, and sign retroreflectivity values within the agency. An agency with an inventory of newer signs on the roads will have less simulated sign maintenance than an agency with older signs. A regularly-updated sign inventory is the most accurate way to determine the base condition, because sign inventories typically include sign sheeting color(s), sheeting type, and some contain retroreflectivity information. Even if the sign sheeting color is unknown, the sign type (stop, yield, warning) is known, and the sheeting color(s) can be assumed from this information. Sign inventories do entail a large investment that many agencies are unwilling to make only for the sake of establishing a base condition if an inventory is not already in place.

For agencies without an inventory or with fewer financial resources, sampling of sign assets can be used to establish a base condition. In the literature, Virginia DOT utilized a sampling inventory by road type and mileage to develop base condition for the state. One-tenth mile sections of road are selected for inventory and retroreflectivity condition assessment to ensure "an acceptable level of accuracy and precision for estimating maintenance needs within each district by system (interstate, primary, secondary)" (Virginia DOT 2006). The base condition developed from sampling will be less accurate (but not unusable) than a comprehensive inventory, however the data collection costs will be less.

3.5.3 Verification and Validation

A simulation determined to be a "valid" representation of the sign system can "be used to make decisions about the system similar to those that would be made if it were feasible and cost-effective to experiment with the system itself" (Law and Kelton 2000). Similar actual and simulated sign system conditions provide greater confidence in the simulation model's ability to approximate the real-world sign system. To validate the simulation, the author developed a simulation scenario that represented the sign conditions and management practices observed during the 2005 portion of the NCSU/NCDOT field study. The input parameters for the validation scenario were developed directly from this 2005 data. The goal of the validation is to have the values output by the simulation in "2006" be similar to the field-measured actual 2006 data values. The simulated and actual 2006 values are compared using the *correlated inspection* and *prediction interval* approaches.

3.5.4 Development of Simulation Scenarios

Along with input parameters, a set of sign management scenarios needs to be developed for the simulation. The sign management scenarios can differ for each agency based on the size of its sign inventory, its administration structure, and its budget priorities. The selected simulation scenarios should focus on scenarios that represent the typical sign conditions and sign management practices that most influence sign performance and cost. Three major parts define a simulation scenario: input distribution (intial sign population), input parameters, and management method.

3.6 Best Sign Retroreflectivity Maintenance Practices for Agencies

The simulation results can be used to determine the level to which agencies will be able to meet the FHWA minimum retroreflectivity standards. This can be done by finding the relationship between dollars spent on sign maintenance and relative compliance with the standards. The findings from this comparative analysis can be used to develop a set of best practices for sign management. Recommendations for agencies may differ based on the size and administrative policies of an agency.

4.0 SIGN EXPERIMENTAL FACILITY

Roadway signs are an essential component of the transportation system. Minimum sign retroreflectivity standards recently included in the Manual on Uniform Traffic Control Devices (MUTCD) by the Federal Highway Administration (FHWA) have focused the attention of administrators and sign managers on improving the nighttime performance of roadway signs (Carlson and Hawkins 2003). Retroreflectivity can be defined as the ratio of the light that the sign reflects to a driver (cd) to the light that illuminates the sign (lx) per unit area (m^2). In straightforward terms it is a measure of how well the sign can be seen at night.

As a result of the new minimum retroreflectivity standards, transportation agencies will need to assess whether their current sign management policies and practices will ensure compliance with the standards. Compliance with the standards will involve establishing an agency-wide sign management strategy and ensuring that there is proof of compliance to protect against lawsuits. Sign management strategies generally involve manually evaluating the retroreflectivity of all signs (or a sample of signs) in a jurisdiction or predicting when signs should be replaced based on information in a comprehensive sign inventory database. This paper directly addresses the "control sign" and other management methods described in the new standard.

To predict when a sign will need replacement, an agency will need to know how long it takes for the retroreflectivity of signs with similar characteristics to deteriorate to the minimum level established by the FHWA. The ASTM sheeting types typically used in the US for roadway signs include Type I, Type III, and Type IX. Type I sheeting is less retroreflective than Types III and IX, and is therefore no longer being used for new installations in many areas. However, the retroreflectivity deterioration behavior of Type I sheeting is the most defined because it has been in use for several decades. Currently in the literature there is limited information about the long-term deterioration behavior of ASTM Type III and IX signs because they are so new and they have not been in service for very long.

4.1 Previous Retroreflectivity Deterioration Research

Sign deterioration has been studied under controlled (where signs are separate and away from traffic) and uncontrolled outdoor conditions, as well as in indoor laboratory tests. Laboratory tests have been found to be unreliable in predicting sign durability, they have been found to be highly variable, and they are relatively expensive as compared to outdoor exposure tests (Ketola 1999).

Signs in controlled outdoor conditions are installed in a restricted outdoor area where they cannot be damaged by vandals or vehicle collisions. As a result, signs in controlled studies only deteriorate because of natural weathering (UV and weather exposure).

Signs studied in uncontrolled conditions are signs that are actually in service along the roads and are exposed to traffic and vandalism as well as to natural weathering. This section will examine both controlled and uncontrolled sign deterioration studies.

4.1.1 Controlled Studies

The main source for controlled sign deterioration data is the National Transportation Product Evaluation Program (NTPEP) of the American Association of State Highway and Transportation Officials (AASHTO). Manufacturers who want their new sign sheeting product to be used in the US submit it to the NTPEP for durability testing. The NTPEP's primary goal is testing for sheeting durability, not retroreflectivity deterioration. Signs tested by NTPEP generally include most sign sheetings used in permanently-installed traffic signs, including Types I, III, and IX. The NTPEP currently tests signs for three years in four states (Minnesota, Arizona, Louisiana, and Virginia) (AASHTO 2005).

NTPEP tests two 4" x 12" sign panels for each sheeting type to be tested, and places them on southern-facing test decks angled 45° from horizontal. According to Carlson and Hawkins, placing the signs at this orientation causes the test panels to deteriorate at double the rate of a vertically mounted sign (Carlson et al. 2003). As a result, the NTPEP test panels effectively deteriorate for six years, although they are only placed outdoors for three years. One sign panel for each sheeting type remains indoors to serve as a control. As a result of the NTPEP tests being conducted in a controlled setting, there is less variability in the results than for uncontrolled tests.

Generally, R^2 values for ordinary least squares deterioration curves (of retroreflectivity versus time) generated from the NTPEP data are greater than 0.8; however, the sample size is small since there are only two weathered samples per sheeting type. The NTPEP program data are not helpful in predicting sign service life (when signs are expected to deteriorate to levels below the FHWA minimum) (Ketola 1999). There is no current source for long-term controlled sign performance data.

4.1.2 Uncontrolled Studies

Five uncontrolled sign deterioration studies have been conducted in the US in recent years. These studies were conducted by the FHWA (Black et al. 1991), the State of Oregon (Kirk et al. 2001), Louisiana State University (Wolshon et al. 2002), Purdue University (Bischoff and Bullock 2002), and North Carolina State University (NCSU) (Rasdorf et al. 2006). These studies measured the retroreflectivity and ages of hundreds of mostly Type I signs in the field and had some difficulty creating well-defined deterioration models from this data. Nearly all of the deterioration models had R^2 values less than 0.5, indicating that age could not explain much of the variability in the deterioration data. These studies found very few Type III signs in the field older than 15 years and could only make limited conclusions about how these signs deteriorate.

The Purdue, Louisiana, and FHWA studies investigated whether cleaning signs prior to measurement would improve retroreflectivity. Each of the studies found that although there is a slight improvement in retroreflectivity with cleaning, it is not statistically significant, and higher-intensity sheetings are less likely to show an improvement with cleaning (Bischoff and Bullock 2002; Black et al. 1991; Wolshon et al. 2002). Another cause of variability in retroreflectivity data is the damage and vandalism signs are subject to in an uncontrolled roadside environment. Further discussion and quantification of sign damage rates can be found in Immaneni et al. (2007).

There are very few Type III encapsulated lens sheeting signs in the field older than 15 years. Therefore, the studies cited above could only make limited conclusions about how these signs deteriorate to the point where they are below the FHWA minimums (Rasdorf et al. 2006). An evaluation of all existing models in the literature found that Type III sign retroreflectivity may fall below the FHWA minimums between 20 years (red, yellow) to 53 years (white) after installation (Immaneni et al. 2009). Type III signs (as well as Type IX signs) are also available as prismatic sheetings. These prismatic sheetings have not been studied because there are very few in the field, although many transportation agencies are currently installing or planning to install these sheeting types. It is precisely because of these shortcomings that we are recommending the facility proposed herein.

4.1.3 Significance

A study of 1057 signs in the field in NC found only 265 Type III signs and 10 Type IX signs (Rasdorf et al. 2006). The maximum ages of these signs were 15 and 5 years, respectively. While Type I signs exist in abundance (and their field age varies from new installations to typically 20 years), this is not the case for Types III and IX. In essence, while there are some Type III and IX signs installed in the field their numbers are low and, except for guide signs (which themselves are hard to measure), their locations are generally not recorded in any NCDOT database. Thus, targeted field studies of these signs are not generally feasible. However, by installing a facility like that presented herein it will be possible to begin to collect these critically-needed data that are not otherwise available and for which not other mechanism exists. These data will allow agencies to develop efficient and cost effective sign management strategies. This facility directly addresses the control sign compliance method and other management methods identified in the new MUTCD standard.

4.2 Need for Sign Retroreflectivity Data

One way of achieving a better understanding of Type III and IX long-term sign deterioration is to establish an experimental sign retroreflectivity measurement facility (ESRMF). An ESRMF is an arrangement of signs in a controlled area that have their retroreflectivity measured at regular intervals to determine how it deteriorates as a function of time and other variables, such as sign orientation and weather conditions. Other variables are identified in the following section.

While field measurement of in-place signs affords valuable data, as demonstrated by the five previous retroreflectivity deterioration studies, there are uncontrollable factors that are faced when using only in-place signs. Vandalism (gunshots, paintballs, and eggs) can cause a sign to deteriorate prematurely as can natural deposits of tree sap and dust. Because of these uncontrollable factors, there is a need to design and build an ESRMF in which a wide range of variables of interest to traffic sign managers can be controlled.

A better understanding of sign sheeting performance will help transportation agencies to better manage their sign assets because they will be able to predict when signs will deteriorate to the point where they require replacement. Improved knowledge about the deterioration of certain sheetings will also improve sign specification and purchasing decisions. For example, the North Carolina DOT owns over one million signs with a replacement value of around $140 million; effective management of this asset can save the agency and its stakeholders millions per year. The findings from the ESRMF will also be helpful to agencies and researchers across the United States because for the first time long-term sign deterioration data will be publicly available for review and analysis.

4.2.1 Sign Maintenance Strategies

Besides the need of researchers and transportation agencies to better understand how sign retroreflectivity deteriorates in the long term, an ESRMF can be a key element of a transportation agency's overall traffic sign management program. The FHWA has developed several retroreflectivity maintenance strategies that DOTs can implement to comply with the standards (Chappell and Schertz 2005). These retroreflectivity maintenance strategies can be divided into two main groups--assessment methods and management methods--and are further broken down in Section 2A.09 of the MUTCD as follows (FHWA 2007a):

- Assessment Methods
  - Visual Nighttime Inspection Method
  - Measured Retroreflectivity Method
- Management Methods
  - Expected Sign Life Method
  - Blanket Replacement Method
  - Control Sign Method

Assessment methods ensure compliance with the standards by evaluating all signs in place on the roadways through either qualitative visual assessment or quantitative retroreflectometer assessment. Management methods, on the other hand, do not involve evaluating every sign in place on the roadways, which can be costly. Instead, management methods predict how long signs with similar characteristics (such as sign color and sheeting type) will maintain an above-standard retroreflectivity, also known as the sign life.

The expected sign life method calculates a sign life from known sign retroreflectivity deterioration rates for combinations of sign sheeting color and sheeting type. When an individual sign's retroreflectivity is predicted to fall below the minimum it is replaced. The blanket replacement method replaces all signs along a corridor, within an area, or of the same sign and sheeting type at intervals based on the expected sign life of the signs. The control sign method uses signs either in an ESRMF or a sample of carefully identified control signs from the field to determine sign life. The control sample of signs is assumed to represent all of the signs in an agency's jurisdiction. The sampling plan should ensure that the quantity and diversity of signs sampled represents the agency's sign population and that there is monitoring of sign retroreflectivity at regular intervals. When a control sign's retroreflectivity is measured by a retroreflectometer and is found to fall below the minimum level, all similar signs in the field should be replaced.

An ESRMF can provide data in support of all the management methods suggested by FHWA. Data from several years of sign retroreflectivity measurements at an ESRMF can be analyzed to determine the sign life of various sign types. This sign life can then be used in the expected sign life or blanket replacement methods. Signs in the ESRMF could also serve as control signs for the control signs method. Thus, the proposed ESRMF addresses all three of the management methods directly.

The FHWA minimum retroreflectivity standards require that transportation agencies can prove compliance with the standards, especially to avoid lawsuits. An ESRMF that is used in conjunction with one of the maintenance strategies recommended by the FHWA will aid agencies and motorists and help prove compliance with the standards. This is especially critical for small cities, towns and municipalities who do not have the large infrastructure or resources to respond to the new standard via assessment methods. They, more than anyone, would benefit from an ESRMF, enabling them to implement one of the more cost efficient management methods for compliance because they would have the data to do so.

4.3 Case Study Design

A design for an experimental sign retroreflectivity measurement facility needs to ensure that the following objectives are met:

- Measure sign retroreflectivity over time in order to effectively and accurately model sign deterioration under real world conditions.
- Determine when signs will fall below the FHWA minimum retroreflectivity standards.
- Evaluate sign sheeting types and colors most used by transportation agencies, both now and in the future.

- Minimize the costs and space requirements associated with the ESRMF.

In order to illustrate how an ESRMF can be designed according to these objectives, an ESRMF design is presented as a case study. The case study design includes a base ESRMF design and suggested optional modifications to show how the design can be customized or expanded, depending on an agency's unique needs.

The ESRMF design process involves the following four steps:

- Sign Selection
- Sign and Facility Layout and Installation
- Data Collection Plan Design
- Cost Analysis

Sign selection entails determining the sign sheeting types and colors to be studied, the sign size, and the required sample size. Signs are selected based on their sheeting type, color(s), cost, and criticality to safety. Once the signs are selected, the necessary sign layout and installation parameters can be determined in order for the signs to all be subject to the appropriate exposure to the sun and weather. A data collection program, to measure sign retroreflectivity and monitor its deterioration over time, must also be designed and implemented. A cost analysis for the proposed ESRMF has been performed and is included. The ESRMF design outlined in this section can be viewed as a base configuration that can be modified depending on the unique needs and requirements of any transportation agency.

4.3.1 Sign Selection

One of the objectives of the ESRMF design is to evaluate the sign sheeting types and colors most commonly used in the field currently and those that will be used in the future. The "most used" criterion motivated the selection of sign sheeting types and colors as well as the actual signs chosen for the ESRMF.

4.3.1.1 Sheeting Type

Sign sheeting types were selected based on the sheeting types that agencies are currently installing or are planning to install in the near future. Major manufacturers of sign sheeting materials are Avery Dennison®, 3M™, Nippon Carbide, ATSM, Inc., Kiwalite®, and LG Lite (FHWA 2005). Our recommended sheetings are as follows:

- Type III encapsulated lens
- Type III prismatic
- Type IX prismatic

Type III encapsulated lens sheeting was selected because the NCDOT, as well as many other DOTs nationwide, is presently using it for all new sign installations on secondary and on most primary roads. Type III prismatic sheeting was selected because it has the potential to maintain its retroreflectivity longer than a more easily damaged encapsulated lens sheeting. Type IX prismatic sheeting is often used on interstate signage and important primary road guide signs. Type I sheeting was not selected for the ESRMF because most agencies across the country have discontinued new installations of Type I sheeting.

4.3.1.2 Colors

Similar to sign sheeting types, sign colors for the ESRMF were selected based on the sign colors most commonly used in permanent signage by most transportation agencies. The requirement that the signs be permanent eliminates orange signs from consideration because they are used only on a temporary basis in work zones. Brown signs were also not included in the ESRMF because they are primarily used to guide drivers to daytime attractions and therefore do not need high visibility at night. The sign colors selected for the ESRMF are as follows:

- White
- Yellow
- Red
- Green

These sign colors are most typically used for regulatory, warning, and guide signs nationally. If an agency would like to evaluate possible deterioration differences between retroreflective sign sheeting, screened ink, overlay film, and digitally printed media of the same color, signs produced using these different manufacturing techniques can be included in the ESRMF for comparison. Blue signs are not included in the basic design of the ESRMF because the FHWA has not proposed minimum retroreflectivity values for blue signs, but they could be added to the ESRMF in a more customized design, as could fluorescent colors if the facility sponsor had an interest in them.

4.3.1.3 Sample Size

To obtain 95% confidence in the analysis results, each sheeting color should have the total sample size indicated in the fifth column of Table 4.1. The total sample size (column 5) is equal to four times the maximum needed sample size per orientation (column 4) because the ESRMF tests signs facing north, south, east, and west.

Table 4.1. Determination of ESRMF Sample Size

(1)	(2)	(3)	(4)	(5)
Sheeting Color	Standard Deviation of R_A from Field Study	Acceptable Difference in R_A Values	Sample Size per Orientation	Total Sample Size
White	15.6	24.4	4	16
Yellow	18.2	19.9	4	16
Red	7.2	5.2	8	32
Green	3.9	4.1	4	16

The sample size per orientation was derived from the standard deviation of R_A values (column 2) with the same Type III sheeting color and age from the NCSU field study (Rasdorf et al. 2006) and an acceptable difference in the ESRMF R_A results (column 3) equivalent to 10% of the average R_A value for the same Type III sheeting color and age. A variance value from field sign data was used instead of a variance from controlled sign data because the field variance would logically be greater and lead to a more conservative (and larger) sample size. The acceptable difference was selected to be as large as 10% to account for often low repeatability of measurements and noisy variability in R_A measurements. Column 4 was calculated from columns 2 and 3 by using the standard sample size formula $[(1.96*\text{Column 2})/\text{Column 3}]^2$ and then rounding to the nearest multiple of 4.

4.3.1.4 Sign Selection

Specific signs were selected for the ESRMF based on a combination of their sheeting color(s), their cost, and how critical they are in the field. Ideal signs would have one to two sheeting colors that could be measured for retroreflectivity, would be critical to driver safety, and would be a typical size. Table 4.2 and Figure 4.1 show the test signs selected as a result of these criteria for the basic ESRMF design.

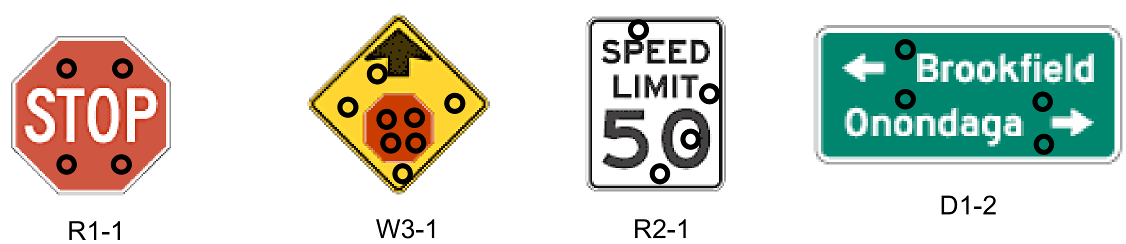
Table 4.2. Color and Size of Signs Selected for ESRMF

Sign Message	Sign Color Background (legend)	Sign MUTCD Code	Sign Size	Per ASTM Sheeting Type		TOTAL Number of Signs
				Number of Test Signs	Number of Extra Signs	
Stop	Red	R1-1	30"	16	5	63*
Stop Ahead	Yellow (Red)	W3-1	36" x 36"	16	5	63
Speed Limit	White	R2-1	24" x 30"	16	5	63
Destination Sign	Green	D1-2	54" x 24"	16	5	63
TOTAL				64	20	252

** Total = 16 + 5 or 21 signs per sheeting times 3 sheeting types*

The Stop (R1-1) sign was selected because it is the most critical red color sign in the field and a high priority on maintaining stop sign retroreflectivity is critical. The 30" Stop sign size is the most widely used size on secondary roads (and is less expensive than the 36" version). The Stop Ahead (W3-1) sign was selected primarily because it has large areas of both yellow and red sheeting and could be measured for both yellow and red retroreflectivity, thereby reducing the number of red Stop signs needed in the ESRMF. Together, the 16 Stop signs and 16 Stop Ahead signs will satisfy the red sign sample size of 32 signs specified in Table 4.1.

The Speed Limit (R2-1) sign was chosen for the ESRMF because it is the most common white background sheeting sign in the field on all road types. The Destination Sign (D1-2) was chosen because it is a green background sign that is commonly used on both secondary and primary roads. Signs with white letters on a darker background such as the Stop and Destination Signs can fail the FHWA minimum standards if there is insufficient contrast between the letters and the background. Sign contrast is quantified using the contrast ratio, which is the ratio of the retroreflectivity of the white letters to the retroreflectivity of the darker background (FHWA 2007a).



Legend
O Retroreflectometer measurement locations on each sign (four per sign per color measured)

Figure 4.1. Signs Selected for Basic ESRMF Design with MUTCD Code

In addition to the 16 test signs needed per ASTM sheeting type (in order to meet sample size requirements) for each sign message and color combination, 5 extra signs should be included. Four of these signs are intended to serve as *substitute* signs. These signs should be exposed to the same environmental conditions in the ESRMF as the 16 test signs but should be placed in separate locations. A substitute sign can be used to replace a test sign that has been damaged during shipping, installation, or the testing period.

The remaining extra sign should serve as a *control* sign. The control sign should be stored indoors so it is protected from deterioration due to the outside environment. The retroreflectivity deterioration not due to environmental effects can be determined by comparing the deterioration of the control sign to that of the test signs. A total of 4 substitute signs and 1 control sign should be ordered for every sign message/color combination in the ESRMF (for a total of 16 + 4 + 1 = 21 signs for each sign/sheeting type combination).

4.3.2 Sign and Facility Layout and Installation

The installation of signs in the ESRMF needs to resemble as closely as possible the typical installation conditions in the field. This requires that the sign height, sign spacing, sign layout, and ESRMF location are designed to approximate the average field conditions in the region the ESRMF represents. All of the signs included in the basic ESRMF design are intended to be installed at approximately the same time to ensure that all signs have the same installation date and therefore can be compared on this basis.

4.3.2.1 Sign Height

The signs in the ESRMF should be installed at a height of five feet from the ground to the bottom of the sign, which is consistent with the MUTCD-specified height for rural roads.

4.3.2.2 Sign Spacing

In the ESRMF, the signs need to be placed far enough apart to ensure that shadows are not cast from one sign onto another. The necessary spacing between the signs to achieve this is based on the angle of the sun and the dimensions of the sign. The basic ESRMF design requires that when the angle between the sun and the ground is 15° or greater, none of the signs, except those facing west when the sun is in the east, etc., are covered by shadow. Since the height of the largest sign (Stop Ahead) is 4.25 ft (the diagonal of a 36″ sign), sign supports need to be spaced at least 16 feet from the nearest sign that could be casting a shadow.

4.3.2.3 Sign and Facility Layout

In order to increase the sign support density in the ESRMF, modules of 16 signs each were designed to minimize shadows and simultaneously test four different sign orientations: north, south, east, and west. Figure 4.2 shows the design of a typical "module" of 16 signs. Each sign, when installed, will have a label on the front of its support with its assigned sign inventory number to aid in data collection. The signs will also be marked with their sign inventory number, the sign manufacture date, and the sign installation date on their back face.

The basic facility layout, as shown in Figure 4.3, will consist of four modules for each sign type collected per each of the three sheeting types, for a total of 12 modules. Per Table 4.2 and Figure 4.1 the four modules per sheeting type consist of the following:

1. 16 Stop signs
2. 16 Stop Ahead signs
3. 16 Speed Limit signs
4. 16 Destination signs

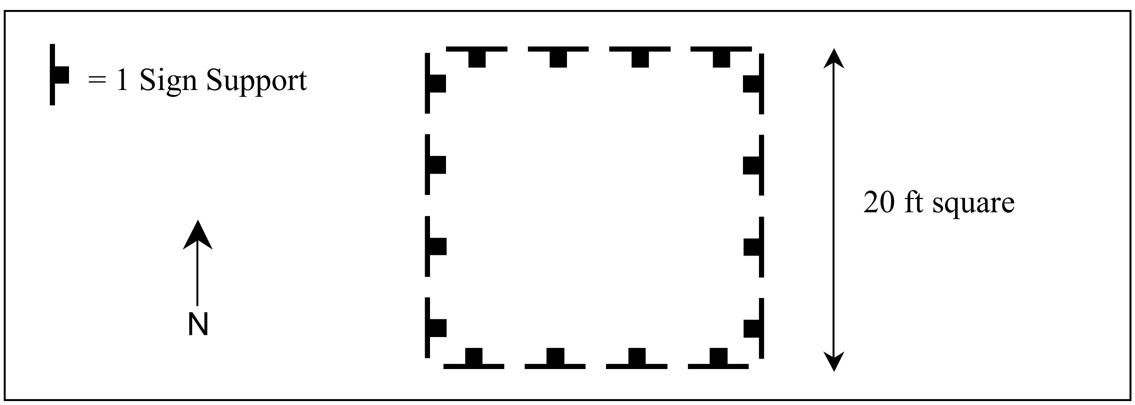


Figure 4.2. Layout of Sign Module

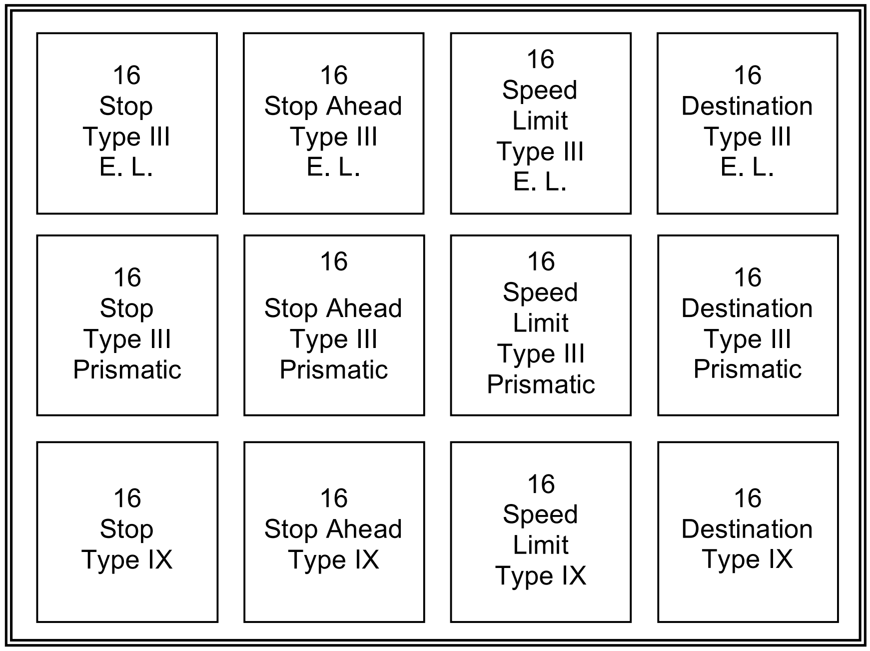


Figure 4.3. Basic 12-Module Sign Facility Layout

A layout of the entire ESRMF is shown in Figure 4.4. This layout includes an area for the basic, 12-module ESRMF, for 15 additional module locations for future ESRMF expansion, and for 3 modules for "substitute" signs that can replace damaged test signs in the original 12-module section. The substitute signs would be exposed and measured along with the signs in the 12-module ESRMF, so they would be ready to be used as substitutes for a damaged test sign if needed.

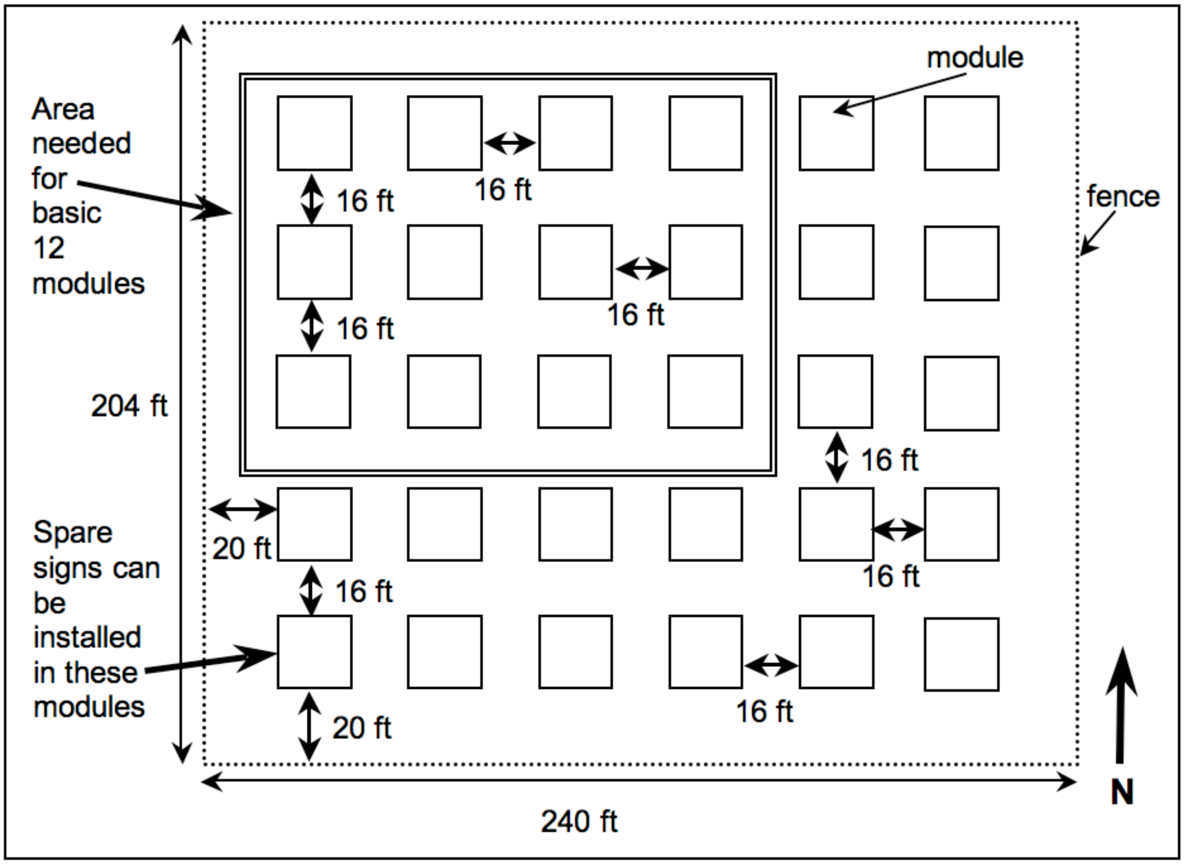


Figure 4.4. 30-Module ESRMF Layout

Other arrangements of the modules, such as the checkerboard design shown in Figure 4.5, are also possible. The checkerboard design provides 15 module locations, which would include the basic 12-module ESRMF as well as 3 substitute sign modules. The final 15 additional module locations would be used to test, for example, blue sheeting signs or for expansion. Note that the proposed facility size is quite large. It allows for a full 100% expansion, providing 30 modules while initially using only 15 (12 for test and 3 for substitute signs). If desired, an agency could reduce the facility to a 5x5 module size allowing 5 extra modules, a 50% expansion.

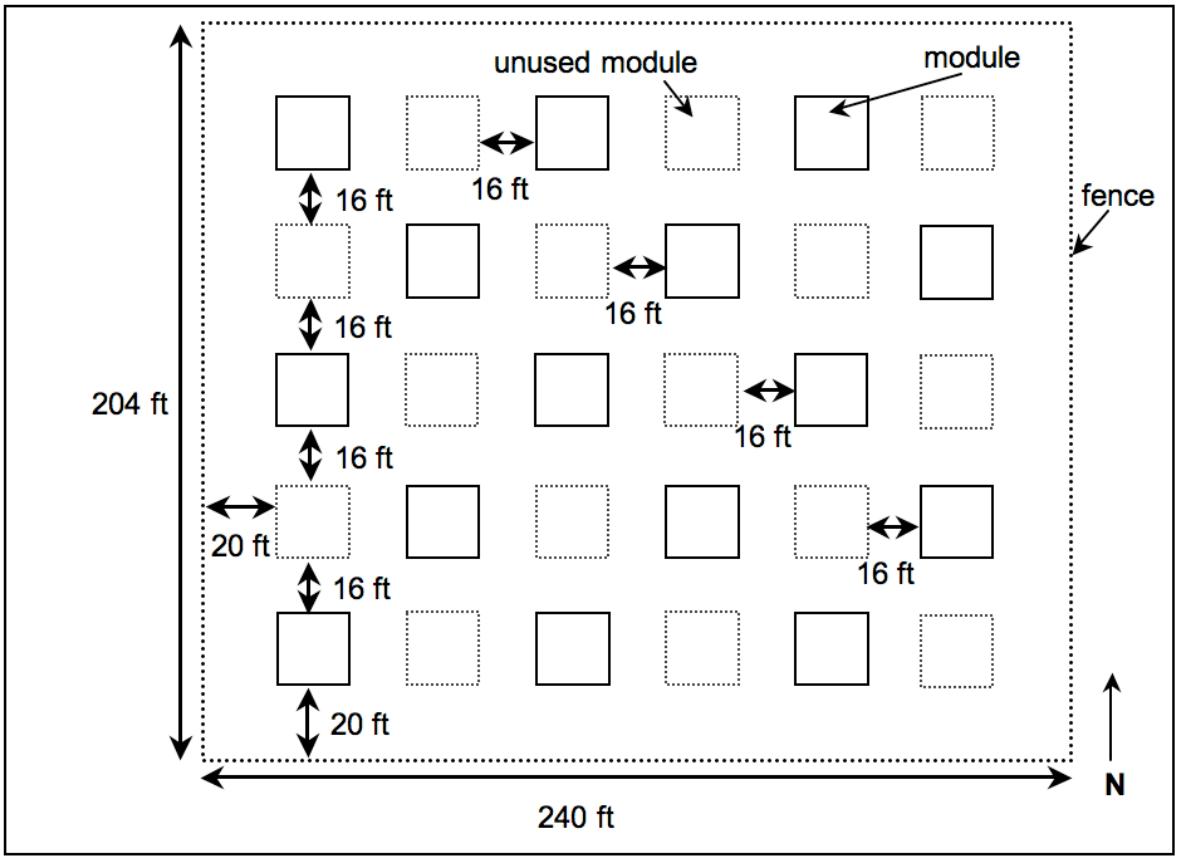


Figure 4.5. Checkerboard ESRMF Layout for 15 Modules

The ESRMF, with a module size of 20 ft square and a spacing of 16 ft between modules, will need a level area at least 204 ft by 240 ft, or 1.12 acres. This area should be as far as possible from surrounding trees and buildings and should have a gravel or bare dirt surface to either eliminate or limit vegetation (grass). This will reduce the cost to maintain the area and the chances of damage to the signs from maintenance operations.

4.3.2.4 Security

Protecting the signs in the ESRMF is critical. Once this facility is put into operation, any significant damage through vandalism or theft would be devastating. Therefore protection is of paramount importance. For this reason, the ESRMF should be surrounded by two enclosures. The inner enclosure is a 9 ft. high wood fence that would be a visual barrier to prevent those outside the ESRMF from even noticing the test facility. The fence should be no taller than 9 ft. so that it does not cast shadows on the signs. The outer enclosure should be another fence located 20 feet further out from the first, acting as a physical barrier to prevent unauthorized access to the ESRMF. The outer fence may not be needed if the ESRMF can be installed within an access-controlled agency facility, such as a locked compound. Both fences should have a gate that is locked at all times. The gate can be located at any convenient location in the ESRMF layout.

4.3.2.5 ESRMF Location

The proposal in NC is to implement an ESRMF in a number of locations. The first location was chosen to be in the greater Raleigh area because of the area's typical NC climate, proximity to the NCDOT research office, proximity to research universities, ease of access, and availability of space. A second priority location would be near the Atlantic coast and the third priority location would be in the Appalachian Mountains. Near the coast there is greater exposure to salty air and sun, while in the mountains the signs are more exposed to cold temperatures, snow, and ice.

In other states, the primary factors may or may not be seaside, mountain, and plain locations, depending on the state's unique geography. More broadly, on a national basis, such facilities would ideally be located in New England, Florida or Georgia, the western mountains, the desert, along the Pacific coast, and in the plains of the northern and southern Midwest. This would provide the broadest climatic and geographic exposure possible. Differences in UV exposure and pollution levels between testing locations should also be considered. An ESRMF cannot cover all conceivable environments in which a sign might be placed. For example, signs near industrial areas may be exposed to chemicals or unusually high levels of dust that will cling to a sign. However, only a small fraction of all signs exist in these atypical environments.

4.3.2.6 Installation Procedure

Signs to be installed in the ESRMF should be selected from the usual sign supplier for the agency or region. The signs selected should not be part of a special run, although the green guide signs and some of the Type III prismatic and Type IX prismatic sheeting signs may need to be specially manufactured because they are not manufactured on a regular basis. Additional signs should be ordered so there are replacement signs in case some signs are damaged during shipping or installation.

Once the signs arrive on site, they should be examined closely for defects. The initial retroreflectivity is to be measured in the four previously identified locations (in Figure 4.1) and compared to the typical initial retroreflectivity value for the sheeting type and color. If the retroreflectivity at all four locations is not within the typical initial range, a replacement sign should be installed in place of the original sign. The replacement sign would need to meet the same initial retroreflectivity criterion.

All of the signs selected for the ESRMF should have a known manufacturing date and both the manufacturing and installation dates for each sign should be recorded. A regular DOT sign crew using typical materials and tools should install the test and substitute signs. Substitute signs should be installed in a module outside of the basic ESRMF installation so they could replace a vandalized or otherwise damaged sign if needed.

The control sign for each module should be stored in a known, secure indoor location and protected from sunlight, weather, and temperature extremes (NTPEP 2008). The control sign should be stored vertically and should be protected by foam packing material. This is to prevent pressure on the sign's face that can cause premature degradation. The control sign for each module should have its retroreflectivity measured at the same time the sign module in the ESRMF is initially measured.

4.3.3 Data Collection Plan Design

Once the ESRMF is installed, all signs should have their initial in-place retroreflectivity measured by a portable retroreflectometer point instrument in the four standard locations using an observation angle of 0.2°, an entrance angle of -4.0°, and a rotational angle of 0°. The rotation angle for the point instrument is determined by the angular position of the instrument on the sign face. Assuming the retroreflector's datum axis to be upward, the rotation angle equals 0° when the instrument is upright (ASTM 2001). This retroreflectivity measurement method is in accordance with the ASTM E1709 standard for retroreflectivity measurement. The retroreflectometer should be calibrated each time it is used, and the same retroreflectometer unit should be used to collect all readings. After the initial measurements all signs should be measured semi-annually.

As noted above, the FHWA minimum retroreflectivity standard is based on a 0.2°/-4.0° measurement geometry. However agencies can decide to measure retroreflectivity using other geometries representing different road user types. It should be noted that the FHWA has established a standard. Any agency deviating from this standard would want to justify doing so because their results would not fit within the framework of other national studies using the standard. Careful consideration should be given to any such deviations.

For each sign type (Stop, Stop Ahead, Speed Limit, and Destination Sign) a template should be created showing the precise location and order in which measurements are to be taken for signs in the ESRMF and control signs. The templates will specify measurement locations to be used over the life of the facility. This will ensure that retroreflectivity measurements are taken in the same locations on each sign over time because slight changes in the retroreflectometer location on the sign may yield different readings (ASTM 2001). The reader is referred back to Figure 4.1 where measurement locations are shown on the four signs selected for the basic ESRMF design. Note that the Stop Ahead sign shows eight locations while the remaining three signs show four. As mentioned previously, this permits the measurement of both the red and yellow colors. Additionally, the retroreflectivity of the Stop sign legend and Destination Sign legend (white letters) should be measured in four places so it can be used to determine the contrast ratio for these signs.

A database for the ESRMF should be implemented. This database will contain the sign inventory number, sign installation date, sign manufacture date, and sign attributes such as sign color, message, orientation, and sheeting type. All signs will have one unique inventory number, except for the Stop Ahead signs, which will have two; one for the yellow sheeting and one for the red sheeting. Each sign, when it is installed, will have a label on the front of its support with its assigned sign inventory number and a label on the back of the sign with the sign inventory number, the sign manufacture date, and the sign installation date.

A technician should record all four retroreflectivity values for each sign/color combination directly into a measurement data log using a personal data assistant (PDA). A sample of the PDA data log is shown in Table 4.3. The measurement date should be included in the filename of the PDA data log. The PDA data log should be uploaded to the main database where the retroreflectivity readings and the measurement date are incorporated into the database file. The main database will calculate an average retroreflectivity reading for each sign and color combination from the four readings. The entire database should be posted on a website and updated semi-annually.

Table 4.3. PDA Data Log Example

INVENTORY #	SIGN MESSAGE	SHEETING COLOR	READING 1	READING 2	READING 3	READING 4
1021	Stop Ahead	Red	45	46	43	45
1022	Stop Ahead	Yellow	210	212	215	208
1023	Stop	Red	50	49	48	51

A university collaboration should be established to ensure the implementation of the data collection and analysis plan and to make data readily available for research use. This would include semi-annual measurement of all signs, data compilation and reporting to the FHWA and the state agency, and posting of all data on the internet. The analysis activity would be performed on an annual and a multi-year basis.

Every variable influencing retroreflectivity degradation and overall sign health should be studied. The variables under consideration should include at least sign type and color, sheeting type, age, orientation, and weather. Deterioration models should be developed and performance results published. The literature has shown that numerous models exist to approximate degradation rates. The authors have proposed one such model (Immaneni et al. 2009).

4.3.4 Cost Analysis

The total cost for an ESRMF consists of the initial cost of the signs and their installation as well as the ongoing operation and maintenance costs for the ESRMF. The cost of signs and installation is fixed and will occur when the ESRMF is installed, while the operation and maintenance costs may vary and will be ongoing for the life of the ESRMF.

4.3.4.1 Signs and Installation

For the basic ESRMF design, the cost of Type III encapsulated lens, Type III prismatic, and Type IX prismatic sheeting signs was obtained from NCDOT's supplier, Correction Enterprises. The cost of sign installation (materials and labor) was obtained from NCDOT Division 6. Table 4.4 lists the prices for each Type III encapsulated lens, Type III prismatic, and Type IX prismatic sheeting sign and its installation. Note that the cost of Type III encapsulated lens sheeting is the same as Type III prismatic. With 21 signs purchased of each sheeting (3) and sign message type (4), the total number of signs to be purchased in the basic ESRMF design is 21 * 3 sheeting types * 4 sign message types = 252. The total cost for Stop signs, for example, would be 21*($74.00 + $74.00 + $76.95) = $4,724, with a total cost for all four sign message types of approximately $30,000.

Table 4.4. Cost of Signs and Installation (S&I) for ESRMF

Sign Message	Sign Color Background (legend)	S&I Cost for Type III Encapsulated Lens Sheeting	S&I Cost for Type III Prismatic Sheeting	S&I Cost for Type IX Prismatic Sheeting	TOTAL
Stop	Red	$74.00	$74.00	$76.95	$4,724
Stop Ahead	Yellow (red)	$83.72	$83.72	$149.85	$6,739
Speed Limit	White	$76.81	$76.81	$96.78	$5,258
Destination Sign	Green	$139.05	$139.05	$194.83	$12,670
	TOTAL	$8,783	$8,783	$11,824	**$29,391**

The cost of the inner wooden fence was estimated to be $25,000 using a fence cost estimating tool with a total fence length of 888 feet, one 10 ft gate, and a fence height of 9 feet. The cost of the outer barbed-wire chain-link fence was estimated to be $35,000 using a fence cost estimating tool with a total fence length of 1048 feet, one 12 ft gate, and a fence height of 8 feet. The installation cost, including the fence, gate, signs, and supports (but excluding site preparations), is estimated to be $90,000.

4.3.4.2 Accessories

There are some fixed data collection equipment costs associated with the ESRMF. A portable point retroreflectometer, such as the RetroSign® 4500, costs approximately $12,000 including accessories. A PDA with accessories and software will add approximately $1,000 to the cost. Assuming that software to manage the ESRMF database costs $1,000, the accessories cost will be $14,000 and the total fixed costs for the ESRMF will be $104,000. Computers and associated peripherals are assumed to be available and to result in no additional costs.

4.3.4.3 Operation and Maintenance

The operation and maintenance costs also include the annual costs associated with data collection and analysis and the costs of maintaining the ESRMF site. The annual cost of data collection will include the costs of the agency or university that is responsible for the

ESRMF's data collection, analysis, and reporting. Allowing a $20,000 annual budget for data collection and analysis and $5000 for ESRMF site maintenance per year, the total annual maintenance and data collection budget is $25,000. Assuming a ESRMF lifetime of 20 years, the total costs are approximately $500,000, excluding inflation.

4.4 Sign Test Facility Customization Options

The ESRMF design aims for flexibility in order to support a broad and robust study, to make available to the research community data that have not heretofore been available, and to allow for customization and specialization in testing. Each location that sets up such a facility can do so in a way to meet its specific needs. In particular, the following are possible extensions or enhancements that could be considered depending on an agency's needs:

- Other sign colors and messages
- Additional sheeting types and other sheeting manufacturers
- Modification of module size and layout
- Data collection changes

The following sections discuss these potential facility customization and expansion options.

4.4.1 Sign Colors and Messages

Adding variables could change the basic sign experimental facility design outlined in the previous sections. Blue signs could be incorporated into the design by adding one additional module per each of the three sign sheeting types. One blue sign that could be used, especially because of both its commonality and its economical size, is the Rest Area sign (MUTCD code D5-2a), shown in Figure 4.6. Adding the D5-2a sign to the basic three sheeting type sign farm design would cost an additional $9,300.

Figure 4.6. Rest Area, Yield, and Keep Right Signs

A greater variety of signs can be selected for each color, such as adding a module of Yield signs (white and red color) or Keep Right signs (white) as shown in Figure 4.6. Because of the criticality of red signs a yield sign would be a particularly ideal addition to the basic design.

4.4.2 Sheeting Types and Manufacturers

Additional sheeting types could be considered in the ESRMF. Possibilities include the new Type XI sheeting (e.g. 3M™ Diamond Grade™ DG3). The basic ESRMF design could also be expanded to include sign sheetings produced by several manufacturers.

4.4.3 Module Size and Layout

The number of signs in each module as well as the number of modules can be modified to create a larger or smaller sample size. If an agency is not concerned about how orientation affects sign deterioration, it can place all signs facing in a direction of their choice. Agencies should check that the selected sample size meets their desired statistical confidence level.

Similarly, an agency may want to simulate accelerated weathering of the signs in the ESRMF. Accelerated weathering can be accomplished in two ways. First, ASTM G7-05 specifies that accelerated weathering can be achieved by orienting the signs to face the equator and to be installed at an angle from to the horizontal that is equal to the geographic latitude of the ESRMF site (ASTM 2004). Second, the NTPEP achieves accelerated weathering by orienting signs to face south and installing them at an angle of 45° to the horizontal, which is also in accordance with ASTM G7-05. As noted earlier, claims have been made that the accelerated weathering method used by NTPEP effectively doubles the deterioration rate of signs (Ketola 1999). In other words, a sign deteriorated three years in the test facility would be representative of six years of deterioration in the field.

Differing site situations may require that an agency modify the basic ESRMF layout. The layout of the modules can be modified to accommodate an unusually shaped site or any other configuration. The checkerboard layout shown in Figure 4.5 can be used to further minimize any shadows on test signs as can an increased spacing between the modules.

4.4.4 Data Collection

An agency can change the data collection specifications to fit their data collection needs. For example, an agency may already own a portable annular retroreflectometer instead of a point retroreflectometer. Costs could also be increased or decreased by changing how often the retroreflectivity data are collected. The authors recommend that data be collected at least semi-annually. Some agencies may wish to incorporate the daily weather conditions at the ESRMF into their sign deterioration analysis to determine if weather conditions play a significant role in sign deterioration. Another variable that agencies may want to consider is change in sign color over time. Sign color measurements can be made using a portable color meter and should follow the procedure outlined by NTPEP (NTPEP 2008).

4.5 Closure

An ESRMF will enable an agency to measure how signs deteriorate over time in a controlled environment that mimics field conditions. The controlled environment limits the effects of vandalism and damage on signs and results in less variability in both deterioration data and models. Better deterioration models can help agencies determine when signs in the field will deteriorate without having to initiate programs to field measure sign retroreflectivity at regular intervals.

The FHWA minimum sign retroreflectivity standards require that agencies implement a sign management and evaluation method. The deterioration models developed from the ESRMF could be used to calculate sign lifetimes that could be used in both the expected sign life or blanket replacement method. The ESRMF could also be used to implement the control sign maintenance method suggested by the FHWA where ESRMF signs can be chosen to represent similar signs in the field. When the retroreflectivity of the test signs in the ESRMF falls below the minimum, similar signs in the field should be replaced.

The ESRMF will assist agencies in determining sign sheeting selection policies, or in other words, which sign sheetings to use for different applications. Currently, there is a particularly significant need for long-term performance data on the newer sign sheetings, beyond the short-term performance data from the NTPEP. If an agency knows how a sign sheeting type deteriorates over time relative to its cost, life-cycle cost analysis can be used to determine the most cost-effective sheeting applications. Thus, facilities such as the ESRMFs recommended here will yield important data that are not available in any other cost-effective way.

4.6 Recommendations

The authors recommend that ESRMFs be built in at least each of the major climatic regions in the United States to best determine how signs in the area deteriorate over time. The facilities could be located in New England, Florida or Georgia, the Rockies, the arid Southwest, the Pacific coast, and the plains of the northern and southern Midwest. ESRMFs built using this design or a variation thereof can be used, along with a sign inventory program, to ensure compliance with the FHWA minimum retroreflectivity standards on a national scale. The data collected by each ESRMF should be made available to all agencies nationwide. Federal funding could be made available for both ESRMFs and the sharing of ESRMF data.

5.0 SIGN DETERIORATION MODEL

The new minimum standard for retroreflectivity has been referred to by some as the nation's largest unfunded mandate. The standard deals with one of the most safety-critical elements of our highway system. It is imperative now that quality data be available in which to base strategic decisions for meeting the standard. Yet there have been only a limited number of such studies. A careful analysis of the data from these studies and a critical analysis of them is provided in this chapter. No such comprehensive analysis has previously been attempted. In addition, data from a new NCSU study is included.

A total of six sign retroreflectivity studies and tests were examined in the process of collecting sign retroreflectivity data for use in a deterioration model. These studies were conducted by the FHWA (Black et al. 1991), the State of Oregon (Kirk et al. 2001), Louisiana State University, (Wolshon et al. 2002), Purdue University (Bischoff and Bullock 2002), and NCSU (Rasdorf et al. 2006).

5.1 Synthesis of Studies

The R^2 values of the regression models from the original FHWA study analysis, the NCSU data, the re-analyzed Oregon data, and the re-analyzed Purdue data have been compiled in Table 5.1 - Table 5.4. These tables also show the sign age when each curve reaches the retroreflectivity level where NCDOT sign inspectors tend to replace signs during their visual inspection process (Rasdorf et al. 2006). For white and yellow signs the NCDOT visual minimum was 20 R_A, and for red and green signs the minimum was 4 R_A.

The upward arrow in Table 5.1 - Table 5.4 indicate that the slope of the curve began to unrealistically increase at some point. The highlighted cells in the tables identify the curves that were found to be the most reasonable for that particular type of sign and color. For a given sign type and color, if the curve with the highest R^2 did not give a satisfactory value for the age at which signs hit the NCDOT visual minimum retroreflectivity, the curve with next best R^2 value was considered.

Based on Table 5.1 the following observations emerged. For Type I white signs there was only one feasible option, the FHWA study linear curve model, which was the only study that had a reasonably high R^2 value (0.52) and reached 20 R_A at 15 years. It was difficult to decide on a deterioration curve for white Type III signs as the highest R^2 value was only 0.19 (FHWA linear curve), and this curve reached the NCDOT visual minimum retroreflectivity at 59 years. It is more likely that these signs would follow a linear pattern for about 20-30 years after which the slope should become steeper and the retroreflectivity would drop to 20 more quickly, but we simply do not have enough data on older signs of this type and color to know this for sure. The R^2 values for the other models were too low to be considered.

Table 5.1. R^2 Values and Extrapolated Sign Life for White Signs

Study	R^2 Values					Sign Age at R_A = 20				
	Lin	Log	Poly	Pow	Exp	Lin	Log	Poly	Pow	Exp
Type I Signs										
FHWA	0.52	-	-	-	-	15	-	-	-	-
NCSU	0.17	0.18	0.19	0.13	0.14	33	>80	↑	>80	37
Type III Signs										
FHWA	0.19	-	-	-	-	59	-	-	-	-
OR	0.01	0.01	0.01	0.01	0.00	>80	>80	↑	>80	>80
Purdue	0.01	0.00	0.03	0.00	0.01	>80	>80	36	>80	>80
NCSU	0.01	0.01	0.01	0.01	0.01	>80	>80	>80	>80	>80

Legend			
-	No Data	**Poly**	Polynomial curve
↑	Sign age could not be computed due to curve trending upwards	**Power**	Power curve
Lin	Linear curve	**Exp**	Exponential curve
Log	Logarithmic curve	**>80**	Very large value

Table 5.2 shows that among Type I yellow signs, the FHWA study linear curve again had a relatively high R^2 value of 0.39 and reached 20 R_A at 15 years. Hence this linear curve was

chosen for Type I yellow signs. For Type III yellow signs, the FHWA linear curve had the highest R^2 value of 0.31, but it also had very high age at which the curve reached $R_A = 20$. The Purdue polynomial curve had an R^2 value of 0.26. Since the Purdue polynomial predicted that retroreflectivity would reach 20 R_A at a more reasonable 24 years, this model was selected.

Based on Table 5.3 the following observations emerged for red signs. For Type I red signs the R^2 values of the NCSU data curves were near 0.40 for all curve types. This was higher than the R^2 value of the linear curve from the FHWA study. The research team decided to consider the linear curve ($R^2 = 0.37$, sign age at $R_A = 4$ is 14 years) as the best fit curve in order to maintain consistency in type of model chosen among the different colors of Type I signs. For Type III red signs the polynomial curve plotted from the NCSU study had the highest R^2 value (0.48); however, the predicted sign life of 11 years for this curve was not consistent with the results of all other models and sign colors. The exponential curve plotted from the NCSU data also had a large R^2 value, but the NCSU research team chose the linear curve because the 21-year sign life is more reasonable. None of the other studies provided superior models.

Table 5.2. R^2 Values and Extrapolated Sign Life for Yellow Signs

Study	**R^2 Values**					**Sign Age at $R_A = 20$**				
	Lin	**Log**	**Poly**	**Pow**	**Exp**	**Lin**	**Log**	**Poly**	**Pow**	**Exp**
Type I Signs										
FHWA	0.39	-	-	-	-	15	-	-	-	-
NCSU	0.22	0.11	0.24	0.12	0.23	21	>80	16	>80	21
Type III Signs										
FHWA	0.31	-	-	-	-	50	-	-	-	-
OR	0.08	0.09	0.09	0.05	0.05	39	>80	↑	>80	42
Purdue	0.17	0.07	0.26	0.07	0.17	57	>80	24	>80	>80
NCSU	0.06	0.07	0.09	0.07	0.08	>80	>80	31	>80	>80

Table 5.3. R^2 Values and Extrapolated Sign Life for Red Signs

Study	R^2 Values					Sign Age at $R_A = 4$				
	Lin	Log	Poly	Pow	Exp	Lin	Log	Poly	Pow	Exp
Type I Signs										
FHWA	0.21	-	-	-	-	14	-	-	-	-
NCSU	0.37	0.36	0.37	0.31	0.40	14	20	15	18	13
Type III Signs										
FHWA	0.17	-	-	-	-	↑	-	-	-	-
OR	0.12	0.06	0.20	0.07	0.13	39	>80	17	>80	78
Purdue	0.34	0.34	0.36	0.24	0.28	24	>80	↑	>80	43
NCSU	0.35	0.15	0.48	0.20	0.42	21	>80	11	>80	43

For Table 5.4 the selection of curves for Type I and III green signs was straightforward. Only the FHWA linear curves had relatively high R^2 values and predicted reasonable times (19 and 37 years) at which signs would reach $R_A = 4$. Although the Type I NCSU polynomial curve had a larger R^2 than the FHWA linear curve, it was not selected because the curve trended upwards.

Table 5.4. R^2 Values and Extrapolated Sign Life for Green Signs

Study	R^2 Values					Sign Age at $R_A = 4$				
	Lin	Log	Poly	Pow	Exp	Lin	Log	Poly	Pow	Exp
Type I Signs										
FHWA	0.31	-	-	-	-	19	-	-	-	-
NCSU	0.27	0.27	0.36	0.19	0.18	21	41	↑	33	19
Type III Signs										
FHWA	0.48	-	-	-	-	37	-	-	-	-
OR	0.00	0.01	0.09	0.01	0.00	↑	↑	13	↑	↑
Purdue	-	-	-	-	-	-	-	-	-	-
NCSU	0.06	0.02	0.11	0.02	0.06	↑	↑	34	↑	↑

5.2 Deterioration Model Incorporating Sign Location

Looking at the selected model results from Table 5.1 - Table 5.4, although some of the R^2 values were respectable (given the general scattered nature of the retroreflectivity data), the sign age estimates tended to be significantly longer than seen in practice. As a result there was a desire to improve the deterioration models, especially in the areas of sign lifetime prediction, and to look for other factors that would explain the scatter.

5.2.1 Survival Analysis

Initially the author considered the area of survival or duration analysis, which models (for some population) the distribution of time between two events. In our case the events are when a sign is first put into service and when its retroreflectivity falls below an established minimum. Survival analysis can also estimate the effect of various factors on the overall survival (life) time. Survival analysis data for a population is generally collected at regular time intervals, such as annually. Looking at the sign data from the literature as well as from the NCSU study, the author found that all of the sign data was what is called "current status data." In other words it is actually population data that was collected once rather than at several intervals over time. This results in heavily left and right censored data, with only a very small percentage of the signs being at failure/death (the established R_A minimum) when the data were collected. Because the sign deterioration data contain only one R_A measurement of each sign, greater statistical certainty about sign lifetime can be gathered from a regression analysis than from a survival analysis. In other words there simply isn't enough long term data on older signs to establish the second event.

5.2.2 Analysis Modifications

The author also revisited the hypothesis that location may have an effect on sign deterioration, although other sign studies have found location not to be as significant as sign age. In the area of pavement deterioration, significant regional effects have been identified (Al-Suleiman 1991). The authors felt that location differences could provide an explanation for some of the data variation and that location might account for both environmental differences and sign management differences. To test this hypothesis the NCSU data were divided by the five NCDOT divisions they were collected in before the new regression models were run. The five NCDOT division locations are shown in Figure 3.1. They range from coastal areas (Divisions 2 and 6) to mountainous areas (Divisions 12 and 13). For some sign sheeting type and color combinations, some divisions' data were excluded from the regression models because of insufficient or poorly distributed data.

5.2.3 Significance of Sign Location

For the R_A vs. sign age relationship, new linear regression models were calculated from the NCSU data for each sheeting type and color combination that determined a different slope and intercept for each NCDOT division with sufficient data for that sign sheeting type and color combination. In all eight of these "division-separated" regression models, the F-values for the division-based intercepts were large enough to indicate that the null hypothesis should be rejected, signifying that division (location) is a significant factor influencing retroreflectivity deterioration.

Table 5.5 gives the sign age estimates at R_A = 50, the FHWA minimum, from the new division-separated linear regression model for Type I white signs. The estimates, shown in the third column, are for each NCDOT division, and an average over all divisions was also calculated. Looking at the number of observations used to determine each model (column 2), the divisions with more observations (e.g. 6, 12, and 13) have narrower 95% confidence limits for the age estimate than the divisions with fewer observations. Division 8 has a much higher age estimate than the other divisions, but only had 11 observations, making division 8's age estimate less certain. For the divisions with more observations, it seems reasonable to predict that a Type I white sign would reach a R_A of 50 between 6 and 8 years old for divisions 2 and 12, and between 9 and 11 years for division 13. This difference in estimated lifetime could be due to variations in sun exposure. Division 13 is situated in a mountainous area where many signs are shaded, while divisions 6 and 12 are in fairly open and exposed rural/suburban settings.

Table 5.5. Age Estimate at FHWA Minimum for Type 1 White by NCDOT Division

NCDOT Division	Number of Type I White Signs Measured	Age Estimate @ R_A = 50, years	95% Confidence Limits	
2	16	8.6	6.4	10.8
6	79	7.3	6.2	8.4
8	11	13.4	10.8	15.9
12	60	7.1	6.0	8.3
13	109	10.4	9.4	11.4
All Divisions	**275**	**9.3**	**8.6**	**10.1**

5.3 Sign Lifetime Estimates for the Division-Separated Regression Models

Division-separated linear regression models were generated for all eight sign sheeting type and color combinations. Section 14.2 contains the SAS output for the division-separated linear regression models. Table 5.6 presents the average sign lifetime estimates with 95% confidence intervals for both the NCDOT and FHWA minimum retroreflectivity levels. A risk level of 5% is considered acceptable for retroreflectivity deterioration (Lundkvist and Isacsson 2007). The sign lifetime estimates presented in the fifth and seventh columns of Table 5.6 are an average of all of the NCSU study data over all NCDOT divisions. Some sign color/sheeting combinations do not have average sign lifetime estimates from all five NCDOT divisions because of insufficient data in certain divisions. As described in Section 5.2.3, the 95% confidence intervals are wider for Type III signs due to smaller sample sizes and a lack of data on older signs. White signs have two different FHWA minimums: a minimum of R_A = 35 for stop sign legend applications and a minimum of R_A = 50 for black on white background applications. Stop signs, which utilize both red and white sheeting, need to satisfy both retroreflectivity minimums (R_A = 7 for stop sign red background) and a minimum 3:1 white to red retroreflectivity ratio. See Table 2.1 for the FHWA minimum retroreflectivity standards.

For comparison and evaluation purposes, the number of observations (n) and the R^2 values for each model are given. Six out of the eight regression models had p values less than 0.005, indicating that the model coefficients and overall model are significant. The yellow and green Type III models had larger p-values, indicating that these two models need some improvement. For the yellow and green Type III models, only one division had sufficient data. The shaded rows in Table 5.6 indicate the four models (white Type III, red Type I and III, and green Type I) that have higher R^2 values than the corresponding "best" literature models identified in Tables 2-5.

Table 5.6. Average Lifetime Estimates for the Division-Separated NCSU Regression Models

Color	Sign Type (beaded)	n	R^2	Age at NCDOT minimum (years)	95% Confidence Interval	Age at FHWA minimum (years)	95% Confidence Interval
White	I	275	0.31*	13	(11, 14)	11 ($R_A = 35$)	(10, 12)
						9.3 ($R_A = 50$)	(8.6, 10.1)
White	III	54	0.31*	16	(7, 25)	15 ($R_A = 35$)	(7, 24)
						14 ($R_A = 50$)	(7, 22)
Yellow	I	259	0.24*	10	(8, 11)	6.6[a]	(6.1, 7.1)
Yellow	III	34	0.14	14	(5, 22)	12	(5, 19)
Red	I	42	0.58*	10	(8, 11)	8	(7, 9)
Red	III	43	0.47*	11	(8, 13)	10	(8, 12)
Green	I	27	0.43*	11	(9, 14)	9	(7, 11)
Green	III	13	0.04	17	(3, 30)	14	(7, 21)

**Regression model p values are less than 0.005*
[a]Sheeting type not recommended for use by FHWA

5.4 Summary and Conclusions

As a result of the FHWA minimum retroreflectivity standards, many US highway agencies are trying to better manage their sign assets. As part of this effort, the NCDOT commissioned NCSU to develop a simulation of the sign inspection process. An essential part of the simulation is prediction of the rate at which sign retroreflectivity decreases with sign age. The purpose of the study was to identify or determine the best sign deterioration prediction curves for Type I and III white, yellow, red, and green signs. This chapter reports on the results of that effort.

To determine the final deterioration curves, the NCSU research team conducted a comprehensive study of available previously published research papers and reports related to sign retroreflectivity deterioration. Earlier study data were re-analyzed to try to discover the optimal function form (for each sign color and type) to predict sign deterioration rates. The NCSU research team also gathered its own sample of retroreflectivity measurements from over 1000 signs across North Carolina.

Table 5.7 summarizes the findings from this work. Six of the selected deterioration models resulted from the FHWA study and two were from the Purdue study. The curve selected from the Purdue study for Type III yellow was polynomial, while all of the others were linear. The selected curve for Type III white signs had the lowest R^2 value of only 0.19 and an implausible prediction that signs would not drop to a level of 20 R_A until they were 59 years old. The other seven curves were better, with R^2 values ranging from 0.21 to 0.52 and predictions that signs would reach the NCDOT visual R_A minimum between 14 and 37 years. The p-values for the regression coefficients and for the overall regression models are significant. However, the standard errors in Table 5.7 are not as low as the research team would like. The variance in all of the studies is probably due to a combination of dissimilarities in the study, measurement method error, retroreflectometer error, and uncontrolled conditions in the field. Hence, Table 5.7 gives a set of the best available sign deterioration curves that those interested in modeling sign performance can use with some confidence, but there is certainly room for future improvement in prediction and precision.

Table 5.7. Sign Deterioration Literature Data Summary

Sign Color	Sign Type	Data Source	Equation y: R_A x: sign age [year(s)]	R^2	Regression Standard Error	Age at NCDOT minimum (years)	Age at FHWA minimum (years)
White	I	FHWA	y = 103.085 - 5.451x	.52	19.1	15	13 (R_A = 35) 10 (R_A = 50)
	III	FHWA	y = 304.089 - 4.815x	.19	32.7	59	56 (R_A = 35) 53 (R_A = 50)
Yellow	I	FHWA	y = 78.794 - 3.906x	.39	17.0	15	7[a]
	III	Purdue	$y = -0.552x^2 + 5.644x + 193.01$	.26	33.6	24	22
Red	I	NCSU	y = 13.085 – 0.635x	.37	3.0	14	10
	III	NCSU	y = 59.632 – 2.658x	.35	9.7	24	20
Green	I	FHWA	y = 15.990 - 0.637x	.31	3.4	19	14
	III	FHWA	y = 53.386 - 1.345x	.48	7.7	37	35

[a]*Sheeting type not recommended for use by FHWA*

Type III signs have much higher retroreflectivity values than Type I signs for the samples examined in this chapter, which are almost all less than 15 years old. This allows a couple of observations to be made. First, if highway agencies replace their Type I signs with Type III signs, retroreflectivity values will significantly increase and essentially remove retroreflectivity as a concern for many years while simultaneously lowering life-cycle costs (Rys and Russell 1995). Second, there is a weak basis for predicting how signs will perform after 15 years or so in the field. For this study the research team assumed that Type III signs will last as long or longer than Type I signs, but there is no empirical evidence to support that assumption at this point. Quite simply, these signs have not been in place long enough to provide adequate data to work with.

The research found that R^2 values were usually less than ideal for the trend lines between age and retroreflectivity. Almost all of the R^2 values from the NCSU data or from the literature were less than 0.5, and many were less than 0.1. This likely means that other factors besides age influence the rate at which signs deteriorate. These factors include measurement method error, retroreflectometer error, and uncontrolled field conditions which lead to damage and weathering. Although the effect of each individual factor may be low, as the literature suggests, the factors collectively cause the scatter in the data. When the authors re-analyzed the NCSU data including NCDOT division as a factor that could account for some location and management differences, significant performance variations from division to division were found. The division-separated linear regression model for Type III white signs is a good alternative to the selected literature Type III white sign model (FHWA model).

In this chapter the discussion was confined to age, which we considered to be the most important factor causing deterioration, and sign location. The other factors, if considered, would be helpful in designing a microscopic simulation of sign performance but would make the simulation almost impossible to apply for most highway agencies. The NCDOT, for example, relies on qualitative visual nighttime sign inspections and does not maintain a sign inventory, so at this point a sign management system that requires any information besides sign color, type, approximate location, and age cannot be practically used.

5.5 Future Research

There are several prime avenues for productive future research to follow up this work. First, future researchers should collect more Type III sign data as the data that were collected in this study and that reported by numerous other studies was primarily for Type I signs. The weakest selected model, i.e., the least amount of reliable available data, was for Type III white signs. Additional studies should also collect more data on old Type III signs (older than 15 years) in order to derive a more accurate deterioration curve for the latter stages of sign life.

Second, a key limitation of all existing studies is the wide data scatter and short duration of data collection. Essentially only snapshots in time are available rather than systematic multi-year studies. As a result, AASHTO should consider conducting research for more than 3 years in its NTPEP program to provide researchers with a more comprehensive data set. If signs were left in place longer more well-founded deterioration rates would be available for study and analysis that would benefit the Departments of Transportation across the country, especially as they attempt to develop strategies to meet the new minimum retroreflectivity standard. The availability of longer term data would also provide researchers with the opportunity to explore other modeling approaches such as survival analysis.

If AASHTO is unwilling or unable to extend its program test duration, states should consider establishing their own sign testing facilities. This will help the individual states in having data for their respective geographic locations and climatic conditions. Chapter 4.0 presented a design for an experimental sign facility intended to meet a wide variety of long term retroreflectivity data needs as well as provide other sign performance data (Rasdorf et al. 2008). The facility includes a base facility design and suggested optional modifications to show how the design can be customized or expanded, depending on an agency's unique needs. Seventeen years ago, FHWA researchers recommended that "a controlled study where climate is constant should be undertaken at approximately 10 sites across the country" (Black et al. 1991).

Third, future studies should be conducted under natural field conditions, i.e., without cleaning signs. Cleaning will give a higher retroreflectivity but it does not represent signs that drivers see at night. Drivers see signs in their natural state and hence, cleaning a sign will not give the desired solution.

Finally, future research must consider not only age, but also other factors that affect sign deterioration. This will help feed a more accurate microscopic simulation. Efforts could then be made to insure that the simulation results could be practically applied even in that do not currently maintain a sign inventory.

6.0 INITIAL SIMULATION MODEL DEVELOPMENT FOR VALIDATION SCENARIO

To simulate the traffic sign asset management system, one must first define the parameters that control the environmental and management functions of the system. These input parameters are based on existing data related to sign materials, environmental exposure, and management practices. For this simulation the input parameters include:

- Initial system condition and distribution
- Deterioration rates
- Damage rates
- Inspection behaviors
- Replacement rates

These parameters can differ for each sign, taking into account sign sheeting type, sign color, sign location, sign message, and sign age. The following sections describe the input parameters and models used to validate the simulation model and in the simulation scenarios.

The 2005-2006 NCDOT sign data set collected as a part of the effort described in Rasdorf, et al. (2006) and referred to in Section 3.1 serves as the basis for the simulation validation scenario. Therefore, the author derived the input parameters for the simulation validation from the 2005 portion of the NCDOT data set. The simulation validation will run the simulation for one year (to 2006) and then compare the 2006 simulation results to the values in the 2006 portion of the NCDOT data set.

Because the goal of the simulation validation is to have the simulation results in 2006 be close in value to the actual 2006 data set, the author developed the asset management parameters directly from the 2005 data. The detail of the input parameters matches the quality of the 2005 data set. If there were not enough signs observed in the 2005 dataset with a certain set of characteristics, the author aggregated several characteristics together.

6.1 Initial System Condition and Distribution

The initial system condition and distribution defines the initial attributes of the sign population being simulated. In the validation scenario, the initial system condition and distribution exactly matches the sign distribution of the 1047 signs measured in 2005 in the NCDOT data collection. This 2005 initial sign distribution contains the sign attributes that determine the signs' route through the simulation. The attributes that are included in the validation initial sign distribution include:

- unique sign identification number
- sheeting type
- background color
- 2005 age
- 2005 background R_A
- road type
- action code

The unique sign identification number is included in the initial sign distribution so that individual signs can be traced through the simulation and their simulated condition can be compared to their actual condition in 2006. Sheeting type, background color, 2005 age, and the 2005 background color retroreflectivity values are important in determining retroreflectivity condition and deterioration. For stop signs only, the legend color (white) and its 2005 retroreflectivity are also necessary to fully define their condition relative to the FHWA minimum retroreflectivity standards because of the 3:1 white to red retroreflectivity contrast ratio requirement. Road type and action code are included in the initial sign distribution because these attributes can affect how a sign is managed (i.e. replaced, inspected) in the system. As a reminder, action codes as defined by the NCDOT are *one* for stop and yield signs, *two* for warning signs, and *three* for all other (i.e. guide) signs.

Because the sign system simulation was constructed using the Arena simulation software, the Arena *ReadWrite* module can be used to read an input data file into the simulation (Seppanen et al. 2005). For the simulation validation scenario, the input file used was a database file derived from 2005 - 2006 NCDOT sign data set that contains the attributes listed above. This input file would then assign to each simulation sign entity attributes exactly matching its real-world counterpart. The input file used for the simulation validation is included in Appendix C: Simulation Input File from 2005 NCSU/NCDOT Data.

6.2 Retroreflectivity Deterioration

The retroreflectivity deterioration behavior of each sign is based on the initial retroreflectivity value in 2005, sign color, and sign sheeting type that is assigned to each sign when the input file is read into the Arena simulation. The retroreflectivity deterioration models in the simulation are based on analysis of the relationship between sign age and retroreflectivity in the 2005 data set for each sign sheeting (2) and sign color (4) combination (8 total). The following section describes the retroreflectivity deterioration models that are used in the simulation validation. Detailed information about the development of these deterioration models can be found in Section 5.0.

In the Arena simulation software, the deterioration models are represented as a set of linear models with a normally distributed intercept and slope. The slope in the deterioration models represents the amount of retroreflectivity a sign is expected to 'lose' in one year. From the initial sign distribution input file, each sign's 2005 retroreflectivity, sign color, and sign type are known. In Arena, the Purdue yellow Type III model is represented as a quadratic, instead of linear, model. For each sign, the simulation software samples a value for the deterioration model slope (or quadratic coefficient) from a normal distribution ($N[\mu,\sigma]$) based on the mean (μ) and standard error (σ) of the slope estimate and then subtracts this sampled value from the 2005 retroreflectivity value to determine the 2006 retroreflectivity value for that sign. For example, in the Green Type I NCSU division-separated model the normal distribution would be expressed as N[-0.982, 0.424]. The first set of validation scenario runs used the NCSU/NCDOT deterioration models and the second set used the best literature models. The goal of this comparison is to select for the validation and main simulation scenarios the deterioration model set that yields the best comparison with the actual 2006 sign conditions.

6.2.1 Selection of Retroreflectivity Deterioration Models

Using the simulation validation scenario, a *combination* of models from the NCSU division-separated models set listed in Table 5.6 and the best literature models set listed in Table 5.7 were found to *best* replicate the deterioration observed from 2005 to 2006 in the NCSU/NCDOT study. When the division-separated NCSU (DS-NCSU) models were used in the validation simulation, the models for White and Yellow Type I and Green Type III did not deteriorate these signs 'enough'. In other words, the slope estimates for these three models were too small, leading to not enough loss in R_A per year. The FHWA models for these three sign type/color combinations had larger slope estimates that, when run through the validation simulation, yielded deterioration similar to what was observed from 2005 to 2006 in the NCSU/NCDOT study. Table 6.1 lists the deterioration models used in the final simulation validation, including the R^2 values, slope estimates, and slope standard errors for each model.

Table 6.1. Final Simulation Validation Retroreflectivity Deterioration Models

				Slope		
Sign Type	**Sign Color**	**Model Source**	**Model R^2**	**Estimate (R_A /year)**	**Standard Error**	**R_a Deterioration Equation**
I	White	FHWA	.52	-5.451	0.217	$R_A = 103.1 – 5.451Age$
I	Yellow	FHWA	.39	-3.906	0.210	$R_A = 78.8 – 3.906Age$
I	Red	DS -NCSU	.58	-0.898	0.171	$R_A = 15.26 - 0.898Age$
I	Green	DS - NCSU	.43	-0.982	0.424	$R_A = 15.13 - 0.982Age$
III	White	DS - NCSU	.31	-5.236	1.217	$R_A = 274.2 – 5.236Age$
III	Yellow	DS - NCSU	.14	-2.554	1.103	$R_A = 211.2 - 2.554Age$
III	Red	DS - NCSU	.47	-3.521	0.667	$R_A = 65.61 - 3.521Age$
III	Green	FHWA	.48	-1.345	0.248	$R_A = 53.39 – 1.345Age$

6.3 Damage

Damage percentages are based on the 2005 NCSU/NCDOT data set. The damage that was found during this study occurred sometime between the time a sign was last inspected (prior to 2005) and the time of the 2005 NCDOT inspection that was observed during the NCSU study. The damage percentages/rates that are used in the simulation validation should be viewed as 'accumulated' damage rates instead of annual damage rates because the time elapsed between inspections is unknown. The data have been sorted by sign color, sign sheeting type, and road type (interstate, primary, secondary) to determine the percent of damaged signs found in 2005 in each category group. In the NCSU/NCDOT data set, sign damage was not observed on interstates or on white and green Type III signs. Table 6.2 gives the number and percent of total signs that the NCDOT sign inspectors identified as damaged (by sign sheeting type, color, and road type).

Table 6.2. 2005 Accumulated Damage Rates by Sheeting Type, Sheeting Color, Age, and Road Type

Sheeting Type	Sheeting Color	Road Type	# Damaged	% Damaged
I	Green	Secondary	3	8.3
	Red	Secondary	3	11.1
	White	Primary	6	7.6
		Secondary	15	7.6
	Yellow	Primary	5	9.3
		Secondary	38	11.9
III	Red	Secondary	2	3.1
	Yellow	Primary	1	7.7
		Secondary	2	3.3
		TOTAL	**75**	**7.2**

In the Arena simulation software the damage rates are represented using the *Decide* module, which takes each sign and by random chance assigns it to one of two outcomes (damaged or undamaged) based on an expected value percentage that should go to one outcome (damaged) over the course of many trials. For the validation, the signs are divided based on their sheeting type, sheeting color, and road type and sent to the respective *Decide* module that corresponds to the sign's attributes. There, the *Decide* module randomly assigns certain signs as damaged based on the percent damaged given in Table 6.2.

6.4 Inspection Behavior

During visual nighttime sign inspections, NCDOT sign inspectors examined each of the signs in the 2005 NCSU/NCDOT data set and decided whether to pass (not reject) or fail (reject) each one. The FHWA minimum sign retroreflectivity standards define a minimum R_A for each sign sheeting type/color combination. If the sign inspectors were perfect, all signs above the minimum R_A in 2005 should have been 'passed' and those below 'failed.' In Table 6.3, a correct 'pass' is listed as a *correct positive* and a correct 'fail' as a *correct negative*. A sign above the minimum R_A that was incorrectly 'failed' is listed as a *false negative* and an incorrectly 'passed' sign is listed as a *false positive*. This two (correct, false) by two (positive, negative) inspection accuracy logic is similar to the inspection accuracy logic used in Kilgour, et al. (2007), with the false negative case corresponding to a Type I Error, and the false positive case corresponding to a Type II Error.

Table 6.3. NCDOT Inspection Behavior by Sheeting Type and Color

Sheeting Type	Sheeting Color	Signs Above Minimum R_A				Signs Below Minimum R_A			
		Correct Positive		False Negative (Type I Error)		Correct Negative		False Positive (Type II Error)	
		No.	%	No.	%	No.	%	No.	%
I	Green	26	89.7	3	10.3	2	15.4	11	84.6
	Red	16	94.1	1	5.9	5	71.4	2	28.6
	White	215	98.2	4	1.8	17	19.1	72	80.9
	Yellow	118	92.9	9	7.1	54	32.0	115	68.0
III	Green	45	97.8	1	2.2	0	-	0	-
	Red	63	94.0	4	6.0	0	-	0	-
	White	55	98.2	1	1.8	0	-	0	-
	Yellow	86	97.7	2	2.3	3	100.0	0	0.0
Total		624	96.1	25	3.9	81	28.8	200	71.2

Table 6.3 lists, for each sheeting type/color combination, the percent of signs above and below the minimum R_A in 2005 that were correctly and incorrectly classified by the inspectors. Overall, the inspectors 'passed' 824 signs (624+200) and 'failed' 106 signs (25+81). There were not enough sign data to further divide the Table 6.3 values by road type, although with more data this factor could be explored.

For a few select groups of signs, the percentages given in Table 6.3 do not apply. All (100%) of signs categorized as damaged were 'failed' (rejected) by the inspectors. Once the damaged signs are removed from the sign population, 4.32% of the remaining signs were found to be rejected due to needing to be upgraded to a higher sheeting type or due to being dirty. All of these rejected upgrade/dirty signs were Type I sheeting and either green, white, or yellow. Sign inspectors identified green and white Type I signs only had upgrade/dirty signs only on secondary roads, while they identified yellow upgrade/dirty signs on primary and secondary roads. Table 6.4 lists the percent of upgrade/dirty signs by sign sheeting type, color, and road type.

Table 6.4. Upgrade/Dirty Signs by Sheeting Type, Color, and Road Type

Sheeting Type	Sheeting Color	Road Type	# of Upgrade / Dirty Signs	# of Signs	%
I	Green	Secondary	1	33	3.0
	White	Secondary	6	183	3.3
	Yellow	Primary/ Secondary	35	330	10.6
Total			42	546	4.32

The remaining signs (after the damaged and upgrade/dirty signs are removed from the sign population) are "inspected" in the simulation according to their retroreflectivity value and Table 6.3. If the sign's retroreflectivity value is below the minimum, the correct negative/false positive percentages apply; if the sign's retroreflectivity is greater than the minimum, the correct positive/false negative percentages apply.

In the Arena simulation software the decisions involved in inspection are represented using the *Decide* modules, which take each sign and by random chance assigns it to one of two outcomes (passed or failed) based on an expected value percentage that should go to one outcome (passed) over the course of many trials. For the validation, the signs are divided based on their sheeting type, sheeting color, and then sent to one of two *Decide* modules, based on whether the sign's retroreflectivity is above or below the minimum R_A. There, the *Decide* module randomly assigns certain signs as 'passed' (not rejected) or 'failed' (rejected) based on the percentages for correct positive/false negative and correct negative/false positive given in Table 6.3.

6.5 Replacement

Once a sign has either 'passed' or 'failed' inspection, it is then either replaced with a new sign or not replaced. Logically, a greater percentage of 'failed' (rejected) signs are replaced than 'passed' (not rejected) signs. The 2005 NCSU/NCDOT data set was analyzed to determine what sign attributes have the greatest influence in determining whether a sign is replaced. First, it was found that damaged signs, upgrade/dirty signs, and signs rejected in the inspection process for having a retroreflectivity below the minimum were all replaced in approximately the same percentages. Table 6.5 lists the number of signs replaced and not replaced by rejection reason. The author performed a 3x2 chi square test (two degrees of freedom) on the data in Table 6.5 and found that the null hypothesis (that there is no difference in replacement behavior due to rejection reason) cannot be rejected because the chi square test statistic for the Table 6.5 data (2.62) was less than the critical value (5.99) at a 95% level of significance. In other words, once a sign is rejected knowledge of why the sign was rejected by the sign crews is lost and the sign's action code determines how quickly sign crews replace the sign.

Table 6.5. Number of Signs Replaced by Rejection Reason

Rejection Reason	Replaced?		Total
	Yes	No	
Damaged	47 (63%)	28 (37%)	75
Upgrade/Dirty	20 (48%)	22 (52%)	42
Low Retroreflectivity	58 (55%)	48 (45%)	106
Total	118 (56%)	98 (44%)	223

Each sign's action code, a replacement priority value assigned to each sign by the NCDOT, was the greatest determining factor for a sign being replaced. Table 6.6 lists rejected signs replaced and not replaced by sheeting type and action code. The percentages in Table 6.6 are averaged over all NCDOT divisions and color combinations. There were insufficient data to further divide the values in Table 6.6 by road type, although this could be investigated in the future.

Table 6.6. Replacement Rates for Rejected Signs (by Action Code)

Sheeting Type	Action Code	Sign Color	Signs Rejected	Signs Replaced		Signs NOT Replaced	
			#	#	%	#	%
I	1	Red (Stop)	9	8	88.9	1	11.1
	2	Yellow	141	87	61.7	54	38.3
	3	White, Green	57	23	40.4	34	59.6
III	1	Red (Stop)	6	4	66.7	2	33.3
	2	Yellow	8	3	37.5	5	62.5
	3	White, Green	2	0	0.0	2	100.0
Total			223	125	56.0%	98	44.0%

Approximately 10% of all signs that were not rejected (passed) by the NCDOT sign inspectors were replaced even though they were satisfactory, as shown in Table 6.7. A possible explanation for the quantity of 'passed' signs that were replaced is the initiative to upgrade all signs to be Type III or greater in North Carolina, especially for signs classified as action code 1 (stop signs) or 2 (yellow warning signs).

In addition to the choice between replacement or being allowed to remain in service, some signs were removed during the 2005-2006 time period. There are two separate groups of signs that are removed. The first group consists of the 5.6% (7/125) of rejected signs that are removed. The simulation considers these signs to be 'replaced' (an action was carried out upon them) due to upgrades or changes. In the simulation these signs are removed after the replacement rates in Table 6.6 designate them for replacement and before the Type I or III sheeting replacement decision point. The second group consists of the 2.3% (19/824) of not rejected signs that are removed. The simulation considers signs that are not-rejected (passed inspection) but still are removed as *not* being "replaced." This second group of signs are removed before reaching the replacement stage of the simulation and are therefore not included in the rates shown in Table 6.7.

Table 6.7. Replacement Rates for Signs That Were Not Rejected (by Action Code)

Sheeting Type	Action Code	Signs NOT Rejected	Signs Replaced		Signs NOT Replaced	
		#	#	%	#	%
I	1	18	1	5.6	17	94.4
	2	229	48	21.0	181	79.0
	3	316	14	4.4	302	95.6
III	1	63	7	11.1	56	88.9
	2	81	3	3.7	78	96.3
	3	98	2	2.0	96	98.0
Total		805	75	9.3%	730	90.7%

6.5.1 Type I to Type III Conversion Rate

Signs in the validation scenario that have been selected for replacement can be replaced with a new sign using either Type I or Type III sheeting. The policy of the NCDOT is to replace all Type I signs with Type III sheeting signs, but because of some remaining inventory of Type I signs, not all signs replaced in the 2005-06 NCSU/NCDOT data set were replaced with Type III. Table 6.8 lists the percent of signs replaced with Type I or III sheeting based on the original sign's sheeting type and action code classification. Note that all original Type III signs and all action code 1 signs were replaced with new Type III signs. The range in Type III replacement values is due to differences between different road types and sign background colors. The values in Table 6.8 could not be divided further by road type because of insufficient data.

For the replacement portion of the validation scenario, the signs were divided based on their action code and rejection status and then sent to one of two *Decide* modules, based on whether the sign has been rejected or not. There, the *Decide* module by random chance assigns certain signs as replaced or not replaced based on the percentages for signs replaced and not replaced given in Table 6.6 and Table 6.7. Signs that were replaced then move to another *Decide* module where they are assigned by chance to be replaced with a sign made of Type I or Type III based on the percentages shown in Table 6.8. For the original sheeting type/action code combinations where there are a range of percentages given, the percentage used is selected from a uniform distribution for each simulation run.

Table 6.8. Sheeting Type Used for Replacement by Action Code

Original Sheeting Type	Action Code	Replace with…		Total #
		Type I	Type III	
I	1	0%	100%	9
	2	3.9% - 4.6%	95.4% - 96.1%	131
	3	33.3% - 37.1%	62.9 % - 66.7%	35
III	all	0%	100%	18
Total		9.8%	90.2%	193

7.0 SIMULATION VERIFICATION AND VALIDATION

The goal of the simulation validation was to compare simulation output data to actual sign system data to determine if the verified simulation model was an accurate representation of the real-world sign system observed during the 2005-06 NCSU/NCDOT study. A simulation determined to be a "valid" representation of the sign system can then "be used to make decisions about the system similar to those that would be made if it were feasible and cost-effective to experiment with the system itself" (Law and Kelton 2000). Similar actual and simulated sign system conditions provide greater confidence in the simulation model's ability to approximate the real-world sign system.

To validate the simulation, the author developed a simulation scenario that represented the sign conditions and management practices observed during the 2005 portion of the NCSU/NCDOT field study. The input parameters for the validation scenario were developed directly from this 2005 data because the validation goal is to have the simulation output values in 2006 be similar to the field-measured 2006 data values. The "non-inspection year" path of the simulation model was not used in the validation scenario because signs on all road types in 2005 were nighttime-inspected.

7.1 Verification

The simulation model was developed one sub-model at a time to allow the authors to verify each sub-model individually. Verification ensures that the simulation model is logically performing as designed. Several techniques were used to verify the logic used in each sub-model. These included checking that sub-model output values logically followed from the input values used and animating the sub-model in the simulation software to check that individual signs proceeded through the sub-model in the expected sequence. For example, if more signs were replaced in a year than were present in the entire system, this would be an indication of an error in the simulation logic. Once a sub-model was verified, another sub-model was connected to it and the verification procedure was repeated until the entire simulation model was verified. After the simulation and its logic were verified the simulation validation could proceed.

7.2 Validation Model

The author developed the validation simulation model to represent how the real-world sign system observed during the NCSU/NCDOT study operated from 2005 to 2006. The validation model begins with the actual sign conditions in 2005 and proceeds to damage, inspect, replace, and deteriorate each sign individually to their conditions in 2006. Figure 7.1 presents a flowchart that illustrates the sign management decisions and steps observed as part of the NCDOT study. For reference, Figure 7.1 provides the actual (from the NCDOT study observations) number of signs following each flowchart connector. Each module in Figure 7.1 is identified by a capital letter.

The validation model begins by "creating" 1,047 individual signs with characteristics defined by an input sign distribution directly derived from the 2005 NCSU/NCDOT sign data (module A). Section 6.1 further explains the sign characteristics assigned to each sign by the simulation. Next, using the damage rates outlined in Section 6.3 and Table 6.2, the simulation labels some signs as "damaged" and sends the undamaged signs to be inspected (B). The inspection process first identifies signs found to be dirty or in need of upgrading using the rates given in Table 6.4 (C). Signs not damaged or identified as dirty or in need of upgrade then continue on to an inspection process that models the nighttime visual inspection performed by the NCDOT sign crews (C). Signs either pass or fail this inspection based on their retroreflectivity, sheeting color, and sheeting type using the rates provided in Table 6.3.

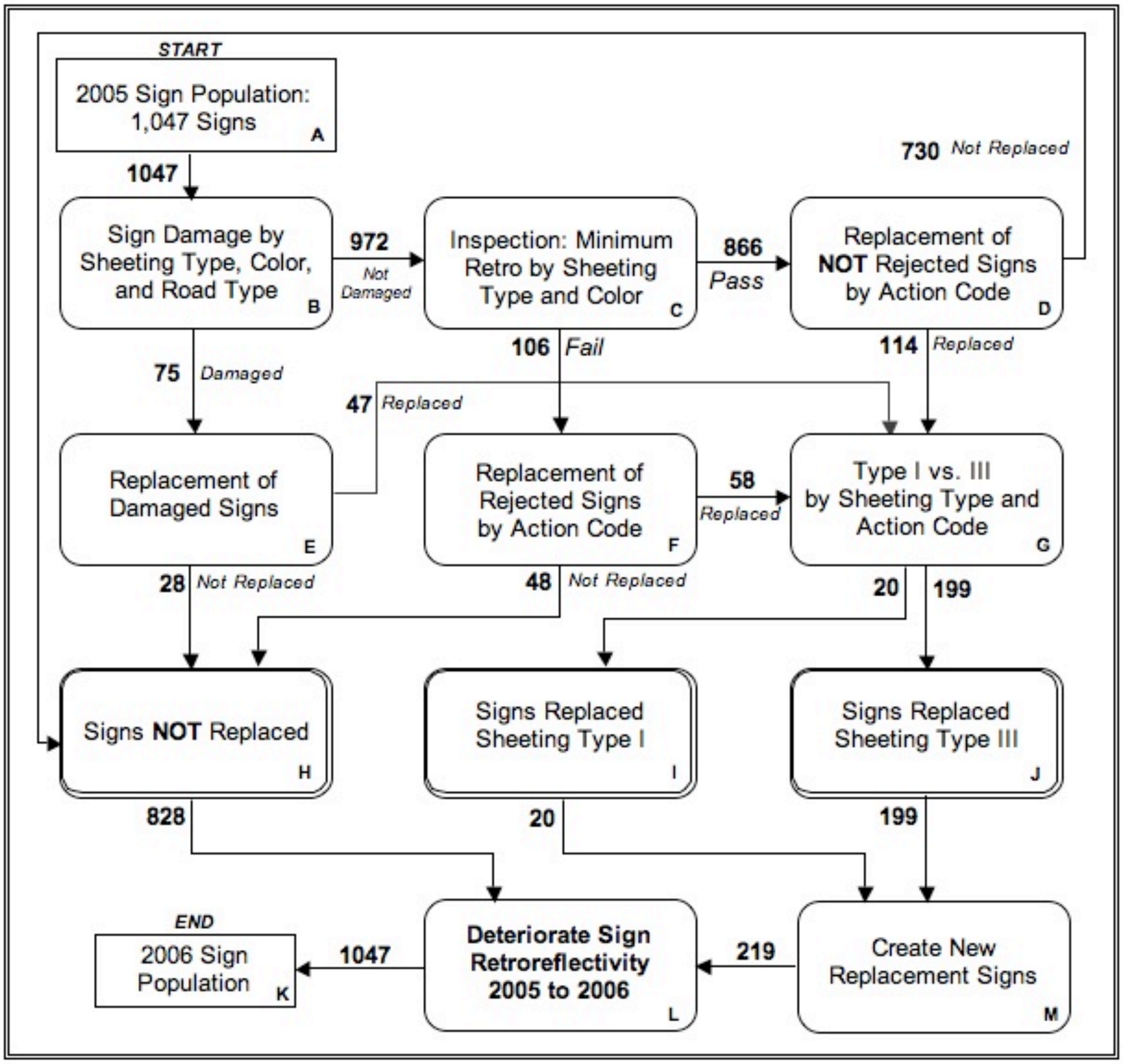


Figure 7.1. Simulation Validation Model with Actual Values

Signs that the simulation identifies as damaged, dirty or needing upgrade, or failing retroreflectivity inspection are all considered to be “failed” and are then evaluated for replacement using the rates in Table 6.6 (modules E and F). Similarly, all signs that are not rejected (failed) move to the “replacement of not rejected signs” sub-model where they are replaced according the rates in Table 6.7 (D). Mirroring what was observed during the

NCSU/NCDOT study, some rejected and not-rejected signs are removed from the sign system by the validation simulation based on percentages observed in the field. After all non-removed signs have passed through the replacement sub-models, the signs that were not identified as being replaced (H) move on to the deterioration sub-model (L) while the signs that are being replaced move to the “Type I vs. III by Sheeting Type” sub-model (G) where they are assigned a replacement sheeting type based on the rates given in Table 6.8. Next, these “to be replaced” signs move to the “Create New Replacement Signs” sub-model (M) where they are replaced with newly installed signs, with an age set to zero and a new, initial retroreflectivity assigned based on Table 8.10 and Section 8.3.5.1. Finally, all signs proceed to the “Deteriorate Sign Retroreflectivity 2005 to 2006” sub-model (L) where each sign’s retroreflectivity value is decreased by the expected loss in retroreflectivity between 2005 and 2006, as described in Table 6.1 and Section 6.2.1. At this point, the validation simulation has brought all 1047 signs from their initial conditions in 2005 to their simulated conditions in 2006.

7.3 Validation Methodology

To provide confidence that the simulation is valid, a series of key system performance measures must be defined, and their actual, NCSU/NCDOT study values compared to their simulated values. The key performance measures should include the output values that are used to evaluate the system’s behavior under various scenarios (Law and Kelton 2000). For the simulation validation, the 14 key performance measures and their actual NCSU/NCDOT study values (in parentheses) were as follows:

1. Number of signs passing minimum retroreflectivity in 2006 (707)
2. Number of signs “damaged” (75)
3. Number of dirty/upgrade signs (42)
4. Number of signs failing retro inspection (106)
5. Number of signs rejected (223)
6. Number of signs not rejected (805)

7. Number of signs rejected + replaced (125)
8. Number of signs rejected + NOT replaced (98)
9. Number of signs not rejected + replaced (75)
10. Number of signs not rejected + not replaced (730)
11. Number of signs removed (26)
12. Number of signs replaced (193)
13. Number of signs replaced with Type I (18)
14. Number of signs replaced with Type III (175)

Comparing the simulated key performance measures to the actual values requires calculating the actual values for each performance measure from the observed and collected NCSU/NCDOT study data. There are only data from two years of observations in the NCSU/NCDOT study; the initial sign system condition and inspection results from 2005 and the sign system condition in 2006. Hence, actual sign system key performance measure values can only be determined for the 2005-2006 time period and not over longer, multi-year periods. Because only one set of actual key performance measure values is available, the validation simulation could only be run for one year. A one-year comparison of a single sign population is enough to validate the model, but can limit the validity of the simulation over the course of multiple years and for other sign populations.

Two methods were utilized to validate the simulation under the limiting conditions of having actual sign condition observations for 2005 to 2006 only. The two methods used are referred to here as the Correlated Inspection Approach and the Prediction Interval Approach. Each method seeks to determine whether the differences between the actual sign system and the simulated modeled sign system are insignificant enough to allow conclusions about the actual system performance to be drawn from simulation model results.

7.3.1.1 Correlated Inspection Approach: Percent Difference

The correlated inspection approach seeks to limit variability in the simulation output by using historical system input data instead of samples from an input probability distribution when validating a simulation model. Since the actual system and the simulation model experience exactly the same input conditions, one can expect a statistically more precise comparison between the actual system performance and the simulated performance (Law and Kelton 2000). For this reason, a file containing the actual 2005 condition and characteristics of all 1047 signs was used to generate all initial sign attributes in the validation simulation. Following the logic of the correlated inspection approach, the actual and simulated key performance measure values should be close in value and hence, have a small percent difference. The percent difference for each key performance measure is calculated as follows:

$$100\left(\frac{\bar{x}_{SIM} - A_{2006}}{A_{2006}}\right) = \%\text{ difference}$$

where:

$\bar{x}_{SIM}$ = mean expected simulated value for a given performance measure

A_{2006} = 2006 actual value for a given performance measure

Ideally, the percent difference should range from 0-7% to be considered excellent and acceptable for validation purposes. A greater than 10% difference could be a cause for concern.

7.3.1.2 Prediction Interval Approach

The prediction interval approach involves estimating what the future simulated key performance measure values will be, based on the mean and standard deviation of these values from an initial set of validation simulation runs. For each performance measure, the prediction interval defines an upper and lower bound in which any future (meaning from an additional set of simulation runs) simulated value is expected to lie within a certain percent confidence. The actual value of the key performance measure should lie within the prediction interval for the simulation values for the simulation to be considered valid. The use of prediction intervals is discussed by Law and Kelton (2000) and by Dittus et al. (1996).

To calculate the prediction interval for each performance measure, the simulation was run over one year (2005 to 2006) 30 times (30 replications) and the 30 simulated performance measure values from the 30 replications were analyzed to get an estimate $\overline{X}$ of the expected value for the performance measure, E(PM), and the standard deviation, s(PM). The probability that any simulated value for a given performance measure will fall between the lower and upper bounds of the prediction interval is equal to 0.95 when the confidence level is set to 95% and a two-tailed interval is used. Using these parameters, the prediction interval at 95% confidence was calculated as follows:

$$\overline{X} \pm K \bullet s$$

$$K = t_{1-\alpha/(2k),\, n-1}\sqrt{\frac{1}{n}+\frac{1}{m}}$$

where:

$\overline{X}$ = mean expected simulated value for a given performance measure, E(PM)

s = standard deviation of expected simulation value, s(PM)

1-α/(2k) = level of confidence, 2-tailed interval , α = 0.975

k = number of sampling periods interested in = 1

m = number of samples per sampling period (usually m = 1)

n = number of background samples (n = 30)

7.3.2 Validation Run Setup

The validation simulation was run for an initial pilot set of 30 replications to determine how many simulation replications would be needed to determine each simulated key performance measure value within an acceptable error of ± 5%. The number of replications needed was determined using the standard deviation of the performance measure value from the 30 replications in the sample size equation that follows (Robertson et al. 2000):

$$n = \frac{\left(Z_{\alpha/2}\right)^2 s^2}{d^2}$$

where:

n = number of simulation runs needed

α = confidence level = 0.05

Z = Z statistic = 1.96 for confidence level of $\alpha/2$

s = standard deviation from initial pilot set of 30 replications

d = acceptable error, error in number of signs

Table 7.1 lists the sample size calculation results for two key performance measures, signs passing the minimum retroreflectivity standards and damaged signs. These two measures were chosen because they are representative of the higher and lower numerical range of expected performance measure values. For the *passing minimum retroreflectivity* performance measure, the acceptable error was set to 1% in the Table 7.1 example, because at the ± 5% error level only one simulation replication would be necessary for the chosen confidence level. From these results, 30 simulation replications are more than adequate to provide an acceptable error of ± 5% for all key performance measures.

Table 7.1. Number of Simulation Replications Needed to Reach an Acceptable Error

Performance Measure (number of signs)	2006 Actual Value	2006 Simulated Value (mean)	Number of pilot runs (n_p)	Standard Deviation	Acceptable Error (d)	Number of Replications Needed (n)
Passing minimum retroreflectivity	707	706.9	30	10.3	7.1 (1%)	8
Damaged	75	74.9	30	7.8	3.8 (5%)	16

7.4 Validation Results

Table 7.2 lists each key performance measure, its actual value in 2006, its simulated 2006 expected value, the percent difference of the expected value from the actual, and the prediction interval (PI) lower and upper bounds. The simulated expected 2006 values for all of the performance measures satisfy the percent difference and prediction interval criteria. For example, the actual number of signs replaced from 2005-2006 was 193, while the mean simulated value was 200.1, resulting in an acceptable percent difference of 3.6%.

Table 7.2. Actual Versus Simulated Values for Key Performance Measures

Performance Measure (Number of signs)	2006 Actual Value	2006 Mean Simulated Value	**% Difference from Actual**	Standard Deviation Around Mean	**95% PI Lower Bound**	**95% PI Upper Bound**
Passing minimum retroreflectivity	707	706.9	**0.01**	10.3	**682.2**	**731.7**
Damaged	75	74.9	**-0.18**	7.8	**56.0**	**93.8**
Upgrade/Dirty, rejected	42	40.9	**-2.54**	5.9	**26.8**	**55.1**
Failing Inspection	106	113.9	**7.45**	12.1	**84.8**	**143.0**
Rejected	223	231.3	**3.71**	13.8	**198.0**	**264.5**
Not Rejected	805	797.4	**-0.95**	13.3	**765.4**	**829.4**
Rejected and Replaced	125	123.4	**-1.25**	9.6	**100.3**	**146.6**
Rejected and Not Replaced	98	101.2	**3.23**	10.8	**75.2**	**127.2**
Not Rejected and Replaced	75	76.6	**2.18**	7.7	**58.1**	**95.2**
Not Rejected and Not Replaced	730	720.7	**-1.27**	14.2	**686.7**	**754.8**
Replaced, total	193	200.1	**3.66**	12.8	**169.2**	**230.9**
Removed	26	25.0	**-3.72**	5.1	**12.7**	**37.4**
Replaced, Type I	18	18.3	**1.85**	3.6	**9.6**	**27.1**
Replaced, Type III	175	177.4	**1.37**	14.6	**142.2**	**212.6**

8.0 SIMULATION MODEL DEVELOPMENT

Traffic signs are an essential component of the transportation system. During the day and night traffic signs provide vital guidance to motorists regarding traffic regulations, destinations, safe speeds, and unexpected road conditions. Minimum sign retroreflectivity standards issued by the Federal Highway Administration (FHWA) for inclusion in the Manual on Uniform Traffic Control Devices (MUTCD) have focused the attention of highway administrators and sign managers on improving the nighttime performance of roadway signs (FHWA 2007a). Retroreflectivity can be defined as the ratio of the light that a sign reflects to a driver (candelas) to the light that illuminates the sign (lux) per unit area (m^2). In straightforward terms it is a measure of how well the sign can be seen at night.

As a result of these standards issued by the FHWA, all highway agencies will have to create and put into practice a sign asset management program that includes addressing the minimum retroreflectivity standards by January 2012 (FHWA 2007a). Highway agencies have until January 2015 to have most of their red, white, yellow, and green ground-mounted signs comply with the new retroreflectivity standards. When January 2015 arrives, both compliance (for the safety and well being of the public) and proof of compliance (to protect against lawsuits) will be necessary. An effective management strategy can support both, while keeping costs down. As some agencies have investments in signs of well into the hundreds of millions of dollars, effective management is critical.

Sign management strategies generally involve manually evaluating the retroreflectivity of all signs or of a sample of signs in a jurisdiction. Alternatively they may consist of predicting when signs should be replaced based on information in a comprehensive sign inventory database. Although the FHWA has provided guidance on what sign management methods will ensure compliance with the standards, there is limited guidance available to agencies on the tradeoffs between the sign retroreflectivity performance and the maintenance costs associated with each management method. These tradeoffs can be explored by creating a model of the sign system that is implemented using simulation software and techniques. The purpose of this paper is to describe a microscopic simulation tool for evaluating different management decisions and methods. The unique aspect of this work is the use of microscopic simulation to model high quantity transportation assets (signs) (Rasdorf et al. 2009).

8.1 Previous Sign Management Modeling Efforts

Studies investigating the impacts of the new standards have focused on analyzing costs at the local (town or county) level and on performing a life-cycle cost analysis to determine the total national cost of upgrading signs to the minimum retroreflectivity standards (Kilgour et al. 2007; Opiela and Andersen 2007). Most analysis consisted of estimating the number of signs by means of an inventory or an approximate method and a fixed, expected sign lifetime, and then performing an economic analysis to calculate the expected costs to replace existing, deficient signs with brighter signs. These life-cycle and economic analyses have a limited ability to test a wide variety of hypothetical management situations, and they do not include other factors that influence sign system performance such as sign damage, inspection accuracy, and sign replacement practices.

Other previous efforts to model sign management have used forecasting techniques to determine future sign performance (sign lifetime) to predict when signs will need replacement. Studies by Wolshon, et al. (2002) and Bischoff and Bullock (2002) used linear regression to develop sign performance models from a sign database to establish sign management and budgeting requirements. These two studies found a great degree of variability of sign performance in the field, and could not identify the source of this variability. Only sign age could be positively correlated to sign deterioration, resulting in sign lifetime estimates with some inherent uncertainty. The FHWA and the Arizona Department of Transportation (ADOT) have developed sign management systems with a feature that forecasts the lifetime of individual signs based on individual sign condition information contained in a sign inventory database (McGee and Paniati 1998; Mueller et al.

2003). ADOT's sign lifetime forecasting model calculates the expected lifetime for each sign in the inventory based on the sheeting material type, sign color, and the direction the sign is facing. The FHWA's forecasting model uses inventory data on sign type, sheeting material type, sign color, age, and regional climate factors to estimate a sign's retroreflectivity value and then projects a sign's remaining service life without the need for field retroreflectivity measurements.

Two studies performed for the North Carolina Department of Transportation (NCDOT) introduced simulation as an alternative technique to model the entire sign management process, from sign installation to sign inspection, deterioration, and replacement. These are the only two studies in the literature that use simulation to model sign management. Unlike the forecasting studies, which focused on forecasting individual sign lifetimes from sign retroreflectivity measurements, the NCDOT studies used simulation to model sign performance and management because of the financial and technical difficulty of inventorying more than one million NCDOT signs (Palmquist and Rasdorf 2002). Both simulation studies used macroscopic simulation models, meaning that groups of signs, rather than each sign individually, moved through the simulation steps. Table 8.1 presents a comparison of the two macroscopic simulation studies to the simulation study described in this paper.

The first study, conducted for NCDOT in 2000, used an age-based sign assessment methodology where the sign population was divided equally into seven age groups and each age group had a different replacement rate, with signs in the older age groups replaced at a higher rate than signs in the younger age groups (Rasdorf et al. 2005). Three different assumed vandalism rates (0, 5, and 10 percent) and inspection frequencies (inspect every year, inspect every 2 years, and inspect every 3 years) were tested in the first simulation to examine the impact of these factors on sign condition and management costs. The simulation program only included yellow and red signs with sheeting classified as Type I (Engineering Grade) by the American Society for Testing and Materials (ASTM).

Table 8.1. Comparison of Past Simulation Studies to Current Study

Simulation Study	**NCDOT (2000)**	**NCDOT (2005)**	**NCSU/NCDOT (2010)**
Method	Macroscopic (spreadsheet)	Macroscopic (spreadsheet)	Microscopic (Arena)
Number of Runs	1 run x 60 simulation years	1 run x 200 simulation years	30 runs x 50 simulation years
No. of Signs (n)	1000	1000	1000
Grouping Criteria and Sign Lifetime	7 one-year age groups, signs initially equally distributed among groups. Assumes 7 year lifetime.	8-20 one-year age groups, signs initially equally distributed among groups. No. of groups varies based on sign type & color. Assumes 8-20 year lifetime.	Grouping: not applicable Sign lifetime undefined, can vary depending on when sign is ultimately replaced.
Signs Considered	Yellow and Red Type I	Yellow, Red, White, Green Type I and III (beaded)	Yellow, Red, White, Green Type I and III (beaded)
Key Processes Modeled	Inspection frequency & accuracy, vandalism	Inspection frequency & accuracy, damage	Inspection frequency & accuracy, replacement, damage, retro. deterioration
Inspection Frequency Model	All signs, every 1, 2, or 3 years	Frequency can vary by road type (interstate, primary, secondary). Road type variation modeled by a single frequency that is a weighted average (No. of signs x interval) over all three road types.	Frequency can vary by road type or all signs can be inspected at the same interval. Road type variation modeled directly (interstate signs inspected annually, secondary every 3 years).
Inspection Accuracy Model	Older signs rejected at a higher rate than younger signs	Older signs rejected at a higher rate than younger signs	Type I / Type II error model based on whether sign above or below min. retro. standard
Replacement Model	Rejection = replacement All rejected signs replaced within one year	Rejection = replacement All rejected signs replaced within one year	Rejection ≠ replacement Replacement rates control replacement of signs
Damage Model	Annual, percent of signs not inspected or not replaced	Annual, rate varies due to inspection frequency, sign color and sheeting type	Annual, single percent of all signs. Not all damaged signs are replaced each year.
Key Output Measures	Steady-state no. of signs in each age group, cost of inspection & replacement	Steady-state no. of signs below standard, cost of inspection & replacement	Annual average no. of signs unsatisfactory, damaged and replaced

The second study conducted for NCDOT in 2005 sought to extend the first study by gathering additional field data and broadening the scope of the original spreadsheet simulation (Harris et al. 2007). Based on field and literature data, the second study used 8-20 one-year age groups to better model longer sign lifetimes. Each sign sheeting type (ASTM Type I or Type III [high intensity, beaded]) and background sign color (white, yellow, red, and green) combination had its own set of age groups. To better represent how signs are judged during field inspections, representative retroreflectivity value ranges were assigned to each of these groups. At the end of a simulation year the signs in a group would ‘deteriorate” to the next group representing signs one year older. The simulation used field-measured values for inspection accuracy and damage (accidental, natural, and vandalism) rate instead of literature rates. These simulation factor values were obtained by analyzing field-collected ground-mounted sign data (Rasdorf et al. 2006). The researchers validated the steady-state results of the second macroscopic simulation by matching them with 2005 field sign data and sign financial data from the NCDOT.

Another assumption made in the second NCDOT simulation study was that the inspection frequency (how often signs are inspected) was applied as a weighted average over all three road classification types (interstate, primary, and secondary) instead of each road type being inspected separately at the actual inspection interval, such as annually, or every three years. Both the first and second NCDOT simulation studies assumed that all signs rejected by inspectors due to low retroreflectivity were replaced within one year. A field data collection effort conducted in 2006 (one year after the initial field study in 2005) found that not all rejected signs were replaced within one year (Rasdorf et al. 2006). Lastly, the second NCDOT simulation study primarily considered the stabilized or steady-state sign system conditions--over 200 years --for various sign management scenarios and therefore was not useful for evaluating short-term sign management and financial issues.

8.2 Microscopic Simulation Model

The questionable assumptions made in the second NCDOT simulation study as described above led the authors to investigate how to further improve their sign management simulation. The following set of requirements for an improved model were developed.

1. Address the uncertainty and variability inherent in sign management.
2. Be applicable to most highway agency sign characteristics and practices by varying input parameters.
3. Include installation, inspection, replacement, damage, and deterioration functions.
4. Model the actual inspection interval used in practice for each road type.
5. Use a Type I (false positive) / Type II (false negative) error model to better represent the inspection process.
6. Allow signs rejected through inspection to be replaced more than one year after inspection to better reflect actual practice.
7. Calculate system sign condition (retroreflectivity and damage) and sign costs for both short (transient) and long (steady state) time periods.
8. Test a variety of sign management scenarios by varying input parameters.
9. Identify promising sign management scenarios.

To address requirement #1, the authors concluded that a microscopic simulation model would more effectively model the uncertainty and variability in sign management. Microscopic simulation is the stochastic (i.e., involves random variations) and dynamic modeling of individual entities as they move through a simulated system. Instead of signs being placed into groups (with similar characteristics) that move as a group through the simulation, each sign would be able to move independently through the sub-models that comprise the simulation, thus yielding a more realistic view of how signs progress through their life-cycles. For example, in a microscopic model signs can deteriorate individually and be rejected based on their own actual retroreflectivity performance instead of belonging to a group with an assumed retroreflectivity value and age.

This microscopic flexibility in how signs move through the system allows the simulation to expand beyond simply evaluating only NCDOT's sign management practices to being able to evaluate those of most other state and local agencies (thus also fulfilling requirement #2).

The simulation can also easily add functionality and respond to future changes, such as new sign sheeting types. Adding functionality for a new sheeting type would only require adding a deterioration model for that sheeting type instead of creating a new part of the simulation with additional age-based groups for the new sheeting type.

The two previous macroscopic simulations approximated but did not actually directly model sign system functions such as deterioration and replacement (requirement #3). A further advantage of microscopic simulation is that it can collect, store, and display condition and replacement data (requirement #7) on each individual sign as it progresses through the simulation year to year, as well as aggregate data on system performance. Because the improved simulation model contains more complex functionality, more intricate scenarios can be tested, including budgeting and scheduling options (requirement #8). For example, the improved simulation model can test changing management practices in intermediate simulation years, such as skipping inspection or replacement one or more years. The microscopic simulation approach allows the sign management model to represent sign system behavior more intuitively and with greater detail as compared with the previous macroscopic approaches.

Because microscopic simulation was being used to simulate sign management, each sign had to be represented in the simulation as a separate entity. The software tool selected for the simulation would need to support dynamic, discrete simulation. The authors selected Arena, a general-purpose discrete event simulation package, because it was easy to use and flexible. The Arena software moves entities one at a time through a flowchart consisting of modules that the user connects together using a graphical user interface instead of programming code (Kelton et al. 2007). The flowchart can be animated (as can the simulation runs) to view the paths that individual signs take through the simulation. The use of flowcharts and animation provide a simple way to easily document, validate, and verify the simulation design. It is also straightforward to change module parameter input values and the flowchart design. The simulation results can also be generated and stored in text or Microsoft Excel files for analysis.

The authors modeled the microscopic simulation after the real-world sign system observed during the 2005 to 2006 NCDOT study described above. A team of graduate research assistants from North Carolina State University (NCSU) collected retroreflectivity and nighttime sign inspection/assessment data in five locations across NC from January to April 2005 (Rasdorf et al. 2006). Five data collection locations were chosen so that the western, central, and eastern portions of NC were represented in the data set. At each location, the research team accompanied a local, two-member NCDOT sign maintenance crew as they performed a nighttime visual condition assessment of each sign along a predetermined route. The research team noted the message, rejection reason, and location of each rejected sign, and used GPS tracking software to record the route followed by the inspectors. The following morning the research team re-traced the previous night's route and measured the retroreflectivity of most of the signs (1,047 total) evaluated in the nighttime visual condition assessment. A follow-up sign data collection in the Winter of 2006 measured the retroreflectivity of the same signs measured in 2005 and noted any signs that were new or replaced during the one-year period between the 2005 and 2006 data collections.

The microscopic sign management simulation described in this paper consists of four major sub-models: damage, inspection, replacement, and deterioration. The progress of each sign through each sub-model is governed by the logical structure of the simulation and the input parameters that control how each sub-model behaves. There are two paths through the simulation: one path for simulation years when there is a scheduled nighttime inspection and one for non-inspection years. Simulation scenarios can be run using a set of input parameters that represent different management policies and initial sign population characteristics and conditions.

8.3 Input Parameters for Simulation Scenarios

To model real world sign management scenarios, it is logical to base the initial simulation parameter values on the real world characteristics of an existing sign population. These initial input parameters are based on existing data related to sign materials, environmental exposure, and management practices. In other words, real world field conditions must be accurately reflected in the values of the parameters. For this simulation model the input parameters included:

- Initial system condition and distribution characteristics,
- Damage rates,
- Inspection behaviors,
- Replacement rates, and
- Deterioration rates.

These parameters can differ for each sign, taking into account sign sheeting type, color, location, message, and age. The simulation model uses these parameters as initial values and inputs to its sub-models. Each sign management scenario has a unique set of input parameters that correspond to the sign management practices and sign system characteristics (of any agency or municipality) the scenario is meant to represent.

Many of the input parameters used to validate the simulation model were used in the main simulation scenarios because they are still applicable to the scenario situations and they represent the best-available information about sign system behavior. For example, the retroreflectivity deterioration parameters determined from the best literature models in Section 6.2.1 are also applicable for the main simulation evaluation. Other parameters, such as sign damage and replacement rates, were slightly modified from their validation simulation format but were still modeled similarly.

The parameters and models used in the simulation scenarios for sign inspection behavior and the base sign condition and distribution are different in a couple of ways from those used in the simulation validation because the simulation scenarios consider multi-year sign system behavior and sign populations that differ from the validation population. The following sections provide further detail for how the input parameters were determined and conceptualized for the simulation scenarios.

8.3.1 Base Sign Population and Condition

Under ideal circumstances, the simulation would begin with initial system condition and distribution information generated directly from a detailed sign inventory database of all signs within the jurisdiction being modeled. The inventory database would be used to assign sign attributes such as sheeting color, road type, and sheeting type to representative signs in the simulation. However, since most agencies do not possess such a detailed sign inventory, the methodology used for generating the initial sign condition and distribution parameters in this simulation assumes that a sign inventory database is not available. Instead the general sign system characteristics are derived from statistical sampling, financial/institutional data, and literature sources. The general sign system characteristics considered were as follows:

- Functional classification of the agency's roads (percent of an agency's roads that are of a certain road type),
- Distribution of sign sheeting color by road type,
- Distribution of sign sheeting type (percent Type I or Type III sheeting), and
- Distribution of sign age.

By using different combinations of these characteristics, the authors created six sign and condition databases to represent various sign management agencies and regions. The six different sign populations considered represent the following sign owners and regions:

1. NCDOT-owned, NCSU multi-division 2005 sign study area
2. NCDOT-owned, entire State of NC

3. State Agency-owned, urban and rural roads
4. County-owned, rural roads
5. Municipal and county-owned, urban roads
6. Town-owned, rural roads

The main difference between the six sign populations is the percent of the agency's roads that are of a certain road type. Populations 1 and 2 were based on previous field data collection and sampling work. Therefore, the distribution of signs by road type, the distribution of sign sheeting color by road type, and the distribution of sign sheeting type were already known. For Populations 3-6, the author used functional classification data from FHWA's *Highway Statistics 2007* to determine the percent of roads by road type (FHWA 2007b). The functional classifications used by the FHWA in *Highway Statistics* were reduced to more general interstate, primary, and secondary road types using the logic given in Table 8.2.

Table 8.2. Conversion from Functional Classification to General Road Type

<table>
<tr><th colspan="2">Rural Areas</th><th colspan="2">Urban Areas</th></tr>
<tr><th>FHWA
Functional Classification</th><th>Road Type
Designation</th><th>FHWA
Functional Classification</th><th>Road Type
Designation</th></tr>
<tr><td rowspan="2">Principal Arterials:
Interstate</td><td rowspan="2">Interstate</td><td>Principal Arterials:
Interstate</td><td rowspan="2">Interstate</td></tr>
<tr><td>Principal Arterials:
Other Freeway and Expressway</td></tr>
<tr><td>Principal Arterials: Other</td><td rowspan="3">Primary</td><td>Principal Arterials: Other</td><td rowspan="2">Primary</td></tr>
<tr><td>Minor Arterials</td><td>Minor Arterials</td></tr>
<tr><td>Major Collectors</td><td rowspan="2">Collectors</td><td rowspan="3">Secondary</td></tr>
<tr><td>Minor Collectors</td><td rowspan="2">Secondary</td></tr>
<tr><td>Local Roads</td><td>Local Roads</td></tr>
</table>

The more general interstate, primary, and secondary road types were used instead of functional classification because the NCDOT/NCSU study found that agencies often base sign management policy decisions (budgeting, replacement, inspection) on similar general road type designations (Rasdorf et al. 2006). The simulation logic includes road type as an important factor in how a sign moves through the simulation network. Table 8.3 lists the percent of roads by mile that are interstate, primary, and secondary for Populations 3-6 (FHWA 2007b).

Table 8.3. General Road Type Percentages for Selected Sign Populations

Population No.	Owner/Region	Percent Interstate	Percent Primary	Percent Secondary	Percent of total USA Miles[1]
3	State / All	8	62	30	20
4	County / Rural	0	14	86	40
5	Municipal and County / Urban	0	10	90	22
6	Town / Rural	0	2	98	14

[1] *Does not include 4% of roads classified with an owner of "Other"*

The percent of roads by mile rather than by lane mile is used because signs were considered to be applicable across all lanes. McGee and Taori (1998) also used total miles instead of lane miles to determine the number of signs along a road.

The percent of roads that are interstate, primary, and secondary for the regions represented by Populations 3-6 can be used with sign densities (signs/mile) to determine the number of signs that are on interstate, primary, and secondary roads. Table 8.4 lists sign densities for interstate, primary, and secondary roads from existing literature sources (Black et al. 1992; Kilgour et al. 2007; McGee and Taori 1998; Palmquist and Rasdorf 2002).

The sign densities from McGee and Taori and Black et al. were taken directly from their reports. The Palmquist and Rasdorf densities were modified from their original format because they included sign colors (blue, brown, etc.) that are not considered by the FHWA minimum retroreflectivity standards. The overall sign densities from the Palmquist and Rasdorf study were modified to just include green, red, stop, white, and yellow signs. Also, the NCDOT-owned secondary roads examined in the Palmquist and Rasdorf study would typically be owned and maintained by county transportation departments in other states. In the Kilgour study densities were calculated from a table of sign counts over a given distance in miles. The Kilgour study did not distinguish between red and white regulatory signs, so the total regulatory sign density was split in proportion to the closest comparable literature density, which was from the Palmquist and Rasdorf study. For Kilgour's Town and City densities, the ratio between red and white signs in the NCDOT (County) / Urban density set was used. For the Kilgour County densities, the ratio between red and white signs in the NCDOT (County) / Rural density set was used.

Table 8.4. Sign Densities by Sign Color from the Literature

Road Owner	Region	Road Classification	Literature Source	Signs per mile				
				Total	Green	Stop and Other Red	White	Yellow
NCDOT	NC	Interstate	P&R	15.40	6.02	2.29	5.06	2.03
NCDOT	NC	Primary	P&R	17.10	1.79	1.08	9.18	5.04
NCDOT	NC	Secondary	P&R	9.71	0.46	0.94	3.62	4.69
State	All	All	M&T	15.25	0.38	2.96	6.60	5.32
NCDOT	All	All	P&R	11.40	0.85	1.00	4.84	4.71
Local	All	All	M&T	8.14	0.06	2.41	2.11	3.57
NCDOT (County)	Rural	Secondary	P&R	7.16	0.38	0.84	1.99	3.95
County	All	All	Kilgour	3.35	0.01	0.36	0.86	2.12
State or County	All	All	Black	11.00	3.00	3.00	1.00	4.00
NCDOT (County)	Urban	Secondary	P&R	30.83	1.45	1.22	19.17	8.99
City	Urban	All	Kilgour	28.00	0.47	1.38	21.66	4.45
City or Town	All	All	Black	29.00	1.00	12.00	6.00	10.00
NCDOT (High Pop. Density County)	Rural	Secondary	P&R	13.89	0.22	1.27	5.91	6.49
Town	All	All	Kilgour	24.21	0.17	1.15	18.02	4.88

Examining Table 8.4, the densities obtained from the Palmquist and Rasdorf study seem to agree reasonably well with the other literature. The densities from the Palmquist and Rasdorf studies were selected for further use in developing the sign populations for the simulation because these densities had detail at the road type level, allowing the difference in percent road type for each of the populations to be taken into account. The sign densities used for Populations 3-6 are given in Table 8.5. The overall densities for each population (shown in **bold** in Table 8.5) were calculated by weighting the road type-specific densities using the percent of the population's road miles that were that road type. Note that the overall densities for each population agree well with the literature densities in Table 8.4.

Table 8.5. Sign Densities by Sign Color For Selected Populations 3-6

Pop. No.	Owner / Region	Signs per Mile					Percent of Pop Miles	Percent of total USA Miles
		Total	Green	Stop and Other Red	White	Yellow		
3	**State / All**	**14.75**	**1.73**	**1.13**	**7.18**	**4.69**	100	**20**
	Interstate	15.40	6.02	2.29	5.06	2.03	8	
	Primary	17.10	1.79	1.08	9.18	5.04	62	
	Secondary	9.71	0.46	0.94	3.62	4.69	30	
4	**County / Rural**	**8.55**	**0.58**	**0.87**	**3.00**	**4.10**	100	**40**
	Primary	17.10	1.79	1.08	9.18	5.04	14	
	Secondary	7.16	0.38	0.84	1.99	3.95	86	
5	**Municipal / Urban**	**29.59**	**1.48**	**1.21**	**18.27**	**8.63**	100	**22**
	Primary	17.10	1.79	1.08	9.18	5.04	10	
	Secondary	30.83	1.45	1.22	19.17	8.99	90	
6	**Town / Rural**	**13.95**	**0.25**	**1.27**	**5.98**	**6.46**	100	**14**
	Primary	17.10	1.79	1.08	9.18	5.04	2	
	Secondary	13.89	0.22	1.27	5.91	6.49	98	

Next, the author calculated the percent of signs by road type and sheeting color by setting the road miles in each population equal to a given value and determining the number of signs that would be present by multiplying the sign density by the number of road miles. Then, dividing the number of signs of each color by the total number of signs would yield the percent of signs by color for each population and road type. Table 8.6 contains the resulting percentages.

Using these percentages, database files were created in Microsoft Excel containing 1,000 signs per population distributed according to the road type and sign color percentages. These files were then imported into a small-scale input distribution simulation in Arena that assigns sheeting type, sign age, and sign retroreflectivity to each sign. For Population 1 (NCDOT/NCSU study) the sheeting type assignments were already known from detailed field data and the resulting percentages are given in Table 8.7.

Table 8.6. Percent of Signs by Road Type for All Selected Populations

Pop. No.	Owner/Region	Road Classification	Percent Green	Percent Red	Percent White	Percent Yellow	Total
1	NCDOT / NCSU 2005 Study Area	All	8.8	9.2	37.3	44.7	100
		Interstate	3.9	0.0	6.0	2.1	12
		Primary	1.3	0.5	9.8	6.4	18
		Secondary	3.5	8.7	21.5	36.2	70
2	NCDOT / All NC	All	7.4	8.7	42.4	41.4	100
		Interstate	1.0	0.4	0.8	0.3	3
		Primary	3.4	2.0	17.2	9.4	32
		Secondary	3.1	6.3	24.4	31.6	65
3	State / All	All	11.7	7.7	48.7	31.8	100
		Interstate	3.3	1.2	2.7	1.1	8
		Primary	7.5	4.5	38.6	21.2	72
		Secondary	0.9	1.9	7.4	9.5	20
4	County / Rural	All	6.8	10.2	35.0	48.0	100
		Primary	2.9	1.8	15.0	8.3	28
		Secondary	3.8	8.4	20.0	39.7	72
5	Municipal / Urban	All	5.0	4.1	61.7	29.2	100
		Primary	0.6	0.4	3.2	1.7	6
		Secondary	4.4	3.7	58.5	27.4	94
6	Town / Rural	All	1.8	9.1	42.8	46.3	100
		Primary	0.3	0.2	1.3	0.7	3
		Secondary	1.5	8.9	41.5	45.6	97

The sheeting type distribution between Types I and III for Populations 2-6 were derived from literature values. State-maintained roads were more likely to have more Type III signs than locally maintained roads (McGee and Taori 1998). Table 8.8 lists the sign sheeting type distribution sets (sets A, B, and C) chosen for each sign population. Since the region corresponding to Population 2 is all of North Carolina, the 75% Type I and 25% Type III distribution (set A) from the NCDOT/NCSU study was used for Population 2. For Populations 4, 5, and 6, the 60% Type I and 40% Type III "local" roads distribution from McGee and Taori was selected (set B). Finally, the "state" distribution of 15% Type I and 85% Type III from McGee and Taori (set C) was used for Population 3.

Table 8.7. Population 1 Sign Distribution by Sheeting Color, Type, and Road Type

Sheeting Color	Sheeting Type	Percent Interstate	Percent Primary	Percent Secondary	All
Green	I	0.1	0.9	3.4	4.4
	III	3.8	0.5	0.1	4.4
	All	3.9	1.3	3.5	8.8
Red	I	0.0	0.0	2.6	2.6
	III	0.0	0.5	6.1	6.6
	All	0.0	0.5	8.7	9.2
White	I	5.5	7.5	18.9	32.0
	III	0.5	2.3	2.6	5.3
	All	6.0	9.8	21.5	37.3
Yellow	I	0.1	5.2	30.5	35.7
	III	2.0	1.2	5.7	9.0
	All	2.1	6.4	36.2	44.7
All	All	12.0	18.1	69.9	100.0

After each sign in a population is assigned a sheeting type, it is then assigned an age (time since installation) using one of two sign age distributions. For Type I and III signs that have been installed by an agency regularly in the past, an "established" age distribution is used that is derived from state-owned sign age data found in McGee and Taori (1998). The established sign age distribution uses a Weibull probability distribution with a β of 5.58 and an α of 1.44. The NCDOT/NCSU study as well as the McGee and Taori study found that Type III signs had a different age distribution than the more established (longer history of installation) Type I signs because the NCDOT and local agencies had just begun installing Type III signs.

Figure 8.1 provides a look at the differences in the distributions of Type I and III signs by age using cumulative percentages. Newer, more recent, installations of Type III signs were found to have an age distribution that corresponded well to an exponential distribution with a mean of 3.06 years using Type III data from the NCDOT/NCSU study.

It is assumed that once 50% or more of an agency's signs are Type III, the Type III signs follow the "established" Weibull sign distribution instead of the new Type III exponential age distribution. In Table 8.8 sign sheeting type distribution sets A and B use the exponential age distribution for Type III signs and the Weibull distribution for Type I signs. Sheeting type distribution set C uses the established (Weibull) sign distribution for both Type I and III signs because there are more than 50% Type III signs in this distribution.

Table 8.8. Sheeting Type Distributions and Applicable Sign Populations and Age Distributions

Set	Percent Type I	Percent Type III	Source	Applicable Sign Populations	Applicable Age Distribution
A	75	25	NCDOT/NCSU	1, 2	split I and III
B	60	40	M&T Local	4, 5, 6	split I and III
C	15	85	M&T State	3	established

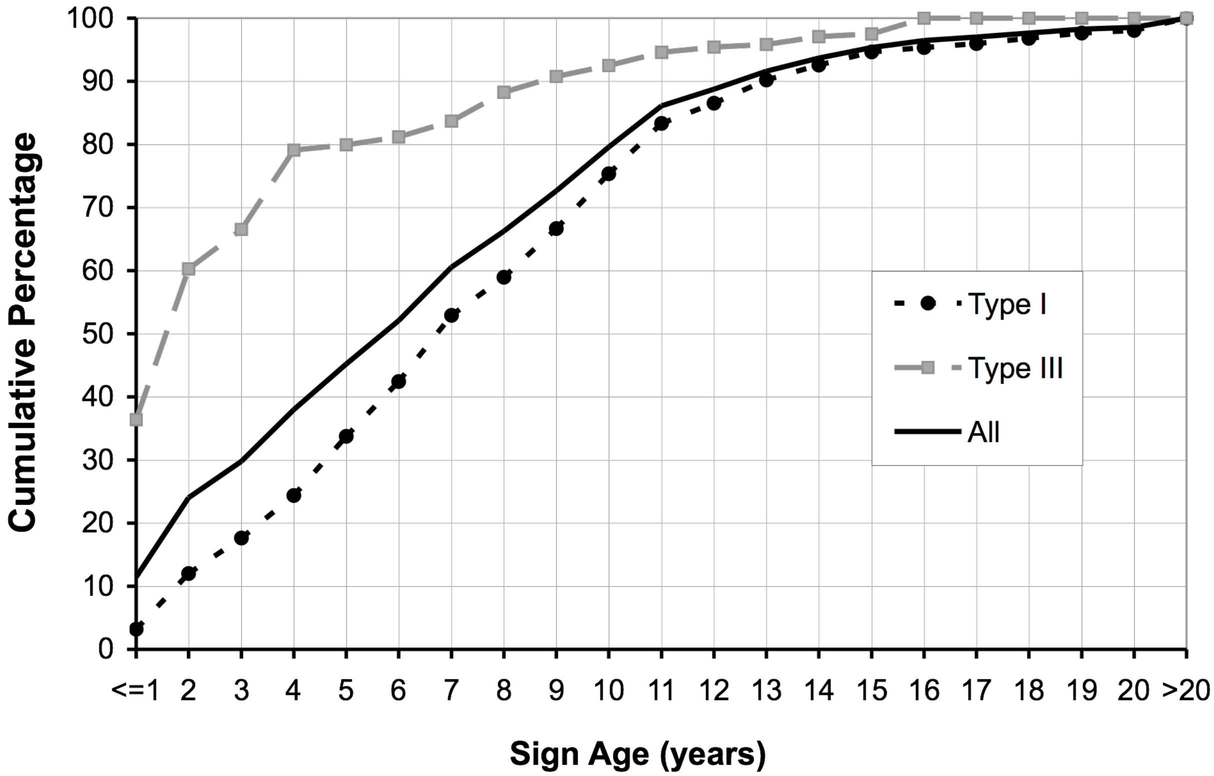


Figure 8.1. Distribution of Sign Age for Type I and III Signs from NCDOT/NCSU Study

The initial retroreflectivity value for each sign in the input sign distributions is then determined based on each sign's assigned age. The program calculates a retroreflectivity (R_A) value for each sign using the appropriate deterioration equation from Table 8.9 based on the sign's sheeting type and color. The intercept values in Table 8.9 specify the sign's retroreflectivity value when it was first installed and are from NTPEP initial sign sheeting retroreflectivity results from tests of 3M™ Type I enclosed lens and Type III encapsulated lens (EL) sheetings (AASHTO 2005). Black et al. (1991) suggest that wide variations in initial sign retroreflectivity values are due to variability in the sheeting delivered from the manufacturer and loss in retroreflectivity during the application of the sheeting material to the sign backing substrate.

The slope values in Table 8.9 estimate the retroreflectivity lost each year of the sign's life after installation. A combination of slope values from the NCSU field data (NCSU) and from the best models found in other studies (FHWA) [reported in Immaneni et al. (2009)] were found to best replicate the deterioration observed from 2005 to 2006 in the NCSU/NCDOT study. These slope values predict annual retroreflectivity deterioration for Type I and Type III (encapsulated lens) materials, and could be improved with more encapsulated lens Type III data. In the future, prismatic Type III and Type IX sheeting deterioration models can also be developed for the simulation.

Table 8.9. Retroreflectivity Deterioration Equations for all Populations

		Intercept (Table 8.10)		Slope (Table 6.1)		
Sign Type	**Sign Color**	**Estimate (R_A)**	**Standard Error**	**Estimate (R_A /year)**	**Standard Error**	**R_A Deterioration Equation**
I	White	95.3	11.1	-5.451	0.217	R_A = 95.3 – 5.451Age
I	Yellow	65.9	7.7	-3.906	0.210	R_A = 65.9 – 3.906Age
I	Red	17.4	3.3	-0.898	0.171	R_A = 17.4 - 0.898Age
I	Green	15.4	1.1	-0.982	0.424	R_A = 15.4 - 0.982Age
III	White	284.3	7.0	-5.236	1.217	R_A = 284.3 – 5.236Age
III	Yellow	227.1	7.8	-2.554	1.103	R_A = 227.1 - 2.554Age
III	Red	54.8	4.3	-3.521	0.667	R_A = 54.8 - 3.521Age
III	Green	49.8	3.0	-1.345	0.248	R_A = 49.8 – 1.345Age

Database files were created in Microsoft Excel containing 1,000 signs per population distributed according to the road type and sign color percentages. These files were then imported into a small-scale input distribution simulation in Arena that assigns sheeting type, sign age, and sign retroreflectivity to each sign. Figure 8.2 illustrates the general logic used by the input distribution simulation in Arena to create sign database files for each sign population (that contain all of the needed sign color, sheeting type, road type, sign age, and retroreflectivity input data) for the main sign system simulation.

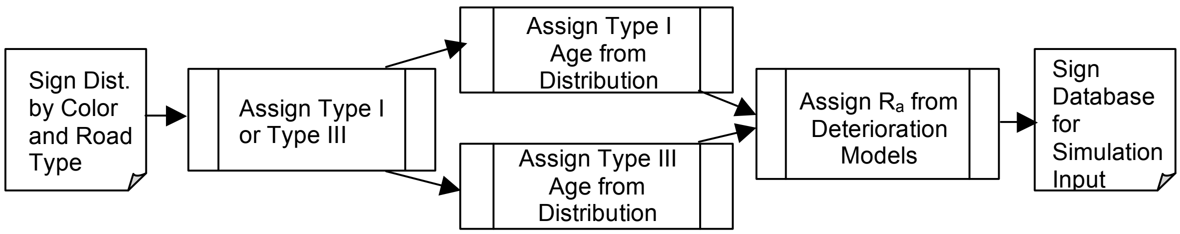


Figure 8.2. Input Distribution Simulation Logic to Assign Sign Sheeting Type, Age, and Retroreflectivity

After the program calculates initial sign retroreflectivity values, it finalizes and saves the input sign database files, as illustrated in the final two steps in Figure 8.2. Each simulation run uses a single input sign distribution database file (representative of a particular population) to limit simulation output variability due to input variability. Otherwise, when comparing two or more simulation scenarios that are based on the same population, variations could be due to the dissimilar input sign distribution database files rather than responses to different scenario input parameters.

Each main simulation scenario run uses one input sign database file to assign initial values (characteristics) to a population of 1,000 signs that the simulation creates. The simulation model then no longer uses the initial sign database file. The 1,000 created signs progress individually through the simulation model, and the characteristics of each sign are modified according to the paths they take through the simulation during the first and each subsequent simulation year.

8.3.2 Sign Damage

The damage input parameters were developed from damage rates observed in a study of NCDOT financial data that was a part of the NCDOT/NCSU sign study (Immaneni et al. 2007). This financial study determined the number of damaged signs that were replaced each year by the NCDOT by calculating the total statewide replacement cost for damaged signs and dividing this cost by the average replacement cost of a single sign. The study found that 4.7% of all signs were replaced due to damage each year.

The NCSU/NCDOT study found that approximately 7.2% of all signs observed during the study were damaged. The study also found that between 2005 and 2006 63% of these damaged signs were replaced (4.5% of all signs were replaced due to damage). This 4.5% number is very close to the 4.7% of all signs replaced due to damage from the financial study, thereby providing a degree of correlation between field measurements and financial records. The remaining 37% of signs that were damaged but not replaced (2.7% of all signs) remained in place in 2006. Therefore, the 7.2% of all signs that were damaged probably included signs newly damaged in 2005 as well as signs with existing damage prior to 2005 that were not replaced earlier. In other words, not all damaged signs are replaced in any year. The simulation must account for these carryover signs.

Two input parameters, original carryover damage (OCO) and annual damage (A), were created to distinguish between the number of existing damaged signs in the system and the number of additional signs damaged each year, respectively. The OCO rate is the percent of all signs that were damaged but not replaced the previous year. For example, say that 2.8% of all signs are still damaged at the beginning of year *n*. During year *n*, an additional 5% percent of signs, known as the "annual damage" rate, are damaged, resulting in 7.8% (2.8 + 5.0) of all signs being damaged at the end of year *n*. A third damage input parameter, annual damage replacement percentage (R%), corresponds to the percent of damaged signs replaced during a year. To continue the example, if R% is set to 60%, then 4.7% (60% of 7.8%) of all signs are replaced due to damage in year *n*. The "new" carryover damage to year *n+1* would then be 3.1% (7.8 - 4.7). The overall damage at the end of year n+1 (D_{n+1}) would then be equal to 8.1% (3.1 + 5.0).

The initial overall damage percent, D_1, is equal to OCO + A. In this paper, the OCO, A, and R% values were chosen to be the same for each sheeting type/color combination because of insufficient data about the differences in damage rates between sheeting colors and types. The NCSU/NCDOT study collected sufficient data to determine the overall damage to all signs but not enough data to show any significant differences in damage for specific sign types (stop, warning, etc.) or road types (e.g. interstate vs. secondary) . This study found that the overall damage (D_n) to all signs ranged from 2% to 11% in various NCDOT Divisions.

8.3.3 Sign Inspection

Two processes model sign inspection in the simulation: inspection frequency and inspection accuracy. Inspection frequency is a measure of how often (typically expressed in years) a sign agency conducts a nighttime inspection of their signs. Generally, this is easy to determine from transportation agency policies and practices. Inspection accuracy involves how well inspectors identify signs that have retroreflectivity values that lie below or above the FHWA or agency minimum retroreflectivity standard values.

The inspection frequencies selected for inclusion in the simulation scenarios take into account that agencies often inspect different road types at different intervals. The NCDOT policy is to visually inspect interstate signs annually, primary road signs bi-annually, and secondary road signs every three years (Rasdorf et al. 2006). Other typical nighttime inspection frequencies used by agencies include inspecting all signs every one or two years. A blanket replacement (warranty-based replacement) maintenance strategy can be represented in the simulation by having all signs inspected at an interval equal to their warranty period and then having all inspected signs replaced. For each of the three road types, the simulation has an input parameter for sign inspection frequency that is set to a value corresponding to the number of years between inspections.

The FHWA minimum sign retroreflectivity standards define a minimum R_A for each sign sheeting type/color combination. If the sign inspectors were perfectly accurate, all signs above the minimum R_A should be 'passed' and those below 'failed.' In the simulation model, a correct 'pass' is considered to be a *correct positive* and a correct 'fail' a *correct negative*. A sign above the minimum R_A that was incorrectly 'failed' is considered a *false negative*, and a sign below the minimum R_A that was an incorrectly 'passed' is considered a *false positive*. This two (correct, false) by two (positive, negative) inspection accuracy logic is similar to the inspection accuracy logic used in Kilgour, et al. (2007), with the false negative case corresponding to a Type I Error, and the false positive case corresponding to a Type II Error. In the simulation logic two input parameters are used to specify inspector accuracy: the percent of signs above the standards that fail inspection (the false negatives) and the percent of signs below the standard that fail inspection (the correct negatives). For example, in a scenario modeling the NCDOT process, signs have correct positive/false negative, false positive/correct negative percentages of 95.0 / **5.0** and 20.0 / **80.0**, respectively (with the input parameters in bold type). A 'perfect' inspection accuracy would be represented with percentages of 100 / **0** and 0 / **100**.

8.3.4 Sign Replacement

Each sign's action code (a replacement priority value) and ASTM sheeting type are the two factors that most influence whether or not a rejected sign is replaced. Because they are the most important signs from a safety point of view, stop signs are assigned an action code of '1,' warning signs an action code of '2,' and all other signs (regulatory and guide signs), an action code of '3.'

In the NCSU/NCDOT study it was found that approximately 53 percent of undamaged rejected signs were replaced within one year. This percentage ranged from 89 percent for "Type I, action code 1" signs to 0 percent for "Type III, action code 3" signs. It was also found that approximately 10% of all signs that were not rejected (passed) by the inspectors were replaced each year even though they were acceptable with respect to the nighttime inspection. The simulation uses six input parameters (representing all combinations of the two sheeting types and three action codes) to determine the number of rejected signs that are replaced in years when sign inspections are conducted (inspection years). There is also an input parameter for the percent of signs that are not rejected that are replaced. It is assumed that the percent of not-rejected signs that are replaced is the same for inspection years and non-inspection years. During non-inspection years the replacement of signs rejected in prior inspection years is controlled by an input parameter that specifies the percent of rejected signs replaced before the next scheduled inspection year.

Signs in the simulation that have been selected for replacement can be replaced with a new sign using either Type I or Type III sheeting. During the field study it was observed that although it was NCDOT policy to replace all Type I signs with Type III signs, some Type I signs were still replaced with new Type I signs because there was some residual stock of new Type I signs. However, all original Type III signs and all "Type I, action code 1" signs were replaced with new Type III signs. The percent of signs replaced with Type I or III sheeting in the simulation model is based on the original sign's sheeting type and action code classification. For signs originally having Type I sheeting, action code 1 and 2 signs were grouped together in the simulation model because they were found to have similar conversion percentages.

In summary, the simulation uses three sheeting type replacement input parameters to correspond to the field study observations. These are the percent of Type I action code 1 and 2 signs that are replaced with Type III signs, the percent of Type I action code 3 signs that are replaced with Type III signs, and the percent of Type III signs that are replaced with Type III signs.

8.3.5 Sign Deterioration Rates

There are several options to choose from in developing sign performance (or deterioration) models. These include models from the literature, collected field data on sign performance, a sign retroreflectivity measurement facility (Harris et al. 2009), and simple sign lifetime models based on sign warranties or professional judgment. This simulation uses the sign deterioration model values and equations given in Table 8.9 (based on a combination of literature and field data) to determine the retroreflectivity deterioration from year to year after the damage, inspection, and replacement simulation functions have been completed. At the end of each simulation year, the number of signs below the FHWA minimum retroreflectivity standards is added to the number of damaged signs to provide a sign system condition measure, termed the number of *unsatisfactory* signs (for that year – not including carryover signs).

8.3.5.1 New Sign Creation: Initial Retroreflectivity Values

After a replaced sign is removed from the simulation sign population, a new sign is created in its place with similar attributes, such as sign color, road type, etc., and an age of zero years. Replaced signs need to have an initial retroreflectivity value assigned to them, corresponding to the retroreflectivity of a newly-installed sign in the field.

The 2006 new sign values from the NCDOT/NCSU data set were the first source for potential information about expected initial sign retroreflectivity values. Table 8.10 gives the count (n), mean retroreflectivity (R_A) value, and standard deviation for seven sheeting color/ASTM type combinations. No signs in the 2006 NCDOT/NCSU data set were replaced with Red Type I sheeting. This data set contains few signs in all of the remaining Type I sheeting colors, and few Green Type III signs and many of the standard deviations are large in comparison to the mean values. The limited number of signs and variation in initial R_A values in the 2006 data set led the researcher to look for other sources for initial sign retroreflectivity values.

Another source for expected initial sign retroreflectivity values was the sign retroreflectivity deterioration models discussed in Section 6.2. Each of these linear models has an initial sign retroreflectivity value equal to the y–intercept (constant) values when the age is set equal to zero. The mean and standard deviation of the y-intercepts from the selected deterioration models listed in Table 6.1 are given in Table 8.10. The three deterioration models from the

FHWA study (Type I white and yellow, Type III green) do not have y-intercept standard deviation values given in the original FHWA report. The mean initial R_A values from the selected deterioration models do not correspond well with the mean initial R_A values from the 2006 data set.

Table 8.10. Comparison of New Sign Initial Retroreflectivity Values

Color	ASTM Type	2006 New Sign Values			Selected Deterioration Models (Table 6.1)		NTPEP Test Deck Results		
		n	Mean (R_A)	Std. Dev. (R_A)	Mean (R_A)	Std. Dev. (R_A)	n	Mean (R_A)	Std. Dev. (R_A)
Green	I	3	22.3	16.6	15.1	4.8	15	15.4	1.1
Red		-	-	-	15.3	1.6	42	17.4	3.3
White		9	77.4	16.4	103.1	(N/A)	72	95.3	11.1
Yellow		6	57.4	10.4	78.7	(N/A)	39	65.9	7.7
Green	III Encap-sulated Lens	6	42.9	1.9	53.3	(N/A)	30	49.8	3.0
Red		19	51.5	8.9	65.6	3.2	15	54.8	4.3
White		19	279.8	18.7	274.2	4.9	15	284.3	7.0
Yellow		131	224.7	17.2	211.2	5.2	27	227.1	7.8
Green	III Prismatic	-	-	-	-	-	12	109.9	4.6
Red		-	-	-	-	-	12	167.8	16.8
White		-	-	-	-	-	12	627.8	42.4
Yellow		-	-	-	-	-	12	465.8	30.4

The NTPEP Test Deck sign sheeting evaluation program collected data on the initial retroreflectivity of most sign sheetings available in the market, including 3M™ products, which account for the majority of sign sheetings installed in NC. Table 8.10 lists the count (n), mean, and standard deviation of NTPEP initial sign sheeting retroreflectivity results from tests of 3M™ Type I enclosed lens, Type III encapsulated lens (EL), and Type III prismatic lens (PR) sheetings. Although the majority of currently installed Type III signs in NC are of the encapsulated lens type, the Type III prismatic sheetings are included in Table 8.10 because they are most likely to be the majority of newly installed ground-mounted signs in NC. This is because 3M™ has discontinued manufacturing of Type III encapsulated lens products and NCDOT specifications call for only prismatic Type III signs (NCDOT Signing

Section 2008). The NTPEP test result values reasonably align with the Type I results from the 2006 data set and agree especially well with the Type III EL 2006 data set values. Therefore, the NTPEP initial sign retroreflectivity values were used in the simulation to determine the initial retroreflectivity of new signs. A normal distribution with a mean and standard deviation equal to the NTPEP values given in Table 8.10 for each sheeting type/color combination determined the initial sign retroreflectivity value assigned to a new sign in the simulation.

8.4 Simulation Logic

Figure 8.3 shows a simplified representation of the simulation model that the authors built using the Arena software. Each block in the Figure 8.3 flowchart is represented in Arena by a sub-model consisting of many interconnected Arena basic modules that perform the function specified in the block.

The simulation begins with an initial set of sign entities being created (typically 1000 signs). The Arena *ReadWrite* module is used to read an input database file that assigns sign color, sheeting type, road type, initial legend and background retroreflectivity values, and age to each sign. Several input database files were created to represent the different sign color and road type characteristics of various jurisdictions. Next, the simulation determines whether a sign is inspected during the current simulation year based on the input sign inspection frequency and sign road type. Signs to be nighttime-inspected follow the "inspection year" path through the damage, inspection, and replacement sub-models. Otherwise, signs follow the "non-inspection year" path. Section 14.7 in the Appendix contains images of each sub-model in Arena.

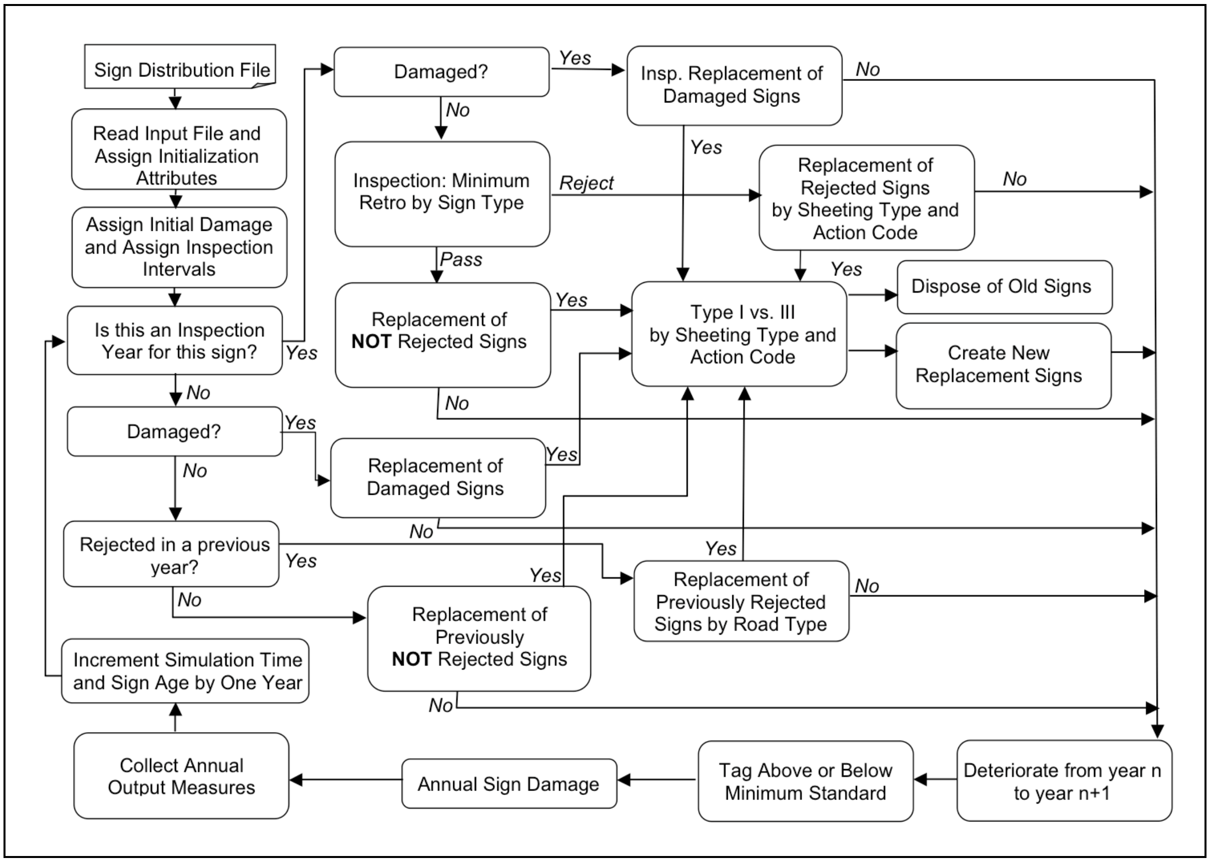


Figure 8.3. Flowchart of Simulation Logic

8.4.1 Sign Damage Model

For the simulation scenarios, three key damage input parameters (OCO, A, and R%) are used to model sign damage and the replacement of damaged signs. In the Arena simulation software the damage rates are represented using the *Decide* module, which takes each sign and, by random chance, assigns it to one of two outcomes (damaged or undamaged) based on an expected value percentage over the course of many trials. The *Decide* module randomly assigns certain signs as being initially damaged based on the initial overall damage percent (D_1, where D_1 = OCO +A) being used in the current simulation scenario.

The damaged signs then progress into the inspection sub-model for the first time. In an inspection year, damaged signs are identified during the inspection process for minimum retroreflectivity but damaged signs are replaced separately from retroreflectivity rejected signs, as shown in Figure 8.3. In a non-inspection year damaged signs are split from non-damaged signs and are replaced separately from previously rejected or not rejected signs. Regardless of whether the simulation year is an inspection year or a non-inspection year, the parameter R% is used to calculate the number of damaged signs that are replaced ($R\% * D_n$). Damaged signs to be replaced are selected at random by a *Decide* module from the population of damaged signs.

After a sign passes through the replacement and deterioration sub-models, the program uses the damage input parameters to calculate the resulting new overall damage (D_{n+1}) for the following year, year n+1, as follows:

$$D_{n+1} = D_n - (R\% * D_n) + A$$

The percent of damaged signs (D_{n+1}) will increase year to year only if the value of R% is so low that it results in fewer signs being replaced ($R\% * D_n$) than are newly damaged (A) each year. Conversely, if more damaged signs are replaced than are newly damaged the percent of damaged signs will decrease each year. The simulation assumes that R% is the same each year regardless of whether there is a nighttime inspection conducted that year.

8.4.2 Sign Inspection Model

Once the simulation has determined that a sign will be inspected based on the input inspection frequencies, it enters the inspection accuracy portion of the model, which first determines if the sign is above or below the minimum retroreflectivity standards. After the signs have been split into above and below standard, a *Decide* module randomly assigns certain signs as ‘passed’ (not rejected) or ‘failed’ (rejected) based on the input parameters for correct positive/false negative for signs above the minimum and correct negative/false positive for signs below the minimum.

8.4.3 Sign Replacement Model

Once a sign has either 'passed' or 'failed' inspection, it is then either replaced with a new sign or not replaced. Logically, a greater percentage of 'failed' (rejected) signs are replaced than 'passed' (not rejected) signs. The sign replacement sub-model consists of five key processes, including:

1. Replacement of damaged signs
2. Inspection year replacement
   a. Replacement of rejected signs by action code and ASTM sheeting type
   b. Replacement of not rejected signs
3. Non-inspection year replacement
   a. Replacement of previously rejected signs by road type
   b. Replacement of previously not rejected signs
4. Type I vs. Type III by ASTM sheeting type and action code
5. Creation of new replacement signs

In both inspection and non-inspection years, the replacement of damaged signs is controlled by the R% input parameter value. For the inspection year replacement simulation process, incoming signs were divided based on whether the sign had been rejected or not. Then, the simulation split rejected signs by ASTM sheeting type and action code. For each action code and sheeting type combination the sub-model then uses the six rejected replacement input parameters to determine how many signs are replaced.

In a non-inspection year, signs are also split into previously rejected or not, and previously rejected signs are then split by road type to accommodate different inspection frequencies. The rejected signs replaced before next inspection year input parameter controls the percentage of signs rejected in previous years that is replaced before being nighttime-inspected again. We have assumed that 100% of rejected signs are replaced before the next inspection. However, it is possible to change this value to another rate, say 80%, to reflect local conditions. The simulation logic assumes that the percent of rejected signs replaced each year is the same in each non-inspection year. For example, if signs are scheduled to be inspected every two years and during the inspection year 70% of rejected signs were replaced, this results in 30% of rejected signs not having been replaced. If 100% of rejected signs are to be replaced before the next inspection, then the entire set of remaining rejected signs (30%) needs to be replaced in year 2. If the signs are scheduled to be inspected every three years, (30/2) = 15% of rejected signs would be replaced (50% of remaining previously rejected signs) in the second year and 15% (100% of remaining) in the third year to ensure that 100% of rejected signs were replaced before the next inspection year.

For all replacement processes, Arena *Decide* modules assign certain signs as replaced or not replaced (by random chance) based on the input parameter percentages previously specified for these for these variables. Signs that were replaced then move to another *Decide* module where they are assigned (again, by chance) to be replaced with a sign made of Type I or Type III sheeting based on the input parameters specified. Next, the sign entities to be replaced are duplicated in the simulation and the duplicate entities are removed. After a replaced sign is removed from the simulation sign population, a new sign is created in its place with similar sign color, road type, etc. attributes and an age of zero years. Replaced signs need to have an initial retroreflectivity value assigned to them corresponding to the retroreflectivity of a newly-installed sign in the field. The NTPEP initial sign retroreflectivity values (intercepts) given in Table 8.10 were used in the simulation to assign the initial retroreflectivity of new signs. A normal distribution with a mean and standard deviation equal to the intercept values given in Table 8.9 for each sheeting type/color combination determined the initial sign retroreflectivity value assigned to a new sign.

8.4.4 Sign Deterioration Model

The simulation uses the sign deterioration model values given in the last column of Table 8.9 to determine the retroreflectivity deterioration from year to year after the damage, inspection, and replacement simulation functions are completed. Each year the sign's slope value, which corresponds to its retroreflectivity loss that year, is re-sampled from a normal distribution with a mean set to the slope estimate and a standard deviation equal to the slope standard error. The sign deterioration sub-model predicts annual retroreflectivity deterioration for Type I and Type III (encapsulated lens) materials, and could be improved with more encapsulated lens Type III data. In the future, prismatic Type III and Type IX sheeting deterioration models can also be developed for the simulation. After the new retroreflectivity values are assigned to the signs, the simulation evaluates whether the sign is above or below the FHWA minimum standard.

8.4.5 Output Measures

Before the start of a new simulation year, a *Decide* module randomly assigns certain signs as being newly damaged based on the annual damage parameter value being used in the current simulation scenario. This is similar to the initial assignment described in the sign damage model section.

After sign deterioration and annual sign damage is calculated, the simulation model collects several key estimates, or output measures for the simulation year. Each output measure provides a count of the number of signs that have passed through certain locations in the simulation network and is collected on an annual basis for the purpose of comparing scenarios over time. These measures include the number of unsatisfactory signs each year (which consists of the number of signs below the FHWA minimum retroreflectivity standards plus the number of damaged signs), the number of signs replaced each year, and the number of signs inspected each year. The number of replaced and inspected signs serve exceedingly well as a surrogate measure of the agency costs associated with installing new signs and conducting nighttime sign inspections.

The simulation model begins a new simulation year after the annual output measures have been written to a file for further analysis. The model adds a year to the age of each sign and increments the simulation year by one. Then the model moves all of the sign entities to the start of the inspection sub-model that determines if a sign will be nighttime-inspected during the current simulation year.

8.5 Discussion

After the simulation was validated as described in Chapter 7.0, the authors ran several simulation scenarios representative of various sign system conditions and management policies. This paper presents the results of one of these scenarios; a "case study scenario" representative of the conditions and policies observed during the NCDOT field study. The input parameters defining this scenario were entered into the Arena simulation model. The input parameters included the parameter values shown in Table 8.11 and a 1,000-sign input database file derived from the observed initial field sign conditions.

In this study, a simulation scenario run consists of 30 simulation replications, each of which uses the same input parameter values, allowing each output measure value to be estimated within an error of ± 5% or less. Each replication continues for 50 years, representing 50 years of future sign conditions and management. The key output measures are determined each year of each replication, resulting in 30 values of each output measure per simulation year, and a total of 1500 values per output measure over the course of 50 years.

The value of 30 simulation replications was chosen based on the results from the pilot run of the simulation during the validation process. Several key output measures (signs replaced, signs rejected, etc.) were chosen and used in a statistical analysis to determine the number of simulation replications necessary to have our simulation estimates be in an error range of ± 5% or less. This analysis indicated that 16 repetitions would be sufficient but 30 were preferred to ensure that the error rate would definitely be in this range.

Table 8.11. Key Input Parameters Used in the Case Study Scenario

Key Input Parameters	Value
Initial Overall Damage Percent, Interstate	0.0
Initial Overall Damage Percent, Primary	6.4
Initial Overall Damage Percent, Secondary	8.6
Inspection Frequency, Interstate (years)	1
Inspection Frequency, Primary (years)	2
Inspection Frequency, Secondary (years)	3
Damaged Signs Replaced (percent) for All Signs, Road Types, and Action Codes	62.7
Signs Above the Minimum Retro and Fail Inspection (percent)	5.0
Signs Below the Minimum Retro and Fail Inspection (percent)	80.0
Rejected Type I Action Code 1 Signs Replaced (percent)	88.9
Rejected Type I Action Code 2 Signs Replaced (percent)	61.7
Rejected Type I Action Code 3 Signs Replaced (percent)	40.4
Rejected Type III Action Code 1 Signs Replaced (percent)	66.7
Rejected Type III Action Code 2 Signs Replaced (percent)	37.5
Rejected Type III Action Code 3 Signs Replaced (percent)	0.0
Not Rejected Signs Replaced (percent) for All Signs, Road Types, and Action Codes	9.3
Rejected Signs Replaced (percent) Before Next Inspection Year	100.0
Type I Action Code 1 and 2 Signs Replaced with Type III Signs (percent)	96.0
Type I Action Code 3 Signs Replaced with Type III Signs (percent)	62.0
Type III Signs Replaced with Type III Signs (percent)	100.0
Annual Damage (percent) for All Signs, Road Types, and Action Codes	4.7

Once the case study scenario run was completed and the results saved to a spreadsheet, the average annual values for several selected output measures were computed. This resulted in each output measure having 50 values, one for each simulation year. Figure 8.4 displays the average annual number of unsatisfactory signs, signs replaced, signs damaged, and Type I signs predicted by the case study scenario simulation run results. Note that a curve showing only the number of Type I signs is shown. The number of Type III signs would be 1000 minus the number of Type I signs. The vertical bars in Figure 8.4 symbolize the upper and lower prediction interval bounds for each average annual output measure value, and the relative standard error for the four key output measures shown is approximately 2%.

The initial overall damage parameter values from Table 8.11 result in about 75 signs out of 1000 being damaged when the simulation begins. This total number of damaged signs (75) remained approximately constant over the 50-year simulation period because the number of damaged signs that were replaced each year (62.7% * 7.5% of signs damaged * 1000 = 47) was equal to the number of signs newly damaged at the start of that year (4.7% * 1000 = 47). The difference between the number of unsatisfactory signs and the number of damaged signs in Figure 8.4 corresponds to the number of signs below the FHWA minimum retroreflectivity standards. In the tenth simulation year the number of signs below the standard dropped to less than 10% of all signs. By year 20 in Figure 8.4, most of the unsatisfactory signs are damaged signs.

The number of signs replaced each year is also relatively constant, but since most signs are replaced by Type III signs that have a greater initial retroreflectivity, the percent of Type I signs decreases to less than 10% within 10 years and to nearly zero within 30 years. The decrease in the number of Type I signs over the first 10 years closely corresponds to the decrease in the number of signs below the FHWA minimum retroreflectivity standards. The number of Type I signs does not decrease at a faster rate (sooner) because the input parameters specify that 38% (100-62) of Type I action code 3 signs and 4% of Type I action code 1 and 2 signs are replaced with new Type I signs each year. After 10 years approximately 14% of the 1000 signs (140 signs) are replaced each year, with 1.5%-2% replaced due to being rejected during nighttime inspection, 4.5% replaced due to damage, and 8% replaced for other reasons (upgrades, changes to sign message, change in traffic control, etc.). The percent of signs replaced for other reasons is controlled by the 'Not Rejected Signs Replaced' input parameter. The simulation results can also be used to predict costs as well as sign condition. If approximately 140 signs out of 1,000 are replaced each year under the policies input into the simulation scenario, an agency can determine their expected annual sign replacement cost by multiplying 0.140 by the number of signs that the agency owns and by the purchase and installation cost per sign.

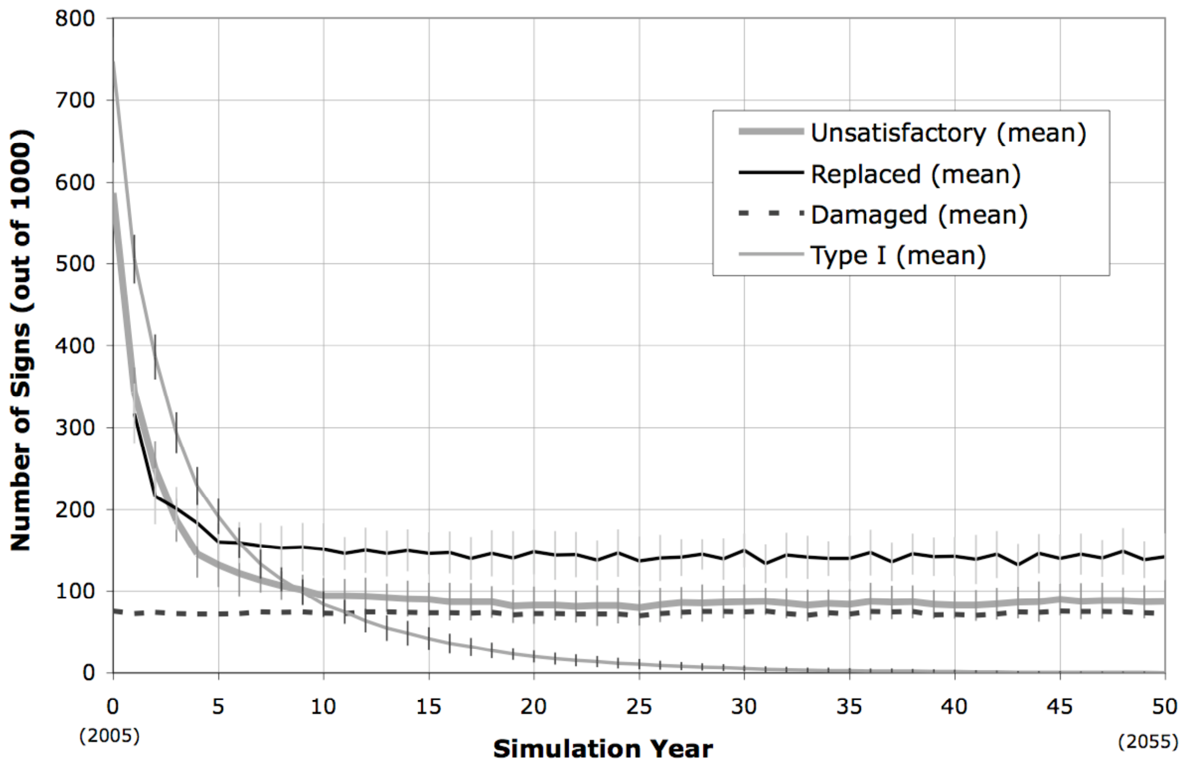


Figure 8.4. Key Output Measures by Simulation Year

The simulation model is capable of additional modeling options that the case study scenario example did not utilize. Besides changing the input database file and input parameters to reflect an agency's sign conditions and policies, the simulation can model what happens when a nighttime-inspection or sign replacement is skipped one year. An annual sign budget can be set for the agency that limits the number of signs that are replaced each year. The input parameter values could increase or decrease over the course of the simulation period instead of remaining constant as in the case study scenario. The simulation output can be modified to collect certain characteristics of each sign annually, allowing a user to observe what is happening to a particular sign as it travels through the simulation year after year. The simulation model can be easily modified through the Arena software to add additional sub-models, functionality, or output measures. If a model user is uncertain about the value of a specific input parameter, he or she can vary the input parameter over its possible range of values to determine how changing that specific parameter affects the simulation outcomes. Through this process, the model user can determine the most critical parameters and sub-model process for their specific region and policies of interest.

The simulation model does have some limitations. The most serious of these is that its validation could only be performed over a one-year time period because there were only two years of sign data available. The NCDOT/NCSU field study, being only a one-year study, was not able to establish replacement rates for two and three year inspection cycles. Having more long-term data would improve the simulation sub-models by providing annual parameter values during non-inspection years that accurately document their year-to-year variability. Many of the sub-models use a basic percentage model to determine whether a sign follows one model path or another because there is not enough data to generate a more complex model reflecting real behaviors. Instead, average percentages were used because they were easy for practitioners to understand and they correspond to an agency's management goals, such as replacing 100% of action code 1 signs within one year. With the exception of the sign deterioration sub-model, there was limited data available on how signs with certain characteristics (such as sign type and road type) would behave differently in each sub-model.

8.6 Conclusions

The authors developed an original microscopic simulation model of the entire sign asset management process to gain a more detailed understanding of the many factors that influence sign performance and of the level of compliance highway agencies can expect to have with the FHWA minimum retroreflectivity requirements. Simulation was chosen to model the sign system because it was an inexpensive way to examine the effects of various management decisions on the performance of the system without having to change the actual sign system in the field. Simulation was also needed to handle the complex behaviors (such as sign deterioration and inspection and interactions) within the sign system. A microscopic simulation model, where each sign can move independently through the simulation (i.e., is treated as an individual), yields a more realistic model of how signs progress through their life cycle because it permits sign characteristics to change independently and enables variability in how signs travel through the simulation steps. Microscopic simulation also allows one to remove many assumptions present in forecasting and macroscopic simulation models that do not represent real-world behavior. For example, an earlier macroscopic simulation model averaged the inspection frequency across all road types while the current microscopic simulation was able to inspect each road type separately at the actual inspection interval. Thus we found microscopic simulation to be ideal for this application.

One of the most noteworthy outcomes of developing the simulation model was revealing the intricacies and dependencies involved in sign management itself. Dividing the sign management process into a flowchart with connected sub-models revealed how the information contained in the field study data set corresponded to specific transportation agency sign management practices. The data were then analyzed to determine the best modeling options for each of the sub-models. The path that each sign takes through the sub-models (thus through the overall model) is determined by the many Arena modules that consider a sign's individual characteristics and route it to the proper location based on the input parameter values. For example, the inspection function was split into a sign damage detection sub-model and a sign retroreflectivity inspection sub-model to better model how these two different sign conditions are managed and behave. A dependency that was revealed was that the replacement of previously rejected signs in a non-inspection year relied upon how many signs were replaced during the previous inspection year.

Creating each sub-model presented several challenges. There was limited previous work to base the sub-models on with the exception of sign deterioration, for which there were some resources and models in the literature. However, the stochastic nature of the simulation required that the sign deterioration sub-model not be a basic linear regression model but instead represent the well-scattered distribution of sign retroreflectivity versus age. The most challenging sub-model to create was the non-inspection year replacement sub-model because there were insufficient data from the field study to build the model upon. Because this sub-model had to be mostly based on observations from the 2006 data collection and discussions with sign inspectors, it contains the most assumptions as a result. Still, because the behavior of each sub-model in the simulation is independent, any one sub-model can be improved as better knowledge of its behavior and characteristics become more well understood. The performance of the overall simulation will then be improved.

Understanding, defining, and modeling the sign system also revealed asset management issues that were not originally obvious. For example, the case study simulation scenario revealed that within 10 years less than 10% of signs would be below the minimum retroreflectivity standards. The decrease in the number of Type I signs over the first 10 years closely corresponds to the decrease in the number of signs below the FHWA minimum retroreflectivity standards, indicating that Type I signs make up the majority of deficient signs based on retroreflectivity. Accordingly, at the 10-year point damage was found to become a more critical sign condition factor than retroreflectivity, given the input parameter values used.

The flexibility in the sub-model and Arena module simulation structure enables the simulation presented here to be capable of evaluating scenarios representative of most typical agency management situations. It is straightforward to go into each module's settings and change them, or change the input parameter values that the modules utilize, to direct the signs through the simulation. Simulation does not work in random order; rather, changes are sequenced and occur based on field-measured and observed sign performance. For example, it is known that signs are lost to damage, and the damage rate for signs in NC is known from the NCDOT/NCSU sign study data. The damage rate value initially entered into the simulation can be changed if warranted to enable another state's use of the simulation. In the case of damage rate, if another state experienced a different damage rate than NC that state's damage rate would be used instead.

In summary, we found that microscopic simulation was well suited to this application. The simulation was successfully built and validated and it can be used by others seeking to further this work. The simulation runs fast, is flexible, and the outputs are logical and make sense. We found that input parameters are critical components of the simulation. If values of parameters are unknown, default values can be used. If field measurements are taken or field studies are conducted to more firmly establish local conditions, these can be used as inputs to fine tune the model. Finally, a key result of this work was the formalization of all the elements of the sign modeling process, shown in abbreviated form in Figure 8.3. No such process articulation had previously been documented. Thus, a framework for understanding the sign asset management process has been created and a simulation model exists to analyze it. Sign asset management is well suited to microscopic simulation.

8.7 Recommendations

Because the simulation results are controlled by the input parameters, the input parameter values selected need to be based upon the best information available, either through field data collection, agency records, or literature values. Gathering the data required to determine the simulation input parameter values with confidence and customizing, verifying, and validating the model requires extensive time and financial resources that many agencies may not possess. However, the microscopic simulation can serve as a fine research tool for learning more about which management practices influence performance and cost. To achieve this a hybrid simulation model could be developed that has reduced input data needs and focuses on the critical practices controlling sign performance and agency costs.

The microscopic simulation model developed in this paper could be improved by comparing the results of a change in sign management policy in the real world to the predicted results from the simulation model. The results of a change in sign policy in the field could be compared to the outcome predicted by the simulation model, further validating the model. A simulation determined to be a "valid" representation of the sign system can then "be used to make decisions about the system similar to those that would be made if it were feasible and cost-effective to experiment with the system itself" (Law and Kelton 2000).

Collecting longer-term data on sign systems would also help strengthen the simulation model, especially by providing more information about how non-inspection year replacements are managed in the field. The sub-models could also be improved to further utilize the capabilities of microscopic simulation if further research was done into the real-world variability of the processes that the sub-models attempt to mimic. For example, more performance and system data about daytime inspections would improve the inspection and replacement sub-models. Incorporating more detailed sign system data from other highway agencies would also strengthen the simulation model by increasing the scope of the simulation's applicability.

9.0 SIMULATION SCENARIOS DEVELOPMENT

The authors' selection of simulation scenarios focused on scenarios that represent the typical sign conditions and sign management practices that most influence sign performance and cost. Three major parts define a simulation scenario: input distribution, input parameters, and management method. The goal was to develop a diverse scenario set that could be used to model how a typical sign system would perform if there were changes in key policies, financial resources, and regional conditions. A total of 176 simulation scenarios were developed and analyzed. A listing of the input parameter values used for each scenario is shown in Section 14.4 (Appendix D: List of Input Parameter Values for Each Simulation Scenario). This chapter explains the logic behind the selection of the input parameter values used in the simulation scenarios and the output measures collected. Section 14.5 in the Appendix contains a table showing the default simulation variable values and the input parameter values used for Scenario 10 (base case scenario).

9.1 Input Parameter Values for the Simulation Scenarios

The input parameters control the simulated sign system's behavior in areas such as damage, inspection frequency, inspection accuracy, replacement, and available funding. Some of these parameters, including inspection frequency and replacement, represent management practices that can be directly controlled by the sign management agency. Many simulation scenarios were developed to test how changes in these controllable practices would influence the sign system. Input parameters that represent conditions and practices that an agency may have limited influence upon include damage, inspection accuracy, and available funding. For these 'uncertain' input parameters, the authors used a range of both typical and unrealistic input values in the selected scenarios to determine the variations that were the most critical and the boundaries of expected system performance.

9.1.1 Sign Input Distributions

Section 8.3.1 describes in detail how the simulation sign input distributions were created for six different initial sign populations. For each of the six initial sign populations used in the simulation scenarios, Table 9.1 provides the percentage breakdown by sheeting color, road type (Interstate, Primary, and Secondary), sheeting type, and percent of signs below the FHWA minimum retroreflectivity requirements. Table 9.2 gives the percent of Type I signs in each input distribution that have retroreflectivity values below the minimum requirements.

Table 9.1. Sheeting Color, Road Type, Sheeting Type, and Percent Failing the MUTCD Requirements by Sign Input Distribution

No.	Owner/Region	White (%)	Yellow (%)	Green (%)	Red (%)	I (%)	P (%)	S (%)	Type I (%)	Type III (%)	% of Total Failing
1	NCSU/NCDOT (2005 Field Data)	37.3	44.7	8.8	9.2	12.0	18.1	69.9	74.7	25.3	51.2
2	NC	42.5	41.3	7.5	8.7	2.6	32.0	65.4	75.3	24.7	38.7
3	State	48.7	31.9	11.7	7.7	8.3	71.9	19.8	13.4	86.6	5.4
4	County	35.0	48.0	6.7	10.3	0.0	28.0	72.0	58.6	41.4	32.8
5	City	61.7	29.2	5.0	4.1	0.0	8.9	94.1	57.5	42.5	23.9
6	Town	42.8	46.3	1.9	9.0	0.0	2.4	97.6	57.9	42.1	31.2

Table 9.2. Percent of Type I Signs by Color Failing the MUTCD Requirements by Sign Input Distribution

No.	Owner/Region	Percent Type I Failing			
		White	Yellow	Green	Red
1	NCSU/NCDOT (2005 Field Data)	41.7	100.0	43.2	7.7
2	NC	18.8	97.5	13.8	8.5
3	State	17.3	100.0	13.3	0.0
4	County	20.7	98.9	16.7	10.1
5	City	17.7	99.4	17.9	8.0
6	Town	17.2	98.5	14.3	10.9

9.1.2 Sign Damage

Table 9.3 contains 21 combinations of original carryover damage (OCO), annual damage (A), and annual damage replacement percentage (R%) that are used in the simulation scenarios. There are 21 combinations because unlike other sign parameters, there is very little information on damage rates in the literature, necessitating that a variety of damage situations be analyzed. The annual damage replacement percentage is used to calculate the new carryover damage (NCO) in the following year using the following formula:

NCO = (OCO + A) – [R% * (OCO + A)]

Combination 3 in Table 9.3 corresponds to the key damage parameters found within the NCDOT/NCSU study area. Most combinations of the three key damage parameters in Table 9.3 (shown in **bold** type) ensure that the new carryover damage is less than or equal to the original carryover damage. This was done to prevent the overall damage rate from increasing from year to year in the simulation scenarios. However, combinations 5, 6, and 7 have a new carryover damage value that is greater than the original carryover damage. These three combinations were included in the scenarios to test what would happen if damage increased year to year.

Table 9.3. Combinations of Key Damage Parameters for the Simulation Scenarios

No.	Original Carryover Damage (OCO)	**Annual Damage (A)**	**Overall Damage (OCO + A)**	**Annual Damage Replacement Percentage (R%)**	New Carryover Damage (NCO)
1	3	4	7	60	2.8
2	3	4	7	100	0
3	2.8	4.7	7.5	62.7	2.8
4	5	2	7	100	0
5	3	4	7	0	7
6	3	4	7	20	5.6
7	3	4	7	40	4.2
8	3	4	7	80	1.4
9	1	6	7	100	0
10	3	2	5	100	0
11	1	4	5	100	0
12	1	2	3	100	0
13	1	2	3	66.6	1
14	1	4	5	80	1
15	3	2	5	40	3

16	3	4	7	57.1	3
17	1	6	7	85.7	1
18	1	8	9	88.8	1
19	3	6	9	66.6	3
20	5	4	9	44.4	5
21	7	2	9	22.2	7

9.1.3 Inspection Frequency

The inspection frequencies selected for inclusion in the simulation scenarios take into account that agencies often inspect different road types at different intervals. During the NCDOT/NCSU study it was found that the NCDOT sign policy is to inspect interstate signs annually, primary road signs bi-annually, and secondary road signs every three years (Rasdorf et al. 2006). The NCDOT sign policy is listed as No. 6 in Table 9.4. The first five rows (No. 1-5) in Table 9.4 correspond to situations where all signs are inspected with the same frequency, regardless of what road they are located on. The blanket replacement (warranty-based replacement) maintenance strategy is represented by No. 5-7, with a warranty period of 7 years for Type I signs and 12 years for Type III signs. These three sets are used with a 100% replacement rate to simulate blanket replacement based on sign warranty periods.

Table 9.4. Inspection Frequencies for the Simulation Scenarios

No.	Inspection Frequency (years)		
	Interstate	Primary	Secondary
1	1	1	1
2	2	2	2
3	4	4	4
4	1	2	3
5	7	7	7
6	12	12	12
7	15	15	15

9.1.4 Inspection Accuracy

The inspection accuracy for the simulation scenarios is modeled similarly to the inspection accuracy in the simulation validation, with the exception that the inspection accuracy rates apply to all colors instead of having a different inspection accuracy rate for each sign color. This consolidation was used for the simulation scenarios to simplify modeling and because most of the sign colors (with the exception of stop/red) had similar inspection accuracy rates in Table 6.3. Table 9.5 lists the inspection accuracies used in the simulation scenarios. No. 1 is derived from the NCDOT/NCSU study data and has separate inspection accuracy rates for red/stop signs. No. 2 was also developed from the NCDOT/NCSU study data and represents the inspection accuracy rate if the rates for all sign colors are combined. The measured retroreflectivity maintenance strategy is represented by No. 3, because all signs are identified correctly in this set. No. 4-7 were created to test how varying the inspection accuracy rates would change the simulation outputs. No. 8 was developed from the inspection accuracy results found as part of the Washington State Study discussed in Section 2.3.1.1 (Lagergren 1987)

Table 9.5. Inspection Accuracies for the Simulation Scenarios

No.	Sheeting Color	Signs Above Minimum R_A		Signs Below Minimum R_A	
		Correct Positive	False Negative	Correct Negative	False Positive
		%	%	%	%
1	All except Red/Stop	96.5	3.5	27.7	72.3
	Red/Stop	94.1	5.9	71.4	28.6
2	All	96.1	3.9	28.8	71.2
3	All	100	0	100	0
4	All	95	5	40	60
5	Al	95	5	60	40
6	All	95	5	80	20
7	All	95	5	90	10
8	All except Red/Stop	72	28	81	19
	Red/Stop	82	18	70	30

9.1.5 Sign Replacement

Sign replacement in the simulation scenarios consists of the following six key processes:

1. Replacement of rejected signs by action code,
2. Replacement of not rejected signs by action code,
3. Replacement of previously rejected signs by action code,
4. Replacement of previously not rejected signs by action code,
5. Replacement of damaged signs (Section 8.3.2), and
6. Type I vs. Type III by sheeting type.

The simulation validation scenario utilized replacement of rejected signs by action code, replacement of not rejected signs by action code, and Type I vs. Type III by sheeting type. Because the simulation validation scenario was only concerned with a one-year period when inspection occurred, there was a need in the main simulation scenarios to include replacement processes for years when signs were not inspected. The simulation assumes that the replacement of not-rejected signs is the same for inspection years and non-inspection years.

Table 9.6 lists the rejected sign replacement rates used in the simulation scenarios. No. 1 is from the NCDOT/NCSU study data and the second set is a representation of a policy where all action code 1 signs, two-thirds of action code 2 signs, and one-third of action code 3 signs are replaced within a year. No. 4 represents replacing all rejected signs during the inspection year (this set is also used for blanket replacement) while No. 7 represents a year where the sign managers have decided to not replace any signs. The rest of the rejected sign replacement values represent possible variations in replacement rates that may be found in the field.

Table 9.7 provides the replacement rates for not rejected signs. The NCDOT/NCSU study found that some signs that were not rejected were still replaced. No. 1 in Table 9.7

represents the percent of not-rejected signs replaced in the NCDOT/NCSU study area. The rest of the replacement rates provide for situations where more or fewer not-rejected signs are replaced. These percentages apply both in inspection and non-inspection years.

Table 9.6. Replacement Rates for Rejected Signs During an Inspection Year

No.	Percent of Rejected Signs Replaced:					
	Sheeting Type I			Sheeting Type III		
	Action Code 1	Action Code 2	Action Code 3	Action Code 1	Action Code 2	Action Code 3
1	88.9	61.7	40.4	66.7	37.5	0
2	100	66.7	33.3	100	66.7	33.3
3	100	66.7	33.3	90	50	25
4	100	100	100	100	100	100
5	90	60	40	70	40	20
6	80	50	30	60	30	10
7	0	0	0	0	0	0
8	90	60	40	90	60	40
9	80	50	30	80	50	30

Table 9.7. Replacement Rates for Not-Rejected Signs

No.	Percent of Not-Rejected Signs Replaced	Percent of Not-Rejected Signs Not Replaced
1	9.3	90.7
2	0	100
3	5	95
4	10	90
5	20	80

Table 9.8 lists the Type I to Type III sheeting conversion rates used in the simulation scenarios. For signs originally having Type I sheeting, action code 1 and 2 signs were grouped together because they were found in the NCDOT/NCSU study to have similar conversion percentages. All of the values except for No. 6-8 assume that signs originally having Type III sheeting are always replaced with Type III sheeting signs.

Table 9.8. Type I to Type III Conversion Rates

Original Sheeting	Type I				Type III	
Action Code	1 and 2		3		All	
Replace with / No.	Type I (%)	Type III (%)	Type I (%)	Type III (%)	Type I (%)	Type III (%)
1	4	96	37	62	0	100
2	0	100	33	67	0	100
3	5	95	20	80	0	100
4	10	90	10	90	0	100
5	0	100	0	100	0	100
6	50	50	50	50	50	50
7	100	0	100	0	100	0
8	75	25	75	25	75	25

9.2 Output Measures

At the end of a simulation year, the simulation model collects several key estimates, or output measures for the simulation year. Each output measure provides a count of the number of signs that have passed through certain locations in the simulation network and is collected on an annual basis for the purpose of comparing scenarios over time. Each output measure is recorded for each simulation year, resulting in 50 measure values per replication and 1500 (50 x 30) measure values per simulation scenario run. The table contained in Section 14.6 in the Appendix contains a listing of all output measures evaluated in this simulation study. These measures include the number of unsatisfactory signs each year (which consists of the number of signs below the FHWA minimum retroreflectivity standards plus the number of damaged signs), the number of signs replaced each year, and the number of signs inspected each year.

10.0 SIMULATION RESULTS

The Federal Highway Administration (FHWA) now requires public highway agencies to implement a sign maintenance program by the year 2012 to bring sign populations into compliance with the minimum maintained retroreflectivity levels specified in the Manual on Uniform Traffic Control Devices (MUTCD). The FHWA has specified that agencies' sign maintenance programs utilize one or more of the five recommended maintenance methods outlined in the MUTCD. The recommended methods are nighttime visual inspection, measured sign retroreflectivity, expected sign life, blanket replacement, and control signs (FHWA 2007a).

Highway agencies additionally have until January 2015 to have most of their red, white, yellow, and green ground-mounted signs comply with the minimum retroreflectivity standards. The FHWA states that agencies can have individual signs within their jurisdiction that are below the minimum levels as long as one of the maintenance methods is in place and is regularly applied by the agency. This new management and minimum retroreflectivity standard is compelling agencies to re-evaluate how they manage their signs and determine how they can meet the standard while remaining within their budgets.

10.1 Background

Since the idea of implementing a minimum retroreflectivity standard took root in the early 1990's, several studies have investigated the potential impacts of the retroreflectivity standards and recommended strategies for achieving compliance. McGee and Taori (1998) collected nationwide data on the distribution of sign age, sign sheeting type, and sign condition and estimated that 5% of state-owned signs and 8% of locally-owned signs would not meet the minimum retroreflectivity levels. Bischoff and Bullock (2002) found that over 98% of the signs in their study area in Indiana should meet or exceed the minimum levels. They also recommended the nighttime visual inspection method to better evaluate the retroreflective performance of signs.

Estimating the nationwide financial impacts of the minimum standard, Opiela and Andersen (2007) determined that the main source of increased costs would come from installing higher quality sign sheeting materials, but that these improved materials would maintain their retroreflectivity longer and result in lower overall service life costs. Kilgour, White, and Bullock (2007) investigated the fiscal impact on local agencies in Indiana, finding that 34-40% of signs in their sample were not compliant with the minimum standard but that many of these non-compliant signs would be replaced during regular agency sign replacement activities. This study also compared the nighttime visual inspection method and the measured retroreflectivity method, which is 100% accurate because each sign's retroreflectivity value is directly measured. Although Kilgour, White, and Bullock found the visual inspection method to be only 88% accurate, they chose visual inspection as their preferred method because it was cheaper, requiring fewer labor hours than the measured retroreflectivity method. As a result of these studies, the nighttime visual inspection method has emerged as the likely preferred maintenance method among the five methods specified by the FHWA.

After the minimum standard was published, the FHWA commissioned a guidebook and "toolkit" to assist small agencies with budgeting for sign replacement and implementing the nighttime visual inspection method consistently (Carlson and Picha 2009). The visual inspection procedure requires a sign crew consisting of a trained inspector (over 60 years old), a driver, a sports utility vehicle or pickup truck, and a standard form for recordkeeping. The guidebook does not specify any requirements on how often the retroreflectivity inspections should be conducted, only suggesting inspecting every year or every other year. The toolkit portion of the guidebook helps agencies estimate their sign replacement budget based on the total number of signs or the total number of centerline miles in the jurisdiction. This guidebook assumed that local agencies would not have the resources to create and maintain a sign inventory that could be used to implement other management methods, including expected sign life, blanket replacement, and control signs. For agencies that do have inventories, a study performed for Pierce County, WA by Ellison (2008) found that a combination of the measured retroreflectivity, expected sign life, and control sign methods worked most successfully.

Although research efforts by the FHWA and others have provided guidance on what sign management methods will ensure conformity with the standards, there is limited advice available to agencies on the tradeoffs between sign condition levels and the maintenance costs associated with each management method. These tradeoffs can be explored by creating a model of the sign system that is implemented using simulation techniques.

A study conducted at North Carolina State University (NCSU) for the North Carolina Department of Transportation (NCDOT) in 2005 used simulation to model the entire sign management process, from sign installation through sign inspection, deterioration, and replacement (Rasdorf et al. 2006). That study chose simulation to model sign performance and management because of the financial and technical difficulty of inventorying more than one million NCDOT signs. Comparing different management methods using sign replacement cost and the number of non-compliant signs as two key criteria, the study found, like previous studies, that nighttime visual inspection could be a cost-effective method for the NCDOT (Harris et al. 2007). Seeking to quantify and validate the assumptions in the original simulation and expand the simulation scope beyond the NCDOT, a new and unique microscopic sign system simulation was developed that could be used to evaluate a wide variety of agency types and sign management practices. That simulation is the subject of this paper.

10.2 Methodology

The Arena simulation software was used to build a simulation model that is believed to be representative of a typical sign system. The simulation was designed to be microscopic, meaning that each sign is represented as a separate entity and is able to follow an individual path through the simulation network. The simulation models a set of field processes that each of the 1000 signs in the system progress through annually. The processes were sign damage, inspection, replacement, and deterioration. They are implemented as sub-models that are modifiable by the simulation input parameters. The simulation model was developed one sub-model at a time, allowing the performance of each sub-model to be verified individually before being incorporated into the overall simulation model.

After each simulation scenario run is complete, the simulation model produces several key output measures on an annual basis that can be used to compare the subject scenario to other sign management scenarios. The simulation was validated by comparing the results of a one-year simulation scenario run that was representative of the sign conditions and management practices observed during a 2005 NCSU/NCDOT study to field-measured year 2006 (one year later) data. Further detail about the development and validation of the microscopic simulation model used in this paper can be found in Harris et al. (2010).

10.2.1 Simulation Capabilities

The simulation model includes several optional features that expand its capabilities. In addition to being able to change the input parameters to reflect an agency's individual sign conditions and policies, the simulation can also represent what happens when a nighttime visual inspection or sign replacement is skipped in a given year. Also, an annual sign budget can be specified, limiting the number of signs that are replaced each year. The *Blanket Replacement* management method can be chosen as an option, and the *Measured Retroreflectivity*, *Expected Sign Life*, and *Control Signs* management methods can be approximated by manipulating the input parameters. The simulation model itself can be easily modified through the Arena software to add additional sub-models, functionality, or output measures. Currently, the simulation focuses on the three sign types (regulatory, warning, and guide) that the FHWA is requiring minimum retroreflectivity compliance for by 2015. The simulation considers ground-mounted signs but does not consider overhead guide signs or street name signs.

During each simulation year the program calculates several key output measure values to facilitate comparisons between simulation scenarios. A simulation scenario *run* consists of 30 simulation *replications*. Each simulation *replication* cycles all 1000 signs through the simulation model 50 times to represent 50 years of sign management processes and condition changes. A 50-year time period was selected because all signs would go through at least two cycles of replacement if sign lifetimes were equal to 25 years or less. Because there are 30 simulation replications per run, each simulation year there are 30 values for each output measure for that particular simulation year. These 30 values are averaged to yield a *mean output measure value* for each simulation year, resulting in 50 mean output measure values (years 1-50) for each output measure. This model design ensures that each *mean output measure value* estimates the actual (real-world) output measure value for that simulation year within an error of ± 5% or less.

10.2.2 Determining Sign Condition and System Costs

Output measures that represent sign conditions and sign management costs are the most useful measures when comparing simulation scenarios because sign management decisions are focused on producing safe conditions economically. Key sign condition output measures produced by the simulation include the number of signs damaged each year and the number of unsatisfactory signs on the roads. Damaged signs include those signs damaged by natural causes (tree sap, water damage, etc.) and by vandalism (paintballs, gunshots, etc.). Unsatisfactory signs are those below the FHWA minimum retroreflectivity standards *plus* the number of damaged signs, counting a sign that meets both criteria only once. The key output measures for sign management costs are the number of signs inspected and the number of signs replaced.

An estimate of the inspection and replacement system costs can be made by using the *signs inspected* and *signs replaced* output measures. The NCSU/NCDOT study estimated that nighttime visual sign inspection costs $0.55 per sign (Rasdorf et al. 2006). Sign managers can use this value (or a value developed from their own data) to estimate their total inspection cost. To determine sign replacement costs, sign managers should determine the local material and labor costs for installing one sign. If this information is unknown, the manager can use a default cost value such as the $150 per sign cost given in the FHWA's *Sign Retroreflectivity Manual and Toolkit* (Carlson and Picha 2009). If the material and labor costs for different sign color and sheeting type combinations (such as Type III encapsulated red signs) are known, the simulation model can be modified to produce *signs replaced* output measures for each combination, yielding a more precise estimate of costs.

The output measures are useful for determining inspection and replacement costs on a yearly basis because the simulation produces these output measure values each simulation year. Because each scenario run encompasses 50 years of sign management processes, there are 50 *mean output measure values* (years 1-50) for each output measure (such as *signs replaced*). However, sets of 50 annual mean output measure values for each key output measure are not helpful when one wishes to easily compare the performance of several simulation scenarios. To facilitate the comparison of multiple simulation scenarios over a 50-year time period, this paper uses two summary values for each scenario: one value to represent sign condition and one for sign system costs. The *unsatisfactory signs summary value* (USSV) is defined as the number of unsatisfactory signs in the tenth simulation year, which can be considered a reasonable period to expect highway agencies to comply with the retroreflectivity requirements. This 10-year period also corresponds to the time between the 2005 NCSU/NCDOT field study and the FHWA's 2015 deadline for compliance. The FHWA has stated that conformance with the minimum retroreflectivity requirements "does not require that every individual sign meet or exceed the minimum retroreflectivity levels at all times" (Carlson and Picha 2009).

The *replacement cost summary value* (RCSV) is defined as the average number of *signs replaced* annually over the first 30 years of the simulation. The 30-year period was selected because nearly all of the Type III signs that were in place at the start of the simulation should have been replaced at least once within 30 years. Multiplying the RCSV by the replacement cost of a Type III sign gives an estimate of the average annual sign maintenance costs associated with a group of 1000 signs.

The RCSV does not incorporate the number of signs inspected because the replacement costs per sign considerably outweigh the inspection cost. For instance, the NCSU/NCDOT study (2006) found that the inspection cost per sign ($0.55) is approximately 0.5-1% of the cost of a newly installed Type III sign ($91.05). The same study found that a new Type I sheeting sign typically costs 80% of the value of a new Type III encapsulated lens sign, because the labor and post costs are the same. Because Type I signs are close in cost to Type III, the average number of signs replaced annually over the first 30 years can be used as a proxy for the management costs associated with a given simulation scenario.

10.2.3 Differences Between Sign Agencies

Ideally, the initial sign population in the simulation would be developed directly from an inventory of an agency's signs. It would then accurately portray that agency's in-service sign population. However, because many agencies lack a detailed sign inventory, the simulation model provides an option to use sign input distributions to generate and approximate the sign population for use in the simulation. The input distributions specify the initial sign colors and types, sheeting materials, ages, road types, and retroreflectivity for the sign population. Six input distributions meant to be representative of various sign owners and regions were selected to typify agency types used in previous studies (Black et al. 1992; Kilgour et al. 2007; Rasdorf et al. 2006) and used by the FHWA (FHWA 2007b). Two of the following input distributions are related to sign study work in North Carolina (numbers 1 and 2), and the other four distributions represent 95% of all public road miles in the United States.

1. NCDOT-owned, NCSU multi-division 2005 sign study area
2. NCDOT-owned, entire State of NC

3. State Agency-owned, urban and rural roads
4. County-owned, rural roads
5. Municipal and county-owned, urban roads
6. Town-owned, rural roads

The main differences between the six sign input distributions presented above are the percent of signs that are of a certain road type and the percent of signs with Type I versus Type III sheeting in the population. Table 10.1 gives a breakdown of each of the six sign populations by sign color, road type, sheeting type, and condition (failing the minimum retroreflectivity requirements). The *State* sign distribution along with the similar *NCSU/NCDOT* and *NC* distributions include some interstate signs while the rest of the distributions only have primary and secondary signs. Further, the signs in the *State* distribution are mostly Type III, but there is a majority of Type I signs in the other five distributions. Hence, the *State* distribution has the lowest percentage of signs that fail the minimum retroreflectivity standards initially. The *NCDOT/NCSU* distribution, which was derived from the field study data, has more deficient signs because these were the study's focus. Type III Prismatic sheeting and other sheeting types are not included in the input distributions because there is limited sign sheeting type distribution and retroreflectivity deterioration information for these sheetings.

Table 10.1. Sign Color, Road Type, Sheeting Type, and Condition by Agency Type

		Sign Color				Road Type			Sheeting Type		Condition
No.	Owner/Region	White (%)	Yellow (%)	Green (%)	Red (%)	I* (%)	P (%)	S (%)	Type I (%)	Type III (%)	% of Total Failing
1	NCSU/NCDOT	37.3	44.7	8.8	9.2	12.0	18.1	69.9	74.7	25.3	51.2
2	NC	42.5	41.3	7.5	8.7	2.6	32.0	65.4	75.3	24.7	38.7
3	State	48.7	31.9	11.7	7.7	8.3	71.9	19.8	13.4	86.6	5.4
4	County	35.0	48.0	6.7	10.3	0.0	28.0	72.0	58.6	41.4	32.8
5	City/Municipal	61.7	29.2	5.0	4.1	0.0	8.9	94.1	57.5	42.5	23.9
6	Town	42.8	46.3	1.9	9.0	0.0	2.4	97.6	57.9	42.1	31.2

* I = Interstate, P = Primary, S = Secondary

In the simulation, results from the six input distributions varied due to the differences in the contents of each sign population. Figure 10.1 illustrates the number of unsatisfactory signs (out of 1000 total signs) each year of the simulation for each of the six sign input distributions. The quantity of damaged signs at the bottom of Figure 10.1 is the same across all sign input distributions and all simulation years because the input parameters used result in the initial damage level persisting year to year. Subtracting these damaged signs from the total number of unsatisfactory signs yields the number of non-compliant signs, or in other words, the number of installed signs that do not meet the FHWA minimum retroreflectivity requirements. Because the *NCDOT/NCSU* input distribution had the highest percent of signs that were initially failing, it has the highest number of unsatisfactory signs in Figure 10.1. Similarly, the low percentage of failing signs in the *State* input distribution resulted in this distribution having the best overall condition.

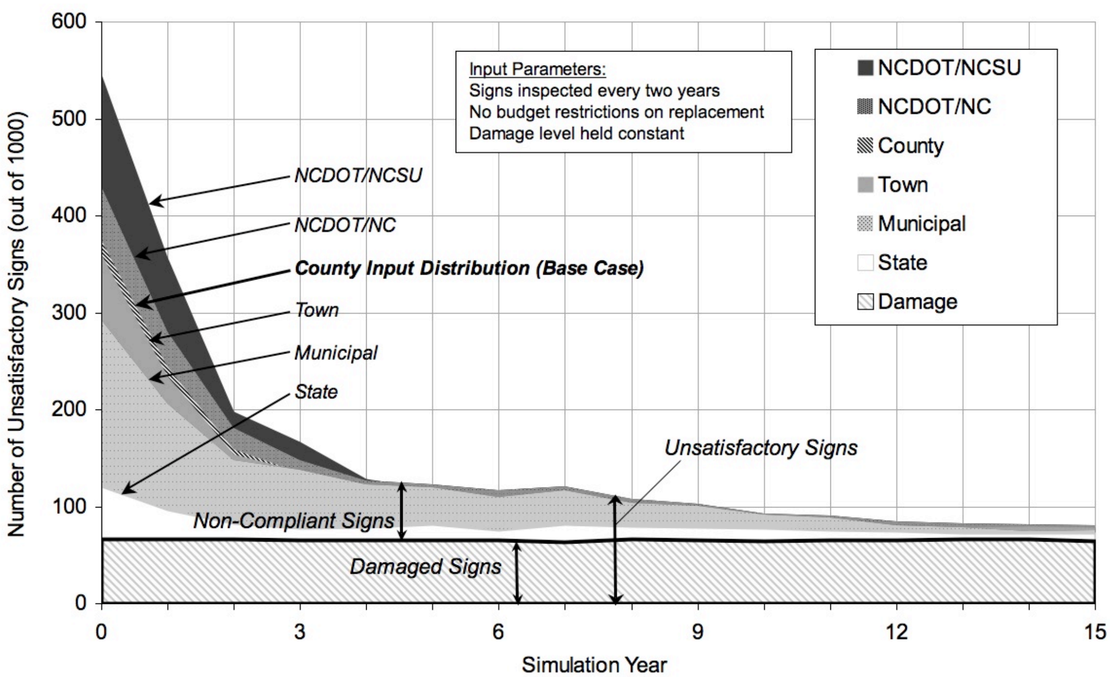


Figure 10.1. Sign Condition Versus Simulation Year for Six Simulation Input Distributions

10.2.4 Selection of Management Scenarios

The authors' selection of simulation scenarios focused on scenarios that represent the typical sign conditions and sign management practices that most influence sign performance and cost. Three major parts define a simulation scenario: input distribution, input parameters, and management method. For ease of comparison, most of the simulation scenarios used the same input distribution, the *County* input distribution, because it is in the middle range of condition performance in Figure 10.1 and represents 40% of all public road miles in the US, the highest proportion of the six selected agency types. Using the county input distribution, the authors created a *base case* scenario representing a typical sign system that is visually inspected at night every two years, has 4% annual and 7% overall damage, replaces most signs with Type III signs, and has no budget restrictions on replacement.

The input parameters control the simulated sign system's behavior in areas such as damage, inspection frequency, inspection accuracy, replacement, and available funding. Some of these parameters, including inspection frequency and replacement, represent management practices that can be directly controlled by the sign management agency. Many simulation scenarios were developed to test how changes in these controllable practices would influence the sign system. Most of the scenarios have inspection every two years, which is typical in the field and has been recommended by the FHWA (Carlson and Picha 2009). Input parameters that represent conditions and practices that an agency may have limited influence upon include damage, inspection accuracy, and available funding. For these 'uncertain' input parameters, the authors used a range of both typical and unrealistic input values in the selected scenarios to determine the variations that were the most critical and the boundaries of expected system performance. The goal was to develop a diverse scenario set that could be used to model how a typical sign system would perform if there were changes in key policies, financial resources, and regional conditions. Further detail about the specific input parameters used in the scenarios can be found in Harris et al. (2010) and in Chapter 9.0.

The scenario selection also aimed to include scenarios representative of the FHWA's recommended sign management methods, including the *nighttime visual inspection*, *expected sign life/control signs*, and *blanket replacement* methods. The *measured retroreflectivity* method was not included in the selected scenario set because many smaller agencies cannot afford their own retroreflectometer and the labor costs associated with solely using this method make it cost-prohibitive in most situations (Carlson and Picha 2009).

The scenarios developed also assume, realistically, that there is no sign inventory available for the sign system being modeled. Most of the scenarios in the selected set, including the *base case* scenario, represent the *nighttime visual inspection* method, which is the method used most often by agencies. Incorporating a variety of input distributions, input parameters, and management methods resulted in an analysis set of 176 simulation scenarios.

10.3 Analysis of Management Scenarios

The goal in setting up the simulation scenarios is to determine how various sign management practices affect sign system conditions and costs over time. The analysis focused on three management methods: nighttime visual inspection, blanket replacement, and expected sign life, and two key sign maintenance functions, sign damage and replacement. For each of these methods and functions the authors sought to establish which management practices result in improved sign conditions and financial savings. The base case scenario is included in each analysis to facilitate comparison between different management practice options.

10.3.1 Damage

Damage is a constant concern for sign maintenance managers. Sign damage is a major component of overall sign system condition that affects sign visibility and reduces safety. Reducing the number of damaged signs on an annual basis is challenging because it would require improvements in sign durability and changes in the community's behavior. The NCSU/NCDOT field study found that the cause of non-knockdown damage is split nearly equally between vandalism (intentional damage) and unintentional natural damage (Immaneni et al. 2007).

The authors ran several simulation scenarios to determine how changes in annual damage rate and replacement of damaged signs affect sign condition and sign replacement costs. The annual damage rates examined in the scenarios ranged from 2 to 8 percent. Lowering the damage rate reduced the number of damaged signs and consequently decreased the number of unsatisfactory signs (represented in the unsatisfactory signs summary value (USSV)). For scenarios where 100% of damaged signs are replaced each year, a 2% damage rate resulted in a USSV value of 44 unsatisfactory signs. After 10 years and a 6% annual damage rate the resulting USSV value was 75 unsatisfactory signs. An increase of 4% in annual damage rate (40 additional signs damaged per year) only resulted in 31 (75 - 44) additional unsatisfactory signs. The 4% increase in damage rate did not correspond to an equal increase in unsatisfactory signs because in scenarios where 100% of all damaged or newly damaged signs are replaced, increased sign damage leads to additional sign replacement. The unsatisfactory signs output measure only counts once for a sign that is both below the minimum retroreflectivity levels and is damaged. If a higher percentage of signs is damaged, a higher percentage of retroreflectivity non-compliant signs is damaged. Assuming that all damaged signs are replaced, the number of unsatisfactory signs is reduced because more of the non-compliant signs have been replaced.

While increasing damage rate does not correspond to an equal increase in unsatisfactory signs, an increase in damage rate *does* correspond to an equal increase in the number of signs *replaced* if *all* damaged or newly damaged signs are replaced each year. The additional signs replaced are equal to the additional signs damaged because of the increased damage rate. In scenarios where 100% of damaged signs are replaced each year, the RCSV for a 6% annual damage rate is 145 signs. The RCSV for a 2% annual damage rate is 108 signs. A 4%

increase in damage rate (from 2% to 6%, 40 more signs damaged) results in 37 more signs being replaced.

The percentage of damaged signs replaced each year varied in the simulation scenarios from 0 to 100%. The simulation assumed that damaged signs are replaced every year, regardless of the nighttime visual inspection schedule. If damaged signs were not replaced at all (0% replacement) the number of damaged signs and, consequently, the number of unsatisfactory signs, would grow each year. Table 10.2 illustrates how increasing the percentage of damaged signs replaced each year affected the USSV when the annual damage rate was 4% and the initial overall damage rate was 7%.

Table 10.2. Sign Condition Summary Values for Damaged Sign Replacement Percentages

Annual Damage Rate (%)	Damaged Sign Replacement Percent (%)	Number of Damaged Signs	USSV (Number of Signs)
4	0	380	398
	20	168	186
	40	94	113
	60	65	84 *(Base Case)*
	80	50	71
	100	40	59 *(Base Case with 100% damage replacement)*

Without any quantitative guidelines on 'acceptable' sign condition from the FHWA, this paper assumes that an *ideal maximum* USSV should be 100 signs out of 1000 total signs, which is 10% of the sign population. With an annual damage rate of 4%, the simulation scenario results indicate that approximately 50% or more of all damaged signs need to be replaced each year to have a USSV of 100 signs or less. As the annual damage rate is increased from 4%, the necessary damaged sign replacement percent would also have to increase to remain below the ideal maximum USSV. The *persistent damage* condition shown at the bottom of Figure 10.1 occurs if the number of damaged signs replaced each year is equal to the number of newly damaged signs each year. The base case scenario exhibits this persistent damage condition because approximately 7% of all signs in the field at any one time are damaged while 60% of these damaged signs are replaced each year, which is approximately equivalent to the 4% of signs newly damaged each year in the base case scenario.

The best way to quickly lower the number of damaged signs and the USSV is to replace more damaged signs than are newly damaged each year. Replacing more damaged signs than are newly damaged each year reduces the backlog of in-service damaged signs. Once the damaged signs backlog has been reduced to zero, this results in the total number of damaged signs in a given year being equal to the number of signs newly damaged that year. This situation occurs, for example, in the *base case with 100% damage replacement* scenario shown in Table 10.2. In this scenario there are 59 unsatisfactory signs in year 10, of which 19 signs are below the minimum retroreflectivity standards and 40 signs (4%) are damaged. So, the number of damaged signs (40) is equal to the number of newly damaged signs (4% of 1000 equals 40). With current technology, prompt replacement of damaged signs is the only way a highway agency can minimize the number of damaged signs on the roadways.

The simulation scenario results indicate that after the first few years of a sign management initiative involving sign replacement using Type III signs, damage is the greatest factor in the number of unsatisfactory signs and the USSV. Figure 10.1 shows that within four years the number of damaged signs makes up a larger share of the unsatisfactory signs than do non-compliant signs. The authors also observed this trend in *100% damage replacement* scenarios where all damaged signs, not just the newly damaged signs, are replaced each year.

10.3.2 Blanket Replacement and Expected Sign Life Methods

The blanket replacement and expected sign life methods are recommended by the FHWA as acceptable alternatives to the traditional nighttime visual sign inspection method. The blanket replacement method involves replacing *all* of the signs along a road corridor (or in a region) at a regular interval equal to the estimated minimum lifetime of the signs. The expected sign life method requires knowing the age of each sign and the expected lifetime of the different types of signs installed in the region. Each year *only* those signs that have an age equal to or greater than their expected lifetime are replaced.

From a simulation-modeling standpoint, the control signs method outlined by the FHWA is interchangeable with the expected sign life method because both require estimating sign life. The control signs method monitors a sample of installed signs to determine sign lifetime while the expected sign life method uses lifetimes generated from sign deterioration models. Hence, the simulation results for the expected sign life method should correspond to an equivalent application of the control signs management method as well. The authors ran several scenarios representative of the blanket replacement and expected sign life methods to investigate how differences in sign management method affect sign condition and sign replacement. These two methods are also compared to the base scenario, which uses the nighttime visual inspection management method.

10.3.2.1 Blanket Replacement

The regular replacement intervals for blanket replacement evaluated were every 7, 12, and 15 years. Seven years corresponds to the warranty period for Type I signs, and therefore, the minimum "official" expected lifetime of any of the signs in the simulation. Using the warranty period as a blanket replacement interval is a conservative approach; however, Ellison (2008) points out that "replacing signs at the end of their warranty period may result in discarding signs significantly before the end of their useful life." Therefore, the authors also chose to evaluate 12- and 15-year replacement intervals because the NCSU/NCDOT study estimated that Type III sign lifetimes could feasibly be 12-15 years or more.

The blanket replacement scenarios assume that no nighttime inspection is performed and that only annual daytime inspections are conducted to identify and replace all damaged signs. In the years when no blanket replacement takes place, signs are still replaced due to damage or they are replaced for other reasons, like changes in traffic control or sign size.

Figure 10.2 demonstrates how the number of unsatisfactory signs varies each simulation year for the blanket replacement, base case (60% damage replacement), and 100% damage replacement base case scenarios. The 12- and 15-year blanket replacement scenarios exhibit peaks in the number of unsatisfactory signs at 12- and 15-year intervals, respectively. The 7-year scenario does not exhibit any peaks, and the number of unsatisfactory signs remains equivalent to the number of signs damaged annually (indicated by the lower dashed line). The unsatisfactory signs values for the 12- and 15-year scenarios match the 7-year scenario's values except when a small peak develops immediately prior to the blanket replacement year. The 12-year scenario peaks at 48 unsatisfactory signs and the 15-year scenario peaks at 90 signs, which is less than the *ideal maximum* USSV.

Figure 10.2 also includes two visual inspection scenarios, the base case scenario and the base case scenario with 100% replacement of damaged signs each year. The blanket replacement scenarios are most similar to the base case with 100% damage replacement because the blanket replacement scenarios also assume 100% damage replacement annually. The regular (60% damage replacement) base case is shown in Figure 10.2 for comparison purposes, and the upper dotted line indicates the higher persistent damage level for the regular base case, which results in a greater number of unsatisfactory signs.

The unsatisfactory signs peaks on the 12-year blanket replacement scenario in Figure 10.2 (points A) are similar in magnitude to the long-term number of unsatisfactory signs in the base case scenario with 100% damage replacement. The 15-year blanket replacement scenario's peaks (points B in Figure 10.2) are about 15% greater than the long-term number of unsatisfactory signs in the regular base case scenario. For all of the scenarios shown in Figure 10.2, the long-term number of unsatisfactory signs is less than the *ideal maximum* USSV of 100 signs. Depending on an agency's tolerance for the number of non-compliant signs and the sheeting type composition of the sign population, a blanket replacement interval greater than 15 years (but probably less than 20 years) may be feasible from a sign condition perspective because the USSV would likely remain below the *ideal maximum* USSV.

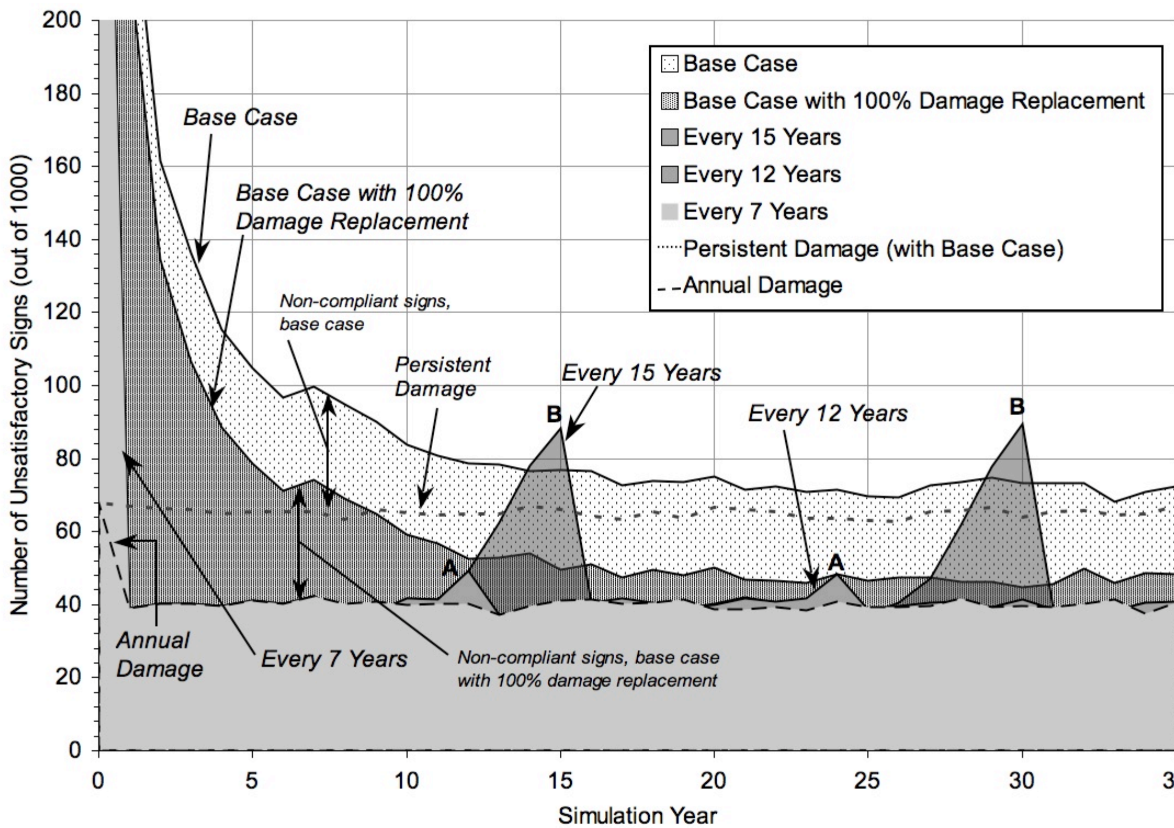


Figure 10.2. Sign Condition Comparison for Blanket Replacement and Base Case Scenarios

From a sign replacement cost perspective, the blanket replacement scenarios did not compare favorably with the visual inspection base case scenarios. Table 10.3 lists the RCSV (number of signs replaced annually, averaged over 30 years) for the three blanket replacement scenarios and the base case scenario with 60% and 100% damage replacement. The base case scenario with 100% replacement is expected to have a RCSV of 124 signs based on the simulation results, while all the blanket replacement scenarios have RCSV values that are greater. The 15-year blanket replacement RCSV value, 146 signs, is still 18% greater than the RCSV for the base case scenario with 100% damage replacement. What is even worse, in comparison to the base case scenarios, many compliant signs in the blanket replacement scenarios are replaced while they are still compliant with the retroreflectivity minimums. Unless the signs considered in the simulation study deteriorate at a faster rate than the simulation's models suggest, the blanket replacement scenarios have a higher replacement cost than the base case scenarios. Blanket replacement could become more cost-competitive with visual inspection if other costs, such as inspection costs associated with nighttime visual inspection, are taken into account.

Table 10.3. Replacement Cost Summary Values for Base Case, Blanket Replacement, and Expected Sign Life Scenarios

Scenario	Total RCSV (No. of Signs)
Base Case (Visual) 60% damage replacement	121
Base Case (Visual) with 100% Damage Replacement	124
Blanket Replacement Every 7 Years	238
Every 12 Years	176
Every 15 Years	146
Expected Sign Life	102
Expected Sign Life with 100% Damage Replacement	105

10.3.2.2 Expected Sign Life

The expected sign life method was approximated in the simulation by having annual "inspections" where the simulation rejects all deficient signs and replaces them with Type III signs immediately. Because the simulation was developed primarily to test the nighttime visual inspection method, it did not include the functionality to reject a sign based on its age, only its retroreflectivity. The goal of the approximated expected sign life scenarios was to provide some estimate of the sign condition and costs the expected sign life method would produce relative to the other sign management methods.

Modeling the expected sign life method in this way automatically reveals some replacement cost savings and sign condition improvements over the base case scenario because unnecessary replacements and non-compliant signs left in-service are eliminated. This expectation is reflected in Table 10.3 where the RCSV values for the expected sign life method are about 20-25 signs less than the base case RCSV values. The 20-25 signs difference corresponds to the signs in the base case that are rejected by inspectors but are actually compliant with the minimum retroreflectivity requirements. Both the expected sign life and base case RCSV values include approximately 85 signs replaced for sign damage and miscellaneous reasons, such as a change in traffic control. Not captured in the RCSV values for the expected sign life scenarios are the additional sign management costs for maintaining an up-to-date sign inventory and developing an accurate sign lifetime model. For instance, the sign retroreflectivity performance model may under or over-estimate the actual average sign lifetime in the region, and there is always some variation in sign lifetime for signs with similar sign color and type characteristics.

Because no non-compliant signs are left in place for the expected sign life scenarios they have a slightly lower number of unsatisfactory signs in the long-term when compared to the base case scenarios. For both the annual and persistent damage situations, the expected sign life scenarios in the first few simulation years have considerably fewer unsatisfactory signs than the base case because in the expected sign life scenarios the simulation replaces all non-compliant signs during the first year. For instance, the USSV for the persistent damage expected sign life scenario is 73 signs while the USSV for the base case is 84 signs. Similarly, the USSV for the annual (100% damage replacement) expected sign life scenario is 47 and the USSV for the base case with 100% damage replacement is 59 signs. The condition difference between the base case and expected sign life scenarios decreases by the fifteenth simulation year to only a 0-5% difference instead of the 10-20% difference observed in USSV (in the tenth year). Although the sign inventory costs were not included in our analysis, the expected sign life method appears to be a competitive alternative to the visual inspection method.

10.3.3 Nighttime Visual Inspection Method - Condition Assessment

The simulation models the nighttime visual inspection maintenance method using the consistent parameters procedure. This procedure requires a sign crew consisting of a driver, a trained inspector 60 years or older, a form for recordkeeping, and a sports utility vehicle or pickup truck. In the simulation scenarios, nighttime inspection is the primary method used to identify non-compliant signs (with low retroreflectivity), while damaged signs and any other signs needing attention are identified primarily during the daytime. Nighttime inspections occur at a frequency equal to one or more years and the frequency can vary by road type.

The simulation models inspection accuracy using a method derived from statistical hypothesis testing that considers two types of error (incorrect rejection and incorrect acceptance). Signs to be inspected are split into two groups based on whether their retroreflectivity value is currently above (compliant) or below (non-compliant) the minimum retroreflectivity standard. Within each group the inspectors fail (reject) a certain percentage of signs. The failure percentages can vary in the simulation for stop signs (which are more important and are probably treated more seriously by inspectors) versus all other sign types. Ideally the failure percentage would be zero for compliant signs and 100% for non-compliant signs. Inspection accuracy is more difficult to control than inspection frequency because inspection accuracy relies upon the training, ability, and consistency of inspectors.

10.3.3.1 Nighttime Inspection Frequency

In larger agencies, the inspection frequency can vary based on road type diversity, while smaller agencies, managing mostly secondary roads, likely have a more uniform inspection frequency. The simulation included one frequency set representative of a large agency where interstate highway signs are inspected annually, primary road signs are inspected every two years, and secondary road signs every three years. The remaining frequency sets inspected all signs, regardless of road type, at intervals of one, two, or four years.

Table 10.4 lists two sets of simulation scenarios – those that maintain a constant inspector accuracy while varying inspection frequency (4 scenarios, A = accuracy) and those that maintain a constant inspection frequency while varying inspector accuracy (7 scenarios, F = frequency). The table also lists the unsatisfactory signs summary value and replacement cost summary value for each scenario. The decision to inspect signs every year (scenario #1A) or every other year (base case scenario) does not considerably change the USSV. The USSV is actually less for the base case scenario than scenario #1A due to random variations in simulation output values. During most simulation years, scenario #1A has fewer unsatisfactory signs than the base case, but after 20-25 years their number of unsatisfactory signs were close in value.

With constant inspector accuracy, the scenario with the next lowest USSV was scenario #123A, in which inspection frequency varies by road type. Scenario #4A, inspecting signs every 4 years, resulted in the greatest USSV value with constant inspector accuracy, however after 20 simulation years the number of unsatisfactory signs is similar for all of the constant inspector accuracy scenarios shown in Table 10.4.

Table 10.4. Summary Values Comparison for Various Inspection Frequencies and Accuracies

Scenario No.	Inspection Frequency (years)			Inspection Accuracy (Percent Failing Inspection)				Summary Values	
				Above Std.		Below Std.			
	Interstate Roads	Primary Roads	Secondary Roads	Stop	All Others	Stop	All Others	USSV (Signs)	RCSV (Signs)
Constant Inspector Accuracy									
Base Case	2	2	2	5	5	80	80	84	121
1A	1	1	1	5	5	80	80	86	130
4A	4	4	4	5	5	80	80	104	109
123A	1	2	3	5	5	80	80	91	115
Constant Inspector Frequency									
1F	2	2	2	5.9	3.5	71.4	27.7	136	112
2F	2	2	2	3.9	3.9	28.8	28.8	143	112
3F	2	2	2	0	0	100	100	84	106
4F	2	2	2	5	5	40	40	117	117
5F	2	2	2	5	5	60	60	95	120
6F	2	2	2	5	5	90	90	81	122
7F	2	2	2	18	28	70	81	72	207

Although the difference in condition is negligible between signs inspected annually (scenario #1A) versus every two years (base case), the RCSV for annual inspections is 7% greater than the RCSV for inspections every other year (130 vs. 121). In general, more frequent inspections lead to a greater number of replaced signs, and therefore, higher system costs. Frequent nighttime inspections also increase the labor cost of nighttime inspections. In some agencies, the labor costs for nighttime inspection are paid from a different budget item than sign replacements, which can create a situation where signs may be inspected, but there are insufficient funds to replace all deficient signs before the end of the fiscal year.

10.3.3.2 Inspection Accuracy

Excellent inspection accuracy can help to improve sign system condition and reduce costs as the constant inspector frequency portion of Table 10.4 shows (lower 7 scenarios). Scenario #3F has "perfect" inspection accuracy because all non-compliant signs and compliant signs are correctly identified. However, scenario #3F in Table 10.4 demonstrates that even with "perfect" inspection accuracy, the sign system cannot reach a USSV of zero because the USSV cannot be less than the number of signs damaged annually in a persistent damage condition. The lowest USSV value in Table 10.4 belongs to scenario #7F, which represents a situation where a greater number of signs above the standard are incorrectly rejected than in the base case scenario or scenario #3F. These incorrect rejections lead to more signs being replaced than are actually necessary.

The highest USSV values correspond to the two scenarios, #1F and #2F, where less than 30% of the signs below the minimums are rejected, resulting in an approximately 70% incorrect acceptance rate. Incorrect acceptances do save on replacement costs, but ultimately result in a decline in sign condition, with USSVs (signs unsatisfactory in the tenth year) higher than the minimum ideal of 100 signs. After 15-20 simulation years, there is less of a difference in the number of unsatisfactory signs in the Table 10.4 scenarios, probably due to most deficient signs being replaced by longer-lasting Type III signs. Improvements in inspection accuracy directly result in a reduction in the RCSV and therefore, sign system costs. Scenario #3F, with "perfect" inspection accuracy has the same USSV as the base case scenario but its RCSV is smaller by 15 signs. Scenario #7F may have the lowest USSV value, but its RCSV value is two times greater than that for scenario #3F because the inspection accuracy in scenario #7F includes a high incorrect rejection rate. Scenario #3F not only has a "perfect" inspection accuracy but is also the least expensive of the seven constant inspector frequency scenarios.

10.3.4 Replacement

In the simulation, sign replacement is divided into two main categories: *rejected replacement* and *not rejected replacement*. Each of these two categories can be separately controlled and examined for their effect on sign condition and sign replacement costs.

Rejected replacement involves the replacement of signs rejected during inspection years. Ideally, all rejected signs would be replaced during the inspection year; however, many agencies need to spread out replacements over several fiscal years because there are insufficient funds to replace all rejected signs promptly. Many agencies devise a priority scheme where more critical rejected signs, including stop and yield signs, are replaced before other signs. Thus, varying the percent of rejected signs replaced in the simulation scenarios was logical. As the percent of rejected signs replaced approaches 100%, sign condition improves and the USSV decreases. Reducing the percent of rejected signs replaced is an ineffective way of reducing costs because, while an agency may realize a 5% savings in the RCSV, there is a 20-30% increase in the USSV due to more non-compliant signs being in service.

Not rejected replacement includes all signs replaced in any simulation year (inspection or non-inspection) that were not found to be damaged or non-compliant by inspectors. In the 2005 NCSU/NCDOT study it was observed that approximately 9% of all not-rejected signs were replaced, often due to the need to upgrade all signs on a post to the same sheeting type. The base case scenario assumes that the *not rejected replacement* is equal to 5% of all not-rejected signs each year, an average of 44 signs per year and 36% of the RCSV (which was a total of 121 signs). Reducing the not rejected replacement rate from 5% to 0% reduced the RCSV 30-40%, a major cost savings. Replacing more signs, as is the case with the 5% rate, did improve USSV by 10-15% because more replacements lead to more new, higher retroreflectivity signs in service. When the not rejected replacement rate was lowered to 0%, the USSV rose from 84 signs to 96 signs, which is still less than the ideal minimum USSV threshold. Thus, it is best to minimize the percent of not rejected signs replaced.

10.3.4.1 Sheeting Type Conversion Rates

The sheeting type conversion rates determine the percentage of Type I and III sheeting signs marked for replacement that are replaced with Type III signs. The base case scenario assumed that 100% of Type III and about 90% of Type I signs were replaced with Type III signs. In scenarios where all signs were replaced with Type III signs, USSV improved slightly over the base case and sign cost (RCSV) remained constant, assuming only a small difference in cost between Type I and Type III signs. When half of all signs to be replaced were replaced with Type I and the other half with Type III, the USSV was 193 signs as compared to 80 signs when 100% of signs were replaced with Type III.

This large increase in USSV and corresponding decrease in sign condition is due to the shorter lifetime of Type I signs. The shorter lifetime of Type I signs also resulted in the half-and-half scenario requiring more signs to be replaced because there were more non-compliant signs. The RCSV for the half-and-half scenario is 157 signs as compared to the 121 signs for the base case and 120 signs when all are replaced with Type III. Thus, replacing all signs with Type III sheeting signs improves condition without raising long-term system costs.

10.3.4.2 Effects of Skipping Maintenance

For various reasons, agencies may occasionally skip performing key sign maintenance functions, including inspection and maintenance for a year or more. This study considered several scenarios where inspection and/or replacement are skipped in a given year to determine the resulting effect on system conditions and cost. All of these scenarios assumed that inspections were performed at an interval of every two years and that replacements were limited to the amount budgeted for sign replacement. The budget limitation was introduced to model situations where an agency would not have additional funds available in the year(s) after a skipped function to quickly catch-up on deferred maintenance. In the scenarios where the skip takes place in an inspection year, the skip happens in the third simulation year and when the skip is in a non-inspection year, the skip happens in the fourth simulation year. The skips were placed within the first 10 years of the simulation because maintenance practices during these early years are more critical in determining the long-term condition and replacement needs for the system. The base case scenario assumes that all required replacements are made and that there are no budget restrictions.

When inspection and/or replacement were skipped the system condition worsened for a period of time and the replacement costs briefly decreased (but remained similar to not skipping scenarios in the long term). Table 10.5 illustrates sign condition over time for four different skipping scenarios: skipping inspection, skipping replacement in an inspection year, skipping replacement in a non-inspection year, and skipping both inspection and replacement in an inspection year.

Each of the skipping scenarios shown in Table 10.5 restricted the sign budget to 121 signs each year (in a population of 1000 signs), which is equal to the RCSV of the base case scenario. Compared to the base case scenario, all of the skipping scenarios exhibited an increase in the number of unsatisfactory signs after the skip year (shaded in the table) and a gradual decrease over approximately 6 inspection cycles (12 years) until the skipping scenarios “catch up” with the base case scenario.

The skip that has the least negative impact on condition in these scenarios is the skipping inspection scenario, because it still allows for some replacements, including replacements for damaged and not-rejected signs. The skipping inspection year replacement and skipping both inspection and replacement scenarios create the worst condition of the skipping scenarios tested because no signs are replaced during the skipped year. Skipping replacement in a non-inspection year falls in between the other scenarios.

The RCSVs for the skipping scenarios shown in Table 10.5 are only about 5% less than the RCSV of the base case scenario, indicating that skips have little effect on long-term sign system costs. Varying the budgeted amount for sign replacements after a skip from the expected RCSV without a skip to an unlimited budget does not considerably affect the long-term RCSV value; it only affects how quickly the worsened sign condition returns to the expected non-skip condition. If there are no replacement budget limits, the signs that were not replaced during the skipped year can simply be replaced during the following year's replacement initiative.

Table 10.5. Unsatisfactory Signs Each Simulation Year When Inspection and/or Replacement is Skipped One Year

Scenario	Year Skipped	RCSV (Signs)	Number of Unsatisfactory Signs in Simulation Year															
			0	1	2	3	4	5	6	7	8	9	10 USSV	11	12	13	14	15
Skip Inspection & Replacement	Year 3 (Inspection Year)	115	376	243	162	217	200	171	153	137	128	114	**105**	91	87	82	81	78
Skip Replacement		116	376	243	162	216	192	167	155	141	136	116	**108**	91	89	83	81	77
Skip Inspection		117	376	243	162	173	179	155	137	126	120	104	**98**	88	84	80	78	78
Skip Replacement	Year 4 (No Insp.)	116	376	243	162	136	187	161	147	135	130	111	**104**	90	88	82	82	79
Base Case	No skip	121	376	243	162	136	115	105	97	100	95	90	**84**	81	79	78	77	77

10.3.4.3 Budget Restrictions

The base case scenario assumes all signs designated for replacement are actually replaced each year and that there are no budget restrictions. However, most agencies have a limited sign replacement budget that is often insufficient to cover all replacement needs in a given year. In some agencies the sign replacement budget is divided by road type, so there may be, for example, sufficient funds to replace interstate signs but not enough funds to replace secondary road signs. The simulation models budget restrictions by limiting the number of signs replaced each year to a constant value; it does not enable different specifications for different road types. Once the replacement budget has been reached, no additional signs are replaced that simulation year.

Table 10.6 provides the number of signs replaced each simulation year for the base case and five different budget-restricted scenarios. The base case scenario replaces 23% of the sign system's total signs (230 signs) during the first simulation year and nearly 20% during the second simulation year. Replacing 23% of a sign population in one year is most likely not within the annual budget of most agencies. Three of the budget restriction scenarios shown in Table 10.6 are possible alternatives to the base case and have a budget set to be higher than or equal to the base case RCSV. Lowering the budget to 121, 127 or 161 signs per year only reduced the RCSV by less than 5% from the base case because the 30-year period considered by the RCSV tends to even out the greater initial replacements of the base case.

In Table 10.6, the shaded cells represent the years when the number of signs replaced in the budget-restricted scenarios does not match the base case scenario. The greater the sign budget, the sooner the number of signs replaced each year matches up with the base case scenario replacements.

Table 10.6. Signs Replaced Each Simulation Year for Various Replacement Budgets

Scenario		USSV (Signs)	RCSV (Signs)	Number of Signs Replaced in Simulation Year														
				1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
5% Not Rejected Replaced	Base Case	84	121	230	196	138	139	119	128	111	124	114	123	107	119	105	118	105
	Budget = 161 Signs	84	120	161	161	161	160	131	135	114	125	113	124	107	118	107	117	105
	Budget = 127 Signs	113	116	127	127	127	127	127	127	127	127	127	127	120	123	105	118	104
	Budget = 121 Signs	142	115	121	121	121	121	121	121	121	121	121	121	121	121	118	119	109
	Budget = 92 Signs	287	92	92	92	92	92	92	92	92	92	92	92	92	92	92	92	92
0% *Not Rejected Replaced*, Budget = 121 Signs		94	79	121	121	121	121	114	101	75	85	72	84	67	79	63	75	61

Sign condition does worsen with budget restrictions as compared to the base case, but the worsened condition is temporary. The scenario with a budget of 161 signs has the same USSV (84 signs) as the base case scenario. The 127 and 121 sign budget scenarios have USSVs of 113 and 142 signs, respectively, but after 12-15 simulation years these two scenarios have a similar number of unsatisfactory signs as the base case. Although the 121 sign budget scenario and the base case have the same RCSV, the USSVs differ because the base case scenario was able to replace the majority of the unsatisfactory signs in the first 5 simulation years.

The replacement costs were considerably less for the 92 sign budget scenario shown in Table 10.6, but its condition was inferior to the other budget scenarios. Because this scenario restricts sign replacements to a level below the base case scenario, it was never able to replace enough signs to lower the number of unsatisfactory signs below the ideal maximum USSV. The USSV for the 92 sign budget scenario is 287 signs, while the USSV for the base case scenario is only 84 signs. Even after 50 simulation years the 92 sign budget scenario has more than 170 unsatisfactory signs.

The budget replacement scenarios illustrate that the sign replacement budget should not be set so low that the sign system is unable to reach an acceptable sign condition. If a sign budget must be cut, savings are more likely to be found by reducing *not rejected replacements* instead of deferring replacement of rejected and damaged signs. Table 10.6 includes a budget scenario wherein the budget is set to the base case RCSV of 121 signs but the not rejected sign replacement rate is set to zero instead of the 5% used in the base case. By reducing the not rejected sign replacement rate to zero, the RCSV drops 35% to 79 signs and USSV increases by 12% to 94 signs.

10.4 Conclusions

The simulation scenario analysis provides quantitative insight on the impact of various sign management practices on sign system costs and conditions. The analysis found that sign damage is a major component of sign condition, and sign managers should consider the replacement of damaged signs in annual budgets. The improvement in sign sheeting materials is such that retroreflectivity is less and less a factor. The key factors are sign damage and replacement policies.

The *blanket replacement* method is probably not as cost-effective as the *nighttime visual inspection* method, but the *expected sign life* method showed promise as an alternative to the visual method. For the nighttime visual inspection method, selecting an initial inspection frequency of every two years resulted in lower costs and similar conditions when compared to inspecting every year. Training inspectors to be as accurate as possible when judging retroreflectivity can realize further savings.

The analysis also found that replacement decisions could have the largest impacts on costs and conditions. Replacing all signs with Type III signs and only replacing deficient signs are two ways to improve the condition of the sign population while lowering replacement costs long-term. Skipping inspection or replacement one year or not having an adequate sign budget may save costs in the short term but can lead to poor long-term sign conditions if the backlog of deficient signs is not addressed.

Based on the findings from the simulation scenarios analysis, the authors offer five *best practices* that agencies can consider when making their sign management decisions:

1. Install only Type III (High Intensity) or better ground-mounted signs.
2. Keep a record of the installation date of each sign (month and year or just year).
3. Prioritize replacement of the most important signs, from a safety perspective (ex. stop signs).
4. Use annual (or even more frequent) daytime inspections to find all sign damage and other obvious (non retroreflectivity-based) sign issues.
5. Begin with a formal nighttime visual inspection of the entire system (if it has never been done before) to determine replacement needs and document the retroreflective condition of the sign system.

In addition to these *best practices*, agencies that have the necessary financial and personnel resources should consider creating and maintaining a sign inventory so that they have the possibility of using the expected sign life method to better target their sign condition assessments and replacement efforts.

10.5 Recommendations

Additional functionality and data can be added to the sign system simulation developed in this study to improve its utility. Adding an age-based rejection capability, in addition to the existing retroreflectivity-based rejection module, would allow the simulation to better model expected sign life method scenarios. Further simulation scenario analysis can focus on the condition and cost tradeoffs associated with varying inspection frequency by sign priority and pairing the expected sign life method with budget restrictions. Additional longer-term data on sign system condition, inspection, and replacement practices could be used to improve the simulation's validation period and scope. Further research and detailed data about sign retroreflectivity deterioration, sign population characteristics, and the costs related to various inspection types and inventory maintenance would improve the accuracy of the simulation condition and cost predictions.

11.0 CONCLUSIONS

The conclusions portion of this thesis is split into five sections, with each section corresponding to the conclusions found in the studies described in the previous chapters. These studies included the sign experimental facility, sign deterioration models, simulation model development, verification and validation of the simulation, and, most importantly, the key findings from the simulation analysis.

11.1 Sign Experimental Facility

An ESRMF enables an agency to measure how signs deteriorate over time in a controlled environment that mimics field conditions. The controlled environment limits the effects of vandalism and damage on signs and results in less variability in both deterioration data and models. Better deterioration models can help agencies determine when signs in the field will deteriorate without having to initiate programs to field measure sign retroreflectivity at regular intervals.

The deterioration models developed from the ESRMF could be used to calculate sign lifetimes that could be used in both the expected sign life or blanket replacement management methods proposed by the FHWA. The ESRMF could also be used to implement the control sign maintenance method suggested by the FHWA where ESRMF signs can be chosen to represent similar signs in the field. When the retroreflectivity of the test signs in the ESRMF falls below the minimum, similar signs in the field should be replaced.

An ESRMF can assist agencies in determining sign sheeting selection policies, or in other words, which sign sheetings to use for different applications. Currently, there is a particularly significant need for long-term performance data on the newer sign sheetings, beyond the short-term performance data from the NTPEP. If an agency knows how a sign sheeting type deteriorates over time relative to its cost, life-cycle cost analysis can be used to determine the most cost-effective sheeting applications. Thus, ESRMF facilities can yield important individual sign year-to-year retroreflectivity deterioration data that are not available in any other cost-effective way.

11.2 Sign Deterioration Models

The purpose of the study was to identify or determine the best sign deterioration prediction curves for Type I and III white, yellow, red, and green signs. To determine the final deterioration curves, the NCSU research team conducted a comprehensive study of available previously published research papers and reports related to sign retroreflectivity deterioration. Earlier study data was re-analyzed to try to discover the optimal function form (for each sign color and type) to predict sign deterioration rates. The NCSU research team also gathered its own sample of retroreflectivity measurements from over 1000 signs across North Carolina. From these efforts, a set of the best available sign deterioration models was developed. These models can be used with some confidence by those interested in modeling sign performance, but there is certainly room for future improvement in prediction and precision.

Type III signs were found to have much higher retroreflectivity values than Type I signs for the samples examined in this study, which are almost all less than 15 years old. This allows a couple of observations to be made. First, if highway agencies replace their Type I signs with Type III signs, retroreflectivity values will significantly increase and essentially remove retroreflectivity as a concern for many years while simultaneously lowering life-cycle costs. Second, there is a weak basis for predicting how signs will perform after 15 years or so in the field. For this study the research team assumed that Type III signs will last as long or longer than Type I signs, but there is no empirical evidence to support that assumption at this point. Quite simply, these signs have not been in place long enough to provide adequate data to work with.

The research found that R^2 values were usually less than ideal for the trend lines between age and retroreflectivity. Almost all of the R^2 values from the NCSU data or from the literature were less than 0.5, and many were less than 0.1. This likely means that may be other factors besides age influence the rate at which signs deteriorate. These factors include measurement method error, retroreflectometer error, and uncontrolled field conditions which lead to damage and weathering. Although the effect of each individual factor may be low, as the literature suggests, the factors collectively cause the scatter in the data. When the author re-analyzed the NCSU data including NCDOT division as a factor that could account for some location and management differences, significant performance variations from division to division were found.

11.3 Simulation Model Development

The authors developed an original microscopic simulation model of the entire sign asset management process to gain a more detailed understanding of the many factors that influence sign performance and of the level of compliance highway agencies can expect to have with the FHWA minimum retroreflectivity requirements. Simulation was chosen to model the sign system because it was an inexpensive way to examine the effects of various management decisions on the performance of the system without having to change the actual sign system in the field. Simulation was also needed to handle the complex behaviors (such as sign deterioration and inspection and interactions) within the sign system. A microscopic simulation model, where each sign can move independently through the simulation (i.e., is treated as an individual), yields a more realistic model of how signs progress through their life cycle because it permits sign characteristics to change independently and enables variability in how signs travel through the simulation steps. Microscopic simulation also allows one to remove many assumptions present in forecasting and macroscopic simulation models that do not represent real-world behavior.

One of the most noteworthy outcomes of developing the simulation model was revealing the intricacies and dependencies involved in sign management itself. Dividing the sign management process into a flowchart with connected sub-models revealed how the information contained in the field study data set corresponded to specific transportation agency sign management practices. The data were then analyzed to determine the best modeling options for each of the sub-models. The path that each sign takes through the sub-models (thus through the overall model) is determined by the many Arena modules that consider a sign's individual characteristics and route it to the proper location based on the input parameter values. For example, the inspection function was split into a sign damage detection sub-model and a sign retroreflectivity inspection sub-model to better model how these two different sign conditions are managed and behave. A dependency that was revealed was that the replacement of previously rejected signs in a non-inspection year relied upon how many signs were replaced during the previous inspection year.

Creating each sub-model presented several challenges. There was limited previous work to base the sub-models on with the exception of sign deterioration, for which there were some resources and models in the literature. However, the stochastic nature of the simulation required that the sign deterioration sub-model not be a basic linear regression model but instead represent the well-scattered distribution of sign retroreflectivity versus age. The most challenging sub-model to create was the non-inspection year replacement sub-model because there were insufficient data from the field study to build the model upon. Because this sub-model had to be mostly based on observations from the 2006 data collection and discussions with sign inspectors, it contains the most assumptions as a result. Still, because the behavior of each sub-model in the simulation is independent, any one sub-model can be improved as further knowledge of its behavior and characteristics become better understood.

The flexibility in the sub-model and Arena module simulation structure enables the simulation presented here to be capable of evaluating scenarios representative of most typical agency management situations. It is straightforward to go into each module's settings and change them, or change the input parameter values that the modules utilize, to direct the signs through the simulation. Simulation does not work in random order; rather, changes are sequenced and occur based on field-measured and observed sign performance. For example, it is known that signs are lost to damage, and the damage rate for signs in NC is known from the NCDOT/NCSU sign study data. The damage rate value initially entered into the simulation can be changed if warranted to enable another state's use of the simulation. In the case of damage rate, if another state experienced a different damage rate than NC that state's damage rate would be used instead.

In summary, the author found that microscopic simulation was well suited to this application. The simulation was successfully built and validated and it can be used by others seeking to further this work. The simulation runs fast, is flexible, and the outputs are logical and make sense. Also, input parameters are critical components of the simulation. If values of parameters are unknown, default values can be used. If field measurements are taken or field studies are conducted to more firmly establish local conditions, these can be used as inputs to fine tune the model. Finally, a key result of this work was the formalization of all the elements of the sign modeling process. No such process articulation had previously been documented. Thus, a framework for understanding the sign asset management process has been created and a simulation model exists to analyze it. Sign asset management is well suited to microscopic simulation.

11.4 Verification and Validation

The author applied the validation scenario to the already verified simulation model and ran the validation scenario to determine the simulated sign system conditions in the year 2006. A set of key performance measures was defined to compare the estimated (simulation) and actual (field-observed) values. The validation simulation was run for 30 replications, allowing each simulated key performance measure to be estimated within an error of ± 5%, which the authors considered to be acceptable. The validation model begins with the actual sign conditions in 2005 and proceeds to damage, inspect, replace, and deteriorate each sign individually to their conditions in 2006. These simulated 2006 sign system results were compared to the actual, field-observed 2006 sign system results and were found to be similar enough to meet the acceptability criteria. For example, the actual number of signs replaced from 2005-2006 was 193, while the mean simulated value was 200, resulting in an acceptable percent difference of 3.6%. Such validation with field data provides confidence in the simulation model's ability to represent the real-world sign system.

11.5 Simulation Results

The simulation scenario analysis provides quantitative insight on the impact of various sign management practices on sign system costs and conditions. The analysis found that sign damage is a major component of sign condition, and sign managers should consider the replacement of damaged signs in annual budgets. The improvement in sign sheeting materials is such that retroreflectivity is less and less a factor. The key factors are sign damage and replacement policies.

The *blanket replacement* method is probably not as cost-effective as the *nighttime visual inspection* method, but the *expected sign life* method showed promise as an alternative to the visual method. For the nighttime visual inspection method, selecting an initial inspection frequency of every two years resulted in lower costs and similar conditions when compared to inspecting every year. Training inspectors to be as accurate as possible when judging retroreflectivity can realize further savings.

The analysis also found that replacement decisions have the largest impacts on costs and conditions. Replacing all signs with Type III signs and only replacing deficient signs are two ways to improve the condition of the sign population while lowering replacement costs long-term. Skipping inspection or replacement one year or not having an adequate sign budget may save costs in the short term but can lead to poor long-term sign conditions if the backlog of deficient signs is not addressed. Agencies that have the necessary financial and personnel resources should consider creating and maintaining a sign inventory or sign installation year labeling system so that they have the possibility of using the *expected sign life* method to better target their sign condition assessments and replacement efforts.

12.0 RECOMMENDATIONS

The primary objective of this dissertation research was to improve traffic sign management and maintenance, and in turn, road safety. This objective was achieved by research focused upon improving knowledge about sign retroreflectivity deterioration, building a microscopic traffic sign management model and simulation, and using the simulation to evaluate which traffic sign management practices will enable agencies to maintain a high level of safety on the road in a cost-effective manner.

This recommendations chapter contains four sections corresponding to recommendations from the sign experimental facility, sign deterioration model, sign simulation model development, and sign management practices studies.

12.1 Sign Experimental Facility

The authors recommend that ESRMFs be built in at least each of the major climatic regions in the United States to best determine how signs in the area deteriorate over time. The facilities could be located in New England, Florida or Georgia, the Rockies, the arid Southwest, the Pacific coast, and the plains of the northern and southern Midwest. ESRMFs built using the design outlined in this thesis or a variation thereof can be used, along with a sign inventory program, to ensure compliance with the FHWA minimum retroreflectivity standards on a national scale. The data collected by each ESRMF should be made available to all agencies nationwide. Federal funding could be made available for both ESRMFs and the sharing of ESRMF data.

12.2 Sign Deterioration Models

Future researchers should collect more Type III sign data (high intensity encapsulated lens and prismatic) as the data that were collected in this study and that reported by numerous other studies was primarily for Type I engineering grade signs. The weakest selected model, i.e., the least amount of reliable available data, was for Type III encapsulated lens white signs. Additional studies should also collect more data on old Type III signs (older than 15 years) in order to derive a more accurate deterioration curve for the critical latter stages of sign life.

A key limitation of all existing studies is the wide data scatter and short duration of data collection. Essentially only snapshots in time are available rather than systematic multi-year studies. As a result, AASHTO should consider conducting research for more than 3 years in its NTPEP program to provide researchers with a more comprehensive data set. Or, the ESRMFs discussed in the previous section could be used to provide additional sign deterioration data. If signs were evaluated over a longer time period, then more well-founded deterioration rates would be available for study and analysis that would benefit the Departments of Transportation across the country, especially as they attempt to develop strategies to meet the minimum retroreflectivity standard. The availability of longer term data would also provide researchers with the opportunity to explore other deterioration modeling approaches such as survival analysis.

Future studies should be conducted to consider natural field conditions, i.e., without cleaning signs. The studies should measure the uncleaned retroreflectivity of signs, clean the signs, and then measured the cleaned retroreflectivity. Cleaning will give a higher retroreflectivity but it does not represent the signs that drivers see at night. Drivers see signs in their natural state and hence, cleaning a sign will not give a true representation of the actual field condition. Finally, future research must consider not only age, but also other factors that affect sign deterioration.

12.3 Simulation Model Development

Because the microscopic simulation results are controlled by the input parameters, the input parameter values selected need to be based upon the best information available, either through field data collection, agency records, or literature values. Gathering the data required to determine the simulation input parameter values with confidence and customizing, verifying, and validating the model requires extensive time and financial resources that many agencies may not possess. However, the microscopic simulation can serve as a fine research tool for learning more about which management practices influence performance and cost. To achieve this a hybrid simulation model could be developed that has reduced input data needs and focuses on the critical practices controlling sign performance and agency costs.

The microscopic simulation model developed in this paper could be improved by comparing the results of a change in sign management policy in the real world to the predicted results from the simulation model. The results of a change in sign policy in the field could be compared to the outcome predicted by the simulation model, further validating the model. Collecting longer-term data on sign systems would also help strengthen the simulation model, especially by providing more information about how non-inspection year replacements are managed in the field.

The sub-models could also be improved to further utilize the capabilities of microscopic simulation if further research was done into the real-world variability of the processes that the sub-models attempt to mimic. For example, more performance and system data about daytime inspections would improve the inspection and replacement sub-models. Incorporating more detailed sign system data from other highway agencies would also strengthen the simulation model by increasing the scope of the simulation's applicability.

Additional functionality and data can be added to the sign system simulation developed in this study to improve its utility. Adding an age-based rejection capability, in addition to the existing retroreflectivity-based rejection module, would allow the simulation to better model *expected sign life* method scenarios. Further simulation scenario analysis can focus on the condition and cost tradeoffs associated with varying inspection frequency by sign priority and pairing the *expected sign life* method with budget restrictions. Additional longer-term data on sign system condition, inspection, and replacement practices could be used to improve the simulation's validation period and scope. Further research and detailed data about sign retroreflectivity deterioration, sign population characteristics, and the costs related to various inspection types and inventory maintenance would improve the accuracy of the simulation condition and cost predictions.

12.4 Best Sign Management Practices

Based on the findings from the simulation scenarios analysis, the authors offer five *best practices* that agencies can consider when making their sign management decisions:

1. Install only Type III (High Intensity) or better ground-mounted signs. Prismatic sheetings are preferable.
2. Keep a record of the installation date of each sign (month and year or just year). This record can be kept in a sign inventory database or each sign could have a large, highly-legible label containing the installation year on the back face of the sign.
3. Prioritize replacement of the most important signs, from a safety perspective (ex. stop signs).
4. Use annual (or even more frequent) daytime inspections to find all sign damage and other obvious (non retroreflectivity-based) sign issues, such as color fading. Be aware that some damage may only affect the nighttime visibility of the sign.
5. Begin with a formal nighttime visual inspection of the entire system (if it has never been done before) to determine replacement needs and document the retroreflective condition of the sign system.

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14.0 APPENDIX

APPENDIX

Contents

14.1 Appendix A: Information Technology Issues for the Management of High Quantity, Low Cost Assets

ABSTRACT

Transportation infrastructure asset management efforts have historically focused on collecting data on assets with high capital costs, such as bridges and pavements. Road signs and pavement markings, on the other hand, are high quantity, low capital cost assets but are also critical elements of the transportation infrastructure. These high quantity assets serve a critical function, safety, and thus they are receiving attention. Mandated by law, the Federal Highway Administration (FHWA) has been working to establish minimum retroreflectivity standards for signs and pavement markings.

This paper seeks to address the information technology (IT) problems that emerge when developing an overall asset management system for high quantity, low cost assets. These IT problems include asset identification, asset location, data availability, data fragmentation, and automated data collection. A discussion of the issues related to these problems is presented herein to promote awareness of the myriad problems that do exist and to facilitate the development of more comprehensive systems to manage the automation of infrastructure asset management systems.

OUTLINE

IT Issues for the Management of High Quantity, Low Cost Assets

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INTRODUCTION

Maintaining aging transportation infrastructure concurrently with transportation budget constraints has resulted in a need for new tools to manage transportation assets. These tools include inventory, condition, and performance databases and models for predicting budget needs, maintenance, and asset performance among others. All of these databases and tools rely heavily on automated sensors and information technology (IT) to streamline the gathering, analysis, and interchange of transportation asset data.

The first major applications of IT to asset management focused on high capital cost assets (Markow, 2007). Some were low quantity, high capital cost assets such as construction equipment, bridges, and traffic signals (for state jurisdictions). These assets have a high unit capital cost, but only exist in limited locations within a transportation agency's jurisdiction. The other major high cost asset, pavements, exists throughout the transportation system, resulting in pavements being both a high quantity and a high cost asset. Of course, IT has been applied to numerous applications. Adams, for example, addressed enterprise-wide data integration for oversize or overweight truck permitting (Adams et al. 2002). In doing so they identified a number of problems associated with data resources to support their application need.

Once management systems were developed using IT for high capital cost assets, the focus began to shift towards low capital cost, high quantity assets that had previously not been considered. Examples of high quantity, low cost assets include guardrails, roadway lighting, pavement markings, and signs, as shown in Figure 1 (clockwise from upper left). In NC, there are over one million road signs (Kirtley and Rasdorf, 2001) with an average replacement cost of $65 each and 78,000 miles of road with pavement markings whose average replacement cost is 35¢ per foot (Sitzabee, 2006).

Figure 1. Guardrail, Lighting, Pavement Marking, and Sign Assets (clockwise from top left)

These high quantity assets are often as critical to the functionality of the transportation system as many of the low quantity assets. On the network level, an asset management system for high quantity, low capital cost assets can enable state transportation agencies to direct budget resources towards the maintenance of assets that are in the poorest condition, are among the most critical to motorist safety, and have the lowest per unit lifecycle costs. For economic savings, state agencies with a very high quantity of certain low cost assets may choose not to keep individual asset data in an inventory at the network level, but instead they may aggregate assets into groups with similar attributes or they may aggregate all assets along a road segment. However, disaggregate, individual asset data is needed to more accurately estimate budgetary needs at the local or project level, where the installation and maintenance responsibility for high quantity, low cost assets typically resides. This paper will focus on asset management issues at the project/local level for these assets, where data can more easily be stored in a disaggregate form, facilitating asset management decisions and analysis at the individual asset level.

IT Elements in Asset Management

Information technology is critical to asset management because IT enables raw and formatted asset data to be processed, stored, and utilized in an asset management system. For high quantity, low cost assets, the most common IT capabilities focus on (Markow, 2007):

- Inventory (quantity and location)
- Current asset condition and age
- Photographic documentation
- Inspection and maintenance data
- Tracking of public comments

Figure 2 proposes how IT interactions could function in an advanced management system for a high quantity, low cost asset or group of assets. In this model, the major data sources are field data collection, automated sensors, and existing data. The existing data is comprised of legacy, historical, and other data. The term "legacy data" is only used to refer to data stored in legacy formats while "historical data" refers to any asset data collected prior to the implementation of the current asset management system.

The three major data sources populate either the inventory and/or the condition assessment databases. The most common and basic asset management systems focus on inventory and condition assessment capabilities alone, while more advanced or mature systems include performance modeling and asset management decision analysis tools.

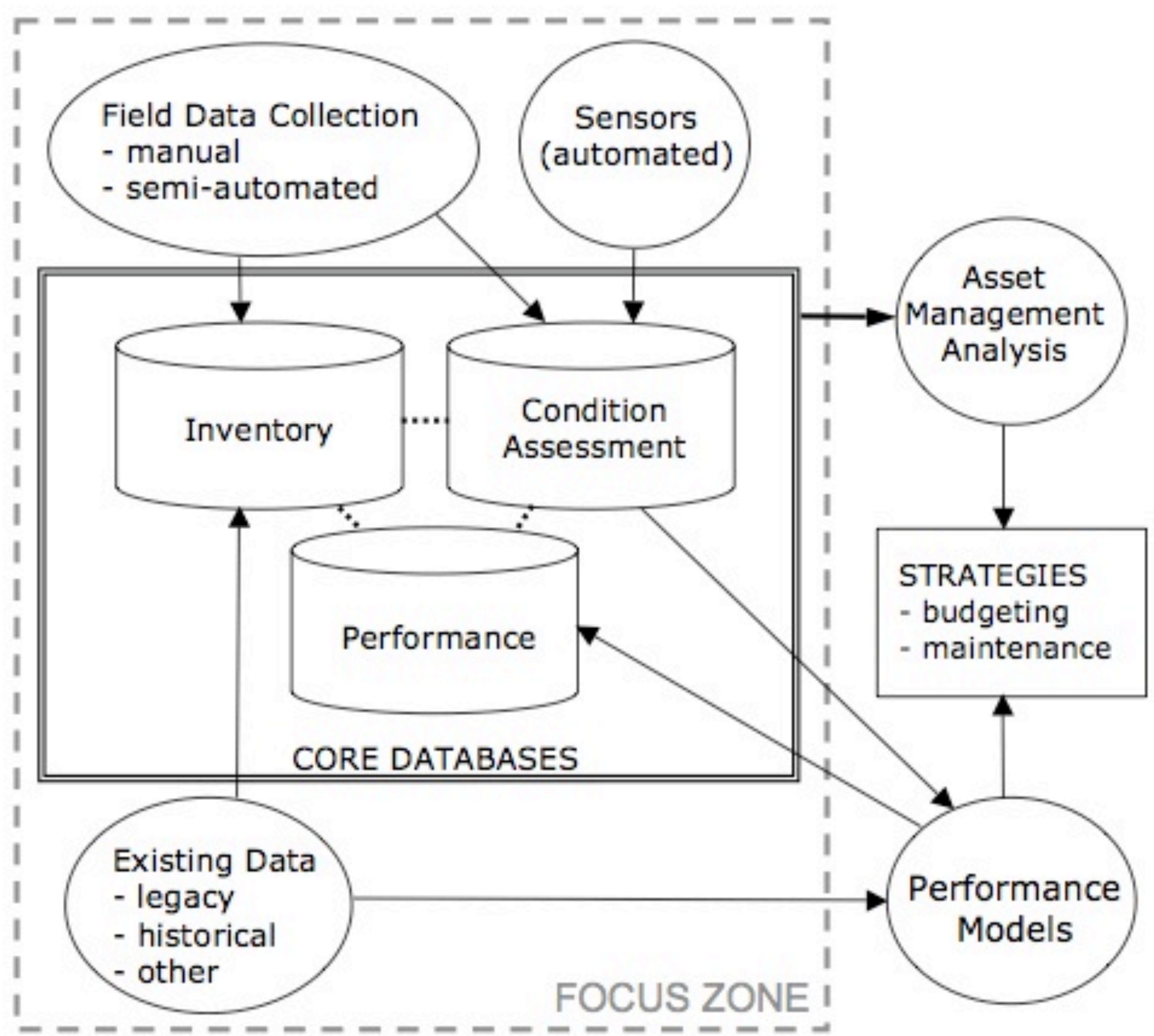

Figure 2. IT Interactions Model in an Advanced High Quantity, Low Cost Asset Management System

The proposed IT interactions model shown in Figure 2 can be categorized as an advanced asset management system because a performance modeling capability is included. Data from recent condition assessments as well as asset attributes from historical data are analyzed by the performance model, which populates the performance database with predicted service life for each asset served by the system. All three of the core databases are relational databases, allowing for complex queries to be generated and input to the asset management component of the system.

The asset management analysis component of Figure 2 evaluates the benefit-cost trade-offs between different management methods and, along with the performance model, generates a set of financial and maintenance management strategies for the asset(s). Reliable data and effective decision-support tools can reduce the costs for asset maintenance, repair, and renewal and lead to timely service with fewer disruptions (Vanier, 2001). This paper will focus on IT interactions within the "focus zone" shown in Figure 2.

Core Databases

The quality and breadth of the data within the core databases (contained within the solid double line of Figure 2) is largely determined by the data sources used to populate the databases. Manual and semi-automated (collected using some automated data collection techniques) field data collection typically contributes to the inventory and condition assessment databases. The condition assessment database can also draw data from automated sensors that report condition information such as temperature, deflection, or stress. Existing data from historical asset management efforts can be used to populate the inventory database if these data are relevant to the desired system IT capabilities. Additionally, the organizational and procedural framework used to collect the existing data can be applied to current field data collection efforts (Markow, 2007).

The inventory database serves as the primary repository of all attribute and positional data for each individual asset. Attribute data consists of the key characteristics of the asset (e.g., age, size, material) and positional data provides information on the location of the asset in space (Rasdorf, 2003; Karimi et al. 2000). By having a separate record for each asset, the quantity of assets matching certain criteria can be easily determined by the system. Photo records of each asset as well as any related installation or replacement cost data can be included in the inventory.

Because each asset in the inventory is given a unique numerical or positional identifier, a relational database management system could be used to perform queries requesting information from any combination of the three core databases. For example, the *Inventory* database would contain information about asset installation dates and the *Condition Assessment* database would contain asset condition data. The relational database system could perform a query that would match asset installation dates and condition data using each asset's unique identifier. Assuming that there is a relationship between asset age and asset condition, the results of this query could be passed to the *Performance Models* module where they would be analyzed to determine the asset age/condition relationship. The developed performance model could then be used to predict when each asset would reach the end of its service life, and the predicted service lives for each asset would be stored in the *Performance* core database.

In addition to the unique identifier, the condition assessment database can include current condition data, information on the specific instrument(s) used to collect the condition data, inspection and maintenance reports, and public comments about asset conditions. Using the data from the condition assessment database and any applicable existing historical data source, the performance model determines the remaining service life for each asset and records this information back into the performance database. IT capabilities for the system need to focus on the concept that the databases themselves are assets to be managed (WERD, 2003).

Asset Management Capability Maturity

Markow (2007) has described how an agency's level of asset management development can range from an initial level, *Basic Infrastructure Management,* to *Growing Application of Asset Management* and to the most mature level, *State-of-the-Art Asset Management*. State-of-the-art, or mature IT asset management capabilities for high quantity, low cost assets can include the following features typically found in pavement, equipment, and bridge management systems (Markow, 2007):

- Benefit-cost and life-cycle cost analysis
- Integrated platform for internal and possibly external access to information
- Accurate asset data collected regularly according to a predetermined schedule
- Mix of data collection technologies used to collect high-quality data cost-effectively
- Customer perceptions of assets regularly updated though surveys or complaint tracking
- Movement from asset-specific management systems to broad-based management systems

The proposed IT asset management model shown in Figure 2 represents a moderately mature system because it includes predicted asset service life and interconnected relational databases. Efforts to apply features of mature asset management systems to high quantity, low cost assets have been hindered by several IT implementation problems. The main focus of this paper is to articulate these issues though an examination of current high quantity, low cost asset management practices and recommend strategies to mitigate these issues.

IT Implementation Problems

For low capital cost assets, several IT problems arise related to collecting, managing, and analyzing asset data. These include:

- Asset identification
- Asset location
- Data availability
- Data fragmentation
- Unsuccessful data collection automation

Asset identification requires (1) assigning a unique identifier to each low value asset and (2) having this number accessible both in an asset management database and in the field at the asset's location. The location of the asset also needs to be included in the transportation infrastructure asset management system's core databases. The location information can be recorded and included in the database using Global Positioning System (GPS) coordinates, a linear referencing system (LRS), or through other means. Spatial technologies are particularly appropriate for integrating highway asset databases with highway geographic and geometric data. In a typical roadway LRS, each roadway is given a unique route number and the distance along the route from a specific point of origin (usually a state or county boundary) is used to locate points along the route. The distance units are usually marked with signs placed along the route (mileposts) to determine the position of either linear features (such as a guardrail segment) or data collection points in the field (Flintsch et. al., 2004).

In addition to an asset's identification number and location, an asset database will include attributes such as installation date, material or component characteristics, and asset condition. These attributes are critical to determining which assets require maintenance, but they are often unavailable. Asset condition information is also needed to determine compliance with minimum performance standards. Recently, the FHWA has included minimum sign retroreflectivity standards in the *Manual on Uniform Traffic Control Devices* (FHWA 2007) and is developing similar minimum standards for pavement markings (Schertz 2002).

The fragmentation of existing data often results from transportation agencies and their private contractors using different data collection standards over time with the net result being that data are stored in dissimilar formats. Automated data collection for low value assets generally involves mobile units that can collect identification, location, and attribute data for hundreds or thousands of assets in a single day. Problems in automated data collection arise in calibrating the mobile unit or other automated data collection equipment, integration of the instruments and hardware in the unit, and integrating the collected data into the asset management system. The following sections expand upon each of these problems and discuss their IT implications.

ASSET IDENTIFICATION

A key IT problem for low capital cost, high quantity assets is asset identification during data collection and analysis. Identification system technology is critical for IT implementations. In current practice, identification takes on several forms, often depending on whether the asset is a point or continuous (linear) asset.

For point assets, the simplest labeling method is to write or attach the asset's identifier directly onto the asset. Figure 3 illustrates two methods used to label sign installation dates. In a project conducted for the North Carolina Department of Transportation (NCDOT), the authors used a permanent marker to write an identification number on each road sign that was included in a study of sign replacement and deterioration (Rasdorf et. al. 2006). Such an identifier is shown in the lower right of Figure 3. The lower left illustrates the use of a preprinted label.

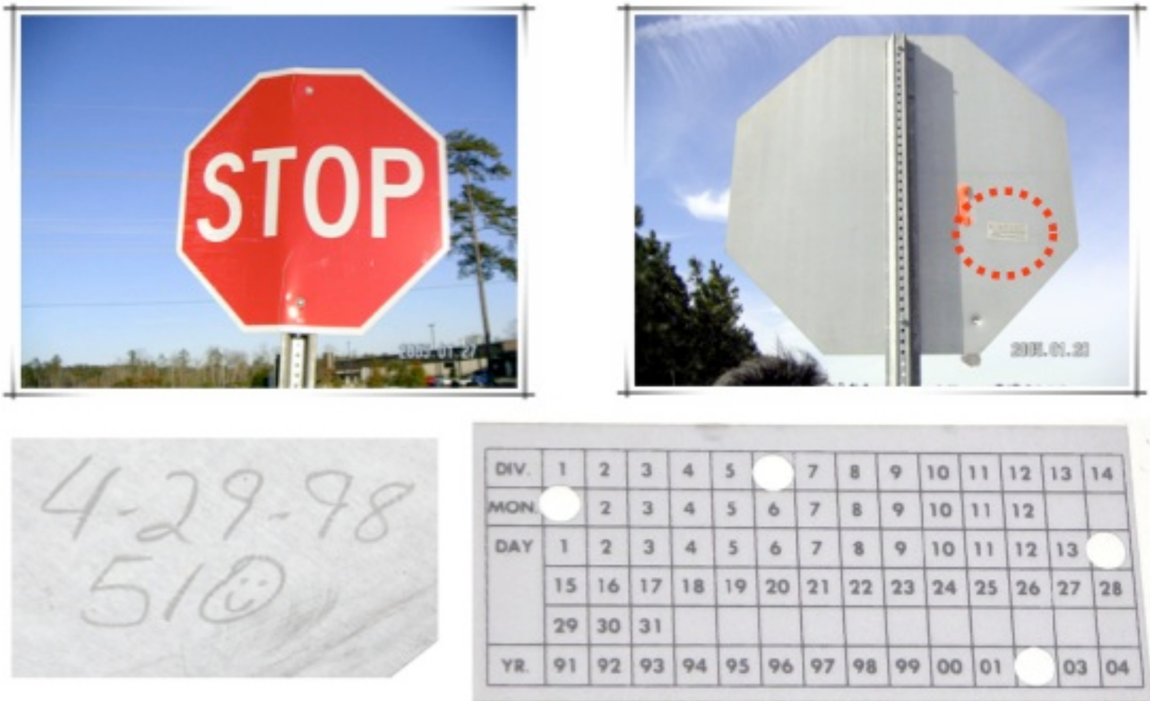

Figure 3. Sample Current Traffic Sign Installation Date Labeling Methods

Continuous assets are those that are linear in nature and which are usually measured in length-based units. Guardrails, for example, may be assessed by foot whereas pavement markings may be assessed by mile. Other assets can be dual identified. Signs, for example, can be identified by a physical identification label as well as by spatial location identification.

Several asset identification issues surface from examination of current practice. The most important issue is that without an identifier, an asset cannot be linked to its attributes in a database. Most often, these assets in the field are not labeled, making it impossible to ensure that the asset is consistently identified over time. For point-specific high quantity data, labeling each asset in the field with an identifier can be a daunting task when millions of low cost assets need labeling. Physically labeling an asset using a sticker or marking can be problematic if the marking fades over time. Furthermore, these basic labels are not machine-readable, which limits complete data collection automation. This is the critical aspect of identification that most severely and negatively impacts the development of an asset management system. Some continuous assets, such as pavement markings, are very difficult to label at all due to their location and linear characteristics. Such assets cannot have an identifier, so they are instead identified by location as a linear feature. Linear features further complicate identification because not all linear features use a common distance unit or linear reference system.

Data identification issues can be addressed through a consistent point and linear asset labeling system and through technologies that facilitate inventory automation. To speed data collection, an asset's identifier can be encoded into a barcode label placed so that field technicians can quickly read it using an electronic data collection device with a barcode reader. However, without a human-readable numeric identifier on the asset, agency staff without a barcode reader would be unable to identify it.

Technologies such as radio frequency identification (RFID) tags could also be used to obtain asset identifiers without the need to approach each asset. RFID is a wireless automatic identification technology that allows for contactless exchange of data between a passive RFID transponder tag and a reader (Dziadak et al. 2007). Signals from RFID tags can be read from a data collection vehicle traveling at or near highway speeds. RFID tags could facilitate an inventory but would not support condition assessment unless the RFID tag was modified to possess sensing features.

ASSET LOCATION

The challenge of identifying assets without an identification label has been met in current practice by referencing assets primarily to their spatial location. For example, within the NCDOT network, location referencing is the primary method used to link asset databases

(Sitzabee et al. 2008). Some jurisdictions have created GIS databases of their road signs by locating assets using GPS. In the authors' prior work with the NCDOT, GPS coordinates for each sign, as well as the road on which the sign was located, were used to represent the asset's location. When the research team returned a year later to re-measure signs, the GPS coordinates, although imprecise, did help the team feel confident that they had identified the same sign (Rasdorf et. al. 2006).

The case of pavement markings in NC is illustrative. A look at the organization of NCDOT's pavement markings data revealed a significant problem with the data collection. The NCDOT pavement marking retroreflectivity data were collected using a localized linear referencing system (LRS) invented by the data collection contractor. The contractor's LRS did not conform to either the state or county milepost LRS system. Furthermore, the NCDOT's contract with the data collection contractor did not prescribe that pavement marking retroreflectivity data be collected using a particular location referencing method. The system used by the contractor is a blended system that uses route identification with the start and end points identified with a milepost, intersection, or offset (Sitzabee, 2006). In some cases the pavement marking retroreflectivity data were recorded with a common name format to identify the start and end point of a data collection run. For example, location data were recorded as beginning at the "Jackson East city limit" and ending at the "Conway West city limit." The common name had to be matched to the route information in order to locate the segment's position. Through this manual, labor-intensive, and costly process that does not support automation and IT, the links could be established to locate each segment. Thus, because of the unique LRS used, the localized referencing system precludes the integration of pavement marking retroreflectivity data with the existing NCDOT database structure.

High quantity, low cost asset location issues are centered on nonexistent, inconsistent and/or imprecise asset location data. A lack of asset location information can arise both in existing data as well as during the data collection process. Existing data may have been collected without location information, or the location information is in a non-standard format that is difficult to incorporate into a database that can be read by a geographic information system (GIS). This problem is acute for low capital cost, high quantity assets because they are often not located at an intersection or other easily recognizable place on a map.

Even if an asset has a GIS-readable location, imprecise location measurement can hinder the ability to distinguish between nearby assets. Generally, as location precision increases, the cost of data collection increases as well. Currently, basic GPS devices can measure with a resolution of ± 30 ft. and more expensive GPS units with differential correction can achieve a resolution of ± 10 ft. Odometers used for determining LRS position have an accuracy of a hundredth of a mile (53 ft). A LRS can also develop errors due to the approximation of the three-dimensional Earth by two-dimensional representations such as maps and GIS (Cai et al. 2006, Rasdorf et al. 2003). This is due to elevation changes causing field-measured distances to be greater than their scaled distances on a map. Errors in GPS coordinates due to satellite geometry and environmental interference can make it difficult to distinguish between two adjacent assets and to determine which side of the road an asset is located on in a GIS application. All these issues can mean that the gigabytes of data collected over many years is worthless – a catastrophic, but altogether too frequent, occurrence.

Because of the spatial aspect of a transportation system, location referencing is a key component to defining asset relationships both in the field and in asset management databases. Ideally, transportation agencies should include not only legal and cost details in their contracts with data collection contractors, but clear technical specifications on what data to collect, how to collect data, how to identify assets, and how to specify asset location with the goal of integrating the data with existing systems. These contracts are a critical part of IT and are essential for developing and maintaining a viable asset management system.

More specifically, for road signs, lighting, and other assets located at a single point, GPS is preferred to a Linear Referencing System (LRS) because GPS coordinates locate a single point in space and are easily imported into a GIS. However, an LRS can work with GIS if used properly and consistently. Integrating GPS data with data collected and stored using a LRS can sometimes be difficult and usually requires significant processing (Flintsch et al. 2004). Due to the precision differences between different location measurement methods, it is important that the devices and specifications used to collect the data are known, are documented, and are dated. If there are any changes in precision over time it is critical that the instrument precision be stored as well as the instrument measurements.

DATA AVAILABILITY

Asset data can be unavailable for several reasons. Data may never have been collected, may have been collected but lost, may be inaccessible, or may be missing. Some historical data may exist but may not be readily available. An agency might know that they once collected the data, but the physical location of the data is unknown. Data can also be inaccessible because the hardware and software that was used to create the data are in some form that is no longer usable (such as obsolete or older versions) or because an agency or company is hesitant to share proprietary data.

Missing Data

Some high quantity, low cost asset databases currently contain missing or partially filled data fields. In NC for example, there are no pavement marking retroreflectivity (condition) data available beyond five years ago and much of the data for the last five years has gaps and missing attributes not to mention the LRS problems identified above (Sitzabee 2006). In many cases the non-available data were recorded with a value of zero. This practice makes the assumption that the value is actually zero and not missing.

Missing fields for a particular asset make it difficult to fully analyze all assets in the asset management system. They can result in the need for additional data collection to obtain the missing information. If the asset is no longer in service, the data can be permanently lost, reducing the effectives of the asset management system. Statistical software counts a zero as a value, which skews the analysis. Unavailable data recorded as a zero requires an extensive effort to clean the database and replace all zeros with null values. The authors suggest that in all areas where data are unavailable, cells should contain a null value so statistical software can deal with the missing data appropriately.

Lack of Data

Presently in many U.S. transportation agencies, inventory and expenditure data on high quantity, low cost assets are simply not kept at the individual item level (Markow, 2007). This is not an area of asset management that is rich in historical data. Unavailable data are a very common problem for low capital cost, high quantity assets. The lack of available data has caused researchers and practitioners to use surrogate replacement measures such as utilizing sign or pavement marking retroreflectivity data from studies conducted in other states. Agencies can either initiate their own data collection program or use existing data already collected by others.

Since the problems related to initiating a data collection effort have already been discussed, this section will focus on the issues associated with using existing data. The key problem with using existing data, as mentioned earlier, is related to standardization. That is, the data that have been collected for one agency will not quite be the data desired by another agency. There will be something different about them that may render them useless for the desired application. However if that turns out not to be the case, the data can be effectively used. Another problem is that many agencies have no central repository for valuable data. That means that a great deal of data collected at the state level is not conveniently stored and thus, is not available for sharing and for general use. Inventories for high quantity, low cost assets are usually incomplete, are organized so others cannot use them, or are out of date.

The authors recommend that agencies identify desired data and determine if the desired data do not currently exist in the organization. Two options are then available: initiate a data collection effort or use the existing data from others. If no historical data is available, an agency needs to design a field data collection program. The program may require equipment (such as vehicles), instruments, hardware and software, labor, and funding.

DATA FRAGMENTATION

If asset data exist, they are often fragmented due to agencies using different and incompatible data collection standards over time and the data being stored in dissimilar formats. During a data collection program, the attributes collected over time can change, creating a database with columns missing depending on when the data were collected. An inconsistent column set can make it impossible to compare changes in asset attributes over time, thus reducing the utility of an asset management system.

Decentralized Control of Asset Data

Current attempts to create agency-wide asset databases have been hindered by different units of the same agency using different column sets and units. For example, in NC there are three organizational units that perform pavement marking inspections and data collection. They are the Work Zone Traffic Control Unit (WZTCU), the State Maintenance Unit, and the individual divisions (field offices). Serving different purposes, each player performs a different kind of inspection on pavement markings and collects a different set of pavement marking data.

The WZTCU is charged with setting standards and specification for pavement markings and they are the lead unit responsible for implementing the legislative standards that will eventually require minimum retroreflectivity levels for pavement markings. As such, the WZTCU collects pavement marking retroreflectivity data using both manual and an contracted automated mobile collection device.

The State Maintenance Unit collects pavement marking data through the Maintenance Condition Assessment Program (MCAP). These data are used to provide a statewide condition of roadside appurtenances. The State Maintenance Unit conducts a manual assessment of a sample of roads. The MCAP is conducted biennially.

The current division level procedures for inspection of existing pavement markings is typically a windshield inspection that assesses the asset in terms of “present, visible, and reflective at night.” The most common recordkeeping methodology is a hardcopy map of the road system. For instance, Division 6 highlights each road using a color system to reflect when it was inspected and when it was remarked. As a result of the different data collection needs of these units, pavement markings data are fragmented in NC. If an agency determines that a centralized asset database would best serve asset management needs, collaboration between each organizational unit that manages that asset is necessary to determine how data should be collected, stored, and accessed.

Inconsistent Data Formats

As mentioned in the data availability section, agencies often use existing data to populate “new” high quantity, low cost asset management databases. In developing their new asset management system, the Tennessee DOT is incorporating digital data going back to the 1970s as well as archived paper forms (Haas and Hensing 2005). Sitzabee (2006) found that existing data on the number of times a pavement marking was snowplowed had multiple entries recorded in a single cell. For example, a cell for a road segment for one year will be recorded as [(2)(3)(3)(5)] instead of [13]. This fragmentation inhibited the use of the snowplowing data.

Data fragmentation issues stem from the different formats and software applications agencies have used to store and manage asset data. Data from earlier years in paper format or in a digital data storage format takes considerable time and money to transfer into a database that can run efficiently on current hardware and software platforms. Even asset data collected in more recent years can be fragmented due to varying digital formats and storage media. This is an ongoing problem.

Proprietary software continues to play a role in IT data fragmentation problems. Proprietary software generally is obtained from a data collection vendor. However, it is seldom the case that such software is long lasting. Additionally, such vendors seldom maintain a level of market share necessary to support the long term maintenance, development, and enhancement of proprietary data collection and storage software and thus, using such software carries a real risk. That risk is magnified through the use of freeware that is not supported by a large open source community.

The authors suggest that data format issues be addressed by accompanying data with a data dictionary (metadata) that identifies each field in the database and provides a complete and clear definition of the data collection logic. The metadata should include an explanation of all units used in the dataset and data need to be recorded with a single value per cell. To cope with evolving software and file formats, agencies should develop a regular schedule to convert existing data to new formats.

DATA COLLECTION AUTOMATION CHALLENGES

Automated data collection often seeks to record data values for the asset's attributes and condition as well as to be able to identify it. Automation is the only way to quickly measure all low capital cost, high quantity assets owned by an agency.

Currently, several automated data collection systems have been developed to both collect inventory and condition assessment data for low cost, high quantity assets. The FHWA constructed for a cost of $210,000 a Sign Management and Retroreflectivity Tracking System (SMARTS) van that automated sign inventory and sign condition data collection (Smith and Fletcher 2001). Some roadway data collection vehicles with a large complement of hardware and software have cost over one million dollars. A study of the performance of the SMARTS van, as compared to a $7,000 handheld retroreflectometer, found its retroreflectivity readings to be unacceptable due to the high variation in measured retroreflectivity values, a low percentage of signs captured by the van on a single pass, and little correlation between the van retroreflectivity readings and the more accurate handheld retroreflectometer such as that shown in Figure 4 (Smith and Fletcher 2001). Images of the SMARTS van and a handheld Retrosign® 4500 retroreflectometer are shown in Figure 4.

Figure 4. Sign Retroreflectivity Measurement: FHWA SMARTS Van and Handheld Retroreflectometer

However, other automated data collection systems have had more success. The mobile pavement marking retroreflectivity measurement vehicle used by NCDOT has accurately measured pavement markings over the last five years for the NCDOT (Sitzabee, et al. 2008). Nonetheless, other pavement marking applications have not been as successful. Washington State performed a pavement marking research project using mobile collection. In this study the variance in the data was so large the research results were inconclusive (Kopf, 2004).

The main challenges for automated data collection systems for high quantity, low cost assets are repeatable condition assessment and the high cost of automation. Automation tends to be very expensive because mobile units containing integrated instruments, video recorders, and computer hardware need to be either purchased or leased. Previous automated data collection efforts have been able to successfully collect asset inventories, but the SMARTS van and Washington State study struggled to collect valid condition assessment data.

Asset Condition Assessment

Another key element of asset management is the inspection of assets. The primary purpose of asset inspection is to determine asset condition, that is, the status of an asset with respect to some performance standard. Personnel can inspect assets or they can be inspected in an automated manner. If humans do the work, the inspection may either be conducted with instruments or visually. These are typically the most commonly used methods. The primary result of an inspection effort is data. Thus, asset inspection also falls under the category of data collection.

In the case of signs and pavement markings, for example, one of the key requirements is to meet a minimum level of retroreflectivity. In January 2008 a federal standard for minimum sign retroreflectivity was released, and a pavement marking retroreflectivity standard is under development. To determine whether or not the standard's criteria are met requires the collection of retroreflectivity data. However, a larger need for the state DOTs is to determine a strategy for meeting the minimum requirement if it is not currently being done. To develop strategies requires a lot more information than only retroreflectivity measurement values.

The main IT issue for condition assessment is agencies neglecting to determine precisely their condition assessment needs. That is, what data really should be collected? Too often an unstudied approach is taken to determining the answer to this question. The result is that the collected data may either contain unneeded information or it may neglect some information that was needed and is highly desirable. In fact, it is often the case that the missing data are critical and their omission can negate the entire purpose of the data collection effort in the first place.

The authors recommend that the most important thing a state agency must do is determine the need for the data it intends to collect (i.e. the ultimate goal for the data). Most often it is the case that the data collected should meet a software application need. In some cases this goes beyond a specific application, and agencies need to consider how this data will be integrated into the overall asset management system. A careful study of the entire scope of the problem is necessary before data collection efforts are undertaken.

Instrumentation Issues

The instruments used in automated data collection often have the ability to collect asset condition data at a very fine level of detail, but also at a very high cost. In the case of high quantity, low cost asset data collection, agencies have run into data storage and processing problems, as well as higher data collection costs if the automated data collection device collects data that is not needed (WERD, 2003).

Presently, asset condition information, especially in the case of linear assets such as pavement markings and guardrails, is averaged over fixed segment lengths to increase efficiency and minimize data collection costs. This averaging can introduce errors because asset conditions in the field that occur over segments that are of different lengths may not be well represented in an asset database. Data collection of linear assets often lends itself to cumulative errors. In some cases automated collection is performed over many miles where a small error per mile can accumulate into a significant error for the entire collection run.

Another problem in data collection automation is that the data collection instruments mounted on these vehicles may be poorly calibrated or the instruments may be damaged. For example, mobile pavement marking retroreflectivity measurement units are subject to errors from variations in the roadway and the vehicle's suspension (Sitzabee 2006).

Instrumentation issues can be managed through agency awareness of calibration errors, aggregation tradeoffs, and integration needs. Calibrating instruments after they are set up and before each daily data collection pass using a handheld retroreflectometer can reduce errors. Data collectors need to consider calibrating their runs by implementing periodic anchor points. Efficiency in automated data collection can be increased by collecting data on multiple types of assets in a single pass (Haas and Hensing 2005). The agency also has to balance cost concerns and data needs when deciding how often to collect data using automation. Data collection automation also requires complex integration among the various hardware and software components included in the mobile unit and the database and asset management software used to analyze and store the data in the overall IT system.

FIELD DATA COLLECTION PROBLEMS

Current field data collection efforts need to consider weather, operating conditions, scheduling, safety, and terrain to be successful. These issues are described briefly in the paragraphs below so that the reader gains an awareness of the impact of seemingly remote issues that can arise when attempting to acquire data in support of an asset management system. In Figure 2, field data collection efforts using sensors are represented by the *Sensors* data source.

For example, data collection often cannot occur during a rain or snow event. Additionally, if the temperature drops below or rises above certain levels some instruments, including computers, cannot be used. To measure engine performance for equipment assets, for example, may require the cooperation of the equipment operator. For measuring the retroreflectivity of newly installed pavement markings, it may be necessary to schedule with both the DOT and the contractor performing the installation. Measuring sign retroreflectivity may require placing personnel in proximity to traffic, clear access to the sign, or overcoming difficult terrain. Pavement markings present an even more dangerous data collection situation. Work on or near construction sites may pose dangers. Finally, access to assets via terrain may be hindered by steep and dangerous slopes, vegetation, or even animal hazards.

There are numerous problems that may be encountered with regard to the field collection of data. These problems include:

- Suitable weather
- Difficult operating conditions
- Scheduling
- Safety
- Terrain

Many data collection devices are sensitive electro-mechanical instruments that are designed for use in controlled and moderate environments. Some are "ruggedized" and some are not. For those that are not, field data collection can pose significant challenges. Some data collection instruments are sensitive to vibration transmitted from a conveyance vehicle as well as to dust, mud, or other contaminants that are typically found at field sites. When these demanding conditions cause a malfunction, it may be necessary to return the instrument to the manufacturer for repairs that may require several weeks to several months to complete, resulting in critical and substantial lost time for data collection.

Often owners, agencies, or other contractors change their work schedule without notifying the data collection team ahead of time. Also, the data collection schedule may change due to the weather as well as to other unforeseeable events such as a vehicle malfunction or operator absence (Rasdorf, et al. 2008).

Thus, weather and environmental factors play a role in the ability to utilize some instruments and sensors and for personnel to safely manually collect data. To mitigate these conditions requires such actions as to install some form of damping method for vibration or filters or covers for dust on instruments. Also, it may be necessary to clean the instrument internally between data collection sessions. When collecting data near project sites, the operator or responsible decision maker may need to be convinced that the data collection process will not interfere with the productivity of their operations and not negatively impact site safety. Data collection will have to be scheduled to accommodate the production schedule or uncertain weather conditions.

SUMMARY AND CONCLUSIONS

Several IT challenges exist when developing asset management systems for low capital cost, high quantity assets. These challenges include asset identification, asset location, data availability, data fragmentation, and automated data collection. Because these assets cost less and there are so many of them, agencies are initially inclined to exclude them from their asset management efforts, instead focusing on higher value assets. However, these assets are critical to public safety, mobility, and overall satisfaction with the highway infrastructure and therefore cannot be ignored. More importantly, low capital cost, high quantity assets are critical to highway safety and motorist navigation. This criticality has been emphasized on the national level by mandates for improved performance and improved management of assets such as traffic signs and pavement markings.

The further development of asset management systems for low cost, high quantity assets is worthwhile. Many of the IT problems outlined in this paper can be overcome through technological improvements, policy changes, and implementation experience. For example, better mobile retroreflective measurement capabilities could lead to a successful implementation of automated sign retroreflectivity measurement, along the lines of what has already been accomplished in pavement marking retroreflectivity measurement. The asset management community can continue to develop, review, and disseminate best practices for low cost, high quantity asset management.

It is hoped that by discussing the issues related to these IT problems, the development of more comprehensive systems to address low capital cost, high quantity asset management will be enabled, enhancing motorist safety and increasing the efficiency of the transportation system.

DISCLAIMER

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, the U.S. Government, or the North Carolina Department of Transportation.

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14.2 Appendix B: SAS Output for NCSU Division-Separated Linear Regression Deterioration Models

This appendix contains the SAS software output for the NCSU division-separated linear regression deterioration models. Some divisions were removed from consideration because of insufficient sample size or unusual variability in retroreflectivity. The following models are included in this appendix:

- Type I Green
- Type 1 Red
- Type 1 White
- Type 1 Yellow
- Type III (beaded) Green
- Type III (beaded) Red
- Type III (beaded) White
- Type III (beaded) Yellow

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	2546.711249	424.451875	24.75	<.0001
Error	21	360.165051	17.150717		
Uncorrected Total	27	2906.876300			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.511984	46.20697	4.141342	8.962593

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	3	2328.781105	776.260368	45.26	<.0001
age*location	3	217.930145	72.643382	4.24	0.0173

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	3	1338.300016	446.100005	26.01	<.0001
age*location	3	217.930145	72.643382	4.24	0.0173

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 06	13.56308240	1.86515348	7.27	<.0001	9.68428340	17.44188140
location 12	15.13152621	4.77819243	3.17	0.0046	5.19473108	25.06832134
location 13	13.44248938	3.45661959	3.89	0.0008	6.25405541	20.63092334
age*location 06	-0.38182983	0.20856541	-1.83	0.0814	-0.81556533	0.05190568
age*location 12	-0.98196581	0.42387727	-2.32	0.0307	-1.86346685	-0.10046478
age*location 13	-0.75152813	0.37631108	-2.00	0.0589	-1.53410987	0.03105361

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	3060.687320	382.585915	54.59	<.0001
Error	34	238.304080	7.008944		
Uncorrected Total	42	3298.991400			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.564291	32.70561	2.647441	8.094762

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	4	2781.494413	695.373603	99.21	<.0001
age*location	4	279.192906	69.798227	9.96	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	4	1268.038800	317.009700	45.23	<.0001
age*location	4	279.192906	69.798227	9.96	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 02	13.63334284	2.06618855	6.60	<.0001	9.43434251	17.83234316
location 08	10.02918820	3.22781085	3.11	0.0038	3.46948732	16.58888907
location 12	15.25544997	1.55852011	9.79	<.0001	12.08815604	18.42274390
location 13	12.49483724	2.21183024	5.65	<.0001	7.99985739	16.98981709
age*location 02	-0.59804317	0.25180822	-2.37	0.0233	-1.10977905	-0.08630730
age*location 08	-0.52632003	0.41997590	-1.25	0.2187	-1.37981375	0.32717369
age*location 12	-0.89818808	0.17128015	-5.24	<.0001	-1.24627122	-0.55010493
age*location 13	-0.78598003	0.34724102	-2.26	0.0301	-1.49165868	-0.08030137

TYPE 1 White Refined Retro

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	1041190.974	130148.872	463.45	<.0001
Error	256	71891.683	280.827		
Uncorrected Total	264	1113082.657			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.298232	27.08465	16.75789	61.87227

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	4	1013348.849	253337.212	902.11	<.0001
age*location	4	27842.125	6960.531	24.79	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	4	419977.3763	104994.3441	373.88	<.0001
age*location	4	27842.1252	6960.5313	24.79	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 02	72.71946825	7.52571828	9.66	<.0001	57.89926773	87.53966877
location 06	85.84502203	3.47133742	24.73	<.0001	79.00900787	92.68103618
location 12	78.74600342	5.58393277	14.10	<.0001	67.74971041	89.74229643
location 13	74.22265903	3.05129729	24.32	<.0001	68.21381896	80.23149911
age*location 02	-2.13120224	0.81205133	-2.62	0.0092	-3.73035372	-0.53205076
age*location 06	-3.91678767	0.50591124	-7.74	<.0001	-4.91306547	-2.92050987
age*location 12	-3.33374342	0.79063142	-4.22	<.0001	-4.89071324	-1.77677360
age*location 13	-1.10089713	0.28874239	-3.81	0.0002	-1.66950997	-0.53228428

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	402710.4003	100677.6001	458.91	<.0001
Error	165	36198.4698	219.3847		
Uncorrected Total	169	438908.8701			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.301187	30.94781	14.81164	47.86006

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	2	387120.2903	193560.1452	882.29	<.0001
age*location	2	15590.1100	7795.0550	35.53	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	2	153055.9036	76527.9518	348.83	<.0001
age*location	2	15590.1100	7795.0550	35.53	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 02	61.98817160	3.82136225	16.22	<.0001	54.44309960	69.53324360
location 06	69.77483389	3.34728140	20.85	<.0001	63.16580875	76.38385902
age*location 02	-2.04085601	0.49926995	-4.09	<.0001	-3.02663737	-1.05507464
age*location 06	-3.03126192	0.41115790	-7.37	<.0001	-3.84307085	-2.21945299

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	28572.24081	14286.12040	424.40	<.0001
Error	11	370.27929	33.66175		
Uncorrected Total	13	28942.52010			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.036134	12.37865	5.801875	46.87000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	1	28558.35970	28558.35970	848.39	<.0001
age*location	1	13.88111	13.88111	0.41	0.5339

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	1	2481.596561	2481.596561	73.72	<.0001
age*location	1	13.881108	13.881108	0.41	0.5339

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 12	50.50305337	5.88193765	8.59	<.0001	37.55699589	63.44911084
age*location 12	-0.30966230	0.48221935	-0.64	0.5339	-1.37101994	0.75169534

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	118011.1517	29502.7879	235.23	<.0001
Error	39	4891.5053	125.4232		
Uncorrected Total	43	122902.6570			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.470427	21.78251	11.19925	51.41395

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	2	113738.1519	56869.0760	453.42	<.0001
age*location	2	4272.9998	2136.4999	17.03	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	2	63274.80562	31637.40281	252.25	<.0001
age*location	2	4272.99978	2136.49989	17.03	<.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 06	65.60938301	3.18434278	20.60	<.0001	59.16844179	72.05032423
location 08	62.19588703	6.95474922	8.94	<.0001	48.12857892	76.26319513
age*location 06	-3.52094608	0.66674539	-5.28	<.0001	-4.86956593	-2.17232622
age*location 08	-3.14065432	1.26316730	-2.49	0.0173	-5.69565135	-0.58565729

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	3608638.082	902159.521	1861.78	<.0001
Error	50	24228.374	484.567		
Uncorrected Total	54	3632866.456			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.306204	8.527991	22.01289	258.1252

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	2	3598156.658	1799078.329	3712.75	<.0001
age*location	2	10481.425	5240.712	10.82	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	2	1962896.793	981448.396	2025.41	<.0001
age*location	2	10481.425	5240.712	10.82	0.0001

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 06	274.2434686	4.85966659	56.43	<.0001	264.4825410	284.0043962
location 08	264.9593928	9.00271184	29.43	<.0001	246.8769139	283.0418717
age*location 06	-5.2362586	1.21714848	-4.30	<.0001	-7.6809733	-2.7915440
age*location 08	-3.6112804	2.04361284	-1.77	0.0833	-7.7159976	0.4934368

The GLM Procedure

Dependent Variable: retroreflectivity

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1563736.138	781868.069	1307.53	<.0001
Error	32	19135.111	597.972		
Uncorrected Total	34	1582871.249			

R-Square	Coeff Var	Root MSE	retroreflectivity Mean
0.143567	11.41416	24.45347	214.2379

Source	DF	Type I SS	Mean Square	F Value	Pr > F
location	1	1560528.445	1560528.445	2609.70	<.0001
age*location	1	3207.693	3207.693	5.36	0.0271

Source	DF	Type III SS	Mean Square	F Value	Pr > F
location	1	1098328.802	1098328.802	1836.76	<.0001
age*location	1	3207.693	3207.693	5.36	0.0271

Parameter	Estimate	Standard Error	t Value	Pr > |t|	95% Confidence Limits	
location 06	221.2067498	5.16146149	42.86	<.0001	210.6931968	231.7203028
age*location 06	-2.5543283	1.10286113	-2.32	0.0271	-4.8007829	-0.3078737

14.3 Appendix C: Simulation Input File from 2005 NCSU/NCDOT Data used in Simulation Validation

This appendix contains the input file table used in the validation scenario.

There are 1047 rows. The columns are defined as follows:

Column 1: Road Type. 1 = interstate, 2 = primary, 3 = secondary

Column 2: Sheeting Type. 1 = Type I (Engineering Grade), 3 = Type III (High Intensity)

Column 3: Main Color. 1= White, 2 = Yellow, 3 = Green, 4 = Red

Column 4: Secondary Color. 0 = none, 1 = White

Column 5: Age of Sign in 2005 (in years)

Column 6: Retroreflectivity (R_A) value of sign's main color in 2005

Column 7: Retroreflectivity (R_A) value of sign's secondary color in 2005 (if present)

Column 8: Action Code. 1 = high priority, 2 = medium priority, 3 = low priority

The use of this table is discussed in Section 6.1.

Also included in this appendix is a figure showing a histogram of the sign ages in the sign input file.

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	1	0	0.30	103.70	0.00	3
1	1	1	0	0.55	93.29	0.00	3
3	1	1	0	0.69	86.34	0.00	3
3	1	1	0	0.70	93.92	0.00	3
3	1	1	0	0.75	97.38	0.00	3
3	1	1	0	0.88	81.92	0.00	3
2	1	1	0	0.96	97.50	0.00	3
3	1	1	0	1.00	98.43	0.00	3
3	1	1	0	1.03	109.04	0.00	3
2	1	1	0	1.05	80.45	0.00	3
1	1	1	0	1.08	87.06	0.00	3
3	1	1	0	1.08	100.22	0.00	3
3	1	1	0	1.13	86.02	0.00	3
2	1	1	0	1.24	95.64	0.00	3
3	1	1	0	1.27	87.06	0.00	3
3	1	1	0	1.34	79.01	0.00	3
3	1	1	0	1.35	77.11	0.00	3
3	1	1	0	1.43	104.53	0.00	3
2	1	1	0	1.45	96.95	0.00	3
3	1	1	0	1.48	118.56	0.00	3
3	1	1	0	1.51	100.67	0.00	3
1	1	1	0	1.56	100.99	0.00	3
2	1	1	0	1.62	87.17	0.00	3
3	1	1	0	1.62	100.34	0.00	3
2	1	1	0	1.63	92.87	0.00	3
3	1	1	0	1.64	103.43	0.00	3
2	1	1	0	1.67	82.66	0.00	3
2	1	1	0	1.68	87.66	0.00	3
3	1	1	0	1.76	105.29	0.00	3
1	1	1	0	1.79	78.42	0.00	3
3	1	1	0	1.82	102.73	0.00	3
2	1	1	0	1.91	92.62	0.00	3
2	1	1	0	2.02	79.75	0.00	3
3	1	1	0	2.03	81.44	0.00	3
3	1	1	0	2.06	80.47	0.00	3
3	1	1	0	2.19	102.11	0.00	3
1	1	1	0	2.26	93.25	0.00	3
3	1	1	0	2.40	77.46	0.00	3
3	1	1	0	2.41	92.17	0.00	3
1	1	1	0	2.42	70.70	0.00	3
2	1	1	0	2.49	99.71	0.00	3
2	1	1	0	2.51	71.25	0.00	3
2	1	1	0	2.52	83.42	0.00	3
3	1	1	0	2.53	86.48	0.00	3
3	1	1	0	2.58	84.55	0.00	3
3	1	1	0	2.58	85.42	0.00	3
3	1	1	0	2.66	88.89	0.00	3
3	1	1	0	2.80	80.42	0.00	3
3	1	1	0	2.82	86.68	0.00	3
2	1	1	0	2.85	83.35	0.00	3
1	1	1	0	2.86	76.45	0.00	3
2	1	1	0	2.91	73.66	0.00	3
3	1	1	0	2.93	89.29	0.00	3
2	1	1	0	2.99	78.44	0.00	3
2	1	1	0	3.03	74.56	0.00	3
3	1	1	0	3.03	46.77	0.00	3

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	1	0	3.04	100.30	0.00	3
1	1	1	0	3.06	86.46	0.00	3
3	1	1	0	3.07	66.61	0.00	3
2	1	1	0	3.11	83.85	0.00	3
3	1	1	0	3.11	84.22	0.00	3
3	1	1	0	3.14	94.72	0.00	3
3	1	1	0	3.17	64.51	0.00	3
3	1	1	0	3.20	69.08	0.00	3
2	1	1	0	3.23	67.52	0.00	3
2	1	1	0	3.31	66.34	0.00	3
2	1	1	0	3.34	92.35	0.00	3
3	1	1	0	3.35	98.21	0.00	3
2	1	1	0	3.45	92.68	0.00	3
3	1	1	0	3.52	74.91	0.00	3
3	1	1	0	3.56	87.57	0.00	3
3	1	1	0	3.57	86.05	0.00	3
2	1	1	0	3.62	90.78	0.00	3
3	1	1	0	3.63	94.98	0.00	3
3	1	1	0	3.70	70.11	0.00	3
3	1	1	0	3.74	78.48	0.00	3
3	1	1	0	3.74	72.43	0.00	3
1	1	1	0	3.78	74.09	0.00	3
2	1	1	0	3.79	70.78	0.00	3
3	1	1	0	3.85	77.14	0.00	3
3	1	1	0	3.88	62.16	0.00	3
1	1	1	0	3.88	94.94	0.00	3
2	1	1	0	3.88	61.64	0.00	3
1	1	1	0	3.91	81.20	0.00	3
2	1	1	0	3.99	73.52	0.00	3
3	1	1	0	4.10	75.83	0.00	3
3	1	1	0	4.18	64.64	0.00	3
3	1	1	0	4.20	71.42	0.00	3
1	1	1	0	4.24	64.20	0.00	3
2	1	1	0	4.34	86.66	0.00	3
3	1	1	0	4.34	80.06	0.00	3
2	1	1	0	4.40	85.80	0.00	3
2	1	1	0	4.44	86.03	0.00	3
3	1	1	0	4.51	89.27	0.00	3
1	1	1	0	4.57	82.88	0.00	3
3	1	1	0	4.60	91.22	0.00	3
3	1	1	0	4.68	69.10	0.00	3
3	1	1	0	4.70	96.26	0.00	3
3	1	1	0	4.76	79.19	0.00	3
1	1	1	0	4.78	78.12	0.00	3
3	1	1	0	4.79	73.26	0.00	3
2	1	1	0	4.80	69.69	0.00	3
3	1	1	0	4.87	59.23	0.00	3
2	1	1	0	4.93	74.11	0.00	3
2	1	1	0	5.01	77.71	0.00	3
3	1	1	0	5.11	57.38	0.00	3
3	1	1	0	5.12	79.35	0.00	3
3	1	1	0	5.18	73.21	0.00	3
1	1	1	0	5.24	81.52	0.00	3
3	1	1	0	5.29	72.58	0.00	3
3	1	1	0	5.31	58.03	0.00	3
3	1	1	0	5.36	74.88	0.00	3
3	1	1	0	5.36	47.55	0.00	3
3	1	1	0	5.38	81.25	0.00	3

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
1	1	1	0	5.43	67.34	0.00	3
2	1	1	0	5.44	81.46	0.00	3
3	1	1	0	5.46	65.50	0.00	3
2	1	1	0	5.57	71.71	0.00	3
3	1	1	0	5.58	77.21	0.00	3
3	1	1	0	5.81	66.06	0.00	3
2	1	1	0	5.84	78.87	0.00	3
3	1	1	0	5.89	74.32	0.00	3
1	1	1	0	5.90	74.07	0.00	3
2	1	1	0	5.91	51.03	0.00	3
2	1	1	0	6.02	70.04	0.00	3
3	1	1	0	6.09	57.58	0.00	3
3	1	1	0	6.09	53.12	0.00	3
3	1	1	0	6.15	70.56	0.00	3
2	1	1	0	6.23	49.11	0.00	3
1	1	1	0	6.33	75.02	0.00	3
3	1	1	0	6.37	69.93	0.00	3
3	1	1	0	6.42	61.50	0.00	3
3	1	1	0	6.45	56.98	0.00	3
2	1	1	0	6.45	62.52	0.00	3
3	1	1	0	6.49	78.13	0.00	3
3	1	1	0	6.51	65.33	0.00	3
1	1	1	0	6.53	50.52	0.00	3
2	1	1	0	6.53	78.61	0.00	3
3	1	1	0	6.56	49.61	0.00	3
3	1	1	0	6.56	54.91	0.00	3
1	1	1	0	6.56	56.15	0.00	3
2	1	1	0	6.62	70.18	0.00	3
3	1	1	0	6.66	42.76	0.00	3
3	1	1	0	6.69	69.80	0.00	3
2	1	1	0	6.75	62.64	0.00	3
3	1	1	0	6.76	72.40	0.00	3
3	1	1	0	6.87	61.11	0.00	3
2	1	1	0	6.92	67.07	0.00	3
3	1	1	0	6.92	50.80	0.00	3
2	1	1	0	6.95	71.99	0.00	3
3	1	1	0	6.97	59.08	0.00	3
1	1	1	0	7.00	55.91	0.00	3
2	1	1	0	7.12	74.12	0.00	3
3	1	1	0	7.22	69.59	0.00	3
2	1	1	0	7.30	57.08	0.00	3
3	1	1	0	7.32	69.62	0.00	3
3	1	1	0	7.33	33.10	0.00	3
2	1	1	0	7.39	53.22	0.00	3
2	1	1	0	7.49	68.65	0.00	3
3	1	1	0	7.49	63.95	0.00	3
3	1	1	0	7.56	58.97	0.00	3
3	1	1	0	7.57	62.78	0.00	3
1	1	1	0	7.57	46.92	0.00	3
3	1	1	0	7.63	54.97	0.00	3
3	1	1	0	7.63	71.31	0.00	3
3	1	1	0	7.64	50.30	0.00	3
3	1	1	0	7.69	76.01	0.00	3
3	1	1	0	7.70	56.95	0.00	3
1	1	1	0	7.70	66.37	0.00	3
2	1	1	0	7.70	57.44	0.00	3
3	1	1	0	7.71	53.24	0.00	3
3	1	1	0	7.78	57.64	0.00	3

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	1	0	7.79	64.46	0.00	3
3	1	1	0	7.82	47.15	0.00	3
3	1	1	0	7.84	68.58	0.00	3
1	1	1	0	7.89	51.84	0.00	3
3	1	1	0	7.92	55.54	0.00	3
3	1	1	0	7.95	51.17	0.00	3
1	1	1	0	8.24	55.51	0.00	3
2	1	1	0	8.36	56.16	0.00	3
3	1	1	0	8.37	38.82	0.00	3
3	1	1	0	8.46	51.17	0.00	3
3	1	1	0	8.51	38.16	0.00	3
3	1	1	0	8.52	63.46	0.00	3
1	1	1	0	8.55	56.81	0.00	3
3	1	1	0	8.58	48.42	0.00	3
1	1	1	0	8.59	68.89	0.00	3
1	1	1	0	8.67	51.92	0.00	3
3	1	1	0	8.71	52.81	0.00	3
3	1	1	0	8.72	82.95	0.00	3
1	1	1	0	8.72	79.56	0.00	3
3	1	1	0	8.73	51.72	0.00	3
2	1	1	0	8.75	69.09	0.00	3
2	1	1	0	8.84	62.92	0.00	3
2	1	1	0	8.91	57.66	0.00	3
3	1	1	0	8.98	58.46	0.00	3
3	1	1	0	9.06	57.96	0.00	3
2	1	1	0	9.08	65.56	0.00	3
3	1	1	0	9.13	38.40	0.00	3
1	1	1	0	9.16	39.62	0.00	3
3	1	1	0	9.19	36.10	0.00	3
3	1	1	0	9.23	47.96	0.00	3
1	1	1	0	9.35	48.84	0.00	3
3	1	1	0	9.41	39.96	0.00	3
3	1	1	0	9.55	55.35	0.00	3
1	1	1	0	9.61	25.01	0.00	3
2	1	1	0	9.62	40.33	0.00	3
2	1	1	0	9.77	34.39	0.00	3
3	1	1	0	9.88	51.46	0.00	3
2	1	1	0	9.94	39.03	0.00	3
3	1	1	0	10.05	44.30	0.00	3
2	1	1	0	10.07	18.04	0.00	3
2	1	1	0	10.12	38.01	0.00	3
1	1	1	0	10.20	36.34	0.00	3
3	1	1	0	10.34	43.02	0.00	3
2	1	1	0	10.43	39.25	0.00	3
3	1	1	0	10.44	31.50	0.00	3
3	1	1	0	10.54	59.74	0.00	3
1	1	1	0	10.69	31.64	0.00	3
3	1	1	0	10.72	54.11	0.00	3
3	1	1	0	10.83	38.53	0.00	3
2	1	1	0	10.88	51.74	0.00	3
3	1	1	0	10.89	48.25	0.00	3
2	1	1	0	10.91	32.66	0.00	3
3	1	1	0	10.95	53.27	0.00	3
1	1	1	0	11.09	39.41	0.00	3
2	1	1	0	11.21	47.07	0.00	3
3	1	1	0	11.29	33.53	0.00	3
3	1	1	0	11.43	63.73	0.00	3
3	1	1	0	11.58	46.26	0.00	3

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	1	0	11.70	40.58	0.00	3
3	1	1	0	11.70	27.72	0.00	3
1	1	1	0	11.77	30.37	0.00	3
1	1	1	0	11.82	19.73	0.00	3
2	1	1	0	11.88	28.47	0.00	3
2	1	1	0	12.00	44.70	0.00	3
3	1	1	0	12.01	30.51	0.00	3
3	1	1	0	12.15	32.86	0.00	3
3	1	1	0	12.49	15.03	0.00	3
1	1	1	0	12.49	44.56	0.00	3
3	1	1	0	12.49	28.87	0.00	3
3	1	1	0	12.74	38.48	0.00	3
3	1	1	0	12.85	31.16	0.00	3
2	1	1	0	12.98	43.96	0.00	3
3	1	1	0	13.33	26.90	0.00	3
3	1	1	0	13.36	25.92	0.00	3
2	1	1	0	13.41	26.04	0.00	3
3	1	1	0	13.49	12.74	0.00	3
3	1	1	0	13.51	30.64	0.00	3
3	1	1	0	13.78	36.24	0.00	3
3	1	1	0	14.02	9.76	0.00	3
3	1	1	0	14.24	34.72	0.00	3
3	1	1	0	14.48	0.99	0.00	3
3	1	1	0	14.59	16.94	0.00	3
3	1	1	0	14.63	12.28	0.00	3
1	1	1	0	14.64	20.55	0.00	3
3	1	1	0	14.72	8.61	0.00	3
3	1	1	0	14.77	28.51	0.00	3
3	1	1	0	15.02	11.51	0.00	3
1	1	1	0	15.04	16.65	0.00	3
3	1	1	0	15.16	0.00	0.00	3
3	1	1	0	16.69	0.00	0.00	3
3	1	1	0	17.14	0.00	0.00	3
1	1	1	0	17.48	11.55	0.00	3
3	1	1	0	17.80	0.00	0.00	3
3	1	1	0	17.86	18.88	0.00	3
1	1	1	0	17.90	0.00	0.00	3
3	1	1	0	18.43	0.22	0.00	3
3	1	1	0	18.68	0.00	0.00	3
2	1	1	0	19.93	0.00	0.00	3
3	1	1	0	19.99	0.00	0.00	3
3	1	1	0	20.15	0.00	0.00	3
3	1	1	0	20.60	0.00	0.00	3
3	1	2	0	0.29	48.85	0.00	2
3	1	2	0	0.34	55.67	0.00	2
2	1	2	0	0.48	65.74	0.00	2
3	1	2	0	0.54	70.76	0.00	2
3	1	2	0	0.57	57.94	0.00	2
2	1	2	0	0.58	58.98	0.00	2
3	1	2	0	0.77	71.51	0.00	2
3	1	2	0	0.78	64.45	0.00	2
3	1	2	0	0.89	72.45	0.00	2
3	1	2	0	0.91	61.31	0.00	2
3	1	2	0	0.96	76.70	0.00	2
3	1	2	0	0.97	56.55	0.00	2
3	1	2	0	1.05	74.49	0.00	2
3	1	2	0	1.05	57.36	0.00	2
3	1	2	0	1.16	58.81	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	2	0	1.17	59.99	0.00	2
1	1	2	0	1.22	62.77	0.00	2
3	1	2	0	1.24	67.42	0.00	2
2	1	2	0	1.26	57.35	0.00	2
3	1	2	0	1.33	52.93	0.00	2
3	1	2	0	1.35	54.45	0.00	2
2	1	2	0	1.41	63.53	0.00	2
3	1	2	0	1.42	65.98	0.00	2
3	1	2	0	1.51	76.31	0.00	2
3	1	2	0	1.51	64.42	0.00	2
3	1	2	0	1.53	60.20	0.00	2
3	1	2	0	1.57	64.69	0.00	2
3	1	2	0	1.67	72.98	0.00	2
3	1	2	0	1.75	57.76	0.00	2
3	1	2	0	1.78	61.21	0.00	2
3	1	2	0	1.80	59.36	0.00	2
3	1	2	0	1.82	63.86	0.00	2
3	1	2	0	1.85	54.86	0.00	2
3	1	2	0	1.89	58.43	0.00	2
3	1	2	0	1.91	66.25	0.00	2
3	1	2	0	1.92	65.58	0.00	2
3	1	2	0	2.08	58.58	0.00	2
3	1	2	0	2.09	59.95	0.00	2
2	1	2	0	2.11	50.69	0.00	2
3	1	2	0	2.20	66.73	0.00	2
3	1	2	0	2.23	56.47	0.00	2
2	1	2	0	2.25	54.31	0.00	2
3	1	2	0	2.26	55.62	0.00	2
3	1	2	0	2.30	67.09	0.00	2
3	1	2	0	2.38	48.96	0.00	2
3	1	2	0	2.44	51.57	0.00	2
3	1	2	0	2.47	62.48	0.00	2
3	1	2	0	2.49	66.39	0.00	2
3	1	2	0	2.52	68.24	0.00	2
3	1	2	0	2.53	62.99	0.00	2
3	1	2	0	2.57	49.40	0.00	2
3	1	2	0	2.60	63.57	0.00	2
3	1	2	0	2.64	59.98	0.00	2
3	1	2	0	2.65	47.90	0.00	2
2	1	2	0	2.67	56.36	0.00	2
3	1	2	0	2.70	56.28	0.00	2
2	1	2	0	2.72	53.97	0.00	2
3	1	2	0	2.72	53.36	0.00	2
3	1	2	0	2.75	66.36	0.00	2
2	1	2	0	2.77	56.40	0.00	2
3	1	2	0	2.80	60.03	0.00	2
3	1	2	0	2.82	62.14	0.00	2
3	1	2	0	2.83	69.12	0.00	2
3	1	2	0	2.96	49.35	0.00	2
3	1	2	0	2.97	64.27	0.00	2
2	1	2	0	3.01	43.41	0.00	2
3	1	2	0	3.05	56.57	0.00	2
3	1	2	0	3.05	58.53	0.00	2
3	1	2	0	3.07	43.99	0.00	2
2	1	2	0	3.08	51.14	0.00	2
3	1	2	0	3.10	49.43	0.00	2
3	1	2	0	3.14	60.55	0.00	2
3	1	2	0	3.20	58.87	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	2	0	3.21	47.15	0.00	2
1	1	2	0	3.25	45.15	0.00	2
3	1	2	0	3.34	47.44	0.00	2
3	1	2	0	3.34	53.92	0.00	2
3	1	2	0	3.37	58.87	0.00	2
3	1	2	0	3.39	58.29	0.00	2
3	1	2	0	3.40	57.62	0.00	2
2	1	2	0	3.41	55.32	0.00	2
2	1	2	0	3.43	54.02	0.00	2
3	1	2	0	3.46	49.66	0.00	2
1	1	2	0	3.48	45.18	0.00	2
3	1	2	0	3.51	63.25	0.00	2
3	1	2	0	3.58	59.36	0.00	2
3	1	2	0	3.58	60.53	0.00	2
2	1	2	0	3.65	56.48	0.00	2
3	1	2	0	3.66	51.31	0.00	2
2	1	2	0	3.70	49.24	0.00	2
3	1	2	0	3.72	42.52	0.00	2
3	1	2	0	3.77	58.17	0.00	2
3	1	2	0	3.79	65.28	0.00	2
3	1	2	0	3.81	56.94	0.00	2
2	1	2	0	3.82	61.23	0.00	2
3	1	2	0	3.85	54.12	0.00	2
3	1	2	0	3.90	69.02	0.00	2
3	1	2	0	3.94	63.25	0.00	2
2	1	2	0	3.97	52.09	0.00	2
3	1	2	0	4.01	46.66	0.00	2
3	1	2	0	4.02	56.49	0.00	2
2	1	2	0	4.02	43.70	0.00	2
3	1	2	0	4.02	40.35	0.00	2
3	1	2	0	4.08	36.65	0.00	2
3	1	2	0	4.13	51.09	0.00	2
2	1	2	0	4.18	52.30	0.00	2
3	1	2	0	4.20	55.06	0.00	2
2	1	2	0	4.31	50.10	0.00	2
3	1	2	0	4.36	52.09	0.00	2
3	1	2	0	4.39	46.11	0.00	2
3	1	2	0	4.49	46.85	0.00	2
3	1	2	0	4.50	54.19	0.00	2
3	1	2	0	4.51	31.97	0.00	2
3	1	2	0	4.52	56.45	0.00	2
3	1	2	0	4.56	50.62	0.00	2
3	1	2	0	4.59	47.14	0.00	2
3	1	2	0	4.59	37.05	0.00	2
3	1	2	0	4.59	47.64	0.00	2
3	1	2	0	4.65	48.64	0.00	2
2	1	2	0	4.66	44.70	0.00	2
3	1	2	0	4.73	52.37	0.00	2
1	1	2	0	4.79	45.55	0.00	2
3	1	2	0	4.80	50.09	0.00	2
3	1	2	0	4.89	38.05	0.00	2
3	1	2	0	4.89	62.85	0.00	2
3	1	2	0	4.90	42.74	0.00	2
3	1	2	0	4.90	65.06	0.00	2
3	1	2	0	4.92	56.50	0.00	2
3	1	2	0	4.93	50.37	0.00	2
3	1	2	0	4.99	55.05	0.00	2
3	1	2	0	5.00	47.02	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	2	0	5.01	40.89	0.00	2
3	1	2	0	5.11	47.73	0.00	2
2	1	2	0	5.14	58.53	0.00	2
2	1	2	0	5.18	47.64	0.00	2
3	1	2	0	5.21	43.08	0.00	2
3	1	2	0	5.25	34.02	0.00	2
3	1	2	0	5.28	43.69	0.00	2
3	1	2	0	5.28	46.22	0.00	2
3	1	2	0	5.29	43.87	0.00	2
3	1	2	0	5.36	35.73	0.00	2
3	1	2	0	5.41	43.52	0.00	2
3	1	2	0	5.41	59.83	0.00	2
3	1	2	0	5.56	30.04	0.00	2
3	1	2	0	5.64	41.43	0.00	2
3	1	2	0	5.67	47.25	0.00	2
3	1	2	0	5.68	31.70	0.00	2
3	1	2	0	5.69	39.45	0.00	2
2	1	2	0	5.71	48.07	0.00	2
3	1	2	0	5.77	43.77	0.00	2
3	1	2	0	5.79	50.20	0.00	2
3	1	2	0	5.82	49.80	0.00	2
3	1	2	0	5.82	54.25	0.00	2
3	1	2	0	5.85	37.66	0.00	2
3	1	2	0	5.86	42.34	0.00	2
3	1	2	0	5.86	43.08	0.00	2
3	1	2	0	5.87	49.11	0.00	2
3	1	2	0	5.87	45.12	0.00	2
3	1	2	0	5.90	51.70	0.00	2
3	1	2	0	5.93	42.22	0.00	2
3	1	2	0	5.99	40.60	0.00	2
3	1	2	0	6.01	34.66	0.00	2
3	1	2	0	6.05	25.13	0.00	2
3	1	2	0	6.07	43.88	0.00	2
3	1	2	0	6.11	51.59	0.00	2
2	1	2	0	6.11	48.24	0.00	2
2	1	2	0	6.17	42.58	0.00	2
3	1	2	0	6.26	52.38	0.00	2
3	1	2	0	6.27	38.51	0.00	2
3	1	2	0	6.30	40.22	0.00	2
3	1	2	0	6.41	39.20	0.00	2
3	1	2	0	6.45	38.24	0.00	2
3	1	2	0	6.46	48.46	0.00	2
3	1	2	0	6.48	41.91	0.00	2
3	1	2	0	6.49	52.21	0.00	2
3	1	2	0	6.55	32.16	0.00	2
3	1	2	0	6.61	43.37	0.00	2
3	1	2	0	6.70	39.60	0.00	2
2	1	2	0	6.75	53.63	0.00	2
3	1	2	0	6.75	41.04	0.00	2
3	1	2	0	6.83	40.64	0.00	2
3	1	2	0	6.83	44.80	0.00	2
3	1	2	0	6.86	39.43	0.00	2
3	1	2	0	6.88	38.07	0.00	2
2	1	2	0	6.90	42.41	0.00	2
3	1	2	0	6.95	45.89	0.00	2
3	1	2	0	7.12	32.33	0.00	2
3	1	2	0	7.14	31.57	0.00	2
3	1	2	0	7.16	40.00	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	2	0	7.19	29.87	0.00	2
3	1	2	0	7.21	33.84	0.00	2
3	1	2	0	7.23	44.28	0.00	2
2	1	2	0	7.25	27.51	0.00	2
3	1	2	0	7.31	52.52	0.00	2
3	1	2	0	7.34	32.25	0.00	2
2	1	2	0	7.34	38.48	0.00	2
3	1	2	0	7.35	53.61	0.00	2
3	1	2	0	7.36	38.59	0.00	2
3	1	2	0	7.36	50.54	0.00	2
3	1	2	0	7.37	38.85	0.00	2
3	1	2	0	7.37	41.85	0.00	2
1	1	2	0	7.39	41.23	0.00	2
3	1	2	0	7.39	38.58	0.00	2
3	1	2	0	7.40	37.45	0.00	2
2	1	2	0	7.42	48.04	0.00	2
3	1	2	0	7.53	37.18	0.00	2
3	1	2	0	7.54	39.88	0.00	2
3	1	2	0	7.55	42.04	0.00	2
3	1	2	0	7.60	28.63	0.00	2
3	1	2	0	7.60	35.14	0.00	2
3	1	2	0	7.67	39.33	0.00	2
3	1	2	0	7.69	42.30	0.00	2
3	1	2	0	7.73	41.54	0.00	2
3	1	2	0	7.77	35.25	0.00	2
3	1	2	0	7.77	37.23	0.00	2
3	1	2	0	7.80	31.17	0.00	2
1	1	2	0	7.80	23.81	0.00	2
3	1	2	0	7.85	33.13	0.00	2
3	1	2	0	7.86	37.93	0.00	2
3	1	2	0	7.99	31.89	0.00	2
3	1	2	0	7.99	35.03	0.00	2
1	1	2	0	8.00	45.36	0.00	2
3	1	2	0	8.00	31.21	0.00	2
1	1	2	0	8.02	28.42	0.00	2
2	1	2	0	8.05	26.67	0.00	2
3	1	2	0	8.05	24.07	0.00	2
3	1	2	0	8.10	22.25	0.00	2
3	1	2	0	8.11	40.67	0.00	2
3	1	2	0	8.11	25.13	0.00	2
3	1	2	0	8.15	41.95	0.00	2
3	1	2	0	8.16	19.20	0.00	2
3	1	2	0	8.16	42.05	0.00	2
3	1	2	0	8.16	39.85	0.00	2
3	1	2	0	8.22	27.45	0.00	2
2	1	2	0	8.29	34.62	0.00	2
3	1	2	0	8.29	37.01	0.00	2
3	1	2	0	8.31	34.46	0.00	2
3	1	2	0	8.34	37.85	0.00	2
3	1	2	0	8.37	28.32	0.00	2
3	1	2	0	8.52	33.03	0.00	2
3	1	2	0	8.56	26.41	0.00	2
3	1	2	0	8.57	25.23	0.00	2
3	1	2	0	8.62	32.58	0.00	2
3	1	2	0	8.62	30.04	0.00	2
3	1	2	0	8.64	44.50	0.00	2
3	1	2	0	8.64	26.97	0.00	2
3	1	2	0	8.72	54.48	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	2	0	8.76	24.84	0.00	2
3	1	2	0	8.80	35.79	0.00	2
2	1	2	0	8.82	36.48	0.00	2
1	1	2	0	8.84	47.91	0.00	2
3	1	2	0	8.84	37.65	0.00	2
2	1	2	0	8.91	37.17	0.00	2
3	1	2	0	8.91	37.80	0.00	2
3	1	2	0	8.94	50.64	0.00	2
3	1	2	0	9.00	32.92	0.00	2
2	1	2	0	9.00	27.76	0.00	2
3	1	2	0	9.02	28.98	0.00	2
3	1	2	0	9.02	20.56	0.00	2
3	1	2	0	9.06	27.80	0.00	2
3	1	2	0	9.10	33.89	0.00	2
2	1	2	0	9.15	33.82	0.00	2
3	1	2	0	9.17	33.45	0.00	2
3	1	2	0	9.23	36.62	0.00	2
3	1	2	0	9.31	18.41	0.00	2
3	1	2	0	9.31	38.68	0.00	2
3	1	2	0	9.32	26.76	0.00	2
3	1	2	0	9.42	30.09	0.00	2
2	1	2	0	9.47	18.60	0.00	2
3	1	2	0	9.54	24.48	0.00	2
1	1	2	0	9.64	26.36	0.00	2
3	1	2	0	9.67	31.10	0.00	2
3	1	2	0	9.69	23.00	0.00	2
3	1	2	0	9.70	34.36	0.00	2
2	1	2	0	9.71	26.58	0.00	2
3	1	2	0	9.78	26.10	0.00	2
2	1	2	0	9.79	19.54	0.00	2
3	1	2	0	9.83	30.58	0.00	2
3	1	2	0	9.94	28.30	0.00	2
3	1	2	0	9.95	27.13	0.00	2
3	1	2	0	9.97	30.37	0.00	2
3	1	2	0	10.06	12.06	0.00	2
2	1	2	0	10.13	36.39	0.00	2
3	1	2	0	10.20	29.01	0.00	2
3	1	2	0	10.34	17.10	0.00	2
3	1	2	0	10.35	35.91	0.00	2
3	1	2	0	10.43	35.01	0.00	2
3	1	2	0	10.49	26.11	0.00	2
2	1	2	0	10.50	22.93	0.00	2
2	1	2	0	10.58	27.24	0.00	2
3	1	2	0	10.72	29.21	0.00	2
3	1	2	0	10.78	26.96	0.00	2
3	1	2	0	10.83	31.15	0.00	2
3	1	2	0	10.85	26.75	0.00	2
3	1	2	0	10.90	28.00	0.00	2
3	1	2	0	11.25	32.56	0.00	2
3	1	2	0	11.30	27.17	0.00	2
3	1	2	0	11.36	11.03	0.00	2
3	1	2	0	11.37	20.13	0.00	2
3	1	2	0	11.46	32.52	0.00	2
3	1	2	0	11.47	37.22	0.00	2
3	1	2	0	11.48	24.38	0.00	2
3	1	2	0	11.52	18.27	0.00	2
2	1	2	0	11.53	22.05	0.00	2
3	1	2	0	11.53	25.42	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
2	1	2	0	11.59	27.85	0.00	2
3	1	2	0	11.60	27.18	0.00	2
2	1	2	0	11.62	21.42	0.00	2
3	1	2	0	11.87	3.18	0.00	2
3	1	2	0	11.94	11.37	0.00	2
3	1	2	0	12.13	41.59	0.00	2
3	1	2	0	12.26	17.41	0.00	2
3	1	2	0	12.27	17.25	0.00	2
3	1	2	0	12.29	24.97	0.00	2
3	1	2	0	12.34	35.80	0.00	2
3	1	2	0	12.36	28.69	0.00	2
3	1	2	0	12.44	14.23	0.00	2
2	1	2	0	12.46	18.90	0.00	2
3	1	2	0	12.46	18.51	0.00	2
3	1	2	0	12.51	16.14	0.00	2
3	1	2	0	12.63	27.54	0.00	2
2	1	2	0	12.70	18.90	0.00	2
3	1	2	0	12.77	25.49	0.00	2
3	1	2	0	12.91	0.00	0.00	2
2	1	2	0	13.01	17.27	0.00	2
3	1	2	0	13.36	17.30	0.00	2
3	1	2	0	13.36	36.17	0.00	2
3	1	2	0	13.44	28.87	0.00	2
3	1	2	0	13.44	1.03	0.00	2
3	1	2	0	13.46	20.29	0.00	2
3	1	2	0	13.53	16.50	0.00	2
3	1	2	0	13.53	22.36	0.00	2
3	1	2	0	13.65	7.93	0.00	2
3	1	2	0	13.81	10.44	0.00	2
3	1	2	0	14.12	0.00	0.00	2
3	1	2	0	14.25	21.73	0.00	2
3	1	2	0	14.30	13.87	0.00	2
3	1	2	0	14.43	5.72	0.00	2
3	1	2	0	14.49	12.55	0.00	2
3	1	2	0	14.49	21.61	0.00	2
3	1	2	0	14.56	19.79	0.00	2
3	1	2	0	14.67	9.08	0.00	2
3	1	2	0	14.68	7.29	0.00	2
3	1	2	0	14.69	17.49	0.00	2
3	1	2	0	14.70	5.11	0.00	2
3	1	2	0	14.77	7.32	0.00	2
3	1	2	0	14.82	8.28	0.00	2
3	1	2	0	14.94	0.00	0.00	2
3	1	2	0	15.03	19.55	0.00	2
3	1	2	0	15.05	6.10	0.00	2
3	1	2	0	15.06	0.00	0.00	2
3	1	2	0	15.12	14.80	0.00	2
2	1	2	0	15.35	0.00	0.00	2
3	1	2	0	15.55	6.60	0.00	2
2	1	2	0	15.71	5.53	0.00	2
3	1	2	0	16.03	9.10	0.00	2
3	1	2	0	16.21	12.11	0.00	2
3	1	2	0	16.42	0.98	0.00	2
3	1	2	0	16.44	0.00	0.00	2
3	1	2	0	17.09	0.00	0.00	2
3	1	2	0	17.18	6.72	0.00	2
3	1	2	0	17.18	9.63	0.00	2
3	1	2	0	17.68	0.17	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	2	0	17.74	0.00	0.00	2
3	1	2	0	17.90	0.00	0.00	2
3	1	2	0	18.15	0.00	0.00	2
3	1	2	0	18.27	0.00	0.00	2
3	1	2	0	18.79	0.00	0.00	2
3	1	2	0	19.77	0.00	0.00	2
3	1	2	0	19.80	3.99	0.00	2
3	1	3	0	0.53	15.88	0.00	3
3	1	3	0	0.74	14.93	0.00	3
3	1	3	0	0.88	15.25	0.00	3
3	1	3	0	1.06	13.82	0.00	3
1	1	3	0	1.08	13.79	0.00	3
1	1	3	0	1.49	12.88	0.00	3
1	1	3	0	1.70	14.88	0.00	3
3	1	3	0	1.75	12.64	0.00	3
1	1	3	0	1.85	13.62	0.00	3
3	1	3	0	2.03	14.31	0.00	3
3	1	3	0	2.12	13.01	0.00	3
3	1	3	0	2.23	12.91	0.00	3
3	1	3	0	2.34	11.82	0.00	3
3	1	3	0	2.64	13.61	0.00	3
1	1	3	0	2.75	11.68	0.00	3
3	1	3	0	2.80	13.57	0.00	3
1	1	3	0	2.96	14.28	0.00	3
2	1	3	0	3.02	14.83	0.00	3
2	1	3	0	3.26	12.42	0.00	3
3	1	3	0	3.45	11.73	0.00	3
1	1	3	0	3.54	13.12	0.00	3
1	1	3	0	4.05	9.16	0.00	3
1	1	3	0	4.14	9.73	0.00	3
3	1	3	0	4.31	13.88	0.00	3
3	1	3	0	4.41	11.74	0.00	3
2	1	3	0	5.01	10.15	0.00	3
3	1	3	0	5.16	12.63	0.00	3
3	1	3	0	5.18	12.70	0.00	3
3	1	3	0	5.23	8.89	0.00	3
3	1	3	0	5.49	11.95	0.00	3
1	1	3	0	5.80	11.75	0.00	3
3	1	3	0	5.96	8.41	0.00	3
2	1	3	0	6.07	9.03	0.00	3
1	1	3	0	6.13	9.24	0.00	3
1	1	3	0	6.34	9.84	0.00	3
1	1	3	0	6.41	9.14	0.00	3
1	1	3	0	6.65	12.19	0.00	3
1	1	3	0	6.87	7.81	0.00	3
1	1	3	0	6.94	8.72	0.00	3
1	1	3	0	7.25	10.37	0.00	3
2	1	3	0	7.36	9.88	0.00	3
1	1	3	0	7.58	11.61	0.00	3
3	1	3	0	8.11	6.99	0.00	3
3	1	3	0	8.41	5.16	0.00	3
1	1	3	0	8.52	8.08	0.00	3
3	1	3	0	8.59	6.23	0.00	3
3	1	3	0	8.86	10.08	0.00	3
3	1	3	0	8.92	5.48	0.00	3
3	1	3	0	8.95	9.22	0.00	3
3	1	3	0	9.09	6.05	0.00	3
1	1	3	0	9.29	7.87	0.00	3

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	3	0	9.43	6.91	0.00	3
3	1	3	0	9.85	6.73	0.00	3
3	1	3	0	9.91	7.86	0.00	3
3	1	3	0	10.11	3.27	0.00	3
1	1	3	0	10.37	5.97	0.00	3
3	1	3	0	10.37	4.83	0.00	3
1	1	3	0	10.55	4.12	0.00	3
1	1	3	0	10.74	5.92	0.00	3
3	1	3	0	10.76	3.44	0.00	3
3	1	3	0	12.14	2.73	0.00	3
2	1	3	0	12.22	2.98	0.00	3
3	1	3	0	12.62	4.65	0.00	3
2	1	3	0	12.97	1.82	0.00	3
2	1	3	0	12.99	3.62	0.00	3
1	1	3	0	13.28	0.40	0.00	3
1	1	3	0	13.72	3.08	0.00	3
3	1	3	0	13.95	0.39	0.00	3
1	1	3	0	15.36	0.00	0.00	3
1	1	3	0	18.47	0.00	0.00	3
3	1	3	0	18.69	0.00	0.00	3
3	1	4	1	0.88	12.98	102.29	1
3	1	4	1	1.24	17.01	81.23	1
3	1	4	1	1.39	17.80	72.87	1
2	1	4	1	1.41	15.01	92.29	1
3	1	4	1	1.47	11.80	99.88	1
3	1	4	1	1.47	15.68	101.76	1
3	1	4	1	1.66	16.64	52.89	1
3	1	4	1	1.75	15.80	95.94	1
3	1	4	1	2.08	14.75	89.11	1
3	1	4	1	2.10	18.71	76.44	1
3	1	4	1	2.44	14.12	62.70	1
3	1	4	1	2.50	12.59	93.33	1
3	1	4	1	2.73	21.70	83.67	1
3	1	4	1	2.81	16.95	76.67	1
3	1	4	1	3.26	13.51	99.55	1
3	1	4	1	3.36	16.78	89.32	1
3	1	4	1	3.50	11.85	68.20	1
3	1	4	1	3.58	18.60	96.23	1
3	1	4	1	4.06	14.48	79.14	1
3	1	4	1	4.07	10.27	66.48	1
3	1	4	1	4.12	11.34	68.55	1
3	1	4	1	4.32	11.66	79.02	1
3	1	4	1	4.37	10.91	77.48	1
3	1	4	1	4.37	12.47	82.88	1
3	1	4	1	4.55	9.87	74.50	1
3	1	4	1	4.59	8.75	78.35	1
3	1	4	1	4.63	18.12	51.09	1
3	1	4	1	4.68	16.12	78.78	1
3	1	4	1	4.74	16.21	66.39	1
3	1	4	1	4.95	11.86	85.97	1
2	1	4	1	5.46	13.77	68.40	1
2	1	4	1	5.66	15.46	35.66	1
3	1	4	1	5.73	11.03	59.92	1
3	1	4	1	5.94	16.17	67.23	1
2	1	4	1	6.17	10.44	76.73	1
3	1	4	1	6.21	18.22	60.15	1
3	1	4	1	6.24	18.41	62.14	1
3	1	4	1	6.63	12.65	63.45	1

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	1	4	1	6.70	11.85	71.58	1
3	1	4	1	6.75	13.22	63.29	1
3	1	4	1	6.85	14.53	72.57	1
3	1	4	1	6.86	9.28	64.48	1
3	1	4	1	6.90	12.70	43.46	1
3	1	4	1	6.92	9.93	62.16	1
3	1	4	1	6.95	14.59	65.32	1
3	1	4	1	7.11	11.34	56.06	1
3	1	4	1	7.20	7.81	81.75	1
2	1	4	1	7.34	12.36	64.59	1
3	1	4	1	7.97	17.29	42.85	1
3	1	4	1	8.85	20.22	60.42	1
3	1	4	1	9.00	11.47	31.48	1
3	1	4	1	9.50	8.83	31.73	1
3	1	4	1	9.60	8.31	61.91	1
3	1	4	1	9.69	14.48	57.49	1
3	1	4	1	9.80	7.47	37.17	1
3	1	4	1	9.81	10.87	59.30	1
3	1	4	1	11.91	5.21	36.77	1
3	1	4	1	11.95	6.04	40.98	1
3	1	4	1	11.97	7.01	24.31	1
3	1	4	1	12.18	1.97	22.42	1
3	1	4	1	12.61	2.68	19.34	1
3	1	4	1	12.79	6.00	33.74	1
3	1	4	1	12.88	11.84	33.01	1
3	1	4	1	13.09	4.30	32.10	1
3	1	4	1	13.12	10.29	11.38	1
2	1	4	1	13.22	4.47	10.24	1
3	1	4	1	13.91	6.88	13.08	1
3	1	4	1	14.00	9.57	31.32	1
3	1	4	1	15.08	2.66	10.93	1
3	1	4	1	16.07	0.37	7.38	1
3	1	4	1	16.16	0.19	26.28	1
3	1	4	1	16.29	0.32	10.53	1
3	1	4	1	16.32	2.11	17.74	1
3	1	4	1	16.62	1.07	21.51	1
3	1	4	1	17.65	6.38	8.82	1
3	1	4	1	18.05	0.00	0.00	1
2	3	1	0	0.00	283.33	0.00	3
3	3	1	0	0.03	283.86	0.00	3
3	3	1	0	0.04	286.40	0.00	3
1	3	1	0	0.05	291.38	0.00	3
2	3	1	0	0.10	279.38	0.00	3
3	3	1	0	0.12	290.09	0.00	3
3	3	1	0	0.12	280.98	0.00	3
2	3	1	0	0.13	280.62	0.00	3
3	3	1	0	0.22	300.35	0.00	3
3	3	1	0	0.23	280.05	0.00	3
3	3	1	0	0.27	289.45	0.00	3
3	3	1	0	0.33	271.75	0.00	3
2	3	1	0	0.33	282.16	0.00	3
3	3	1	0	0.41	286.85	0.00	3
2	3	1	0	0.42	291.20	0.00	3
3	3	1	0	0.46	278.09	0.00	3
3	3	1	0	0.49	283.83	0.00	3
1	3	1	0	0.53	297.81	0.00	3
3	3	1	0	0.58	289.47	0.00	3
3	3	1	0	0.67	275.46	0.00	3

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	3	1	0	0.71	283.50	0.00	3
3	3	1	0	0.72	276.21	0.00	3
3	3	1	0	0.84	287.41	0.00	3
3	3	1	0	0.85	285.44	0.00	3
1	3	1	0	0.90	282.41	0.00	3
3	3	1	0	0.93	293.94	0.00	3
3	3	1	0	0.96	273.72	0.00	3
1	3	1	0	1.00	280.49	0.00	3
2	3	1	0	1.09	282.99	0.00	3
3	3	1	0	1.17	280.71	0.00	3
2	3	1	0	1.19	283.80	0.00	3
2	3	1	0	1.30	291.77	0.00	3
1	3	1	0	1.32	270.73	0.00	3
3	3	1	0	1.35	287.92	0.00	3
3	3	1	0	1.39	264.20	0.00	3
3	3	1	0	1.40	282.94	0.00	3
3	3	1	0	1.41	270.21	0.00	3
1	3	1	0	1.41	273.20	0.00	3
3	3	1	0	1.45	277.51	0.00	3
3	3	1	0	1.70	270.73	0.00	3
1	3	1	0	1.86	277.30	0.00	3
2	3	1	0	1.90	274.95	0.00	3
2	3	1	0	1.92	277.28	0.00	3
2	3	1	0	1.96	277.78	0.00	3
3	3	1	0	1.98	276.02	0.00	3
3	3	1	0	2.09	273.44	0.00	3
3	3	1	0	2.26	281.39	0.00	3
3	3	1	0	2.31	282.64	0.00	3
3	3	1	0	2.38	267.23	0.00	3
2	3	1	0	2.49	277.40	0.00	3
2	3	1	0	2.52	276.03	0.00	3
2	3	1	0	2.66	275.31	0.00	3
3	3	1	0	2.67	269.54	0.00	3
2	3	1	0	2.70	266.99	0.00	3
3	3	1	0	2.74	270.18	0.00	3
3	3	1	0	2.83	281.92	0.00	3
1	3	1	0	2.87	285.95	0.00	3
3	3	1	0	2.95	266.91	0.00	3
3	3	1	0	2.98	278.23	0.00	3
2	3	1	0	3.00	280.63	0.00	3
3	3	1	0	3.26	264.11	0.00	3
3	3	1	0	3.29	275.86	0.00	3
3	3	1	0	3.33	260.08	0.00	3
3	3	1	0	3.36	261.62	0.00	3
2	3	1	0	3.58	270.97	0.00	3
1	3	1	0	3.59	263.34	0.00	3
3	3	1	0	3.67	270.07	0.00	3
2	3	1	0	3.67	268.54	0.00	3
1	3	1	0	3.75	273.97	0.00	3
3	3	1	0	3.87	254.14	0.00	3
3	3	1	0	4.13	278.21	0.00	3
2	3	1	0	4.22	265.92	0.00	3
3	3	1	0	4.46	266.43	0.00	3
1	3	1	0	4.52	257.90	0.00	3
1	3	1	0	4.57	252.28	0.00	3
3	3	1	0	4.82	277.70	0.00	3
2	3	1	0	5.06	257.59	0.00	3
3	3	1	0	5.25	262.50	0.00	3

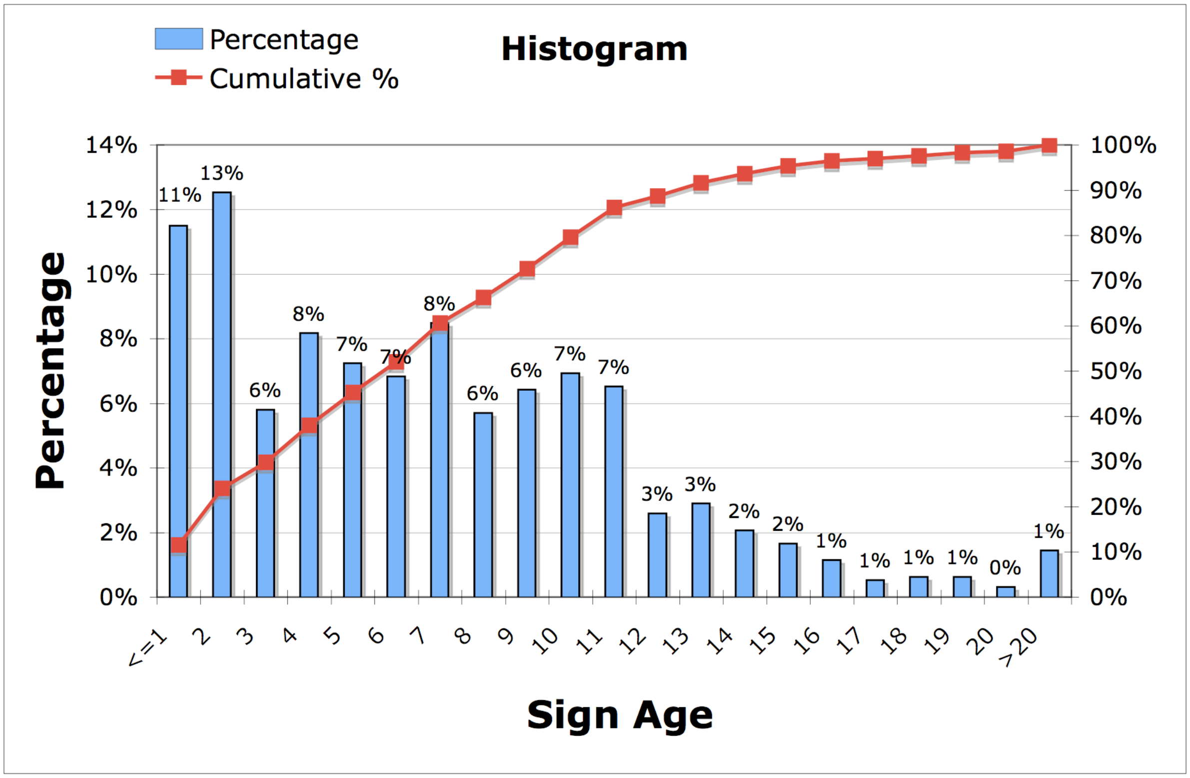
Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	3	1	0	5.66	256.92	0.00	3
2	3	1	0	5.72	261.01	0.00	3
3	3	1	0	5.93	255.42	0.00	3
3	3	1	0	6.07	262.23	0.00	3
3	3	1	0	6.43	254.37	0.00	3
1	3	1	0	6.87	251.90	0.00	3
3	3	1	0	6.98	244.75	0.00	3
3	3	1	0	7.61	242.93	0.00	3
3	3	1	0	8.08	235.35	0.00	3
2	3	1	0	9.57	242.46	0.00	3
3	3	1	0	10.81	230.23	0.00	3
3	3	2	0	0.02	222.73	0.00	2
3	3	2	0	0.03	228.53	0.00	2
3	3	2	0	0.06	224.48	0.00	2
3	3	2	0	0.06	218.15	0.00	2
3	3	2	0	0.09	216.07	0.00	2
2	3	2	0	0.10	227.41	0.00	2
3	3	2	0	0.16	242.13	0.00	2
3	3	2	0	0.17	225.14	0.00	2
2	3	2	0	0.18	223.92	0.00	2
3	3	2	0	0.19	222.26	0.00	2
3	3	2	0	0.21	227.23	0.00	2
3	3	2	0	0.23	229.58	0.00	2
3	3	2	0	0.24	223.86	0.00	2
3	3	2	0	0.26	223.96	0.00	2
3	3	2	0	0.28	232.78	0.00	2
3	3	2	0	0.29	226.85	0.00	2
3	3	2	0	0.31	238.52	0.00	2
3	3	2	0	0.32	224.07	0.00	2
3	3	2	0	0.35	208.59	0.00	2
3	3	2	0	0.36	237.78	0.00	2
2	3	2	0	0.41	230.84	0.00	2
3	3	2	0	0.41	223.10	0.00	2
3	3	2	0	0.42	224.03	0.00	2
1	3	2	0	0.46	240.39	0.00	2
3	3	2	0	0.53	230.77	0.00	2
3	3	2	0	0.58	207.77	0.00	2
2	3	2	0	0.62	228.92	0.00	2
3	3	2	0	0.63	223.16	0.00	2
3	3	2	0	0.69	224.34	0.00	2
3	3	2	0	0.70	225.79	0.00	2
3	3	2	0	0.75	235.86	0.00	2
3	3	2	0	0.76	233.22	0.00	2
3	3	2	0	0.81	239.08	0.00	2
3	3	2	0	0.85	236.70	0.00	2
3	3	2	0	0.88	211.57	0.00	2
3	3	2	0	0.99	230.53	0.00	2
3	3	2	0	1.02	225.63	0.00	2
3	3	2	0	1.06	222.74	0.00	2
3	3	2	0	1.15	221.54	0.00	2
3	3	2	0	1.21	229.82	0.00	2
3	3	2	0	1.22	219.21	0.00	2
3	3	2	0	1.29	224.52	0.00	2
3	3	2	0	1.34	223.89	0.00	2
3	3	2	0	1.38	221.90	0.00	2
2	3	2	0	1.40	214.65	0.00	2
3	3	2	0	1.41	226.15	0.00	2
3	3	2	0	1.50	216.59	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	3	2	0	1.52	230.32	0.00	2
1	3	2	0	1.54	220.02	0.00	2
3	3	2	0	1.58	213.59	0.00	2
3	3	2	0	1.68	217.16	0.00	2
3	3	2	0	1.80	220.63	0.00	2
3	3	2	0	1.92	218.78	0.00	2
3	3	2	0	1.94	235.22	0.00	2
3	3	2	0	1.99	223.00	0.00	2
2	3	2	0	2.01	218.76	0.00	2
3	3	2	0	2.17	217.24	0.00	2
2	3	2	0	2.24	221.55	0.00	2
2	3	2	0	2.27	233.51	0.00	2
3	3	2	0	2.28	218.43	0.00	2
3	3	2	0	2.34	213.79	0.00	2
3	3	2	0	2.50	219.03	0.00	2
2	3	2	0	2.53	224.36	0.00	2
2	3	2	0	2.64	226.53	0.00	2
3	3	2	0	2.67	218.98	0.00	2
3	3	2	0	2.71	230.55	0.00	2
3	3	2	0	2.71	220.58	0.00	2
3	3	2	0	2.75	220.51	0.00	2
2	3	2	0	2.75	209.66	0.00	2
3	3	2	0	3.01	222.25	0.00	2
2	3	2	0	3.02	224.27	0.00	2
3	3	2	0	3.03	214.56	0.00	2
3	3	2	0	3.08	208.14	0.00	2
3	3	2	0	3.13	216.94	0.00	2
3	3	2	0	3.25	216.08	0.00	2
3	3	2	0	3.26	217.32	0.00	2
3	3	2	0	3.36	230.27	0.00	2
3	3	2	0	3.45	215.10	0.00	2
3	3	2	0	3.53	234.75	0.00	2
2	3	2	0	3.53	222.38	0.00	2
3	3	2	0	3.62	234.06	0.00	2
2	3	2	0	3.63	214.57	0.00	2
3	3	2	0	3.72	213.08	0.00	2
2	3	2	0	3.85	216.40	0.00	2
3	3	2	0	3.89	222.19	0.00	2
3	3	2	0	3.96	220.42	0.00	2
3	3	2	0	4.25	224.65	0.00	2
3	3	2	0	4.38	225.64	0.00	2
2	3	2	0	4.39	217.62	0.00	2
3	3	2	0	4.51	221.64	0.00	2
3	3	2	0	4.83	215.40	0.00	2
3	3	2	0	4.87	219.54	0.00	2
3	3	2	0	5.27	209.46	0.00	2
2	3	2	0	5.38	208.66	0.00	2
3	3	2	0	6.13	216.31	0.00	2
3	3	2	0	6.22	211.81	0.00	2
3	3	2	0	6.24	207.69	0.00	2
1	3	2	0	6.40	206.13	0.00	2
3	3	2	0	6.72	212.45	0.00	2
3	3	2	0	6.95	220.84	0.00	2
1	3	2	0	6.98	202.51	0.00	2
3	3	2	0	7.74	201.70	0.00	2
3	3	2	0	7.81	209.76	0.00	2
1	3	2	0	7.93	215.03	0.00	2
3	3	2	0	8.01	208.78	0.00	2

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	3	2	0	8.56	187.34	0.00	2
1	3	2	0	8.90	192.70	0.00	2
3	3	2	0	9.01	201.25	0.00	2
3	3	2	0	9.60	191.37	0.00	2
3	3	2	0	9.66	206.73	0.00	2
2	3	2	0	9.77	194.57	0.00	2
2	3	2	0	10.11	182.53	0.00	2
3	3	2	0	10.24	183.76	0.00	2
3	3	2	0	11.09	194.47	0.00	2
3	3	2	0	11.11	195.38	0.00	2
3	3	2	0	11.16	197.75	0.00	2
3	3	2	0	11.16	182.59	0.00	2
2	3	2	0	17.06	193.22	0.00	2
1	3	3	0	0.06	47.04	0.00	3
3	3	3	0	0.11	51.72	0.00	3
1	3	3	0	0.22	47.31	0.00	3
3	3	3	0	0.40	46.72	0.00	3
2	3	3	0	0.75	49.91	0.00	3
3	3	3	0	0.89	53.04	0.00	3
3	3	3	0	0.91	48.76	0.00	3
1	3	3	0	1.32	50.54	0.00	3
1	3	3	0	1.32	45.68	0.00	3
1	3	3	0	1.36	46.95	0.00	3
1	3	3	0	1.45	42.99	0.00	3
1	3	3	0	1.92	55.42	0.00	3
3	3	3	0	2.60	46.79	0.00	3
1	3	3	0	4.75	38.19	0.00	3
1	3	3	0	4.77	45.32	0.00	3
2	3	3	0	5.70	48.89	0.00	3
3	3	3	0	6.84	40.91	0.00	3
3	3	3	0	10.08	35.81	0.00	3
3	3	4	1	0.07	51.83	282.55	1
3	3	4	1	0.21	52.56	286.93	1
3	3	4	1	0.22	53.25	277.28	1
3	3	4	1	0.29	49.69	288.49	1
3	3	4	1	0.62	43.02	292.18	1
3	3	4	1	0.69	59.91	276.54	1
3	3	4	1	0.72	56.67	296.01	1
3	3	4	1	1.05	59.46	274.33	1
3	3	4	1	1.08	47.80	282.65	1
3	3	4	1	1.46	47.20	287.46	1
3	3	4	1	1.59	48.09	260.50	1
3	3	4	1	1.93	42.16	287.46	1
3	3	4	1	2.13	37.49	281.84	1
3	3	4	1	2.22	47.56	270.19	1
3	3	4	1	2.27	47.53	266.57	1
3	3	4	1	2.65	41.69	275.00	1
3	3	4	1	3.04	48.82	259.96	1
3	3	4	1	3.22	43.77	277.37	1
3	3	4	1	3.30	46.21	264.71	1
3	3	4	1	3.54	45.67	269.83	1
3	3	4	1	3.67	40.55	269.18	1
3	3	4	1	4.27	33.28	258.79	1
3	3	4	1	4.37	49.63	256.75	1
3	3	4	1	4.51	38.95	263.48	1
3	3	4	1	4.56	39.15	255.15	1
3	3	4	1	4.70	46.36	249.17	1
3	3	4	1	5.30	38.84	268.15	1

Road Type	Sheeting Type	Main Color	Sec. Color	2005 Age	2005 Main Ra	2005 Sec Ra	Action Code
3	3	4	1	6.45	27.43	253.27	1
3	3	4	1	7.57	33.37	249.57	1
3	3	4	1	9.49	23.90	232.34	1
3	3	4	1	10.07	17.07	235.18	1
3	3	4	1	10.51	25.15	234.45	1

Histogram of Sign Input File values by Sign Age



14.4 Appendix D: List of Input Parameter Values for Each Simulation Scenario

No	Input File	Overall Damage Rate	Annual Damage Rate	Damage Replacement Percentage	Frequency Set	Inspection Frequency, Interstate	Inspection Frequency, Primary	Inspection Frequency, Secondary	Accuracy Set	Above Min and Fail, not Stop	Above Min and Fail, Stop	Below Min and Fail, not Stop	Below Min and Fail, Stop	Rejected Set	Rejected Type I AC 1 Replaced	Rejected Type I AC 2 Replaced	Rejected Type I AC 3 Replaced	Rejected Type III AC 1 Replaced	Rejected Type III AC 2 Replaced	Rejected Type III AC 3 Replaced	Not Rejected Set	Not Rejected Signs Replaced	Conversion Set	Type I, AC 1 & 2 replaced with Type III	Type I, AC 3 replaced with Type III	Type III replaced with Type III	Percent Rejected Replaced before Next Inspection	Budget	No.
1	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	None	None
2	NCDOT/NC	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
3	State	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
4	County	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
5	Municipal	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
6	Town	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
7	NCDOT/NCSU	7	4	60	**2**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
8	NCDOT/NC	7	4	60	**2**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
9	State	7	4	60	**2**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
10	County	7	4	60	**2**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
11	Municipal	7	4	60	**2**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
12	Town	7	4	60	**2**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
13	NCDOT/NCSU	7	4	60	**4**	4	4	4	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
14	NCDOT/NC	7	4	60	**4**	4	4	4	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
15	State	7	4	60	**4**	4	4	4	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
16	County	7	4	60	**4**	4	4	4	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
17	Municipal	7	4	60	**4**	4	4	4	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
18	Town	7	4	60	**4**	4	4	4	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
19	NCDOT/NCSU	7	4	60	**1**	1	1	1	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
20	NCDOT/NC	7	4	60	**1**	1	1	1	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
21	State	7	4	60	**1**	1	1	1	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
22	County	7	4	60	**1**	1	1	1	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
23	Municipal	7	4	60	**1**	1	1	1	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
24	Town	7	4	60	**1**	1	1	1	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
25	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	**6**	50	50	50	100		
26	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	**7**	0	0	0	100		
27	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	**5**	100	100	100	100		
28	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	**8**	25	25	25	100		
29	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	**1**	96	62	100	100		
30	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	**2**	100	67	100	100		
31	NCDOT/NCSU	7	4	60	**6**	1	2	3	6	5	5	80	80	5	90	60	40	70	40	20	3	5	**4**	90	90	100	100		
32	NCDOT/NCSU	7	4	**100**	**9**	7	7	7	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
33	NCDOT/NCSU	7	4	**100**	**10**	12	12	12	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
34	NCDOT/NCSU	7	4	**60**	**9**	7	7	7	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
35	NCDOT/NCSU	7	4	**60**	**10**	12	12	12	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
36	NCDOT/NCSU	7	4	**100**	**9**	7	7	7	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
37	NCDOT/NCSU	7	4	**100**	**10**	12	12	12	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
38	NCDOT/NCSU	7	4	**100**	**11**	15	15	15	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
39	NCDOT/NCSU	7	4	**60**	**11**	15	15	15	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
40	County	7	4	**fix - annual**	**9**	7	7	7	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
41	County	7	4	**fix - annual**	**10**	12	12	12	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		

No	Input File	Overall Damage Rate	Annual Damage Rate	Damage Replacement Percentage	Frequency Set	Inspection Frequency, Interstate	Inspection Frequency, Primary	Inspection Frequency, Secondary	Accuracy Set	Above Min and Fail, not Stop	Above Min and Fail, Stop	Below Min and Fail, not Stop	Below Min and Fail, Stop	Rejected Set	Rejected Type I AC 1 Replaced	Rejected Type I AC 2 Replaced	Rejected Type I AC 3 Replaced	Rejected Type III AC 1 Replaced	Rejected Type III AC 2 Replaced	Rejected Type III AC 3 Replaced	Not Rejected Set	Not Rejected Signs Replaced	Conversion Set	Type I, AC 1 & 2 replaced with Type III	Type I, AC 3 replaced with Type III	Type III replaced with Type III	Percent Rejected Replaced before Next Inspection	Budget	No.
42	County	7	4	**fix - annual**	**11**	15	15	15	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
43	County	7	4	**fix - annual**	**fix - 1/7**	7	7	7	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
44	County	7	4	**fix - annual**	**fix - 1/12**	12	12	12	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
45	County	7	4	**fix - annual**	**fix - 1/15**	15	15	15	**9**	100	100	100	100	**4**	100	100	100	100	100	100	**2**	0	**5**	100	100	100	100		
46	County	7	4	60	2	2	2	2	**1**	3.5	5.9	27.7	71.4	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
47	County	7	4	60	2	2	2	2	**2**	3.9	3.9	28.8	28.8	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
48	County	7	4	60	2	2	2	2	**3**	0	0	100	100	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
49	County	7	4	60	2	2	2	2	**4**	5	5	40	40	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
50	County	7	4	60	2	2	2	2	**5**	5	5	60	60	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
51	County	7	4	60	2	2	2	2	**7**	5	5	90	90	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
52	County	7	4	60	2	2	2	2	**8**	28	18	81	70	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
53	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	**80**		
54	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	**60**		
55	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	**0**		
56	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	**1**	9.3	3	95	80	100	100		
57	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	**2**	0	3	95	80	100	100		
58	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	**4**	10	3	95	80	100	100		
59	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	**5**	20	3	95	80	100	100		
60	County	7	4	60	2	2	2	2	6	5	5	80	80	**1**	88.9	61.7	40.4	66.7	37.5	0	3	5	3	95	80	100	100		
61	County	7	4	60	2	2	2	2	6	5	5	80	80	**2**	100	66.7	33.3	100	66.7	33.3	3	5	3	95	80	100	100		
62	County	7	4	60	2	2	2	2	6	5	5	80	80	**3**	100	66.7	33.3	90	50	25	3	5	3	95	80	100	100		
63	County	7	4	60	2	2	2	2	6	5	5	80	80	**4**	100	100	100	100	100	100	3	5	3	95	80	100	100		
64	County	7	4	60	2	2	2	2	6	5	5	80	80	**6**	80	50	30	60	30	10	3	5	3	95	80	100	100		
65	County	7	4	60	2	2	2	2	6	5	5	80	80	**7**	0	0	0	0	0	0	3	5	3	95	80	100	100		
66	County	7	4	60	2	2	2	2	6	5	5	80	80	**8**	90	60	40	90	60	40	3	5	3	95	80	100	100		
67	County	7	4	60	2	2	2	2	6	5	5	80	80	**9**	80	50	30	80	50	30	3	5	3	95	80	100	100		
68	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	50	not activated	
69	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	not activated	**1000**
70	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	not activated	**1000**
71	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	not activated	**1000**
72	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	**Expected**	138
73	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	**Expected**	**167**
74	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	**Expected**	188
75	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	30yr avg	121
76	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	30yr avg	119
77	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	30yr avg	111
78	County	7	4	60	**Insp skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	**Expected**	**135**
79	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	not activated	1000
80	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	not activated	1000
81	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	not activated	1000
82	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	**Expected**	138
83	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	**Expected**	141
84	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	**Expected**	172
85	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	30yr avg	121
86	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	30yr avg	119
87	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	30yr avg	111
88	County	7	4	60	**Irep skip, 3 (2)**	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	**Expected**	135

No	Input File	Overall Damage Rate	Annual Damage Rate	Damage Replacement Percentage	Frequency Set	Inspection Frequency, Interstate	Inspection Frequency, Primary	Inspection Frequency, Secondary	Accuracy Set	Above Min and Fail, not Stop	Above Min and Fail, Stop	Below Min and Fail, not Stop	Below Min and Fail, Stop	Rejected Set	Rejected Type I AC 1 Replaced	Rejected Type I AC 2 Replaced	Rejected Type I AC 3 Replaced	Rejected Type III AC 1 Replaced	Rejected Type III AC 2 Replaced	Rejected Type III AC 3 Replaced	Not Rejected Set	Not Rejected Signs Replaced	Conversion Set	Type I, AC 1 & 2 replaced with Type III	Type I, AC 3 replaced with Type III	Type III replaced with Type III	Percent Rejected Replaced before Next Inspection	Budget	No.
89	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	not activated	1000
90	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	not activated	1000
91	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	not activated	1000
92	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	Expected	139
93	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	Expected	125
94	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	Expected	80
95	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	30yr avg	121
96	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	30yr avg	119
97	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	30yr avg	111
98	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	not activated	1000
99	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	not activated	1000
100	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	not activated	1000
101	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	Expected	138
102	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	Expected	141
103	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	Expected	172
104	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	30yr avg	121
105	NCDOT/NCSU	7.5	4.7	62.7	6	1	2	3	6	5	5	80	80	1	88.9	61.7	40.4	66.7	37.5	0	1	9.3	1	96	62	100	100	Paper #1	
106	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	25	not activated	
107	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	80	30yr avg	119
108	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	Expected	135
109	County	7	4	60	NIrep&Insp, 3 (2)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	30yr avg	111
110	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	75	not activated	
111	County	7	4	60	2	2	2	2	6	5	5	80	80	1	88.9	61.7	40.4	66.7	37.5	0	3	5	3	95	80	100	0	rep rej test #2	
112	County	7	4	60	2	2	2	2	6	5	5	80	80	2	100	66.7	33.3	100	66.7	33.3	3	5	3	95	80	100	0	rep rej test #3	
113	County	7	4	60	2	2	2	2	6	5	5	80	80	3	100	66.7	33.3	90	50	25	3	5	3	95	80	100	0	rep rej test #4	
114	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	3	5	3	95	80	100	0	rep rej test #5	
115	County	7	4	60	2	2	2	2	6	5	5	80	80	6	80	50	30	60	30	10	3	5	3	95	80	100	0	rep rej test #6	
116	County	7	4	60	2	2	2	2	6	5	5	80	80	7	0	0	0	0	0	0	3	5	3	95	80	100	0	rep rej test #7	
117	County	7	4	60	2	2	2	2	6	5	5	80	80	8	90	60	40	90	60	40	3	5	3	95	80	100	0	rep rej test #8	
118	County	7	4	60	2	2	2	2	6	5	5	80	80	9	80	50	30	80	50	30	3	5	3	95	80	100	0	rep rej test #9	
119	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	2	0	3	95	80	100	100	budget test	80
120	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	2	0	3	95	80	100	100	budget test	92
121	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	2	0	3	95	80	100	100	budget test	121
122	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	2	0	3	95	80	100	100	budget test	127
123	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	2	0	3	95	80	100	100	budget test	161
124	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	budget test	80
125	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	budget test	92
126	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	budget test	121
127	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	budget test	127
128	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100	budget test	161
129	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	6	50	50	50	100		
130	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	7	0	0	0	100		
131	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	5	100	100	100	100		
132	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	8	25	25	25	100		
133	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	1	96	62	100	100		
134	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	2	100	67	100	100		

No	Input File	Overall Damage Rate	Annual Damage Rate	Damage Replacement Percentage	Frequency Set	Inspection Frequency, Interstate	Inspection Frequency, Primary	Inspection Frequency, Secondary	Accuracy Set	Above Min and Fail, not Stop	Above Min and Fail, Stop	Below Min and Fail, not Stop	Below Min and Fail, Stop	Rejected Set	Rejected Type I AC 1 Replaced	Rejected Type I AC 2 Replaced	Rejected Type I AC 3 Replaced	Rejected Type III AC 1 Replaced	Rejected Type III AC 2 Replaced	Rejected Type III AC 3 Replaced	Not Rejected Set	Not Rejected Signs Replaced	Conversion Set	Type I, AC 1 & 2 replaced with Type III	Type I, AC 3 replaced with Type III	Type III replaced with Type III	Percent Rejected Replaced before Next Inspection	Budget	No.
135	County	7	4	60	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	4	90	90	100	100		
136	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	Expected	121
137	County	7	4	60	NIrep skip, 4 (3)	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	0	Expected	159
138	NCDOT/NCSU	7.5	4.7	62.7	6	1	2	3	6	5	5	80	80	1a	83.3	57.1	42.4	50	20	0	1	9.3	1	96	62	100	100	Paper #1 true	
139	County	7	2	100	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
140	County	7	4	0	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
141	County	7	4	20	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
142	County	7	4	40	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
143	County	7	4	80	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
144	County	7	4	100	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
145	County	7	6	100	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
146	County	5	2	100	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
147	County	5	4	100	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
148	County	3	2	100	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
149	County	3	2	66.6	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
150	County	5	4	80	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
151	County	5	2	40	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
152	County	7	4	57.1	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
153	County	7	6	85.7	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
154	County	9	8	88.8	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
155	County	9	6	66.6	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
156	County	9	4	44.4	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
157	County	9	2	22.2	2	2	2	2	6	5	5	80	80	5	90	60	40	70	40	20	3	5	3	95	80	100	100		
158	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	2	0	3	95	80	100	100	no budget	from run 158
159	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	2	0	3	95	80	100	100	budget test	45
160	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	2	0	3	95	80	100	100	budget test	63
161	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	2	0	3	95	80	100	100	budget test	85
162	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	2	0	3	95	80	100	100	budget test	107
163	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	2	0	3	95	80	100	100	budget test	131
164	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	3	5	3	95	80	100	100	budget test	90
165	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	3	5	3	95	80	100	100	budget test	105
166	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	3	5	3	95	80	100	100	budget test	118
167	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	3	5	3	95	80	100	100	budget test	140
168	County	7	4	60	2	2	2	2	6	5	5	80	80	4	100	100	100	100	100	100	3	5	3	95	80	100	100	budget test	163
169	County	7	4	100	2	2	2	2	3	0	0	100	100	4	100	100	100	100	100	100	2	0	5	100	100	100	100	"perfect" runs	
170	County	7	4	100	2	2	2	2	3	0	0	100	100	4	100	100	100	100	100	100	3	5	5	100	100	100	100		
171	County	7	4	60	2	2	2	2	3	0	0	100	100	4	100	100	100	100	100	100	2	0	5	100	100	100	100	"perfect" runs	
172	County	7	4	60	2	2	2	2	3	0	0	100	100	4	100	100	100	100	100	100	3	5	5	100	100	100	100		
173	County	7	4	60	1	1	1	1	3	0	0	100	100	4	100	100	100	100	100	100	3	5	5	100	100	100	100	expected life	
174	County	7	4	100	1	1	1	1	3	0	0	100	100	4	100	100	100	100	100	100	3	5	5	100	100	100	100	control signs	
175	County	7	4	60	1	1	1	1	3	0	0	100	100	4	100	100	100	100	100	100	2	0	5	100	100	100	100		
176	County	7	4	100	1	1	1	1	3	0	0	100	100	4	100	100	100	100	100	100	2	0	5	100	100	100	100		

14.5 Appendix E: Table of Simulation Input Parameters and Variables

The table below contains the 74 variables used in the Arena sign system simulation developed as a part of this research. Each variable's function is described and its initial value for the base case scenario is given. Some of the variables serve as input parameters for the simulation scenarios while the other variables keep track of essential simulation functions and processes.

The variables that serve as input parameters are shaded. The initial values of the input parameters change for each scenario according to the values given in Section 14.4, Appendix D: List of Input Parameter Values for Each Simulation Scenario.

	Input Parameter/Variable	Abbreviation in Arena Simulation	Initial Value (Base Case)
1	Number of signs in the system	numsigns	1000
2	Estimated Type I White Deterioration Slope	White1Est	-5.451
3	Type I White Deterioration Slope Standard Deviation	White1SE	0.217
4	Estimated Type I Yellow Deterioration Slope	Yellow1Est	-3.906
5	Type I Yellow Deterioration Slope Standard Deviation	Yellow1SE	0.210
6	Type I Red Deterioration Slope Standard Deviation	Red1SE	0.171
7	Estimated Type I Yellow Deterioration Slope	Red1Est	-0.898
8	Estimated Type I Green Deterioration Slope	Green1Est	-0.982
9	Type I Green Deterioration Slope Standard Deviation	Green1SE	0.424
10	Estimated Type III White Deterioration Slope	White3Est	-5.236
11	Type III White Deterioration Slope Standard Deviation	White3SE	1.217
12	Estimated Type III Yellow Deterioration Slope	Yellow3Est	-2.554
13	Type III Yellow Deterioration Slope Standard Deviation	Yellow3SE	1.103
14	Estimated Type III Red Deterioration Slope	Red3Est	-3.521
15	Type III Red Deterioration Slope Standard Deviation	Red3SE	0.667
16	Estimated Type III Green Deterioration Slope	Green3Est	-1.345
17	Type III Green Deterioration Slope Standard Deviation	Green3SE	0.248
18	Initial Overall Damage Percent, Interstate	InterstateInitDamage	7
19	Initial Overall Damage Percent, Primary	PrimaryInitDamage	7
20	Initial Overall Damage Percent, Secondary	SecondaryInitDamage	7
21	Stop Signs Above the Minimum Retro and Fail Inspection (%)	StopAboveFailPercent	5
22	All Other Signs Above the Minimum Retro and Fail Inspection (%)	OthersAboveFailPercent	5

	Input Parameter/Variable	Abbreviation in Arena Simulation	Initial Value (Base Case)
23	Stop Signs Below the Minimum Retro and Fail Inspection (%)	StopBelowFailPercent	80
24	All Other Signs Below the Minimum Retro and Fail Inspection (%)	OthersBelowFailPercent	80
25	Rejected Type I Action Code 1 Signs Replaced (percent)	T1AC1Replace	90
26	Rejected Type I Action Code 2 Signs Replaced (percent)	T1AC2Replace	60
27	Rejected Type I Action Code 3 Signs Replaced (percent)	T1AC3Replace	40
28	Rejected Type III Action Code 1 Signs Replaced (percent)	T3AC1Replace	70
29	Rejected Type III Action Code 2 Signs Replaced (percent)	T3AC2Replace	40
30	Rejected Type III Action Code 3 Signs Replaced (percent)	T3AC3Replace	20
31	Not Rejected Signs Replaced (percent) for All Signs, Road Types, and Action Codes	NotRejPercentRep	5
32	Inspection Frequency, Interstate (years)	InspectIntI	2
33	Inspection Frequency, Primary (years)	InspectIntP	2
34	Inspection Frequency, Secondary (years)	InspectIntS	2
35	Damaged Signs Replaced (percent) for All Signs, Road Types, and Action Codes	DamRepPercent	60
36	Annual Damage (percent) for All Signs, Road Types, and Action Codes	AnnualDamagePercent	4
37	Current Simulation Year	SimYear	0
38	Simulation Year when Simulation Ends	SimLimit	50
39	Output File Format (1= partial, 2 = full)	OutputStyle	1
40	Skip Inspection? (1 = yes, 2 = no)	SkipInsp	2
41	Year when inspection will be skipped	InspExYr	2
42	Skip Non-Inspection Year Replacement? (1 = yes, 2 = no)	SkipNIRep	2
43	Year when non-inspection year replacement will be skipped	NIRepExYr	3
44	Skip Inspection Year Replacement? (1 = yes, 2 = no)	SkipIRep	2
45	Year when inspection year replacement will be skipped	IRepExYr	4
46	Rejected Signs Replaced (percent) Before Next Inspection Year	NiRepTotalPercent	100
47	Previous year's count of the number of replaced signs	BudgetCounter	0
48	Maximum number of signs budgeted for replacement in a given simulation year	ReplacementBudget	140
49	Have any skips happened in this replication? (1 = yes, 2 = no)	Skip	2
50	Count of how many signs in the budget have been replaced in a given simulation year	Tracker	0
51	Type I Action Code 1 and 2 Signs Replaced with Type III Signs (percent)	T1AC12RepT3	95
52	Type I Action Code 3 Signs Replaced with Type III Signs (percent)	T1AC3RepT3	80

	Input Parameter/Variable	Abbreviation in Arena Simulation	Initial Value (Base Case)
53	Type III Signs Replaced with Type III Signs (percent)	T3RepT3	100
54	Percent of rejected Interstate Signs replaced during the most recent inspection year	IRPI	0
55	Percent of rejected Primary Signs replaced during the most recent inspection year	PRPI	0
56	Percent of rejected Secondary Signs replaced during the most recent inspection year	SRPI	0
57	Percent of rejected Interstate Signs replaced during the previous simulation year	IRPY	0
58	Percent of rejected Primary Signs replaced during the previous simulation year	PRPY	0
59	Percent of rejected Secondary Signs replaced during the previous simulation year	SRPY	0
60	Percent of rejected Interstate Signs replaced during the current simulation year	IRPY1	0
61	Percent of rejected Primary Signs replaced during the current simulation year	PRPY1	0
62	Percent of rejected Secondary Signs replaced during the current simulation year	SRPY1	0
63	Previous year's count of rejected but not replaced interstate signs	IntRejNotRepOldCount	0
64	Previous year's count of rejected but not replaced primary signs	PriRejNotRepOldCount	0
65	Previous year's count of rejected but not replaced secondary signs	SecRejNotRepOldCount	0
66	Previous year's count of rejected interstate signs entering the replacement submodel	IntRejEnterRepOldCount	0
67	Previous year's count of rejected interstate signs entering the replacement submodel	PriRejEnterRepOldCount	0
68	Previous year's count of rejected secondary signs entering the replacement submodel	SecRejEnterRepOldCount	0
69	Are interstate signs inspected this simulation year? (1 = yes, 2 = no)	InspectyearI	2
70	Are primary signs inspected this simulation year? (1 = yes, 2 = no)	InspectyearP	2
71	Are secondary signs inspected this simulation year? (1 = yes, 2 = no)	InspectyearS	2
72	Year position in the inspection cycle for interstate signs	InspectcycleI	1
73	Year position in the inspection cycle for primary signs	InspectcycleP	1
74	Year position in the inspection cycle for secondary signs	InspectcycleS	1

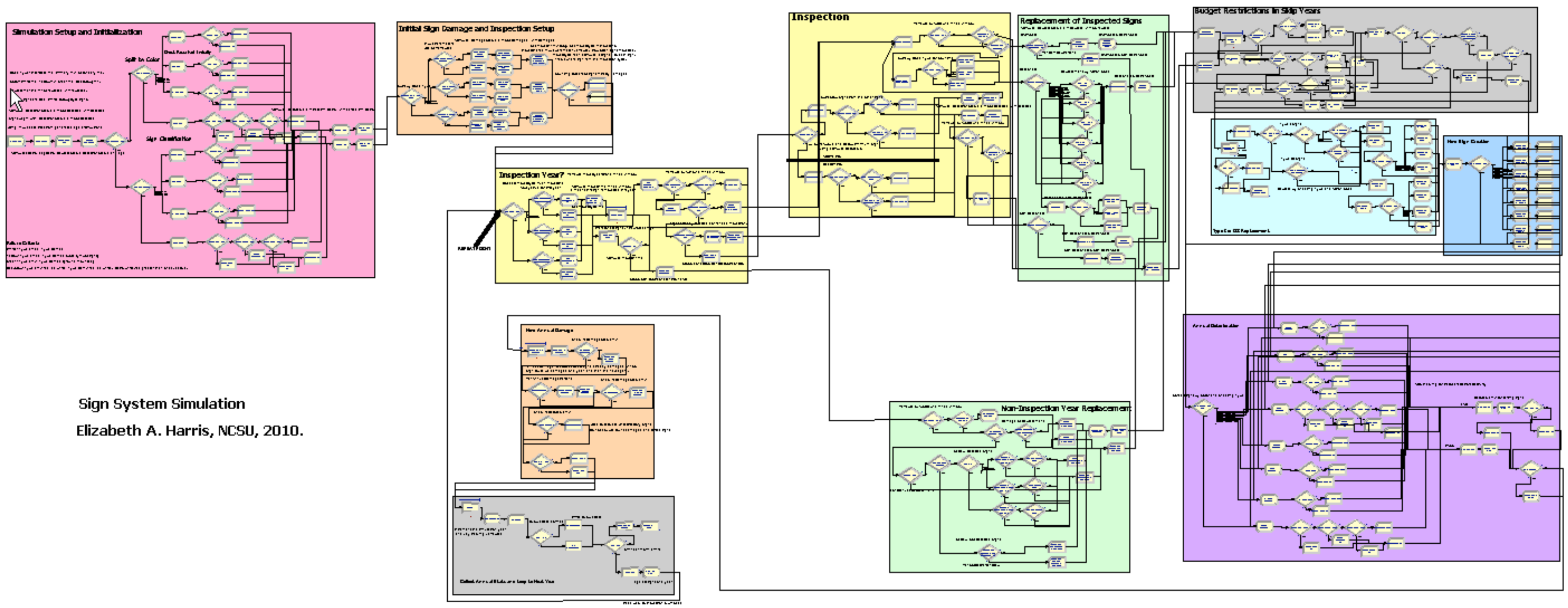
14.6 Appendix F: Table of Simulation Output Measures

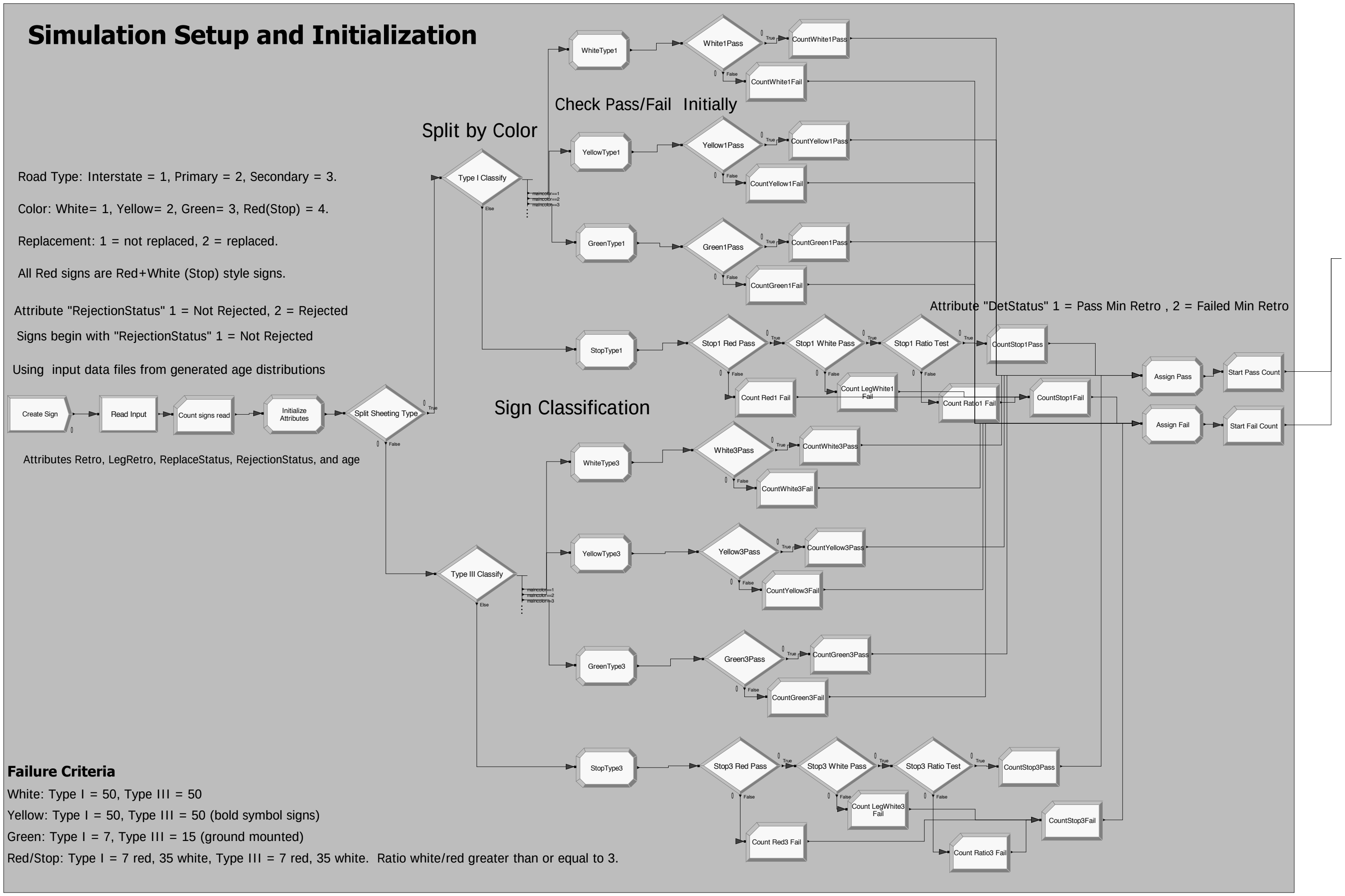
The table below provides the output measure values recorded for the partial output option, which was used for most of the simulation scenarios analysis. The full output option was primarily used for debugging/verification purposes. Each output measure is recorded for each simulation year, resulting in 50 measure values per replication and 1500 (50 x 30) measure values per simulation scenario run.

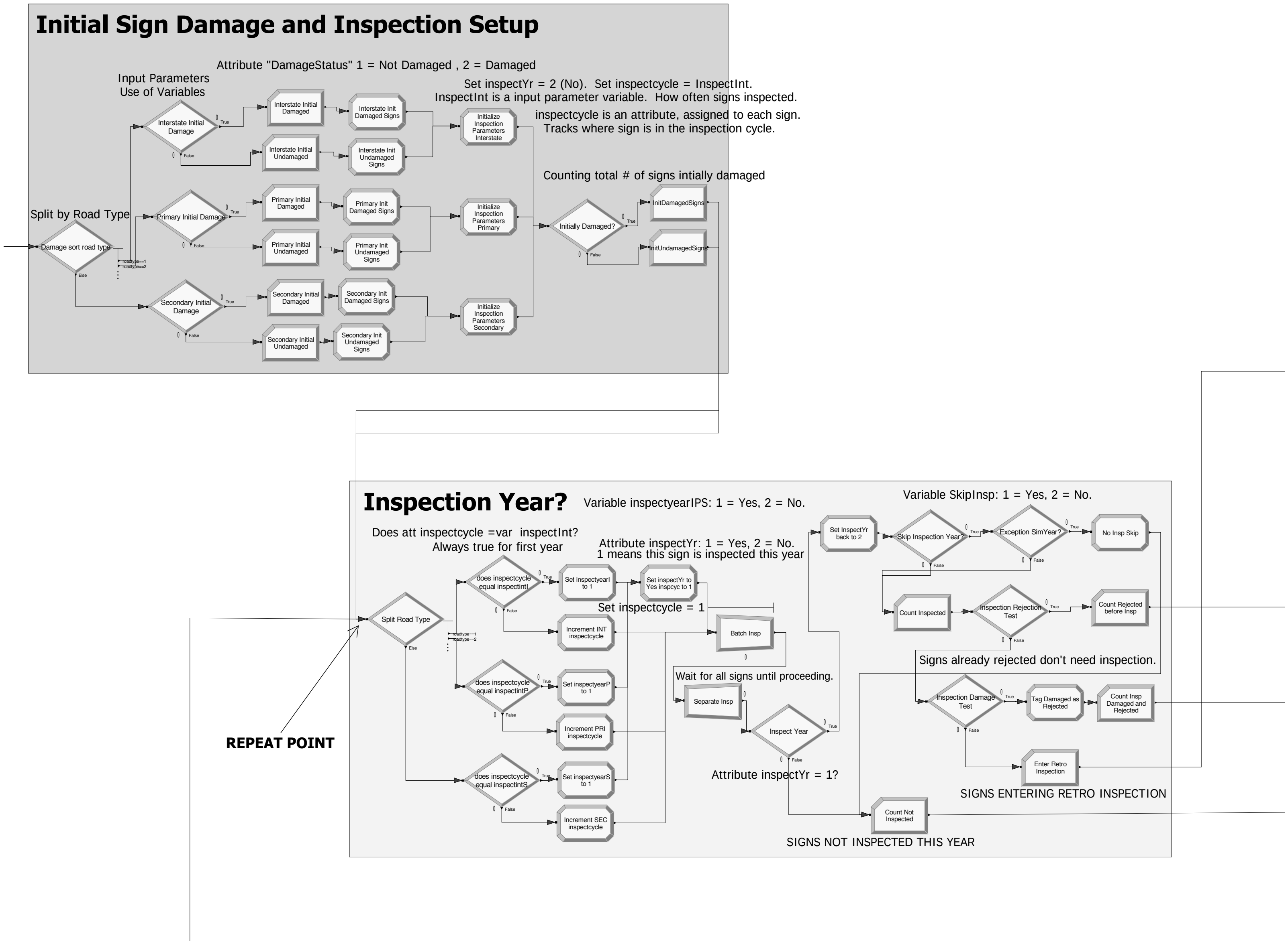
	Output Measure	**Name in Arena Simulation**
1	Current simulation year	SimYear
2	Number of signs inspected	Count Inspected
3	Number of signs inspected and found to be damaged	Count Insp Damaged and Rejected
4	Number of signs above the minimum retroreflectivity standard that enter the inspection submodel	Count AboveMin
5	Signs rejected during a previous inspection year that were not replaced	Count Rejected Before Insp
6	Total number of signs replaced in a non-inspection year	Count Replace and Not Insp
7	Number of damaged signs replaced in a non-inspection year	Count RepDamaged in Not Insp
8	Number of previously rejected signs replaced in a non-inspection year	Count RepRejected in Not Insp
9	Number of signs inspected and rejected by inspectors for poor retroreflectivity	Count Retro Rejected
10	Number of rejected signs to be replaced in an inspection year	ReplacedRejected
11	Number of damaged signs to be replaced in an inspection year	Count RepDamaged in Insp
12	Total number of signs replaced	Enter Sheeting Type
13	Number of signs that are Type I at the end of the simulation year	Count Type I
14	Number of damaged signs at the end of the simulation year	Count New Overall Damage
15	Number of signs above the minimum retroreflectivity standard at the end of the simulation year	AfterDetPass
16	Number of signs either damaged or below the minimum retroreflectivity standard at the end of the simulation year	Unsatisfactory Signs
17	Number of signs marked for replacement that were not replaced because of insufficient budget funds	Signs not rep due to budget
18	Number of signs replaced with Type I sheeting	Replace with Type I

14.7 Appendix G: View of Simulation Submodels and Modules in Arena

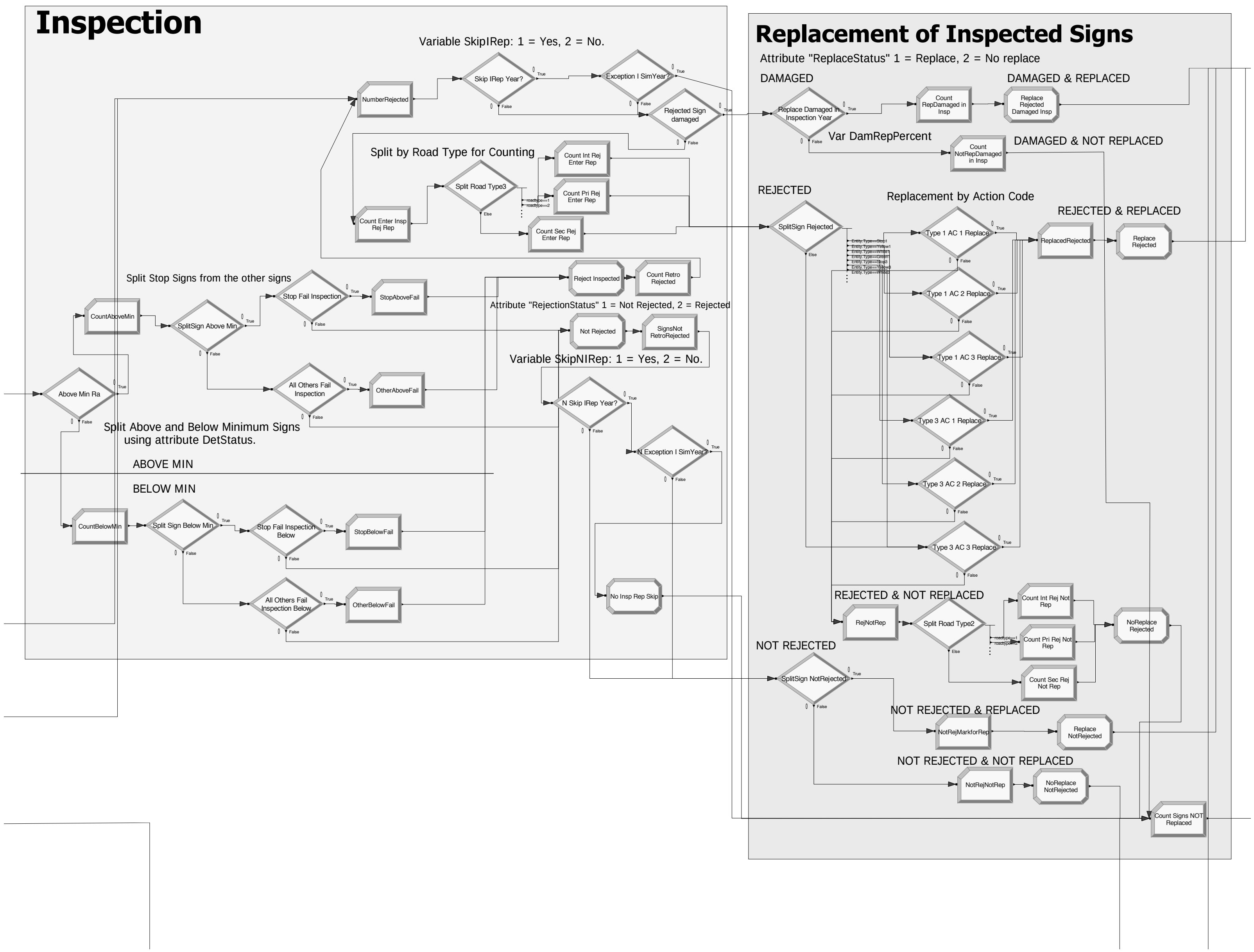
The image below shows a view of the entire simulation model. The following pages show close-up views of each simulation submodel.

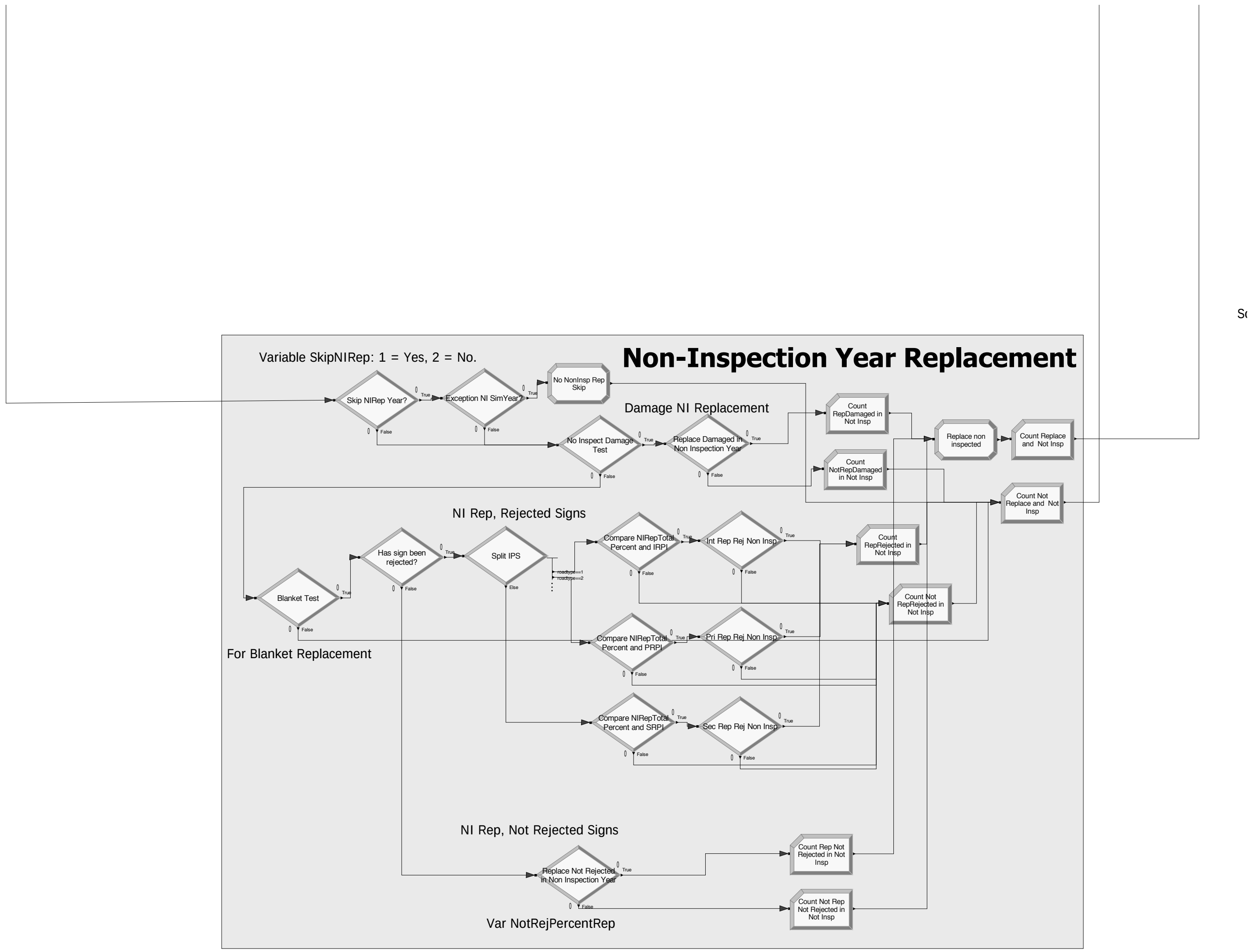



Simulation Setup and Initialization
Road Type: Interstate = 1, Primary = 2, Secondary = 3.
Color: White= 1, Yellow= 2, Green= 3, Red(Stop) = 4.
Replacement: 1 = not replaced, 2 = replaced.
All Red signs are Red+White (Stop) style signs.
Attribute "RejectionStatus" 1 = Not Rejected, 2 = Rejected
Signs begin with "RejectionStatus" 1 = Not Rejected
Using input data files from generated age distributions
Attributes Retro, LegRetro, ReplaceStatus, RejectionStatus, and age
Create Sign
Read Input
Count signs read
Initialize Attributes
Split Sheeting Type
Split by Color
Type I Classify
Type III Classify
Check Pass/Fail Initially
Sign Classification
WhiteType1
White1Pass
CountWhite1Pass
CountWhite1Fail
YellowType1
Yellow1Pass
CountYellow1Pass
CountYellow1Fail
GreenType1
Green1Pass
CountGreen1Pass
CountGreen1Fail
StopType1
Stop1 Red Pass
Stop1 White Pass
Stop1 Ratio Test
CountStop1Pass
Count Red1 Fail
Count LegWhite1 Fail
Count Ratio1 Fail
CountStop1Fail
Attribute "DetStatus" 1 = Pass Min Retro , 2 = Failed Min Retro
Assign Pass
Assign Fail
Start Pass Count
Start Fail Count
WhiteType3
White3Pass
CountWhite3Pass
CountWhite3Fail
YellowType3
Yellow3Pass
CountYellow3Pass
CountYellow3Fail
GreenType3
Green3Pass
CountGreen3Pass
CountGreen3Fail
StopType3
Stop3 Red Pass
Stop3 White Pass
Stop3 Ratio Test
CountStop3Pass
Count LegWhite3 Fail
CountStop3Fail
Count Red3 Fail
Count Ratio3 Fail
Failure Criteria
White: Type I = 50, Type III = 50
Yellow: Type I = 50, Type III = 50 (bold symbol signs)
Green: Type I = 7, Type III = 15 (ground mounted)
Red/Stop: Type I = 7 red, 35 white, Type III = 7 red, 35 white. Ratio white/red greater than or equal to 3.

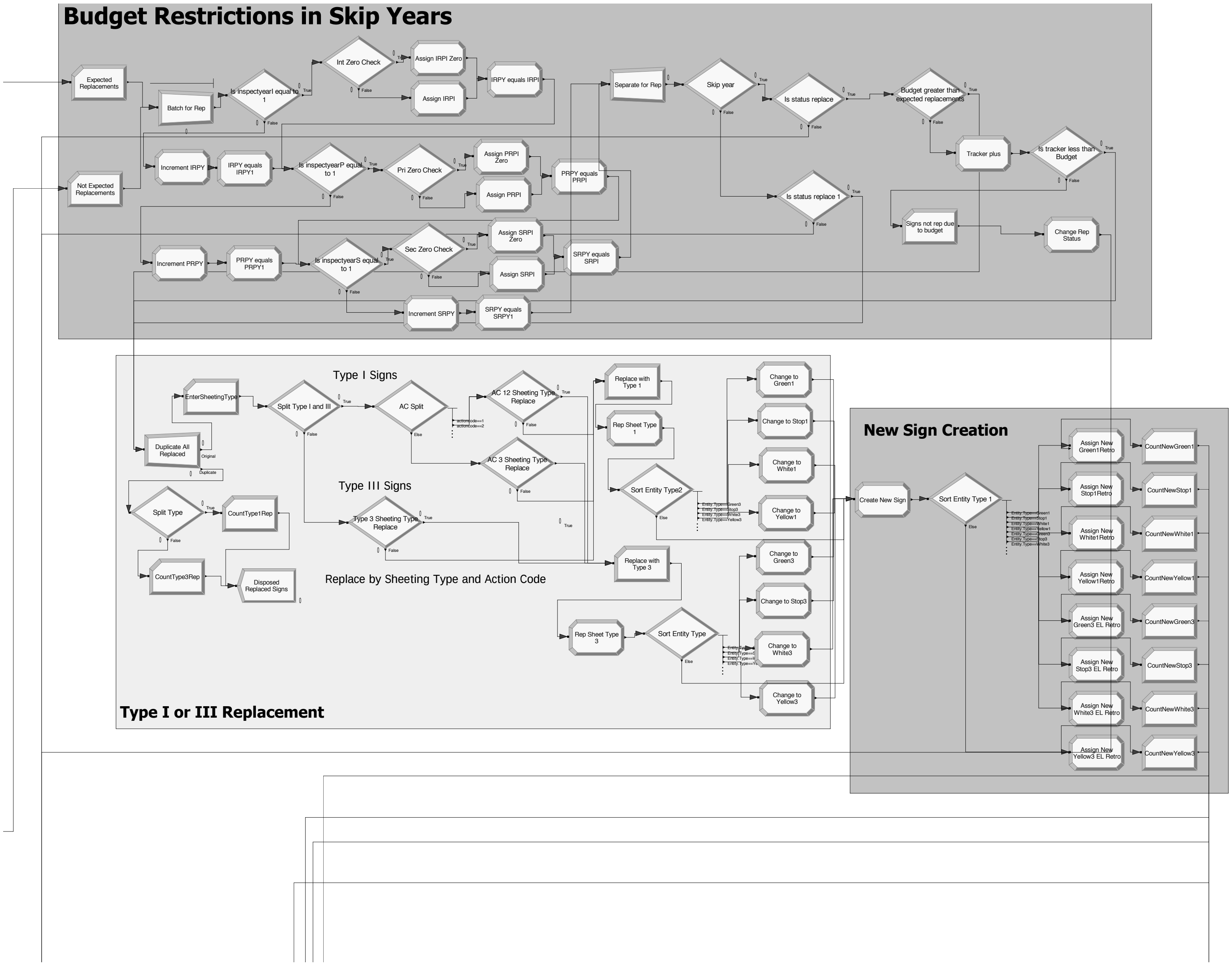


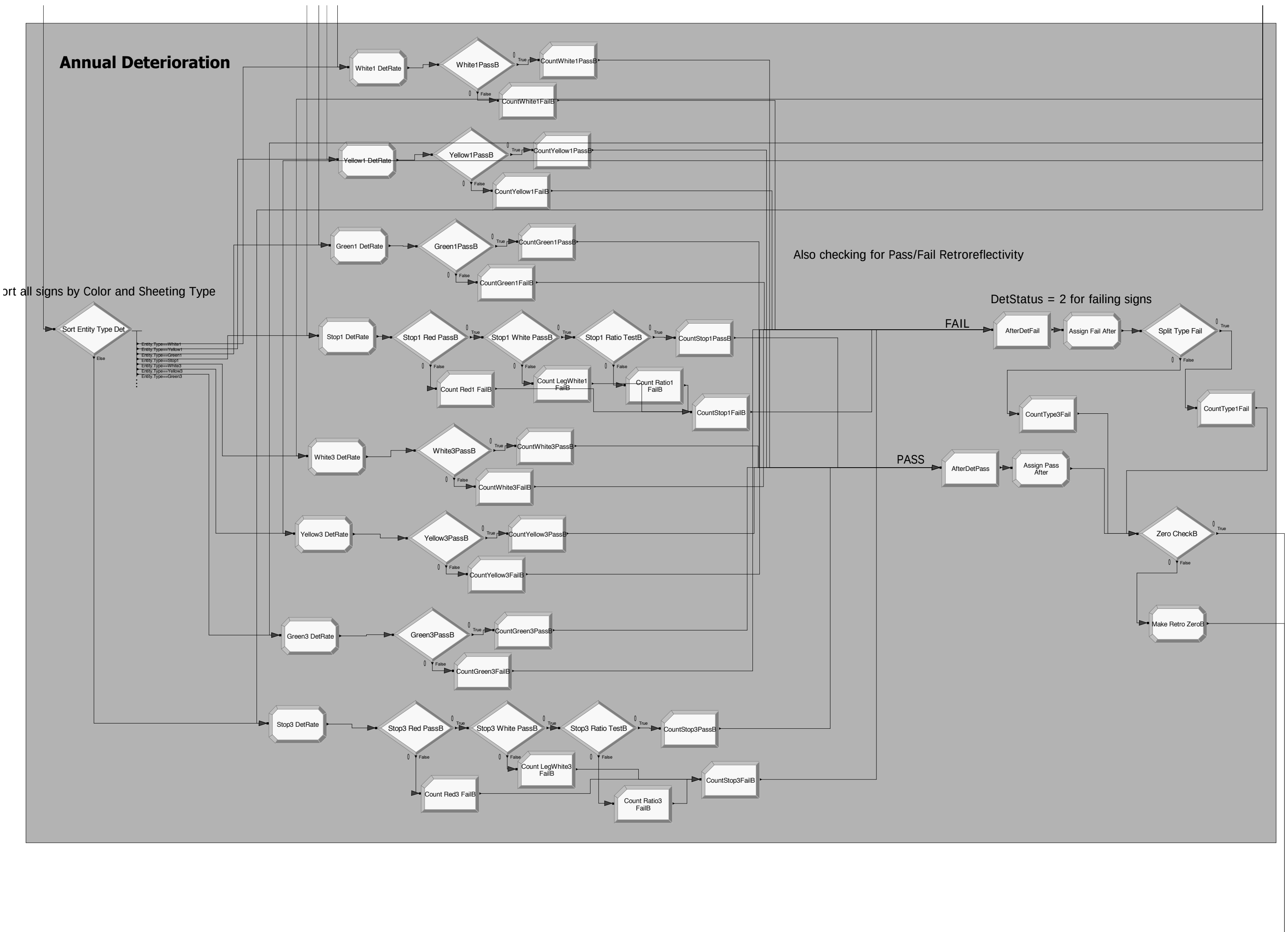
Initial Sign Damage and Inspection Setup
Attribute "DamageStatus" 1 = Not Damaged , 2 = Damaged
Input Parameters
Use of Variables
Set inspectYr = 2 (No). Set inspectcycle = InspectInt.
InspectInt is a input parameter variable. How often signs inspected.
inspectcycle is an attribute, assigned to each sign.
Tracks where sign is in the inspection cycle.
Interstate Initial Damage
Interstate Initial Damaged
Interstate Init Damaged Signs
Interstate Initial Undamaged
Interstate Init Undamaged Signs
Initialize Inspection Parameters Interstate
Counting total # of signs intially damaged
Split by Road Type
Damage sort road type
Primary Initial Damage
Primary Initial Damaged
Primary Init Damaged Signs
Primary Initial Undamaged
Primary Init Undamaged Signs
Initialize Inspection Parameters Primary
Initially Damaged?
InitDamagedSigns
InitUndamagedSigns
Secondary Initial Damage
Secondary Initial Damaged
Secondary Init Damaged Signs
Secondary Initial Undamaged
Secondary Init Undamaged Signs
Initialize Inspection Parameters Secondary
Inspection Year?
Variable inspectyearIPS: 1 = Yes, 2 = No.
Variable SkipInsp: 1 = Yes, 2 = No.
Does att inspectcycle =var inspectInt?
Always true for first year
Attribute inspectYr: 1 = Yes, 2 = No.
1 means this sign is inspected this year
Set InspectYr back to 2
Skip Inspection Year?
Exception SimYear?
No Insp Skip
does inspectcycle equal inspectintI
Set inspectyearI to 1
Set inspectYr to Yes inspcyc to 1
Set inspectcycle = 1
Split Road Type
Increment INT inspectcycle
Batch Insp
Count Inspected
Inspection Rejection Test
Count Rejected before Insp
Signs already rejected don't need inspection.
Wait for all signs until proceeding.
does inspectcycle equal inspectintP
Set inspectyearP to 1
Separate Insp
Inspection Damage Test
Tag Damaged as Rejected
Count Insp Damaged and Rejected
REPEAT POINT
Increment PRI inspectcycle
Inspect Year
does inspectcycle equal inspectintS
Set inspectyearS to 1
Attribute inspectYr = 1?
Enter Retro Inspection
SIGNS ENTERING RETRO INSPECTION
Count Not Inspected
Increment SEC inspectcycle
SIGNS NOT INSPECTED THIS YEAR

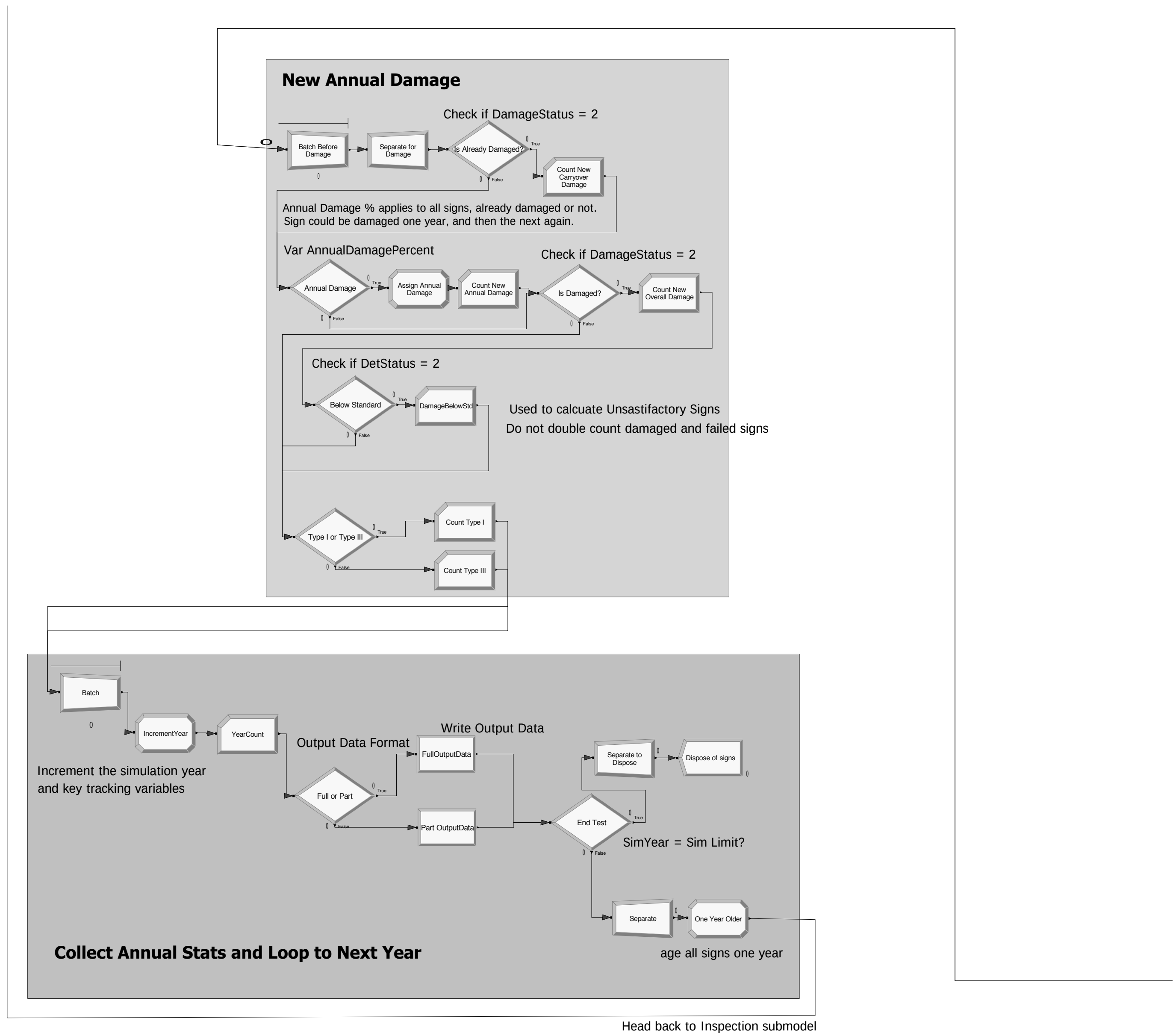

Inspection
Variable SkipIRep: 1 = Yes, 2 = No.
NumberRejected
Skip IRep Year?
Exception I SimYear?
Rejected Sign damaged
Split by Road Type for Counting
Count Int Rej Enter Rep
Split Road Type3
Count Pri Rej Enter Rep
Count Enter Insp Rej Rep
Count Sec Rej Enter Rep
Split Stop Signs from the other signs
Reject Inspected
Count Retro Rejected
CountAboveMin
SplitSign Above Min
Stop Fail Inspection
StopAboveFail
Attribute "RejectionStatus" 1 = Not Rejected, 2 = Rejected
Not Rejected
SignsNot RetroRejected
Variable SkipNIRep: 1 = Yes, 2 = No.
All Others Fail Inspection
OtherAboveFail
Above Min Ra
N Skip IRep Year?
Split Above and Below Minimum Signs
using attribute DetStatus.
N Exception I SimYear?
ABOVE MIN
BELOW MIN
CountBelowMin
Split Sign Below Min
Stop Fail Inspection Below
StopBelowFail
No Insp Rep Skip
All Others Fail Inspection Below
OtherBelowFail
Replacement of Inspected Signs
Attribute "ReplaceStatus" 1 = Replace, 2 = No replace
DAMAGED
DAMAGED & REPLACED
Replace Damaged in Inspection Year
Count RepDamaged in Insp
Replace Rejected Damaged Insp
Var DamRepPercent
DAMAGED & NOT REPLACED
Count NotRepDamaged in Insp
REJECTED
Replacement by Action Code
REJECTED & REPLACED
SplitSign Rejected
Type 1 AC 1 Replace
ReplacedRejected
Replace Rejected
Type 1 AC 2 Replace
Type 1 AC 3 Replace
Type 3 AC 1 Replace
Type 3 AC 2 Replace
Type 3 AC 3 Replace
REJECTED & NOT REPLACED
Count Int Rej Not Rep
RejNotRep
Split Road Type2
NoReplace Rejected
Count Pri Rej Not Rep
NOT REJECTED
Count Sec Rej Not Rep
SplitSign NotRejected
NOT REJECTED & REPLACED
NotRejMarkforRep
Replace NotRejected
NOT REJECTED & NOT REPLACED
NotRejNotRep
NoReplace NotRejected
Count Signs NOT Replaced



Non-Inspection Year Replacement
Variable SkipNIRep: 1 = Yes, 2 = No.
Skip NIRep Year?
Exception NI SimYear?
No NonInsp Rep Skip
Damage NI Replacement
No Inspect Damage Test
Replace Damaged in Non Inspection Year
Count RepDamaged in Not Insp
Count NotRepDamaged in Not Insp
Replace non inspected
Count Replace and Not Insp
Count Not Replace and Not Insp
NI Rep, Rejected Signs
Has sign been rejected?
Split IPS
Compare NIRepTotal Percent and IRPI
Int Rep Rej Non Insp
Count RepRejected in Not Insp
Count Not RepRejected in Not Insp
Blanket Test
For Blanket Replacement
Compare NIRepTotal Percent and PRPI
Pri Rep Rej Non Insp
Compare NIRepTotal Percent and SRPI
Sec Rep Rej Non Insp
NI Rep, Not Rejected Signs
Replace Not Rejected in Non Inspection Year
Count Rep Not Rejected in Not Insp
Count Not Rep Not Rejected in Not Insp
Var NotRejPercentRep


Budget Restrictions in Skip Years
Expected Replacements
Batch for Rep
Is inspectyearI equal to 1
Int Zero Check
Assign IRPI Zero
Assign IRPI
IRPY equals IRPI
Separate for Rep
Skip year
Is status replace
Budget greater than expected replacements
Not Expected Replacements
Increment IRPY
IRPY equals IRPY1
Is inspectyearP equal to 1
Pri Zero Check
Assign PRPI Zero
Assign PRPI
PRPY equals PRPI
Is status replace 1
Tracker plus
Is tracker less than Budget
Signs not rep due to budget
Change Rep Status
Increment PRPY
PRPY equals PRPY1
Is inspectyearS equal to 1
Sec Zero Check
Assign SRPI Zero
Assign SRPI
SRPY equals SRPI
Increment SRPY
SRPY equals SRPY1
Type I Signs
EnterSheetingType
Split Type I and III
AC Split
AC 12 Sheeting Type Replace
Replace with Type 1
Rep Sheet Type 1
Change to Green1
Change to Stop1
Change to White1
Change to Yellow1
Duplicate All Replaced
AC 3 Sheeting Type Replace
Sort Entity Type2
Type III Signs
Split Type
CountType1Rep
Type 3 Sheeting Type Replace
Replace with Type 3
CountType3Rep
Disposed Replaced Signs
Replace by Sheeting Type and Action Code
Change to Green3
Change to Stop3
Rep Sheet Type 3
Sort Entity Type
Change to White3
Change to Yellow3
Type I or III Replacement
New Sign Creation
Create New Sign
Sort Entity Type 1
Assign New Green1Retro
Assign New Stop1Retro
Assign New White1Retro
Assign New Yellow1Retro
Assign New Green3 EL Retro
Assign New Stop3 EL Retro
Assign New White3 EL Retro
Assign New Yellow3 EL Retro
CountNewGreen1
CountNewStop1
CountNewWhite1
CountNewYellow1
CountNewGreen3
CountNewStop3
CountNewWhite3
CountNewYellow3


Annual Deterioration
ort all signs by Color and Sheeting Type
Sort Entity Type Det
White1 DetRate
White1PassB
CountWhite1PassB
CountWhite1FailB
Yellow1 DetRate
Yellow1PassB
CountYellow1PassB
CountYellow1FailB
Green1 DetRate
Green1PassB
CountGreen1PassB
CountGreen1FailB
Stop1 DetRate
Stop1 Red PassB
Stop1 White PassB
Stop1 Ratio TestB
CountStop1PassB
Count Red1 FailB
Count LegWhite1 FailB
Count Ratio1 FailB
CountStop1FailB
White3 DetRate
White3PassB
CountWhite3PassB
CountWhite3FailB
Yellow3 DetRate
Yellow3PassB
CountYellow3PassB
CountYellow3FailB
Green3 DetRate
Green3PassB
CountGreen3PassB
CountGreen3FailB
Stop3 DetRate
Stop3 Red PassB
Stop3 White PassB
Stop3 Ratio TestB
CountStop3PassB
Count LegWhite3 FailB
Count Red3 FailB
Count Ratio3 FailB
CountStop3FailB
Also checking for Pass/Fail Retroreflectivity
DetStatus = 2 for failing signs
FAIL
AfterDetFail
Assign Fail After
Split Type Fail
CountType3Fail
CountType1Fail
PASS
AfterDetPass
Assign Pass After
Zero CheckB
Make Retro ZeroB


New Annual Damage
Check if DamageStatus = 2
Batch Before Damage
Separate for Damage
Is Already Damaged?
True
False
Count New Carryover Damage
Annual Damage % applies to all signs, already damaged or not.
Sign could be damaged one year, and then the next again.
Var AnnualDamagePercent
Check if DamageStatus = 2
Annual Damage
Assign Annual Damage
Count New Annual Damage
Is Damaged?
Count New Overall Damage
Check if DetStatus = 2
Below Standard
DamageBelowStd
Used to calcuate Unsastifactory Signs
Do not double count damaged and failed signs
Type I or Type III
Count Type I
Count Type III
Batch
IncrementYear
YearCount
Increment the simulation year
and key tracking variables
Output Data Format
Write Output Data
Full or Part
FullOutputData
Part OutputData
End Test
SimYear = Sim Limit?
Separate to Dispose
Dispose of signs
Separate
One Year Older
age all signs one year
Collect Annual Stats and Loop to Next Year
Head back to Inspection submodel