RESEARCH & DEVELOPMENT

Sign Replacement Strategy

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16. Abstract

The major objective of this study is to develop and analyze systematic and efficient sign replacement strategies for the North Carolina Department of Transportation (NCDOT). The research team developed a microscopic simulation model to study sign replacement strategies and analyze the trade-off between sign cost and condition. This model simulates sign damage, blanket replacement, grace period, daytime inspections, spot replacement (replacement initiated outside regular inspections), and retroreflectivity deterioration. This is the first model to successfully represent blanket replacement being conducted at a rate of one area per year (which results in balanced workload and cost over time) and the first to quantify the benefits of a grace period.

A set of 24 sign replacement strategies were developed and further studied. The sign replacement strategies were obtained by crossing the different levels of the three control variables: blanket replacement cycles (10, 15, 18, and 20 years), grace period (0, 3, and 5 years), and daytime sign inspections (presence and absence).

The authors found that daytime inspections are an effective way of achieving a low number of unsatisfactory signs while having little effect on cost. Grace period was found to be efficient in reducing costs. In addition, longer replacement cycles (e.g., 20 years) that consider daytime inspections and a grace period resulted in more cost-efficient strategies than those with shorter replacement cycles (e.g., 10 years). This study was based on NC sign data, therefore, its results provide insights into effective practices that could result in more cost-efficient sign replacement strategies.

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EXECUTIVE SUMMARY

Traffic signs play a major role on the national highway system because they provide users with important information such as warnings, regulations, and directions. To ensure sign visibility at night, the Manual on Uniform Traffic Control Devices (MUTCD) requires transportation agencies to meet minimum sign retroreflectivity levels through sign maintenance program

Traffic signs are an essential part of any transportation system. However, signs are subjected to different kinds of damaged and deterioration as they age. Therefore, transportation agencies are responsible for replacing unsatisfactory signs and ensuring their visibility and legibility both during the day and at night. The Manual on Uniform Traffic Control Devices (MUTCD) recommends five sign retroreflectivity maintenance methods to ensure that signs perform above minimum retroreflectivity levels required by the manual.

For many years the North Carolina Department of Transportation (NCDOT) has adopted the Nighttime Visual Inspection method. While Interstate signs are inspected and replaced (when needed) every year, signs on primary and secondary roads have had a more flexible schedule. Although this method has worked well, it has disadvantages. As reported by Re and Carlson (2012), Nighttime Visual Inspection could potentially result in lawsuits by drivers that had crashes because the inspections are subjective. Other areas of concern are overtime pay, schedule modifications, productivity loss caused by fatigue, and the stress and dangers of the more difficult nighttime working conditions.

Starting in July of 2017, NCDOT adopted a Routine Maintenance Improvement Plan (RMIP) (NCDOT, 2016), in which the Blanket Replacement method was implemented to maintain signs considering a sign service life of 10 years. However, more study was needed in the field to identify systematic and cost efficient sign replacement strategies and to further assess sign life.

To do so, the research team developed a sign replacement simulation model to evaluate systematic and cost-efficient sign replacement strategies and analyze the trade-off between sign cost and condition. The sign replacement model simulates sign damage, blanket replacement, grace period, daytime inspections, spot replacement (replacement initiated outside regular inspections), and retroreflectivity deterioration. This is the first model to successfully represent blanket replacement being conducted at a rate of one area per year (which results in balanced workload and cost over time) and the first to quantify the benefits of a grace period.

The model enables NCDOT to represent its sign population and condition through input parameters. By varying some input parameters and conducting experiments, the research team was able to assess the performance of different sign replacement strategies using NC sign data. The main output measures collected from the simulation include the number of unsatisfactory signs (signs that are damaged and/or noncompliant – below the required minimum retroreflectivity levels) and strategy cost (sum of inspection and replacement costs).

The sign replacement strategies were obtained by crossing the different levels of the three control variables: four levels of blanket replacement cycles (10, 15, 18, and 20 years), three levels of grace period (0, 3, and 5 years), and two levels of daytime sign inspection (presence and absence). That resulted in 24 sign replacement strategies that were further analyzed in this study.

One of the first conclusions that it was possible to draw from the simulation results is that with technological advances of sign sheeting and manufacturing, retroreflectivity deterioration is not the major factor influencing the number of unsatisfactory signs as it was in the past. The use of more retroreflective material such as microprismatic Type III sheeting allows signs to perform above required minimum retroreflectivity levels for at least 15 to 20 years. Thus, the major factor influencing the number of unsatisfactory signs is sign damage rate. In fact, the simulation showed that replacement cycles of 10, 15, and 18 years did not result in any noncompliant signs. In the case of a 20 year replacement cycle, the results indicated a very low number of noncompliant signs (less than 0.25%).

With respect to the replacement cycle length, simulation results indicated that, for strategies without a grace period and daytime inspections, a shorter replacement cycle (10 years) led to higher costs but also to a lower percentage of unsatisfactory signs than did longer replacement cycles (e.g., 20 years). However, the same did not hold true for sign replacement strategies that utilized a grace period and daytime inspections.

Daytime inspections were found to be very efficient in reducing the percentage of unsatisfactory signs (26% to 35% reduction) while only slightly increasing strategy cost (up to 4.7% cost increase). While daytime inspections had a major positive impact on the percentage of unsatisfactory signs, grace period had a major positive impact on strategy costs, reducing them by up to 12% without having any negative impact on the percentage of unsatisfactory signs. In addition, a grace period of 5 years was more efficient in reducing the costs than a grace period of 3 years.

Considering all strategies analyzed, the ones with a replacement cycle of 15 and 20 years, daytime inspections, and a grace period resulted in some of the most cost efficient strategies. Therefore, the research team recommends that NCDOT consider conducting periodic daytime inspections to keep the number of unsatisfactory signs under control. A daytime inspection cycle of 5 years was found to be efficient in doing so.

In addition, when using the Blanket Replacement method, a grace period practice also should be considered for adoption. A grace period of 5 years is preferable to 3 years for providing greater savings without increasing the number of unsatisfactory signs. Also, by adopting the Blanket Replacement method, agencies do not need to maintain a robust sign database inventory. Instead, a simple record keeping of the replacement areas and years of replacement is sufficient.

This study provides insights about effective practices that result in more cost-efficient sign replacement strategies. The authors found that daytime inspections are an effective way of achieving a low number of unsatisfactory signs while having little effect on cost. Grace period was found to be efficient in reducing costs. In addition, longer replacement cycles (e.g., 20 years) that consider daytime inspections and a grace period resulted in more cost-efficient strategies than those with shorter replacement cycles (e.g., 10 years).

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1.0 INTRODUCTION

Traffic signs play an important role in transportation systems because they provide drivers with valuable roadway safety information (WTIC, 2013). The Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009) classifies signs as regulatory (e.g., speed limit and stop), warning (e.g., right curve and road closed), and guide signs (e.g., distance guide sign and interstate route). In a study conducted in 2009, Rasdorf et al. (2009) pointed out the importance of traffic signs as being critical part of the transportation system and having a major impact on road safety. A survey conducted by Markow (2007) with 39 transportation agencies also showed that, from the agencies' perspective, the number one objective of signs is to improve public safety by reducing the number and risk of accidents. Given their importance, it is extremely relevant to ensure that signs are visible and legible to drivers both during the day and at night.

While during the day the sunlight makes signs visible (even in a cloudy day), transportation agencies have to find alternative ways to ensure that signs are visible at night. Schertz (2005) reported that although only one-fourth of all travel occurs at night, almost 50% of all traffic fatalities happen in these same hours. To address the nighttime visibility issue, the MUTCD (FHWA, 2009) requires transportation agencies to adopt one of two options: artificial illumination of the sign or signs manufactured with retroreflective sheeting. In the United States, most agencies opted for using retroreflective sheeting instead of artificial illumination of signs (Carlson and Picha, 2009). That is explained by the low maintenance cost of retroreflective signs when compared with the cost of artificial lightning. Nevertheless, there are some transportation agencies that use artificial illumination in special cases as occurs often with overhead guide signs in urban areas.

Through the years, signs suffer damages (e.g., bent, bullet holes, and mold) and are often stolen. In addition, as signs age and weather, their retroreflective properties deteriorate, decreasing the level of visibility of the signs at night. Because of this, the Federal Highway Administration (FHWA) published in 2009 a revised edition of the Manual on Uniform Traffic Control Devices (FHWA, 2009) that establishes minimum sign retroreflectivity standards that transportation agencies must comply with. In addition, the manual also describes five sign maintenance methods, from which agencies can choose one or more methods to ensure that they achieve sign legibility and minimum retroreflectivity levels. Those methods are classified into assessment (Nighttime Visual Inspection and Measured Retroreflectivity methods) and management (Blanket Replacement, Expected Sign Life, and Control Signs).

By improving the nighttime visibility through retroreflectivity compliance, the FHWA expects that drivers will "better navigate the roads at night and thus promote safety and mobility" (FHWA, 2007). In addition, maintaining signs at or above minimum retroreflectivity levels is also part of "FHWA's efforts to be responsive to the needs of older drivers whose visual capabilities are declining" (FHWA, 2007). Another reason to meet the minimum retroreflectivity requirements of the MUTCD is to reduce liability risk (McCarthy et al, 2013).

Transportation agencies are required to have a sign management program, which includes both a sign maintenance method and a sign replacement strategy. This research focuses on sign replacement strategies and answers the question "is there an implementable lower cost sign replacement strategy that meets or exceeds current sign performance levels?" To answer this question requires a well-founded sign replacement model that accurately links sign replacement, number of unsatisfactory signs, and strategy cost.

1.1 North Carolina Department of Transportation

In North Carolina, the NCDOT is responsible for maintaining and replacing signs (microprismatic Type III) on a roadway network of almost 80,000 miles, which includes Interstates (2%), primary roads (17%) and secondary roads (81%) (NCDOT, 2018). The NCDOT is divided into 14 divisions and each division has an office that is responsible for a number of counties. For many years the NCDOT did not have a statewide sign replacement strategy; each division approached sign replacement in a different way following a few state guidelines, which were based on the Nighttime Visual Inspection method (one of the five sign retroreflectivity maintenance methods recommended by the MUTCD (FHWA, 2009)).

During the years that the NCDOT adopted the Nighttime Visual Inspection method, Interstate signs were inspected and replaced (when needed) every year while signs on primary and secondary roads had a more flexible schedule. Although this method worked well for years, it has disadvantages. As reported by Re and Carlson (2012), nighttime inspections could potentially result in lawsuits by drivers that had crashes because the inspections are subjective. Other areas of concern are overtime pay, schedule modifications, productivity loss caused by fatigue, and the stress and dangers of the more difficult nighttime working condition.

Starting in July of 2017, NCDOT adopted a Routine Maintenance Improvement Plan (RMIP) (NCDOT, 2016), in which the Blanket Replacement method was implemented to maintain signs considering a sign service life of 10 years. However, more study was needed in the field to identify systematic and cost efficient sign replacement strategies and to further assess sign life. To do so, the research team developed a sign replacement simulation model to evaluate systematic and cost-efficient sign replacement strategies and analyze the trade-off between sign cost and condition.

1.2 Importance of Maintaining Signs

Traffic signs are an important feature of the highway system. They provide drivers with valuable information and are mainly classified as regulatory, warning, and guides signs. Therefore, it is imperative that signs are visible during both the day and night. Section 2A.22 (Maintenance) from the MUTCD states that maintenance activities should "consider proper position, cleanliness, legibility, and daytime and nighttime visibility" of traffic signs (FHWA, 2009). Thus, transportation agencies are in charge of developing sign maintenance and replacement programs that best fit their sources and needs while complying with MUTCD requirements.

One way of ensuring daytime visibility is conducting inspections during the day to detect missing, damaged, and obstructed signs. With respect to nighttime visibility, signs need to be above the minimum sign retroreflectivity. It is worth mentioning that nighttime visual inspection is just one out of five sign maintenance methods that can be used to comply with minimum retroreflectivity standards. Once sign inspectors identify damaged, deteriorated, and missing signs, they request a service order to replace those signs. Then, those signs are replaced by new signs. The major reasons to replace signs are as follows.

- Deterioration (retroreflectivity, age, and fade)
- Loss (theft)
- Damage (environmental, accidental, and vandalism)
- Road reconstruction
- Change in regulations
- Sign is no longer needed

1.2.1 National Crashes Caused by Signs

In 2008 a research was published in which the authors conducted a survey to identify critical crash causations (NHTSA, 2008). The research team collected information about 5,471 crashes, which represented an estimated 2,189,166 crashes nationwide for a period of 2 and a half years. The authors explained that crashes often happen due to a casual chain of events rather that due to a unique event. The research focused on critical reasons that caused the last event on the causal chain that lead to the crash. The critical reasons were attributed either to the driver, vehicle, environment, or roadway. The authors noted that these critical reasons should not be confused with the cause of a crash. After analyzing the crash data, the authors found that 39,844 out of 2,189,166 crashes were attributed to roadway critical reasons (e.g., road design, lick roads, and view obstruction). From those roadway-related crashes, around 1,452 (3.6%) were related to signs and signals (e.g., a missing stop sign in an intersection).

Another study (conducted by Retting et al., 2003) analyzed 1,788 crash reports of vehicle crashes at stop signs in four U.S. cities and that occurred between 1996 and 2000. The authors found that drivers did not stop at the stop sign in 304 (17%) of all crashes. The researchers stated that most of the crashes where drivers did not stop at the sign happened at night and portion of the drivers involved in them reported not having seen the stop sign. According to the authors, these findings reinforce the importance of maintaining signs in good conditions and with proper retroreflectivity levels to ensure they are visible at night.

1.2.1.1 Crash Costs

Blincoe et al. (2015) also conducted a study to analyze the economic and societal impact of crashes. The authors stated that crashes that happened in 2010 totaled an economic (monetary) cost of $242 billion nationwide. Economic costs are easier to quantify and include medical, property damage, market productivity loss, insurance, legal claims, congestion, and others. According to the authors, each crash fatality (due to any reason) represents a *lifetime* economic cost of $1.4 million to the society. A severely injured person (who survived the crash) represents an average of $1.0 million in economic costs to society, from which medical costs and lost productivity account for over 80% of the costs. In addition, the research team estimated *lifetime* comprehensive cost of crashes, which includes both monetary (economic) and nonmonetary lost quality-of-life (e.g., pain, suffering, and death) costs. Doing so, the comprehensive nationwide cost of crashes in 2010 added up to $836 billion. The authors stated that each crash fatality (due to any reason) represents a lifetime comprehensive cost of $9.1 million to the society. A severely injured person (who survived the crash) represents an average of $5.6 million in comprehensive costs to society. These findings highlight the substantial negative impact that motor vehicle crashes have on society.

1.2.2 North Carolina Crashes Caused by Signs

In North Carolina, the Division of Motor Vehicles (DMV) published the “2010 Traffic Crash Facts” (NCDMV, 2011) which showed that there were 213,553 crashes in 2010 in NC. From those crashes, 8,739 (4.1% of total) were related to traffic controls (signs and signals) that were not working properly. Examples of traffic controls considered in the report are stop signs, yield sign, stop and go signal, flashing signal with stop sign, warning sign, etc. Note that the document did not specify how many from these crashes were related to only signs. From these traffic-control related crashes, 17 (0.2% of traffic control crashes) were fatal and 2,717 (31.1% of traffic control crashes) resulted in injuries.

The “2016 Traffic Crash Facts” (NCDMV, 2017) showed that there were 267,494 crashes in 2016 in NC, representing an increase of 25.3% in relation to 2010 total crashes. From those crashes, 8,247 (3.1% of total) were related to traffic controls that were not working properly, which is less than the reported in 2010 (8,739). The document pointed out that from these traffic-control related crashes, 20 (0.2% of traffic control crashes) were fatal and 3,623 (43.9% of traffic control crashes) resulted in injuries.

1.2.2.1 Crash Costs

Based on those studies and crash data, it can be said that crashes have a substantial economic and comprehensive (including lost quality-of-life) costs to society as it was studied and explained by Blincoe et al. (2015) (who considered nationwide data). In relation to NC, the “2010 Traffic Crash Facts” (NCDMV, 2011) calculated a comprehensive average crash annual cost of $10,704 million in NC (all crashes) with an average cost per crash of $38,362. Note that this value is an average per crash and does not consider if it resulted in injuries or fatalities. Considering that there were 8,739 crashes related to traffic controls in 2010, it is possible to estimate an average annual crash cost of over $335 million in 2010 due to traffic controls that were not working properly.

Following the same logic, the “2016 Traffic Crash Facts” (NCDMV, 2017) calculated an average crash annual cost of $ 25,649 million in NC (all crashes) with a comprehensive average cost per crash of $ 77,312. Considering that there were 8,247 crashes related to traffic controls in 2016, it is possible to estimate an average annual cost of over 637 million in 2016 due to traffic controls not working properly.

Still considering the 2010 lifetime costs from both Blincoe et al. (2015) and the 2010 NC crash data (NCDMV, 2011), it was possible to calculate the *lifetime* economic and comprehensive costs of crashes that happened in NC due to traffic controls that were not working properly and resulted in fatality. Thus, the statewide lifetime economic cost in 2010 was $23.8 million (17 fatalities x $1.4 million per fatality) and the statewide lifetime comprehensive cost in 2010 was $154.7 million (17 fatalities x $9.1 million per fatality)

1.2.3 <u>Summary</u>

Based on the number of crashes caused by (or related to) signs and the economic and comprehensive costs they represent for the society, the importance of maintaining signs in good condition is clear. This becomes even more evident when considering the cost to maintain signs, which are low when comparing to the costs of crashes to the society. For instance, the NCDOT’s expenditure to maintain signals and ground mounted signs in 2016 was $28 million (NCDOT, 2016) while the estimated annual comprehensive crash cost due to traffic controls (signs and signals) not working properly in NC was estimated in over $637 million.

1.3 Sign Retroreflectivity

Retroreflective sign sheeting contains either prismatic reflectors or glass beads that reflects a portion of the light incident on it back to the source. It is the retroreflective sheeting that enables a driver to see signs at night (Carlson and Picha, 2009). Because of the significant advances in the retroreflectivity of sheeting, in the durability, and extended warranties on the sheeting, and improvements in car and truck headlighting, most transportation agencies are moving away from the use of sign illumination in favor of high grade of retroreflective sheeting.

Figure 1.1 illustrates how sign retroreflectivity works. In this case, a car headlight (original light source) illuminates a retroreflective Stop sign. As the light illuminates the sign, a portion of this light reflects back to the car “in a cone-like shape, centered around the light’s incidental path” (3M, n.d.[1]) making the sign is visible to the driver. The efficiency of a retroreflective sheeting depends on the how much light disperses (are not directed to the driver) and the amount of light that returns to the light source within the cone of retroreflectivity (3M, n.d.[2]). A higher performance sheeting has less light dispersion.

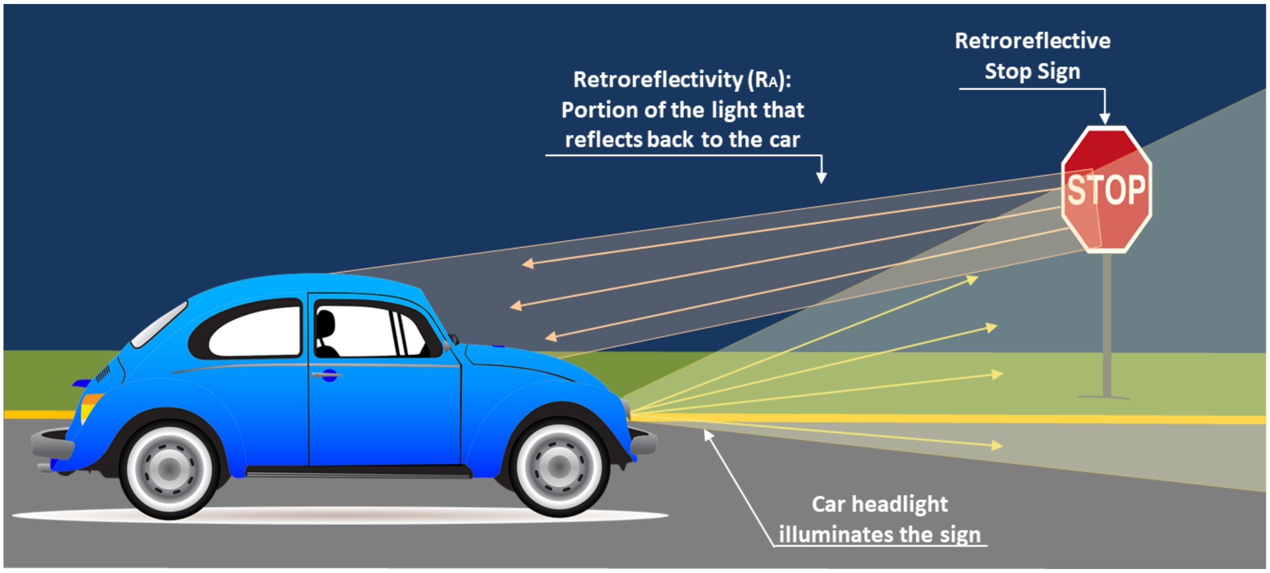


Figure 1.1 Scheme of How Sign Retroreflectivity Works

The level of retroreflectivity of a sign sheeting can be measured by a retroreflectometer and it is known as coefficient of retroreflectivity (R_A). The R_A is calculated as the ratio of light that strikes the sign and the portion of this light that is reflect back to the source. The unit of measure is candelas per lux per meters square ($cd/lx/m^2$) (Re et al., 2011), which is defined by Immaneni et al. (2009) as “the ratio of light a sign reflects to a driver [candela (cd)] to the light that illuminates the sign [lux (lx)], per unit area [square meter (m^2)].”

Many studies were conducted to assess how retroreflectivity deteriorates over the years and, although many of them suggested that sign retroreflectivity deteriorates as signs age, only few obtained successes in proving this relationship (Wolshon et al., 2002; Re et al., 2001; Immaneni et al., 2009; Jiang and Zhou, 2012; and Boggs et al., 2013). Figure 1.2 illustrates how sign retroreflectivity deterioration affects nighttime visibility. When a traffic sign is installed, it is very bright and visible to drivers at night; however, as this sign ages and retroreflectivity deteriorates, the sign becomes less and less bright and less visible at night, which can result in serious safety issues.

Mohan et al. (2012) explained that retroreflectivity deterioration is caused by chemical processes involving ultraviolet (UV) radiation as a primary factor. According to the authors, pigments of the sheeting absorbs UV radiation, which causes oxidation of the pigment and fading of the sheeting. Black et al (1991) stated that oxygen, in combination with UV radiation, also contributes to photo-oxidative decomposition of the sheeting surface. The next section discusses the minimum retroreflectivity standard that transportation agencies have to comply with.

Figure 1.2 Scheme of How Retroreflectivity Deterioration Affects Sign Visibility at Night

It was in 1984 that the Center for Auto Safety requested the Federal Highway Administration (FHWA) to establish requirements for minimum sign and pavement marking retroreflectivity levels (Immaneni et al., 2007). In 1993, the Department of Transportation Appropriations Act mondated that the FHWA include minimum retroreflectivity standards in the MUTCD. The FHWA included the minimum sign retroreflectivity standards in the MUTCD in 2009 in Section 2A.08 (Maintaining Minimum Retroreflectivity).

Table 1.1 was obtained from the manual and shows the minimum retroreflectivity levels that transportation agencies shall comply with. As is shown in the table, retroreflectivity levels depend on the sign color and the type of sheeting. . This report refers to the different types of sign sheeting (e.g., Type I, Type III, etc.) based on the ASTM D4956 standards (ASTM, 2017). Transportation agencies need to be aware that besides the minimum levels of retroreflectivity, they also need to comply with minimum sign contrast ratios of 3:1 for regulatory signs in the colors red and white (e.g., stop and yield signs). The contrast ratio can be obtained by dividing the white retroreflectivity by red retroreflectivity. One also may note that white, yellow, and orange Type I sheeting is no longer allowed by the manual. For those colors, transportation agencies can opt for any Type II sheeting and above.

The following traffic signs are exceptions to the MUTCD minimum retroreflectivity levels and do not require compliance with the minimum retroreflectivity standards prescribed in the manual. In those cases, transportation agencies can decide whether or not they will include those signs in minimum retroreflectivity maintenance programs (FHWA, 2009).

- “A. Parking, Standing, and Stopping signs (R7 and R8 series)
- B. Walking/Hitchhiking/Crossing signs (R9 series, R10-1 through R10-4b)
- C. Acknowledgment signs
- D. All signs with blue or brown backgrounds
- E. Bikeway signs that are intended for exclusive use by bicyclists or pedestrians” (Section 2A.08 of MUTCD; FHWA, 2009).

It is important to say that, although MUTCD (FHWA, 2009) specifies minimum sign retroreflectivity levels, it also states that transportation agencies are not required to have 100% of their signs in compliance with the retroreflectivity standards at all times on the condition that those agencies adopt at least one of the sign maintenance methods recommended by the MUTCD

(Hummer et al., 2013; Carlson and Picha, 2009) that are known to ensure general compliance with the standard.

Table 1.1 MUTCD (FHWA, 2009) Minimum Maintained Retroreflectivity Levels

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
White on Green	W*; G ≥ 7	W ≥ 120; G ≥ 15			Post-mounted
Black on Yellow or Black on Orange	Y*; O*	Y ≥ 50; O ≥ 50			2
Black on Yellow or Black on Orange	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 48 inches and for all sizes of bold symbol signs
[3] For text and fine symbol signs measuring less than 48 inches
[4] Minimum sign contrast ratio ≥ 3:1 (white retroreflectivity ÷ red retroreflectivity)
* This sheeting type shall 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
- W2-7,8 – Double Side Roads
- 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 – Grade Crossing Advance Warning
- W11-2 – Pedestrian Crossing
- W11-3,4,16-22 – Large Animals
- 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
- W20-7 – Flagger
- W21-1 – 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 as W14-3 (No Passing Zone), W4-4P (Cross Traffic Does Not Stop), or W13-1P,2,3,6,7 (Speed Advisory Plaques), use the largest sign dimension to determine the proper minimum retroreflectivity level.

Source: MUTCD (FHWA, 2009)

1.4 Sign Damage

Although sign retroreflectivity is one of the most studied topics on sign maintenance programs, sign damage is also a relevant factor to be considered. Any sign replacement strategy must consider sign damage. A few studies have approached sign damage rates and its implications in analyzing different sign maintenance methods (Boggs et al., 2013; Evans et al., 2008; Harris et al., 2007; Harris et al., 2009; Hawkins ad Carlson, 2014; Immaneni et al., 2007; Hummer et al., 2013, and Pike and Carlson, 2014). Pike and Carlson (2014), for example, found that 21.5% of the signs surveyed during a study had major damage to the point of not being legible to drivers. Similar, Boggs et al. (2013) also concluded from a field survey in Texas that 28% of the signs were significantly damaged. Therefore, knowing that such high damage rates enlist agencies can seek to determine in which locations their signs have higher damage rates allowing them to better distribute better their resource allocation in order to maintain signs visibly and legibly (Boggs et al., 2013).

There are many types of damages. The literature does not show a standard categorization of the damage types. For instance, Immaneni et al. (2007) organized them into three categories: vandalism, which is deliberately caused by humans (e.g., gunshots and spray paint), natural damage (e.g., mildew and scratches), and accidental an unintentional damage caused by humans (e.g., knockdowns and damage by mowing equipment). Evans et al. (2008) characterized damage differently by organizing sign damage in the following categories: bending, peeling, vandalism, cracking, and other. Table 1.2 shows a list of possible causes of damages that was compiled based on the papers listed above and based on meetings conducted with NCDOT sign maintenance personnel.

On this report, different types of damage are organized into three categories: environmental, accidental, and vandalism. This classification follows the same idea as the one presented by Immaneni et al. (2007) with some slight differences. Environmental damages are those caused by the nature itself, for example, damage by water, wind, sun, tree sap, mold, tree rubbing, etc. Accidental damages are unintentionally caused by humans, for example, damages by collisions (cars and other vehicles), mowing equipment, pollutions, and compression. Vandalism damages are intentionally caused by humans, for example, eggs, paintball, spray paint, stones, and stickers.

Table 1.2 Types, Causes, and Examples of Sign Damage

	Types of Damage		
	Environmental	**Accidental**	**Vandalism**
Caused By	Tree sap Tree rubbing Water (rain and flood) Wind Snow Sun Sand Mold Dust Pollution	Collision Mowing equipment Compressions (storage space) Stones or debris	Gunshot Stickers Paintball Eggs Spray paint Stones Beer bottle
Examples of Damage	Scratches Mildew Dirty	Bending Broken Knockdown Dirty	Holes Stains Graffiti Scratches

Figure 1.3 to Figure 1.6 show examples of sign damage (photos taken by the author on January 30, 2018). Figure 1.3 shows two *added lane* signs located in the same area. Note how faded the signs on the left is in comparison to the second sign, probably caused by aging and sun exposure. The second sign in Figure 1.3 was under a tree and, although the color was fairly conserved, it contained a considerable amount of sap and was clearly dirty. This may not be a problem during the day but has the potential to reduce the visibility of the sign during the night. Both signs were installed in 1994 (24 years old) by NCDOT in Division 5.

Figure 1.3 Example of Deteriorated and Damaged Signs: Faded and Tree Sap Content

Figure 1.4 shows two damaged regulatory signs (*do not enter* and *stop*). The sign on the left (do not enter) is not vertically aligned, which may have been caused by collision, strong wind, or vandalism. The transportation agency responsible for that sign may either replace or fix it. There was no installation date on the back of the *do not enter* sign. The second sign (*stop*) was vandalized with white spray paint. Also, it shows signs of fading on the bottom part of it. Ideally, that *stop* sign would be replaced. The *stop* sign shown in the Figure 1.4 was installed in 1987 (31 years old).

Figure 1.4 Example of damaged Signs: Non-aligned and Spray Painted

Figure 1.5 shows a damaged guide sign that was installed in 1989 (29 years old). Observing the picture on the left, it is possible to note that the guide signs is bent and contains bullet holes. The picture on the right shows a close-up of a bullet hole on the sign. Note that the background green sheeting is totally damaged around the hole, allowing water infiltration between the sheeting and aluminum and causing possible mold problems.

Figure 1.5 Example of damaged Signs: Scratched and Gun Shot

Figure 1.6 shows two signs that have now been replaced. Those pictures were taken on visit to NCDOT Division 8 on October 6, 2017. The weight limit sign on the left was replaced because it contained a large amount of dirt, which compromised its visibility to drivers. The installation year of the *weight limit* sign was 2006 (11 years old). A possible cause for this damage is truck emissions and excessive dust in the area. The picture on the right shows a school zone sign, which was faded, cracked, and bent. The installation year of the yellow sign is unknown.

Figure 1.6 Example of damaged Signs: Dirty, Faded, Cracked, and Bent

1.5 Problem Statement

Although there has been significant progress in the field of sign management research in the last few years, there is still room for improvement in some areas. This section lists and describes the problems addressed in this research.

Problem 1: *There is not a consensus regarding sign retroreflectivity deterioration and sign service life*. Although a number of studies were conducted to determine sign retroreflectivity deterioration models and sign service life (Clevenger et al. 2012, Dumont et al. 2013, Kipp and Fitch 2009, Immaneni et al 2009, Pulver et al. 2018, and others), they did not reach a consensus regarding their conclusions. For instance, Pike and Carlson (2014) recommended for Type III sheeting a sign service life of 15 years while Pulver et al. (2018) recommended 10 years. That divergence also extends to sign retroreflectivity deterioration and its couses. For instance, Pulver et al. (2018)

found sign orientation to be a significant factor on retroreflectivity deterioration while other authors found that sign orientation was not a significant factor (Bischoff and Bullock 2002; Evans et al. 2012; Kipp and Fitch 2009; Re et al 2011; and Wolshon et al 2002). Therefore, there is a need to determine a reasonable sign service life based on previous sign retroreflectivity deterioration studies.

Problem 2: *Previous studies analyzed and compared different sign maintenance and replacement methods without considering DOT's resources nor organizational structure.* Any asset management program should consider both resources (labor, equipment, material, and technology), organizational structure, and business process. For instance, studies conducted by Harris et al. (2007), Harris et al. (2012), Hummer et al. (2013), and Dumont et al. (2013) did not consider the costs of data collection, sign inventory database implementation, and maintenance in their sign maintenance cost analysis study. However, the absence of a sign inventory database within a transportation agency should be considered a major barrier to the implementation of the Expected Sign Life method. As Rasdorf et al. (2009) pointed out, there are great challenges involved in the development and maintenance of a database for high volume and low-cost assets such as signs. Thus, for NC, having a large number of signs and tracking all of them can be a difficult task. Therefore, there is a need to analyze the five sign maintenance methods described by the MUTCD while considering NCDOT's resources, structure, and processes.

Problem 3: *Existing models that investigated the Blanket Replacement method did not properly apply the concept of an area-based approach.* Although previous studies (e.g., Harris, 2010; Harris et al, 2012; Hummer et al., 2013) analyzed the Blanket Replacement method, they used a different approach from the current study. At the time the foundational work of the previous studies was conducted, the concept of implementing blanket replacement by areas in order to balance workload and expenditures through the years was new and it was not addressed as it has now been in the present research. Therefore, there is a need to develop a new model for the Blanket Replacement method that considers an area-based approach.

Problem 4: *Existing models that investigated the Blanket Replacement method did not attempt to mitigate the risk of sign material waste, one of the major disadvantage of the Blanket Replacement method.* Although the literature reviewed often cited material waste as one of the major disadvantages of this method, none addressed practices to mitigate the material waste issue. At most, Re and Carlson (2012) described a case in which a grace period was adopted by a state DOT; however, there was not a further assessment nor analysis of that practice. Therefore, there is a need to further investigate practices that have the objective of mitigating sign material waste when adopting the Blanket Replacement method. In addition, a quantification of the benefits of such practice is also desired.

1.6 Research Objectives

One of the objectives of this research project was to develop a sign replacement model considering the NCDOT organization structure, personnel, and current business processes. Such a model should be capable of providing the NCDOT with a set of optimal sign replacement strategies that are systematic, cost efficient, and independent of sign inventory. In addition, sign retroreflectivity deterioration and reasonable service life are assessed as part of optimal sign replacement strategies. The objectives of this research are listed below.

Objective 1: Determine a reasonable sign service life based on previous sign retroreflectivity deterioration studies.

Objective 2: Determine a sign maintenance method suitable for the NCDOT considering that it does not have a sign inventory database.

Objective 3: Develop a new sign replacement model based on the Blanket Replacement method that considers an area-based approach. In addition, spot replacement and daytime inspections will also be considered and their costs and benefits quantified.

Objective 4: Identify a field practice that reduces sign material waste and quantify its benefits and costs.

1.7 Research Methods Overview

An overview of the research methodology is presented in Figure 1.7. In some cases, a more detailed description of the methodology is described at the beginning of a chapter.

Phase	Activities
Literature Review	• Conducted a literature review covering the following topics: sign retroreflectivity deterioration, sign service life, sign damage, sign maintenance methods, sign management cost, transportation management models.
Sign Manufacturing and Replacement Processes	• Visited two sign shops (Bunn Sign Shop and Central Virginia Sign Shop) to learn and observe the steps involved in the sign manufacture process. • Rode along with sign crews in NC to observe and document the sign replacement process.
DOTs Sign Management Programs	• Met traffic and sign engineers from NC, VA, and SC DOTs to observe, document, and assess which sign management programs they have in place, as well as their practices, benefits, and challenges.
Sign Service Life and Retroreflectivity Deterioration	• Conducted an extensive review of state of the art sign research results, which included properties of sign sheeting material, previous studies, and sign warranty information. • Analyzed sign life from five different perspectives as follows: (1) glass-beaded and microprismatic sheeting; (2) retroreflectivity deterioration models; (3) sign service life; (4) departments of transportation practices; and (5) sign warranty.
Sign Maintenance Methods	• Analyzed the five sign maintenance methods recommended by the MUTCD to assess their suitability in light of the current literature and the technological developments of recent years. • Selected the most suitable sign maintenance method for the NCDOT considering that it does not have a sign inventory database.
Simulation Model Development	• Analyzed three types of models (physical, analytical, and simulation) to identify the most suitable model to represent the sign replacement system. • Selected simulation to model sign replacement strategies, selected the kind of simulation that was the most suitable to do so. • Developed a model that has capabilities to simulate sign damage, blanket replacement, grace period, daytime inspections, spot replacement, and retroreflectivity deterioration.
Strategy Development and Analysis	• Developed a set of sign replacement strategies to be simulated. • Collected output measures (e.g., strategy cost and number of unsatisfactory signs) from the simulation • Analyzed the results to identify a set of optimal sign replacewment strategies.

Figure 1.7 Research Methodology Overview

1.8 Contributions

This research presents a set of contributions to NCDOT's body of knowledge in the topical areas noted below. The findings of this research can be considered by NCDOT and possibly to improve the current sign replacement strategies.

Sign service life for microprismatic Type III sheeting. Most previous studies considered sign service life to be the same as sign warranty even though there was evidence that this approach is very conservative and leads to sign material waste (signs replaced before the end of their service life). After analyzing Type III sheeting sign service life from five different perspectives, the research team concluded that the NCDOT may consider a sign service life ranging anywhere from

15 to 20 years for white, yellow, red, and green signs. This sign service life range is significantly above the sign warranty period of 10 to 12 years for Type III sheeting. This finding would enable NCDOT to improve its sign maintenance practices, utilize signs to the full extent of their service life, and free labor resources for other critical transportation infrastructure needs.

Critical analysis (considering NCDOT's resources, structure, and processes) of the five sign maintenance methods recommended by the MUTCD. Based on the literature reviewed, various DOTs' experiences, and typical DOT management policies, the research team observed that there is a trend of transportation agencies transitioning from assessment to management methods to maintain sign retroreflectivity. The research team concluded that the Expected Sign Life method is most appropriate for agencies that have a sign inventory database or small agencies that plan to implement a sign database. However, with respect to the NCDOT, the Blanket Replacement method is the most appropriate for achieving compliance with the MUTCD requirements.

Development of an authentic sign replacement simulation model. A major contribution of the present research was the development of a microscopic sign replacement simulation model based on the Blanket Replacement method. Although previous research (Harris, 2010; Harris, 2012; Hummer, 2013) analyzed the Blanket Replacement method, it was under a different approach from the current study. At the time the foundational work of the previous studies was conducted, the concept of conducing blanket replacement by areas in order to balance workload and expenditures through the years was new and it was not addressed by previous research. This sign replacement model simulates and quantifies the cost of an area-based blanket replacement, which has not previously been done in the literature.

Quantification of grace period benefits. Another contribution of this study was a thorough investigation of a practice to reduce sign material waste when adopting the Blanket Replacement method. From the practices observed in the literature and in the field, utilization of a grace period showed promising for doing so. Therefore, the research team incorporated a grace period sub-model into the sign replacement model. It was the first time that a study included this practice. Grace period was included in the analysis and its benefits were quantified for the first time in a study.

Quantification of daytime inspection benefits and costs. Daytime inspections are conducted to identify and replace damaged signs. The research team incorporated a daytime inspection sub-model into the sign replacement simulation model. Daytime inspections were included in the analysis and their benefits and costs were quantified for the first time in a study.

Identification of a set of optimal strategies. Optimal replacement strategies must be realistic and implementable, which requires consideration of budget, available resources (labor, equipment, and material), in place constraints, and business culture (inside the NCDOT and its divisions). This research considered all these aspects to develop and analyze different sign replacement strategies. At the end of the study, the research team identified a set of optimal strategies, which included longer replacement cycles, the presence of daytime inspections, and a grace period.

1.9 Structure of Report

This report is organized in chapters. Each chapter provides a description of its topic, theoretical and practical contributions, research methods (when needed), findings, and conclusions.

Chapter 2 presents a comprehensive literature review of different aspects of sign replacement. Chapter 3 covers sign manufacturing and sign replacement processes with the objective of providing the background and greater subject matter depth. Chapter 4 describes sign management programs adopted by three DOTs (NC, SC, and VA) including their practices, benefits, and challenges. The findings and discussions drawn from this chapter enable DOTs and transportation managers to gain insights into problems and solutions that may help them improve their sign maintenance practices.

Chapter 5 outlines and details a comprehensive sign life study (based on five different perspectives) that has the objective of determining a sign service life for microprismatic Type III sheeting (the type of sheeting used by NCDOT and by many other transportation agencies). Chapter 6 presents a critical analysis of the five sign maintenance methods recommended by the MUTCD and describes the reasons for selecting the Blanket Replacement method to be further considered in this study.

Chapter 7 describes the sign replacement simulation model development, including input parameters, simulation logic, and output measures. Chapter 8 presents the sign replacement strategies development using NCDOT sign data. Chapter 9 presents the simulation results and data analysis.

Chapter 10 presents the overall conclusions and recommendations for future research. Chapter 11 lists previous studies and documents referenced in this research. The report concludes with Chapter 12 which presents appendices pertinent to the current research.

2.0 LITERATURE REVIEW

The first step in this research project was to examine the current literature to determine the extent to which similar work has been attempted and to determine the progress made by researchers and other state DOTs. The literature review is organized by topics that are relevant to the present work as follows: sign retroreflectivity deterioration and compliance, sign service life, sign damage, sign maintenance methods, sign management costs, and simulation-based studies.

2.1 Sign Retroreflectivity Deterioration and Compliance

Many studies were conducted to determine retroreflectivity deterioration curves (Black et al., 1991; Immaneni et al., 2009; Clevenger et al. 2012; Pike and Carlson, 2014; etc.). Understanding how sign retroreflectivity deteriorates and which factors are involved in that process are necessary to develop deterioration models. Most researchers estimate sign service life based on the deterioration models developed through field survey studies. This section organized the retroreflectivity deterioration studies into two groups: (1) field survey studies in which researchers collected data from in-service signs that were located in the field, mostly on primary and secondary roads, and (2) studies that collected data from out-of-service signs, meaning that instead of the signs being located on the highway system, they were in a yard or facility where researchers could control some conditions (e.g., avoidance of vandalism).

2.1.1 <u>In-Service Sign Field Survey Studies</u>

Most retroreflectivity deterioration studies conducted field surveys to collect sign data, in which the number of signs surveyed varied from 137 to 5,722 signs (Black et al, 1991; Clevenger et al, 2012; Evans et al., 2012; Kirk et al., 2001; and others). All these studies used a retroreflectometers to measure sign retroreflectivity. In addition to retroreflectivity and age, which were collected in all field surveys, most researchers also registered sign age, sheeting color, sheeting type, location, orientation, and visual assessment (overall sign condition, e.g., poor, adequate, and good). Most studies suggested a strong correlation between sign age and retroreflectivity deterioration, however the mathematical models developed based on the field data had low R^2 values. R^2 (R squared), also known as coefficient of determination, is an indicator of how close the real data is from the curve obtained from the mathematical model. It ranges from 0 to 1, with 1 indicating a perfect match of between the real data and the curve.

One of the most comprehensive retroreflectivity study was conducted by Black et al. (1991) in which the authors collected data on 5,722 signs across the U.S., including Types II and III glass beaded sheeting. The authors developed deterioration models for the different colors and sheeting types and found that age was one of the major factors affecting retroreflectivity. In addition to age, the authors also found that precipitation, ground elevation, and temperature were significant factors as well. On the other hand, sign orientation to the sun was not found to be a significant factor on sign deterioration. Another finding was that by washing signs, the retroreflectivity improved by almost 12% in Type II signs and almost 8% in Type III signs. An interesting finding was that most of the signs up to 12 years old were performing above the minimum initial retroreflectivity levels (minimum levels to be considered Type II or III at the moment of manufacturing).

Kirk et al. (2001) conducted a study for the Oregon Department of Transportation (Oregon DOT) to assess which factors affect sign retroreflectivity. The research team collected data on 137 washed signs within Oregon. All signs were Type III and were distributed in four colors (white, yellow, green, and red). Although the authors did not find a strong trend between retroreflectivity deterioration and age, they stated that the variability of retroreflectivity readings was greater for older signs. The deterioration models had low R^2 values and therefore would not be suitable for estimating sign service life based on age. The authors also analyzed the effect of sign orientation on retroreflectivity deterioration and found that signs oriented to west and south: had greater retroreflectivity variability than signs oriented to other directions. Kirk et al. (2001) was one of the few studies to show some correlation between retroreflectivity and sign orientation; however, the authors also stated that during the field survey, the orientation of some signs were wrongly recorded, and therefore, the link between retroreflectivity and sign orientation is somewhat uncertain.

Wolshon et al. (2002) also conducted a field survey and collected data on 237 signs (unwashed and washed) across Louisiana. These signs were distributed into Types I and III in three colors (white, yellow, and green). The research team intended to assess whether or not any of the following factors had a significant effect on retroreflectivity deterioration: age, sheeting color, sheeting type, location, offset (distance a sign is installed from the shoulder), sign height, and sign orientation. About 92% of the signs within warranty were compliant with the minimum retroreflectivity levels while only 43% of the signs out of warranty were compliant. The authors found that age was the only significant factor affecting retroreflectivity deterioration. The research team also claimed that by washing sign faces, they obtained an average of 33% improvement in retroreflectivity, which indicates that transportation agencies could clean or wash their signs during maintenance activities in order to increase their sign service life. Based on the field data, Wolshon et al. (2002) developed deterioration models for all combinations of sheeting types and colors; however, they did not state the R^2 value of the models.

In a study conducted for NCDOT, Immaneni et al. (2007) collected field data on 1,057 signs across NC, including Types I and III sheeting in four colors (white, yellow, green, and red). The authors conducted a simple retroreflectivity analysis in this paper; however, deterioration was not the main topic of that study. They found that 13% of the 1,057 signs were non-compliant; however, the authors pointed out the fact that most of the noncompliant signs were Type I sheeting, considered to have a shorter sign service life, while most Type III sheeting were still in compliance with the minimum retroreflectivity levels.

In 2008, Pierce County, WA, conducted a study to compare different signs maintenance methods and the impact that a sign inventory would have in those methods (Ellison, 2008). When analyzing the control sign method, they collected data on 311 in-service signs to verify their retroreflectivity levels and to determine their relationship to age, sign type (Types I and III), and sheeting color (white, yellow, green, and red). The authors concluded that red and yellow Type III sheeting signs that were 10 to 12 years old were well above the minimum retroreflectivity levels. With respect to Type I sheeting, the research team stated that white signs from 10 to 12 years old were also above the minimum retroreflectivity levels while the green Type I signs should be replaced.

Re et al. (2011) reported that the Texas Transportation Institute collected data on 859 Type III unwashed signs in 21 counties throughout Texas. The research team found that considering all signs surveyed, 99% were in compliance with the minimum retroreflectivity levels. The likelihood of a sign between 10 and 12 years to be noncompliant was 2% and for signs from 12 to 15 years the likelihood increased to 8%. Like Wolshon et al. (2002), Re et al. (2011) concluded that age was a major factor affecting retroreflectivity deterioration. In addition, location (region where signs were installed) also was found to be a significant. Although the authors developed deterioration models based on the field data to estimate sign service life, they indicated that the R^2 values were low and, therefore, the models were somewhat questionable.

Kipp and Fitch (2009) also conducted a study to evaluate different sign maintenance methods for the Vermont Agency of Transportation. The authors collected data on 618 signs Types III and IX in five different colors (white, green, red, yellow, and yellow-green fluorescent); all signs were compliant with the minimum retroreflectivity levels. Of all of the factors studied, the authors found that those affecting retroreflectivity deterioration were sheeting color, type, and manufacturer. In general, Type IX sheeting is more retroreflective than Type III and from the two sheeting manufacturers studied, one had a clearly better performance. Deterioration models were developed; however, as most of the other studies, the R^2 values were very low. Although Kipp and Fitch (2009) did not find sign orientation as a significant factor in retroreflectivity deterioration, they indicated that sign orientation can lead a sign sheeting to fade faster.

Evans et al. (2012) collected data on 1,433 signs in Utah and found that 91% of the signs were compliant with minimum retroreflectivity levels. The data set collected by this research team was one of the most complete among the studies reported here, being comparable to Wolshon et al. (2002), Kipp and Fitch (2009), Pike and Carlson (2014), and Pulver et al. (2018). The research team collected data on signs Types I, III, IX, and IX in four colors (white, yellow, green, and red). Beside the basic data collected in most research (sign age, retroreflectivity color and type, location), the authors also collected photos, offset, height, orientation, and visual assessment data. Evans et al. (2012) found that Type I sheeting accounted for most of the noncompliant signs. When analyzed apart, 97% of Type III sheeting signs were compliant. The authors suggested Utah DOT to replace all signs Type I by Type III to increase the retroreflectivity compliance rate.

Similar, Boggs et al. (2013) also conducted a retroreflectivity study for Utah DOT, in which they a conducted a field survey with and collected data on 1,716 signs (Types III, IX, and XI), including location, elevation, precipitation, temperature, and wind. It is interesting to point out that this field survey was the second largest one related to sign retroreflectivity, being behind only on Black et al. (1991), who collected data on 5,722 signs. Boggs et al. (2013) found that 93% of the signs surveyed were compliant and indicated that, indeed, retroreflectivity performance deteriorates as signs age. The authors also found that the number of noncompliant signs increased with an increase in average precipitation, elevation, and seasonal temperature swing.

In a research study conducted for the Minnesota DOT, Preston et al. (2014) studied expected sign service life and used different research methods to do so, including field survey. During the field survey, the research team collected valid retroreflectivity readings in 379 signs. The data collected included sign age, sheeting type (I, IV, IX, and XI) and background color (white, yellow, green, and red). To analyze the data, the authors disaggregated the data into subsets by age, sheeting type, and sheeting color. Mathematical models were developed for all combinations of data set; however, some models were considered inconclusive because they showed sign retroreflectivity increasing as signs aged, which goes against the common knowledge.

Although other models trended downwards, Preston et al. (2014) concluded the amount of data per subset was not enough to validate the models and, and therefore, considered all deterioration models as inconclusive due to the limited data available in each subset. In addition, the R^2 values were very low too. At the end, the authors commented that even though the deterioration models were inconclusive, they noted that most signs performed above the minimum retroreflectivity levels, even after achieving the end of warranty period. Based on that, the authors believed that the sign service life could be extend to 12 to 20 years for Type I sheeting and to 15 to 30 years for Types IX, IX, and XI sheeting.

Pike and Carlson (2014) conducted a research study for Wyoming DOT to evaluate sign service life. To do so, the research team collected data on 525 signs located in Wyoming and 783 sheeting samples (Types I, III, and IV). The data set included retroreflectivity, assign age, sheeting color and type, photos, pollution, elevation, precipitation, location, and visual assessment (poor, adequate, and good). The authors stated that all signs measured were compliant with the minimum retroreflectivity levels. The research team developed deterioration models in function of sign age by sheeting type and color. Like Preston et al. (2014), Pike and Carlson (2014) noted that retroreflectivity slightly increased as sign aged for Type III sheeting. With respect to Type IV sheeting, the authors found a huge difference in retroreflectivity readings depending on the orientation of the sheeting; in general, horizontal Type IV sheeting resulted in linear trends that were almost constant as signs aged while vertical Type IV sheeting resulted I models with downward trend, indicating that sign retroreflectivity was deteriorating as signs aged (the opposite of what they found for Type III sheeting).

Khalilikhah et al. (2015) conducted a study in Utah in which they collected retroreflectivity measurements (using retroreflectometer) on over 1,700 in-service signs. One of the research steps was verify if digital daytime images collected by an equipped vehicle containing LIDAR sensor and a laser road image system could be used to assess sign retroreflectivity compliance. From all signs measured in field, the authors were able to compare almost 1,500 of them with their respective digital image. The authors found most of Type I signs were noncompliant (74%). Signs Type III (glass beaded) had noncompliance rate of 3% while Type III HIP (prismatic), IX, and XI were almost all compliant with the minimum retroreflectivity lev els (noncompliance rate ~ 0%).

The most recent sign retroreflectivity study was conducted by a research team from the University of South Carolina. Pulver et al. (2018) conducted a field survey in South Carolina State and collected data on 1,599 signs in four colors (white, yellow, green, and red). Although the author did not mention the types of sheeting that were surveyed, it is very likely that they were Types III and above (information based on the South Carolina DOT *Engineering Directive ED-4: Retroreflective Sheeting for Rigid Highway Signs*). From the 1,599 signs observed, less than 1% was noncompliant with the MUTCD standards. The authors collected a significant amount of information during the field survey, including sign age, type, legend, sheeting color/type, sign orientation, offset, height, location, pollutions, wind, frost/dew, orientation, and degree of shade.

Pulver et al. (2018) observed that it was the first time that the variable degree of shade was considered in a retroreflectivity study, which was based on observations that signs located in shade were more likely to contain mildew, dirt and tree sap. From all variables analyzed, Pulver et al. (2018) concluded that sign age, sheeting color, and degree of shade were significant factors on retroreflectivity deterioration. In addition, the authors also found that orientation (northwest direction) was significant for red signs. Different from the previous studies, the deterioration models developed by Pulver et al. (2018) had a good adjusted R^2 value, varying from 0.35 to 0.67.

Although most of the studies cited in the literature investigated sign retroreflectivity under normal conditions, either during the day with retroreflectometer or ate night with visual inspections, there was one conducted by Hildebrand (2003) that studied the effect of frost and dew on sign retroreflectivity levels. The objective of the study was to quantify the reduction in retroreflectivity caused by frost or dew. Thus, the researcher collected data of 130 Type I and glass beaded Type III in service signs (in eastern Canada) in different conditions. For all 130 signs, retroreflectivity measures were collected for three conditions (dry, frost, and dew). The author found that when signs were frost, the retroreflectivity levels reduced by almost 80%, in some case, being below the minimum levels required by the MUTCD. Signs covered with dew had an average reduction of 60% of retroreflectivity. The author concluded that in regions where frost and dew are common, agencies need to consider them when adopting a sign maintenance method. In addition, better quality of sheeting should be used in those areas based on the fact that Type III sheeting had overall better performance than Type I sheeting.

2.1.2 Out-of-Service Sign Studies

Few retroreflectivity studies have been conducted with signs that are located on a controlled environment (e.g., yard or facility). These signs are referred to as out-of-service signs because they are not installed along roads of a highway system. This section will discuss some of these studies that collected sign data in a control sign facility (or yard). In other words, researchers installed signs of different materials and colors on yards that frequently were surrounded by fences with the objective of avoiding any kind of vandalism. Then, research teams would collect retroreflectivity data through the years. There are two main reasons to conduct sign control studies. The first reason is to keep track of the retroreflectivity of control signs as a representative sample of all in-service signs; when the control signs achieve retroreflectivity levels below than the minimum required by MUTCD, all in-service signs that are represented by that control group is replaced (Kipp and Fitch, 2009). The second reason is also to track sign retroreflectivity deterioration through the years; however, in this case, the goal of the researchers is to collect enough retroreflectivity data to develop valid deterioration models (Jiang and Zhou, 2012; Huang et al., 2013; and Preston et al., 2014).

Kipp and Fitch (2009) collected two years of retroreflectivity data of various sign sheeting types (I, IV, IX, and XI) and colors (white, yellow, green, red, and fluorescent yellow green). The sheeting samples were cut in rectangular shapes and placed in a structure similar to a sign rack (see Figure 12.3 in Appendix 12.1). The authors stated that they would keep measuring retroreflectivity levels of those samples (control signs) through the years with the objective of determining when in-service signs made of the same type of material and color should be replaced

Jiang and Zhou (2012) analyzed 12 years of sign data of 130 retroreflective signs (Types I, II, and III) installed in a control sign facility (yard) in Beijing, China, and concluded that age was one of the main factors affecting sign retroreflectivity. In addition, the authors also listed temperature, altitude, climate, and humidity as being significant factors in sign retroreflectivity deterioration. The authors developed retroreflectivity deterioration models and, although the R^2 values were low, they stated that quadratic and cubic models were better than linear models to predict sign retroreflectivity as a function of sign age.

Similar, Huang et al. (2013) conducted a retroreflectivity study in 2013 in China where they observed and measured retroreflectivity of 230 signs located in a control sign facility (test square) for over 12 years. The variety of signs included Types I, II, and III in three colors (white, green, and blue). A quickly and important note here is that sign sheeting in China is referred in a different way. According to the authors, Type I is high-intensity grade in China and Type III is engineering grade in Chine. Therefore, we must be careful to avoid any confusion with U.S. nomenclature.

The researchers developed deterioration models in function of sign age for all combinations of sheeting types and colors, and based on the results, the authors stated that quadratic and cubic models resulted in better R^2 values than linear models (same as Jiang and Zhou, 2012). They also recognized that the R^2 values were not high, but that was consistent with previous studies. Preston et al. (2014) also installed a sign rack with new and used traffic signs in one of the Minnesota DOT's facility. The researchers planned to collect sign retroreflectivity deterioration data through the years and, based on that data, to develop deterioration models. According to the authors, it would be possible to estimate sign service life for different sheeting materials (Types I, IV, IX, and XI) and colors based on the deterioration models.

2.1.3 Summary

This section showed that most studies observed that retroreflectivity deteriorates as signs age, however, only a few studies were successful in showing so (Re et al., 2011, Wolshon et al., 2002; Jiang and Zhou, 2012; Boggs et al., 2013; and Pulver et al., 2018). Sign sheeting type and color also were found to be significant factors in sign retroreflectivity deterioration. With respect to sign orientation, only two out of seven studies considered it as significant in retroreflectivity deterioration. Pulver et al. (2018) found that degree of shade was a significant factor and that signs in the shade tend to deteriorate faster because they often contain mildew and dirt. It was the first time that degree of shade was considered as a variable in a retroreflectivity deterioration study.

In relation to sign retroreflectivity compliance with the minimum levels required by the MUTCD (FHWA, 2009),

Table 2.1 shows a summary of the field survey studies by noncompliance rate. Note that most studies found compliance rates above 90% (Kirk et al, 2001; Kipp and Fitch, 2009; Re et al., 2011; Clevenger et al., 2012; Evans et al., 2012; Dumont et al., 2013; Boggs et al, 2013; Hawkins and Carlson, 2014; Pike and Carlson, 2014; and Pulver et al., 2018). One of the few studies that found noncompliance rates greater than 10% was Immaneni et al. (2007), but the authors justified that most of the noncompliant signs were Type I sheeting. Wolshon et al. (2002) found that 57% of the signs that were over the warranty period were noncompliant with the minimum retroreflectivity levels; however, if only Type III signs are considered in the analysis, the percentage of noncompliant signs that are over guarantee drops to 40.7%.

Table 2.1 Summary of Papers by Sign Noncompliance Rate

Authors	Location	Comments	Sample Size (Signs)	Noncompliance Rate (Retroreflectivity Below Minimum)
Boggs et al. (2013)	Utah		1,716	7.0%
Clevenger et al. (2012)	Pennsylvania		1,007	2.8%
Evans et al. (2012)	Utah		1,433	9.0%
Hawkins and Carlson (2001)	Texas		49	2.0%
Immaneni et al. (2007)	North Carolina	Data collected by research team	1,057	12.7% (most Type I signs)
Khalilikhah et al. (2015)	Utah	Noncompliance rate by type: Type I: 74% Type III (glass beaded): 97% Type III (prismatic): 0% Type IX: 0.5% Type XI (prismatic): 0%	1,466	7.3% (most Type I signs)
Kipp and Fitch (2009)	Vermont		618	0%
Kirk et al. (2001)	Oregon	Signs within 10 years; based on Oregon DOT standards	137	0%
Pike and Carlson (2014)	Wyoming		525	0%
Pulver et al. (2018)	South Carolina		1,599	< 1%
Re et al. (2011)	Texas	Signs 10 to 12 years: 2%; Signs 12 to 15 years: 8%	859	1%
Wolshon et al. (2002)	Louisiana	Signs within warranty	149	8%
Wolshon et al. (2002)	Louisiana	Signs over warranty	88	57%

2.2 Sign Service Life

Sign service life (also known as life expectance) is the time between the installation (or manufacturing) of an asset and its replacement (or removal). In the case of signs, their service life can be determined by age rather than by routine inspections with the objective of tracking retroreflectivity and damage (Thompson et al., 2012). Based on a survey of 39 transportation agencies, Markow (2007) reported a sign service life ranging from 10 to 30 years depending on the sign sheeting type and color.

Many retroreflectivity studies concluded that the use of sheeting manufacturer's warranty period as sign service life is very conservative and it is not considered a good practice. Most studies found the signs out of warranty performed well above the minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). In addition, although the practice of using warranty period as sign service life may guarantee compliance with MUTCD, it often results in replacing signs before retroreflectivity deteriorates below the minimum required, which increases the costs to maintain signs (Re et al., 2011; Re and Carlson, 2012; Preston et al., 2014; and Pike and Carlson, 2014).

Re and Carlson (2012) explained that a warranty period of a sheeting does not represent its true service life; instead, it refers to a period in which it is expected the sign retroreflectivity to deteriorate 20% in relation to its initial value (of a brand-new sign). In addition, manufacturers need to be somewhat conservative with relation to the warranty period because it is the same for different regions under totally different weather conditions (e.g., Alaska and Arizona) (Re and Carlson, 2012). Preston et al. (2014) cited that one of the explanations for signs performing well above the minimum retroreflectivity standards is the fact that sheeting manufacturers keep improving the quality of retroreflective sheeting.

Immaneni et al. (2009) were able to estimate sign service life by sheeting type and color. From the two types of sheeting studied (Types I and III), the most relevant results are those that refers to Type III sheeting, which are commonly used nowadays. For Type III sheeting, the authors found that the sign service life is about 20 to 30 years for white sheeting, 24 years for both yellow and red sheeting, and 37 years for green sheeting. Preston et al. (2014) also concluded that the sign service life could be extend to 12 to 20 years for Type I sheeting and to 15 to 30 years for Types IV, IX, and XI sheeting. Similarly, Pike and Carlson (2014) conducted a study for Wyoming DOT and also found that signs were performing well above the minimum retroreflectivity levels after the end of the warranty period. The authors found that it could be considered a sign service life of at least 13 to 14 years for Type III sheeting and at least 15 to 21 years for Type IV sheeting horizontally applied (depending on the sheeting color). Overall, the authors recommend that the Wyoming DOT adopt a sign service life of at least 15 years.

Ellison (2008) described the efforts of County Pierce (WA) in measuring the retroreflectivity of 311 Type I and Type III signs that were from 10 to 12 years old. Based on the results of the data analysis, Type III signs were performing well above the minimum retroreflectivity levels required by the MUTCD. White Type I signs were still performing above the minimum required levels white green Type I signs were non compliant with the minimum retroreflectivity levels.

Kipp and Fitch (2009) conducted a study for Vermont DOT and at the end they recommended the transportation agency adopt 15 years for red signs and 15 to 20 years for white, yellow, and green signs. Clevenger et al. (2012) conducted an interesting survey with various DOT offices in many states to assess relevant information related to signs maintenance methods. Two sets of information were relevant for this body of knowledge: (1) which signs maintenance methods the DOTs were adopting and (2) what was the sign service life the DOTs were adopting. Dumont et al. (2013) also conducted a similar study, but in that case, the sign service life information was obtained through literature review instead of surveys.

A filed survey was conducted by Clevenger et al. (2012) who collected data of 1,000 signs located in Pennsylvania. Although the authors could not establish a direct correlation between sign age and retroreflectivity deterioration, they stated that, based on the observed data, there was enough evidence that signs between 16 and 18 years would still be above the minimum retroreflectivity levels.

On the other hand, different from all previous studies, Pulver et al. (2018) recommended South Carolina DOT (SCDOT) to consider sign service life as 10 years, the same as the sign warranty period in SC. The authors developed retroreflectivity deterioration models that predicted minimum sign service life of 25 years for red signs, 12 years for yellow signs, and 11 years for both white and green signs (the study did not specify the type of sheeting analyzed). However, despite the deterioration models predictions, the authors recommended SCDOT to keep their sign service life of 10 years (which is currently based on the warranty period of SC signs). The research team explained that such recommendation was based on failure rate, which was defined by them as the number of signs replaced at age *i* divided by the total number of signs at age *i*. According to the authors, signs that are 10 years old have a failure rate of over 0.5, meaning they have a chance greater than 50% of being replaced. However, that should not be a surprise in the case of SC where the sign replacement method adopted by SCDOT is the Expected Sign Life method based on sign warranty period, which is 10 years. If all signs that are 10 years or older are required to be replaced due to the current sign maintenance method, it explains the reason why Pulver et al. (2018) found a high probability of sign failure at 10 years. Therefore, using the failure rate (as described by Pulver et al., 2018) may not be a good option to determine sign service life. Probably the deterioration models developed by the authors are more realistic in predicting sign service life than is the failure rate.

A summary of the papers related to sign service life is presented in Table 2.2 and it is organized by authors, location, and sign service life. The third column in the table lists the sign service life adopted by DOTs at the time of the studies listed in the first column. Such information was obtained mainly through surveys (Clevenger et al., 2012; Kipp and Fitch, 2009; and Re and Carlson, 2012). The last column of the table shows the recommended sign service life, if any, resulted of the study. In general, most DOTs are already adopting, or studies suggests that they could adopt, a sign service life beyond the warrant period (15 years and above). There are four DOTs from this literature review that still adopt the sign service life as the same as manufacturer warranties(Arkansas, Maine, North Carolina, and South Carolina).

Table 2.2 Summary of Papers by State and Sign Service Life

Authors	Location	Sign Service Life	
		DOTs Practice	Study Findings or Recommendation
Clevenger et al. (2012)	Arkansas	10 years for Type III (based on warranty)	-
Dumont et al. (2013) and Clevenger et al. (2012)	Indiana	18 years for Type III and above	-
Clevenger et al. (2012)	Maine	10 years for Type III (based on warranty)	-
Clevenger et al. (2012)	Massachusett s	16 to 18 years for Type VIII and above	-
Clevenger et al. (2012)	Michigan	Expected: 15 years for Type III and above Actual: 17 years (due to budget)	-
Dumont et al. (2013)	Minnesota	12 years for Type III 15 years for Type IX and XI	Minimum: 15 years for all signs; Maximum: 20 years for Type IV and 30 years for Types IX and XI
Clevenger et al. (2012)	Mississippi	10 to 12 years for Type III and 15 years for Type XI	-
Clevenger et al. (2012)	New York	12 to 15 years for Type III and above	-
Immaneni et al. (2009) and Rasdorf and Machado (2018a)	North Carolina	10 years for Type III (based on warranty)	20 to 30 years white Type III; 24 years for yellow and red Type III 37 years for green Type III (Immaneni et al., 2009)
Clevenger et al. (2012) and Dumont et al. (2013)	Ohio	15 years for Type III and above	

Table 2.2 Summary of Papers by State and Sign Service Life (Cont.)

Authors	Location	Sign Service Life	
		DOTs Practice	Study Findings or Recommendation
Clevenger et al. (2012)	Oklahoma	15 years for Type III and above	
Clevenger et al. (2012)	Pennsylvania	-	Minimum: 15 years for Type III
Pulver et al. (2018)	South Carolina	10 years for Type III (based on warranty)	10 years for Type III and above.
Clevenger et al. (2012)	South Dakota	12 years for Type III 15 years for Types IV, VI, VIII, and X 18 years for Types IX and XI	-
Kipp and Fitch (2009) and Clevenger et al. (2012)	Vermont	15 years for Type III	15 years for red Type III 15 to 20 years for white, yellow, and green Type III (Kipp and Fitch, 2009)
Clevenger et al. (2012)	Virginia	15 years for Type IX	-
Clevenger et al. (2012) and Dumont et al. (2013)	Wisconsin	12 years for Type III	-
Clevenger et al. (2012) and Pike and Carlson (2014)	Wyoming	12 years for Type III	Minimum: 13 to 14 years for Type III 15 to 21 for Type IV Recommendation: 15 years (Pike and Carlson, 2014)

2.3 Sign Damage

Although sign retroreflectivity rates are important, transportation agencies also should take into consideration sign damage rates when choosing the adoption of one or more of the sign maintenance methods described by the MUTCD (FHWA, 2009). Major damages cause loss of sign legibility, which can represent a risk for drivers because enables signs to convey the message to drives (Boggs et al., 2013). The damage issue is more critical by the fact that the sign legibility is affected both during the day and at night (Khalilikhah et al., 2016). Another factor to be considered by transportation agencies is the cost to maintain and replace damaged signs with the objective to offer a satisfactory overall sign condition to the population. Therefore, transportation agencies need to consider damage in their sign maintenance program.

Many studies were conducted to investigate sign damage caused and rates across the U.S. The most common method used by researchers to assess sign damage was conducting visual assessment while doing field survey. Khalilikhah et al. (2016) was one of the few studies that used an equipped car to register images of signs and then process the information.

For instance, Immaneni et al. (2007) studied sign damage rates in NC. The research team rejected 197 out a total of 1,057 inspected signs due to low retroreflectivity and/or damage. According to the authors, a sign could be rejected due to one or more reasons (e.g., low retroreflectivity and paintball marks). Sign damage was classified into vandalism (e.g., gunshots and paintball marks) and natural damage (e.g., tree sap). The results showed that from the 197 rejected signs, 40% were vandalized and 30% presented natural damages. The research team also stated that the overall sign replacement rate due to damage per year in NC was 4.7% of all signs.

After analyzing sign field data from Utah Department of Transportation, Boggs et al. (2013) found that verifying only retroreflectivity levels on road signs was not sufficient to guarantee legibility of signs on the roads. While only 7% of the signs failed in meeting the retroreflectivity requirements, 28% of the signs were not legible due to damage. Therefore, the research team decided to study main factors that could be the cause of sign damage and legibility loss by analyzing data from 1,716 signs located within Utah. From those, 28% had major damage, meaning that there was legibility loss. The types of damage were classified into vandalism, aging, and environmental. The researchers concluded that the four major factors affecting damage rates were average annual precipitation, seasonal temperature swing, elevation, and location (canyon mountain, urban, and rural). The author suggested that by knowing in which locations signs have higher damage rate, transportation agencies can distribute better their resource allocation in order to maintain sign visibility and legibility. Evans et al. (2012) also collected data of 1,433 signs throughout Utah (1.5% of Utah DOT's sign inventory) and found the damage rates in two of the four regions of Utah Department of Transportation were significant, ranging from 25% to 30% of the surveyed signs.

Khalilikhah et al. (2016) conducted a study to correlate sign vandalism and demographics of local population. The research team collected information and images of 97,314 signs using an equipped car in Utah. From the signs surveyed, almost 7% were damaged and were classified into three categories (aging/environmental, vandalism, and unknown). The authors stated that from those damaged signs, at least 22% was caused by vandalism (equivalent to 1.5% of the 97,314 signs). The findings showed that counties with higher population populated, higher-income, and higher education (at least one associate degree) have a lower vandalism rate.

Khalilikhah and Heaslip (2016) also investigated the effect of damage on sign visibility by conducting a field survey in which they collected data and resisted photos of 1,683 signs in Utah, from which 8% were damaged. The authors found that damage was a significant factor contributing to sign retroreflectivity deterioration for glass beaded Type III sheeting. According to the authors, when glass beaded Type III signs were damaged, they had lower retroreflectivity performance than non damaged signs. However, the same did not hold true for prismatic Type III, IX, and XI. Signs manufactured with these materials had a higher performance (retroreflectivity levels) independent of being damaged or not.

Hawkins and Carlson (2001) conducted a study for Texas DOT to compare the results of nighttime visual inspection and measured sign retroreflectivity. The research team analyzed 200 Types I, II, and III signs that were in-service and removed from the field for study purpose. After assessing sign overall condition (including damages) and measuring the retroreflectivity of all signs, the authors selected 49 to conduct the study. The study consisted of displaying those 49 signs along a short route and asked Texas DOT sign crews to conduct visual nighttime inspections on these signs. Although only one sign out 49 signs was noncompliant with the minimum retroreflectivity levels, inspectors rejected 26 signs (53%). Analyzing the results, the authors observed that most of the signs were rejected due to damages and inconsistency on the sign face rather than due to low retroreflectivity. The authors pointed out that most of the rejected signs were Type I sheeting, which Texas DOT had been replacing by Type III since 1993. Based on these results, Hawkins and Carlson (2001) concluded that measuring sign retroreflectivity is not enough for a sign maintenance program; visual assessment of the sign is useful in detecting damages and inconsistencies that affect the sign legibility, and therefore, which signs should be replaced.

Pike and Carlson (2014) observed different types of damage during a field survey in which they collected data on 525 signs in Wyoming. Besides retroreflectivity data, the authors also observed major sign damages, including damages caused by shotgun, vandalism (stickers and spray paint), errant vehicles, and dirt. The authors found that 21.5% of the signs were damaged even though all surveyed signs were above the minimum retroreflectivity levels. The authors also stated only Type I signs presented color fading issues. The same was not noted for Type III and IV signs. Pike and Carlson (2014) concluded that that although signs were performing well above the minimum retroreflectivity levels, they would most likely need to be replaced before the end of their service life due to damages.

As the studies discussed herein, sign damage rates should be considered by a transportation agency while analyzing different sign maintenance methods. Table 2.3 shows a summary of the field survey studies organized by damage rates.

Table 2.3 Summary of Papers by Damage Rate

<table>
<tr><th rowspan="2">Authors</th><th rowspan="2">Location</th><th rowspan="2">Sample Size (Signs)</th><th colspan="4">Damage (by type)</th><th rowspan="2">Overall Damaged</th></tr>
<tr><th>Vandalism</th><th>Aging</th><th>Natural and Accidental</th><th>Unknown</th></tr>
<tr><td>Boggs et al. (2013)</td><td>Utah</td><td>1,716</td><td>6.0%</td><td>4.6%</td><td>12.0%</td><td></td><td>28.0%</td></tr>
<tr><td>Evans et al. (2012)</td><td>Utah</td><td>1,433</td><td>8.6%</td><td></td><td>-</td><td></td><td>19.8%</td></tr>
<tr><td>Khalilikhah et al. (2016)</td><td>Utah</td><td>97,317</td><td>1.5%</td><td colspan="2">3.0%</td><td>2.4%</td><td>7%</td></tr>
<tr><td>Khalilikhah and Heaslip (2016)</td><td>Utah</td><td>1,683</td><td></td><td></td><td></td><td></td><td>8%</td></tr>
<tr><td>Hawkins and Carlson (2001)</td><td>Texas</td><td>49</td><td>-</td><td></td><td>-</td><td></td><td>51.0%</td></tr>
<tr><td>Immaneni et al. (2007)</td><td>North Carolina [1]</td><td>1,057</td><td>7.4%</td><td></td><td>5.7%</td><td></td><td>-</td></tr>
<tr><td>Immaneni et al. (2007)</td><td>North Carolina [2]</td><td>1,681</td><td>1.3%</td><td></td><td>0.9%</td><td></td><td>2.3% *
4.7% **</td></tr>
<tr><td>Pike and Carlson (2014)</td><td>Wyoming</td><td>525</td><td>11.0%</td><td></td><td>11.0%</td><td></td><td>21.5%</td></tr>
</table>

[1] Data collected by the NCSU research team
[2] Data collected by NCDOT sign inspection crews
* Damage rate of sign identified during field inspection.
** Overall damage rate that includes signs identified during inspections and signs reported out of inspection.

It can be observed that while most of the studies reported low retroreflectivity noncompliance rates (Kirk et al, 2001; Kipp and Fitch, 2009; Re et al., 2011; Clevenger et al., 2012; and others), damage rates were significantly high, which in some cases achieved over 20% of total signs inspected (Boggs et al., 2013 and Pike and Carlson, 2014). Vandalism showed to be one of the main causes of major sign damages, Pike and Carlson (2014) reported a vandalism damage rate of up to 11%. As reported by Pike and Carlson (2014), signs are likely to be replaced before achieving the end of service life (with respect to retroreflectivity).

Khalilikhah and Heaslip (2016) suggested that agencies open a communication channel with the population to report damaged signs. As an example, the authors cited that people can report damaged and missing signs to New York City by phone or online. A similar approach is also adopted by the NCDOT that provides an online and phone service to enable the population to report problems related to signs, shoulders, traffic lights, and other transportation assets. With respect to signs, one of the first questions on the NCDOT online form is if the problem is with a stop sign. Then, it is asked if the person is reporting a knocked down or a damaged signs. Those questions help the agency to organize their priority to replace or repair the reported signs.

2.4 Sign Maintenance Methods

The MUTCD (FHWA, 2009) describes five methods that transportation agencies can choose from for adoption to ensure minimum retroreflectivity levels. Those methods are classified into two categories: assessment and management. Assessment methods include visual nighttime inspection and measured sign retroreflectivity, which can be considered as a reactive approach because signs are replaced after they are detected as being below the minimum retroreflectivity levels.

Management methods include Expected Sign Life, Blanket Replacement, and Control Signs. Those are proactive methods that replace signs before they achieve retroreflectivity levels below the minimum required. Management methods not require transportation agencies to assess retroreflectivity of individual signs. Instead, those methods are based on sign service life. The premise if the signs should perform above the minimum retroreflectivity levels required by the MUTCD during their service life. When those signs achieve their service life, they are replaced. A more detailed description of these five methods is provided below.

This section covers previous studies that focused on the analysis or implementation of different sign maintenance methods. Most of the researchers opted for studying the five methods recommended by MUTCD (Carlson and Picha, 2009; Clevenger et al., 2012; Dumont et al., 2013; and Re and Carlson, 2012). Other studies concentrated on more specific sign maintenance methods, for example, Kipp and Fitch, 2009, Hummer et al., 2013, and Hawkins and Carlson, 2014.

Re and Carlson (2012) conducted a study based on previous studies and also surveyed transportation agencies across the U.S. to know which sign maintenance methods they were adopting. They found that the Expected Sign Life method was the most used, followed by the Visual Nighttime Inspection and Blanket Replacement methods. Similar, Clevenger et al. (2013) also conducted a survey and observed that most states were interested in the Expected Sign Life method. The authors stated that 13 out 27 states were planning to adopt the Expected Sign Life method. In addition, five of the 12 states that were already using the Expected Sign Life method indicated that they combined it with another method, often with Blanket Replacement (Indiana, Mississippi, New York, Ohio, and Wisconsin).

Kipp and Fitch (2009) conducted a study for Vermont Agency of Transportation and analyzed three sign maintenance methods: Measured Retroreflectivity, Blanket Replacement, and Control Signs methods. At the end of the study, the research team recommended the transportation agency to adopt the Blanket Replacement method because it does not require retroreflectivity measurements of individual signs nor a sophisticated inventory database. A simple sign inventory would serve the agency's needs and sign age could be easily obtained from the inventory.

Another author described the efforts of Pierce County, WA, in analyzing and evaluating some maintenance methods (Ellison, 2008). The author explained that Pierce County was interested in selecting one of the methods recommended by MUTCD considering that they had a good sign inventory. The methods analyzed were the Nighttime Visual Inspection, Measured Retroreflectivity, Expected Sign Life, and Control Signs. After concluding the study, Pierce County opted to use a combination of three sign maintenance methods.

Harris et al. (2007) used a macroscopic simulation model to analyze and compare different sign maintenance methods while considering the costs associated with them. The authors studied four of the five methods recommended by MUTCD: Nighttime Visual Inspection, Measured Retroreflectivity, Expected Sign Life, and Blanket Replacement (replacement cycles based on warranty period) methods. Although Expected Sign Life and Blanket Replacement scenarios resulted in less than 5% noncompliance rates, they were the most costly methods, with increases of 48% in costs. Measured Retroreflectivity scenarios resulted in significant increase in cost and up to 10% noncompliance rate. The authors concluded that the Nighttime Visual Inspection method was the method that offered greater cost benefit to NCDOT because it would not require major investments and would reduce the number of noncompliant signs by 10%.

Hummer et al. (2013) also used a simulation (microscopic) to evaluate the Nighttime Visual Inspection, Blanket Replacement, and Expected Sign Life. By the end of the study, Hummer et al. (2013) concluded that the Blanket Replacement method was not cost competitive when compared to the Nighttime Visual Inspection method. On the other hand, the Expected Sign Life method seemed to be a good alternative to the Nighttime Visual Inspection method. However, it is needed to point out that the Expected Sign Life scenario analyzed in this study did not take into consideration the cost of maintaining a sign inventory.

2.4.1 Overview

There were also studies that focused on the analysis or implementation of different sign maintenance methods recommended by the MUTCD (FHWA, 2009). The sign maintenance methods are categorized into assessment (nighttime visual inspection and measured retroreflectivity) and management (expected sign life, blanket replacement, and control signs) (FHWA, 2013).

Visual nighttime inspection consists of trained sign inspectors riding along the roads at night and visually inspecting all signs to identify those that are below minimum retroreflectivity levels. The deficient signs identified during the nighttime inspections are then replaced. The measured retroreflectivity method consists of measuring the retroreflectivity of all signs using a handheld or mobile retroreflectometer during daytime inspections. The measurement procedure follows the "ASTM Standard Test Method E1709-00e1, which requires a minimum of four retroreflectivity measurements to be taken of the sign background and legend, if applicable" (FHWA, 2007). This is the most objective of the methods, but it is also the highest labor intensive.

Table 2.4 Sign Retroreflectivity Maintenance Methods Description, Advantages, and Disadvantages

Method	Description	Advantages	Disadvantages
Visual nighttime inspection	Trained sign inspectors ride along the roads at night and visually inspect all signs to identify those that are below minimum retroreflectivity levels. These are then replaced.	Does not require retroreflectometers; Other aspects of signs are assessed (e.g., damage and knockdown); Inspectors can evaluate more than signs (e.g., pavement markings and shoulders); Development of a sign inventory while driving roads.	Need for trained inspectors; Highly subjective; Overtime labor cost; Depend on weather.
Measured retroreflectivity	Sign inspectors measure retroreflectivity levels of all signs using a retroreflectometer and replace those below the minimum.	Objective evaluation; Data collection can be used to generate deterioration models; Sign retroreflectivity can be measured during the day.	High retroreflectometer cost; Inspectors exposed to roadway hazards; Some signs are located in areas of difficult access; High labor intensive.
Expected sign life	Sign crews replace all signs that exceed their expected life. DOTs often estimate expected sign life based on field experience, warranty, or retroreflectivity deterioration rates. To track expected sign life, agencies stamp the installation date on the back of the sign. Doing so allows sign crews to identify and remove signs that are beyond their expected life.	Reduced material waste; Accurate record; Possible extension of sign service life; Provide data for planning, scheduling, and budgeting.	Signs may fade before the end of service life; Sign service life maybe over estimated or under estimated; High administrative and management cost; Requires a detailed inventory database.
Blanket replacement	Sign crews replace all signs in a corridor or area (section). Those signs are replaced at regular long-term intervals that are based on the expected sign life.	Simple and straightforward; Regular replacement cycles; Sign inventory may not be required if agency keeps track of when the signs in an area/corridor are replaced.	High chances of replacing signs before the end of their service life; Daytime inspections still needed to detect damaged signs; Determination of the replacement cycles is required.
Control sign	Instead of checking the retroreflectivity level of all field signs inspectors monitor the retroreflectivity of control signs, which are representative of all other signs of a given type installed on the same date.	Data collection throughout the year; Data collection can be used to generate deterioration models; Centrally located; Less costly.	Requires a retroreflectometer; There is no guidance on what is considered an adequate sample size; High installation and maintenance cost of a control sign facility.

The expected sign life method replaces only the signs that have achieved the end of their service life. This method requires an updated sign inventory database to keep track of sign age and location. The blanket replacement method is similar to the expected sign life method in that signs are replaced based on their service life. The difference is that signs are replaced by group (e.g., red signs) or by geographical area (sections or corridor). There is no need to keep track of the age of individual signs. The control signs method consist of measuring the retroreflectivity of control signs, which are representative of all other signs of a given type installed on the same date. An overview of these five methods is provided in Table 2.4 (FHWA, 2009, FHWA, 2013). In addition, advantages and disadvantages for each method is listed (FHWA 2007; Re and Carlson, 2012; Clevenger et al., 2012; and Dumont et al., 2013).

The next subsections describe major findings and recommendations from previous studies for each one of the five sign maintenance methods recommended by MUTCD.

2.4.2 Nighttime Visual Inspections

There are many debates about whether or not the Nighttime Visual Inspection is one of the best ways of maintaining signs. Some agencies opt for it because it does not require significant investment while others consider it as a subjective method with no guarantees. This section focuses on studies that covered the Nighttime Visual Inspection method.

Re and Carlson (2012) found that 13 of the agencies surveyed adopted the Nighttime Visual Inspection as the primary sign maintenance method. Most of them conducted those inspections during the winter when nights are longer. They also found that agencies that did not use nighttime inspection decided so because they were concerned about an increase in lawsuits. An interesting point made by the authors is the lack of standards to determine the frequency in which nighttime inspections should be conducted.

Hawkins and Carlson (2001) mentioned some benefits of the Nighttime Visual Inspection method. The authors compared inspector reject rate with the results that the research team obtained by measuring sign retroreflectivity. Although only one sign was noncompliant, the inspectors rejected 26 out 49 signs, most of them because they contained major damages and irregularities on the sign faces. The research team concluded that a visual assessment is desirable because it can detect not only noncompliant signs, but also damaged signs. The authors explained that only measuring sign retroreflectivity levels is not enough to maintain them in an overall good condition.

On the other hand, Immaneni et al. (2007), who also analyzed inspectors' accuracy, had a different conclusion. In this study, the authors were interested in comparing inspectors' accuracy with actual retroreflectivity level of the signs. The research team found that inspection accuracy varied from 47% to 51%, depending on the color of the signs. That shows that although some signs were noncompliant, the inspectors did not reject them. A lesson learned from this study is that agencies that desire to adopt the Nighttime Visual Inspection method must train their inspectors and standardize the inspection procedures in order to increase the inspector' accuracy; otherwise, a significant number of noncompliant signs are not identified during nighttime inspections, therefore, they are not replaced.

Rasdorf et al. (2006) conducted a study to evaluate the Nighttime Visual Inspection method. The authors cited as advantages of this method the speed in which visual inspections can be conducted and that it is possible to train crews to do the work. However, there are also disadvantages. For instance, the quality of inspection and replacement practices are a result of employees' performance. For example, there are employees that work in the same county for years and they are proud of keeping signs in good condition in their county. On the other hand, there are temporary employees that do not have this sense of pride, and as a consequence, perform a lower quality work, resulting in an inferior sign condition. Another point mentioned by the authors is whether or not this method provides enough liability protection to transportation agencies against lawsuits.

Other disadvantages of the Nighttime Visual Inspection method were mentioned by Ellison (2008) who stated that Pierce County opted for eliminating nighttime inspections because it would be necessary to train inspectors, assign overtime and shift differential, use two-person crews, make two trips (one to inspect and one to replace/maintain), and could result in replacement of signs that were above the minimum retroreflectivity levels.

2.4.3 Measured Retroreflectivity

The Measured Retroreflectivity method is the most objective method to comply with the minimum retroreflectivity levels (Carlson, 2011). Nevertheless, is the least adopted method among the transportation agencies they surveyed; only two agencies had adopted it (Re and Carlson, 2012). The major reasons for this were the high cost of retroreflectometers, labor intensive, and the difficulty in measuring some signs due to barrier constraints in the field. In Dumont et al.'s (2013) study, the option of Minnesota DOT (MnDOT) adopting the Measured Retroreflectivity method was eliminated by the task force members because, according to most of them, there were too many disadvantages in this method, including high cost, lack of effective plan, and complex. Ellison (2008) mentioned that Pierce County studied the possible adoption of this method, however, it was disregarded for being too labor intensive.

Carlson (2011) described a set of disadvantages of manually measuring retroreflectivity, including the fact that the device must be in contact with the surface of the sign, time consuming, difficult access to some signs (e.g., overhead signs), equipment cost, small reading area, etc. However, the author presented an alternative that would eliminate the disadvantages of the used of retroreflectometers, and as a consequence, make feasible the adoption of the Measured Retroreflectivity method by transportation agencies. The author referred to an Advanced Mobile Asset Collection (AMAC) System, which is an equipped vehicle (van) that records retroreflectivity levels of signs while in movement. Carlson (2011) showed that the AMAC System had a good performance in measuring retroreflectivity. One challenge cited by the author was the measurement of signs manufactured with prismatic sheeting, which may be a concern considering the most agencies currently adopt prismatic signs.

Khalilikhah et al. (2015) studied the capability of assessing sign retroreflectivity compliance through digital daytime images. The authors measured the retroreflectivity of in-service signs to determine their compliance and then analyzed the digital of these same signs collected by an equipped vehicle. At the end of the study, the authors found that daytime digital images were not reliable to assess sign compliance. Most of the signs that were considered in poor condition through the analysis of the digital images were still performing above the minimum retroreflectivity levels.

2.4.4 Expected Sign Life

Re and Carlson (2012) stated that the Expected Sign Life method was the most used method, being adopted by 17 of the surveyed participants. Agencies said that, in order for this method to be successful, it is necessary to know how many signs they have and to maintain an efficient and accurate sign inventory. Another study that showed the potential of the Expected Sign Life method was Dumont et al.'s (2013). The authors conducted a cost analysis of different sign maintenance methods and, based on it, recommended MnDOT to adopt a combination of the Expected Sign Life (primary method) and Visual Inspection (both daytime and nighttime). The secondary method (visual inspection) would start when signs achieved the end of the expected service life. So, instead of automatically replacing those signs, visual inspections would be conducted to assess the likelihood of extending sign service life. The authors pointed out the importance of keeping the inventory database updated.

In the case of Pierce County, Ellison (2008) said that the Expected Sign Life method was one of the favorites because of the existing sign inventory that allowed them to determine the number and location of signs above their sign service life. However, after investigating this method further, Pierce County concluded that the Expected Sign Life method could result in major material waste, with materials being replaced before their actual service life. That was a disadvantage cited by other authors as well (Re and Carlson, 2012; Clevenger et al, 2012; and Dumont et al., 2013).

It is worth to mention that this method requires a detailed sign inventory database to keep track of the age and location of individual signs. As signs achieve their service life, agencies can locate them through the database and schedule replacement. Ellison (2008) described how sign inventory was found to be a powerful tool to help Pierce County (WA) to meet the minimum retroreflectivity levels. SCDOT is another transportation agency that also uses a sign inventory to identify signs that are close to the end of their service life.

However, a sign inventory database may not be feasible for all transportation agencies. Rasdorf et al. (2009) studied the challenges involved in the development and maintenance of a high volume and low cost asset (e.g., signs). For states as NC that has a large number of signs (over 1 million; Kirtley and Rasdorf, 2001), tracking all of them can be a difficult task. Some of the problems identified by the authors are asset identification (unique numbers), GPS location, general sign information record (sign type, sheeting type, installation date, asset condition, etc.), and unsuccessful automated data collection.

Balali et al. (2015) stated that whereas most state DOTs developed asset management systems for bridges and pavement (high cost and low quantity assets), most agencies do not have a similar system for assets such as traffic signs (low cost and high quantity assets) because of the high cost associated with the traditional data collection methods. As an alternative to the traditional methods, Balali et al. (2015) studied the effectiveness of creating (or updating) a sign inventory databased by using Google Street View images. The proposed system was capable of identifying, classifying, and determining the probable location of signs by analyzing Google Street View images. The authors used the proposed system to analyze 6.2 miles of a highway and found an accuracy of almost 95% of sign classification.

Although the system proposed by Balali et al. (2015) seems to be promising and inexpensive, the 5% inaccuracy is still an issue that needs to be addressed. In addition, the authors mentioned that the spatio-temporal representation of signs obtained from Google Street View had potential to enable DOTs to observe sign degradation and plan sign replacement. However, it would be risky for agencies to rely on such images to determine sign deterioration over time because this approach depends on the frequency that Google Street View images are updated, which is unknown.

He et al. (2017) conducted a study to assess the feasibility of building or updating highway asset inventory using airborne LIDAR. The authors collected data on four segments of highways in Utah. The asses covered in the study were overhead signs, traffic signals, bridges, billboards, light pole, and culverts. Although the research team concluded that airborne LIDAR was an efficient method to collect quantities and location of some road assets, the technology did not identify any ground mounted signs because of the low point density of the LIDAR data. This study shows the challenges involved in creating and updating a sign inventory database, especially of ground mounted signs that represent most of state maintained signs. In addition, the airborne LIDAR was able to identify and locate other assets than ground mounted signs, but it did not assess the assets condition, which is an important component of any inventory.

Therefore, transportation agencies that desire to adopt the Expected Sign Life method need to consider the feasibility do develop and maintain a sign database inventory into account when making a decision.

2.4.5 Blanket Replacement

Re and Carlson (2012) stated that the Blanket Replacement method was the third most used method, being adopted by seven of the surveyed participants. Agencies mentioned that the reason to adopt this method was the fact that it is a simple and straightforward method. However, a concern was that the Blanket Replacement method does not account for signs replaced due to damage and knockdown. Therefore, those signs that were replaced due to damage between the blanket replacement cycles would be replaced again before achieving the end of their service life.

Dumont et al.'s (2013) mentioned that the MnDOT task force members evaluated the Blanket Replacement method as having many benefits such as being simple, providing consistency, and cost efficiency. However, the task force had already decided to adopt a combination of two sign maintenance methods for MnDOT. And when they considered the Blanket Replacement method in combination with another method, it was not as efficient as other options that they had.

2.4.6 Control Signs

Re and Carlson (2012) reported few agencies adopted this method. According to the authors, most of the agencies did not consider it as an option because besides having to acquire retroreflectometers, it was costly to maintain a system to manage sign data. Similar, Dumont et al.'s (2013) said that MnDOT task force members eliminated the option of control sign as a maintenance method to be used by MnDOT because it was difficult to combine it with another method in order to mitigate the control sign method's disadvantages.

Re and Carlson (2012), however, pointed out that there are advantages in adopting this method. For instance, one of the transportation agencies said that it was possible to extend their blanket replacement cycle from 14 to 18 years based on analysis of retroreflectivity data obtained from control signs. Pierce County (WA) seemed to have had a good experience with the Control Signs method (Ellison, 2008). The county created sign control groups to represent red, yellow, white, and green sheeting and Type I and Type III sheeting. The agency's personnel kept track of the control signs retroreflectivity. After analyzing the benefits, Pierce County concluded that the Control Signs method was a good option and that an accurate sign inventory was useful because it was able to list the control signs in a way of creating an efficient inspection route based on the signs' identification numbers.

Kipp and Fitch (2009) used the Control Signs method in their study to assess retroreflectivity. The authors received sheeting samples of various colors and types from manufacturers. The research team placed those samples on sign racks in a lab facility and collected retroreflectivity for two years by the time of the publication of the article. Although the authors could not draw conclusions based on the data collected from the control signs because of limited amount of data, they stated that Control Signs method was a good practice. The main reason relied on the fact that this method does not require assessment of individual signs. At the end, the authors recommended the continuous data collection of control signs.

Following a different approach, Harris et al. (2009) did not study the benefits or disadvantages of the Control Signs method; but instead, proposed the design of a control sign facility for agencies that desire to adopt such method. The research team recognized that there was need for more retroreflectivity data on a controlled environment (e.g., a patio or yard protected with fence). That retroreflectivity data could be used to give support to all other sign maintenance methods. The proposed sign control facility had three objectives: (1) retroreflectivity measurement over the years, (2) identify when signs are no longer compliant with the standards, and (3) minimize space and cost to maintain the facility. To achieve those objectives, the following steps are needed: select the signs to be studied (type and colors), design the facility and layout, develop a data collection plan, and analyze costs.

2.4.7 Summary

The literature review shows that all sign replacement methods have advantages and disadvantages (Clevenger et al., 2012; Dumont et al, 2013; Re and Carlson, 2012). In some cases, researchers concluded that the combination of two or more methods was advantageous because then it is possible to reduce weakness of individual methods (Dumont et al, 2013; Re and Carlson, 2012).

Table 2.5 shows a summary of sign maintenance methods adopted by 45 of the 50 states. The information was obtained from various sources in the literature and are also shown in the table (second column). As it is possible to note, the Expected Sign Life is the most used method, followed by the Nighttime Visual Inspection and Blanket Replacement methods, which is in accordance with Re and Carlson's (2012) findings.

Table 2.5 Sign Maintenance Method Adopted by State

State DOT	Authors	Nighttime Inspection	Measured Retro	Expected Sign Life	Blanket Replacement	Control Signs
Alabama	Re and Carlson (2012)	x				
Alaska	Clevenger et al. (2012)	x	x			
Arizona	Clevenger et al. (2012)	x		x		
Arkansas	Clevenger et al. (2012)				x	
California	Clevenger et al. (2012)	x				
Colorado	Re and Carlson (2012)				x	
Delaware	Clevenger et al. (2012)	x		x		
Florida	Re and Carlson (2012)	x				
Idaho	Re and Carlson (2012)	x				
Illinois	Re and Carlson (2012)				x	
Indiana	Clevenger et al. (2012)			x	x	
Iowa	Clevenger et al. (2012)	x				
Kansas	Re and Carlson (2012)				x	
Kentucky	Clevenger et al. (2012)	x		x		
Louisiana	Clevenger et al. (2012)			x		
Maine	Clevenger et al. (2012)			x		
Massachusetts	Clevenger et al. (2012)	x			x	
Michigan	Clevenger et al. (2012)			x	x	
Minnesota	Huynh et al. (2018)				x	
Mississippi	Clevenger et al. (2012)			x	x	
Missouri	Re and Carlson (2012)	x				
Nebraska	Kipp and Fitch (2009)	x				
New Hampshire	Re and Carlson (2012)	x				
New Jersey	Re and Carlson (2012)			x		
New York	Clevenger et al. (2012)			x	x	
North Carolina	Rasdorf and Machado *	x			x	
North Dakota	Clevenger et al. (2012)	x				
Ohio	Clevenger et al. (2012)			x	x	
Oklahoma	Clevenger et al. (2012)					
Oregon	Kipp and Fitch (2009)	x				
Pennsylvania	Re and Carlson (2012)			x		
South Carolina	Rasdorf and Machado *	x		x		
South Dakota	Clevenger et al. (2012)			x		
Texas	Re and Carlson (2012)	x				
Utah	Huynh et al. (2018)				x	
Vermont	Clevenger et al. (2012)			x		x
Virginia	Rasdorf and Machado *	x		x	x	
West Virginia	Kipp and Fitch (2009)			x		
Wisconsin	Clevenger et al. (2012)			x	x	
Wyoming	Clevenger et al. (2012)	x				
TOTAL	**40**	**20**	**1**	**18**	**15**	**1**

* Information obtained in meetings of the authors with NC, VA, and SC DOTs

2.5 Sign Management Cost

Some authors also conducted sign replacement and maintenance analysis while others provided transportation agencies with a budget estimation tool that automatically calculates sign replacement cost. This section briefly describes the main findings from the literature reviewed that are related to sign maintenance cost.

Rasdorf et al. (2005) evaluated the Nighttime Visual Inspection method and to do so they authors considered a sign replacement cost of $30 per sign (Type I), visual inspection cost of $0.17 per sign, and measured retroreflectivity (with retroreflectometer) cost of $2.33 per sign.

In the study conducted by Harris et al. (2007), the authors analyzed sign inspection and replacement costs to compare the performance of different sign maintenance methods. The authors estimated that the Nighttime Visual Inspection method cost was $0.55 per sign while the cost of the Measured Retroreflectivity method was $2.80 per sign (these costs did not consider vehicle costs). It is not surprising that the Measured Retroreflectivity method is more expensive than visual nighttime. Two main reasons for this difference is that the Measured Retroreflectivity method is labor intensive and requires the use of a retroreflectometer, which is expensive. With respect to replacement cost, the authors indicated that it varied according to the type of sign and material, with Type III sheeting being more expensive than Type I sheeting.

After simulating different sign maintenance methods in Excel, Harris et al. (2007) observed that one of the Nighttime Visual Inspection scenarios resulted in an increase of 9.3% in the annual cost per sign (compared with the NCDOT practice at the time of the research) and a reduction of 10.4% in the number of noncompliant signs. With respect to management methods, the authors said that although the Blanket Replacement and Expected Sign Life methods were successful in reducing the number of noncompliant signs to 5% and 0%, respectively, they resulted in a drastic increase of annual cost per sign. For instance, the Blanket Replacement method increased the cost per sign from $3.43 to $6.22, which is a cost increase of 81%. Similarly, the Expected Sign Life method increased the cost per sign from $3.43 to $5.09, which represents an increase of 48%. This study confirms the idea that sign maintenance methods that generate better results (lower number of non-compliant signs) often result in higher costs. Thus, transportation agencies need to analyze cost-benefits and decide what risks they are willing to take; how many non-compliant signs they are willing to leave in the field in exchange of a cheaper sign maintenance program.

Like Harris et al. (2007), Dumont et al. (2013) also conducted a cost analysis to evaluate different sign maintenance methods. What is interesting in this study is that the authors analyzed the adoption of multiple methods combined (e.g., the Expected Sign Life method combined with Control Signs method). The assumptions and inputs considered by the authors to do the cost analysis were failure rate (8% per year), cost of sign material and installation ($200/sign), inspection rate (40 signs/hour), and labor cost ($45/hour). They analyzed six combinations of method and obtained lower cost when using the Expected Sign Life method combined with both Nighttime and Daytime Visual Inspections, which resulted in $2.9 million per year. In contrast, the Expected Sign Life method (based on a 12 to 15 sign service life) resulted in the highest cost, which was estimated in $5.65 million/year.

In the study conducted by Harris et al. (2007), the authors estimated costs of sign inspection and maintenance based on NCDOT average costs for labor, material, and equipment. Different from DOTs, some small transportation agencies do not have enough data to conduct a cost analysis and estimate future budgets. Thus, a “Sign Retroreflectivity Handbook” was developed by Carlson and Picha (2009) and it provides small agencies with a budget estimation tool. This tool enables agencies to estimate sign maintenance budgets and also indicates which sign maintenance method is the most suitable for that specific agency while considering resources and current practices. The budget estimation tool is a valuable tool for agencies that do not have a sign inventory. In such case, the only information that the transportation agency needs to enter is the total number of signs under its jurisdiction. The tool calculates the proportion of signs for each sign category (regulatory, warning, and guide sign). Then, a noncompliance rate is applied, which results in the expected number of noncompliant signs per category. The last step is to calculate the cost of sign replacement, which is done by multiplying the number of noncompliant signs times $150, which is the average sign installation cost. The value of $150 per sign includes labor, equipment, and material.

Harris et al. (2009) conducted a cost analysis of the implementation and maintenance of a control sign facility, which would be necessary for the adoption of the Control Signs method. They determined the costs of the facility, control signs, maintenance software, retroreflectometer, data analysis, and facility maintenance. The cost of signs varied according to the type of sign and sheeting type (Types III and IX). The authors estimated the minimum number of signs (varying sign type and sheeting) needed was 252, which totaled approximately $30,000 (including installation cost). Cost of the facility (considering fences and gate) was estimated as $60,000. Accessories such as retroreflectometer and inventory database system were estimated as $14,000. All costs listed so far are to implement the sign control facility and together summed $104,000.

In addition, Harris et al. (2009) also estimated operation and maintenance cost as being $25,000 per year. At the end, the authors found that the total investment to build a control sign facility and maintain it for 20 years was $500,000. That is a significant amount of money. For some transportation agencies, this could mean even more than the annual sign budget available. Thus, although control sign facilities can provide agencies with good quality sign deterioration data, it requires a significant investment. Therefore, it is necessary to conduct a cost benefit analysis to determine whether or not a control sign facility is a feasible option for the agency.

As shown in the literature review, most studies focused on retroreflectivity deterioration and evaluation of different sign maintenance methods; however, only a few studies evaluated cost when analyzing deterioration and maintenance methods. Cost benefit analysis is a powerful tool that enable agencies to access what alternatives better fit their needs. For example, it does not matter if Alternative A results in the best overall sign condition if that same alternative costs more than the available budget to maintain signs. Each agency has an amount of resources available and a cost analysis takes this into consideration; the same option that is better for a DOT might not be the best option for a small transportation agency. For instance, while Harris et al. (2009) found that the Nighttime Visual Inspection method offered the best cost benefit method for NCDOT while Dumont et al. (2013) concluded that a combination of the Expected Sign Life method and both Nighttime and Daytime Visual Inspections was the best match for MnDOT. Thus, cost analysis should be considered by any transportation agency during a decision-making process.

2.6 Transportation Management Models

Transportation systems are essential for the economic growth of any area as well as the quality of life of its population (Bernhardt and McNeil, 2004). For years, transportation agencies and researchers have invested efforts to develop models to assist in the decision making process involving expansion and maintenance of the existing transportation infrastructure and assets.

Some of these efforts focused on optimization models while others focused on simulations to answer “what if” kind of questions. Both approaches are further discussed in this section.

2.6.1 Maintenance Optimization Models

Dekker (1996) conducted a literature review related to maintenance optimization models and their applications in the industry. The author described maintenance optimization models as mathematical models that maintenance cost and benefits are quantifies and balanced in order to identify an optimal maintenance strategy. However, quantifying maintenance benefits of some systems can be a difficult task, which results in maintenance being often a function of cost only, which has negative implications. According to Dekker (1996), one of the objectives of maintenance management is to ensure system life and asset management, which means to keep a system with a desirable performance while minimizing the maintenance costs. Thus, both performance and costs should be considered in the analysis.

Another factor to be considered in maintenance optimization models is the deterioration of the system (or parts of the system), which can be modeled using deterministic or stochastic methods, although the latter is the most common for including assessment of risk and/or uncertainty. Once again, Dekker (1996) mentioned the challenges involved in modeling the deterioration of a system because it requires a significant amount of effort to collect data, the system deterioration depends of the current maintenance policy, and it is difficult to quantify the benefits of maintenance policies.

By the time of that study, Dekker (1996) mentioned that road maintenance was a promising area for maintenance optimization, which showed to be true in the past decades. Currently, most DOTs have pavement and bridge management systems that consider maintenance optimization models to assess in the decision making process.

Later, Wang (2002) conducted a survey to document and classify maintenance policies of deteriorating systems. The topic of that study was related to the one described by Dekker (1996), however under a different perspective. According to the author, many maintenance and replacement models have been developed for different systems and they can be mostly classified into two categories: corrective maintenance (CM) and preventive maintenance (PM). CM means that an action is taken after the system fails and PM means that an action is taken before the system fails. By actions, the author referred to replacement or repair of the system. The maintenance policies described in Wang’s study were really interesting in the fact that they can be applied to any system. For instance, an example of CM policy applied to traffic signs is the Nighttime Visual Inspection method in which signs are replaced only after they fail (retroreflectivity falls below the minimum required levels). On the other hand, the Blanker Replacement method is an example of PM age-dependent policy, in which signs are replaced before they can fail based on their age.

At the end of the study, Wang (2002) stated that most maintenance policies found in the literature focused on minimizing maintenance costs without considering the system’s reliability performance. Based on that, the author pointed out to fact that the purpose of maintenance policies is exactly to improve the system’s reliability performance. Therefore, an optimal maintenance policy should not consider only cost, but also the system’s performance, which is the same assessment made by Dekker (1996). Vilarinho et al. (2017) also shared the same beliefs than Dekker (1996) and Wang (2002) in stating that the success of a maintenance policy depends on the “balance of maintenance performance, risk, and costs.”

Vilarinho et al. (2017) applied a maintenance optimization model to conduct PM of an automotive company. The author highlighted the importance of finding a balance between the different factors involved in a maintenance policy. For instance, the author explained that a PM policy is often less costly than a CM policy because it reduces the risk of system failure, which reduces productivity loss, idle time, labor cost, and other related costs. On the other hand, a high frequency of preventive maintenance activities can also lead to high maintenance costs because recourses are spent without a real need.

Alaswad and Xiang (2017) also conducted a literature search about maintenance optimization models for deteriorating systems. The authors focused on condition-based management (CBM) policies. A CBM model is different from an age-dependent PM policy by the fact that condition assessment is the driving factor of the model. For example, while an age-dependent PM policy depends on the probability of failure defined based on historical data, a CBM policy focuses on a continuously condition assessment that is used to determine when a system requires maintenance. The authors also described the most common optimization criteria used for CBM, which included cost minimization, reliability maximization, and multicriteria. In the case of multicriteria, as the name suggests, there are more than one criterion considered in the optimization and they are often in conflict with each other. Therefore, a multicriteria optimization has the objective in determining the best balance among the different criteria.

Applying the concept of multicriteria optimization described by Alaswad and Xiang (2017) to a sign system, it means that both replacement cost and sign overall condition are considered in the optimal strategy. For example, a strategy that yields extremely low cost is likely to result in poor sign condition, which is unacceptable as an optimal strategy. Therefore, an optimal strategy is the result of a balance of replacement cost and sign condition, which are the two main criteria considered in the decision making process of a sign replacement strategy.

Liu and Frangopol (2005) used multicriteria maintenance optimization for deteriorating bridges. The objective of the authors was to consider more than one criterion (e.g., cost) to identify optimal maintenance strategies. Therefore, in addition to maintenance cost, the authors also considered structure performance and safety as criteria to be considered in the optimization analysis. The authors explained that a multicriteria maintenance optimization approach results in a set of optimal maintenance strategies from which managers can select the most desirable tradeoff between cost, performance, and safety.

A similar approach was adopted by Barone and Frangopol (2014) who also applied multicriteria optimization to the life-cycle maintenance of deteriorating structures with focus given to bridges. As described by Liu and Frangopol (2005), Barone and Frangopol (2014) explained that by using multicriteria optimization, a set of optimal strategies are defined instead of only one strategy. From these set of optimal strategies, managers can selected the most appropriate strategy according to their objectives.

While Liu and Frangopol (2005) considered three criteria in their analysis (cost, performance, and safety), Barone and Frangopol (2014) considered two criteria, referring to their analysis as "bi-objective optimization." The optimization models analyzed by Barone and Frangopol (2014) considered minimizing cost as the major objective (criterion). The second criterion considered in the analysis varied among the models and included one of the following: reliability, risk, availability, or hazards. While reliability and risk were performance indicators of a system, availability and hazards were based on failures distributions over the structure life cycle. In addition to optimization maintenance models, another technique that has been used in transportation management field is simulation modeling as it is discussed in the next section.

A studies conducted by Cooksey et al. (2011) focused on a different aspect of asset management. Rather than developing models to implement asset management, the authors were interested in measuring the level of asset management implementation of state DOTs. Therefore, Cooksey et al. (2011) developed an asset management assessment model to measure the level of implementation of asset management practices within agencies. The major purpose of the model was to identify strengths and weaknesses of agencies and provide agencies with information that could be used to improve their asset management programs. A multicriteria analysis was performed in which the authors defined five criteria (based on the literature and interviews with five DOTs) to measure the implementation level of asset management. In addition, the authors also attributed weight to each of those criteria based to their priority in the decision making process. Some of the most important criteria were found to be policy goals and objective, followed by quality information and analysis, and asset management culture. Project delivery, planning and programing had lower weight. One of the major findings of this study was identifying asset management culture as a major criterion to be considered in asset management implementation.

2.6.2 Simulation Models

Some management models have the objective of answering the "what if" kind of questions and they do so by simulating different scenarios changing some parameters (e.g., budget, condition, etc.). In addition, there are management models that combine database, inventory, and simulation as discussed next.

In 1998, de la Garza et al. published a study describing a decision support system (DSS) that was developed with the objective of assisting in the decision making process of infrastructure management policies. The main component of the DSS was highway management system (HMS), which included bridges and pavement. Besides storing information (condition) of the infrastructure, the HMS also had the capability of simulating pavement and bridge deterioration (or improvement) according to the budget available. The system allowed users to observe different scenarios by changing the budget allocation and assessing what would be the future condition of the infrastructure. To simulate deterioration of improvement of the infrastructure, the authors used analytical models to represent the correlation between condition, deterioration over time, and maintenance cost to improve asset condition.

Bernhardt and McNeil (2004) developed a pavement management simulation model that is similar to the one proposed by de la Garza et al. (1998) in which it also correlates pavement condition, deterioration over time, and maintenance cost to improve condition. However, while de la Garza et al. (1998) considered center mile for pavement, Bernhardt and McNeil (2004) considered pavement sections (section of the pavement that are representative of the overall pavement condition). The simulation allowed the authors to analyze different scenarios that included reduced budget, accelerated deterioration, and changing in technology. At the end, the authors state the importance of simulation as a tool in pavement management systems and how it can have influence in current and future asset condition and costs for the agency.

With respect to traffic signs, simulation models are a powerful tool to analyze sign management strategies and there are reasons for that. First, it is possible to simulate how signs deteriorate and are damaged over the years. Second, it is possible to address management uncertainties by simulating a more realistic sign management scenario. And third, simulation models provide users with important information (measure outcomes) that is essential for an efficient cost benefit analysis.

Harris et al. (2007) and Immaneni et al. (2007) studies are related to each other. While Harris et al. (2007) described how the macroscopic simulation model was developed using Microsoft Excel and validated by comparison with field data, Immaneni et al. (2007) described a field survey that was conducted with the objective of collecting sign data and use that data as input parameters in the simulation. The authors referred to the simulation model as being a macroscopic model because signs with similar features (age, color, sheeting type, and initial retroreflectivity level) were grouped and moved together through the various simulation sub models. Some examples of sub models are damage and deterioration models.

To validate the simulation model, Harris et al. (2007) used field data of ground-mounted signs as inputs and compared the simulation results with actual field and cost data from the North Carolina Department of Transportation (NCDOT). The simulation model considered nighttime inspection accuracy, inspection frequency, retroreflectivity deterioration, damage rate, and different alternatives of sign replacement and maintenance methods. The authors explained that a sign could be rejected for two reasons: either low retroreflectivity or above the expected life. The research team ran 30 scenarios in the simulation model by varying sign maintenance method, rejection criteria, conversion rate from Type I sheeting to Type III sheeting, and inspection frequency. The most important outcomes obtained from the model were annual cost per sign and number of noncompliant signs.

Following the same idea, Harris et al. (2012) developed a simulation model to study and compare the performance and compliance of different sign maintenance methods. However, differently from Harris et al. (2007), the simulation model developed by Harris et al. (2012) was a microscopic model. The main objectives of the authors were to improve and reduce the uncertainty of previous (macroscopic) simulation models that were developed by NCSU researchers (Harris et al., 2007). To do so the research team used Arena simulation software and represented each sign by an individual entity in the model. According to the authors, the microscopic model allowed signs to move independently of each other through the sub models, resulting in a more realistic representation of the overall sign condition and sign maintenance operations. Harris et al. (2012) described the microscopic simulation model as being capable of representing the sign system with greater details when compared to previous macroscopic sign models.

The simulation developed by Harris et al. (2012) consisted of four sub models: sign damage, replacement, inspection, and retroreflectivity deterioration models. The signs, represented by individual entities, could individually move through the sub models, which is the main feature of microscopic simulation model. In addition, the researchers were able to vary input parameters in the simulation model with the objective of running different sign maintenance methods. The ability of varying input parameters was desired because it allowed different transportation agencies to use the model by entering their own data into the simulation. After validating the overall simulation model, different management methods (scenarios) were simulated; for each scenario, the researchers ran 30 replications of 50 years, which resulted in outputs with errors within ± 5%, which was considered as acceptable by the research team.

Using the microscopic simulation model developed by Harris et al. (2012), Hummer et al. (2013) simulated 1,000 signs in which the initial sign condition (percentage of signs below the minimum retroreflectivity levels) and distribution (sign color, sheeting type, and road type) were based on previous studies existing in the literature. At the end of the study, the authors mentioned that it was possible to change input parameters of the simulation model, which enabled other transportation agencies to use the model by entering their own sign data. In addition, it was also possible to enter sign budget as an input, which could work as a constraint to be considered in the simulation of different sign management methods. The research team validated the simulation model by comparing the simulation results and sign field data collected in 2006 by the team. Based on these studies, the next section summarizes the main findings related to sign simulation models.

Table 2.6 summarizes the simulation studies discussed herein. Immaneni et al. (2007) and Harris et al. (2007) were listed together because they are part of the same study and the same occurs for Harris et al. (2012) and Hummer et al. (2013). The input parameters were similar in both studies while the measured output slightly changed among studies. The macroscopic simulation model calculated sign inspection and replacement costs while the microscopic model focused more on number of inspected, noncompliant, damaged, and replaced signs.

Table 2.6 Summary of Papers by Simulation Features, Inputs Parameters, and Output Measures

Authors	Type of Simulation	Software	Input Parameters	Output Measures
Immaneni et al. (2007) and Harris et al. (2007)	Macroscopic	Microsoft Excel	• Initial sign conditions • Damage rate • Deterioration rates • Replacement rate • Inspection frequency • Inspection accuracy	• Number of rejected signs * • Number of signs replaced • Cost of Inspection • Cost of Replacement
Harris et al. (2012) and Hummer et al. (2013)	Microscopic	Arena Simulation	• Initial sign conditions • Damage rate • Deterioration rate • Replacement rate • Inspection frequency • Inspection accuracy	Annual values of: • Number of noncompliant signs • Number of signs damaged • Number of signs inspected • Number of signs replaced

* Number of signs rejected includes both noncompliant and damaged signs.

2.6.3 Summary

It is a consensus in the literature reviewed that as systems deteriorate, the use of maintenance optimization models is a valuable and efficient tool to assist managers in their decision making processes. Another aspect that is often mentioned in the literature is the importance of considering a set of criteria rather than only one factor. For instance, while maintenance cost is an important factor, factors such as system performance and safety also need to be considered in the analysis. In those cases, a multicriteria maintenance optimization model can be used to analyze the tradeoff between the different factors being considered in the study. In addition, multicriteria optimization models result in a set of optimal strategies from which managers can select the one that best attend their priorities.

In addition, the literature also showed that simulation models are a powerful tool in transportation management. With respect to signs, simulation models were able to successfully simulate sign condition and estimate annual maintenance and replacement costs within a margin of error of ±5%. In addition, Harris et al. (2012) showed that a microscopic simulation model was able to reduce management uncertainties because signs could move independently through the simulation sub models, which is a more realistic representation. In other word, signs deteriorate individually, and the simulation model would randomly assign damage to signs, which is a more accurate representation of what happens in the field.

2.7 Research Gaps

Although there has been significant progress in the field of sign management research in the last few years, there is still room for improvement. Throughout the literature review, four key concepts were identified as gaps in sign management research.

First, although there were many studies that focused on sign service life, few of them used their findings to evaluate the different sign maintenance methods. Studies have shown that sign service life goes beyond the warranty period, in some cases, suggesting that a sign service life of 15 to 30 years for Type III sheeting. While previous studies mostly used warranty period as sign service life, it is important to reevaluate sign maintenance alternatives using more realistic sign service life.

Second, most studies compared different sign maintenance and replacement methods without considering agencies' resources or organizational structure. For example, the absence of a sign inventory database within a transportation agency should be considered a major constraint for the implementation of the Expected Sign Life method. As Rasdorf et al. (2009) pointed out, there are great challenges involved in the development and maintenance of a database for high volume and low-cost assets such as signs. Accurately tracking signs can be a difficult task. Studies conducted by Harris et al. (2007), Harris et al. (2012), Hummer et al. (2013), and Dumont et al. (2013) did not consider the costs of data collection, sign inventory database implementation, and maintenance in their sign maintenance cost analysis study.

Third, although previous research (Harris, 2010; Harris, 2012; Hummer, 2013) analyzed the Blanket Replacement method, the concept of conducing blanket replacement by areas in order to balance workload and expenditure through the years was new and it was not previously addressed by previous research. This concept of blanket replacement by areas, when applied correctly, enables transportation agencies to budget, plan, and schedule replacement work of future years. In addition, although it is often cited in the literature that one of the disadvantages of the Blanket Replacement method is material waste, there was not a research that evaluated field practices to reduce material waste.

Fourth, few studies considered cost benefit analysis in sign replacement or management strategy selection. That is an important factor to be considered in the study because the same maintenance and replacement method that best suits a state department of transportation probably is not the same for a small transportation agency. A cost benefit analysis of different sign replacement strategies provides upper management with valuable information to assist in the decision-making process.

Therefore, more research is needed to address those gaps. A more realistic sign service life needs to be identified for microprismatic Type III sheeting. An agency's resources and organizational structure needs to be considering when evaluating different sign replacement strategies. When considering the Blanket Replacement method, the research needs to consider a blanket replacement by area and practices to mitigate material waste need to be identified and its benefits quantified. In addition, a cost benefit analysis is of major importance to provide upper management with valuable information.

3.0 SIGN MANUFACTURING AND REPLACEMENT PROCESSES

Sign replacement strategies are often (if not always) related to the type of sheeting used to manufacture a sign. For instance, a sheeting that is expected to last longer the others requires less maintenance work; however, this same sheeting is likely to be more expensive than others are. To get more familiar with the main topic of this research, signs, and retroreflective sheeting, the research team visited two sign shops. The first one was the Bunn Sign Shop (Bunn, NC) that NCDOT divisions order from. In addition, the research team also visited the Central Virginia Sign Shop (CVSS) (South Chesterfield, VA) that has a different organizational structure than Bunn Sign Shop.

Although the topic of this report is sign replacement from a management perspective, understanding the factors involved in the field activities is important. Examples of these factors are equipment used in sign replacement and average size of sign crews. Therefore, this author also drove along with sign crews in NC to observe and document sign replacement process.

This chapter describes the sign manufacture process observed in the two sign shops visited as well as the sign replacement process observed in the field. This information provides insights about the different factors involved in sign replacement strategies and help the reader to become more familiar with the topic of this research.

3.1 Sign Manufacturing

This section covers the Bunn Sign Shop and CVSS sign manufacture processes that are further described in the following subsections.

3.1.1 Bunn Sign Shop

The research team visited the Bunn Sign Shop on February 14, 2017 to observe the sign manufacture process. The objective of this visit was to learn and observe the steps involved in the sign manufacture process. The Bunn Shop Sign is a correction facility (prison) and has 20 to 25 employees and 100 to 150 inmates. The shop manufactures all type of signs (e.g., red, yellow, green, blue, and brown) and decals for NCDOT, tax supported entities, and for state employees. Some example of clients other than NCDOT are Bertie county, Pitt county, Cumberland county schools, national guard, fire departments, toll roads (E-ZPass), and the NC State Bureau of Investigation.

It can be said that the facility is divided into two production lines. One line is where the large signs are manufactured (mostly overhead, ground-mounted guide signs, and street signs). The other production line is where smaller signs are manufactured (e.g., route shields, stop signs, warning signs, and arrows).

Since 2006, all signs have been manufactured using high intensity prismatic (HIP) Type III sheeting and above from 3M. Non-reflective black sheeting is used for letters, borders, and arrows to make contrast in a high intensity prismatic background sheeting (e.g., the black lettering and arrow on an exit only sign). The Bunn Sign Shop offers a warranty of 12 years for all signs, which is the same warranty offered by the sheeting manufacturer.

The sign manufacture process includes six steps as listed in Table 3.1. After signs are manufactured, they are packed and taken to the patio. There are two patios outside to stock signs while waiting for a contractor to pick them up or while waiting to be delivered to the NCDOT divisions. When the signs are delivered to NCDOT divisions they are grouped by destination on the patio. The signs usually don’t stay more than one day outside. Some of the signs located on the patio have a red circle on them. This red circle means that NCDOT already completed that project, NCDOT has already signed the contract, and the contractor can come to pick the signs up.

Table 3.1 Bunn Sign Shop Manufacturing Process

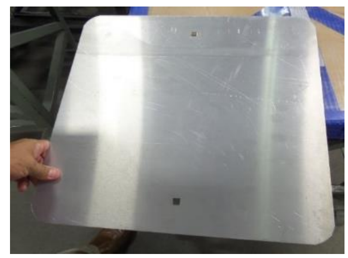
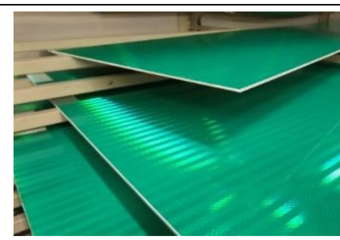
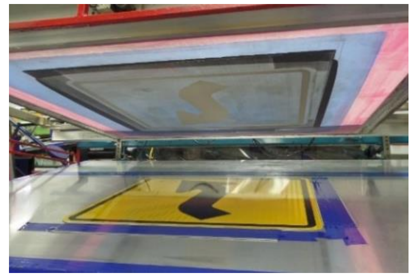
Steps	Description	Photo
1	Aluminum treatment: cut the metal and its corners, polish the metal surface to avoid any defect or prominence that might damage the sheeting).	
2	Get holes punched in. Those holes are used to attached the sign aluminum sheet to the sign pole.	
3	Mark manufacture date. For example, the picture shows a sign that was manufactured on July 20, 2017.	
4	Apply the background sheeting to the sign. The sign shown herein is received a green sheeting background.	
5	Add the content of the sign: add the content of the sign (e.g., arrows, letters, route shields, and numbers). a) Overlay: Cut sheeting as needed (e.g., the white letters for overhead guide signs) and then apply it to the background sheeting. An example is overhead guide signs in which the white letters and arrows are cut and then applied to the green background.	

Table 3.1 Bunn Sign Shop Manufacturing Process (Cont.)

Steps	Description	Photo
5	b) Silk Screening: Application of a screen-printed sheeting to a sign background. Screen-printed sheeting is any sheeting that had its content applied through ink. Signs that are screen-printed with ink on top of the background sheeting are placed in an oven for about 1.5 hours at 170°F to dry. c) Combination: There are also signs that use both methods (a) and (b). An example is a "stop ahead" sign. Its black arrow and borders are first screen-printed on the yellow background (method (b)) Then, an octagonal red decal is applied to the sign (method (a)).	 
6	Supervisor check. A supervisor checks that content of the sign matches the drawings and specifications. Quality inspection. A sign shop inspector visually inspects and uses a retroreflectometer to determine whether or not the retroreflectivity is as expected and to verify that there are no scratches or damage to the surface of the sign.	

3.1.2 Central Virginia Sign Shop (CVSS)

The research team visited the CVSS on September 08, 2017 to observe the sign manufacture process. The objective of this visit was to learn, observe, and compare the steps involved in the sign manufacture process with the ones observed in the Bunn Shop Sign. The first difference is the number of people working in at CVSS, which is about 15 employees when operating at full capacity, although at the time of the visit the number of employees was fewer due to a renovation process of the sign shop. The CVSS manufactures all types of signs (e.g., red, yellow, green, blue, and brown), banners, posters, and decals for the nine VDOT districts. The CVSS is a self-sufficient Sign Shop, meaning that the revenue from sales are enough to pay the utilities and operations; the building is maintained by the Richmond District Facilities. At the time of the visit, the Sign Shop was being renovated and, therefore, it was not possible to observe the full operational capacity.

The CVSS facility consists of two buildings (the main building and the storage building). The main building is the largest one of the two and is where the offices are located. Both small and large signs are manufactured in this main building.

All the sheeting used by the CVSS is manufactured by 3M with the exception of orange sheeting, which is manufactured by Avery Dennison. The Sign Shop uses only Type IX sheeting which is a very-high-intensity retroreflective sheeting having highest retroreflectivity characteristics at short road distances. At the time of the meeting, we were unable to determine the warranty period offered by the sheeting manufacturer.

One of the major differences in relation to Bun Sign Shop is that the CVSS orders approximately 80% of its aluminum sheets (which are used to manufacture small signs; e.g., stop sign) pre-sized. The pre-sized aluminum sheets arrive at the CVSS having already been cut to the right dimensions, with round corners, holes, and the VDOT logo marked on the back of the sign, which eliminates that steps 1 through 3 that we saw in the Bunn Sign Shop.

The advantage of the pre-sized aluminum sheets is that they require less labor and processing time to produce small and mass production signs. As a result, if small signs (e.g., speed limit) are being manufactured using the screen-printed process, the CVSS can produce up to 700 signs per day. However, in the case of large signs (e.g., overhead guide signs), the CVSS orders aluminum sheets that need to be cut and shaped by the sign shop labor, which take longer to be produced.

The sign manufacturing process at the CVSS includes the following manufacturing steps shown in Table 3.2. After the signs are manufactured, the CVSS employees package the signs and take them to the storage building. The CVSS deliveries signs ton only one district (South West). All other districts will send crews to pick up their signs at the CVSS.

Table 3.2 CVSS Shop Manufacturing Process

Steps	Description	Photo
1	Aluminum treatment. For small signs, most of the aluminum sheets ordered by the CVSS are pre-sized and used for mass production of small signs. These sheets already contain round borders and punched holes. For large signs, the sign shop does not order pre-sized aluminum sheets. Instead, the CVSS orders regular aluminum sheets and does all work of cutting the sheets, their borders, and punching holes.	
2	Apply the background sheeting to the sign. The sign shown in the next column is received a white sheeting background.	

Table 3.2 CVSS Shop Manufacturing Process (Cont.)

Steps	Description	Photo
3	Add the content of the sign: add the content of the sign (e.g., arrows, letters, route shields, and numbers). a) Overlay: Cut sheeting as needed (e.g., the white letters for overhead guide signs) and then apply to the background sheeting. The picture shows an example of a white shield road sign that had the black numbers cut and applied to the signs. b) Silk Screening: Application of a screen-printed sheeting to a sign background. Signs that are screen-printed with ink on top of the background sheeting are placed in a rack room to dry, where they will remain for 24 hours until the ink is dried. The picture shows one of the machines to screen-print signs. c) Digital Printing: Sign content is printed on the surface of a sheeting. This method uses printers and is mostly used to manufacture banners and decals. In some few occasions, this method may be used to manufacture signs too. This method is faster and allows printing different colors at the same time (different from the screen-printed process that requires the application of one color at a time with intervals of 24 hours to dry the ink). d) Combination: There are also signs that are manufacture by using the combination of two or more of the methods (a), (b), and (c).	   
4	Supervisor and quality check. A supervisor checks the quality and whether the content of the sign matches the drawings and specifications. There use not use of retroflectometer to measure initial sign retroreflectivity.	

3.1.3 <u>Differences between the CVSS and the Bunn Sign Shop Process</u>

There are some minor and major differences between the sign manufacturing process of the Bunn Sign Shop and CVSS. These include the following:

- Aluminum sheets: while the Bunn Sign Shop cuts all the aluminum sheets that they are used in their signs, about 80% of all aluminum sheets ordered by the CVSS (for small signs) are pre-sized and already contains round corners and holes. This difference in raw and pre-sized sheets allows the CVSS to produce signs faster than the Bunn Sign Shop.
- Screen-printing method – time required to dry the ink: while the Bunn Sign Shop has an oven that allows the ink applied to the sheeting to dry within 1.5 hours, the CVSS does not have an oven. Therefore, signs that are screen-printed at the CVSS are placed in the rack room and will remain there for 24 hours to allow the ink to dry.
- Sign Assembly: the CVSS does not assemble signs (attach steel frames on the back of signs). If sign assembly is requested by a district, the CVSS will order pre-made assemblies and send them directly to the field where the sign will be installed. The VDOT district crew is responsible for attaching the assembly on the back of the sign prior installation. This process is different from the one adopted by the Bunn Sign Shop which assembles all the signs prior delivery to the NCDOT divisions.
- Storage of large signs in external areas: the Bunn Sign Shop has two external areas (referred as patios) where they store large signs (e.g., guide signs and logo signs) until the moment these signs are delivered to the client. The CVSS does not have such an external area to store signs. All signs (small and large) are stored inside the storage building until the time at which they are picked up or delivered to the VDOT districts.

3.2 Field Sign Replacement

The author visited the NCDOT Division 9 on March 28, 2018. Division 9 consists of five counties: Stokes, Forsyth, Davie, Davison, and Rowan. For the purpose of sign inspections and replacement, each county is divided into sections with an average of 18 to 26 sections per county. Division 9 has approximately 68,335 signs and its sign replacement strategy is based on a section (area) approach.

The key goal of this visit was to observe and document sign replacement activities in the field. Division 9 replaces signs by section, which is a small geographical area. Doing so avoids that sign crews will be randomly driving throughout the division to replace signs. In addition, to ensure that all counties are being benefited with the sign replacement activities, Division 9 maintains one sign crew per county. This author rode along with a sign crew and took notes and pictures of the process, which is documented in this section.

3.2.1 <u>Overview</u>

Each field sign crew consists of two members who are responsible for both daytime inspection and sign replacement in one county. There is one sign crew per county and all crews conduct their work by section. These crews focus on traffic signs. However, if they observe a major issue related to other road features while conducting sign inspection or replacement work, they do report the problem to the appropriate office.

When crews begin their work within a section, the first step is to conduct a daytime inspection to identify signs that are old, missing, or damaged. In some cases, crews also identify signs that need maintenance work such as alignment or cleaning. In the following days of the daytime inspection, crews go back to the inspected roads and replaced the signs that were found to be deficient in their previous inspection visit. It is important to point out that the crews replace all signs identified as being deficient in both the daytime inspections (recently conducted) and the nighttime inspections (conducted over the winter months). The signs replaced fall into at least one of the following categories.

- Rejected (during nighttime visual inspection due to poor retroreflectivity levels)
- Damaged (for any reason, for example, bent, holes, peeling, etc.)
- Old (older than 8 to 10 years)
- Lost (theft)

As part of their routine, crew members arrive at 7 am to discuss the work that will be performed that day, which can be either daytime inspection or sign replacement. After discussing and reviewing the plan of work for that day, crews will go to the field to perform the work planned. In the case of sign replacement activities, crews load the trucks with the new signs that will be used to replace the ones in the field. In addition to those signs already identified to be replaced, crew members load additional *Stop* signs (which are considered to be priority) to ensure their availability if needed.

Figure 3.1 shows a sign truck used by the NCDOT. Those trucks are equipped with new signs, sign poles, tools, ladders, and other equipment and material necessary to replace signs.

Figure 3.1 Sign Truck Equipped with Tools and Material for Sign Replacement

3.2.2 <u>Sign Components</u>

First, it is necessary to provide a brief description of the sign components as shown in Figure 3.2 to then understand how they are replaced. As shown in the figure, there are two poles that are assembled together: base pole and sign pole. The bottom part, referred as the "base pole," can be compared to a foundation because it is the part that is fixed deeply into the ground and ensures the stability of the sign. It is 4 feet long and needs to be insert in the ground until only 18 inches is above the ground surface. The top pole, referred as the “sign pole,” is where a sign is installed with two bolts. Once the sign is attached to the sign pole, the crew connects the sign pole to the base pole (which is already installed in the correct position in the ground). Knowing this information is helpful to understand the sequence of sign replacement activities, which is discussed in the next subsection.

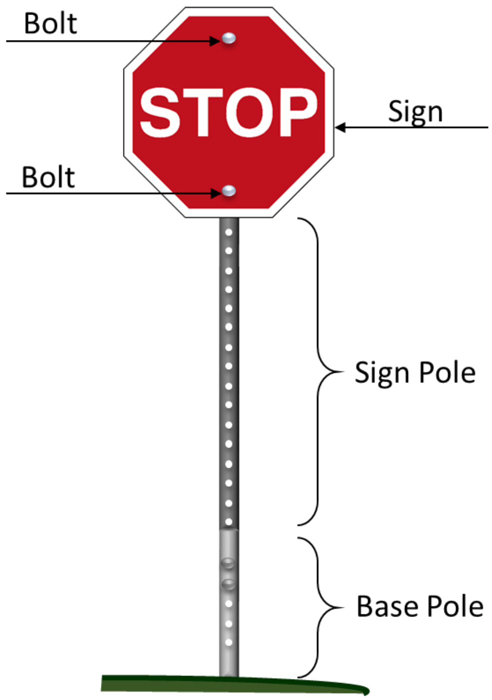


Figure 3.2 Sign Components (Parts)

3.2.3 <u>Sign Replacement Procedure</u>

Around 7:30 to 8:00 am, crews depart in their respective trucks to the sections where they will work on until 2:30 to 3:00 pm. At each location where the crews stop, they verify which signs should be replaced and then perform the work when possible. Once the work is completed, one of the crew members enters the information on the FR-1101 form (see Appendix 12.4) that is later submitted to their supervisor. When the crews go back to the Division 9 facility, they dispose the old signs in a bin. Once this bin is full, those signs are delivered to the Bunn Sign Shop in Bunn, NC to be disassembled and reused.

In general, the sequence of sign replacement activities is as follows.

1. Disassemble and remove the sign pole from the base pole
2. Remove the base pole from the ground
3. Disassembly the sign from the sign pole
4. Place old sign and poles in the truck (in some cases, old poles can be reused)
5. Attach the new sign to a sign pole
6. Clean the new sign
7. Install a new base pole in the ground
8. Connect the new sign (already on the sign pole) to the base pole
9. Check the alignment of the sign while assembling it on the base pole
10. Place an installation date sticker on the back of the sign

11. Write the initials of the names of the crew members on the back of the sign
12. Highlight in yellow the roads where the service was performed (on the map of the section)
13. Fill out form FR-1101 with information about the signs that were replaced in that location

For exemplification purpose, Figures 3.3 to 3.5 show a sign crew replacing a Wrong Way sign (all photos were taken by the author on March 28, 2018). Figure 3.3 shows the sign crew separating the deficient sign from base pole. After doing so, they also remove the base pole from the ground. Figure 3.4 shows the crew assembling the new sign to the sign pole. Figure 3.5 shows crew installing the new sign by assembling it to the base pole that is already on the ground. A detailed and complete sequence of this sign installation is presented in Appendix 12.4. In addition, Appendix 12.5 described the sign replacement work performed by a sign crew on March 28, 2018 in Section 7 of Forsyth County (Division 9).

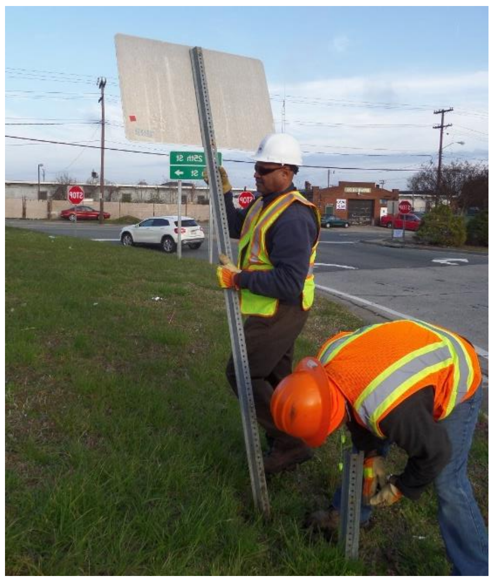


Figure 3.3 Removing a Deficient Sign

Figure 3.4 Assemble of a Wong Way Sign to the Pole

Figure 3.5 Crew Members Installing a Wong Way Sign

3.2.4 Assessment of the Sign Replacement Process

Division 9 has a well structured sign replacement process. The way that the activities are organized allows the sign crews to know in advance which signs they need to replace as well as the location of those signs. In addition, the crews work by section, meaning that all signs to be replaced each day are located not far from each other. However, it was possible to note that even though the crews have a work plan, sometimes there are unknown situations that can prevent the work from being done. For example, there was a location where a set of signs need to be replaced; however, the crew was not able to do so because of the interference with utility pipes and lines passing underground at that location, which prevented the crew of drilling and driving the lower pole into the ground.

Another factor that needs to be taken into consideration is the intensity of the traffic in some locations. In some cases, the sign crew chose to return the following day in the morning because the traffic was becoming too intense in the afternoon. Overall, the crew members were very familiar with their sign replacement routine and were able to efficiently replace the signs. After the replacement, the old signs, bolts, and poles were loaded on the truck, being later disposed in a bin set aside for their collection. The crew made sure that there were no materials nor equipment left on the ground before departing to a next location. When the crew members returned to the Traffic Service Department, their supervisor collected the FR-1101 forms that contains detailed information of work completed and the material and equipment used during the sign replacement process that day. The supervisor then enter the data into the sign database maintained by Division 9.

4.0 DOTs SIGN MANAGEMENT PROGRAMS

Given the importance of signs, it is extremely relevant that transportation agencies develop sign management programs to ensure that signs are visible and legible to drivers. The Federal Highway Administration (FHWA) (1999) describes a generic asset management program as having the following components: goals and policies, budget allocations, asset inventory, condition assessment and performance modeling, evaluation of alternatives, short and long term plans, program implementation, and performance monitoring. Thus, an efficient sign management program is expected to contain most of these components.

Since 2012, many DOTs have improved their sign management programs and many seem to be transitioning from sign assessment methods to management methods. To better understand the current trends, the research team contacted three of the four largest state-maintained highway systems in the US (NC, VA, and SC; FHWA, 2017) to identify advances in traffic sign asset management.

This chapter describes the findings and discussions drawn from these meetings enabling other DOTs and transportation managers to gain insights into problems and solutions that may help them improve their sign maintenance practices.

4.1 Methodology

The research team met traffic and sign engineers from these DOTs on 13 occasions as listed below with the objective of observing, documenting, and assessing which sing maintenance methods they have in place, as well as their practices, benefits, and challenges.

- NCDOT Division 9 in Winston-Salem, NC on January 04, 2017, on October 19, 2017, and on January 9, 2019
- NCDOT Division 8 in Carthage, NC on February 03, 2017 and on October 06, 2017
- NCDOT Signing Office in Garner, NC on October 17, 2017, on April 06, 2018, and on September 11, 2018
- NCDOT Maintenance Office in Raleigh, NC on January 16, 2018
- NCDOT Division 2 in Greenville, NC on May 29, 2018
- NCDOT Division 4 in Wilson, NC on May 29, 2018
- SCDOT Headquarters in Columbia, SC on August 31, 2017
- VDOT District Office in Salem, VA on September 15, 2017

The meetings were held in each DOT facility and had an average duration of 2 hours. Once the research team arrived at the meeting location, a brief introduction about the research and the main literature review findings were presented to the engineers and personnel who were attending the meetings. Then, the research team asked questions about their sign maintenance program (e.g., which sign maintenance method they used; what were the challenges, what were the benefits, etc.). The following subsections describe the main information and findings resulting from the meetings with the NCDOT, SCDOT, and VDOT.

4.2 Findings

Table **4.1** shows a summary of the sign maintenance methods adopted by the three DOTs, which is discussed in the next subsections.

Table 4.1 Sign Maintenance Method Summary

DOTs	State-Owned Mileage	Maintenance Method	Sign Sheeting	Sign Service Life	Sign Inventory
NCDOT	79,637	The Blanket Replacement method (10 year cycle; in implementation phase) (Daytime and nighttime inspections are still conducted during the implementation of the Blanket Replacement method)	Minimum prismatic Type III	10 years (Warranty: 12 years)	No
SCDOT	41,340	The Expected Sign Life (10 years) combined with the Nighttime Visual Inspection	Minimum prismatic Type III	10 years (Warranty: 10 years)	Yes (statewide)
VDOT	58,821	The Blanket Replacement method (10-15 year cycle), Nighttime and Daytime Visual Inspections	Prismatic Type IX	15 to 30 years (Warranty: 10 years)	In progress

4.2.1 NCDOT

NCDOT has 14 divisions and is the second largest state-maintained highway system in the US, with a total roadway network of almost 80,000 miles, which includes Interstates (2%), primary roads (17%) and secondary roads (81%) (NCDOT, 2017).

4.2.1.1 Sign Service Life

Since 2006, NCDOT has been using signs manufactured with Type III and above prismatic sheeting, which have a warranty period of 12 years starting from the date the sign was manufactured. The NCDOT Routine Maintenance Improvement Plan (RMIP) (NCDOT, 2016) specifies the sign service life in NC as 10 years (less than the sign warranty).

4.2.1.2 Sign Maintenance Method

Up to 2017 NCDOT used the Nighttime Visual Inspection method to ensure compliance with minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). Sign crews conducted nighttime inspections every other year on Primary roads and every three years on Secondary roads. In addition, daytime inspections were also conducted to identify damaged and missing signs.

NCDOT started implementing the RMIP in July 2017. RMIP is a long-term maintenance program that covers the following roadway assets: ditches, shoulders, pipes, pavement markings, and signs. In relation to signs, the RMIP describes the Blanket Replacement method (mostly by area) based on a sign service life of 10 years (NCDOT, 2016).

According to the "2016 Maintenance Operations and Performance Analysis Report (MOPAR)" (NCDOT, 2016), the objective of the RMIP is to encourage NCDOT divisions to adopt planned maintenance practices and also to "hold divisions accountable for production levels." NCDOT divisions are now required to forecast their future budgets based on the plan that they submitted in July 2017. Additionally, at the end of the year they are required to report their progress in meeting their planned work goals. Doing so allows the NCDOT Maintenance Office to identify areas that demand more investment, better forecast future budgets, and more efficiently distribute its resources throughout the state. Overall, NCDOT divisions (visited by the research team) believe that the Blanket Replacement is a preferred sign maintenance method.

Although NCDOT does not have a sign inventory, the department maintains a Maintenance Condition Assessment Program (MCAP) that is used by NCDOT to monitor and evaluate assets' conditions within NC. MCAP data includes the number of signs inspected and the number of signs to be replaced for any reason. Such data is available in MCAP by county and by type of road (Interstate, primary, and secondary). In addition to the numbers of signs, MCAP also stores cost data by work function. From the meetings with the NCDOT divisions, some sign maintenance practices stood out as follows.

Area-Based Approach for Blanket Replacement Implementation. Area-based replacements (often referred to as sections by some agencies) create a routine that helps laborers better understand the processes involved in sign maintenance and replacement. It also gives personnel a sense of "ownership" which results in a set of benefits such as the following.

- Increased depth of knowledge about a specific area.
- Reduction of idle time.
- Increase in labor productivity.
- Reduction in distance traveled to accomplish work.
- Decrease of sign unit cost per square foot (this unit cost includes labor, material, and equipment).
- Improved employee morale.

A clear definition of areas promotes efficiency (reduce idle time and increase productivity) because it prevents sign crews from randomly driving division roads without having a set of established goals. In addition, upper management can make it clear to personnel what the expected productivity level for each crew is. Then, crew member's evaluations can more fairly be based on their productivity. Thus, an area-based approach to sign work is highly beneficial and is currently a key component of RMIP success.

Sign Recycling. One approach to sign management is a practice of recycling signs by reusing them as spot replacement signs when they are younger than 5 years (relatively new) and are in a good condition. That is, during a blanket replacement in a specific area, if a relatively new sign is replaced it is saved and used in some other area to replace a bad or damaged sign there. Thus, when blanket replacement occurs no signs are replaced that are less than 5 years old.
To illustrate this better, consider that a county may be divided into ten areas (Area 1, Area 2, Area 3, etc.) and that signs are blanket replaced at a rate of one area per year. Consider also that sign crews are conducting blanket replacement in Area 1 during the 1st year of the cycle. When doing so, sign crews might identify signs in good condition and younger than 5 years. Thus, instead of discarding them, the sign crews will stock and use these signs for spot replacements in other areas that are scheduled to be replaced in the following years.

4.2.1.3 Sign Management Program

The NCDOT sign management program is in a process of improvement with the implementation of the RMIP. The Department has defined a set of goals and policies that considers both short and long term plans. With respect to condition assessment, both nighttime and daytime inspections are still conducted to assess sign condition. To define a more cost-efficient budget allocation, the NCDOT recently initiated a sign replacement research study conducted by the North Carolina State University (NCSU) to investigate the trade-offs between different sign replacement strategies. The next step is to monitor the performance of the RMIP through the years. However, an aspect that the FHWA (1999) considers important for an asset management program is an asset inventory, which the NCDOT does not maintain for signs. Instead, the RMIP describe the development of a sign inventory; however, this task will take some years to initiate as priority is being given to the inventory of other assets first.

4.2.2 SCDOT

SCDOT has seven districts and is the fourth largest state-maintained highway system in the US, with a total roadway network of 41,340 miles (FHWA, 2017), including Interstates (2%), primary roads (17%), and secondary roads (81%) (SCDOT, 2014).

4.2.2.1 Sign Service Life

Around 2005, SCDOT initiated a program to replace Type I sheeting with Type III or above on primary and secondary roads. In 2015 SCDOT adopted an Engineering Directive Document "ED-4" that requires districts and counties to use a minimum of Type III (high intensity grade or prismatic high intensity) sheeting. According to the "ED-57" document, the sign service life is 10 years, which is based on the sheeting manufacturer warranty of 10 years.

4.2.2.2 Sign Maintenance Method

SCDOT has a statewide sign replacement strategy with a standardized sign maintenance method (Expected Sign Life), Daytime and Nighttime Inspections, and a sign inventory database. To maintain control of the sign maintenance process, SCDOT uses a Highway Maintenance Management System (HMMS). One of the modules of the management system is sign inventory and maintenance. This module contains all relevant sign information, including location, type of sign, manufacture date, sheeting type, installation date, and a record of inspections.

To ensure sign retroreflectivity compliance with MUTCD (FHWA, 2009), SCDOT adopted ED-57 in 2012 which specifies the Expected Sign Life method to maintain its signs. In addition to the Expected Sign Life method, nighttime inspections are still conducted as a control method to verify whether or not signs meet the retroreflectivity requirements described in the MUTCD.

All this is possible because each sign has a unique identification number. This identification number (barcode) is placed on the back of each sign when it is manufactured. Thereafter, any action or data related to the sign (e.g., replacement and maintenance) uses the identification number to enter it into the HMMS, enabling SCDOT districts to identify signs that are older than the expected life. In addition, the system has the signs' exact GPS location, allowing sign crews to go directly to the locations where signs need to be replaced.

SCDOT also uses its HMMS in the extreme case of a natural disaster (hurricanes, earthquake, flooding) when many signs can be totally lost or severely damaged. The HMMS, containing a complete statewide sign inventory, helps to identify all signs that were lost, the type of signs, their specification, and their exact location, enabling districts to plan the work necessary to replace them.

4.2.2.3 Sign Management Program

The SCDOT contains a mature sign management program when considering the components described by the FHWA (1999). The agency has a well-defined set of goals and policies that also considers short and long-term plans. To evaluate sign condition assessment, the agency conducts both daytime and (not so often) nighttime inspections. In addition, the SCDOT contains a robust and statewide HMMS that includes sign inventory. The agency also monitors the performance of its program by evaluating data contained in the HMMS. Looking for improvement areas in their program, the SCDOT recently sought to determine the sign service life in SC with the objective of evaluating their practices.

4.2.3 VDOT

VDOT, with nine districts, is the third largest state-maintained highway system in the US, with a total roadway network of 58,821 miles (FHWA, 2017). These include Interstates (2%), primary roads (14%), and secondary roads (84%).

4.2.3.1 Sign Service Life

Since 2010 VDOT has adopted prismatic sheeting (Type IX) with a warranty period of 10 years starting from the date the sign was manufactured. However, according to VDOT's Sign Maintenance and Retroreflectivity Compliance Plan (SMRC Plan), the service life of the Type IX sheeting actually ranges from 15 (minimum) to 30 (maximum) years. Thus, VDOT believes that with this sheeting they will significantly reduce their sign replacement frequency.

4.2.3.2 Sign Maintenance Method

In 2017, the VDOT Traffic Engineering Division developed an SMRC Plan to be used as a guideline for maintaining minimum retroreflectivity levels. An important observation is that "the Plan does not present a centralized, or standardized statewide approach to sign retroreflectivity; rather, it allows each unit (district) within VDOT to allocate resources in a way that best serves the area's needs."

According to VDOT's SMRC Plan, the sign replacement rate in the state can be estimated based on the number of signs annually manufactured by the Central Virginia Sign Shop (CVSS), which is approximately 90,000 signs per year. This number of signs is equivalent to 10% of all VDOT signing inventory. The annual cost to manufacture these signs is about $2.9 million or $32 per sign not including installation.

VDOT uses a combination of the Blanket Replacement (based on sign service life) and Daytime and Nighttime Visual Inspections methods. The blanket replacement is conducted by corridor in cycles of 10 to 15 years, which ensures that signs will be below the minimum sign service life of 15 years found in previous studies. Daytime inspections identify damaged and missing signs and are conducted during maintenance activities and routine inspections. Nighttime inspections focus on retroreflectivity levels and occur at a lower frequency than daytime inspections. Signs on primary roads follow the pavement maintenance cycle and are inspected every 8 or 10 years. On other roads, nighttime inspections occur near the end of the replacement cycle (which is between

10 and 15 years) to ensure that signs in good condition will not be replaced, thus increasing the sign service life observed in the field.

VDOT planned to use a new HMMS system and start loading data into it in 2018 so that districts can rely on the HMMS to accurately determine when to perform blanket replacement based on sign service life simply by knowing the location and age of the signs. VDOT believes that once signs are blanket replaced, the districts can drastically reduce the number of inspections during the sign warranty period because all replaced signs are expected to be in new condition.

4.2.3.3 Sign Management Program

The VDOT sign management program was improved with the implementation of the SMRC Plan. Similar to the NCDOT and SCDOT, the VDOT has a set of goals and policies that considers short and long-term plans. To evaluate sign condition assessment, the agency conducts both daytime and nighttime inspections. Additionally, VDOT is in the process of creating a sign database inventory which will be part of its HMMS. The agency also evaluates alternatives to improve their program and, after selecting one alternative, monitors its performance. An example was the selection of Type IX sheeting that, according to VDOT and the literature, has a longer service life than Type III.

4.3 Discussion

The case study results are analyzed in the subsections below. Key best practices related to sign service life, sign maintenance methods, and sign inventory are identified.

4.3.1 Sign Service Life

Among the three DOTs that the research team visited, only VDOT has a less conservative sign service life. By using a more advanced type of sheeting (Type IX), the agency adopted a sign service life of 15 years which resulted in a reduction in both inspection frequency and labor hours. According to VDOT, improving the quality of sheeting was the factor that brought the most positive impact to their sign maintenance program.

Both NCDOT and SCDOT use a sign service life of 10 years for Type III sheeting, which is considered by the majority of the literature to be a conservative approach (Clevenger et al., 2012; Kipp and Fitch, 2009; Dumont et al., 2013; Preston et al., 2014; Re et al., 2011; Re and Carlson, 2012). Most of previous studies recommended 15 years or above for Type III sheeting (Clevenger et al., 2012;, Dumont et al., 2013; Immaneni et al., 2009; Kipp and Fitch 2009; Pike and Carlson, 2014).

Most NCDOT and SCDOT traffic engineers believed that, although a 10 year service life is conservative, it would protect the agencies from lawsuits and liability. As a result, they would be able to make a stronger case that their sign maintenance procedures are adequate and that nearly all signs are younger than 10 years old and within the warranty period. Thus, it is less likely that an agency would be found to be legally at fault.

On the other hand, some engineers defended the idea that since Type I sheeting was phased out, meeting the minimum retroreflectivity requirements from the MUTCD is no longer a problem and that signs are expected to last more than 10 years in the field, perhaps significantly more so. Clevenger et al. (Clevenger et al., 2012) obtained data from sheeting manufacturers and an interesting statement made by one was that “warranties protect public agencies against manufacturing defects, but the goal is to create products that far outlast the warranty period.”

Complimenting this statement, there were many field survey studies that concluded that most signs were compliant with MUTCD minimum retroreflectivity levels. In some cases, the noncompliance rate was less than 1% of all signs surveyed (Pike and Carlson, 2014, Kirk et al., 2001; Kipp and Fitch, 2009; Re et al., 2011; Pulver et al., 2018), further confirming that it is no longer retroreflectivity that is the governing factor in sign safety. Thus, adopting a 10 year sign service life is a conservative approach that often results in a premature replacement of signs in good condition. An option for those DOTs that desire to be conservative would be to use a higher quality of sheeting (as VDOT did) that would provide them with a longer sign service life and still protect them from lawsuits.

4.3.2 Sign Maintenance Method

All of NCDOT, SCDOT, and VDOT use management methods to maintain sign retroreflectivity above the minimum required. Those methods are based on sign expected life with some variations. Additionally, some DOTs use a combination of methods, usually coupling the Nighttime Visual Inspection with another method.

For its management method, SCDOT developed a statewide sign inventory (integrated into HMMS) to enable them to know when a sign needs to be replaced and where the sign is located. Because SCDOT had been using the Expected Sign Life method for many years, the sign crews were already accustomed to the process and to HMMS data entry. As a result, productivity increased. In addition, SCDOT still conducts nighttime inspections on all roads of the state at least once a year to verify that signs are in a good condition.

VDOT uses a combination of the Blanket Replacement, Daytime, and Nighttime Inspections methods. However, those inspections occur at much lower rate than in other DOTs. Given that the sign replacement cycle adopted by VDOT is 10-15 years, nighttime inspections will start on the 10th year of the replacement cycle. The daytime inspections have the objective of identifying damaged and stolen signs while the objective of the nighttime inspections is to assess whether or not signs are still above the minimum retroreflectivity level. If so, inspections crews would return after two years (in the 12th year of the cycle) for the same assessment. By doing so, the agency can potentially extend the sign service life based on field observation and assessment.

NCDOT adopted the Blanket Replacement method based on a sign service life of 10 years. The objective is to replace 1/10 of the state-owned signs per year. However, NCDOT is just beginning the transition (begun in 2017) from the Nighttime Visual Inspection to the Blanket Replacement method. Currently, some divisions conduct both Blanket Replacement and Nighttime Visual Inspection methods, which leads to a debate about whether or not NCDOT should eliminate the nighttime inspections. Consideration is being given to eliminating nighttime inspections because the Blanket Replacement method already ensures that all signs would be above minimum retroreflectivity levels. Others consider nighttime inspections to be valuable and important to maintaining the signs in good condition, primarily by identifying damage.

Considering the literature reviewed and

Table 2.5, it is possible to note that most of the DOTs adopted either assessment methods (mostly visual inspections) or management methods (mostly sign expected life). On the other hand, some studies showed that combinations of two or more methods were advantageous (Dumont et al., 2013; Re and Carlson, 2012). All of NCDOT, SCDOT, and VDOT adopted a combination of assessment and management methods. However, not all of the three achieved a balance among the different methods.

SCDOT and VDOT reduced their frequency of their nighttime inspections because signs are expected to perform above the minimum required retroreflectivity levels when adopting a management method. Hence, the primary sign maintenance method used by VDOT and SCDOT is either the Expected Sign Life or the Blanket Replacement methods while the Nighttime Visual Inspection is a secondary method. NCDOT is a different case in which it is not clear whether the primary maintenance method is the Blanket Replacement or Nighttime Visual Inspection.

4.3.2.1 Sign Maintenance Program Implementation

NCDOT has just begun the transition from the Nighttime Visual Inspection to the Blanket Replacement method. The NC case study shows that the transition can result in problems. The major problems that arose were shortages of sign material and labor and a larger scope of work. These are discussed below.

Sign Material Shortage. In NC, one of the problems has been a sign material shortage. The problem lies in the fact that NCDOT requires all divisions to replace about 1/10 of their signs per year. As a result, there is a higher sign demand from all divisions that the sign shop had not previously faced. Because there was little to no advance notice given on the rollout of the RMIP implementation the sign shop was initially unable to meet all sign demand because they were having difficulty in obtaining ink and aluminum sheeting to manufacture the signs. As a consequence, there was initially not enough sign material available to meet the new demand.

Personnel Shortage. In some cases, there are not enough personnel to handle all the sign work. There are even some sign crews that consist of a single person, which has a negative impact on productivity. In addition, because of the limited manpower, divisions are unable to conduct both daytime inspections and blanket replacement. During the meetings with the divisions, it was noted that shortages require personnel to work late (passed 5pm) and on Saturdays to complete the added work.

Scope of Work. Another challenge faced while implementing the Blanket Replacement method was that sign personnel have a variety of duties to meet the varied work demands of the agency. For instance, when there is road construction, or a utility company is working on a road, it is often necessary to close a lane or determine a detour. In such cases, signs crews need to install detour signs and barricades. Then, when the service (or construction) is concluded, the sign crew needs to go back to collect the signs and barricade. All this work takes time and disrupts the sign inspection and replacement process.

The engineers suggested that perhaps all sign replacement activities could be coordinated with the replacement of other roadway features and could be done at one time using a corridor approach (by performing that work in combination with resurfacing a road, for example). Instead of replacing and maintaining signs in an area, paving another road, replacing the ditches in another area and so on, all road features could be replaced and/or maintained in a specific corridor while the agency is resurfacing that part of the road. However, it is important to note that different features have different life cycles. For instance, pavement marking (paint) may be redone every 4 years while signs may be replaced every 10 years.

4.4 Beneficial Sign Maintenance Practices

Based on this study's discussions through the case studies and on the literature reviewed, the research team selected a set of practices that can be considered by other DOTs to improve their sign maintenance programs. Practices that can be used independent of the sign maintenance method adopted include the following.

- Train personnel to conduct daytime inspections and observe signs while conducting other work activities.
- Track both sign manufacture and installation dates to determine sign life and age.
- Use a combination of sign maintenance methods to optimize the maintenance program.
- Consider using a higher quality of sheeting to increase sign life (as VDOT does).

When using the Expected Sign Life method (such as SCDOT does), agencies could consider the following practices.

- Use bar codes to identify signs.
- Maintain a sign inventory that contains sign installation date, age, and GPS location.
- Utilize an integrated system of software and hardware (bar code reader, tablet, computer, GPS).

When using the Blanket Replacement method (NCDOT and VDOT), agencies could consider the following practices.

- Replace signs by areas (counties or sections) that are delineated by roads (corridors).
- Reuse replaced signs that are less than 5 years old and in good condition.
- Do a nighttime inspection near the end of the sign service life (as VDOT does) to determine whether or not the sign service life in an area can be increased. Alternatively, evaluate a set of control signs near the end of the sign service life for the same purpose.
- Provide sign shop support for increased sign manufacturing load when first implementing the Blanket Replacement method.
- If resources are available, create a sign inventory. However, the Blanket Replacement method can be done without an inventory.

4.5 Conclusions

This study covered an extensive literature search and three case studies. Based on all that was discussed so far, it was possible to present a set of beneficial practices that other state DOTs can consider in their maintenance program that could result in cost reductions and safety improvements.

Final considerations include the fact that the Expected Sign Life method does require a sign inventory and a level of automation is required to know sign age and location because there is not necessarily statewide area or corridor uniformity in age. Combining the Blanket Replacement with the Expected Sign Life method, on the other hand, enables the work to be accomplished without maintaining an inventory. However, the agency should retain knowledge of the boundaries of the areas and the years in which their signs were replaced.

Both the Expected Sign Life and the Blanket Replacement methods also significantly reduce the need for daytime and nighttime inspections. Instead of these being conducted annually, they may be conducted toward the end of the sign service life. If such inspections (full inspection, random sampling, or a set of control signs) reveal nearly full compliance, it may be the case that replacement may be delayed in that area, thus effectively increasing sign life. In doing so the replacement method is linked directly to field performance and MUTCD compliance levels rather than to a theoretical estimate of sign life. That is, the actual implementation of a replacement method can be fine tuned based on performance over time and adjustments and corrections can be made when necessary.

With respect to a sign management program, the SCDOT is the only one among the three DOTs that has a mature program in place, which consists of a statewide program that contains a robust sign inventory database. Both NCDOT and VDOT are improving their sign management program by adopting new plans (RMIP and SMRC Plan, respectively). In addition, while VDOT already started creating its sign inventory database, NCDOT will also create such inventory to assist them in the maintenance and management of signs.

These findings have implications for maintaining and replacing other roadway assets. Furthermore, they could inform infrastructure asset management in general. Numerous agencies maintains civil infrastructure assets. The paper thus directly addresses infrastructure system operations.

5.0 SIGN DETERIORATION AND SERVICE LIFE

It is important to understand sign retroreflectivity deterioration and service life as well as their effect in a sign replacement strategy. Although a number of studies were conducted to determine sign retroreflectivity deterioration models and sign service life (Clevenger et al. 2012, Dumont et al. 2013, Kipp and Fitch 2009, Immaneni et al 2009, Pulver et al. 2018, and others), they did not reach a consensus regarding their conclusions. For instance, Pike and Carlson (2014) recommended for Type III sheeting a sign service life of 15 years while Pulver et al. (2018) recommended 10 years. That divergence also extends to sign retroreflectivity deterioration. For example, Pulver et al. (2018) found sign orientation to be a significant factor on retroreflectivity deterioration while other authors found that sign orientation was not a significant factor (Bischoff and Bullock 2002; Evans et al. 2012; Kipp and Fitch 2009; Re et al 2011; and Wolshon et al 2002).

5.1 Methodology

In an attempt of reaching a consensus on this topic, the author conducted an extensive review of the state of the art, which includes properties of sign sheeting material, previous studies, and sign warranty information. In addition, the research team also met with traffic engineers from three state Department of Transportation (DOTs) in NC, SC, and VA. The purpose of those meetings was to understand their sign maintenance program and the factors that govern these programs (e.g., retroreflectivity and sign service life). The objective of this chapter is to determine the reasonable sign service life of microprismatic Type III sheeting, which is a type of sheeting used by many transportation agencies.

This study looked at sign life from five different perspectives as follows.

- Glass-beaded and microprismatic sheeting
- Retroreflectivity deterioration models
- Sign service life
- Departments of Transportation practices
- Sign warranty

All the five perspectives are discussed throughout this chapter. The findings and conclusions of this chapter can assist DOTs to develop or improve their own sign maintenance program.

5.2 Glass Beaded and Microprismatic Sheeting

The first perspective on sign life is from the point of view of sheeting types and differences between them. Sign sheeting can be made with glass beads or micro-prism materials. The material used to manufacture sign sheeting has a major impact on its retroreflectivity performance. For many years, glass beaded Type III sheeting was vastly used by transportation agencies. The majority of all previous studies focused on sign retroreflectivity deterioration and sign service life collected data on glass beaded Type III sheeting (Black et al, 1991, Bischoff and Bullock, 2002; Rasdorf et al., 2006; Re et al., 2011; Pike and Carlson, 2014; and Preston et al., 2014, among others). Other authors typically did not specify whether the signs they surveyed were made with glass beads or microprisms, but most likely the signs were all glass beaded because they were the majority of in-service signs when the studies were conducted.

With improvements in sheeting technology, transportation agencies started using microprismatic sheeting because it is measurably and significantly more retroreflective than glass beaded sheeting. By 2011, when the Federal Highway Admiration published the “Traffic Sign Retroreflective Sheeting Identification Guide,” glass beaded Type III sheeting was no longer sold in the U.S

(FHWA, 2011). However, while adopting the use of microprismatic sheeting many agencies did not correspondingly adopt new sign replacement strategies accounting for the extended service life of these signs.

Figure 5.1 shows the structure of an encapsulated glass bead sheeting (Cunard, 1990). Figure 5.2 shows a close-up of a glass bead and how retroreflectivity acts on the bead much like the reflectors used in surveying. As shown in the figure, light beams hit the glass bead and are reflected back toward the source. Because of the spherical shape of the beads they reflect light back to the source but they also disperse it into a broader range of angles than does microprismatic sheeting. The longer the sighting distance the less light is visible to the original light source.

Figure 5.3 shows the structure of a microprismatic sheeting (Cunard, 1990). Figure 5.4 shows a retroreflective micro-prism as well as the incident and reflected light beams to and from it. With microprismatic sheeting the light is reflected back to the source in a narrower range of angles than it is in a glass beaded sheeting and, because of that, it can be seen at greater sighting distances.

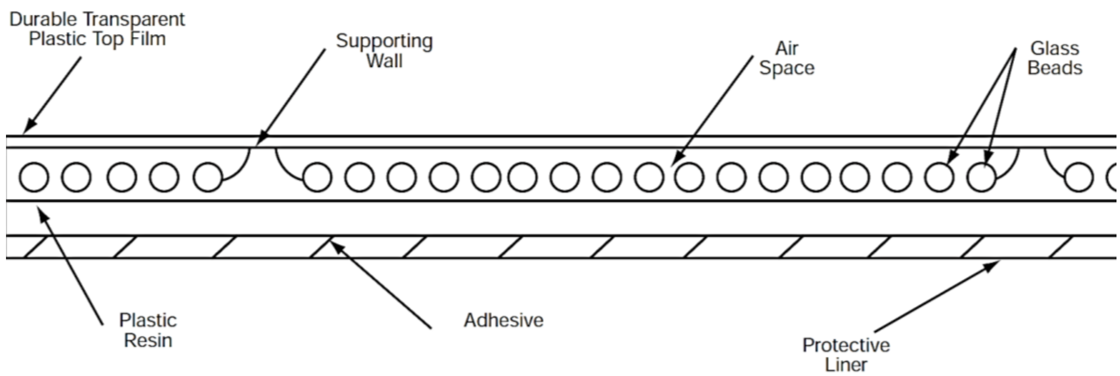


Figure 5.1 Structure of Encapsulated Glass Beads (Type III) Sheeting
Source: Figure 1 from "Maintenance Management of Street and Highway Signs" by Cunard (1990)

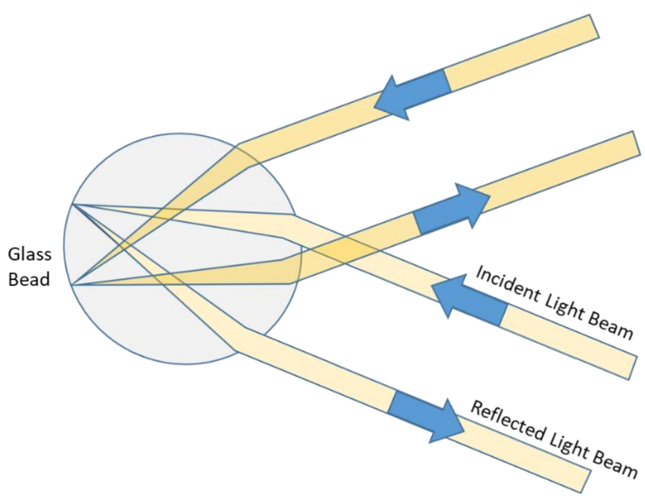


Figure 5.2 Scheme of a Glass Bead and Incident and Reflected Light
Note: This figure is based on *Figure 2* from "Maintenance Management of Street and Highway Signs" by Cunard (1990)

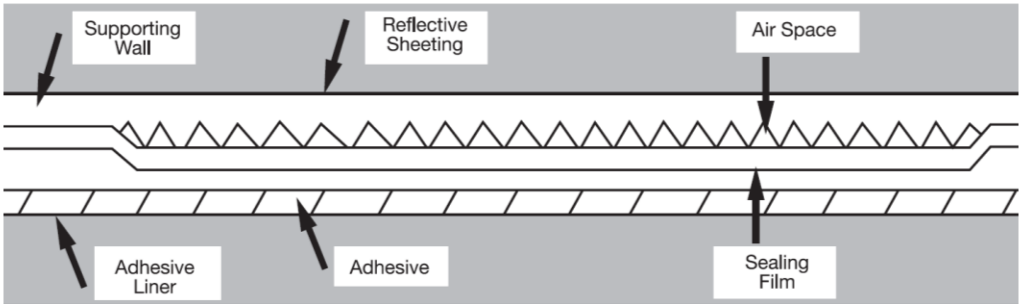


Figure 5.3 Structure of Microprismatic (Type III) Sheeting
Source: Figure 1 "Maintenance Management of Street and Highway Signs" by Cunard (1991)

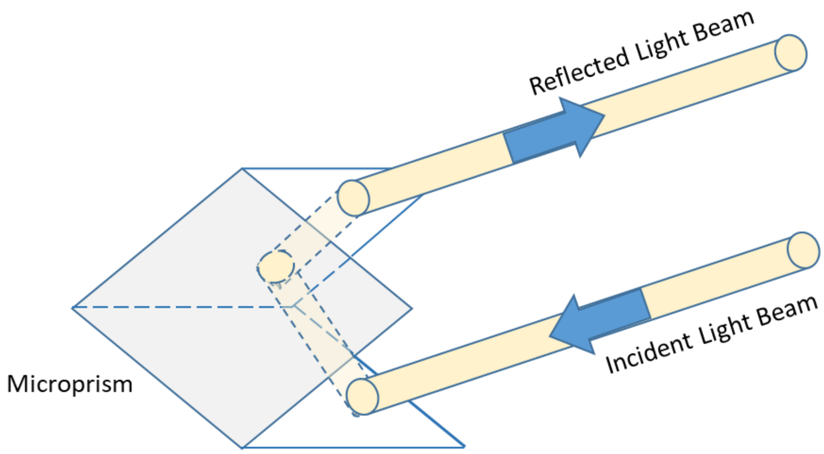


Figure 5.4 Scheme of a Micro-prism, Incident, and Reflected Light
Note: This figure is based on *Figure 2* from "Maintenance Management of Street and Highway Signs" by Cunard (1990)

Table 5.1 shows the initial retroreflectivity for both glass beaded and microprismatic Type III sheeting for the four colors considered in this study. The retroreflectivity levels for microprismatic sheeting shown in the third column of the table were obtained from "D4956 – 17 Standard Specification for Retroreflective Sheeting for Traffic Control" (ASTM, 2017) and refer to the minimum retroreflectivity levels for a sheeting to be classified as microprismatic Type III sheeting. The fourth column shows maximum retroreflectivity levels of microprismatic Type III sheeting found in the U.S. market (3M, 2018). The last column in the table shows the improvement in retroreflectivity when upgrading from a glass-beaded sheeting to a microprismatic sheeting.

As shown in Table 5.1, microprismatic sheeting has a significantly higher retroreflective performance than glass beaded sheeting, which is caused by the different paths of the light beams in the different sheeting material. Yellow microprismatic sheeting had the greatest retroreflectivity improvement ranging from 59% to 147% in relation to glass beaded. White microprismatic sheeting also had a significant retroreflectivity improvement ranging from 44% to 127%. Red sheeting had an improvement ranging from 44% to 87% while green sheeting had an improvement ranging from 11% to 24%.

Based on this information, it can be implied that the results from previous studies related to (glass beaded) Type III sheeting were somewhat conservative when compared to the current (microprismatic) Type III sheeting now used by DOTs. More importantly, while retroreflectivity deterioration models from previous studies are expected to be overestimated, their reported sign service life is expected to be underestimated.

Table 5.1 Initial Retroreflectivity (R_A) and Improvement from Encapsulated Glass Beaded to Microprismatic Type III Sheeting

Color	Glass Beaded Sheeting *	Microprismatic Sheeting		Improvement From Glass Beaded to Microprismatic
		Minimum * +	Maximum ++	
White	250	360	560	44% to 124%
Yellow	170	270	420	59% to 147%
Red	45	65	84	44% to 87%
Green	45	50	56	11% to 24%

Note: R_A = candelas per lux per square meter (cd/lx/m^2).
Improvement from grass beaded to microprismatic = ($R_{A\ Microprismatic}$ - $R_{A\ Glass\ Beaded}$) / $R_{A\ Glass\ Beaded}$
*Values obtained from ASTM D4956-17 “Standard Specification for Retroreflective Sheeting for Traffic Control” (ASTM, 2017). Those are the minimum retroreflective values for glass beaded Type III sheeting (second column) and microprismatic Type III sheeting (third column).
[+] Nippon Carbide sheeting manufacturer stated that its microprismatic Type III and IV sheeting meet the minimum values specified by ASTM D4956-17 (Nippon Carbide, 2015). Both Avery Dennison and Orafol Americas Inc. sheeting manufacturers stated that their microprismatic Type III and IV sheeting exceed the minimum values specified by ASTM D4956-17 (Avery Dennison 2018; Orafol 2016).
[++] Values obtained from 3M sheeting manufacturer for its microprismatic Type III and IV sheeting (3M, 2018).

5.3 Retroreflectivity Deterioration Models

The second perspective presented in this chapter is from studies identified in the literature regarding retroreflectivity deterioration over time. The research team conducted an extensive literature review of these studies that includes and describes their sign retroreflectivity deterioration models for different types and colors of sign sheeting. While some authors tried to find a correlation between retroreflectivity deterioration and a set of variables (e.g., sign offset, orientation, and degree of shade), others focused on deterioration and sign age.

For the purpose of this study, the research team decided to consider only models that correlated retroreflectivity deterioration with sign age. The reason is that any other variable (such as sign orientation or location) would require specific and individual data about each sign that cannot be obtained without having a sign database inventory. In addition, the influence on retroreflectivity of some variables changes over time. For example, the “degree of shade” variable introduced by Pulver et al. (2018) changes over time because the vegetation around a sign changes.

Table 5.2 shows a summary of studies that focused on models correlating retroreflectivity deterioration of Type III sheeting and sign age. The first column specifies the color of the sign sheeting. The second columns identifies the authors and their studies. The third column shows their retroreflectivity deterioration models. Sign retroreflectivity is expressed in cd/lx/m^2 and sign age in years. The fourth column shows the R-squared (R^2) of the equation.

Table 5.2 Summary of Retroreflectivity Deterioration Models from Previous Studies

Color	Author	Deterioration Model	R^2
White	Black et al. (1991)	311.011 - 4.612 x Age	NA
	Bischoff and Bullock (2002)	253.71 - 0.8632 x Age	0.0152
	Rasdorf et al. (2006)	262.63 - 0.7135 x Age	0.0117
	Kipp and Fitch (2009)	$436.8 \times Age^{-0.355}$	0.1304
	Immaneni et al. (2009)	304.089 - 4.815 x Age	0.19
	Re et al. (2011)	265 - 6.2 x Age	0.08
	Clevenger et al. (2012)	758.31 - 32.078 x Age	0.2527
	Huang et al. (2013) **	$393.0087 - 2.845 \times Age - 0.0455 \times Age^2 + 0.002 \times Age^3$	0.581
	Pike and Carlson (2014)	261.57 + 0.8524 x Age	0.0041
	Preston et al. (2014)	424.03 - 7.555 x Age	0.1995 +
Yellow	Black et al. (1991)	246.39 - 3.206 x Age	NA
	Bischoff and Bullock (2002)	222.47 - 3.5768 x Age	0.1902
	Rasdorf et al. (2006)	$216.35 + 1.2742 \times Age - 0.2514 \times Age^2$	0.0855
	Kipp and Fitch (2009)	329.9 - 78.88 x Ln (Age)	0.1275
	Immaneni et al. (2009)	$193.01 + 5.644 \times Age - 0.552 \times Age^2$	0.26
	Re et al. (2011)	251 - 6.8 x Age	0.19
	Clevenger et al. (2012)	523.53 - 20.24 x Age	0.2533
	Pike and Carlson (2014)	204.2 + 1.1171 x Age	0.0085
	Preston et al. (2014)	416.07 - 14.14 x Age	0.6853 +
Red	Black et al. (1991)	38.686 + 0.610 x Age	NA
	Bischoff and Bullock (2002)	51.836 - 2.0298 x Age	0.3236
	Rasdorf et al. (2006) *	-	-
	Kipp and Fitch (2009)	72.9 - 4.35 x Age	0.0266
	Immaneni et al. (2009)	59.632 - 2.658 x Age	0.35
	Re et al. (2011)	52 - 1 x Age	0.09
	Clevenger et al. (2012)	94.055 - 4.0818 x Age	0.1537
	Pike and Carlson (2014)	49.324 + 0.4731 x Age	0.0042
	Preston et al. (2014)	74.858 - 0.822 x Age	0.0381 +
Green	Black et al. (1991)	55.15 - 1.82 x Age	NA
	Rasdorf et al. (2006) *	-	-
	Kipp and Fitch (2009)	$96.1 \times Age^{-0.2038}$	0.0377
	Immaneni et al. (2009)	53.386 - 1.345 x Age	0.48
	Clevenger et al. (2012)	71.165 - 0.8512 x Age	0.0467
	Huang et al. (2013) **	$49.1926 - 0.005 \times Age - 0.0066 \times Age^2 + 3.8 \times 10^{-5} \times Age^3$	0.369
	Pike and Carlson (2014)	30.66 + 1.4328 x Age	0.1746
	Preston et al. (2014)	47.843 + 0.6521 x Age	0.7697 +

Notes: NA: not available.

* In Rasdorf et al. (2006), the plots and equations for both red and green sheeting are the same, which most likely indicates some editing mistake. Because it was not possible to determine which deterioration model belong to which color sheeting, they are not shown in the table.

** Huang et al. (2013) uses the Chinese nomenclature: Type I is high intensity grade (ASTM Type III) and Type III is engineering grade (ASTM Type I).

+ Preston et al. (2014) considered their models inconclusive due to the small sample size.

As Table 5.2 shows, most of the models are linear regression (with a few exceptions) and R-square values are generally low. One of the explanations for having low R-square values is that there are variables other than age affecting retroreflectivity. For instance, Kipp and Fitch (2009) found that sheeting manufacturers also have an impact on sign retroreflectivity. In other cases, the color fading of the sign sheeting also can affect sign retroreflectivity (Pike and Carlson, 2014). Preston et al. (2014) was one of the few studies that achieved high R-squared (above 0.5); however, the authors explained that they considered their models to be inconclusive because there were low numbers of data points (small sample size per sheeting color). Huang et al. (2013) also obtained relatively high R-squared for white (R-squared = 0.581) and green sheeting (R-squared = 0.369).

To better visualize, understand, and analyze these models, they (every model in Table 5.2) were grouped and plotted by sheeting color as shown in Figures 5.5 to 5.8. These figures are discussed in the following subsections.

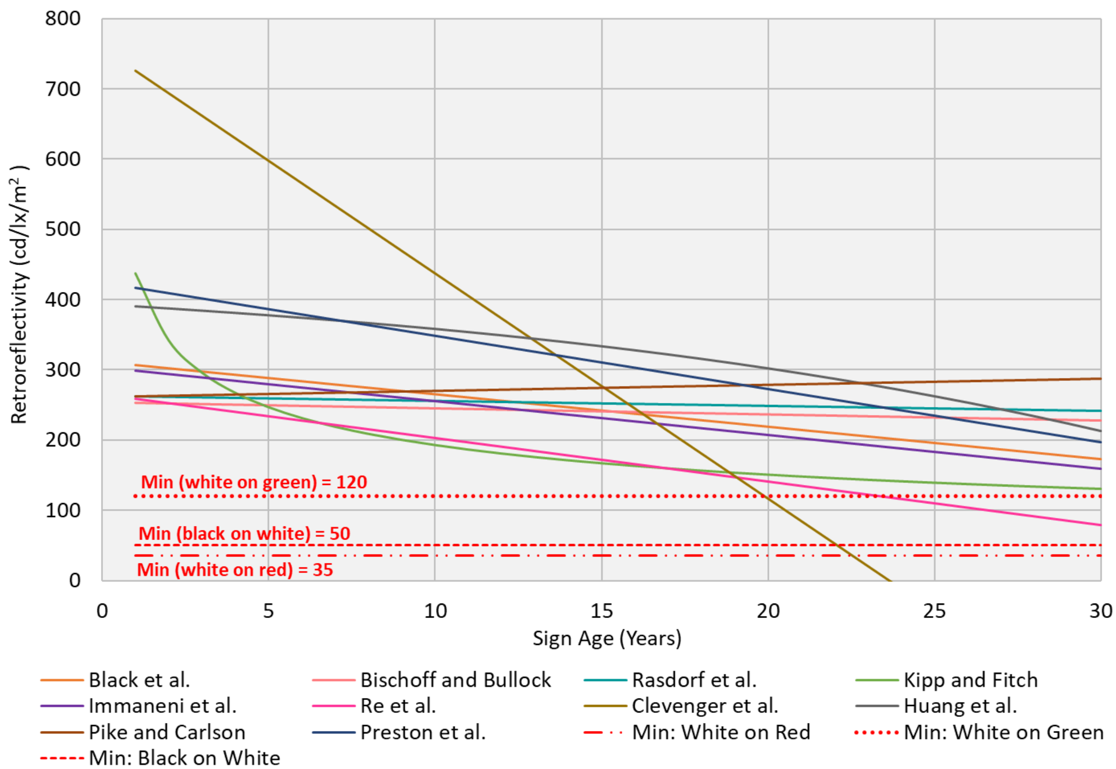


Figure 5.5 White Type III Retroreflectivity Deterioration Models

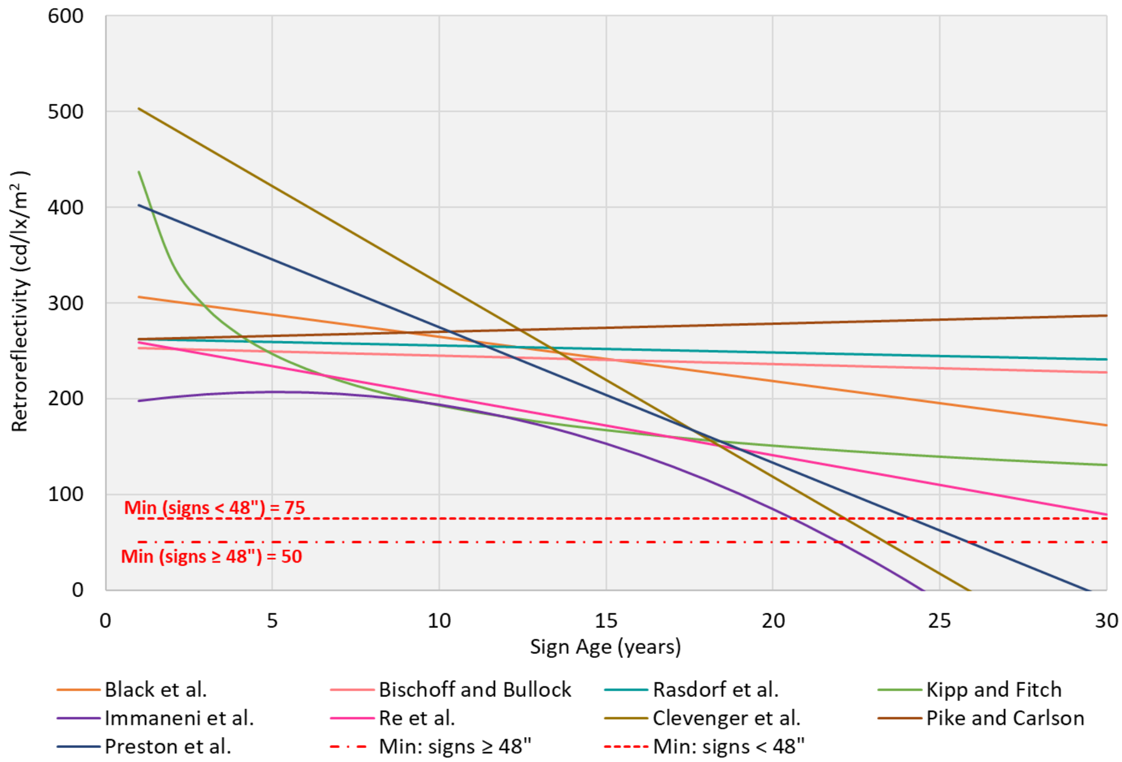


Figure 5.6 Yellow Type III Retroreflectivity Deterioration Models

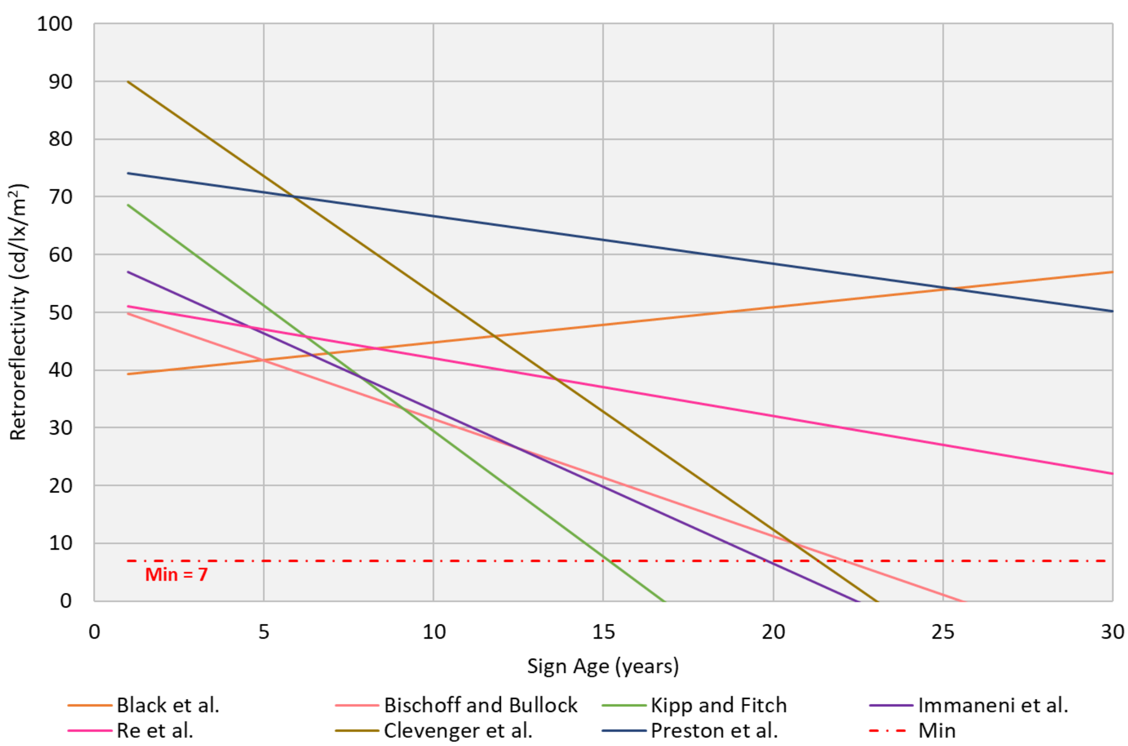


Figure 5.7 Red Type III Retroreflectivity Deterioration Models

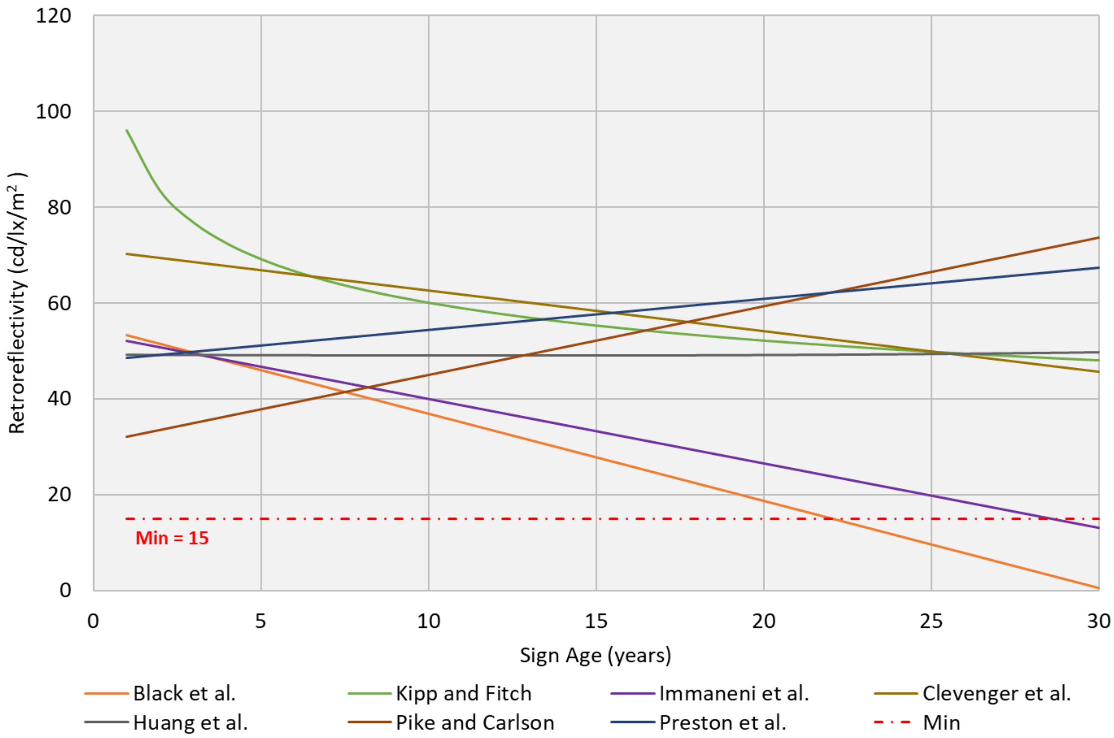


Figure 5.8 Green Type III Retroreflectivity Deterioration Models

5.3.1 White Sheeting

Figure 5.5 shows the deterioration models for white Type III sign sheeting. It is possible to compare the 10 models with MUTCD (FHWA, 2009) minimum required retroreflectivity values. These are shown in Figure 5.5 by the three red and dashed horizontal lines. For white, these lines indicate 120 (white on green), 50 (black on white), and 35 cd/lx/m^2 (white on red). The plot shown in Figure 5.5 allowed the research team to observe the following.

- White sheeting on green signs: two models predicted a sign retroreflectivity deterioration life ranging from 20 to 24 years. Eight models indicated that white sheeting will perform above minimum retroreflectivity levels for at least 30 years.
- White signs: one model predicted a sign retroreflectivity deterioration life of 22 years. Nine models indicated that white sheeting will perform above the minimum retroreflectivity levels for at least 30 years.
- White sheeting on red signs: one model predicted a sign retroreflectivity deterioration life of 23 years. Nine models indicated that white sheeting will perform above the minimum retroreflectivity levels for at least 30 years.

5.3.2 Yellow Sheeting

Figure 5.6 shows the deterioration models for yellow Type III sign sheeting. It is possible to compare the nine models with MUTCD (FHWA, 2009) minimum required retroreflectivity values. These are shown in Figure 5.6 by the two red and dashed horizontal lines. For yellow these lines indicate 75 (signs smaller than 48 inches) and 50 cd/lx/m^2 (signs greater or equal 48 inches). The plot shown in Figure 5.6 allowed the research team to observe the following.

- Yellow signs smaller than 48”: three models predicted a sign retroreflectivity deterioration life ranging from 21 to 24 years. Six models indicated that yellow sheeting will perform above the minimum retroreflectivity levels at least for 30 years.
- Yellow signs greater than 48”: three models predicted a sign retroreflectivity deterioration life ranging from 22 to 26 years. Six models indicated that yellow sheeting will perform above the minimum retroreflectivity levels for at least 30 years.

5.3.3 Red Sheeting

Figure 5.7 shows the deterioration models for red Type III sign sheeting. As it was expected and extensively discussed in the literature, red sheeting has the lowest retroreflectivity compared to the other colors of sheeting. In the graph, it is possible to compare seven deterioration models with MUTCD (FHWA, 2009) minimum required retroreflectivity value. This is shown in Figure 5.7 by the red and dashed horizontal line that indicates 7 cd/lx/m^2. The plot shown in Figure 5.7 allowed the research team to observe the following.

- One model predicted a sign retroreflectivity deterioration life of 15 years old. Three models predicted a sign retroreflectivity deterioration life ranging from 20 to 22 years. The other three models indicated that red sheeting will perform above the minimum retroreflectivity levels for at least 30 years.

5.3.4 Green Sheeting

Figure 5.8 shows the deterioration models for green Type III sign sheeting. It is possible to compare the seven models with the MUTCD (FHWA, 2009) minimum required retroreflectivity value. This is shown in Figure 5.8 by the red and dashed horizontal line that indicates 15 cd/lx/m^2. The plot shown in Figure 5.8 allowed the research team to observe the following.

- Two models predicted a sign retroreflectivity deterioration life ranging from 22 to 29 years. The other five models indicated that green sheeting will perform above the minimum retroreflectivity levels for at least 30 years.

5.4 Sign Service Life

The third perspective we considered in this study was that of sign service life. Although sign service life and retroreflectivity are somewhat related, they are not the same. To avoid confusion, a brief description is provided for these two terms. Retroreflectivity is a property of a sheeting material that reflects light back to its source (e.g., a car) and, as a result, makes signs visible to drivers at night. Retroreflectivity can be measured with the use of a device known as a retroreflectometer. Sign service life is how long a sign remains in the field before it needs to be replaced. One way of estimating sign service life is based on retroreflectivity levels. In other words, it is based on how long a sign is expected to remain above the minimum retroreflectivity levels required by MUTCD (FHWA, 2009).

Some previous researchers, after analyzing sign retroreflectivity deterioration, recommended sign life periods for Type III sheeting based on their findings as shown in Table 5.3. As the table shows, most of the studies recommended a sign service life of 15 years or more.

Note that from the six studies shown, only one recommended 10 years for Type III sheeting (Pulver et al. 2018). Despite the fact that the deterioration models’ predictions indicated that the sign service life was greater than 10 years, Pulver et al. (2018) recommended that South Carolina DOT keep their sign service life of 10 years (which is currently based on the warranty period of South Carolina signs). That recommendation was based on a term called failure rate, which was defined as the number of signs replaced at age *i* divided by the total number of signs at age *i*. According to the authors, signs that are 10 years old have a failure rate of over 0.5, meaning they have a greater than 50% chance of being replaced.

This outcome should not be a surprise in the case of South Carolina because they adopt the Expected Sign Life method based on sign warranty period (10 years). Thus, if all signs that are 10 years or older are required to be replaced due to the current sign maintenance method, it explains the reason why Pulver et al. (2018) found a high probability of sign failure at 10 years given their sign failure definition. Therefore, using the failure rate (as described by Pulver et al. 2018) may not be a good option to determine sign service life. The deterioration models developed by the authors are probably more realistic in predicting sign service life than is the failure rate.

All the other five studies recommend at least 15 years for sign service life. Pike and Carlson (2014), Dumont et al. (2013), and Clevenger et al. (2012) recommended a minimum sign service life of 15 years for Type III sheeting. Clevenger et al. (2012), who surveyed 1,007 in service signs, stated that the research team had a high degree of confidence in recommending 15 years and that simple statistical analysis showed that there were high probabilities that signs from 16 to 18 years would still be performing above the minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). In the case of Immaneni et al. (2009), the sign life recommended ranged from 20 to 37 years depending on the sign color. Kipp and Fitch (2009) recommended sign service life ranging from 15 to 20 years.

Table 5.3 Type III Sign Service Life and Previous Studies' Recommendations

Location	Authors	Sign Service Life-
South Carolina	Pulver et al. (2018)	10 years
Minnesota	Dumont et al. (2013)	Minimum: 15 years
Pennsylvania	Clevenger et al. (2012)	Minimum: 15 years
Wyoming	Pike and Carlson (2014)	Minimum: 15 years
North Carolina	Immaneni et al. (2009)	White signs: 20 to 30 years Yellow and red signs: 24 years Green signs: 37 years
Vermont	Kipp and Fitch (2009)	Red signs: 15 years White, yellow, and green signs: 15 to 20 years

5.5 Departments of Transportation Practices

The fourth perspective is that of DOTs, more specifically, what they were doing in practice. Among the studies we found that focused on determining sign service life, two of them conducted surveys of state DOTs to register which sign service life they adopted, if any, and the reason (Clevenger et al 2012 and Dumont et al. 2013). Other studies identified DOT practices of the state where the study was being conducted (Immaneni et al. 2009; Kipp and Fitch 2009; and Pulver et al. 2018). The research team also visited three states DOTs (North Carolina, South Carolina, and

Virginia) to document their sign management practices (including the sign service life they adopted).

Table 5.4 compiles the Type III sheeting information obtained from these previous studies. The first column lists the sign service life, which ranges from 10 to 18 years. The second column shows the DOTs that have adopted this sign life and the last column shows the total number of DOTs adopting that practice. A total of 15 DOTs used Type III sheeting when the previous studies were conducted.

In the case of the Mississippi DOT, its sign service life ranges from 10 to 12 years. Thus, Mississippi DOT was counted in Table 5.4 as adopting both 10 and 12 years sign service life practices. New York also follows the same logic because, according to Kipp and Fitch (2009), they had a 12 year blanket replacement cycle, but had to extend to 15 years due to limited funding.

Five out of 15 DOTs adopted a 10 year sign life for Type III sheeting. Most of these DOTs (Arkansas, Maine, Mississippi, and South Carolina) did so based on sign sheeting warranty with no further explanation nor study. North Carolina DOT recently adopted a sign service life of 10 years, making it to be the only DOT to adopt a sign service life below the sheeting warranty, which is 12 years.

Six out of 15 DOTs adopted a 12 year sign life for Type III sheeting. In some cases, DOTs such as South Dakota, Mississippi, and Minnesota adopted a sign service life based on a combination of sheeting warranty and another method (e.g., test decks and field experience) (Clevenger et al 2012 and Dumont et al. 2013). There is not much information regarding the other three DOTs' choice.

Five out of 15 DOTs adopted a 15 year sign life for Type III sheeting. Michigan DOT used its field experience to determine a sign service life of 15 years (Clevenger et al., 2012). Ohio and Vermont DOTs adopted 15 years based on research (Clevenger et al., 2012 and Dumont et al., 2013). Although it is not explicit in the literature, a study conducted by Oklahoma in partnership with the Federal Highway Administration (FHWA) (Ahmed, 1994) specified a 15 year sign life for Type III sheeting based on three sources, including "data obtained from Oklahoma DOT field divisions."

Indiana DOT was the only DOT found in the literature that adopted an 18 year sign life for Type III sheeting. Indiana DOT conducted a field study and found that Type III sheeting performed well up to 18 years old (Clevenger et al. 2012).

Table 5.4 Type III Sign Service Life and DOTs' Practice

Sign Service Life	Location	Number of DOTs to Adopt
10 years	Arkansas, Maine, Mississippi, North Carolina, South Carolina	5
12 years	Minnesota, Mississippi, New York, South Dakota, Wisconsin, Wyoming	6
15 years	Michigan, New York, Ohio, Oklahoma, Vermont	5
18 years	Indiana	1
Total		**15**

As the literature reviewed shows, a sign life of 10 to 12 years is mostly based on or is related to sheeting warranty. DOTs that adopted sign service lives of 15 years and above justified their choice based on studies and/or field experience. Most DOTs (10 out 15, not considering Mississippi) adopted a sign service life above the warranty period for Type III sheeting. Sign service life ranging between 12 and 15 years seemed to be commonly and well accepted by DOTs with one adopting 18 years as their sign service life.

5.6 Sign Warranty

The fifth and final perspective considered was that of sign warranty, that is, how warranted retroreflectivity compares with minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). This section focuses on warranty of microprismatic Type III sheeting for the reason that glass beaded Type III sheeting is not sold anymore in the U.S. (FHWA, 2011).

The overall warranty coverage for microprismatic Type III sheeting is between 10 to 12 years depending on the sheeting manufacturer. Some manufacturers warrant their sheeting for both a specific number of years and for a performance level ranging between 70% and 80% of the initial retroreflectivity. Although a 10 year warranty is a common practice for Type III sheeting, it does not mean that it is a rule of the market. Manufactures and transportation agencies may opt to have a different arrangement that attends the needs from the parties involved. For instance, the North Carolina DOT has an arrangement for a 12 year warranty.

Nevertheless, independent of the type of warranty agreement an agency may have with a sheeting manufacturer, the use of sheeting manufacturer's warranty period as a sign service life is very conservative and it is not considered to be good practice. Although the practice of using warranty period as sign service life may guarantee compliance with MUTCD, it often results in replacing signs before retroreflectivity deteriorates below the minimum required, which increases the costs to maintain signs (Re et al., 2011; Re and Carlson, 2012; Preston et al., 2014; and Pike and Carlson, 2014).

Re and Carlson (2012) explained that a warranty period for sheeting does not represent its true service life; instead, it refers to a period in which retroreflectivity is expected to deteriorate 20% in relation to its initial value (of a brand-new sign). In addition, manufacturers need to be somewhat conservative with relation to the warranty period because the warranty is the same for different regions under different weather conditions (e.g., Alaska and Arizona) (Re and Carlson, 2012). Preston et al. (2014) suggested that one of the explanations for signs performing well above their minimum retroreflectivity is the fact that sheeting manufacturers continue to improve the quality of retroreflective sheeting. In addition, a representative of the Avery Dennison sheeting manufacturer stated "warranties protect public agencies against manufacture defect, but the goal is to create products that *far outlast the warranty period*."

Because the literature reviewed often cited the fact that signs outlive their warranty period (often considerably), it seemed logical to draw a comparison between the warranted retroreflectivity and minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). Table 5.5 shows this comparison. The first column lists the sign colors. The second column lists the minimum initial retroreflectivity levels of a sheeting (by color) for it to be classified as microprismatic Type III sheeting. Some products available in the market exceed the minimum initial retroreflectivity levels shown in the second column of the table (see *Notes* of Table 5.5) (3M, 2018; Avery Dennison, 2018; and Orafol, 2016). The third and fourth columns show the warranted levels for 70% and 80% of the initial retroreflectivity. The fifth column lists the minimum required retroreflectivity levels required by MUTCD (FHWA, 2009) which are far lower than microprismatic sheeting initial retroreflectivity (column 2). The last two columns (sixth and seventh) show how much the warranted retroreflectivity levels are above the minimum levels required by the MUTCD (FHWA, 2009).

Table 5.5 Initial Retroreflectivity, Warranted Retroreflectivity, and Minimum Retroreflectivity

Color	Minimum Initial R_A * +	Warranted R_A		Minimum R_A (MUTCD)	Above the Minimum R_A ++	
		70% of Initial R_A	80% of Initial R_A		70% of Initial R_A	80% of Initial R_A
White	360	252	288	120[a] 50[b] 35[c]	132[a] 202[b] 217[c]	168[a] 238[b] 253[c]
Yellow	270	189	216	75[d] 50[d]	114[d] 139[d]	141[d] 166[d]
Red	65	45.5	52	7	38.5	45
Green	50	35	40	15	20	25

Notes: Retroreflectivity unit of measure is candelas per lux per square meter (cd/lx/m^2)
* Minimum initial retroreflectivity levels of microprismatic Type III sheeting (ASTM, 2017)
\+ Avery Dennison, Orafol Americas Inc., and 3M sheeting manufacturers stated that their microprismatic Type III and IV sheeting exceed the minimum values specified by ASTM D4956-17 (Avery Dennison 2018; Orafol 2016; 3M, 2018).
++ Above the Minimum R_A = Warranted R_A – Minimum R_A
[a] White on green
[b] Black on white
[c] White on red
[d] Signs smaller than 48 inches
[e] Signs greater or equal 48 inches

From Table 5.5 it is possible to observe that at the end of the warranted period, signs still perform well above the minimum retroreflectivity levels (last two columns). For instance, consider a warranty of 80% of the initial sign performance (fourth column). In this case, a white sign (black on white) is expected to have a retroreflectivity of 288 cd/lx/m^2 (360 x 80%) at the end of the warranty period. The warranted retroreflectivity level of a white sign is 238 cd/lx/m^2 (288 – 50) which is far above the minimum retroreflectivity level (50 cd/lx/m^2). The same is valid for other sign colors. Therefore, considering the comparison show in Table 5.5 and previous studies' results, it can be said that replacing signs based on their warranty period means replacing them prior the end of their service life.

5.7 Conclusions

When the previous deterioration studies were conducted, the most commonly used type of sheeting was glass beaded Type III and, as shown in Figures 5.5 to 5.8, all colors with exception of red performed above the minimum retroreflectivity for at least 20 years. In the case of red sheeting, only one study (Kipp and Fitch, 2009) indicated a sign service life of 15 years; the other studies indicated 20 years and above for red sheeting (the same as the other colors). In addition, five out of six studies recommended a service life of 15 years or above for Type III sheeting.

An aspect to be considered with respect to sign sheeting is that manufacturers are in a constant process of improvement of the quality of retroreflective sheeting (Preston et al., 2014). For instance, microprismatic Type III sheeting replaced glass beaded Type III sheeting in the U.S. market because of its higher retroreflectivity performance. Such technology improvement results in a greater sign service life.

Most previous retroreflectivity studies found that glass beaded signs were expected to perform above the minimum retroreflectivity levels for more than 15 (red) or 20 years (white, yellow, and green). If those results were found for glass-beaded sheeting, it is reasonable to expect that microprismatic sheeting has an even greater sign service life than 15 or 20 years (found for glass beaded). In other words, microprismatic sheeting is expected to last even longer than previous predictions. The reason this assumption cannot conclusively yet be verified is because microprismatic sheeting studies are unavailable, have not yet been done, or have not yet been completed.

Thus, it may be the case that sign technology has evolved to the point that retroreflectivity is no longer the main factor that determines a sign replacement cycle. As Pike and Carlson (2014) indicated, it is most likely that signs will be replaced due to vandalism or other types of damage rather than because of retroreflectivity.

With respect to DOTs' practice, the most used sign service life are 10, 12, and 15 years with one DOT adopting a sign service life of 18 years for Type III sheeting (Indiana). Although sign service lives of 10 and 12 years are often used by DOTs, they are conservative, especially considering that most DOTs adopted those values based on sign warranty. The deterioration models (Table 5.2) also showed that signs in all colors perform well above the minimum retroreflectivity levels at the ages of 10 and 12 years, indicating that those are underestimated sign service lives.

After analyzing the literature reviewed and information obtained from DOTs, the research team concluded that the adoption of a service life smaller than 15 years for microprismatic Type III sheeting should be avoided for replacing signs before the end of their service life, which is in accordance with the five different studies of previous related work. A sign service life of 15 years seems to be the most balanced among DOTs' practices and previous studies recommendations. All deterioration models also showed that Type III sheeting is expected to perform above the minimum retroreflectivity levels for all colors at an age of 15 years. Still according to this study, some transportation agencies may opt for adopting a sign service life ranging from 15 to 20 years for white, yellow, and green sheeting.

These findings have implications for agencies that adopt or plan to adopt any of the three sign management methods recommended by the MUTCD (FHWA, 2009). The chapter thus directly addresses transportation asset management and can be useful for numerous transportation agencies.

6.0 SIGN MAINTENANCE METHODS

The MUTCD (FHWA, 2009) recommends five sign maintenance methods to ensure that sign retroreflectivity is compliant with the minimum levels required by the manual. This chapter analyzes each one of those methods to assess their suitability in light of the current literature and the technological development of recent years. At the end of this analysis, the research team decided to focus on the Blanket Replacement method to develop sign replacement strategies. In addition, a set of practices related to this method were also described, some of which have the objective of mitigate the disadvantages of the Blanket Replacement method.

6.1 Analysis of the Maintenance Methods

To analyze the different methods recommended by the MUTCD (FHWA, 2009), the research team considered literature review, various DOTs' experiences, and typical DOT management policies.

6.1.1 <u>Nighttime Visual Inspection</u>

This method is the most used by DOTs (20 out 40 states). What makes the Nighttime Visual Inspection method so popular is the fact that it does not require expensive equipment nor a database. In addition, inspectors can assess other road features while performing the inspection. However, the Nighttime Visual Inspection method does require inspector training and it is a subjective method of evaluation because it depends on a visual assessment. As a result, Immaneni et al. (2007) found that nighttime inspector accuracy ranged between 54 and 83% depending on sign color. Such information indicates that an agency that uses nighttime inspection to maintain signs may be vulnerable to legal claims.

One disadvantage of the Nighttime Visual Inspection method is that they result in productivity loss. To conduct nighttime inspection, personnel typically work up to 50 hours per week. DOTs can either pay overtime or work with a compensatory time system to address the time worked beyond 40 hours per week. When compensatory time system is used, laborers earn (to take off) 1.5 hour per each 1 hour worked above the weekly 40 hours. Thus, if a laborer works 45 hours in a week, this worker has earned 7.5 hours (1.5 x 5 hours that exceed that weekly 40 hours) to be taken off at a later time. As a result, the agency productivity is negatively affected because it loses 1.5 labor hours that could be potentially used to maintain (e.g., straighten and clean) and replace signs, or to conduct other work. In addition, laborers who work more than 40 hours per week have their productivity reduced because of fatigue, reduced attention, and the stress of more difficult nighttime working conditions (low illumination (if any), low visibility, increased susceptibility to theft, etc.).

Another point to be considered is that a DOT could achieve a better overall sign condition if laborers were allocated to sign maintenance and replacement activities (a proactive approach) instead of conducting nighttime inspections (a reactive approach). According to traffic engineers from one of the transportation agencies visited by the research team, although nighttime inspections represented only 2% of the division's total budget, it is still a significant amount of money that could be better invested if spent on maintenance and replacement activities. In a simple calculation, it was possible to determine that the annual $50,000 spent by this agency in nighttime inspections was enough to install over 500 new ground mounted signs (considering an average cost of $87.5/sign).

In the visits to some of the NCDOT divisions, some traffic engineers also speculated that nighttime inspections may be related to a potential increase in the number of workers compensation claims.

Although numbers were not discussed during the meetings, it was reported that workers are more likely to suffer an injury while working under the more challenging conditions of nighttime work. For example, during a nighttime inspection a crew member exits the vehicle to tag a sign that was identified as noncompliant (low retroreflectivity); however, because it is dark and the laborer cannot see very well where he/she steps, which results in a greater chance of being injured. This would increase the likelihood of a worker compensation claim. Thus, based on the experience of the engineers it is believed that the numbers of workers compensation claims are lower when nighttime inspections are not conducted.

The NCDOT adopted the Nighttime Visual Inspection method for many years. While Interstates signs are inspected and replaced (when needed) every year, signs on primary and secondary roads have a more flexible schedule. Although this method has worked well, it has disadvantages. As reported by Re and Carlson (2012), the Nighttime Visual Inspection could potentially increase the number of lawsuits by drivers that had crashes because the inspections are subjective. Other areas of concern are overtime pay, schedule modifications, productivity loss caused by fatigue, and the stress of the more difficult nighttime working condition. Based on the literature, the disadvantages listed by NCDOT traffic engineers, and the fact that the NCDOT adopted the visual nighttime inspection method for many years and recently decided to change its approach, the research team opted to not further consider this method in this study

6.1.2 Measured Retroreflectivity

This method consists of inspectors measuring retroreflectivity of individual signs, which usually requires a minimum of three readings per sign (but also often many more) that are then averaged to assess whether or not the sign is above the minimum retroreflectivity levels. In some cases, such as with yield signs, inspectors are required to measure two colors (white and red) on the sign, which adds a total of six readings (three per color). All this process is highly labor intensive as stated in the literature. Re and Carlson (2012) indicated that in most cases inspectors would need ladders to measure signs' retroreflectivity because of signs' height (the lower edge of the signs is often 7 feet above the ground). In addition, some signs are simply difficult to access, which exposes inspectors to roadway hazards and can lead to labor compensation claims.

Another point to be considered is that this method is weather dependent. For instance, a sign field study conducted by Vereen at al. (2002) also described the difficulty of measuring retroreflectivity of signs on a rainy day. According to the authors, the research team could not obtain accurate readings when the sign was wet, meaning that the data collection (retroreflectivity levels), being weather dependent, was conditional to dry conditions. Another disadvantage of the Measured Retroreflectivity method is that it requires the use of expensive equipment (e.g., retroreflectometers) that can range from $10,000 to $12.000 (Re and Carlson, 2012).

An indicator that the Measured Retroreflectivity method is not the best method to maintain signs is that only one (Alaska) out of 40 states has adopted it (see

Table 2.5). It is quite reasonable that a DOT with a relatively low state-maintained mileage (5,630 road miles: Alaska DOT, 2017) has adopted the Measured Retroreflectivity method. However, other states (e.g., TX, NC, and VA) have a total roadway network that is more than 10 times larger than the Alaska highway system. Because of the larger highway network, states as TX, NC, and VA also have a significantly larger number of traffic signs to maintain than Alaska does. Immaneni et al. (2007). estimated in 2007 that NCDOT had a sign inventory of 969,905 signs. VDOT estimates that there are almost 900,000 signs state maintained in VA (VDOT, 2017). As stated by Vereen et al. (2002), "Identifying how many signs the state has, along with what type, color, and where they are, can be beneficial when formulating sign maintenance alternatives. A technique that may be feasible and cost efficient for 1,000 signs may not be for 1,000,000 signs."

For instance, NC (the second largest state-maintained highway system in the US) has a total roadway network of almost 80,000 miles (NCDOT, 2017), which is more than 14 times larger than the Alaska highway system, the only DOT in the literature that adopts the Measured Retroreflectivity method. Because of the larger highway network, NC also has a significantly larger number of traffic signs to maintain than Alaska does. Palmquist and Rasdorf (2001) estimated that NCDOT had a sign inventory of 969,905 signs. This number of signs would require many more man-hours to measure the retroreflectivity of all signs in NC. Other disadvantages are that inspectors are exposed to roadway hazards while taking the retroreflectivity measures, increasing the risk of workers compensation claims. In some cases, sign crews cannot measure retroreflectivity of signs that are located in areas of difficult access. Thus, the research team opted to omit it giving the evidence that this method is not the most suitable to NCDOT when compared to other maintenance methods.

6.1.3 Expected Sign Life

The Expected Sign Life method consists of replacing signs that achieved their expected service life. To keep track of sign age and know when to replace it, an agency must have a detailed inventory database to identify and locate the sign. The Expected Sign Life method is one of the most used by DOTs (18 out 40 states; see

Table 2.5) mostly because, as shown by the literature, it reduces material waste, provides an accurate record, and retains data for planning, scheduling, and budgeting. However, as mentioned earlier, it also requires a detailed inventory database.

Creating a statewide sign inventory database requires a significant amount of work and capital investment. Vereen et al. (2002) estimated the cost for creating a sign inventory in NC through manual data collection, which consisted of a two-member crew riding the roads and recording inventory data for each sign. The authors estimated that NCDOT would have to invest between $1.6 million and $4.1 million to create a sign inventory. This cost includes planning time, field data collection, coding, data entry into the database, overhead, benefits, travel, equipment, and material costs. The research team noted that the estimated cost of $1.6 to 4.1 million was to plan and implement a sign inventory database. This cost did not consider inventory annual maintenance costs.

Not only does a sign inventory require high administrative and management cost to maintain, but it is also of major importance to ensure that the database is accurate; otherwise, it loses its credibility. For instance, SCDOT has a well-structured and maintained sign inventory database that uses barcodes (for sign identification in the field and in the inventory database for data entry in the system with the objective of reducing errors). In spite of the efforts of SCDOT, a recent study (unpublished information; Huynh et al., SCDOT SPR 727 Sign Life Expectancy, Interim Meeting, August 22, 2017) showed that accurate data entry still may be a problem. By comparing field data collected by the research team and the data entered into the database by crew members, the researchers found the following information.

- 1.6% of the signs surveyed had mismatching installation years in the database.
- 2.7% of the signs surveyed did not have an installation date recorded in the database.
- Sign orientation in the database was not accurate because crew members entered the direction of the route instead of the geographic direction of the sign.

As a result, the Expected Sign Life method requires training and a continuous minding of crew members on how to enter data into the database and on the importance of entering accurate data. Adopting the Expected Sign Life method would be more convenient in the case of DOTs that have statewide and standardized maintenance and replacement programs because all sign data could be stocked in a central inventory database, as is the case for SCDOT. All sign crews in the state would be able to collect the same data type and conduct the same process to enter such data into the database.

However, although the Expected Sign Life method seems to be an interesting option to be considered in this study, it is necessary to recall that NCDOT does not have a statewide sign inventory system. Some NCDOT divisions have in house inventory database, but they are far of being a robust and integrated system as the one owned by SCDOT, for example. As cited before, an accurate sign inventory is essential for the success of the Expected Sign Life method. In addition, sign workers need to get familiar with equipment used to collect data (if automated) and would need to be trained in the procedures of sign data collection to keep uploading and updating the sign inventory database. This factor should not be underestimated considering that some transportation agencies often hire sign laborer in the condition of temporary employees. Therefore, every time a new employee starts in the sign crew, he/she would require training about the sign inventory database and sign data collection.

After analyzing the Expected Sign Life method, the research team concluded that once the NCDOT does not own a statewide sign inventory, this sign maintenance method is no longer feasible. As a result, the research team considered the absence of a statewide sign inventory system in NC as a resource constraint. Therefore, the research team opted to not further consider it giving the evidence that this method is not the most suitable to NCDOT.

6.1.4 Control Sign

For the control sign method, a group of signs (e.g., stop signs) is represented by a sample of signs that are installed on the same date. That allows inspectors to measure retroreflectivity of the sample signs rather than of all signs in that group. From the literature summarized in

Table 2.5, only one state (Vermont) adopts the control sign method, which was used as a secondary method while the primary method was the Expected Sign Life (Dumont et al., 2013).

Although this method is not as time consuming as the Measured Retroreflectivity method, it still consumes a significant number of labor hours depending on the sample size. One of the major issues with this method is to determine an adequate sample size, which has not been well defined in the literature so far. Like the Measured Retroreflectivity method, this system requires a retroreflectometer. In addition, it is necessary to collect data (often on an annual basis) and maintain a sign inventory database to keep track of the sample signs and their retroreflectivity throughout time. In case the transportation agency opts for installing the sample signs in field, they are subject to vandalism and loss in case of crashes, which would affect the effectiveness of the maintenance method.

On the other hand, if the agency decides to build a sign control facility, more investment is necessary. Harris et al. (2009) studied the cost of building and maintaining a control sign facility. According to the authors, it would be necessary an initial investment of $104,000 to build the infrastructure and purchase the equipment necessary while the annual maintenance cost would be $25,000. Although the cost of building and maintaining such facility is not unreasonable, the control sign method also requires trained people to collect and analyze data, which can be time-consuming and expensive (Re and Carlson, 2012, Dumont et al., 2013). In addition, similar to the Expected Sign Life method, there is always the challenge of maintaining the inventory database updated with accurate data.

Considering those disadvantages and the fact that NCDOT does not have a control sign facility, a sign inventory database, nor personnel to analyze this type of data, the research team decided to not consider the control group method as an optimal sign replacement strategy for the NCDOT.

6.1.5 Blanket Replacement

The Blanket replacement method consists of replacing all signs (or a group of signs) in an area or along a corridor (or a combination of both) in cycles that are determined by the sign service life. This method was used by 15 out of 40 states shown in

Table 2.5, indicating that it is a feasible method. The Blanket Replacement method is easy to implement, does not require expensive equipment (e.g., retroreflectometers) and software, and the most important, it does not requires a sign inventory. As discussed earlier, a sign inventory requires a high initial investment and its maintenance is often costly, time consuming, and subject to mistakes in data entry. A technician with some expertise would also be required to analyze the data obtained from the inventory database and translate it into information that is valuable for upper management.

From all sign maintenance methods analyzed from the MUTCD, the Blanket Replacement showed to be the method that best attends the needs of the NCDOT while considering some resources constraints. It is unanimity in the literature that this method is straightforward and of simple implementation besides having low administrative cost. Another major advantage of the Blanket Replacement method when analyzing the NCDOT resources is that it does not require a sign database inventory. As already discussed, a sign inventory database would require from the NCDOT a high initial investment and annual maintenance costs. Thus, a method that does not require a sign inventory already has a great advantage over others that require in the case of the NCDOT.

The Blanket Replacement method also allows a transportation agency to plan and schedule future work and budget. It removes the subjectively from the Nighttime Visual Inspection method, which increases the liability protection of the NCDOT against lawsuits.

While this study was in progress, the NCDOT published the Maintenance Operations Performance Analysis Report (MOPAR) that described a new maintenance plan known as the Routine Maintenance Improvement Plan (RMIP) that considers the adoption of the Blanket Replacement method. During a meeting of the research team with a NCDOT division that had already performed blanket replacement, a set of benefits from replacing signs by geographic area (e.g., counties or sections) were mentioned, which included increased depth of knowledge about a specific area, reduction of worker idle time, increase in labor productivity, reduction in distance traveled to accomplish work, and improved employee morale.

Considering that the Blanket Replacement is an easy and straightforward method to implement and the fact that it does not require the implementation and maintenance of a detailed sign inventory database, the research team decided to focus on this maintenance method to develop sign replacement strategies.

However, the RMIP considers a blanket replacement cycle based on a sign service life of 10 years. There is no further information on how NCDOT divisions should implement it nor whether a sign service life of 10 years, considered too low, was specified. Although the Blanket Replacement method offers a set of benefit as already discussed, if not done properly, it might result in a costly and inefficient strategy. Therefore, more study is needed in the field to identify systematic and cost efficient sign replacement strategies based on blanket replacement that can be considered by the NCDOT.

6.2 Method Selected: Blanket Replacement

Based on the literature reviewed and meetings with traffic engineers, the research team selected the Blanket Replacement method as the focus of this study. From the meetings with the various agency engineers, some practices stood out as follows.

6.2.1 Area-Based Approach

It was mentioned that area-based replacements (often referred to as sections by some agencies) create a routine that helps laborers better understand the processes involved in sign maintenance and replacement. It also gives personnel a sense of "ownership" which results in a set of benefits such as the following.

- Increased depth of knowledge about a specific geographic area.
- Reduction of idle time.
- Increase in labor productivity.
- Reduction in distance traveled to accomplish work.
- Decrease of sign unit cost per square foot (this unit cost includes labor, material, and equipment).
- Improved employee morale.

A clear definition of areas promotes efficiency (reduce idle time and increase productivity) because it prevents sign crews from randomly driving division roads without having a set of established goals. In addition, upper management can make it clear to personnel what the expected productivity level for each crew is. Then, crew member's evaluations can more fairly be based on their productivity. Thus, eventually, an area-based approach to sign work is highly beneficial and is a key component of RMIP success.

Figure 6.1 illustrates the area-based blanket replacement approach. Assume a transportation agency is conducting a 10-year blanket replacement. This agency divides the state, division, or county into ten areas with the same (or a similar) number of signs. As shown in the figure, there are 10 areas, each one with 1,000 signs, for example. Each area (section) does not necessarily have the same physical area; rather, they have about the same number of signs. Each year, signs in an area are replaced. For example, in Year 1, signs in Area 1 are replaced; in Year 2, signs in Area 2 are replaced, and so on. Another benefit of an area-based approach is that it allows an agency to distribute and balance the sign work over the years because each year a new area is replaced.

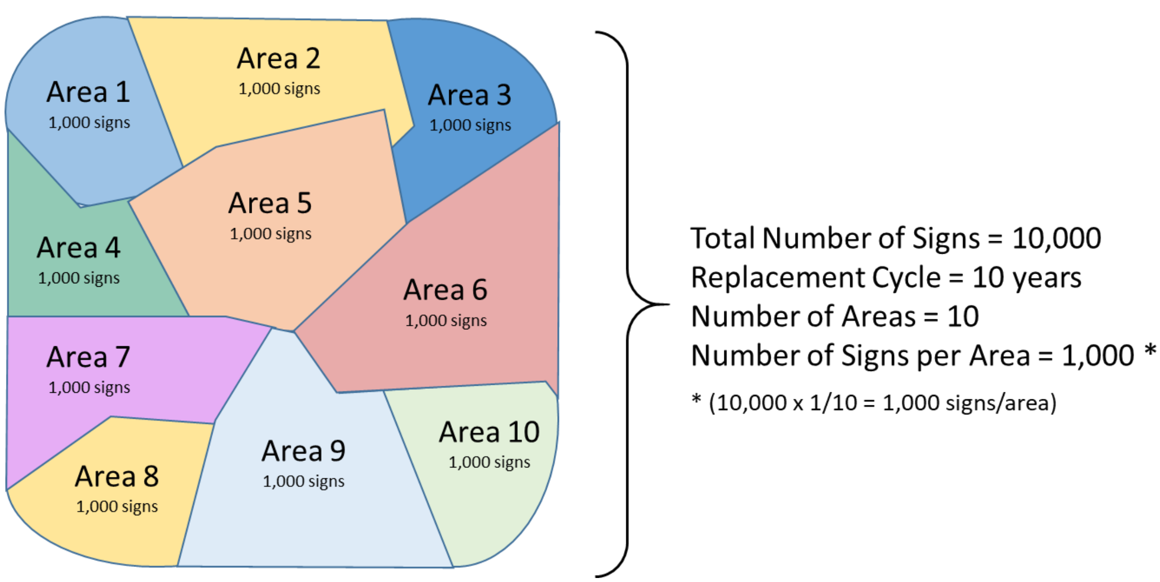


Figure 6.1 Signs per Area in a Sign Replacement Strategy

6.2.2 Week Schedule

In order to improve labor productivity and avoid situations in which sign crews drive roads with no specific goals (which would decrease productivity), a week long replacement and maintenance schedule is organized as follows.

- Four days per week: sign replacement crews work on sections and according to the blanket replacement scope of work for four days per week. By doing so, sign crews do not have to drive often across the division to conduct spot replacement unless it is a priority case (e.g., stop sign). Therefore, the blanket replacement work is interrupted with less frequency and less labor time is spent driving from one section to another. As a result, the labor productivity increases.
- One day per week: sign maintenance crews conduct spot replacement where it is needed (it can be in different sections) one day per week. Spot replacements cover damaged or missing signs that were reported either by the division's staff or by its citizens. Red signs (e.g., stop and yield signs) are exceptions and they are immediately replaced due to their importance.

6.2.3 Material Waste Mitigation

Reusing signs and a grace period are two ways to avoid discarding signs that still have remaining life. Both practices have the intent of reducing material waste when using the Blanket Replacement method. Based on the literature and NCDOT divisions' experiences, both practices seem to be successful in reducing material waste when adopting this method.

6.2.3.1 Reused Signs

Reusing signs is one way to avoid discarding signs that still have remaining life. This practice has the intent of reducing material waste when using the Blanket Replacement method and consists of reusing signs that were replaced during the blanket replaced, but that are relatively young and in good conditions.

Consider a blanket replacement cycle of 10 years and with continuous spot replacement. In a year of blanket replacement, we replace all signs. However, we do not dispose all replaced signs. If a replaced sign is younger than 5 years old and is in good condition, it can be stored to be used later. All the other signs (older than five and/or damaged) are disposed. The used signs in storage should later be installed in field locations (sections) where the overall sign age is not older than 5 years old. As a result of this practice, the maximum sign age in any field location is 10 years. Figure 6.2 shows the general concept of reusing signs when conducting blanket replacement.

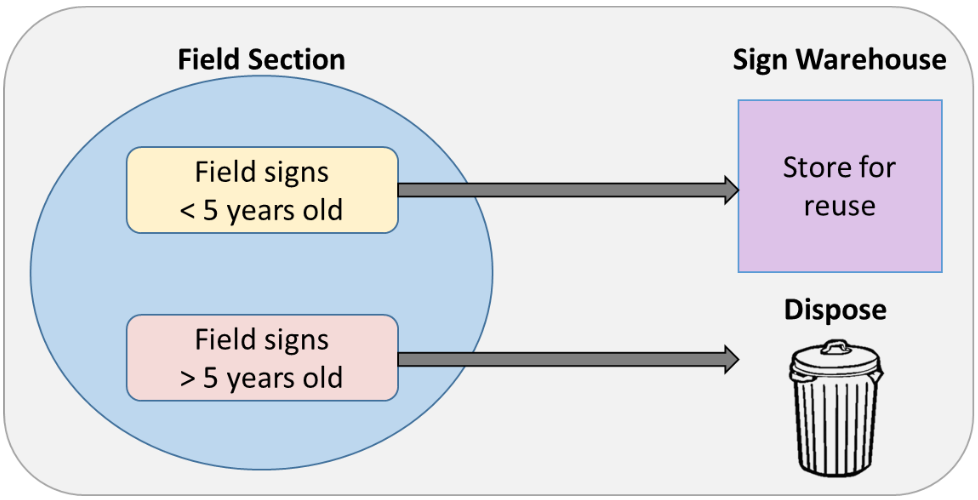


Figure 6.2 Reuse Signs When Conducting Blanket Replacement

Both the literature and meetings with NCDOT divisions show that there are some agencies that adopt a reused sign practice. For instance, Re and Carlson (2012) described a case in which a local transportation agency collected signs in good condition in previous blanket replacement cycles and reused them for spot replacement of damaged or knocked down signs. Similarly, one of the NCDOT divisions also indicated that they reuse signs that are younger than 5 years (relatively new) and are in a good condition. Those signs are stored and later used to replace damaged signs. By doing so, agencies save money by reducing material waste.

6.2.3.2 Grace Period

Grace period is another way to avoid discarding signs that still have remaining life when adopting the Blanket Replacement method. Grace period is a practice that consists of sign crews not replacing signs that are within a tolerance age (grace period) and in good condition while conducting blanket replacement.

Consider a blanket replacement cycle of 10 year and with continuous spot replacement. In a year of blanket replacement, replace only signs that are either damaged or older than 5 years. If a sign is younger than 5 years old and in good condition, do not replace it. These five year old signs will stay in place until the next replacement cycle (if not replaced due damage before that), achieving the maximum sign age of 15 years (when they will be finally replaced). Figure 6.3 shows the general concept of grace period when conducting blanket replacement.

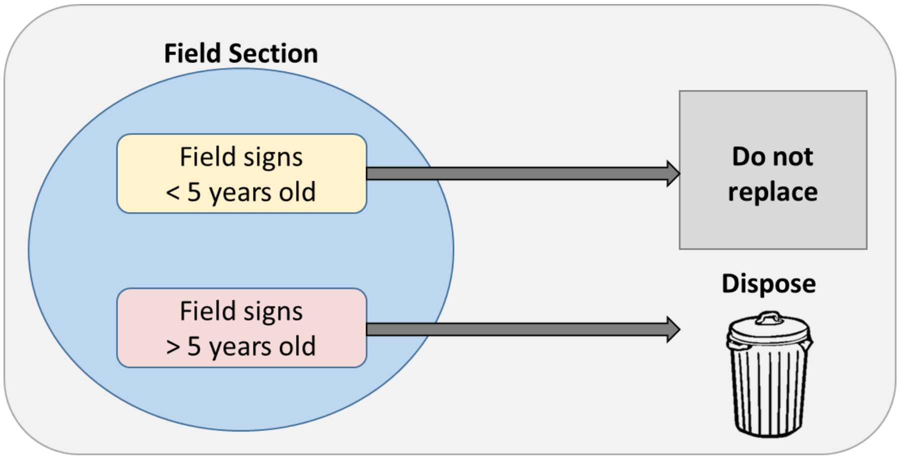


Figure 6.3 Grace Period When Conducting Blanket Replacement

This practice is present in the literature and is also used by one of the NCDOT divisions. In Re and Carlson's (2012) study, the authors described two DOTs that used grace period with the objective of reducing material waste while using the Blanket Replacement method as their primary sign replacement method. In both cases, the agencies conduct blanket replacement, but instead of replacing all signs, they replaced only those that are older than the grace period.

One of these DOTs combined a blanket replacement cycle of 15 years with a grace period of 3 years, meaning that the maximum age of a sign in the field would be 18 years, which is acceptable by that DOT. Another DOT combined a blanket replacement cycle of 10 years with a grace period of 6 years, which resulted a maximum sign age of 16 years. In the case of NCDOT, the research team also recorded a similar approach used by one of the divisions. In this case, the division is adopting a 10 year sign replacement cycle but they use a grace period of 5 years, meaning that the maximum sign age will be 15 years at the next replacement cycle.

6.2.3.3 Practice Selected: Grace Period Practice

The research team believes that grace period offers more advantages and fewer disadvantages than reuse of signs. When considering the reuse of signs, a clear advantage is that sign material is saved if the crew members can reuse some signs to later replace damaged signs. However, this practice also has some disadvantages. For example, the agency needs to store those used signs (that will be later reused during spot replacement). Doing so requires both storage space, extra material handling and transportation, as well as record keeping. Additionally, used signs should be stored in a different area (e.g., shelf) than new signs to avoid confusion. This too requires extra effort and record keeping.

Considering that an agency conducts blanket replacement every year in a different area (or corridor), the agency will possess used signs of different ages. Thus, it would be appropriate to have someone responsible to keep track the signs' ages and type. If a used sign spends a long time in storage and it ages to its service life, the agency may prefer to discard the sign instead of using it. Based on these observations, the research team believes that sign reuse may reduce material waste, but it also increases labor hours for tracking, handling, and storage.

A grace period practice reduces not only the material waste but the labor hours as well. First, if a sign in good condition and within the grace period, crew members do not need to spend time removing it and installing a new one in its place. Instead, they will just check the sign installation date and visually inspect the sign. If the sign meets the requirements of age and condition, it is left in the field. In addition, the grace period practice does not require a storage area for used signs nor personnel to keep track of reused signs' age and type.

Based on the significant advantages of the grace period practice over the reused sign practice, the research team concludes that the grace period results in greater overall benefits than reused signs. Thus, only the grace period practice is further analyzed in this study.

6.2.3.4 Exception to Grace Period

Although grace period reduces sign material waste while using the Blanket Replacement method, it is necessary to discuss whether or not it should be applied to all signs. For instance, red signs are of major importance to the traffic system and applying these practices to them could increase the risk of noncompliance.

Red signs include wrong way, do not enter, yield, and stop signs. Red signs have a high risk of liability in the case of crashes (Palmquist and Rasdorf, 2001), thus, they require special attention. Most of the previous studies that developed retroreflectivity deterioration models found that red signs perform above the minimum retroreflectivity levels at the age of 20 years or more (see Table 5.2 and Figure 5.7). Kipp and Fitch (2009) was the only study whose deterioration model estimated a sign service life of 15 years for red signs.

Although most deterioration models indicated that red signs can perform above the minimum retroreflectivity levels for over 15 years, the literature also shows that retroreflectivity is not the only concern related to red signs. Many studies pointed out that color fading is a common issue in red signs (Black et al., 1991, Bischoff and Bullock, 2002; Carlson et al., 2011; and Dumont et al., 2013). Considering the importance of red signs and the risk of color fade as the signs age, the research team decided to exclude them from grace period practice. In other words, when it is a year of blanket replacement, all red signs are replaced, with no exception. That reduces the risks associated to red signs, leaving only environmental and vandalism risk associated.

6.3 Conclusions

The research team analyzed all five sign maintenance methods recommended by the MUTCD while considering literature reviewed and information obtained from traffic engineers. After balancing advantages and disadvantages of each method, the research team concluded that the Blanket Replacement is one of the most promising replacement methods for mid to large state DOTs that do not have a detailed sign inventory database. The replacement strategy proposed herein will consider the Blanket Replacement method with an area-based approach for all the advantages already mentioned in this chapter. In addition, the research team also decided to further study the impact of grace period practice (applied to all signs but red) to mitigate the problem related to sign material waste when adopting the Blanket Replacement method.

7.0 SIMULATION MODEL DEVELOPMENT

Although there has been significant progress in the field of sign management research in the last few years, there is still room for improvement. Most previous studies compared different sign maintenance and replacement methods without considering agencies' resources or organizational structure. The model described herein was developed based on the NCDOT structure and the fact that it does not have a sign inventory database. The objective was to provide the NCDOT with sign replacement strategies that are systematic, cost efficient, and independent of sign inventory. After analyzing the five sign maintenance methods recommended by the MUTCD, the research team decided that the one most appropriate for the target agencies of this study is the Blanket Replacement method.

Although previous research (Harris, 2010; Harris, 2012; Hummer, 2013) analyzed the Blanket Replacement method, the concept of conducing blanket replacement by areas in order to balance workload and expenditure through the years was new and it was not previously addressed by previous research. It is in the present work. This study also analyzed and quantified the benefits of a grace period, which can be used to reduce the risk of wasting good sign material when implementing the Blanket Replacement method.

7.1 Methodology

The sign replacement management process is represented by a complex system. This system includes, in some cases, over one million signs of different types that deteriorate and suffer damage through the course of many years. Some of these signs are inspected, some are replaced, and others remain in the field. In addition, cost and overall sign condition (number of unsatisfactory signs) need to be taken into consideration as a method of measuring performance.

With the objective of developing systematic and cost-efficient sign replacement strategies, the research team desired to gain more insights about the system and how different replacement policies affect costs and overall sign condition. This section (*Methodology*) discusses which type of model is the most suitable to gain understanding about the sign replacement system and provides a brief description of the software selected to be used in this research.

7.1.1 Types of Models

There are three types of models: physical, analytical, and simulation (Kelton et al., 2014). This section provides a brief description of these three models and whether or not they are suitable for this research.

7.1.1.1 Physical

When possible, physical models are used to give a feeling of reality, dimension, and interaction of the model with environmental. For example, during the design of a large hydropower plant, it is common to build a 3D physical model to represent the entire system, including reservoir, dam, powerhouse, spillway, etc. By using this physical model, hydraulic engineers can measure water flow direction and speed in strategic areas, enabling them to design the proper hydraulic structure and dam protection for that system. Although physical model are very useful, they are often expensive and (as other models) is not recommended to all systems. For instance, a physical model is not appropriate to represent a sign replacement system because how you model hundreds of thousands of signs of different types, and then randomly assigns annual damage to them while still account for deterioration. That would require a large amount of work to track all data collected of all signs in the system, which makes a physical model infeasible for a sign replacement system.

7.1.1.2 Analytical

The second type of model described by Kelton et al. (2014) was analytical models, which are mathematical representations. Altiok and Melamed (2007) defined analytical models as equations that establish relation among different variables. Advantages of analytical models include low cost when compared to other models (physical and simulation) and they can

Retroreflectivity deterioration models developed by previous researchers are examples of analytical models. These models established a relationship between sign retroreflectivity deterioration and a set of factors (e.g., sign age, sign orientation, and sign color). However, as a system becomes more complex, funding an analytical solution can be very complicated. Considering the sign replacement system, it would be very complex to find an analytical solution for it.

7.1.1.3 Simulation

The third type of model described by Kelton et al. (2014) was simulation models that are capable of representing a large range of systems, including more complex systems that would not be possible to be represented by analytical models. Harris (2010) described simulation theory as being straightforward and of easier application than analytical methods. One of the major advantages of simulation is the capability of performing experiments by changing some input parameters and analyzing how those changes affect the overall system performance. Simulation often uses specific computer software to represent a real or proposed system, its components, and processes through time. In addition, with advances in technology and software, simulation is becoming a more accessible tool. A benefit of simulation over analytical models cited by AbouRizk (2010) is its flexibility in modeling logic, meaning that modern simulation software allows users to build complex decision structures in a more intuitive way.

In the case of the sign replacement system, a simulation model can represent individual signs in the system through the years as well as the processes involved such as inspections and replacement. In addition, Halpin (1977) showed that simulation is an ideal tool for systems that contains repetitive tasks (AbouRizk, 2010), which is the case of replacement and inspections activities that are often conducted in cycles.

Kelton et al. (2014) also mentioned that by building a simulation model, often analysts think that it is helpful to gain insights about the system and even improvement ideas, in some cases even without analyzing the output measures. That is explained by the fact that it is necessary to define a system, its parts and procedures before modeling it, which helps analysts to better understand the system being studied.

Another benefit of the simulation is that by creating an experiment, it is possible to analyze and compare different sign replacement strategies (scenarios) by changing some key factors (e.g., replacement cycle). The analysis of these different scenarios provide the upper management with information to assist in their decision making process.

7.1.1.4 Summary
Considering all benefits of computer simulation, the research team decided to use it to develop the sign replacement model. When Harris (2010) conducted a sign maintenance study, the author also concluded that simulation was the appropriate tool to represent a statewide traffic sign system.

7.1.2 Simulation Classification
After selecting simulation to study different sign replacement strategies, it was necessary to select the kind of simulation that was the most suitable to do so. In general, simulations can be classified in three dimensions: Static versus Dynamic; Continuous versus Discrete; and Deterministic versus Stochastic (Kelton et al, 2014).

7.1.2.1 Static versus Dynamic
This classification refers to the passage (or not) of time in the system. In static models, time is not is not a factor at all. Winston (2004) describes it as if a system was being simulated at exactly point in time. Static simulation is also referred as Monte Carlo. An example of static model is simulating the probability of winning a solitaire card game. A person can play it 50 times and count how many times he/she won (each game is a simulation). Then, calculate the probability of winning based on the outcome of the 50 games. Note that in this example, each game is independent of the other and time is not a factor.

On the other hand, dynamic models simulate systems over time (e.g., seconds, hours, days, etc.). For example, the airport traffic for the duration of one day or the customer line in a bank during business hours. Most systems are dynamic and evolves over time, as it is the case of the sign replacement system. Time plays a major role in sign replacement strategies because it determines how signs age, deteriorate, and damage. In addition, time also if strongly related to the frequency that signs are inspected and replaced. Therefore, the simulation model developed in this study is dynamic.

7.1.2.2 Continuous versus Discrete
This classification applies only to dynamic models and refers to how a state variable changes over time in the system. First, a state variable is any variable that can be used to describe the status of the system (Winston, 2004). In a continuous model, state variables can change continuously over time, as it is the case of pressure and temperature. It can be said that as the temperature in a pressure pot increases, the pressure continuously increases.

On the other hand, in a discrete model, state variables change at discrete points in time. For example, consider a line in an ice cream store. Every time a costume joins the line, the state variable “queue length” increases by one unit (costumer) in a specific time. It is not possible to continuously increment the costumer queue length over time (e.g., 2.2 customers; 2.3 customers, 2.4 customers, etc.). Hence, a line in an ice cream store is a dynamic and discrete model. The same is valid for the sign replacement model in which the state variables (e.g., number of damaged signs, replaced signs, inspected signs, etc.) change at discrete points in times.

7.1.2.3 Deterministic versus Stochastic
Deterministic models are those that do not have any random variables. There is no uncertainty or randomness in the system. An example cited by Kelton et al. (2014) was a manufacturing line that has fixed interarrival time between parts and service time with no breakdown. In this

manufacturing line example, the time to produce 100 parts will be always the same because there is no randomness in the system. A user can run 10 replications of this system and the output will be always the same.

Differently, a stochastic model contains at least a random variable or considers some failure in the system, some kind of randomness. For instance, if that same manufacturing line from the previous example has a fixed interarrival time between parts, but now instead of a fixed service time, it has a service time randomly varying from 2 to 4 seconds. Now, if a user runs again 10 replications, each one of them will result in a different time to produce 100 parts. By introducing this randomness in the manufacturing line model, it became a stochastic model.

The sign replacement system is a stochastic model for the randomness that is associate with it. For example, it is known that every year a number of signs is damaged, but exactly which signs are damaged is unknown. Still thinking about damaged signs, a sign that was damaged in a previous year may be damaged again in following years (or not).

Another random aspect of the sign replacement model is what is called by spot replacement and will be further explained in details throughout this report. But in summary, spot replacement refers to any replacement that is initiated when a person (e.g., citizen and police patrol) reports a damaged sign to a transportation agency. As a result, the agency spot replaces that specific sign, which was not in their original schedule. As the reader may suspect, people other than transportation agency workers do not walk around looking for damaged signs. Instead, they might see a damaged sign on the way to work and call to the agency to report it. This portion of damaged signs that is randomly reported, and as a resulted, replaced. Thus, the sign replacement model also needs to account for this level of randomness of signs that are reported and spot replaced.

7.1.2.4 Summary

After analyzing the different simulation classifications to represent the sign replacement system, the research team decided to model the sign replacement system with a stochastic, dynamic, and discrete-event simulation model.

7.1.3 Software

The sign replacement model was developed using Simio Simulation Software (Simio LLC), which is a software that according to Joines and Roberts (2015) has increased its market share in both industry and academic institutions.

Simio Simulation Software was chosen based on of benefits that it offers. Simio is a modern and user-friendly simulation package that does not require programming. After learning how to operate the system, the user can develop any model using Simio. Its interface is very intuitive and objects can be represented by static or animated pictures from its own library. In the case of the sign replacement model, picture of signs by color were imported into the simulation library. Another benefit of Simio was mentioned by Kelton et al. (2014) and Joines and Roberts (2015) who said that Simio is a multi-paradigm modeling, meaning that it incorporates all the following models: discrete events, processes, objects, and agent-based modeling (ABM). In addition, Simio is capable of interacting with a range of databases and spreadsheets, which can be very useful when saving some results of replications (Joines and Roberts, 2015).

7.2 Simulation Model Overview

Based on the literature reviewed and meetings with traffic engineers, the research team created a sign replacement model to simulate sign damage, blanket replacement, grace period, daytime inspections, spot replacement, and retroreflectivity deterioration. The model enables transportation agencies to represent their sign population and condition through input parameters. By varying some input parameters and conducting experimentations, these agencies can assess the performance of different sign replacement strategies. The main output measures collected from the simulation include number of unsatisfactory signs (sum of damaged and noncompliant signs) and strategy cost (sum of inspection and replacement costs). The next subsections describe the model as well as its capabilities and features.

7.3 Input Parameters

Input parameters are the values that are entered into a model to represent a specific system. These enable the model to be used by different transportation agencies that desire to adopt the Blanket Replacement method. However, one agency may adopt a replacement cycle of 10 years; another agency may choose 15 years. All such decisions can be controlled by the input parameters of the model.

7.3.1 Sign Population by Color and Road Class Percent

One of the input parameters required in the simulation model is sign population (by color and road class) and its unit of measure is percentage of total signs. The present study did not consider signs on Interstate highways because they represent a small portion of the state maintained signs and they are often inspected on an annual basis. In addition, many signs on Interstates are overhead guide signs that are not covered in this study because they are replaced in a different cycle and their cost has a great variability as well as their size.

Blue, brown, and orange signs are not a part of the present study because they do not follow the same general rules that apply to the other colors (white, yellow, green, and red). Blue and brown signs, as specified in Section 2A.08 of the MUTC (FHWA, 2009), can be excluded from a retroreflectivity maintenance program. Because they are not as important as regulatory, warning, and guide signs, blue and brown signs are replaced at greater life cycle durations. In addition, in the specific case of logo signs (a type of blue signs), the money used to maintain them comes often from a logo sign program instead of the regular signing budget. Thus, logo signs are maintained separately from other signs.

In the case of orange signs, Orange signs are very important to ensure driver and labor safety in work zones, but they are temporary and are often installed in different work zones over the years. This process of assembling, disassembling, and transporting orange signs between work zones increases their damage rate when compared to other ground mounted signs. As a result, orange signs need to be replaced more frequently.

Hence, ground mounted white, yellow, green, and red signs on primary and secondary roads were considered in this study and for simulation. The input parameters related to sign population are measured as a percentage of the total number of signs and their sum should add to 100%.

7.3.2 Annual Sign Damage Rate

Another simulation input parameter is the annual sign damage rate and its unit is percentage of the total number of signs. Every year a number of signs are damaged for different reasons, including environmental (e.g., scratches, mildew, cracked), vandalism (e.g., holes, stains, graffiti, scratches), and accidental (e.g., bending, broken, knockdown). The annual damage rate is the percentage of signs that are damaged every year and need to be replaced as a result. It may be the case that a sign that was already damaged in previous years may be damaged again in the current year. On the other hand, it may be the case that a sign is damaged for the first time in the current year. Either way, both of them are counted in the annual sign damage rate.

7.3.3 Spot Replacement Rate

Spot replacement rate is used as an input parameter in the simulation and its unit is percentage of damaged signs. Spot replacement refers to any sign replacement that is initiated outside of an inspection (daytime or nighttime) or a blanket replacement. For example, a citizen observes that a stop sign was knocked down at an intersection and he/she reports the incident. When the DOT replaces that sign, this study classifies it as a spot replacement because it was not initiated by a standard sign inspection.

Another classic example of spot replacement is when a transportation agency personnel (e.g., pavement crews) are driving the roads for other work activity purposes and notice a damaged or missing sign. These agency personnel also report the damaged or missing sign to the sign crew (who is responsible for replacing it). In this case, although the sign was spotted by agency personnel, it was not identified during a standard sign inspection and, therefore, it is referred to as spot replacement. The unique aspect of spot replacement is that it occurs continuously every year because it is not linked to inspections nor to scheduled replacements.

The present research team decided to utilize the annual spot replacement as a function of the number of damaged signs (e.g., 40% of all damaged signs) rather than a fixed spot replacement rate as a function of the total number of signs (e.g., 2% of all signs). That is justified by the fact that if there are few damaged signs in service, there are not many damaged signs in the field for people to spot and report to a transportation agency. On the other hand, if there is a larger number of damaged signs in service, it makes sense that citizens, highway patrol, and agency personnel start spotting those damaged signs with more frequency and report them to agency sign crew.

7.3.4 Blanket Replacement Cycle

The blanket replacement cycle is used in the simulation as an input parameter and its unit is years. Defining the sign replacement cycle is a decision of the agency upper management and it is directly related to the sign service life. Many studies have concluded that adopting a sign service life that is the same as the warranty period provided by the manufacturer for the signs is very conservative (Re and Carlson, 2012).

In addition, most previous studies that investigated sign retroreflectivity deterioration and sign service life indicated that Type III signs outlive their warranty and perform above minimum retroreflectivity levels for at least 15 to 20 years (Clevenger et al., 2012; Bischoff and Bullock, 2002; Dumont et al., 2013; Immaneni et al., 2009; Kipp and Fitch, 2009; Pike and Carlson, 2014; Rasdorf et al., 2006; Re et al., 2011). Type IX and XI sheeting are known to have an even greater sign service life than Type III sheeting does.

7.3.4.1 Grace Period

Grace period is a practice that consists of sign crews not replacing signs that are within a tolerance age (grace period) and in good condition while conducting blanket replacement. It was conceived to reduce sign material waste, which is one of the major disadvantages of the Blanket Replacement method.

Although this practice was identified by Re and Carlson (2012) and has been adopted by at least one DOT, the present study is the first one to consider the use of a grace period and to analyze and quantify its impacts on sign replacement costs. After assessing the literature and DOT experiences, the research team established realistic rules for incorporating a grace period into the simulation model.

The major rule is that grace period does not apply to red signs because of their safety criticality and the fact that many studies pointed out that color fading is a common issue in red signs (Black et al., 1991, Bischoff and Bullock, 2002; Carlson et al., 2011; and Dumont et al., 2013). Considering the importance of red signs and the risk of color fade as the signs age, they were excluded from grace period practice. The second rule is that grace period applies only to undamaged non-red signs. The third is that it applies to signs that are the same age as or younger than the grace period. In other words, signs that are red, damaged, and/or older than the grace period are replaced during a blanket replacement year.

7.3.5 Daytime Inspections

Daytime inspection is used in the simulation as an input parameter and its unit is years. When conducted, daytime inspections have the objective of identifying any type of physical damage or missing signs. While driving the roads during daytime inspections crews are looking for the following.

- Knockdown signs due to collisions
- Improper sign orientation (if they are oriented perpendicular to the road)
- Deteriorated signs due to age
- Cracked, dirty, or peeling signs
- Missing (stolen signs (theft))
- Damaged signs (vandalism such as bullets, graffiti, stones, and bends)
- Damaged signs (mowing)
- Vegetation hiding signs

Sign replacement strategies can either consider daytime inspections or not. If daytime inspections are considered in the scenario, it is noteworthy that they are not conducted in a year of blanket replacement because of the simple fact that is unreasonable to inspect signs that are already scheduled to be replaced in that same year due to blanket replacement.

Figure 7.1 illustrates a generic timeline of one area (see Section 6.2.1) and indicates in which years blanket replacement and daytime inspections occur for different combinations of blanket replacement and daytime inspection cycles. The timeline shown in the top of the figure illustrates a scenario that consists of a blanket replacement cycle of 10 years and a daytime inspection cycle of 5 years. Note that there is no inspection in years 2001 and 2011 when blanket replacement occurs. The timeline shown at the bottom of the figure illustrates a scenario that consists of a blanket replacement cycle of 15 years and a daytime inspection cycle of 5 years. Note that in this case there are two inspections (years 2006 and 2011) within the blanket replacement cycle. And again, there is no inspection in years of blanket replacement (2001 and 2016).

In addition to the daytime inspection cycle, the simulation also allows the user to select which damaged signs are replaced during the inspections. There are some DOTs that assign priority replacement to signs according to their safety criticality. For example, if there were a budget constraint, red signs would be replaced first due to their importance. The research team defined sign replacement priority based on NCDOT system, which is Priority 1 (red signs), Priority 2 (yellow signs), Priority 3 (other signs). Based on this, the research team built in this function in the simulation, allowing the user to choose one of the following options with respect to which signs are replace during daytime inspections.

- Priority 1 (red signs)
- Priority 2 (yellow signs)
- Priorities 1 and 2 (red and yellow signs)
- Priorities 1, 2, and 3 (all signs: red, yellow, white, and green)

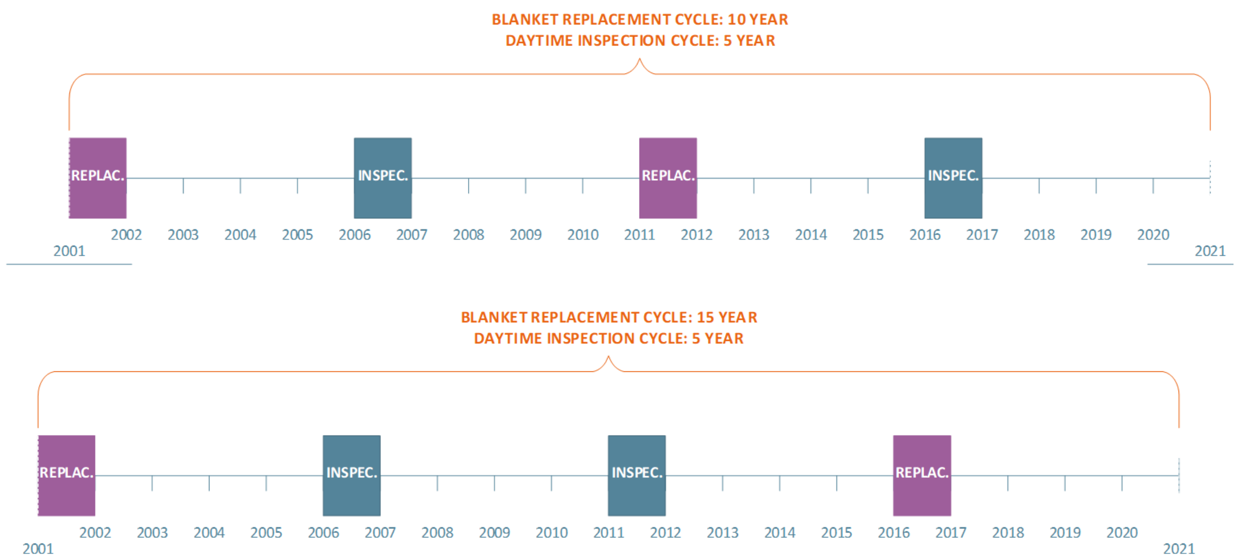


Figure 7.1 Interaction of Daytime Inspection and Blanket Replacement Cycles

7.3.6 Sign Retroreflectivity Deterioration Models

Sign retroreflectivity deterioration models were included into the simulation to ensure that a user does not enter an unreasonable blanket replacement cycle as an input parameter without the results showing the consequences of that choice. For example, if signs do not deteriorate through the years, a replacement cycle of 40 years (unreasonable) would lead to an extremely low strategy cost yielding a situation in which all signs are still compliant (above minimum retroreflectivity levels). This strategy is not realistic and would lead the user to wrong conclusions.

By including retroreflectivity deterioration models, a replacement cycle of 40 years (unreasonable) would still lead to an extremely low strategy cost. However, this time the percentage of non-compliant signs (below minimum retroreflectivity levels) would be almost (if not) 100%, which would make that strategy quite unfeasible.

Therefore, users enter one retroreflectivity deterioration model for each sign color (white, yellow, green, and red) in function of sign age (years). If a transportation agency has a study that developed deterioration models of signs located in its geographical area, those models are preferable. If a local sign deterioration study is not available, agencies can obtain models from the literature (Black et al.; 1991; Clevenger et al., 2012; Bischoff and Bullock, 2002; Dumont et al., 2013; Immaneni et al., 2009; Kipp and Fitch, 2009; Pike and Carlson, 2014; Rasdorf et al., 2006; Re et al., 2011) (See Chapter 6, Section 6.3).

7.3.7 Sign Installation Unit Cost

Sign installation cost is one of the main factors considered by upper management when analyzing different sign replacement strategies. It is measured in dollars per sign ($/sign). Sign installation cost refers to all costs incurred in the installation of a ground mounted sign, which includes material (e.g., sign sheeting, pole, and bolts), labor, and equipment (sign truck). Agencies that have an average sign installation cost (per sign) can directly enter this value in the simulation as an input parameter. On the other hand, if the sign installation unit cost is not available, it is possible to estimate it using Equation (7.1) below.

$$SIUC = \left(\frac{LHC}{LP} + \frac{EHC}{EP} + MSFC\right) \times Average\ Sign\ Size \qquad Eq.\ (7.1)$$

Where:

SIUC = sign installation unit cost ($/sign)
LHC = labor hourly cost ($/hour)
LP = labor productivity (square feet/hour)
EHC = equipment hourly cost ($/hour)
EP = equipment productivity (square feet/hour)
MSFC = material square foot cost ($/square foot)
Average sign size = average size of a ground mounted sign (square feet)

7.3.8 Daytime Sign Inspection Unit Cost

Daytime sign inspection cost, measured in dollars per sign ($/sign), is the second cost component considered in this study. Sign inspection cost depends on three factors: equipment cost, labor cost, and inspection productivity (number of signs inspected per hour). If an agency does not track their costs related to daytime inspections, this cost can be estimated using the Equation (7.2) below.

$$DSIUC = \frac{(LHC \times L + EHC \times E)}{(Average\ Speed\ \times Average\ Number\ of\ Signs\ per\ Mile)} \qquad Eq.\ (7.2)$$

Where:

DSIUC = daytime sign inspection unit cost ($/sign)
LHC = labor hourly cost ($/hour)
L = number of labors per crew (usually, two men per crew)
EHC = equipment hourly cost ($/hour)
E = number of equipment per crew (usually, one sign truck per crew)
Average speed = speed that a sign crew drives while inspecting signs (miles/hour)
Average number of signs per mile (signs/mile)

7.3.9 Summary

Table 7.1 shows a list of the input parameters that a user needs to enter into the simulation model to run it. The first column lists the input parameters. The second column classify the type of data (e.g., integer, real, etc.). The third column shows the units of measure (e.g., signs and $).

Table 7.1 Input Parameters Summary

Input Parameter	Type	Unit
Number of signs simulated	Integer	Signs
Period simulated	Integer	Years
Blanket replacement cycle	Integer	Years
Grace period	Integer	Years
Daytime inspection cycle	Integer	Years
Daytime inspection priority	String	-
Annual damage rate	Real	%
Annual spot replacement rate	Real	%
Average sign replacement cost	Real	$
Average sign inspection cost	Real	$
Percent white signs on primary roads *	Real	%
Percent white signs on secondary roads *	Real	%
Percent yellow signs on primary roads *	Real	%
Percent yellow signs on secondary roads *	Real	%
Percent green signs on primary roads *	Real	%
Percent green signs on secondary roads *	Real	%
Percent red signs on primary roads *	Real	%
Percent red signs on secondary roads *	Real	%
Retroreflectivity deterioration model for white signs	Expression	$cd/lx/m^2$
Retroreflectivity deterioration model for yellow signs	Expression	$cd/lx/m^2$
Retroreflectivity deterioration model for green signs	Expression	$cd/lx/m^2$
Retroreflectivity deterioration model for red signs	Expression	$cd/lx/m^2$

Note: * The sum of the percentage of signs on primary and secondary roads should add up 100%.

7.4 Simulation Logic

The model represents a Blanket Replacement strategy wherein signs are replaced following an area-based approach, with a sign replacement rate of one area per year. The number of areas is often defined by the replacement cycle: a 10 year replacement cycle results in 10 areas; a 12 year replacement cycle results in 12 areas, and so on. Each area is expected to have approximately the same number of signs, which allows a uniform work load through the years.

Figure 7.2 illustrates an example of an area-based replacement approach. In this example, a division (or county) has a total of 10,000 signs. Blanket replacement is conducted on a 10 year replacement cycle, meaning that the division (or county) is divided into 10 areas of about 1,000 signs each. The replacement rate is one area per year.

As Figure 7.2 shows, the division is replacing in Year 1 all signs (1,000 signs) in Area 1, which is represented by the color blue. The other areas in Year 1 are light gray, meaning that their signs will be replaced in next cycle. In Year 2, Area 1 shifted color from blue to dark gray, which means that the signs there were already replaced. In this same year, sign replacement starts in Area 2 (yellow). All the other areas (Area 3 to 10) are light gray because they are waiting for their replacement cycles, which will occur in the following years. In Year 3, Areas 1 and 2 are dark gray because their signs were already replaced in previous cycles. In this same year, sign replacement starts in Area 3 (pink). All the other areas (Area 4 to 10) are light gray because they are waiting for their replacement cycles. This process occurs for all areas in a period of 10 years, when a new replacement cycle starts from Area 1 gain, repeating the entire process, area by area.

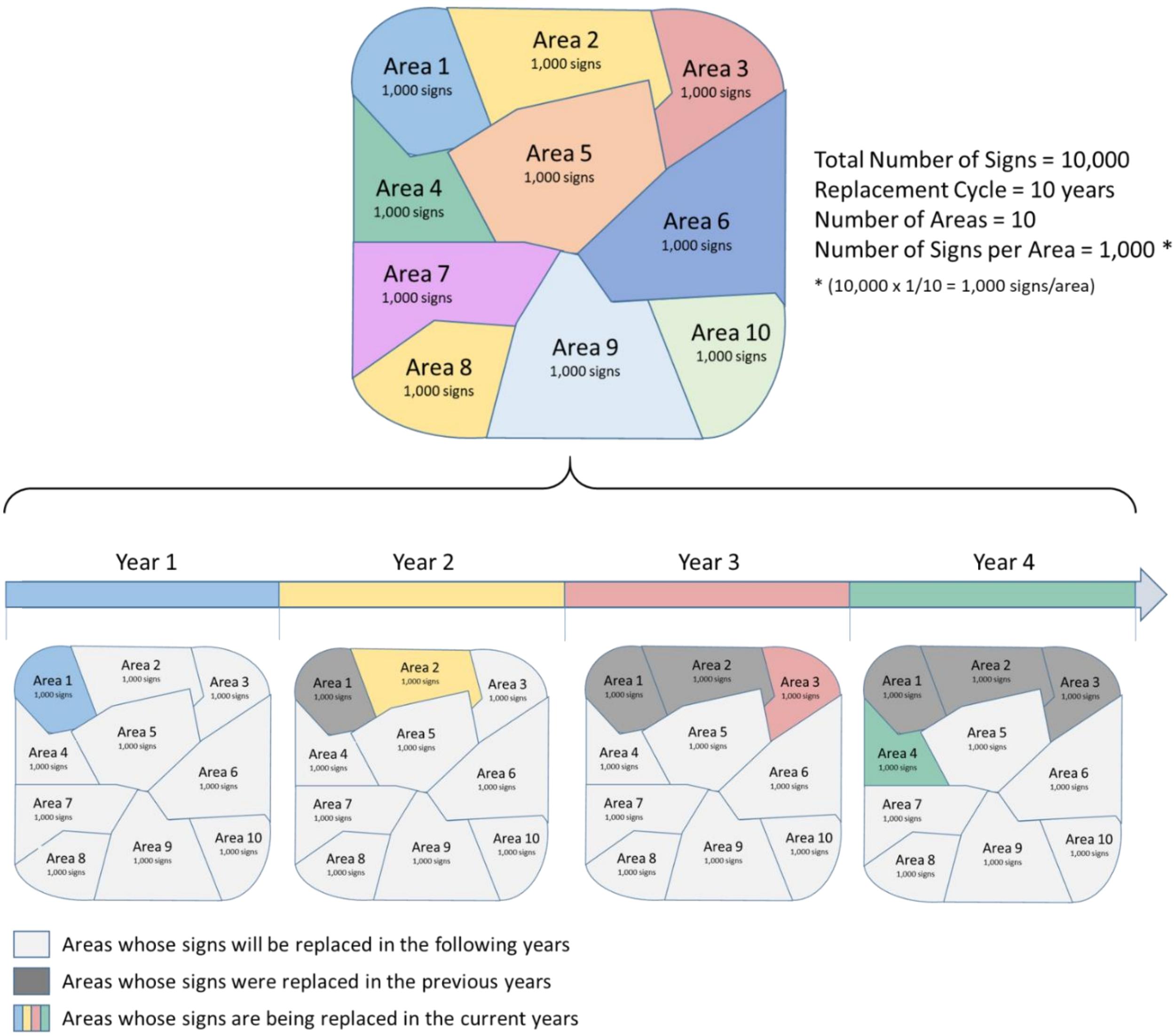


Figure 7.2 Blanket Replacement Strategy Using an Area-Based Approach

To simplify the understanding of the simulation model, we use one scenario as an example throughout this section. The input parameters of the scenario are shown in Table 7.2 and are consistent with the information provided in Figure 7.2. A total of 10,000 signs of a division (or county) are simulated for the period of 50 years. A state, division, or county is divided into 10 areas, indicating that there are 1,000 signs per area. The blanket replacement cycle is 10 years. The grace period is 3 years, indicating that only signs older than 3 years or damaged (any age) are replaced during blanket replacement. Daytime inspection cycle is 5 years. During daytime inspection, only damaged signs of priorities 1 and 2 (red and yellow) are replaced. The annual damage rate is 4% and from the damaged signs, 41% are spot replaced. The costs considered in this scenario are $80.00 per replaced sign and $0.40 per inspected sign.

Table 7.2 Input Parameters of Simulation Logic Scenario

Input Parameters	Values
Number of Yeas Simulated	50 years
Number of Signs	10,000 signs
Number of Areas	10 areas
Blanket Replacement Cycle	10 years
Grace Period	3 years
Number of Areas	10
Daytime Inspection Cycle	5 years
Sign Replacement Priority (for inspections)	1 and 2 (red and yellow)
Annual Damage Rate	4%
Spot Replacement Rate	41% *
Replacement Unit Cost	$80.0 per sign
Inspection Unit Cost	$0.4 per sign

* Spot Replacement Rate = 41% of damaged signs

Figure 7.3 illustrates the simulation logic that shows how signs (represented by individual entities) move through the simulation sub-models. The boxes in Figure 7.3 are numbered from 1 to 34. These numbers are referred in this paper as steps and are used to describe the simulation to the reader.

The first thing to note in the simulation logic is that there are two *loops* (year and area). The inner loop is the year loop (*Steps 21, 15, and 9*). Signs within an area are simulated year by year. Every time the signs pass by the year loop, one year is added to the simulation of that specific area. All signs in an area are simulated for a period of time specified by a user (e.g., 50 years). The outer loop is the *area loop* (*Steps 22, 16, and 10*). After one area is completed, the simulation advances to the next area and repeats the process. After all areas are simulated for all years, signs move to step 34 and the simulation ends.

After initializing the simulation model (*Step 1*), a user enters the input parameters (*Step 2*). The simulation model creates signs that are represented by individual entities (*Step 3*). Because signs are simulated by areas, the number of signs created in this step depends on the total number of signs and areas simulated (*Signs Created = Signs Simulated / Number of Areas*). The first signs to be simulated are those in Area 1 (S*tep 4*).

In this *Step 5*, color (white, yellow, green, or red), road class (primary and secondary) are randomly assigned to signs following the sign proportion entered by the user. After color is assigned, this step also assigns initial retroreflectivity (primary and secondary colors) and sign replacement priority to each sign depending on its color. Then, signs follow to *Step 6* (*define year*).

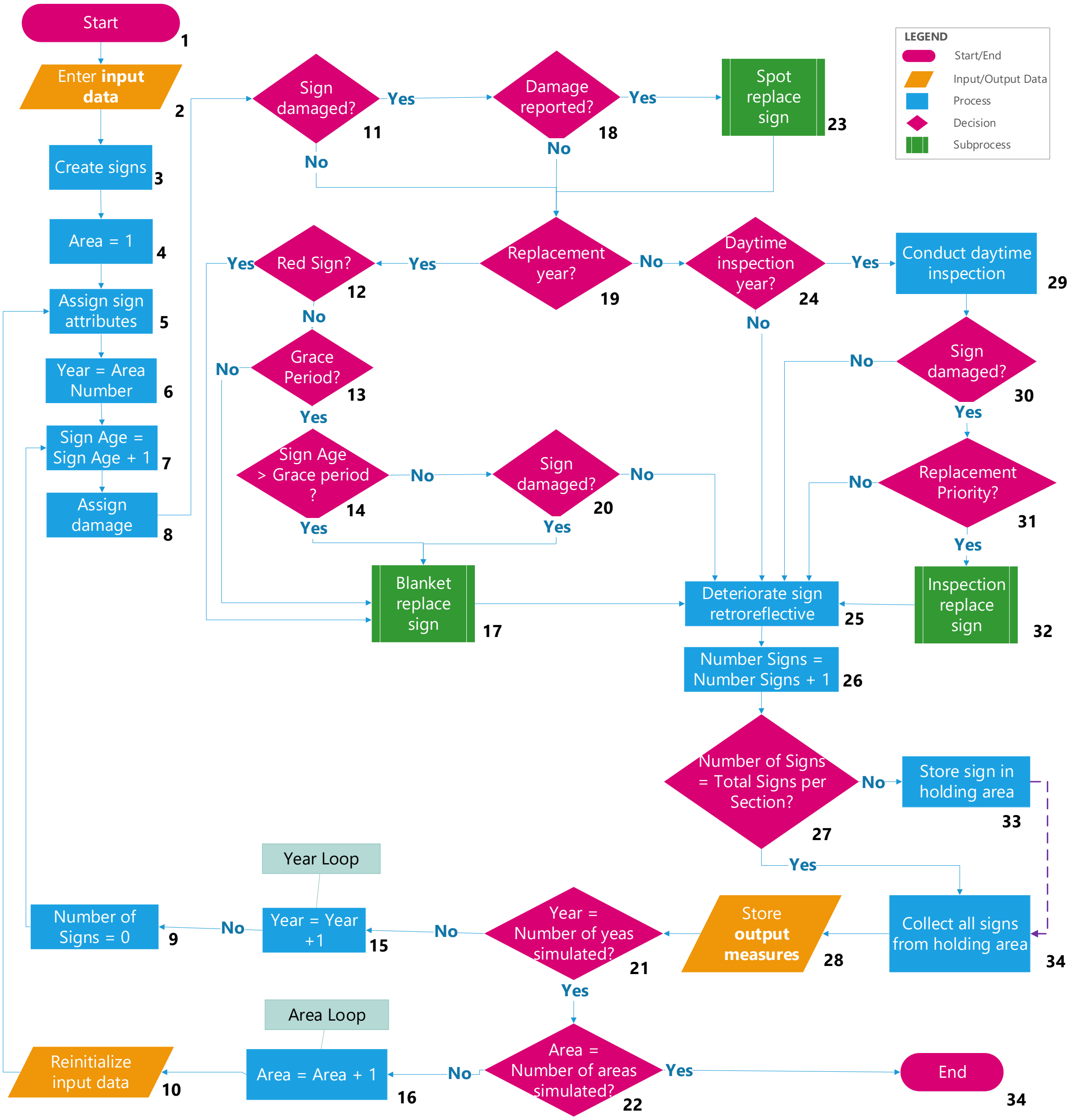


Figure 7.3 Sign Replacement Strategy Simulation Logic

Step 6 defines the first year to be simulated for each area. The simulation logic assumes that a blanket replacement strategy is being implemented for the first time in Area 1. Following this assumption, while signs in Area 1 are blanket replaced in Year 1, there is no information about what replacement activities are being performed in the other areas. Thus, data for Area 2 starts being collected in Year 2, when this area passes by its first blanket replacement. The same occurs for the other areas: data of Area 3 starts being collected in Year 3, data of Area 4 starts being collected in Year 4, and so on. To represent this in the simulation, we define the first year simulated of an area as being the number of the area. Then, signs follow to *Step 7* (*add one year to sign age*).

Every time a sign passes by *Step 7*, one year is added to its age, which is tracked by the simulation. For example, when the sign is just created in *Step 4*, the variable Sign Age is defined as zero (0). When the sign passes the first time through *Step 8*, one year is added to its age, updating Sign Age to 1 year old. Each subsequent year, one year will be added to Sign Age. Then, signs follow to *Step 8* (*assign damage*).

7.4.1 Sign Damage Sub-Model

The Sign Damage Sub-Model consists of *Steps 8* and *11* that are described next.

Step 8: Assign damage. This step randomly assigns damage to signs according to the damage rate entered by the user (e.g., 4.0% as shown in Table 7.2). The two possible outcomes are that signs are either damaged or undamaged. However, it is additionally necessary to consider whether or not that specific sign was already damaged in a previous year, which is defined by the variable *Beginning of Year (BOY) Damage ID* (see first column of Table 7.3).

The model randomly assigns a *Temporary Damage ID* variable for each sign based on the annual damage rate entered by the user (e.g., 4%) (second column of Table 7.3). Thus, the *Temporary Damage ID* variable of 4% of the signs is assigned as "yes," indicating that the sign was damaged in the current year (e.g., Year 2). The remaining 96% of the signs have their *Temporary Damage ID* assigned as "no," indicating that they were not damaged in Year 2.

The *Effective Damage ID* variable (last column of Table 7.3) refers to the effective damage status of a sign. The *Effective Damage ID* is a combination of the *BOY Damage ID* and *Temporary Damage ID.* Thus, a sign is undamaged if it was not damaged prior to that year nor was damaged in the current year. However, if a sign was damaged in any prior year (previously damaged but never replaced) or in the current year, the *Effective Damage ID* will be "yes."

Table 7.3 Sign Damage ID

BYO Damage ID [1]	Temporary Damage ID [2]	Effective Damage ID [3]
No	No	No
No	Yes	Yes
Yes	No	Yes
Yes	Yes	Yes

[1] Based on the previous years
[2] Based on the annual damage rate of the current year
[3] Depends on both BYO and Temporary Damage IDs

Step 11: Damage check. This step checks whether or not a sign is damaged. In *Step 11*, if the variable *Effective Damage ID* indicates that the sign is damaged, the sign follows to *Step 18 (damage reported check)*. However, if the sign is undamaged, it follows to *Step 19 (replacement year check)*.

7.4.2 Spot Replacement Sub-Model

Before running the simulation, the user may enter a spot replacement rate, which is the percent of damaged signs that are expected to be identified, reported (by citizens, highway patrols, or DOT personnel), and replaced (e.g., 40%). If the user enters zero (0) as the spot replacement rate, the model assumes that there is no spot replacement in the strategy. Considering the scenario described in Table 7.2, we have a spot replacement rate of 41% of the damaged signs. The Spot Replacement Sub-Model consists of *Steps 18* and *23* that are described next.

Step 18: Damage report check. All signs that follow to *Step 18* are damaged. Once the damaged signs enter this step, 41% of them are randomly tagged as reported while the remaining signs (59%) are tagged as not reported. If the sign is tagged as reported, it follows to *Step 23 (spot replacement)*. If the sign is tagged as not reported, it follows to *Step 19 (replacement year check)*.

Step 23: Spot replacement. Damaged signs that were reported follow to *Step 23* where they are replaced by new signs. When a sign enters *Step 23*, its information (sign color, road class, and sign replacement priority) is stored in a temporary table to be later assigned to the new sign. After the sign information is stored, the damaged sign is disposed and a new sign is installed (created). The features are assigned to the new sign based on the information stored in the temporary table, which is then deleted. Two other variables are defined for the new sign: *Effective Damage ID* (no, which means undamaged) and Sign Age (1 year old). In this step, a unit cost is associated with each replaced sign. The installation cost includes labor, material, and equipment costs. After *Step 23*, signs follow to *Step 19 (replacement year check)*.

7.4.3 Blanket Replacement Sub-Model

Before running the simulation, the user may enter a blanket replacement cycle (in years). If the user enters zero (0), the model assumes that there is no blanket replacement through the years simulated. Alternatively, if the user enters a blanket replacement cycle of 10 years, it means that signs will be blanket replaced every 10 years.

The Blanket Replacement is the most complex sub-model of the system because of the number of steps that it consists of (*Steps 19, 12, 13, 14, 20*, and *17)*. All these steps are explained next. The research team decided to group *Steps 13, 14*, and *20* into a Grace Period secondary sub-model because of their correlation.

Step 19: Replacement year check. This step determines whether or not the current year is a year of blanket replacement. Consider a 10 year replacement cycle. In this case, a blanket replacement is conducted in the first simulated year of each area and then every 10 years thereafter. For example, if Area 1 is being simulated; blanket replacements occur in Years 1, 11, 21, and so on. If *Step 19* determines that the current year is a year of blanket replacement, signs follow to *Step 12 (red signs check)*. Otherwise, if it is not a year of blanket replacement, signs follow to the daytime inspection sub-model (*Step 24 -daytime inspection year check*).

Step 12: Red sign check. If it is a year of blanket replacement, all red signs are replaced no matter what. Grace period does not apply to red signs. Thus, this step identifies red signs and sends them directly to *Step 17 (blanket replacement).* If a non-red sign passes by step 12, the sign then follows to the grace period check (step 13). Conversely, if a sign is identified as any other color than red it follows to *Step 13 (grace period check)*.

Step 17: Blanket replacement. When a sign enters *Step 17,* its information (sign color, road class, and sign replacement priority) is stored in a temporary table to be later assigned to the new sign. After the sign information is stored, the damaged sign is disposed and a new sign is installed (created). The features are assigned to the new sign based on the information stored in the temporary table, which is then deleted. Two other variables are defined for the new sign: *Effective Damage ID* (no, which means undamaged) and Sign Age (1 year old). . In this step, a unit cost is associated with each replaced sign. The installation cost includes labor, material, and equipment costs. After *Step 17*, signs follow to *Step 25 (retroreflectivity deterioration).*

7.4.3.1 Grace Period Secondary Sub-Model

Before running the simulation, the user may enter a grace period (in years). If the user enters zero (0) as grace period, the model assumes that grace period practice is not adopted in that sign replacement strategy. Alternatively, if the user enters a grace period (e.g., 3 years), it means that only signs older than the specified grace period or damaged (any age) are replaced during the blanket replacement. Undamaged signs younger than 3 years are not replaced and remain in the field until the next replacement cycle (if the sign is not spot replaced before then). The Grace Period consists of *Steps 13*, *14*, and *20*, which are explained next.

Step 13: Grace period check. This step determines whether or not the scenario is considering a grace period. If the grace period practice is not adopted (grace period equal to zero), the sign follows to *Step 17 (blanket replacement)*. On the other hand, if grace period is different from zero (e.g., 3 years), signs follow to *Step 14 (sign age check)*.

Step 14: Sign age check. This step determines whether or not a sign is older than the grace period. In this step, sign age is compared to the grace period. If a sign (damaged or undamaged) is older than the grace period, it follows to *Step 17 (blanket replacement)* to be replaced. However, if a sign is younger than or the same age as the grace period (e.g., Sign Age = 2 ≤ Grace Period = 3), it follows to *Step 20 (damage check)* to check whether or not it is damaged.

Step 20: Damage check. This step checks whether or not a sign is damaged. If a sign is identified as damaged, the sign follows to *Step 17 (blanket replacement)*. Otherwise, if the sign is undamaged, it follows to *Step 25 (deteriorate retroreflectivity)*.

7.4.4 <u>Daytime Inspection Sub-Model</u>

Before running the simulation, the user may also enter a daytime sign inspection cycle (in years). If the user enters zero (0) for the sign inspection cycle, the model assumes that there are no daytime inspections through the years simulated. Alternatively, if the user enters a sign inspection cycle of 5 years, for example, it means that signs will be inspected every five years (excluding years of blanket replacement). The example shown in Table 7.2 also specifies that only Priorities 1 and 2 (red and yellow) signs are replaced during daytime inspections. The Daytime Inspection Sub-Model consists of *Steps 24, 29, 30, 31,* and *32,* which are explained next.

Step 24: Daytime inspection year check. This step determines whether or not the current year is a year of daytime inspection. Considering an inspection cycle of 5 years and the fact that inspections do not occur in years of blanket replacement, signs in Area 1 are inspected in Years 6, 16, 26, and so on. There are no inspections in Area 1 in Years 11 and 21, for example, because they are years of blanket replacement. If it is a year of daytime inspection, signs follow to *Step 29 (daytime inspection conduction)*. Otherwise, they follow to Step 25 *(deteriorate retroreflectivity)*. Figure

7.4 illustrates the years of blanket replacement and daytime inspections for Areas 1, 2, 3, and 4 considering the sign replacement scenario described in Table 7.2. The purple boxes represent blanket replacement while the orange boxes represent daytime inspections for the respective areas.

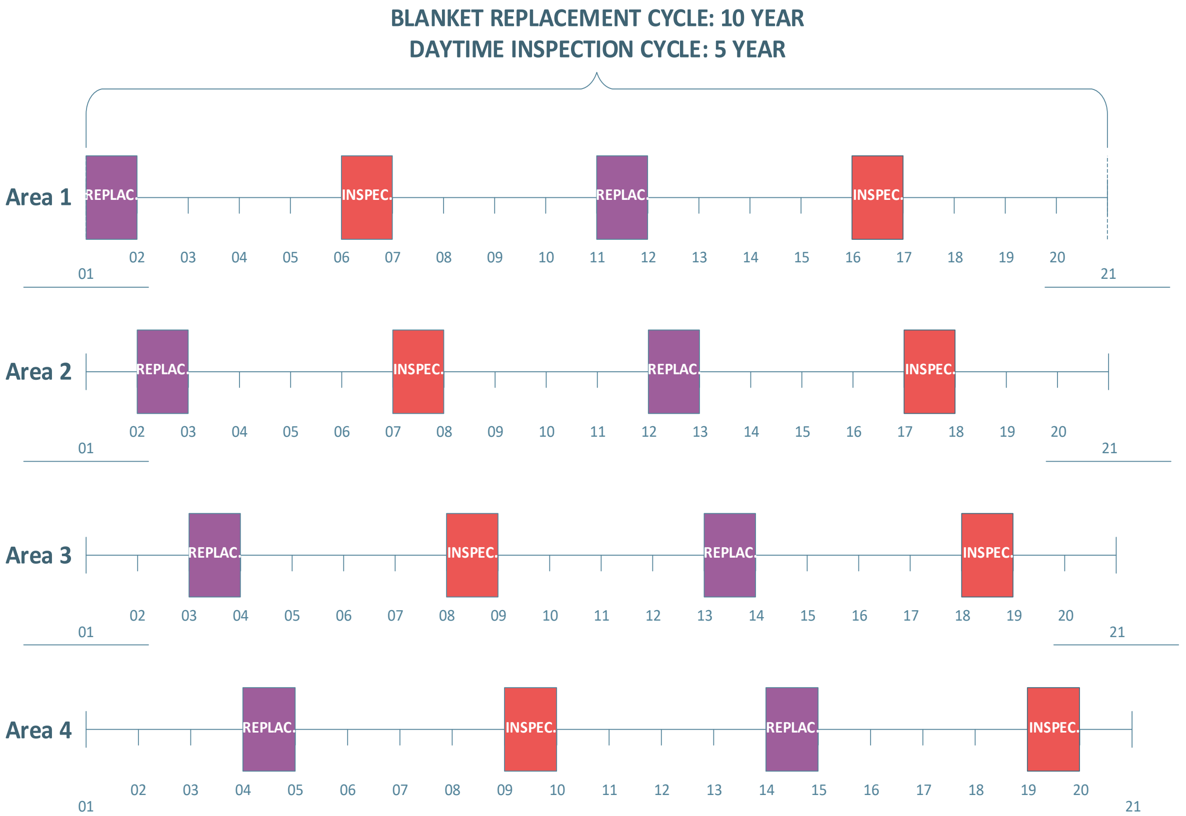


Figure 7.4 Sign Replacement Years and Daytime Inspection Years for Different Areas

Step 29: Daytime inspection conduction. This step conducts daytime inspections. In this step, a unit cost is associated with each inspected sign. The inspection cost includes labor and equipment. After the sign exits this step, it follows to *Step 30 (damage check).*

Step 30: Damage check. This step checks whether or not a sign is damaged. If a sign is identified as damaged, the sign follows to *Step 31 (replacement priority check)*. Otherwise, if the sign is undamaged, it follows to *Step 25 (deteriorate retroreflectivity).*

Step 31: Replacement priority check. This step checks the inspection replacement priority entered by the user. Signs selected by the user follow to *Step 32* (*inspection replacement*). Signs that are not of the priority follow to *Step 25* (*retroreflectivity deterioration*). For example, a replacement Priorities 1 and 2 (red and yellow signs) means that only damaged red and yellow signs are replaced during daytime inspections.

Step 32: Inspection replacement. When a sign enters *Step 32*, its information (sign color, road class, and sign replacement priority) is stored in a temporary table to be later assigned to the new sign. After the sign information is stored, the damaged sign is disposed and a new sign is installed (created). The features are assigned to the new sign based on the information stored in the temporary table, which is then deleted. Two other variables are defined for the new sign: *Effective Damage ID* (no, which means undamaged) and Sign Age (1 year old). In this step, a unit cost is associated with each replaced sign. The installation cost includes labor, material, and equipment costs. After *Step 32*, signs follow to *Step 25 (deteriorate retroreflectivity)*.

7.4.5 Retroreflectivity Deterioration Sub-Model

The Retroreflectivity Deterioration Sub-Model consists of *Step 25.*

Step 25: Deteriorate retroreflectivity. This step calculates the sign retroreflectivity at that age based on the deterioration models entered as input parameters. The simulation selects the appropriate deterioration model (which depends on the color) to calculate the sign retroreflectivity at that age. It is noteworthy that the simulation does not calculate a sign retroreflectivity for black sheeting (secondary color of yellow and white signs) because it is a non retroreflective material.

7.4.6 Output Measure Sub-Model

The Output Measure Sub-Model consists of *Steps 26, 27, 28, 33,* and *34,* which are described next.

Step 26: Sign count. This step counts the number of signs in each *year loop* (as it is shown later, *Step 9* resets sign count at the end of a year loop; makes it equal zero).

Step 27: Sign count check. This step checks to see if all signs of an area completed a year loop. First, assume that only one sign (Sign #1) out of 1,000 signs of Area 1 went through all process of Year 1. When Sign #1 enters Step 27, the model verifies that there are more signs going through the Year 1 *loop*. In this case, *Steps 27* does not allow Sign #1 to continue and, instead, sends it to *Step 33 (holding area)* where the sign will remain until the last sign of Area 1 passes by all processes prior to *Step 27*. When Sign #1,000 arrives at *Step 27,* Sign #1,000 follows to *Step 34 (collect signs of hold area).*

Step 33: Holding area. This step was necessary to ensure that all signs of an area were processed year by year. Thus, this step holds signs within a *year loop* until all signs of an area (e.g., Area 1) complete the *loop*. Considering the scenario of Table 7.2, signs will remain in the holding are until the last sign (Sign #1,000) completes enters *Step 34 (collect signs of hold area).*

Step 34: Collect signs of hold area. *W*hen the Sign #1,000 enters *Step 34*, all signs that were in the holding area (*Step 33*) are collected and they all follow together to *Step 28 (store output measures).*

Step 28: Store output measures. After all signs of an area completed the *year loop*, a set of output measures are collected at the end of the year simulated (after replacement activities are conducted through the year). Those measures enable the comparison among different sign replacement scenarios over time. The measures are listed below and further discussed in detail in Section 8.3 (Output Measures). After all the output measures of a *year loop* are collected in *Step 28*, signs follow to *Step 21 (year simulation check)*. The output measures collected by the model are listed and described in Section 8.4 of this chapter.

7.5 Output Measures

The simulation model collects output measures that enable comparison of the different sign replacement strategies considered in this study. The model collects annual, cumulative, and average annual output measures.

The *annual output measures* are collected at the end of each year simulated and stored in excel files (one file per scenario simulated). Each excel file has a set of tables that are populated with annual number of sign and cost data. The research team used these annual output measures to verify the sign replacement simulation model. The annual output measures were also used in the analysis of two pilot strategies that the research team ran to determine three aspects of the simulation model: (1) transient interval removal, (2) simulation length, and (3) number of replications necessary to obtain a desired half width (see Appendix 12.7).

After analyzing these pilot strategies, the research team identified the transient interval as being the first 20 years of the simulation. Obaidat and Papadimitriou (2003) stated that removing the transient interval from the results and analysis is essential in any simulation study. Therefore, the authors removed observations from the first 20 years of simulation and considered only data collected from Years 21 to 50 in further analysis.

The model also calculates the *average annual output measures* (using Equation (7.3)) through the period in which the simulation is stabilized (Years 21 to 50). The research team used the average annual measures to compare the different sign replacement strategies. After running a number of replications for each strategy, the simulation model calculates the mean and half width (h) for a 95% confidence interval.

$$Average\ Annual\ Output\ Measure = \frac{\sum_{i=(TP+1)}^{n}(Annual\ Output\ Measure_{\ i})}{(n - Transient\ Period)}\ Eq.\ (7.3)$$

Where

Average Annual Output Measure = average of an annual output measure through the years without considering the transient period
Annual Output Measure $_i$ = Annual output measure collected in year i
i = year simulated (when the model is stabilized, thus $21 \leq i \leq 50$)
n = total number of years simulated (50 years)
TP = transient period that precedes the stabilization of the output measures (first 20 years)

7.5.1 Number of Damaged, Noncompliant, and Unsatisfactory Signs

Every time a sign is damaged, the simulation tags it as damaged. Once a signs is damaged, it will remain damaged until it is replaced by a new (undamaged) sign during spot, blanket, or inspection replacement. At the end of each year (EOY), the simulation calculates the number of damaged. Damaged signs that were replaced during the year are not considered in this calculation.

The simulation also tags noncompliant signs, which are those signs below the minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). At the end of each year, the simulation calculates the number of noncompliant signs at the end of year (EOY). Noncompliant signs that were replaced during the year are not considered in this calculation.

With respect to unsatisfactory signs, they are defined as signs that are damaged, noncompliant, or both damaged and noncompliant. In this case, at the end of each year the simulation calculates the annual number of unsatisfactory signs. This number is determined by adding all signs that are only damaged, only noncompliant, and both damaged and noncompliant.

7.5.2 Number of Inspected Signs

The simulation also calculates the number of signs that are inspected during daytime inspections. It will be always equivalent to the number of signs in an area given that the inspection rate is one area per year. The number of inspected signs is used to calculate the cost of inspections (explained later in this chapter).

7.5.3 Number of Replaced Signs

Signs can be replaced in three situations in the simulation model. If a replacement is initiated by damage report, it is classified as spot replacement because it can occur anytime in the year, any year. Transportation agencies do not have control of spot replacement. A sign can also be replaced as scheduled during a blanket replacement. The third situation in which a sign can be replaced is during daytime inspections. When those inspections are conducted and damaged signs are detected. Those damaged signs are then replaced, also referred here as number of signs inspected replaced.

Based on that, the simulation model calculates three output measures related to the number of replaced signs: number of signs replaced due to daytime inspection, number of signs replaced due to blanket replacement, and number of spot replaced signs. Each time a sign is blanket replaced, the simulation adds a unit to the annual number of blanket replaced signs. The same occurs with signs that are replaced due to daytime inspection and spot replacement; each time this event occurs, a unit is added to the annual number of signs replaced due to daytime inspections and annual number of signs replaced due to spot replacement.

In addition, the simulation calculates the total number of replaced signs, which is obtained by adding the numbers of signs replaced due to daytime inspections, blanket replacement, and spot replacement.

$$No.of\ Signs\ Replaced = Blanket\ Replaced + Spot\ Replaced + InspectedReplaced$$

7.5.4 Daytime Inspection Cost

The simulation calculates daytime inspection costs by multiplying the number of inspected signs by the daytime sign inspection unit cost (DSIUC) (average $/sign inspected) as shown by the Equation (7.4) below. The inspection cost includes labor and equipment.

$$Inspection\ \ Cost = No.of\ Inspected\ Signs\ \times\ DSIUC \qquad Eq.\ (7.4)$$

7.5.5 Replacement Cost

The simulation calculates replacement costs by multiplying the number of replaced signs by the sign installation unit cost (SIUC) (average $/sign replaced). A note that the replacement cost includes material, labor, and equipment as it was shown in section 8.1 of this chapter.

The replacement cost is calculated for the three situations in which signs can be replaced: blanket replacement cost, spot replacement cost, and inspected replacement cost. They are obtained by multiplying the number of signs replaced (by reason) by the unit replacement cost as Equations (7.5) to (7.7) show. Having the replacement cost by type of replacement may be helpful if an agency wants to verify where the major part of the strategy cost is being spent.

$$Blanket\ Replacement\ Cost = BlanketReplaced\ \times\ SIUC \qquad Eq.\ (7.5)$$

$$Spot\ Replacement\ Cost = Spot\ Replaced\ \times\ SIUC \qquad Eq.\ (7.6)$$

$$Inspected\ Replacement\ Cost = Inspected\ Replaced\ \times\ SIUC \qquad Eq.\ (7.7)$$

In addition, the total replacement cost is also calculated by multiplying the total number of signs replaced (by any reason) by the unit replacement cost as shown by the equations below.

$$Replacement\ Cost = No.of\ Signs\ Replaced \times SIUC \qquad Eq.\ (7.8)$$

7.5.6 Strategy Cost

The strategy cost is calculated by adding the total replacement cost and inspection cost as Equation (7.9) shows.

$$Strategy\ Cost = Replacement\ Cost + Inspection\ Cost \qquad Eq.\ (7.9)$$

The cost of each strategy has a major implication in this study because it enables a comparison of different strategies. Traffic engineers can make decisions based on this information. For instance, there may be a scenario that results in a low percent of unsatisfactory signs; however, this same scenario is likely to result in an extremely high cost. An analysis of the tradeoff between sign condition and cost needs to be conducted by transportation agencies and the simulation provides information to do so.

7.5.7 Number of Years Damaged Signs Stay in the System

The research team also calculated the maximum and average numbers of years damaged signs stay in the system. Those measures can be used as an indicator of how efficient a strategy is. For instance, scenarios that result in damaged signs staying in the system for too long might be not part of the set of optimal strategies. To calculate the average numbers of years damaged signs stay in the system, only the age of damaged signs were considered. Undamaged signs were not included in this calculation.

7.5.8 Signs Prematurely Replaced

The sign replacement simulation model also estimates the number of signs prematurely replaced and the cost associated to them. Signs that are "prematurely replaced" are undamaged signs that are replaced before the end of their service life, estimated to be the same as the blanket replacement cycle. For example, an agency that adopts a 10 year blanket replacement cycle considers that the sign has a service life of 10 years (whether or not this sign service life of 10 years is not being discussed herein. Instead, the simulation model considers the sign service life as the same as the blanket replacement). Now consider that a seven year old undamaged sign is replaced during a blanket replacement year. This means that this signs was prematurely replaced because theoretically it still had three remaining years of service life.

The estimation of signs prematurely replaced and their impact (cost) were calculated in three steps. The first step was to calculate the average annual number of signs prematurely replaced. In the second step, the simulation estimates the average remaining life of those signs that were prematurely replaced (Equation (7.10)), which was calculated by the difference between the blanket replacement cycle (considered the same as the sign service life) and the average age of the replaced signs.

$$ARL = \frac{1}{n} \times \left(\sum_{i=1}^{n} (BRC - Sign\ Age_i) \right) \qquad Eq.\ (7.10)$$

Where:

ARL = average remaining life (years) of signs prematurely replaced
n = annual average number of signs prematurely replaced
i = 1, 2, 3, …, n
$Sign\ Age_i$ = age of the i^{th} undamaged sign being prematurely replaced
BRC = blanket replacement cycle (years)

The third step was to associate a cost to those signs being prematurely replaced (sign salvage value). To do so, it was assumed a constant sign depreciation through its service life. In other words, if a sign costs $100 and has a sign service life of 10 years (based on the replacement cycle), the depreciation of this sign is $10 per year. Therefore, if that same sign was replaced at the age of seven years (three years before the end of its service life), it has a salvage value of $30 ($10/year x 3 years). The research team calculated the average annual prematurely replacement cost (AAPRC) using Equation (7.11).

$$AAPRC = n \times \text{ARL} \times \frac{SIUC}{BRC} \qquad Eq.\ (7.11)$$

Where:

AAPRC = Average Annual Prematurely Replacement Cost
n = annual average number of signs prematurely replaced (signs)
ARL = average remaining life (years) of signs prematurely replaced
SIUC = sign installation unit cost ($/sign)
BRC = blanket replacement cycle (years)

7.6 Confidence Interval

For experimentation purposes, Simio Simulation Software uses t-test to calculate confidence intervals as shown by Equation (7.12) (Joines and Roberts, 2015). For this research purpose, a 95% confidence interval was adopted. Besides being well accepted in the literature, a 95% confidence interval was also adopted by Harris (2010) when simulating different sign maintenance methods in the past. In other words, this means that there is 0.95 probability of any output measure resulted from the simulation to fall within its confidence interval (*mean* ± *half width*).

$$\bar{X} \mp t_{m-1,1-\frac{\alpha}{2}} \times \frac{\hat{s}}{\sqrt{m}} \qquad Eq.\ (7.12)$$

Where (definition obtained from Joines and Roberts, 2015):

$\bar{X}$: sample mean of an output measure
$t_{m-1,1-\frac{\alpha}{2}}$: upper *1-α/2* critical point from the Student's t distribution with *m-1* degrees of *m* number of replications.
m: number of replications
α: 0.05 for a confidence interval of 95%
$\hat{s}$: sample standard deviation of an output measure

7.7 Number of Replications

The simulation software allows the user to control the number of replication for each scenario. This is an important feature of simulation because, as explained by Kelton et al. (2014), it is possible to improve estimations by increasing the number of replications of an experiment. A larger number of replication leads to a smaller h (*half width*) and a narrower confidence interval. For example, five replications will result in better estimations than only one replication.

However, that does not mean that a user should run as many replication as possible to obtain the tightest confidence interval because that would not be realistic. It is likely that a user does not have so much certainty about the system to do so. In addition, a very large and unreasonable number of replications could consume a significant amount of computer time to run it (Kelton et al., 2014). Therefore, a balance must be reached between number of replications and the "precision" of the confidence interval.

To calculate the number of replications necessary, the research team considered an acceptable error of ±5% from the mean value obtained from the simulation. Based on it, it is possible to calculated the number of replications by using the Equation (7.13) (Joines and Roberts, 2015). The first step is to run a number of replications (e.g., m_0 =10 replications) and obtain *half-width* h_0 from these n_0 observations. The second step is to calculate the target *half-width h*, that is 5% of the *mean* obtained from m_0 observations. The third step is to calculate the number of replications needed.

$$m = m_0 \times \frac{h_0^2}{h^2} \qquad Eq.\ (7.13)$$

Where (definition obtained from Joines and Roberts, 2015):

m: number of replications needed to obtain a target *half-width h* (within 5% of the mean)
h: target *half-width h* (within 5% of the mean; based on the acceptable error)
m_0: initial number of replications
h_0: *half-width* h_0 from m_0 observations

7.8 Simulation Verification and Validation

The research team met with signing and delineation managers and traffic engineers before and during the model development process to discuss the simulation logic and to determine which field procedures (e.g., grace period) should be included in the model. Those meetings and feedback were essential for the research team to develop a model that was truly realistic.

Based on these meetings, the research team built in a grace period field procedure into the simulation to enable an agency to spare signs younger than a threshold age (grace period) if they wish to do so. With respect to daytime inspections, there are agencies that conduct it with the objective of identifying damaged signs while other agencies believe that their workers can identify damaged signs while riding roads for other activities than sign inspection. Thus, the research team also built in this function in the simulation to allow a transportation agency to consider daytime inspections in its strategy.

After developing the simulation model, the research team felt confident that it sufficiently represents how the Blanket Replacement method operates in the field and that the model's functions allow transportation agencies to analyses different strategies. In addition, it is the first time that the benefits (if any) of grace period were quantified in a research study.

The model logic was verified using techniques similar to those described by Harris (2010). The research team analyzed the logic, animation, and output measures. The sub-models were verified individually. In some cases, the interactions between two or more sub-models were also verified to ensure that they were working properly. The research team used sign data from NC as input to run and verify the logic of the sub-models. The first step was to check if the sub-models were built following the simulation logic. The second step was to use animation to verify whether or not the signs were moving through the system as expected. The third and last step was to analyze output measures to guarantee that the results of the simulation were correct and coherent with the input parameters entered. Then, each sub-model was added and connected to the overall sign replacement model. The verification of the sub-models are shown in Appendix 12.6

After verifying the logic of the model, the research team hoped to use NC sign data to run the model and compare the simulation results with real data. However, the NCDOT currently is in transition from the Nighttime Visual Inspection to the Blanket Replacement method. As a result, neither the sign replacement rate not the use of daytime inspection is uniform across divisions.

Thus, it was not possible to draw a direct comparison between the simulation results and the NC field data as the research team initially expected. Kelton et al. (2015) stated that in the case when accurate records of the real system do not exist, it might not be possible to validate the simulation. In such case, the author recommends the developer to focus efforts in the simulation verification, ensuring that the system is working as expected and use the best judgment of professionals familiar and knowledgeable about the system. The research team followed both recommendations from Kelton et al. (2015).

In addition, the research team believes that when the RMIP is 100% implemented, it will be possible to validate the simulation by using field data as input parameters and comparing the simulation results with NC field data. At that point in time, the sign replacement simulation model will be representing the real NCDOT sign replacement system in place.

7.9 Limitations

Despite the strengths of the proposed sign replacement model, it has some limitations that must be addressed in future work. First, this present model relied on the assumption that inspectors identify all (100%) damaged signs during daytime inspections. However, it may be the case that only one portion of the damaged signs are identified during daytime inspections. Therefore, further study is needed to estimate the accuracy of daytime inspections (e.g., how much of damaged signs the inspectors identify).

Second, although the model was verified using different methods and face validity, it was not possible to conduct a predictive validation that compares the results of the simulation with the system's behavior because there was not available real system performance measures representative of a Blanket Replacement strategy. Thus, future research should focus on measuring the real system performances to enable a straight comparison with the proposed model.

Finally, the scope of the sign replacement model was limited to the Blanket Replacement method. This method was found to be the most appropriate for the transportation agencies targeted in this study. However, more research can be conducted in order to expand the scope of the model, perhaps adding one of the most adopted sign management methods adopted by states DOTs (the Expected Sign Life method).

8.0 NCDOT SIGN REPLACEMENT STRATEGIES DEVELOPMENT

This chapter presents the development of the NCDOT sign replacement strategies to be further studied in the simulation model. The first section of this chapter (Section 9.1) describes part of the input parameters that represents NC sign general conditions and are fixed values in the simulation. Those input parameters include sign population by color and road class, sign damage rate, spot replacement rate, sign retroreflectivity deterioration models, and sign cost.

The second section (Section 9.2) describes the remaining simulation input parameters, also referred as control variables. By control variables, the research team refers to the input parameters that are manipulated to design different sign replacement strategies and assess their effect on output measures (e.g., strategy cost and number of unsatisfactory signs). The control variables include blanket replacement cycles, grace period, and daytime inspection.

The last section (Section 9.3) describes the sign replacement strategies that represent a factorial experiment by crossing all levels of the three control variables (blanket replacement cycles, grace period, and daytime inspection).

8.1 Fixed NC Input Parameters

Part of the input parameters of the simulation model are referred to as *fixed* input parameters because they represent general sign conditions and are fixed values in the simulation across the different sign replacement strategies analyzed. These fixed input parameters and their values are shown in Table 8.1 and described in the next subsections. The first column of Table 8.1 lists the input parameters. The second column classifies the type of data (e.g., integer, real, etc.). The third column shows the unit of measure (e.g., signs and $).

Table 8.1 Input Parameters Summary

Input Parameter	Unit	Values
Number of signs simulated	Signs	10,000
Period simulated	Years	50
Annual damage rate	%	4.04
Annual spot replacement rate	%	41.09
Average sign replacement cost	$	81.31
Average sign inspection cost	$	0.35
Percent white signs on primary roads *	%	17.65
Percent white signs on secondary roads *	%	20.05
Percent yellow signs on primary roads *	%	9.69
Percent yellow signs on secondary roads *	%	32.43
Percent green signs on primary roads *	%	3.44
Percent green signs on secondary roads *	%	3.17
Percent red signs on primary roads *	%	2.08
Percent red signs on secondary roads *	%	6.49
Retroreflectivity deterioration model for white signs +	$cd/lx/m^2$	304.089 – 4.815 Age
Retroreflectivity deterioration model for yellow signs+	$cd/lx/m^2$	193.01 + 5.644 Age – 0.552 Age^2
Retroreflectivity deterioration model for red signs +	$cd/lx/m^2$	59.632 – 2.658 Age
Retroreflectivity deterioration model for green signs +	$cd/lx/m^2$	53.386 – 1.345 Age

Note: * The sum of the percentage of signs on primary and secondary roads should add up 100%.
\+ Sign retroreflectivity deterioration models obtained from Immaneni et al. (2009)

8.1.1 Sign Population by Color and Road Class

Palmquist and Rasdorf (2001) and Kirtley and Rasdorf (2001) conducted field surveys to count and estimate the total number of signs maintained by the NCDOT, which was found to be around 969,900 signs. They classified the signs by color and road class. From those, the current research team selected the signs of interested for this study, which included white, yellow, green, and red signs on primary and secondary roads. Interstate signs were not considered because they represent a small percentage of all signs, they are inspected on an annual basis, and they are often overhead signs. Table 8.2 shows the sign count of the signs simulated obtained from Palmquist and Rasdorf (2001). Table 8.3 shows the percentage of signs by type on primary and secondary roads, which are 32.86% (289,291 / 880,439 * 100) and 67.14% (591,148 / 880,439 * 100) respectively. Those are the values used in the simulation.

Table 8.2 Sign Count by Color on Primary and Secondary Roads

Sign Type / Road Class	White	Yellow	Green	Red (combined)*	Total
Primary	155,365	85,297	30,286	18,343	**289,291**
Secondary +	220,524	285,559	27,885	57,180	**591,148**
				Total	**880,439**

+ Signs on Primary Roads = Signs on US Route + Signs on NC Route

* Red signs combined = (Red sign + Stop signs) from Palmquist and Rasdorf (2001)

Table 8.3 Sign Percentage by Color on Primary and Secondary Roads

Sign Type / Road Class	White	Yellow	Green	Red (combined)	Total
Primary	17.65%	9.69%	3.44%	2.08%	32.86%
Secondary +	25.05%	32.43%	3.17%	6.49%	67.14%
				Total	**100%**

8.1.2 Sign Damage Rate

The current research used damage (environmental and vandalism) rates introduced by Rasdorf et al. (2006) that were drawn from a detailed and comprehensive study (1,681 signs surveyed). Rasdorf et al. (2006) also observed nighttime visual inspections conducted by NCDOT personnel and used NCDOT financial data to determine the number and percent of signs replaced per year and the reason. The number of signs replaced by year due to environmental and vandalism damage (considered in the current research to be the annual damage rate) was found to be 4.04% (2.94% due to vandalism and 1.10% due to environmental damage). The following subsections describe the Rasdorf et al. (2006)'s study methodology and how they determined the replacement (and damage) rates in NC.

8.1.2.1 Number of Signs Replaced Due to Inspection

Rasdorf et al. (2006) collect field sign data and classified sign damage into environmental and vandalism. A total of 1,681 signs were inspected and registered. From those, 4.10% needed to be replaced (for any reason). Table 8.4 shows a breakdown of the replacement rate by reason.

Table 8.4 Number of Signs Replaced Due to Nighttime Visual Inspections

Reason	Number of Signs Replaced	Percent of Signs Replaced (Total 1,681)
Low Retroreflectivity	29	1.73%
Environmental Damage	16	0.95%
Vandalism Damage	24	1.43%
Total	69	4.10%

Source: Table 9.8 from Rasdorf et al. (2006)

From Table 8.4, it is possible to determine that the number of signs failing nighttime inspection in a given year because of damage is 2.38% (0.95% + 1.43%) of all inspected signs. However, it is important to point out that these rates are the result of only nighttime visual inspections and are not representative of the total replacement rate in NC. Damaged sign identified during daytime inspections and spot replacement are not included in these numbers. Thus, they are somewhat on the low side. Because of that, Rasdorf et al. (2006) also used financial data to determine the NC total damage rate as explained next.

8.1.2.2 Total Number of Signs Replaced

Using NCDOT financial data, Rasdorf et al. (2006) were able to estimate the total number of signs replaced per year in NC. First, the authors obtained NCDOT's 2005 annual expenditure for replaced signs, which were classified by NCDOT into two financial codes: 4302 (low retroreflectivity and environmental damage) and 4301(vandalism). Then, they calculated an average 2006 sign cost of $52.83 (per sign), which was obtained by weighting the costs of white, stop, and yellow signs. Knowing the annual expenditure to replace signs and an average sign cost (Table 8.5), it was possible to estimate the number of signs replaced (last column of Table 8.5) annually.

Table 8.5 Number of Signs Replaced per Year in NC

Reason	Financial Code	Replacement Cost ($)	Average Sign Cost ($)	Number of Signs Replaced
Low Retroreflectivity	4302	$1,580,515	$52.83	29,917
Environmental Damage				
Vandalism Damage	4301	$1,506,487		28,516

Source: Table 9.12 from Rasdorf et al. (2006)

8.1.2.3 Percent of Signs Replaced

In a previous study conducted by Palmquist and Rasdorf (2001), it was estimated that NC had a total of 969,905 signs. Considering the total number of signs in NC and the number of signs replaced per year, Rasdorf et al. (2006) calculated the percent of signs replaced (which is also referred as the annual replacement rate).

Table 8.6 shows a combined replacement rate for low retroreflectivity and environmental damage. To determine the individual rate for each one of those, Rasdorf et al. (2006) used data from the nighttime visual inspections (shown in Table 8.4). Note that the replacement rate for low retroreflectivity and environmental damage are combined (second and third rows of Table 8.6). To determine the individual rate for each one of those, Rasdorf et al. (2006) used data from the nighttime visual inspections (shown in Table 8.4) to estimate them. Table 8.7 shows the final calculations of the replacement rate in NC. Sign replacement due to low retroreflectivity accounts for 1.99%, environmental damage accounts for 1.10%, and vandalism represents 2.94% of all signs in NC.

Table 8.6 Sign Replacement Rate per Year in NC (Low Retroreflectivity and Environmental Damage Combined)

Reason	Number of Signs Replaced	Total Number of Signs in NC	Percent of Signs Replaced
Low Retroreflectivity	29,917	969,905	3.08%
Environmental			
Vandalism	28,516		2.94%
Total	58,433	969,905	6.02%

Source: Table 9.13 from Rasdorf et al. (2006)

Table 8.7 Total Sign Replacement Rate by Reason per Year in NC

Reason	Percent Signs Replaced +	Number of Failed Signs ++	Calculation	Percent of Signs Replaced
Low Retroreflectivity	3.08%	29	3.08% x (29/(29+16))	1.99%
Environmental		16	3.08% x (16/(29+16))	1.10%
Vandalism	2.94%	24	-	2.94%
Total	6.02%	69	-	6.02%

Source: + Table 8.6: data from financial data (nighttime inspection and spot replacement)
++ Table 8.4: data from nighttime visual inspection

8.1.2.4 Summary of Damage Rates

The Rasdorf et al. (2006) sign study defined, with a high level of confidence, sign damage rates by cause (environmental and vandalism). The current sign damage rate should be close to 4% (as shown in
Table **8.8**) even though the numbers of signs in the state might be higher than when the study from Rasdorf et al. (2006) was conducted. Thus, the current study used the total damage rate, also referred in this text as *annual damage rate*, of 4.04% (1.10% + 2.94%) as shown in
Table **8.8**.

Table 8.8 Annual Sign Damage Rate in NC

Damage	Percent of Signs Replaced	Rounded Percent of Signs Replaced
Environmental	1.10%	1%
Vandalism	2.94%	3%

Total	4.04%	4%

8.1.3 Spot Replacement

The current research also used the spot replacement rate (any replacement that is initiated outside of a daytime or nighttime inspection) calculated by Rasdorf et al. (2006). For example, a citizen who is driving by an intersection near his/her home may observe that a stop sign was knocked down at the intersection and he/she contacts NCDOT to report the damage. When NCDOT replaces that sign, this study classifies it as spot replacement because it was not initiated by a standard sign inspection.

When Rasdorf et al. (2006) conducted their study, they found that 4.04% of all signs were annually damaged and that 1.66% of all signs were spot replaced because of damage. In other words, 41.09% (1.66% / 4.04%) of all damaged signs were identified outside of normal inspections and then replaced. This spot replacement rate of 41.09% is referred herein as converted spot replacement rate and is show in Table 8.9. The converted spot replacement rate of 41.09% of damaged signs was used as an input parameter in the simulation.

Table 8.9 Converted Spot Replacement Rate Due Damage in NC

Damage Rate +	Spot Replacement Rate +	Converted Spot Replacement Rate ++
4.04%	1.66%	41.09% *

+ Percent of all signs

++ Converted Spot Replacement Rate = (Spot Replacement Rate / Damage Rate) x 100

* 41.09% of damaged signs

8.1.4 Sign Retroreflectivity Deterioration Models

The sign retroreflectivity deterioration models used in the simulation were developed by Immaneni et al. (2009) who analyzed data from six studies conducted across the U.S. that were focused on sign retroreflectivity deterioration of in service signs (Black et al., 1991; AASHTO, 2005; Kirk et al., 2001; Wolshon et al., 2002; Bischoff and Bullock, 2002; and Rasdorf et al., 2006).

Immaneni et al. (2009) evaluated different regression models (linear, logarithmic, polynomial, power, and exponential) for each of the available data sets with the objective of identifying the best fit. At the end of the study, the author developed a new set of deterioration models for Type III signs for different sheeting colors that resulted in better fitting and higher R^2 values than the original models. The deterioration models proposed by Immaneni et al. (2009) are shown in Table 8.10. The authors mentioned the fact that the standard error (last column of the table) is higher than they desired. However, that was most likely due a combination of differences among the studies, retroreflectometer measurements error, and uncontrolled filed conditions.

The models shown in Table 8.10 are appropriate for the present study, especially considered that part of the data analyzed by Immaneni et al. (2009) was collected in NC (over 1,000 signs). In addition, the R^2 values of these models are good compared to other models in the literature (see Table 5.2). Therefore, the models shown in Table 8.10 were used in the simulation for the NC Case Study.

Table 8.10 Sign Retroreflectivity Deterioration Models for Simulation

Sign Color	Data Source	Deterioration Model *	R^2	Regression Standard Error
White	FHWA (Black et al., 1991)	R_A = 304.089 – 4.815 Age	0.19	32.7
Yellow	Purdue (Bischoff and Bullock, 2002)	R_A = 193.01 + 5.644 Age – 0.552 Age^2	0.26	33.6
Red	NCSU (Rasdorf et al., 2006)	R_A = 59.632 – 2.658 Age	0.35	9.7
Green	FHWA (Black et al., 1991)	R_A = 53.386 – 1.345 Age	0.48	7.7

Notes: * Retroreflectivity unit of measure is candelas per lux per square meter (cd/lx/m^2) and Age in years

8.1.5 Sign Cost

Sign cost is a major part of this study because it is one of the main factors considered by upper management when analyzing different sign replacement strategies. In this study, there are two sign cost components (sign installation and daytime sign inspection unit costs) that were calculated based on the NCDOT Fiscal year 2017-2018 labor ($25.65 per hour), equipment ($17.85 per hour), and material ($8.02 per square foot) unit costs.

8.1.5.1 Sign Installation Unit Cost

Sign installation unit cost refers to all costs incurred in the installation of a ground mounted sign; thus, the unit of measure is dollar amount per sign ($/sign). This cost includes material (e.g., sign sheeting, pole, and bolts), labor, and equipment (e.g., sign truck). While these costs are the same state wide, the sign installation unit cost ($/sign) may vary from division to division because it depends on work productivity.

For this study purpose, the research team used average installation work productivity of to 6.68 square feet per man hour based on data collected by Division 9 over a period of one year. Table 8.11 shows the labor productivity in Fiscal Year 2017-2018 by labor.

Table 8.11 Division 9 Sign Installation Labor Productivity in Fiscal Year 2017-2018

Labor	Work Accomplished (Square Feet)	Man Hours	Productivity (Square Feet / Man Hour)
Labor 1	3,664.16	533.25	6.87
Labor 2	5,152.93	760.25	6.78
Labor 3	2,607.25	437.00	5.97
Labor 4	2,559.04	401.00	6.38
Labor 5	4,783.60	755.00	6.34
Labor 6	4,584.38	674.25	6.80
Labor 7	3,861.27	504.00	7.66
Labor 8	140.35	29.00	4.84
Division Wide	**27,352.98**	**4,093.75**	**6.68**

The productivity ranged from 4.84 to 7.66 square feet per man hour division wide. Note that the lowest productivity of 4.84 square feet per hour was *Labor 8* who worked only 29 hours in sign installation, significantly less than the other laborers. The average labor productivity for the entire division was 6.68 square feet per man hour (27,352.98 square feet / 4,093.75 man hours).

The productivity of the equipment was considered to be double the labor productivity because most (if not all) signs crews consist of two workers and one sign truck. Therefore, equipment productivity is 13.36 square feet per hour. In addition, the present research team also calculated an average ground mounted sign area based on NC sign data collected by Palmquist and Rasdorf (2001). The average area was determined to be 6.16 square feet per sign. The sign installation unit cost (SIUC) was calculated using Equation (7.1), which resulted in \$81.31 per sign.

$$SIUC = \left(\frac{\$25.65/hour}{6.68\ sf/hour} + \frac{\$17.85/hour}{13.36\ sf/hour} + \$8.02/sf\right) \times 6.16\ sf/sign\ = \$81.31/sign$$

8.1.5.2 Daytime Inspection Unit Cost

Daytime sign inspection unit cost depends on equipment cost, labor cost, and inspection productivity (number of signs inspected per hour). Two assumptions were considered to estimate the sign inspection unit cost. The first assumption was that a truck and a two-man crew were required to conduct daytime visual inspections. The second assumption was based on NCDOT data indicating that a two-man crew can inspect an average of 200 signs per hour. The 200 inspected signs per hour was obtained considering an average speed of 40 miles per hour times an average of five signs per mile per road direction (NCDOT estimates that there are 10 signs per mile, five in each direction). The research team then calculated the daytime sign inspection unit cost (DSIUC) using Equation (7.2), which resulted in \$0.35 per sign.

$$DSIUC = \frac{(\$25.65/hour \times 2) + (\$17.85/hour \times 1)}{(40\ miles/hour\ \ \times 5\ signs/mile)} = \$0.35/sign$$

8.2 Control Variables

The remaining simulation input parameters are referred to as *control variables* because they are used (controlled) to model different sign replacement strategies. The control variables include sign replacement cycles, grace period, and daytime inspection, which are discussed in the next subsections.

8.2.1 <u>Blanket Replacement Cycle</u>

NCDOT has used microprismatic Type III sheeting since 2005. Most of the literature reviewed showed that Type III sheeting is expected to perform above the minimum retroreflectivity levels required by the MUTCD for at least 15 to 20 years (see Chapter 5). However, even though a sign service life of 10 years is not expected to be part of an optimal sign replacement strategy, it was considered and simulated in the present study because this is the sign life described in the NCDOT RMIP (NCDOT, 2016). Thus, it is a benchmark strategy.

The research team also simulated a sign service life of 15 years. As discussed in Chapter 6 and previously shown in the literature review, all signs colors performed above the minimum retroreflectivity levels at the age of 15 years old in all models. Another point considered by this author is that most of the previous studies recommended a sign life of at least 15 years of Type III sheeting.

The research team also simulated a sign service life of 15 years based on the fact that most previous studies recommended this sign life for Type III sheeting (see Chapter 5). A sign service life of 18 years was also simulated because in most sign retroreflectivity deterioration studies, Type III signs perform above minimum retroreflectivity levels at this age. Only one deterioration model of red sheeting indicated a sign service life lower than 18 years (Kipp and Fitch, 2009). It is worth mentioning that Kipp and Fitch (2009) analyzed glass beaded Type III sheeting, which has a lower retroreflectivity performance than microprismatic Type III sheeting.

Finally, a sign service life of 20 years was also simulated. The research team chose 20 years as maximum sign service life and replacement cycle because it was the consensus among most deterioration studies that Type III signs would perform above the minimum required retroreflectivity levels at this age.

8.2.2 Grace Period

The concept of grace period was created to reduce material waste. Strategies that adopt a grace period consider that during a year of blanket replacement, undamaged signs that are the same age or younger than the grace period are not replaced. Re and Carlson (2012) identified a DOT that used a grace period of three years and one of the NCDOT divisions adopted a grace period of five years. Given that no previous studies quantified grace period effects, the research team decided to investigate its impact on sign replacement strategies.

Although a grace period might reduce material waste, it grace period is associated with a risk of noncompliance for allowing that signs remain in the field for a longer period. To reduce the risk of noncompliance, the research team investigated a sign age in which white, yellow, and green signs are expected to perform above the minimum retroreflectivity levels (recalling that grace period does not apply to red signs). Analyzing the retroreflectivity deterioration models shown in Figures 5.5, 5.6, and 5.8 (Chapter 5), most models indicated that white, yellow, and green signs are compliant with the MUTCD (FHWA, 2009) requirements at least up to 25 years. In the case of yellow signs, three out 11 models indicated that their service life was between 20 and 25 years. Based on that, the research team established that the maximum age of an in service sign (excluding red signs), considering the grace period, should be 25 years.

Therefore, three options of grace period (zero, three, and five years) were selected based on both the literature and NCDOT practices. Many other possibilities could have been studied; however, the objective of the team was first to quantity the effect of grace periods on sign replacement strategies.

Combining the replacement cycles considered in this study with grace period of zero (absence), three, and five years result in a maximum possible sign age of 25 years.

Table **8.12** shows maximum sign ages (for white, yellow, and green signs) as a function of the combination of replacement cycle and grace period.

Table 8.12 Maximum Sign Age Considering Replacement Cycle and Grace Period Adopted

Replacement Cycle	Grace Period		
	Absence – 0 Year	3 years	5 years
10 years	10	13	15
15 years	15	18	20
18 years	18	21	23
20 years	20	23	25

8.2.3 <u>Daytime Inspection</u>

Daytime inspections are conducted to identify damaged signs and replace them. The research team sought to assess the impact that daytime inspections (or their absence) have on the number of damaged signs (in the field) for different sign replacement strategies.

After simulating strategies with no daytime inspection, if the absence of daytime inspections does not contribute to a higher overall number of unsatisfactory signs, these inspections might be eliminated in the set of optimal strategies. However, if daytime inspections are shown to have a positive impact in reducing the number of unsatisfactory signs, the agency may opt to conduct them.

It is worthy to note that daytime inspections are not conducted in a year of blanket replacement by the simple fact that is unreasonable to inspect signs are already known to be replaced in that same year due to blanket replacement. The sign replacement strategy either considers daytime inspections or not (yes or no; presence or absence). In other words, daytime inspection is a binary control variable. For strategies using daytime inspections, their cycles and frequency between replacement years are expected to occur as shown in Table 8.13.

Table 8.13 Strategies that Consider Daytime Inspections: Daytime Inspection Cycles and frequency in Function of Replacement Cycles

Replacement Cycle	Daytime Inspection Cycle	Daytime Inspection Frequency
10 year	5 year	1
15 year	5 year	2
18 year	6 year	2
20 year	5 year	3

8.3 Sign Replacement Strategies

The sign replacement strategies are represented by a factorial experiment (4x3x2) that was obtained by crossing the different levels of the three control variables. Therefore, crossing the four levels of blanket replacement cycles (10, 15, 18, and 20 years), three levels of grace period (0, 3, and 5 years), and two levels of daytime sign inspection (presence and absence), there were 24 sign replacement strategies to be simulated in this study.

Table 8.14 shows the configuration of each sign replacement strategies. The first column lists the strategies that vary from 1 to 24. The second column indicates the blanket replacement cycle. Note that there are four levels of this control variables. The third column shows the grace period. A grace period of 0 year indicates that the practice is not adopted in the strategy (i.e., there is an absence of grace period). The last column indicates the presence or absence of daytime inspections. In the strategies that consider daytime inspections, their cycle is defined according to Table 8.13 and is a function of the blanket replacement cycle.

Table 8.14 Sign Replacement Strategies and Control Variables Crossing Levels

Strategies	Blanket Replacement Cycle	Grace Period	Daytime Inspections		
			A/P	Cycle	Frequency*
1	10 year	0 year	Absent	-	0
2	10 year	0 year	Present	5	1
3	10 year	3 years	Absent	-	0
4	10 year	3 years	Present	5	1
5	10 year	5 years	Absent	-	0
6	10 year	5 years	Present	5	1
7	15 year	0 year	Absent	-	0
8	15 year	0 year	Present	5	2
9	15 year	3 years	Absent	-	0
10	15 year	3 years	Present	5	2
11	15 year	5 years	Absent	-	0
12	15 year	5 years	Present	5	2
13	18 year	0 year	Absent	-	0
14	18 year	0 year	Present	6	2
15	18 year	3 years	Absent	-	0
16	18 year	3 years	Present	6	2
17	18 year	5 years	Absent	-	0
18	18 year	5 years	Present	6	2
19	20 year	0 year	Absent	-	0
20	20 year	0 year	Present	5	3
21	20 year	3 years	Absent	-	0
22	20 year	3 years	Present	5	3
23	20 year	5 years	Absent	-	0
24	20 year	5 years	Present	5	3

Note: A/P: absence or presence of daytime inspections
* Frequency of daytime inspection between years of blanket replacement

9.0 RESULTS AND ANALYSIS

A set of sign replacement strategies were developed and described in Chapter 8. Before running all the strategies of interest, it was necessary to define three aspects of the simulation: transient removal, simulation length (stopping criteria), and number of replications. Transient removal consists of removing from the data analysis the observations collected during the transient interval, which is the period when the simulation is warming up and that precedes the steady-state. As described by Obaidat and Papadimitriou (2003), removing the transient interval from the results and analysis is essential in any simulation study. The simulation length can be determined by using a stopping criteria that determines how long it is necessary to run the simulation to obtain a desired half width (h). In addition, it was necessary to define the number of replications necessary to obtain an acceptable error of ± 5% as described in Chapter 7 (Section 7.7).

To conduct those analysis, the research team ran 10 replications of two pilot strategies to identify and determine the transient interval, simulation length (stopping criteria), and number of replications necessary to obtain an acceptable error of ± 5%. One of the pilot strategies was Strategy 4 (see Table 8.14) because it is one of the most critical, containing the shortest blanket replacement cycle (10 years), the shortest grace period different from zero (3 years), and considering daytime inspections. In addition, Strategy 24 (see Table 8.14) was also selected as a pilot strategy because it contains the longest blanket replacement cycle (20 years), the longest grace period (5 years), and considers daytime inspections.

To define the transient period, simulation length, and number of replications necessary, the research team analyzed two output measures (number of unsatisfactory signs and strategy cost) resulted from the simulation of the two the pilot strategies (Strategies 4 and 24). A complete description of these analyses is provided in Appendix 12.7.

After analyzing the results of the pilot strategies, the research team concluded the following.

- The transient period ends in Year 20. Therefore, for data analysis purpose, the authors considered observations collected from Year 21 through Year 50.
- A simulation length of 50 years, excluding the transient interval (first 20 years), was found to be enough to obtain a half width of less than 5%.
- Ten replications were found to be enough to obtain a half width less than 5%.

Therefore, each one of the 24 strategies shown in Table 8.14 was replicated ten times and simulated 10,000 signs for a period of 50 years each. After running all 24 strategies, the research team collected the average annual output measures resulted from the simulation model, which consider observations collected from Year 21 to year 50 (30 years of data).

For exemplification purpose, a complete set of results of annual output measures (which is different from *average* annual output measures; see Section 7.5 for more information) for one replication of Pilot Strategy 24 is shown in Appendix 12.9. Note that the first cycle has incomplete data in all tables resulting from the simulation. That happens because the initial sign condition is unknown. A complete data set starts being collected in the second cycle.

This chapter presents the results of the 24 sign replacement strategies from Table 8.14 and discusses them. The authors focused the data analysis on the number of unsatisfactory signs and strategy cost because they are indicators of the efficiency of different strategies. As previously discussed, the number of unsatisfactory signs depends on number of damaged, noncompliant, replaced, and inspected signs while the strategy cost depends on replacement and inspection costs.

These two output measures are the major factors considered by transportation agencies in a decision-making process to select an optimal sign replacement strategy.

9.1 Overall Analysis

Both the number of unsatisfactory signs and strategy cost are affected by other measures such as number of signs replaced, number of signs damaged, etc. Table 9.1 shows the results related to the output measures that affect both the number of unsatisfactory signs and strategy cost. The first four columns of the table describe the strategies and their respective control variables, which include blanket replacement cycle (BRC), grace period (GP), and daytime inspections (DI). The columns in the middle of Table 9.1 (sixth to tenth columns) show the average annual number of damaged, noncompliant, unsatisfactory, replaced, and (daytime) inspected signs. The last three columns (eleventh to thirteenth) show the average annual cost data, including replacement cost, inspection cost, and strategy cost. The strategy cost (sum of inspection and replacement costs) shown in the last column of Table 9.1 was reported with three significant digits.

The number of damaged signs (6th column) at the end of the year (after replacement activities are taken) is overall between 3 and 5% of the signs. With respect to noncompliant signs (7th column), almost all strategies do not result in noncompliant signs. Only Strategies 19 to 24 (20 year replacement cycle) that results in few noncompliant signs. The number of unsatisfactory signs (8th column) is the same as damaged signs for strategies that have zero noncompliant signs (Strategies 1 to 18). For the other strategies (19 to 24), the number of unsatisfactory signs depends on both the number of damaged and noncompliant signs. The number of replaced signs (9th column) always considers a blanket replacement of an area plus spot replacement (all areas) and daytime inspection (for strategies that consider it). Number of daytime inspected signs (10th column) considers signs that were inspected in an area for those strategies that consider it.

As expected, strategies that do not consider daytime inspections resulted in zero inspected sign and inspection cost. With respect to noncompliant signs, most of the strategies (1 to 18) did not result in any noncompliant sign. Strategies 19 to 24 that consider a 20 year replacement cycle resulted in few noncompliant signs, which was less than 0.25% of all signs simulated.

From now on, this section focuses on the number of unsatisfactory signs and strategy cost output measures. A brief discussion of the effect of the control variables on these output measures is provided. At the end of this section, the author conducted a multicriteria analysis with the objective of facilitating the analysis of the different strategies by the NCDOT.

Table 9.1 Sign Replacement Strategies and Average Annual Results

Strategy	Control Variables				Average Annual Number of Signs					Average Annual Cost		
	BRC	GP	DI									
			A/P	Freq.*	Damaged	Noncompliant**	Unsatisfactory***	Replaced	Inspected	Replacement	Inspection	Strategy+
1	10	0	A	0	424	0	424	1,332	0	$108,286	$0	$108,000
2	10	0	P +	1	310	0	310	1,340	1,000	$108,947	$350	$109,000
3	10	3	A	0	424	0	424	1,232	0	$100,192	$0	$100,000
4	10	3	P +	1	310	0	310	1,251	1,000	$101,684	$350	$102,000
5	10	5	A	0	424	0	424	1,174	0	$95,434	$0	$95,000
6	10	5	P +	1	310	0	310	1,216	1,000	$98,896	$350	$99,000
7	15	0	A	0	457	0	457	1,013	0	$82,349	$0	$82,000
8	15	0	P +	2	309	0	309	1,022	1,332	$83,110	$466	$84,000
9	15	3	A	0	457	0	457	946	0	$76,934	$0	$77,000
10	15	3	P +	2	309	0	309	962	1,332	$78,240	$466	$79,000
11	15	5	A	0	457	0	457	906	0	$73,642	$0	$74,000
12	15	5	P +	2	309	0	309	940	1,332	$76,411	$466	$77,000
13	18	0	A	0	475	0	475	908	0	$73,846	$0	$74,000
14	18	0	P +	2	343	0	343	914	1,110	$74,352	$389	$75,000
15	18	3	A	0	475	0	475	853	0	$69,333	$0	$69,000
16	18	3	P +	2	343	0	343	862	1,110	$70,089	$389	$70,000
17	18	5	A	0	475	0	475	820	0	$66,644	$0	$67,000
18	18	5	P +	2	343	0	343	837	1,110	$68,061	$389	$68,000
19	20	0	A	0	484	20	503	855	0	$69,550	$0	$70,000
20	20	0	P +	3	309	21	328	866	1,500	$70,376	$525	$71,000
21	20	3	A	0	484	20	503	804	0	$65,402	$0	$65,000
22	20	3	P +	3	309	21	328	821	1,500	$66,745	$525	$67,000
23	20	5	A	0	484	24	507	774	0	$62,970	$0	$63,000
24	20	5	P +	3	309	23	331	804	1,500	$65,350	$525	$66,000

Note: BRC: Blanket replacement cycle
GP: Grace period
DI: Daytime inspection
A/P: Absence or Presence of daytime inspections
* Freq.: Frequency of daytime inspections between blanket replacement years
** Noncompliant: Below the required minimum retroreflectivity levels
*** Unsatisfactory: Signs that are damaged and/or noncompliant
+ Strategy cost reported with three significant digits.

The simulation results represent a population of 10,000 signs. However, transportation agencies have different sign population size. Therefore, the authors divided the simulation results by the number of signs simulated (10,000) to obtain an average annual percentage of unsatisfactory signs and an average annual strategy cost per sign. This data transformation enables agencies to estimate their costs based on the number of signs they maintain. Table 9.2 shows this data transformation.

The first column of Table 9.2 lists the strategies. The second to fifth columns show the control variables. The sixth column is the Average Annual Number of Unsatisfactory Signs (AAUS) and the seventh column is the Average Annual Strategy Cost (AASC). The last two columns of the table show the transformed data (simulation results divided by 10,000 signs). The AAUS divided by 10,000 signs resulted in the Average Annual Percentage of Unsatisfactory Signs (AAPUS). The AASC divided by 10,000 signs resulted in the Average Annual Strategy Unit Cost (AASUC) per sign.

Table 9.2 Sign Replacement Strategies and Results Divided by 10,000 Signs

Strategy	Control Variables				Results for 10,000 Signs		Simulation Result Divided by 10,000 Signs	
	Blanket Replacement Cycle	Grace Period	Daytime Inspections					
			A/P	Freq.	AAUS	AASC	AAPUS	AASUC
1	10	0	A	0	424	$108,286	4.2%	$10.80
2	10	0	P +	1	310	$109,297	3.1%	$10.90
3	10	3	A	0	424	$100,192	4.2%	$10.00
4	10	3	P +	1	310	$102,034	3.1%	$10.20
5	10	5	A	0	424	$95,434	4.2%	$9.50
6	10	5	P +	1	310	$99,246	3.1%	$9.90
7	15	0	A	0	457	$82,349	4.6%	$8.20
8	15	0	P +	2	309	$83,576	3.1%	$8.40
9	15	3	A	0	457	$76,934	4.6%	$7.70
10	15	3	P +	2	309	$78,706	3.1%	$7.90
11	15	5	A	0	457	$73,642	4.6%	$7.40
12	15	5	P +	2	309	$76,877	3.1%	$7.70
13	18	0	A	0	475	$73,846	4.8%	$7.40
14	18	0	P +	2	343	$74,741	3.4%	$7.50
15	18	3	A	0	475	$69,333	4.8%	$6.90
16	18	3	P +	2	343	$70,478	3.4%	$7.00
17	18	5	A	0	475	$66,644	4.8%	$6.70
18	18	5	P +	2	343	$68,450	3.4%	$6.80
19	20	0	A	0	503	$69,550	5.0%	$7.00
20	20	0	P +	3	328	$70,901	3.3%	$7.10
21	20	3	A	0	503	$65,402	5.0%	$6.50
22	20	3	P +	3	328	$67,270	3.3%	$6.70
23	20	5	A	0	507	$62,970	5.1%	$6.30
24	20	5	P +	3	331	$65,875	3.3%	$6.60

Note: + Daytime inspection cycles as indicated in Table 8.14
AAUS: Average Annual Number of Unsatisfactory Signs
AASC: Average Annual Strategy Cost
AAPUS: Average Annual Percentage of Unsatisfactory Signs
AASUC: Average Annual Strategy Unit Cost

As Table 9.2 shows, the strategy cost per sign (ASSUC) decreases as the replacement cycle increases. This was expected given that a greater replacement cycle results in fewer signs being replaced each year. As a result, the annual cost of a strategy per sign is lower for a replacement cycle of 20 years than it is for 10 years. Strategy 2 resulted in the highest AASUC ($10.90), which considered a replacement cycle of 10 years and the presence of daytime inspections. This same strategy correspondingly resulted in one of the lowest percent of unsatisfactory signs (AAPUS = 3.1%). Strategy 23 (18 year replacement cycle; 5 year grace period, absence of inspection) resulted in the lowest AASUC ($6.30) among all alternatives. However, as expected, this same strategy also resulted in the highest percentage of unsatisfactory signs (AAPUS= 5.1%). These extreme cases show the importance of finding a balance between strategy cost and percentage of unsatisfactory signs. Most likely, strategies 2 and 23 would not be consider as optimal sign replacement strategies by traffic sign managers.

9.1.1 Daytime Inspections

With respect to daytime inspections, it is possible to note from Table 9.2 that they were efficient in reducing the percentage of unsatisfactory signs in all alternatives that considered inspections. There was a reduction in the AAPUS ranging from 26% ((4.2 - 3.1) / 4.2) on a 10 year replacement cycle to 35% ((5.1 - 3.3) / 5.1) on a 20 year replacement cycle. In other words, if there were 100 unsatisfactory signs in the field, strategies that consider daytime inspection could reduce this number by 26 to 35, depending on the replacement cycle adopted.

Those results highlighted the importance of conducting daytime inspections to detect and replace damaged signs. Strategies with a 20 year blanket replacement cycle that had daytime inspections (Strategies 20, 22, and 24) had an AAPUS of 3.3%, which is compatible with strategies that have shorter replacement cycles with daytime inspection (AAPUS ranging from 3.1% to 3.4%). The good performance of Strategies 20, 22, and 24 with respect to the AAPUS was achieved because although their replacement cycle was long (20 years), their daytime inspection cycle was 5 years, reducing drastically the number of damaged signs, and as a consequence, the number of unsatisfactory signs.

In addition, the results also show that within strategies using the same replacement cycle, daytime inspections were basically the only variable affecting the percentage of unsatisfactory signs (grace period did not have a similar affect). Daytime inspections remove damaged signs from the field, thereby reducing the number of unsatisfactory signs. Daytime inspections do lead to a slight increase in the cost (AASUC) (only 1% to 2%), which might be justified considering the benefits of those inspections.

9.1.2 Grace Period

This study quantified the benefits of grace period for the first time. No other study in the literature has done so. The results shown in Table 9.2 indicate that grace period was efficient in reducing the AASUC of all strategies that considered it. Table 9.3 shows only the odd numbered strategies that were used to analyze the efficiency of grace period without the influence of daytime inspections. The costs (AASUC) of Strategies 3 and 5 ($10.00 and $9.50, respectively) were compared to the AASUC of Strategy 1 ($10.80) as shown in the last two columns of Table 9.3. As the table shows, a grace period of 3 years (Strategy 3) resulted in a reduction of 7.4% (($10.80 - $10.00) / $10.80) when compared to Strategy 1 (no grace period). A grace period of 5 years (Strategy 5) resulted in a reduction of 12.0% when compared to the AASUC of Strategy 1.

Similar comparisons were drawn for the other replacement cycles. A 3 year grace period provided a reduction ranging from 6.1% to 7.4% of the base strategy AASUC and a grace period of 5 years lead to greater savings, ranging from 9.5% to 12.0% (see Table 9.3).

Table 9.3 Grace Period Impact on Annual Average Strategy Unit Cost (AASUC)

Strategy	Blanket Replacement Cycle	Grace Period	AASUC	AASUC Reduction Due to Grace Period	
				($)	(%)
1	10 year	0 year	$10.80	$0.00	0.0%
3	10 year	3 years	$10.00	$0.80	7.4%
5	10 year	5 years	$9.50	$1.30	12.0%
7	15 year	0 year	$8.20	$0.00	0.0%
9	15 year	3 years	$7.70	$0.50	6.1%
11	15 year	5 years	$7.40	$0.80	9.8%
13	18 year	0 year	$7.40	$0.00	0.0%
15	18 year	3 years	$6.90	$0.50	6.8%
17	18 year	5 years	$6.70	$0.70	9.5%
19	20 year	0 year	$7.00	$0.00	0.0%
21	20 year	3 years	$6.50	$0.50	7.1%
23	20 year	5 years	$6.30	$0.70	10.0%

Another benefit observed from the grace period practice is that it does not have a negative effect on the number of unsatisfactory signs. For example, consider Strategies 2, 4, and 6 (Table 9.2) that have the same replacement cycle and consider daytime inspections. The only changing control variable is the grace period. However, there is no change in the percentage of unsatisfactory signs (3.1% for all three strategies).

Although that may sound odd, it is a result of the design of the grace period in this study. First, the grace period is not applied to red signs, which are the most safety critical signs and have the shortest service life among all colors. Second, grace period is not applied to damaged signs either. Therefore, if a sign crew member identifies a 1 year old damaged sign during the blanket replacement, he/she replaces that sign no matter what. This avoids an increase in the number of damaged signs and, as a consequence, the number of unsatisfactory signs.

9.1.3 Blanket Replacement Cycle

Considering Strategies 1, 7, 13, and 19 (absence of daytime inspection and grace period), the only changing variable is the replacement cycle. The longest replacement cycles resulted in a reduction in cost (AASUC) by 35% and an increase in the percent of unsatisfactory signs (AAPUS) by 19%. To mitigate the increase of AAPUS when adopting longer replacement cycles, it is necessary to consider both daytime inspections and grace periods to result in more cost-efficient strategies.

With respect to noncompliance (below minimum retroreflectivity), strategies with replacement cycles of 10, 15, and 18 years resulted in zero noncompliant signs. A replacement cycle of 20 years (Strategies 19 to 24) resulted in noncompliant signs (see Table 9.1), which did not occur for other strategies. However, the annual number of noncompliant signs was so low that it did not have a major impact on the AAPUS.

9.1.4 Summary

The results of the simulation clearly quantified damage rate as a major factor to be considered in any sign replacement strategy. This was expected based on the literature reviewed. In fact, it can be observed that damage is now a more critical factor than retroreflectivity when analyzing different sign replacement strategies. This is due to advances in sheeting material and manufacturing process quality improvement.

The results also show that a grace period has a positive impact on strategy costs without increasing the percentage of unsatisfactory signs. On the other hand, daytime inspections considerably reduce the percentage of unsatisfactory signs while only slightly increasing strategy costs. Overall, this study demonstrates that replacement cycles of 15 and 20 years with daytime inspections and a grace period are efficient in reducing strategy costs while keeping a low percentage of unsatisfactory signs.

9.2 Multicriteria Analysis

Most maintenance policies found in the literature, according to Wang (2002), focused on minimizing maintenance costs without considering the system's reliability performance. However, optimal strategies should not consider only cost, but also the system performance (Dekker, 1996; Wang, 2002; Vilarinho et al., 2017). One of the challenges of considering system performance in maintenance strategies is due to the difficulty of quantifying the benefits of maintenance. In the case of sign replacement strategies, the benefits of different strategies were measured through the percentage of unsatisfactory signs. A lower percentage of unsatisfactory signs in the system indicated a better overall performance of the sign replacement strategy.

In the case that more than one factor is considered in the analysis of different strategies, the literature reviewed recommends the use of multicriteria analysis (or optimization) (Liu and Frangopol, 2005; Barone and Frangopol, 2014; Alaswad and Xiang, 2017). Liu and Frangopol (2005) explained that a multicriteria optimization approach results in a set of optimal strategies from which managers can select the most desirable tradeoff between cost, performance, and safety. Therefore, the present research team conducted a multicriteria analysis considering the percentage of unsatisfactory signs and strategy cost in the analysis of different sign replacement strategies.

However, while AASUC is a monetary ($) factor, AAPUS is measured as a percent of the total signs. That may present a challenge for decision makers when evaluating different strategies. Canada et al. (2005) described that in cases where multiple criteria are considered in the analysis of different strategies, the ultimate goal is to use a single measure of value for those criteria that (when associated with each strategy) allows decision makers to draw their conclusions. In this study, our criteria (factors) are AASUC ($) and AAPUS (percentage of signs).

To conduct a multicriteria analysis considering both non-monetary and monetary factors in the analysis, the research team adopted a common value scale as it is explained in the next sub-section. The multicriteria analysis was conducted in three steps. The first was to determine a common value scale for both AASUC and AAPUS. The second step was to determine the importance (weight) of each of these factors in the decision making. The third step was to conduct a weighted evaluation of all 24 strategies. At the end of this section, the results of the multicriteria analysis are discussed.

9.2.1 Common Value Scale

The objective of a common value scale is to associate a single measure of value to different factors (non monetary and monetary) while conducting a multicriteria analysis. The first step was to define a rating range, also known as natural scale that corresponded to the worse and best case for each one of the factors of interest (AASUC and AAPUS). In the case of AASUC, the worst case was represented by the maximum cost of all strategies, which is $10.90 (see Strategy 2 in Table 9.2). Conversely, the best case was represented by the minimum cost of all strategies, which is $6.30 (see Strategy 23 in Table 9.2). A similar process was conducted for the AAPUS. The worst case was represented by the maximum percentage of unsatisfactory signs among strategies, which is 5.1% (see Strategy 23 in Table 9.2). Conversely, the best case was represented by the minimum percentage of unsatisfactory signs among all strategies, which is 3.1% (Strategies 2, 4, 6, 8, 10, and 12 of Table 9.2). Table 9.4 shows the natural scale range for AASUC and AAPUS.

Table 9.4 Natural Scale Range of AASUC ($) and AAPUS (%)

Average Annual Measures	Worse Case	Best Case
AAPUS (Unsatisfactory Signs)	5.1%	3.1%
AASUC (Strategy Cost)	$10.90	$6.30

Note: the worst and best case were obtained by analyzing AASUC and AAPUS of Table 9.2 for the 24 strategies.

The second step was to define a common value scale range. The common value scale is what Canada et al. (2005) referred to as a “single measure of value.” The research team defined the common value scale range from 0 to 100 because it is an intuitive range that allows managers and analysts to conduct an easier and straightforward comparison among different strategies. The worst case is represented by 0 and the best case is represented by 100 on the common value scale.

The third step was to translate the natural scale of the two factors into a common value scale. The translation process was made by plotting the common value scale (y-axis) ranging from 0 to 100 against the natural scale (x-axis) for the two factors using the values shown in Table 9.4.

Figure 9.1 shows the AASUC translation from natural (monetary $) to common scale. Note that the natural scale ranges from $10.90 to $6.30 while the common scale ranges from 0 to 100. The equation shown in the figure is the AASUC conversion rate from natural (*x*) to common (*y*) scale. The same procedure was conducted with the AAPUS, as shown in Figure 9.2. The AAPUS natural scale ranges from 5.1% to 3.1% while the common scale ranges from 0 to 100. The equation shown in the figure is the AAPUS conversation rate from natural (*x*) to common (*y*) scale.

Equations (11.1) and (11.2) show the conversion of AASUC and AAPUS from natural to common value scale. These equations were used to calculated the AASUC and AAPUS of the 24 strategies in the common value scale as shown in the last two columns of Table 9.5 (note that now both factors are measured in the same scale).

$$AASUC_{COMMON\ SCALE} = -21.739 \times AASUC_{NATURAL\ SCALE} + 236.96 \qquad Eq.\ (11.1)$$

$$AAPUS_{COMMON\ SCALE} = -5{,}000 \times AAPUS_{NATURAL\ SCALE} + 255.00 \qquad Eq.\ (11.2)$$

Where:

AASUC $_{\text{COMMON SCALE}}$: Annual average strategy unit cost on the common value scale
AASUC $_{\text{NATURAL SCALE}}$: Annual average strategy unit cost on the common natural scale
AAPUS $_{\text{COMMON SCALE}}$: Annual average percentage of unsatisfactory signs on the common value scale
AAPUS $_{\text{NATURAL SCALE}}$: Annual average percentage of unsatisfactory signs on the common natural scale

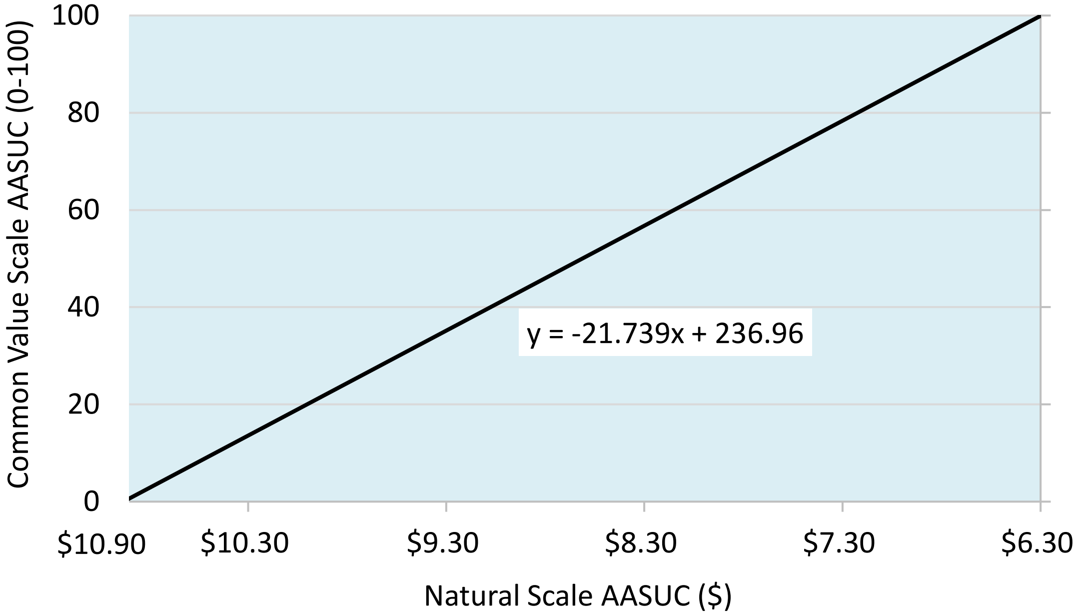


Figure 9.1 Translation of AASUC Natural Scale to Common Value Scale

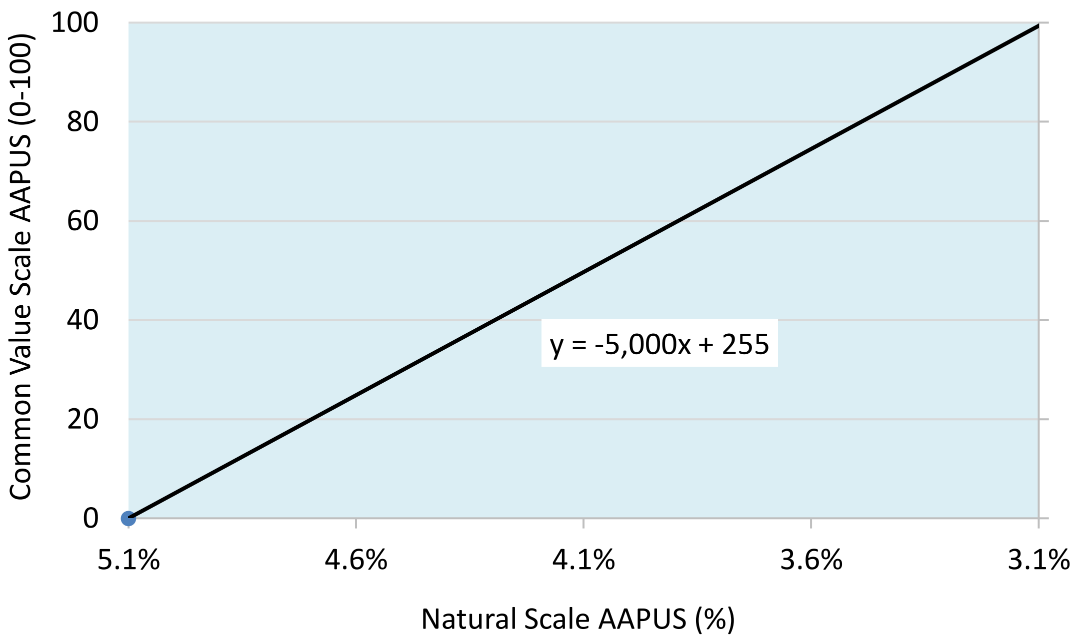


Figure 9.2 Translation of AAPUS Natural Scale to Common Value Scale

Table 9.5 AAPUS and AASUC in the Common Value Scale (Range from 0 to 100)

Strategy	Blanket Replacement Cycle	Grace Period	Daytime Inspections		Natural Scale		Common Value Scale	
			A/P	Freq.	AAPUS	AASUC	AAPUS **	AASUC ***
1	10	0	A	0	4.2%	$10.80	45.0	2.2
2	10	0	P +	1	3.1%	$10.90	100.0	0.0
3	10	3	A	0	4.2%	$10.00	45.0	19.6
4	10	3	P +	1	3.1%	$10.20	100.0	15.2
5	10	5	A	0	4.2%	$9.50	45.0	30.4
6	10	5	P +	1	3.1%	$9.90	100.0	21.7
7	15	0	A	0	4.6%	$8.20	25.0	58.7
8	15	0	P +	2	3.1%	$8.40	100.0	54.4
9	15	3	A	0	4.6%	$7.70	25.0	76.1
10	15	3	P +	2	3.1%	$7.90	100.0	65.2
11	15	5	A	0	4.6%	$7.40	25.0	76.1
12	15	5	P +	2	3.1%	$7.70	100.0	69.6
13	18	0	A	0	4.8%	$7.40	15.0	76.1
14	18	0	P +	2	3.4%	$7.50	85.0	73.9
15	18	3	A	0	4.8%	$6.90	15.0	87.0
16	18	3	P +	2	3.4%	$7.00	85.0	84.8
17	18	5	A	0	4.8%	$6.70	15.0	91.3
18	18	5	P +	2	3.4%	$6.80	85.0	89.1
19	20	0	A	0	5.0%	$7.00	5.0	84.8
20	20	0	P +	3	3.3%	$7.10	90.0	82.6
21	20	3	A	0	5.0%	$6.50	5.0	95.7
22	20	3	P +	3	3.3%	$6.70	90.0	91.3
23	20	5	A	0	5.1%	$6.30	0.0	100.0
24	20	5	P +	3	3.3%	$6.60	90.0	93.5

Note: + Daytime inspection cycles as indicated in Table 8.14
** AAPUS $_{\text{COMMON SCALE}}$ = -5,000 (AAPUS $_{\text{NATURAL SCALE}}$) + 255
*** AASUC $_{\text{COMMON SCALE}}$ = -21.739 (AASUC $_{\text{NATURAL SCALE}}$) + 236.96

9.2.2 Weighting Factors

Once both factors (AAPUS and AASUC) are measured using the same common value scale, the next step was to determine the importance of each factor. The importance of a factor can be measured by attributing a weight to each one of them. The weights of the two factors should sum to 1.00. Canada et al. (2005) described different techniques to assign weights to factors. Some of the techniques described by the authors are uniform weight, rank sum weight, and rank reciprocal weight. However, all those weighting factors techniques are strongly dependent on the priorities of upper management. In the case of sign replacement in NC, it is the NCDOT traffic engineers that judge which factor has higher priority and by how much. In general, it is cost or sign condition? Each transportation agency has a different priority that depends on their culture, organizational structure, and resources.

Therefore, the present author did not attempt to judge the priority and importance of AAPUS and AASUC for the NCDOT. Instead, we simply analyzed different combinations of factors' weights and provided an interpretation for each combination. For instance, consider that α is the weight factor of AAPUS and β is the weight factor of AASUC. Now, if cost is the only driver for a transportation agency, then AASUC has a weight of β =1.00 (maximum) and AAPUS has a weight of α =0.00 (minimum). The different combinations of factors' weights were obtained by decreasing the weight of one factor (e.g., α) by 0.25 while increasing the weight of the second factor (e.g., β) in increments of 0.25. Table 9.6 shows the factors' weights combination and their respective interpretation.

Table 9.6 Weight Combinations Interpretation for AAPUS and AASUC

Combination No.	AAPUS Weight (α)	AASUC Weight (β)	Interpretation
1	1.00	0.00	Percentage of unsatisfactory signs is the only factor considered in the decision making process. The strategy cost is not considered in this combination.
2	0.75	0.25	Both strategy cost and percentage of unsatisfactory signs are considered in the decision making process. However, the percentage of unsatisfactory signs has a major importance in the decision-making process than strategy cost does.
3	0.50	0.50	Both strategy cost and percentage of unsatisfactory signs are equally considered in the decision making process.
4	0.25	0.75	Both strategy cost and percentage of unsatisfactory signs are considered in the decision making process. However, strategy cost has a major importance in the decision-making process than the percentage of unsatisfactory signs does.
5	0.00	1.00	Strategy cost is the only factor considered in the decision making process. The percentage of unsatisfactory signs is not considered in this combination.

Note: The sum of the factors' weights adds up to 1.00 (α + β = 1.00).

9.2.3 Weighted Evaluation Score of Strategies

The third step of the multicriteria analysis is to calculated the weighted evaluation score of all 24 strategies. At this point, both AASUC and AAPUS are measured in the same common value scale and a set of weight combinations was defined for these two factors. Thus, it was possible to calculate the weighted evaluation score (WE) for each strategy for each weight combination by using Equation (11.3).

$$WE = (AAPUS_{COMMON\ SCALE} \times \alpha) + (AASUC_{COMMON\ SCALE} \times \beta) \qquad Eq.\ (11.3)$$

Where:

WE: Weighted evaluation score

$AAPUS_{COMMON\ SCALE}$: Annual average percentage of unsatisfactory signs on the common value scale

$AASUC_{COMMON\ SCALE}$: Annual average strategy unit cost on the common value scale

α: weight of the factor AAPUS ($0 \leq \alpha \leq 1$)

β: weight of the factor AASUC ($0 \leq \beta \leq 1$)

The weighted evaluation score ranges from 0 to 100 (the same as the common value scale). The higher the weighted evaluation score is, the better the strategy is compared to the others within that same weight combination. Table 9.7 shows the five weight combinations and their respective weighted evaluation scores (WE) for each of the 24 strategies analyzed. Figure 9.3 shows a column graph of the data contained in Table 9.7. Five columns were plotted for each strategy. Each column represents one weighted combination from Table 9.7.

9.2.4 Discussion

For the weight combination 1 (eight column of Table 9.7) in which percentage of unsatisfactory signs is the only factor considered in the decision-making process (α =1.00 and β=0.00), the highest weighted evaluation score (WE =100.0) are those strategies with a 10 and 15 year replacement cycle that consider daytime inspections (Strategies 2, 4, 6, 8, 10, and 12). Still considering weight combination 1, Strategies 20, 22 and 24 had the second largest weighted evaluation score (WE =90.0). These strategies consist of a 20 year replacement cycle with daytime inspections. Strategies 14, 16, and 18 that have an 18 year replacement cycle and daytime inspections had a performance slightly lower (WE = 85.0) to the strategies that considered a 20 year replacement cycle and daytime inspections (Strategies 20, 22, and 24). That is because Strategies 14, 16, and 18 have two daytime inspections between replacement years while Strategies 20, 22, and 24 have three daytime inspections between replacement years. With more inspections, more damaged signs are identified and replaced. Thus, the percentage of unsatisfactory signs is lower for Strategies 20, 22, and 24, resulting in a higher WE score. All other strategies that did not have daytime inspection had a considerably lower weighted evaluation score (WE < 50).

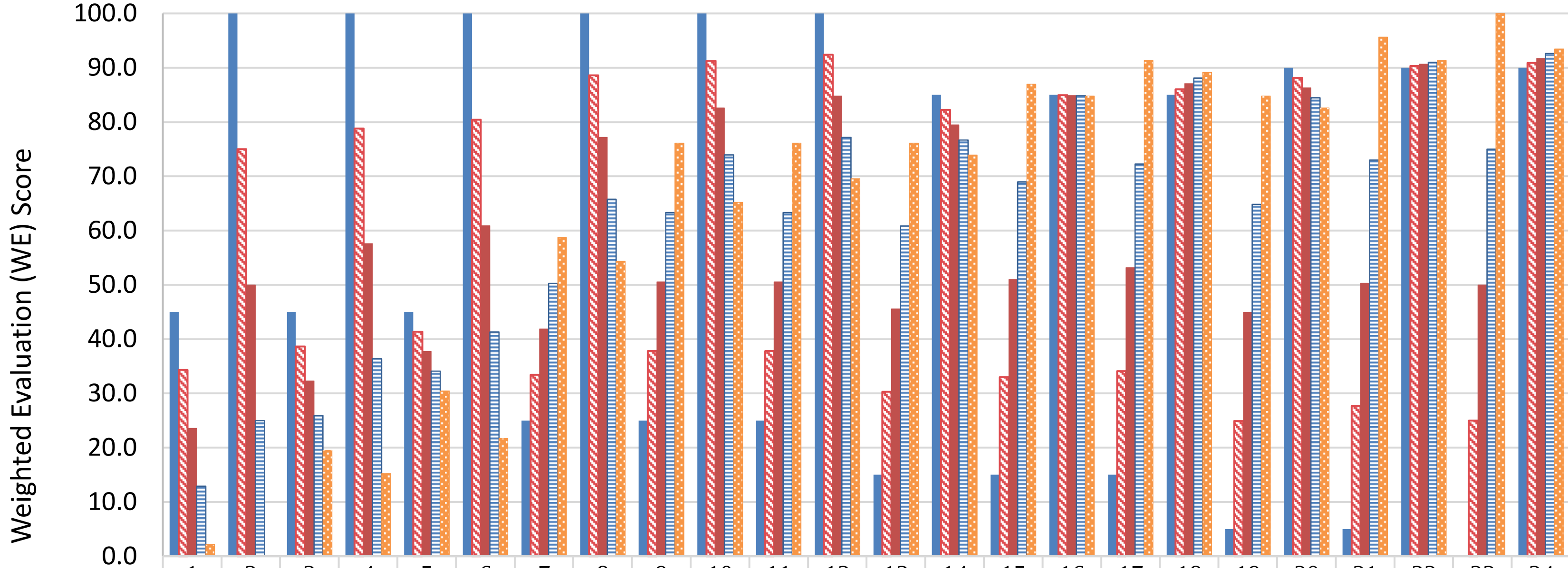
For the weight combination 2 (ninth column of Table 9.7), in which percentage of unsatisfactory has a higher weight than strategy cost ($\alpha > \beta$), the strategies with daytime inspections had a better performance than the strategies without inspections (similar to what occurred for weight combination 1). Strategy 12 had the best performance with a weighted evaluation score of 92.4, followed by Strategy 10 with a weighted evaluation score of 91.3. Both strategies consist of a 15 year replacement cycle, daytime inspections, and a grace period. The advantage of Strategy 12 over Strategy 10 is that the first one had a grace period of 5 years while the second one had a grace period of 3 years. With a grace period of 5 years, Strategy 12 had a lower strategy unit cost, which made it a more attractive alternative than Strategy 10. Analyzing the weight combination 2, it is possible to note that grace period started playing a role in the weighted evaluation score, which did not occur in the weight combination 1.

Still considering the weight combination 2, Strategies 24 (WE = 90.9) and 22 (WE = 90.3) had the third and fourth best performance, respectively. Both strategies consist of a 20 year replacement cycle with daytime inspections and a grace period. Similar to what happened to Strategies 12 and 10, the advantage of Strategy 24 over Strategy 22 is that the first one had a grace period of 5 years while the second one had a grace period of 3 years. Overall, strategies that consisted of 10 and 18 year replacement cycles and had daytime inspections (Strategies 2, 4, 6, 14, 16, and 18) did not have as good performance as those with 15 and 20 year replacement cycles. All other strategies that did not have daytime inspections had considerably lower weighted evaluation score (WE < 50).

Table 9.7 Weighted Evaluation (WE) Score of Sign Replacement Strategies by Weight Combination

Strategy	Blanket Replacement Cycle	Grace Period	Daytime Inspections		Common Scale		Weighted Evaluation (WE)				
			A/P	Freq.	AAPUS	AASUC	Comb 1* α =1.00 β=0.00	Comb 2* α =0.75 β=0.25	Comb 3* α =0.50 β=0.50	Comb 4* α =0.25 β=0.75	Comb 5* α =0.00 β=1.00
1	10	0	A	0	45.0	2.2	45.0	34.3	23.6	12.9	2.2
2	10	0	P +	1	100.0	0.0	100.0	75.0	50.0	25.0	0.0
3	10	3	A	0	45.0	19.6	45.0	38.6	32.3	25.9	19.6
4	10	3	P +	1	100.0	15.2	100.0	78.8	57.6	36.4	15.2
5	10	5	A	0	45.0	30.4	45.0	41.4	37.7	34.1	30.4
6	10	5	P +	1	100.0	21.7	100.0	80.4	60.9	41.3	21.7
7	15	0	A	0	25.0	58.7	25.0	33.4	41.9	50.3	58.7
8	15	0	P +	2	100.0	54.4	100.0	88.6	77.2	65.8	54.4
9	15	3	A	0	25.0	76.1	25.0	37.8	50.5	63.3	76.1
10	15	3	P +	2	100.0	65.2	100.0	91.3	82.6	73.9	65.2
11	15	5	A	0	25.0	76.1	25.0	37.8	50.5	63.3	76.1
12	15	5	P +	2	100.0	69.6	100.0	92.4	84.8	77.2	69.6
13	18	0	A	0	15.0	76.1	15.0	30.3	45.5	60.8	76.1
14	18	0	P +	2	85.0	73.9	85.0	82.2	79.5	76.7	73.9
15	18	3	A	0	15.0	87.0	15.0	33.0	51.0	69.0	87.0
16	18	3	P +	2	85.0	84.8	85.0	84.9	84.9	84.8	84.8
17	18	5	A	0	15.0	91.3	15.0	34.1	53.2	72.2	91.3
18	18	5	P +	2	85.0	89.1	85.0	86.0	87.1	88.1	89.1
19	20	0	A	0	5.0	84.8	5.0	24.9	44.9	64.8	84.8
20	20	0	P +	3	90.0	82.6	90.0	88.2	86.3	84.5	82.6
21	20	3	A	0	5.0	95.7	5.0	27.7	50.3	73.0	95.7
22	20	3	P +	3	90.0	91.3	90.0	90.3	90.7	91.0	91.3
23	20	5	A	0	0.0	100.0	0.0	25.0	50.0	75.0	100.0
24	20	5	P +	3	90.0	93.5	90.0	90.9	91.7	92.6	93.5

Note: * Comb: Weight Combination as described in Table 9.6.
Freq.: Frequency of daytime inspections between blanket replacement years
A/P: Absence or Presence of daytime inspections
AAPUS: Average Annual Percentage of Unsatisfactory Signs
AASUC: Average Annual Strategy Unit Cost
α: weight of the factor AAPUS ($0 \leq \alpha \leq 1$)
β: weight of the factor AASUC ($0 \leq \beta \leq 1$)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Combination 1	45.0	100.	45.0	100.	45.0	100.	25.0	100.	25.0	100.	25.0	100.	15.0	85.0	15.0	85.0	15.0	85.0	5.0	90.0	5.0	90.0	0.0	90.0
Combination 2	34.3	75.0	38.6	78.8	41.4	80.4	33.4	88.6	37.8	91.3	37.8	92.4	30.3	82.2	33.0	84.9	34.1	86.0	24.9	88.2	27.7	90.3	25.0	90.9
Combination 3	23.6	50.0	32.3	57.6	37.7	60.9	41.9	77.2	50.5	82.6	50.5	84.8	45.5	79.5	51.0	84.9	53.2	87.1	44.9	86.3	50.3	90.7	50.0	91.7
Combination 4	12.9	25.0	25.9	36.4	34.1	41.3	50.3	65.8	63.3	73.9	63.3	77.2	60.8	76.7	69.0	84.8	72.2	88.1	64.8	84.5	73.0	91.0	75.0	92.6
Combination 5	2.2	0.0	19.6	15.2	30.4	21.7	58.7	54.4	76.1	65.2	76.1	69.6	76.1	73.9	87.0	84.8	91.3	89.1	84.8	82.6	95.7	91.3	100.	93.5

10 Year Replacement Cycle — 15 Year Replacement Cycle — 18 Year Replacement Cycle — 20 Year Replacement Cycle

Strategies (*x-axis*)

Figure 9.3 Weighted Evaluation Score of Sign Replacement Strategies by Weight Combination

*Note: the combinations1 to 5 refer to the weight combinations described in Table 9.6

For the weight combination 3 (tenth column of Table 9.7), in which percentage of unsatisfactory and strategy cost are equally considered in the decision-making process ($\alpha = \beta = 0.5$), both daytime inspection and grace period played a role in the weighted evaluation score. It is also possible to notice a subtle trend of replacement cycle influencing the weighted evaluation score with longer replacement cycles leading to higher scores (while still considering daytime inspection and grace period).

In weight combination 3, the best weighted evaluation scores are concentrated in strategies that had 18 and 20 year replacement cycles with daytime inspections. Strategy 24 had the best performance (WE = 91.7) followed by Strategy 22 (WE = 90.7). Both strategies consist of a 20 year replacement cycle, daytime inspections, and a grace period. The advantage of Strategy 24 over Strategy 22 is that Strategy 24 had a grace period of 5 years while Strategy 22 had a grace period of 3 years. Strategy 18 had the third best performance with a weighted evaluation score of 87.1. This strategy consists of an 18 year replacement cycle with daytime inspections and a 5 year grace period. The fourth best performance was Strategy 20 (WE = 86.3) that consists of a 20 year replacement cycle with daytime inspections and no grace period. Strategies 16 (WE = 84.9), 12 (WE = 84.8), and 10 (WE = 82.6) also had good performance, all of them with daytime inspections and a grace period. Strategies with a 10 year replacement cycle (1 to 6) had an overall lower weighted evaluation score than other strategies (WE < 61). All strategies that did not consider daytime inspections also had lower weighted evaluation scores (WE < 54).

For the weight combination 4 (eleventh column of Table 9.7), in which strategy cost has a higher weight in the decision-making process ($\alpha < \beta$) than unsatisfactory signs, the results were very similar to those of combination 3. The five highest weighted evaluation scores were concentrated in the strategies that consisted of 18 and 20 year replacement cycles with daytime inspections, from which four strategies had a grace period (Strategies 16, 18, 22, and 24) and one did not (Strategy 20).

In weighted combination 4, Strategy 24 had the best performance (WE = 92.6) followed by Strategy 22 (WE = 91.0). Both strategies consist of a 20 year replacement cycle, daytime inspections, and a grace period. Again, the advantage of Strategy 24 over Strategy 22 is that the first one had a grace period of 5 years while the second one had a grace period of 3 years. Strategy 18 had the third best performance (WE = 88.1), followed by Strategy 16 (WE = 84.8) in fourth place. Those two strategies (18 and 16) consist of an 18 year replacement cycle with daytime inspections and grace period. A grace period of five years (Strategy 18) resulted in greater benefits than a grace period of 3 years (Strategy 16). The fifth best strategy for combination 4 was Strategy 20 (WE = 84.5), which consists of a 20 year replacement cycle and daytime inspections without a grace period.

It is clear and obvious that strategies with shorter replacement cycles (Strategies 1 to 12) are not among the best options when strategy cost has a higher weight than percentage of damaged signs. Indeed, strategies with a 10 year replacement cycle (Strategies 1 to 6) resulted in the worst weighted evaluation score (WE < 42) for the weight combination 4.

The last weighted combination is the number 5 (last column of Table 9.7) and indicates that strategy cost is only factor considered in the decision-making process ($\alpha = 0.00$ and $\beta = 1.00$). Once the percentage of unsatisfactory signs is no longer a factor to be considered, the strategies with greater replacement cycles had the best performance. Daytime inspections stop being a major factor as was the case in the other combinations. As a result, the two strategies with higher weighted evaluation scores did consider daytime inspections (Strategies 21 and 23). Strategy 23 (WE = 100.0) had the best performance followed by Strategy 21 (WE = 95.7). Both these strategies consist of a 20 year replacement cycle with a grace period and no inspections. Once again, a longer grace period of 5 years (Strategy 23) led to a better weighted evaluation score than a grace period of 3 years (Strategy 21).

Still considering the weight combination 5, Strategies 24 (WE = 93.5) and 22 (WE = 91.3) had the third and fourth best performance, respectively. Both strategies consist of a 20 year replacement cycle, with daytime inspections and grace period. Again, a grace period of 5 years led to better results. Strategies 13 to 18 (18 year replacement cycle) had weighted evaluation performance ranging from 73.9 (satisfactory) to 91.3 (good). Strategies 7 to 12 (15 year replacement cycle) had weighted evaluation scores ranging from 54.4 to 69.6 (satisfactory). Strategies 1 to 6 (10 year replacement cycle) had weighted evaluation scores ranging from 0.0 (very poor) to 30.4 (poor).

9.2.5 Summary

With results presented here, transportation agencies have valuable information to consider in their sign replacement decision-making process. Upper management can evaluate the priorities of the agency with respect to sign condition (percentage of unsatisfactory signs) and strategy unit cost (cost per sign per year). This study provided five possible combinations of priority and, based on them, calculated a weighted evaluation score (WE) for each sign replacement strategy. After establishing its priorities, a transportation agency can analyze the scores shown in Table 9.7 and Figure 9.3 to identify which strategies attend their best interest.

10.0 CONCLUSIONS AND FUTURE WORK

After analyzing the literature and information obtained from DOTs, the research team concluded that the adoption of a service life shorter than 15 years for microprismatic Type III sheeting should be avoided because it results in replacing signs before the end of their service life. A sign service life of 15 years seems to be the most balanced among DOTs' practices and previous studies' recommendations. All deterioration models but one (red signs; Kipp and Fitch, 2009) showed that Type III sheeting performs above the minimum retroreflectivity levels for all colors at an age of 20 years. Therefore, adopting a sign service life ranging from 15 to 20 years is realistic.

By evaluating the five sign retroreflectivity maintenance methods described by the MUTCD, the research team identified the **Blanket Replacement method** as being the most suitable for the NCDOT considering the number of state-maintained signs in NC and the fact that the NCDOT does not have a sign inventory database.

The simulation model developed by the research team was successful in representing blanket replacement of one area per year, which resulted in an overall balanced sign replacement workload and cost over time. Never before had an area based approach to sign modeling been implemented. In addition, it is the first time that both grace period and daytime inspections were incorporated into a model, studied, and their benefits quantified. The use of **simulation showed itself to be efficient** in representing a sign system. It allowed the representation of a complex physical system and the manipulation of control variables (sign replacement cycle, grace period, and daytime inspection cycle) to run experiments and compare alternative sign replacement strategies. Another positive aspect of the simulation is that it permits the representation of the random aspects of a sign system, including sign damage and spot replacement.

A set of sign replacement strategies based on the Blanket Replacement method were developed (by varying replacement cycle, grace period, and daytime inspections), simulated, and analyzed. Although the authors used NCDOT data to run the simulation, the simulation results are good indicators for other transportation agencies with respect to the trade-off of different strategies and the benefits of practices such as daytime inspections and grace periods.

One of the first conclusions that it is possible to draw from the simulation is that with technological advances of sign sheeting and manufacturing, **retroreflectivity deterioration is not the major factor** influencing the number of unsatisfactory signs as it was in the past. The use of more retroreflective material such as microprismatic Type III sheeting allows signs to perform above required minimum retroreflectivity levels for at least 15 to 20 years. The major factor influencing the number of unsatisfactory signs is sign damage. Thus, replacement cycles of 10, 15, and 18 years did not result in any noncompliant signs. Even in the case of a 20 year replacement cycle, the results indicated a very low number of noncompliant signs (less than 0.25%).

With respect to the **blanket replacement cycle** length, simulation results indicated that, for strategies without a grace period and daytime inspections, a shorter replacement cycle (10 years) led to higher costs but a lower percentage of unsatisfactory signs than did longer replacement cycles (e.g., 20 years). However, the same did not hold true for sign replacement strategies that considered grace period and daytime inspections. When those were included, longer replacement cycle lengths significantly reduced costs while keeping a low percentage of unsatisfactory signs.

Daytime inspections were found to be very efficient in reducing the percentage of unsatisfactory signs (26% to 35% reduction) while only slightly increasing strategy cost (up to 4.7% cost increase). While daytime inspections had a major positive impact on the percentage of unsatisfactory signs, **grace period** had a major positive impact on strategy costs, reducing them by up to 12% without having any negative impact on the percentage of unsatisfactory signs. In addition, a grace period of 5 years was found to be more efficient in reducing costs than a grace period of 3 years.

Considering all strategies analyzed, those with a replacement cycle of 15 and 20 years, daytime inspections, and a grace period resulted in some of the most cost efficient strategies. Therefore, the research team recommends that NCDOT **considers conducting periodic daytime inspections** to keep the number of unsatisfactory signs under control. A daytime inspection cycle of 5 years was found to be efficient in doing so.

In addition, when using the Blanket Replacement method, a **grace period practice also should be adopted**. A grace period of 5 years is preferable to 3 years for providing greater savings without increasing the number of unsatisfactory signs. Also, by adopting the Blanket Replacement method, agencies do not need to maintain a robust sign database inventory. Instead, a simple record keeping of the replacement areas and years of replacement is sufficient.

The research team also conducted a **multi-criteria analysis** considering different weights (importance level) for strategy cost and unsatisfactory signs. By doing so, the NCDOT can establish what its priority is and, based on it, select sign replacement strategies that resulted in a higher weighted evaluation score (WE).

During the implementation phase of the RMIP for sign management, which consists of the Blanket Replacement method, it is suggested that well defined areas that have approximately the same number of signs be defined. It is also important to track those areas and record the years in which their signs were replaced. A critical aspect of the blanket replacement implementation is its first replacement cycle. During the first cycle, divisions may opt to conduct periodic nighttime visual inspections to identify noncompliant signs in areas that are scheduled to be the last replaced within a replacement cycle. During the nighttime inspections, sign crews can also assess sign damage. Once the first replacement cycle is completed, there is no need to continue conducting nighttime visual inspections. In the meantime, spot replacement continues to be conducted every year in all areas.

Finally, the sign replacement simulation model developed by the authors enabled the analysis of different replacement strategies to assess the impact of replacement cycle, grace period, and daytime inspections on two of the most important key factors considered by traffic managers: sign condition and replacement cost. The simulation allows users to change the input parameters to represent, with more fidelity, NCDOT's needs and operational practices. In addition, as retroreflective sheeting is improved over time, new sign retroreflectivity deterioration models can be updated in the simulation to assess the performance of longer blanket replacement cycles.

10.1 Future Work

As discussed in Chapter 7, it was not possible to conduct a validation of the sign replacement model proposed herein by comparing real system data with the model output measures. Future efforts should be undertaken to address this limitation. The NCDOT is currently implementing the Blanket Replacement method. Once the initial implementation phase is completed, a sufficient data set that includes strategy cost and number of unsatisfactory signs will be available. When that happens, it will be possible to use field data as input parameters and compare the simulation results with field measured data.

With respect to daytime inspections, this is the first time this kind of inspection was studied and its benefits quantified. However, further study is needed in this area. For instance, this report made a comparison between two grace period thresholds (3 and 5 years). Results showed that a grace period of 5 years is more preferable than 3 years because it led to a lower strategy cost while not negatively affecting the number of unsatisfactory signs. Likewise, the research team believes that a sensitivity analysis for daytime inspection frequency should be conducted. Therefore, future research efforts should investigate the effects of different daytime inspection frequencies on both strategy cost and number of unsatisfactory signs. Table 10.1 below shows a set of proposed daytime inspection cycles and frequencies considering an 18 year blanket replacement cycle.

Table 10.1 Proposed Daytime Inspection Cycles and Frequencies Considering an 18 Year Blanket Replacement Cycle

Daytime Inspection Factor	18 Year Replacement Cycle			
Inspection Cycle (Years)	2	3	6	9
Frequency of Inspections within a Replacement Cycle	8	5	2	1

In addition, future research will investigate daytime inspections considering different sign replacement priorities. The present study assumed that all signs found to be damaged during daytime inspections were replaced no matter what. However, it would be interesting to investigate the effects that sign replacement priority (e.g., replace only red signs because of their safety criticality) have on strategy cost and the number of unsatisfactory signs.

Finally, the research team recommends a much more **urgent need**. As the new RMIP is implemented, a study of how to measure its success and tis performance is highly recommended. What parameters should NCDOT be examining as this process is implemented and executed? What data should and can be collected? How can success be measured without data? What technology is needed? How can this be done without process disruption, in a manner that does not detract from the work? Answers to these questions could put a salient monitoring and assessment system in place to ensure and to quantify the success and achievement of the new process.

11.0 REFERENCES

AbouRizk, S. (2010). "Role of Simulation in Construction Engineering and Management," *Journal of Construction Engineering and Management*, American Society of Civil Engineers, Washington D.C., Volume 136, Number 10, Pages 1140 – 1153.

Ahmed, S. (1994). "Evaluation of Retroreflective Sheeting for use on Roadways," Report FHWA/OK Volume 95, Number 02, Oklahoma Department of Transportation, Oklahoma City, Ok. Retrieved on 11/28/18 from: file:///C:/Users/pvmachad/Downloads/FHWA-OK-95-02%20Evaluation%20of%20retroflective%20sheetings%20for%20use%20on%20roadway%20traffic%20signs.pdf

Alaska Department of Transportation (Alaska DOT) (2017). "State of Alaska: Certified Public Road Mileage in Centerline Miles." Retrieved on 11/28/18 from http://dot.alaska.gov/stwdplng/transdata/pub/2017cprmFinal.pdf

Alaswad, S. and Xiang, Y. (2017). "A Review on Condition-Based Maintenance Optimization Models for Stochastically Deteriorating System," *Reliability Engineering and System Safety*, Elsevier Science Ltd, Volume 157, Pages 54-63. Retrieved on 2/17/19 from: https://doi.org/10.1016/j.ress.2016.08.009

American Association of State Highway and Transportation Officials (AASHTO) (2005). "Three Year Results of Outdoor Exposure Data on Sign Sheeting Materials." 2000 NTPEP Deck, AASHTO's National Transportation Product Evaluation Program.

American Society for Testing Materials (ASTM) D4956-17 (2017). "Standard Specification for Retroreflective Sheeting for Traffic Control," ASTM International, West Conshohocken, PA. DOI: 10.1520/D4956-17.

Avery Dennison (2018). "Avery Dennison® T-6000 & W-6000 HIP Series High Intensity Microprismatic Retroreflective Film - Product Data Sheet," Avery Dennison Corporation, Niles, IL. Retrieved on 12/06/18 from: https://reflectives.averydennison.com/content/dam/averydennison/reflective-responsive/documents/english/pdb/retroreflective-sheeting/T6000_WW_ENG_04122018.pdf

Balali, V., Rad, A., and Golparvar-Fard, M. (2015). "Detection, Classification, and Mapping of U.S. Traffic Signs Using Google Street View Imaged for Roadway Inventory Management," *Visualization in Engineering*, Springer International Publishing, Volume 3, Number 1, Pages 1-18 Retrieved on 2/17/19 from: https://doi.org/10.1186/s40327-015-0027-1

Barone, G. and Frangopol, D. (2014). "Life-Cycle Maintenance of Deteriorating Structures by Multi-Objective Optimization Involving Reliability, Risk, Availability, Hazard and Cost," *Structural Safety*, Elsevier Science Ltd, Volume 48, Pages 40-50. Retrieved on 2/17/19 from: https://doi.org/10.1016/j.strusafe.2014.02.002

Bernhardt, S. and McNeil, S. (2004). "Modeling Interdependencies in Infrastructure Management Using Complex Systems," *Eighth International Conference on Applications of Advanced Technologies in Transportation Engineering*, American Society of Civil Engineers, Beijing, China, Pages 261-265.

Bischoff, A. and Bullock, D. (2002). “Sign Retroreflectivity Study,” Publication FHWA/IN/JTRP-2002/22. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.

Black, K., McGee, H, Hussain, S., and Rennilson, J. (1991). “Service Life of Retroreflective Traffic Signs,” Publication FHWA-RD-90-101, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Blincoe, L., Miller, T., Zaloshnja, E., and Lawrence, B., (2015). The Economic and Societal Impact of Motor Vehicle Crashes 2010 (Revised). National Highway Traffic Safety Administration, Washington, DC. Retrieved on 8/13/18 from https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812013

Boggs, W., Heaslip, K., and Louisell, C. (2013). “Analysis of Sign Damage and Failure: Utah Case Study,” *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C. Number 2337, Pages 83 – 89.

Carlson, P. and Picha, D. (2009). “Sign Retroreflectivity Manual: How to Meet the New National Standard for Small Agencies, Federal Land Management Agencies, and Tribal Governments,” *Project FHWA-CFL/TD-09-005,* Federal Highway Administration, Washington D.C.

Carlson, P., Park, E., and Andersen, C. (2009). “Benefits of Pavement Markings A Renewed Perspective Based on Recent and Ongoing Research,” *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C., Number 2107, Pages 59 – 68.

Carlson, P. (2011). “Evaluation of Sign Retroreflectivity Measurements from the Advanced Mobile Asset Collection (AMAC) System,” Texas Transportation Institute, College Station, TX.

Clevenger, K., Colello, K., and Quirus, J. (2012). “Retroreflectivity of Existing Signs in Pennsylvania,” *Report No FHWA-PA-2012-003-E01041-W09*. Mc Cormick Taylor Engineers and Planners, Philadelphia, PA.

Cooksey, S., Jeong, D., and Char, M. (2011). “Asset Management Assessment Model for State Departments of Transportation,” *Journal of Management in Engineering*, American Society of Civil Engineers, Washington D.C., Volume 27, Number 3, Pages 159 – 169.

Cunard, R. (1990). “Maintenance Management of Street and Highway Signs,” NCHRP Synthesis of Highway Practice 157, Transportation Research Board National Research Council, Washington, D.C.

Dekker, R. (1996). “Applications of Maintenance Optimization Models: A Review and Analysis,” *Reliability Engineering and System Safety*, Elsevier Science Ltd, Volume 51, Number 3, Pages 229-240. Retrieved on 2/17/19 from: https://doi.org/10.1016/0951-8320(95)00076-3

De la Graza, J., Drew, D., and Chasey, A. (1998). “Simulating Highway Infrastructure Management Policies,” *Journal of Management in Engineering*, American Society of Civil Engineers, Washington D.C.,Volume 14, Number 5, Pages 64-72.

Dumont, T., Johnson, S., Lechtenberg, B., Lott, H., McGraw, J., Moser, M., Persoon, R., Tayse, J., Wenkel, K., Chalupnik, T., and Ficek, B. (2013). "Evaluation of MnDOT's Sign Replacement Method," *Project 15310.000*, Minnesota Department of Transportation, Saint Paul, MN.

Ellison, J. (2008) "Tapping into the Power of a Traffic Sign Inventory to Meet the New Retroreflectivity Requirements," Compendium of Technical Papers, Institute of Transportation Engineers 2008 Annual Meeting and Exhibit, Anaheim, CA.

Evans, T., Heaslip, K., Boggs, W., Hurwitz, D., and Gardiner, K. (2012). "Assessment of Sign Retroreflectivity Compliance for Development of a Management Plan," *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C., Number 2272, Pages 103 – 112.

Federal Highway Administration (FHWA) (1999). "Asset Management Primer," U.S. Department of Transportation, Washington, D.C. Retrieved on 3/22/2019 from: https://www.mdt.mt.gov/publications/docs/brochures/research/toolbox/fhwa/asstmgmt.pdf?bcsi_scan_e881b9121136f8e3=0&bcsi_scan_filename=asstmgmt.pdf

Federal Highway Administration (FHWA) (2007). "Methods for Maintaining Traffic Sign Retroreflectivity," Publication No FHWA-HRT-08-026, U.S. Department of Transportation, Washington, D.C. Retrieved on 3/18/2019 from: https://safety.fhwa.dot.gov/roadway_dept/night_visib/policy_guide/fhwahrt08026/fhwahrt08026.pdf

Federal Highway Administration (2009). "Manual on Uniform Traffic Control Devices: 2009 Edition," U.S. Department of Transportation, Washington, D.C. Retrieved on 2/17/19 from: https://mutcd.fhwa.dot.gov/pdfs/2009/mutcd2009edition.pdf

Federal Highway Administration (2013), "Maintaining Traffic Sign Retroreflective." Retrieved on 2/17/19 from: https://safety.fhwa.dot.gov/roadway_dept/night_visib/sign_retro_4page.pdf

Federal Highway Administration (2014), "2014 Traffic Sign Retroreflective Sheeting Identification Guide." Retrieved on 2/17/19 from: https://safety.fhwa.dot.gov/roadway_dept/night_visib/sign_visib/sheetguide/

Federal Highway Administration (2017). "Highway statistics 2016 Table HM-81: State Highway Agency-Owned Public Roads," U.S. Department of Transportation, Washington, D.C. Retrieved on 06/28/18 from: https://www.fhwa.dot.gov/policyinformation/statistics/2016/hm81.cfm

Harris, E., Rasdorf, W., and Hummer, J. (2007). "Analysis of Traffic Sign Asset Management Scenarios," *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C., Number 1993, Pages 9 – 15.

Halpin, D. (1977). "Cyclone: Method for Modeling of Job Site Processes," *Journal of the Construction Division*, American Society of Civil Engineers, Washington D.C., Volume 103, Number 3, Pages 489 – 499.

Harris, E., Rasdorf, W., and Hummer, J. (2009). "A Control Sign Facility Design to Meet the New FHWA Minimum Sign Retroreflectivity Standards," *Public Works Management & Policy*, SAGE Journals, Washington D.C., Volume 14, Number 2, Pages 174 – 194.

Harris, E. (2010). “Sign Maintenance Strategies for Agencies to Comply with the FHWA Minimum Retroreflectivity Standards,” North Carolina State University, Raleigh NC.

Harris, E., Rasdorf, W., and Hummer, J. (2012). “Development of a Microscopic Simulation to Model Traffic Sign Management and Performance,” *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, Washington D.C., Volume 26, Number 2, Pages 172 – 182.

Hawkins, H. and Carlson, P. (2001). “Sign Retroreflectivity: Comparing Results of Nighttime Visual Inspections with Application of Minimum Retroreflectivity Values,” *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C., Number 2464, Pages 11 – 20.

He, Y., Sonf, Z., and Liu, Z. (2017). “Updating Highway Asset Inventory Using Airborne LIDAR,” *Measurement*, Elsevier Ltd, Volume 104, Pages 132-141. Retrieved on 2/17/19 from: https://doi.org/10.1016/j.measurement.2017.03.026

Hildebrand, E. (2003). “Reductions in Traffic Sign Retroreflectivity Caused by Frost and Dew,” *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C., Number 1844, Pages 79-84.

Hummer, J, Harris, E., and Rasdorf, W. (2013). “Simulation-Based Evaluation of Traffic Sign Retroreflectivity Maintenance Practices,” *Journal of Transportation Engineering*, American Society of Civil Engineers, Washington D.C., Volume 139, Number 6, Pages 556 – 564.

Huang, W., Hu, L., and Jiang, M. (2013). “Retroreflectivity and Deterioration Characteristics of Sheeting Used for In-Service Guide Signs,” *Journal of Highway and Transportation Research and Development*, American Society of Civil Engineers, Washington D.C., Volume. 7, Number 2, Pages 88-93.

Huynh, N., Mullen, R., and Pulver, Z. (2018). “Sign Life Expectancy,” Final Report FHWA-SC-17-11, Department of Civil and Environmental Engineering, University of South Carolina. Columbia, SC.

Immaneni, V., Rasdorf, W., Hummer, J., and Yeom, C. (2007). “Field Investigation of Highway Sign Damage Rates and Inspector Accuracy,” *Public Works Management & Policy*, SAGE Journals, Washington D.C., Volume 11, Number 4, Pages 266 – 278.

Immaneni, V., Hummer, J, Rasdorf, W., Harris, E., and Yeom, C. (2009). “Synthesis of Sign Deterioration Rates Across the United States,” *Journal of Transportation Engineering*, American Society of Civil Engineers, Washington D.C., Volume 135, Number 3, Pages 94 – 103.

Jiang, M. and Zhou, R. (2012). “Research of In-Service Regulatory Sign Sheeting, Retro-reflectivity and Deterioration Characteristics,” *Proceedings of the 12th International Conference of Transportation Professionals*, American Society of Civil Engineers, Beijing, China, August 3-6, 2012.

Joines, J. and Roberts, S. (2015). *Simulation Modeling with SIMIO: A Workbook* (4thd Edition). Raleigh, NC: Simio LLC.

Kelton, W., Smith, J., and Sturrock, D. (2014). *Simio and Simulation: Modeling, Analysis, Applications* (3rd edition). Sewickley, PA: Simio LLC.

Kelton, W., Sadowski, R., and Zupick, N. (2015). *Simulation with Arena* (6th Edition). New York, NY: McGraw-Hill Education.

Khalilikhah, M., Heaslip, K., and Song, Z. (2015). "Can Daytime Digital Imaging Be Used for Traffic Sign Retroreflectivity Compliance?," *Measurement*, Elsevier Science Ltd, Volume 75, Pages 147-160. Retrieved on 2/17/19 from: https://doi.org/10.1016/j.measurement.2015.07.049

Khalilikhah, M. and Heaslip, K. (2016). "The Effects of Damage on Sign Visibility: An Assist in Traffic Sign Replacement," *Journal of Traffic and Transportation Engineering*, Elsevier Science Ltd, Volume 3, Number 6, Pages 571-581. Retrieved on 2/17/19 from: https://doi.org/10.1016/j.jtte.2016.03.009

Khalilikhah, M., Heaslip, K., and Hancock, K. (2016). "Traffic Sign Vandalism and Demographics of Local Population: A Case Study in Utah," *Journal of Traffic and Transportation Engineering*, Elsevier Science Ltd, Volume 3, Number 3, Pages 192-202. Retrieved on 2/17/19 from: https://doi.org/10.1016/j.jtte.2015.11.001

Kipp, W. and Fitch, J. (2009). "Evaluation of Measuring Methods for Traffic Sign Retroreflectivity*," Final Report 2009-8*, Vermont Agency of Transportation, Montpelier, VT.

Kirk, A., Hunt, E., and Brooks, E. (2001). "Factors Affecting Sign Retroreflectivity," *Final Report SR 514*, Publication OR- RD-01-09, Oregon Department of Transportation, Salem, OR.

Kirtley and Rasdorf (2001). "A North Carolina Sign Study: Sign Count Approximation Using Field Inventory Sampling and Calculated Sign Densities for NC Primary Routes." Technical Report, Department of Civil Engineering, North Carolina State University, Raleigh, NC.

Liu, M. and Frangopol, D. (2005). "Multiobjective Maintenance Planning Optimization for Deteriorating Bridges Considering Condition, Safety, and Life-Cycle Cost," *Journal of Structural Engineering*, American Society of Civil Engineers, Washington D.C., Volume 131, Number 5, Pages 833-842.

Markow, M. (2007). "Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Markings, Culverts, and Sidewalks," NCHRP Synthesis of Highway Practice 371, Transportation Research Board National Research Council, Washington, D.C.

McCarthy, L., Liang, J., Park, S., McFadden, J., and Trieu, V. (2013). "Risk-Based Method for Development and Management of a Traffic Sign Inventory for Local Agencies," *Public Works Management & Policy,* SAGE Journals, Washington D.C., Volume 18, Number 1, Pages 82 – 95.

Mohan, S., Gangopadhyay, S., Singh, S., and Ahlawat, A. (2012). "Deterioration of Retro-Reflective Sheet Under Outdoor Weathering and Weather-O-Meter," *International Journal of Transportation Science and Technology*, Elsevier Science Ltd, Volume 1, Issue 1, Pages 61-72. Retrieved on 3/13/19 from: h https://doi.org/10.1260/2046-0430.1.1.61

National Highway Traffic Safety Administration (2008). National Motor Vehicle Crash Causation Survey, Report to Congress. Washington, DC. Retrieved on 8/13/18 from https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811059

Nippon Carbide (2015). "Nikkalite High Intensity Micro-prismatic 94000 Series," Nippon Carbide Industries (USA) Inc, Cerritos, CA. Retrieved on 12/06/18 from: http://www.nikkalite.com/images/HIM.pdf

North Carolina Department of Transportation (2016). "2016 Maintenance Operations and Performance Analysis Report (MOPAR)." Retrieved on 02/02/18 from: https://connect.ncdot.gov/resources/Asset-Management/MSADocuments/2016%20Maintenance%20Operations%20and%20Performance%20Analysis%20Report%20(MOPAR).pdf

North Carolina Department of Transportation (2018). "North Carolina Official State Mileages." Retrieved on 03/18/2019 from: https://connect.ncdot.gov/resources/State-Mapping/Documents/Official_State_Mileage.pdf

North Carolina Division of Motor Vehicles (2011). North Carolina 2010 Traffic Crash Facts. North Carolina Department of Transportation, Raleigh, NC. Retrieved on 8/13/18 from https://connect.ncdot.gov/business/DMV/DMV%20Documents/2010%20Crash%20Facts.pdf

North Carolina Division of Motor Vehicles (2017). North Carolina 2016 Traffic Crash Facts. North Carolina Department of Transportation, Raleigh, NC. Retrieved on 8/13/18 from https://connect.ncdot.gov/business/DMV/DMV%20Documents/2016%20Crash%20Facts.pdf

Obaidat, M and Boudriga, N. (2010). *Fundamentals of Performance Evaluation of Computer and Telecommunication Systems*. Hoboken, NJ: John Wiley & Sons, Inc.

Obaidat, M. and Papadimitriou, G. (2003). *Applied System Simulation: Methodologies and Applications*. Norwell, MA: Kluwer Academic Publishers.

Orafol Americas (2016). "Oralite® 5900 High Intensity Prismatic Grade – Technical Datasheet," Orafol Americas, Black Creek, GA. Retrieved on 12/06/18 from: https://www.orafol.com/tl_files/content/downloads/technicaldatasheets/americas/en/oralite/oralite-5900.pdf

Palmquist, M., and Rasdorf, W. (2002). "Sign Count Approximation Using Field Inventory Sampling and Calculated Sign Densities: Analysis, Improvements, and Methods." Technical Report, Department of Civil Engineering, NC State University, Raleigh, NC.

Pike, A. and Carlson, P. (2014) "Evaluation of Sign Sheeting Service Life in Wyoming," *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C. Number 0758, Pages 88 – 94.

Preston, H., Atkins, K., Lebens, M., and Jensen, M. (2014). "Traffic Sign Life Expectancy," *Final Report 2014-20*, Minnesota Department of Transportation, Office of Material and Road Research, Mendota Heights, MN.

Pulver, Z., Huynh, N., and Mullen, R. (2018) "Evaluation of Expected Traffic Sign Life in South Carolina," Transportation Research Board: Journal of the Transportation Research Board, Transportation Research Board of the National Academies, Washington D.C. Number 2258, Pages 88 – 94.

Rasdorf, W., Hummer, J., Harris, E., Immaneni, V., and Yeom, C. (2006). "Designing an Efficient Nighttime Sign Inspection Procedure to Ensure Motorist Safety," Report FHWA/NC/2006-08, North Carolina Department of Transportation, Raleigh, NC.

Rasdorf, W., Hummer, J., Harris, E., and Sitzabee, W. (2009). "IT Issues for the Management of High-Quantity Low-Cost Assets," *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, Washington D.C., Volume 23, Number 2, Pages 91 – 99.

Re, J., Miles, J., and Carlson, P. (2011). "Analysis of In-Service Traffic Sign Retroreflectivity and Deterioration Rates in Texas," *Transportation Research Board: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington D.C., Number 2258, Pages 88 – 94.

Re, J. and Carlson, P. (2012). "Practices to Manage Traffic Sign Retroreflectivity: Synthesis of Highway Practice," *NCHRP Synthesis 431*, National Cooperative Highway Research Program, Washington, D.C.

Retting, R., Weinstein, H., and Solomon, M., (2003). Analysis of Motor-Vehicle Crashes at Stop Signs in four U.S. Cities. Journal of Safety Research, No. 34, Pages 485-489.

Schertz, G. (2005). "The Importance of Sign Retroreflectivity," American Public Works Association Reporter, Washington, D.C. Retrieved on 3/21/2019 from:
http://www3.apwa.net/Resources/Reporter/Articles/2005/7/The-importance-of-sign-retroreflectivity

Thompson, P., Ford, K., Arman, M., Labi, S, Sinha, K., and Shirole, A. (2012). "Estimating Life Expectancies of Highway Assets," NCHRP Report 713, National Cooperative Highway Research Program, Washington, D.C.

Vereen, S., Hummer, J., and Rasdorf, W. (2002). "A Sign Inventory Study to Assess and Control Liability and Cost," Report No. FHWA/NC/2002-17. North Carolina Department of Transportation, Raleigh, NC.

Vilarinho, S., Lopes, I., and Oliveira, J. (2017). "Preventive Maintenance Decisions Through Maintenance Optimization Models: A Case Study," *Procedia Manufacturing*, Elsevier Science Ltd, Volume 11, Pages 1170-1177. Retrieved on 2/17/19 from:
https://doi.org/10.1016/j.promfg.2017.07.241

Virginia Department of Transportation (VDOT) (2017). "VDOT's Sign Maintenance and Retroreflectivity Compliance Plan: Draft," VDOT Traffic Engineering Division.

Wang, H. (2002). "A Survey of maintenance Policies of Deteriorating Systems," *European Journal of Operational Research*, Elsevier Science Ltd, Volume 139, Number 3, Pages 469-489. Retrieved on 2/17/19 from: https://doi.org/10.1016/S0377-2217(01)00197-7

Wisconsin Transportation Information Center (WTIC) (2013). "Wisconsin Transportation Bulletin: Meeting Minimum Sign Retroreflectivity Standards," Madison, UW. Retrieved on 3/18/2019 from:
http://epdfiles.engr.wisc.edu/pdf_web_files/tic/bulletins/Bltn_023_Retroreflectivity.pdf

Winston, W. (2004). *Operations Research: Applications and Algorithms (4th Edition)*. Belmont, CA: Thomson Brooks/Cole.

Wolshon, B., Degeyter, R., and Swargam, J. (2002). "Analysis and Predictive Modeling of Road Sign Retroreflectivity Performance," *16th Biennial Symposium on Visibility and Simulation*. Iowa City, Iowa, June 2–4, 2002.

3M (2018). "3M™ High Intensity Prismatic Reflective Sheeting Series 3930 - Product Bulletin Series 3930," 3M Transportation Safety Division, Saint Paul, MN. Retrieved on 11/28/18 from:

https://multimedia.3m.com/mws/media/254031O/3m-high-intensity-prismatic-reflective-sheeting-series-3930-product-bulletin.pdf

3M (n.d. [1]). “Explained: ASTM standards for traffic signs,” 3M Company. Retrieved on 03/19/19 from: https://www.3m.com/3M/en_US/road-safety-us/resources/road-transportation-safety-center-blog/full-story/~/astm-standards-for-traffic-signs/?storyid=5011bc7a-64cc-4b28-93cd-84aa9707d5dd

3M (n.d. [2]). “What Is Retroreflectivity and Why Is It Important?,” 3M Company. Retrieved on 04/10/19 from: https://www.3m.com/3M/en_US/road-safety-us/resources/road-transportation-safety-center-blog/full-story/?storyid=328c8880-941b-4adc-a9f9-46a1cd79e637

12.0 APPENDIX

12.1 Definitions

Although traffic signs are constantly present in our lives, one that is not a researcher of the field might not know some of the technical terms. Therefore, before advancing into the topic of this research, the author opted for defining and clarifying below some terms that are often used.

- *Ground-mounted sign* is referred as “a post-mounted sign” by MUTCD (FHWA, 2009). It is a sign that is 100% located on the side of a road outside of the shoulders. Figure 12.1 shows a stop sign as an example of a ground-mounted sign.
- *Sign legend*, in simple words, is what the sign means, which information the sign conveys. It can be in the form of words, symbols, and arrows (MUTCD, FHWA, 2009). Sign legend is also often referred as “sign message.” The right side of Figure 12.1 shows the portion of the signs that is known as the sign legend. In the example illustrated, the sign legend is in the form of a word and means “stop.”
- *Sign sheeting* is a kind of flexible material available in different colors (e.g., red, white, green, and yellow) that is used to manufacture traffic signs. A sheeting is applied on the surface of an aluminum sheet during the manufacturing process of a sign. There are different types of sign sheeting and each is classified according to its material. The left portion of Figure 12.1 illustrates the main components of a sign, including the sign sheeting.
- *Retroreflectivity*, according to the MUTCD (FHWA, 2009), is a property of a material’s surface that enables it to reflect light back to the original source. Sign retroreflectivity, then, is a measure of the quantity of light that strikes the sign and return back to the original source (e.g., a car or a truck).
- *Retroreflective sheeting* is a sheeting that has retroreflectivity properties. In other words, a retroreflective sheeting is able to reflect back to the original source the portion of the light that strikes it. The main benefit of using retroreflective sheeting on traffic signs is that they become brighter and visible to drivers at night when the cars’ headlamps illuminate the sign. The most common types of retroreflective sheeting are made with glass beads and micro-prisms.

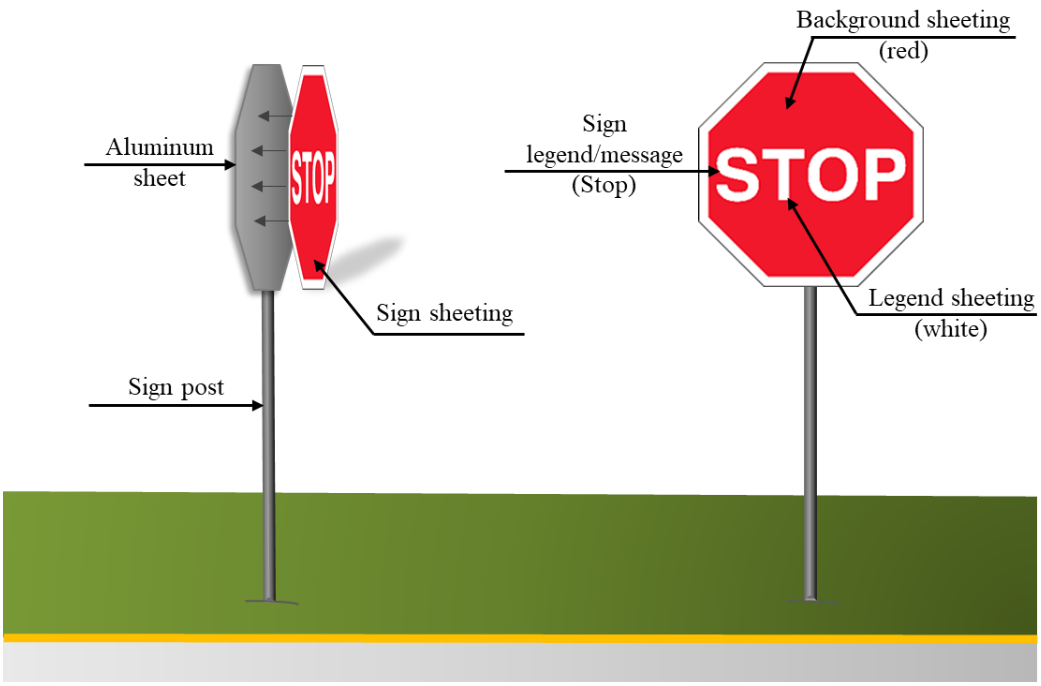


Figure 12.1 Example of Ground-Mounted Sign (Stop Sign)

- *Sign service life* is the time period that a retroreflective traffic sign is expected to perform above the minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). Sign service life does not account for damages (e.g., gunshots, spray paint, tree sap, etc.). Sign service life depends mainly on the color and type of sheeting used to manufacture the sign.
- *Maintenance* means to take case of assets over their life time. Some examples of sign maintenance activities are sign inspection, sign condition assessment, sign alignment, retroreflectivity compliance, and sign cleaning.
- *Replacement* is the act of replacing an asset for any giver reason. For example, signs are often replaced because of deterioration, damage, and regulation changes.
- *Sign service life* is the period that a retroreflective traffic sign is expected to perform above the minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). Sign service life does not account for damages (e.g., gunshots, spray paint, tree sap, etc.). Sign service life depends mainly on the color and type of sheeting used to manufacture the sign.
- *Sign rack* is a structure often used in studies of retroreflectivity deterioration and control sign maintenance methods. Researchers install traffic signs (or retroreflective sheeting samples) in various colors and collect retroreflectivity data through the years with the objective of developing a deterioration model or/and estimating sign service life. In addition, sign racks are also often studied when the research team objective is to assess the efficiency of control sign maintenance method (as described in the MUTCD). Figure 12.2 and Figure 12.3 show examples of sign racks used in studies that analysis sign control maintenance method.

- *Noncompliant sign* is a sign that is below the minimum retroreflectivity levels required by the MUTCD (FHWA, 2009). As the term suggests, the sign is not compliant with the MUTCD retroreflectivity standard.
- *Damaged sign* is a sign that is somehow damaged, which can be due to one or more reasons. Many damages are caused by eggs, gunshots, spray paint, tree sap, paintballs, vehicle crashes, stickers, and mowing equipment.
- *Rejected sign* is a sign that was rejected by a sign inspector either because it was noncompliant with the minimum retroreflectivity levels required by the MUTCD (FHWA, 2009) or presented a major level of damage.
- *Failure rate* is the percentage of rejected signs (sum of noncompliant and damaged signs) in relation to the total number of signs inspected.
- *Replacement rate* is the percentage of signs replaced in a period with respect to the total number of signs inspected or the overall number of signs maintained by a transportation agency. Ideally, replacement rate would be the same as failure rate. However, due to budget limitations, the replacement rate is often lower than the failure rate.
- *DOT* stands for department of transportation and is a state owned agency. DOTs are responsible for maintaining state-owned roads, which consist of Interstates, primary and secondary roads.
- *Primary roads* are state maintained roads consisting of Interstates, U.S. routes, and N.C. roads. Although Intestates are part of the primary road system, NCDOT often refers to them apart from U.S. and N.C. roads because they have unique features such as higher traffic volume, lower number of signs, higher posted speeds, and fewer road miles when compared to U.S. and N.C. roads. For the purpose of this study, the term "primary roads" is used to describe only U.S., and N.C. roads, which are part of the scope of work. Interstate roads are referred to directly by their own name.
- *Secondary roads* are any state maintained roads that are not classified as primary roads. Most of NC's secondary road miles consists of rural roads.

Figure 2.1 shows an example of a ground-mounted sign. The sign consists of three main components as shown in the left portion of the figure: aluminum sheet, sign, sheeting, and sign post. The right portion of the picture shows a front view of the same sign. In this specific case, the sign consists of two colors (red and white) and it legend means "stop."

Figure 12.2 and Figure 12.3 show examples of a sign racks that are often used by DOTs or researchers to track retroreflectivity deterioration and sign service life. For example, the signs shown in Figure 12.2 could be a representative sample of regulatory, warning, and guide signs that are installed on the highway system. Both Jiang and Zhou (2012) and Huang et al. (2013) used sign racks that contained signs (such as those in Figure 2.2) rather that sheeting samples. Slightly different, Figure 12.3 shows a sign rack that contains samples of only sign sheeting in the four sheeting colors most studied by researchers. The samples could be from the same material or different types of sheeting. Kipp and Fitch (2009) used sign racks similar to the one described in Figure 12.3 in his studies.

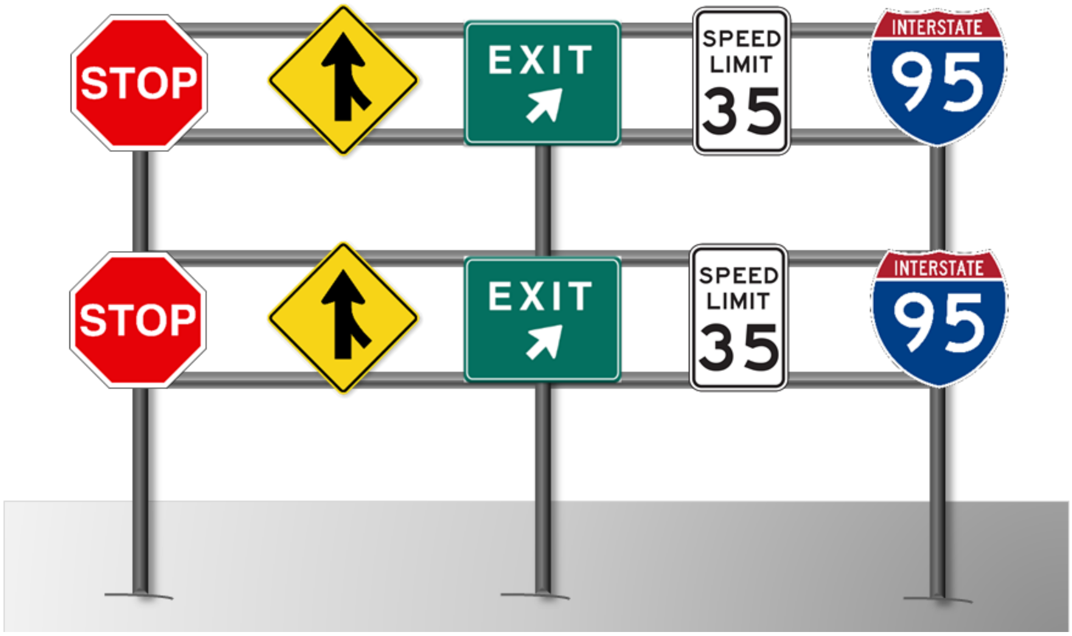


Figure 12.2 Sign Rack with Different Color Signs

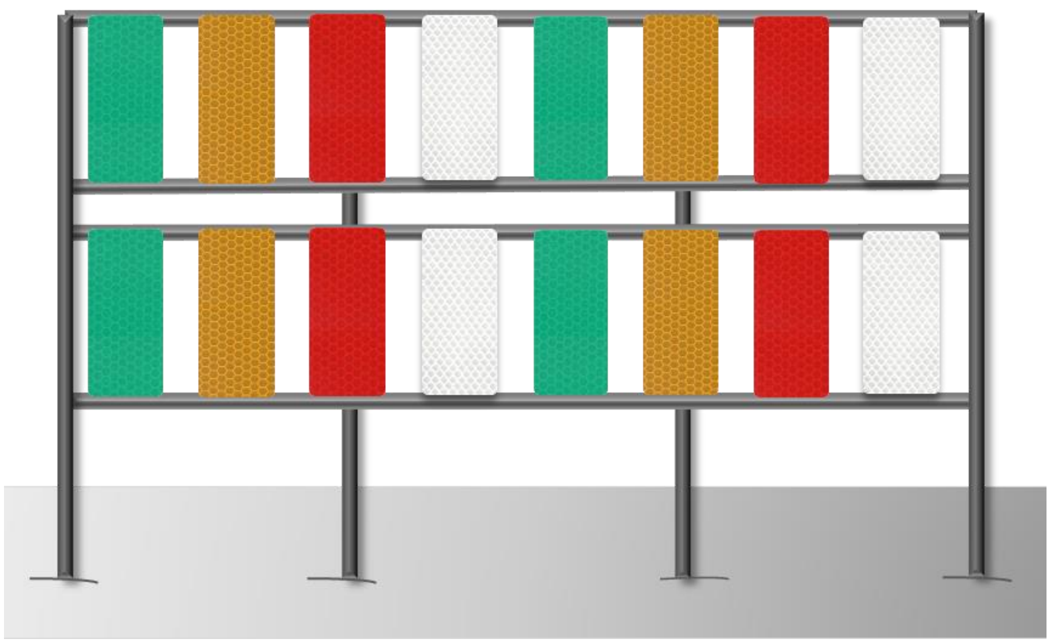


Figure 12.3 Sign Rack with Sheeting Samples in Different Colors

12.2 NCDOT Standard Practice for Sign Sheeting

STATE OF NORTH CAROLINA
DEPARTMENT OF TRANSPORTATION

MICHAEL F. EASLEY
GOVERNOR

LYNDO TIPPETT
SECRETARY

July 7, 2003

8-10-03
Larry Stallings -
Please confirm this
Practice is in the
TEPPL. Troy

MEMORANDUM

To: Division Engineers

From: J. D. Goins, P.E.
Chief Engineer - Operations

T. A. Peoples, P.E.
State Traffic Engineer

Subject: Standard Practice for Sign Sheeting

Attached is the standard practice for sign sheeting. This practice is intended to ensure statewide consistency in sheeting usage on regulatory, warning, guide, and temporary traffic control work zone signs.

Signs fabricated using brighter retro-reflective sheeting are needed to increase sign conspicuity and legibility, in particular, for older drivers. Type III (High Intensity) sheeting has a higher target value, longer service life, and a better life cycle cost than Type I (Engineering Grade) sheeting. As a result, the statewide implementation of this standard practice will result in lower overall sign costs and increased safety. The practice requires the use of Type III sheeting for all regulatory, warning (other than school, pedestrian, bicycle, and highway-rail grade crossing signs), and guide signs.

The practice also increases the retro-reflective sheeting requirement for school, pedestrian, bicycle, highway-rail grade crossing, and work zone signs. School, pedestrian, and bicycle warning signs currently require Type IX fluorescent yellow-green sheeting. Highway-rail grade crossing advance warning signs will require Type IX fluorescent yellow sheeting. Traffic control work zone signs will require Type VII, VIII, or IX fluorescent orange sheeting. These requirements are included in the standard practice.

These guidelines supercede those detailed in our joint memorandum of June 10, 2002. The effective date of January 1, 2005 for this practice provides the Department adequate time to exhaust existing inventories of signs fabricated with Type I (Engineer Grade) and Type II (Super Engineer Grade) sheeting. Additionally, the practice permits existing signs with Type I or Type II sheeting to remain in place until the signs have reached the end of their service life or are no longer needed.

MAILING ADDRESS:
TRAFFIC ENGINEERING AND SAFETY SYSTEMS BRANCH
1561 MAIL SERVICE CENTER
RALEIGH NC 27699-1561

TELEPHONE: 919-733-3915
FAX: 919-733-2261

WEBSITE: WWW.DOH.DOT.STATE.NC.US

LOCATION:
122 NORTH MCDOWELL STREET
RALEIGH NC 27603

However, effective immediately, as existing Type I and Type II sheeting inventories are exhausted, your inventories shall be replenished with the appropriate type sheeting as specified in the attached standard practice.

If additional information is needed, please advise.

JDG/TAP/sk/mm

Attachment

cc: Len A. Sanderson, P.E., w/atta.
David Allsbrook, P.E., w/atta.
Deputy Division Engineers, w/atta.
Division Operation Engineers, w/atta.
Regional Traffic Engineers, w/atta.
Division Traffic Engineers, w/atta.
Traffic Services Supervisors, w/atta.
Chuck Congleton, w/atta.
Jim Rand, w/atta.
Sandy Nance, w/atta.
Terry Hopkins, P.E., w/atta.
Tony Wyatt, P.E., w/atta.
Ron King, P.E., w/atta.
Stuart Bourne, P.E., w/atta.
Ken Ivey, P.E., w/atta.
Sign Oversight Committee, w/atta.
Barry Jenkins, AGC, w/atta.

North Carolina Department of Transportation
Division of Highways
Transportation Mobility and Safety Division

STANDARD PRACTICE for Retroreflective Sign Sheeting

This standard practice establishes three grades of retroreflective sheeting. Contract documents establish the performance requirements for each grade and requires that retroreflective sheeting materials be pre-qualified by the Transportation Mobility and Safety Division – Signing and Delineation Unit.

The retroreflective sheeting grades are intended to establish meaningful minimum retroreflectivity intervals with brightness differences that would be detected by most drivers. Materials meeting the requirements for Grade B would also meet the requirements for Grade C, and materials meeting the requirements for Grade A would also meet the requirements for Grades B and C.

The following are standard examples of applications (also summarized in table) for the various grades of retroreflective sheeting:

North Carolina Grade C – Retroreflective sheeting materials meeting Grade C, commonly referred to as "regular grade", are typically of encapsulated microscopic glass bead lens or unmetallized microprismatic construction. Grade C should typically be used on all regulatory, warning, and guide signs, unless indicated otherwise.

North Carolina Grade B – Retroreflective sheeting materials meeting Grade B, commonly referred to as "intermediate grade", are typically of unmetallized microprismatic construction. Grade B shall be used for all school zone signs, bicycle and pedestrian crossing signs (fluorescent yellow-green); and highway-rail crossing signs (fluorescent yellow). Grade B shall also be used for all work zone signs (fluorescent orange). Grade B should be used for signs (regulatory, warning, and guide) located in areas with high levels of ambient lighting (urban freeways, downtown districts, etc.).

North Carolina Grade A – Retroreflective sheeting materials meeting Grade A, commonly referred to as "premium grade", are typically of unmetallized microprismatic construction. Grade A should be used for the legend, border, shields and arrows of left-mounted shoulder or overhead-mounted guide signs.

TABLE
Sheeting Usage by Grade

Sign Type	Description	Legend & Border	Background
Regulatory	Typical Shoulder Mount	C	C
Warning		C	C
Guide		C	C
Fluorescent Warning	School Zone	B	B
	Bicycle Crossing	B	B
	Pedestrian Crossing	B	B
	Highway-Rail Crossing	B	B
	Work Zone	B	B
Guide	Overhead Mount	A	C
	Left Shoulder Mount	A	C
Regulatory	High Ambient Lighting Locations (ex., urban freeways)	B	C
Warning		B	C
Guide		B	C

Note: Non-reflective black sheeting or opaque black inks must be used when black is required.

12.3 FHWA 2014 Traffic Sign Retroreflective Sheeting Identification Guide

U.S. Department of Transportation
Federal Highway Administration
1200 New Jersey Avenue, SE
Washington, DC 20590
202-366-4000

Safety

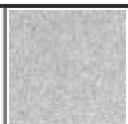
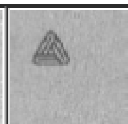
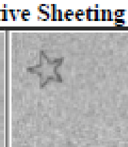
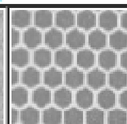
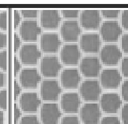
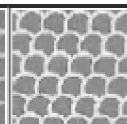
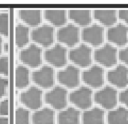
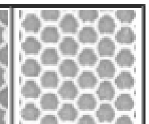
2014 Traffic Sign Retroreflective Sheeting Identification Guide

Download Version
PDF [537 KB]

This document is intended to help identify sign sheeting materials for rigid signs and their common specification designations. It is not a qualified product list. FHWA does not endorse or approve sign sheeting materials. Many other sheeting materials not listed here are available for delineation and construction/work zone uses.

Many sign sheeting materials have watermarks and/or patterns that are used to identify the material type and manufacturer. The watermarks shown in this guide have been enhanced. The watermarks will be less visible in practice and may not be present on smaller pieces of sheeting due to the spacing.

Retroreflective Sheeting Materials Made with Glass Beads

Example of Sheeting (Shown to scale)								
ASTM D4956-04	I	II	II	III	III	III	III	III
ASTM D4956-13	I	II	II	III	III	III	III	III
AASHTO M268-13	(1)	(1)	(1)	A	A	A	A	A
Manufacturer	Several companies	Avery Dennison®	Nippon Carbide	3M™	ATSM, Inc.	Avery Dennison®	Nippon Carbide	ORAFOL Americas Inc
Brand Name	Engineer Grade	Super Engr Grade	Super Engr Grade	High Intensity	High Intensity	High Intensity	High Intensity	ORALITE® High Intensity
Series	Several	T-2000	15000	2800 3800	ATSM HI	T-5500	N500	5800
NOTES:	(2) (8)	(3) (4) (9)	(4)	(3) (4) (9)	(4)	(4)	(4)	(4)

1) Sheeting material does not meet minimum AASHTO classification criteria.
2) Glass Bead Engineer Grade sheeting is uniform without any patterns or identifying marks.
3) Material no longer sold in the United States as of the date of this publication.
4) Section 2A.08 of the 2009 MUTCD (http://mutcd.fhwa.dot.gov) does not allow this sheeting type to be used for new legends on green signs.

- ASTM D4956-04 is referenced in Table 2A-3 of the 2009 MUTCD.
- ASTM D4956-13 is the most current ASTM sign sheeting specification (the 2013 version is designated by "-13").
- AASHTO M268-13 is the most current AASHTO specification (the 2013 version is designated by "-13").

Manufacturer Contact Information

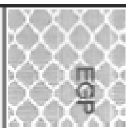
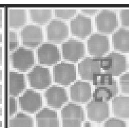
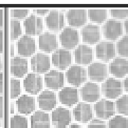
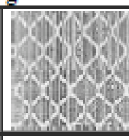
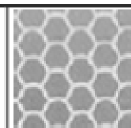
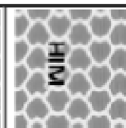
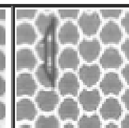
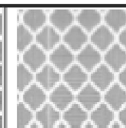
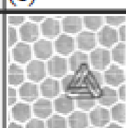
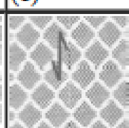
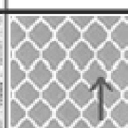
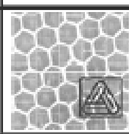
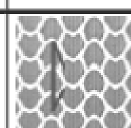
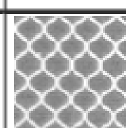
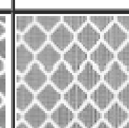
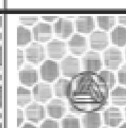
3M – http://www.3M.com/roadwaysafety
ATSM, Inc. – http://www.atsminc.com
Avery Dennison – http://www.reflectives.averydennison.com
Nippon Carbide – http://www.nikkalite.com
ORAFOL Americas Inc. – http://www.orafolamericas.com

FHWA Publication Number: FHWA-SA-14-022. You may download and print the electronic version of this document, available at www.fhwa.dot.gov/retro

This document is intended to help identify sign sheeting materials for rigid signs and their common specification designations. It is not a qualified product list. FHWA does not endorse or approve sign sheeting materials. Many other sheeting materials not listed here are available for delineation and construction/work zone uses.

Many sign sheeting materials have watermarks and/or patterns that are used to identify the material type and manufacturer. The watermarks shown in this guide have been enhanced. The watermarks will be less visible in practice and may not be present on smaller pieces of sheeting due to the spacing.

Retroreflective Sheeting Materials Made with Micro-Prism

Example of Sheeting (Shown to scale)								
D4956-04	(5)	(5)	III, IV	III, IV, X	(5)	(5)	(5) / X	(5)
D4956-13	I	I	III, IV	III, IV	III, IV	III, IV	VIII	VIII
M268-13	(6)	(6)	B	B	B	B	B	B
Manufacturer	3M™	Avery Dennison®	Avery Dennison®	3M™	ORAFOL Americas Inc	Nippon Carbide	Nippon Carbide	3M™
Brand Name	EGP	PEG	HIP	HIP	ORALITE® HIP	HIM	Crystal Grade	Reflective Sheeting
Series	3430	T-2500	T-6500	3930	5900/5930	CRG 94000	CRG 92000	3940
NOTES:	(8)	(8)						
Example of Sheeting (Shown to scale)								
D4956-04	VIII	VII, VIII, X	IX	IX	(5)	(5)	(5)	(5)
D4956-13	VIII	VIII	IX	IX	IX	IX	XI	XI
M268-13	B	(7)	B	B	B	B	D	D
Manufacturer	Avery Dennison®	3M™	3M™	Avery Dennison®	Nippon Carbide	ORAFOL Americas Inc	3M™	Avery Dennison®
Brand Name	MVP Prismatic	Diamond Grade™ LDP	Diamond Grade™ VIP	OmniView™	Crystal Grade	ORALITE®	Diamond Grade™ DG3	OmniCube™
Series	T-7500	3970	3990	T-9500	95000	7900	4000	T-11500
NOTES:		(9)			(9)			

5) Material was either unavailable in 2005 (previous version of this Guide) or unassigned in the 2004 version of ASTM D4956.
6) Sheeting material does not meet minimum AASHTO classification criteria.
7) Material has been discontinued prior to AASHTO M268-10.
8) Section 2A.08 of the 2009 MUTCD (http://mutcd.fhwa.dot.gov) does not allow this sheeting type to be used for new yellow or orange signs, or new legends on green signs.
9) Material no longer sold in the United States as of the date of this publication.

Resources

Federal Highway Administration – https://www.fhwa.dot.gov/retro
Manual on Uniform Traffic Control Devices (MUTCD) – http://mutcd.fhwa.dot.gov
Texas A&M Transportation Institute – http://tti.tamu.edu/visibility
ASTM – http://www.astm.org
AASHTO – http://www.transportation.org

Page last modified on May 27, 2014.

Safe Roads for a Safer Future
Investment in roadway safety saves lives

12.4 Sign Replacement Field Procedure Photos

This appendix illustrates the replacement of a red sign in Division 9. All photos were taken by the author during the field trip on March 28, 2018. The first step is removing the deficient signs. It is possible to note in Figure 12.4 that the first thing the crew does is to separate the sign from the crew base pole. After doing so, they remove the base pole.

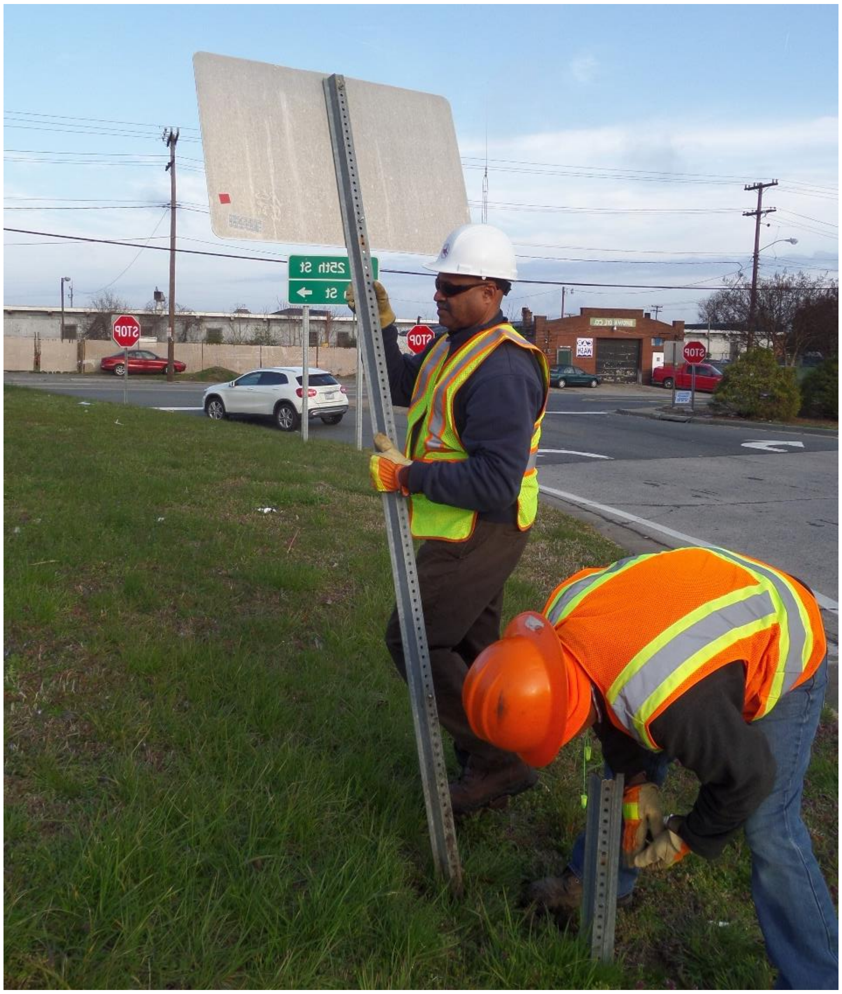


Figure 12.4 Removing a Deficient Sign

Then the crew placed the deficient sign (still attached to its pole) on the bed of the truck to facilitate the disassembly of sign and pole (see Figure 12.5). Note on the right side of truck the new sign (wrong way) that will be installed.

Figure 12.5 Separating the Deficient Sign from the Sign Pole

Figure 12.6 shows an installation date sticker on the back of a wrong way sign that was replaced. This sign was installed by Division 9 on August 11, 2008.

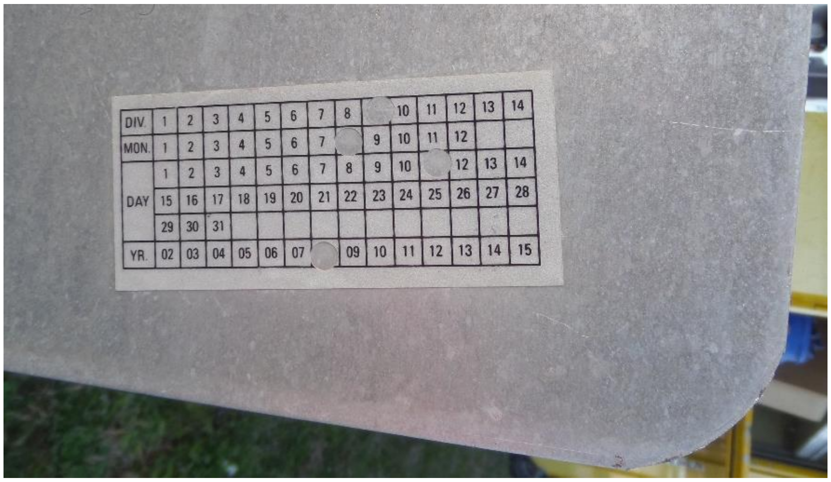


Figure 12.6 Installation Date Sticker on the Back of a Sign

Figure 12.7 shows one of the crew members assembling the new sign (wrong way) to the sign pole.

Figure 12.7 Assemble of the New Sign to the Pole

Figure 12.8 shows the installation date sticker on the back of the new sign indicating that this sign was installed by Division 9 on March 28, 2018. In addition, the crew members write their initials on the back of the sign.

Figure 12.8 Installation Date Sticker on the Back of the new Sign

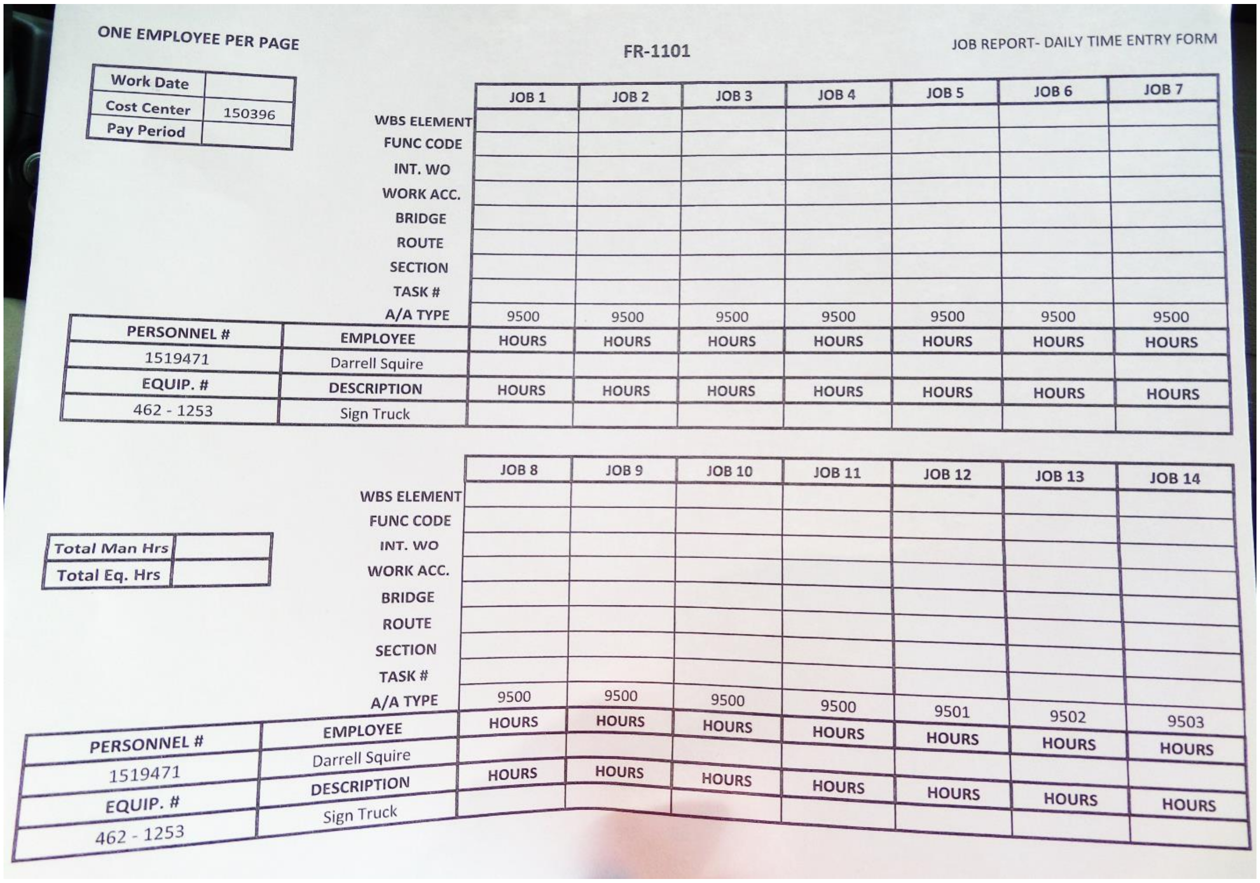
Figures 12.9 and 12.10 shows the two crew members installing the new sign (wrong way). At that moment, they were attaching the sign pole to the base pole. Figure 12.11 shows one of the crew members checking whether or not the signs was correctly aligned.

Figure 12.9 Crew Members Installing a New Sign

Figure 12.10 Worker Attaching the New Sign Pole to the Base Pole

Figure 12.11 Crew Member Checking with a Level the Pole Alignment

Figure 2.12 shows the FR-1101 form. Sign crew members are required to fill out this form while conducting sign replacement activities. There a set of information that the crew needs to enter and there is one form for each crew member.



ONE EMPLOYEE PER PAGE

FR-1101

JOB REPORT- DAILY TIME ENTRY FORM

Work Date	
Cost Center	150396
Pay Period	

	JOB 1	JOB 2	JOB 3	JOB 4	JOB 5	JOB 6	JOB 7
WBS ELEMENT							
FUNC CODE							
INT. WO							
WORK ACC.							
BRIDGE							
ROUTE							
SECTION							
TASK #							
A/A TYPE	9500	9500	9500	9500	9500	9500	9500

PERSONNEL #	EMPLOYEE	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS
1519471	Darrell Squire							
EQUIP. #	DESCRIPTION	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS
462 - 1253	Sign Truck							

Total Man Hrs	
Total Eq. Hrs	

	JOB 8	JOB 9	JOB 10	JOB 11	JOB 12	JOB 13	JOB 14
WBS ELEMENT							
FUNC CODE							
INT. WO							
WORK ACC.							
BRIDGE							
ROUTE							
SECTION							
TASK #							
A/A TYPE	9500	9500	9500	9500	9501	9502	9503

PERSONNEL #	EMPLOYEE	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS
1519471	Darrell Squire							
EQUIP. #	DESCRIPTION	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS	HOURS
462 - 1253	Sign Truck							

Figure 12.12 R-1101 Form

12.5 Sign Replacement Field Procedure Description

On March 28, 2018, Patricia Machado rode along with the sign crew to observe and document typical work routine and sign replacement activities to ensure that the research team fully understand the process.

The sign crew replaced signs in seven different locations. At each location where the crew stopped, they verified which signs should be replaced and then performed the work when possible. Once the work was completed, one of the crew members would enter the information on the FR-1101 form. The following subsections describe the signs replaced in each location and any unforeseen situation that they might have occurred.

1st Location

The sign crew left the Traffic Service Department around 8:00 am and travels in the direction of Forsyth County, Section 7. At 8:15 they arrived at the first location where a total of seven signs were replaced, including two *Wrong Way*, two *Do Not Enter*, and three *Stop* signs. All the existing signs (except for one of the Stop signs) were 10 years old (installed in 2008), therefore, they needed to be replaced according to the crew members. The only sign that was not 10 years old was a *Stop* sign that was previously installed by the city and was larger than it should be. The work performed at the 1st location lasted 1.5 hours. At 9:45 the crew left that location for the next stop. Appendix III shows pictures of the main activities involved in sign replacement.

2nd Location

The crew arrived at the 2nd location at 9:50 am where they planned to replace a set of three signs that were assembled together: *to*, *south*, and a *US 52* route sign. However, the work was not performed because one of the signs was not available in the truck. As three signs were assembled together, the crew could either replace all or none sign. In this case, the crew made a note to return in the following day and replace those signs.

3rd Location

The crew arrived at the 3rd location at 10:05 am where they planned to replace four signs: *right lane must turn right*, *no parking any time*, *bike route*, and a *right arrow directional* sign. All those signs were previously installed on a power pole owned by the city, which is not allowed. In addition, the signs were visibly deteriorated (e.g., faded and rusty). It was not possible to determine the signs' age because there was no installation date on their back.

Although the signs need to be replaced as soon as possible, the crew was not able to do so because of the interference with utility pipes and lines at this location. The crew had planned to remove the old signs from the power pole, install a new base (sign) pole, assemble the new signs, and attach the new sign pole to the base pole. However, to install the new signs apart from the power pole, it was necessary to cut a hole on the concrete of the sidewalk to install the base pole. After investigating the area and its surroundings, the sign crew observed that both power lines and gas pipes were passing beneath the concrete at this location. The problem that the exactly location of those lines and pipes was uncertain. Thus, there was a risk of accidently puncturing gas pipes and/or power lines while installing new signs. Therefore, sign crews are advised to follow the steps listed below.

- Mark the location with white spray paint where the crew plans to install the new signs.
- Call 811 to notify them that NCDOT plans to install a new sign pole at that location.

- “Call 811” will contact utility companies (e.g., gas, power, water, and phone) that might have lines and/or pipes in that area.
- Utility companies send their personnel to verify if they have some utility at that location and if so, to mark with spray paint what their location is.
- NCDOT waits to hear back from the utility companies (it can take days).
- NCDOT checks that all underground utilities were marked with spray paint by the utility companies.
- A sign crew will return to the location and installs the new signs.

The sign crew remained at the 3rd location for 10 minutes, leaving at 10:15 am. This was the time necessary to access the area, determine that utilities might be underground, and call 811.

4th Location
The crew arrived at the 4th location at 10:30 am where they installed two sets of signs: a *pedestrian traffic sign* and a *25 mph speed limit sign*. This situation was slightly different from the previous locations because there was no predecessor signs there. According to the sign crew, one set of *pedestrian* and *25mph* signs was knocked down by a vehicle and had already been removed from the field. Originally, there was not a second set of signs, which was not in compliance with MUTCD (FHWA, 2009) that requires pedestrian signs on both sides of the road (or street). Thus, the sign crew replaced a knocked down set of original signs and also installed a new set of the same signs across the street.

One of the set of signs needed to be installed on the concrete, which required the sign crew to drill a hole in the concrete prior starting the installation of the sign itself. This process required more time than a straightforward ground sign installation. The crew remained in the 4th location for 1.2 hours, leaving at 11:40 am. After installing signs at this location, the crew took a one-hour lunch break.

5th Location
The crew arrived at the 5th location at 12:55 pm where they installed one *45 mph speed limit* sign and a set of two signs, which consisted of *south* and *US 311* route signs. Those signs were located on the same side of the road, which facilitated the work. The installation date of both signs was 2005 and the crew based the replacement on the signs exceeding their 10 year service life. The work was completed at 1:15 pm.

6th Location
The 6th location was near the previous location and on the same road. The sign crew arrived there at 1:18 pm. The worked performed included the replacement of two *delineator hazard strip* signs, one on each sign of the road. Because this portion of the road had a speed limit of 45 mph, the crew members were careful in crossing the road while carrying the materials to install the sign in the opposite side of the road from where the truck was parked. There were no specific problems with the installation of signs at this location. The sign crew left that location at 1:40 pm.

7th Location
The 7th location was on the same road as the 5th and 6th sign locations. The crew arrived at the 7th location at 1:45 pm. At this location, the crew members not only replaced two speed limit signs

(*45 mph* and *55 mph*) but they also trimmed a portion of a plant that was climbing one of the signs. Again, the crew needed to be careful when crossing to the other side of the road as the traffic was becoming more intense in that area because of the time of day. The crew left the 7th location at 2:10 pm.

Return to the Office
After the 7th location, one of the crew members drove Patricia in a separate truck back to the Traffic Service Department office because the main crew was going to perform work other than sign replacement. They were discontinuing sign replacement activities because of the intensity of traffic at that time. It was reported by the crew that after the other truck went back to the office, the crew would dispose the signs in a bin and submit the FR-1101 form to their supervisor.

12.6 Simulation Logic Verification

12.6.1 Sign Attribute Sub-Model

The Sign Attribute Sub-Model, as the name suggests, assigns color, road class, initial retroreflectivity, and sign replacement priority to each sign. Besides sign attributes, this sub-model also changes the picture signs. When a sign first arrives at the sub-model, it is represented by a black triangle. After passing by the Sign Attribute Sub-Model, a new picture is assigned to each sign depending on its color as is shown in Figure 12.13. For example, if a user enters that 100% of the signs are white, after the signs pass by this sub-model, all signs should be represented by the picture of a *Speed Limit* sign. The same is valid for the other colors.

Green Sign *Red Sign* *White Sign* *Yellow Sign*

Figure 12.13 Pictures Assigned to (Undamaged) Signs Depending on Their Colors

The major part of the verification of this sub-model was to ensure that the number of signs generated by the simulation model was proportional to the input data entered. Thus, the research team ran 30 replications of 10,000 signs each and collected the output measures with a 95% confidence interval.

Table 12.1 shows the results obtained from the simulation. The first column of the table lists the sign colors and the second column lists the road classes. The simulation results are shown in the middle of the table. The third column shows the mean number of signs. The fourth column shows the half width (*h*) for a 95% confidence interval. The fifth column shows the lower bound, which is obtained by subtracting the half width from the mean number of signs (*mean* - *h*). The sixth column shows the upper bound, which is obtained by adding the half width to the mean number of signs (*mean* + *h*). The seventh and eighth columns show the NC sign data used to run the simulation. While the seventh column shows the percentage of signs by color and road class, the eighth column shows these values considering that 10,000 signs were simulated.

To verify this sub-model, the research team analyzed whether or not the NC sign data was within the confidence interval. As Table 12.1 shows, all NC sign data (seventh column) was contained within the 95% confidence interval (fifth and sixth columns). For example, the expected number of white signs on primary roads was 1,765 based on NC data. This number was within the 95% confidence interval obtained from simulation, which ranged from 1,761 to 1,789 signs. Therefore, the Sign Attribute Sub-Model was verified by comparing simulation results and NC input data.

Table 12.1 Verification of Number of Signs by Color and Road Class

Sign Color	Road Class	Simulation Results – Number of Signs				NC Sign Data	
		Mean	Half Width	Lower Bound	Upper Bound	(%)	Number of Signs
White	Primary	1,775	14	1,761	1,789	17.65	1,765
Yellow	Primary	966	12	954	978	9.69	969
Green	Primary	342	7	335	349	3.44	344
Red	Primary	209	4	205	213	2.08	208
White	Secondary	2,508	13	2,495	2,521	25.05	2,505
Yellow	Secondary	3,227	16	3,211	3,243	32.43	3,243
Green	Secondary	322	8	314	330	3.17	317
Red	Secondary	652	10	642	662	6.49	649

With respect to the other sign attributes (initial retroreflectivity, and sign replacement priority to each sign), the research team verified that they were automatically assigned to each sign depending on the sign color. For example, all red signs were assigned replacement Priority 1. The same holds true to other sign colors.

12.6.2 <u>Sign Damage Sub-Model</u>

The Sign Damage Sub-Model randomly assigns damage to signs according to the annual damage rate entered as input data. When this sub-model assigned damage to a sign, the picture of the sign changes, now being represented by a picture of a damaged sign as shown in Figure 12.14. In other words, if a sign remains undamaged after passing by the Sign Damage Sub-Model, it does not change the picture. However, if a sign leaves this sub-model damaged, it should be represented by one of the pictures shown in Figure 12.14. This feature (picture change) is valuable because it enabled the research team to check whether or not signs were following the right path in the simulation.

Green Sign   *Red Sign*   *White Sign*   *Yellow Sign*

Figure 12.14 Pictures Assigned to Damaged Signs Depending on Their Colors

The analysis of output measures for this sub-model was conducted in two steps. The first step was to verify if the Sign Damage Sub-Model was generating the correct number of signs that are annually damaged. The second step of the output measure analysis consisted of verifying the annual effective number of damaged signs in the system (further explained in this section). Both steps are described below.

12.6.2.1 Number of Signs That Are Annually Damaged

The first step of the output measure analysis was to verify whether or not the number of signs that are annually damaged corresponds to the annual sign damage rate entered as an input parameter. Thus, the research team ran 30 replications of 10,000 sign each and collected the output measures with a 95% confidence interval. Table 12.2 shows the input parameters entered in the simulation model.

Table 12.2 Input Parameters

Input Parameters	Scenario
Number of years simulated	1 year
Number of signs simulated	10,000 signs
Annual damage rate	4.04%
Annual spot replacement rate	NA
Blanket replacement cycle	NA
Grace period	NA
Daytime inspection cycle	NA
Daytime inspection replacement priority	NA

Note: NA - Not Applicable

Table 12.3 shows the results from the simulation as well as the NC sign data for comparison purposes. The first four columns of the table show the simulation results. The first column shows the mean number of signs that are annually damaged. The second column shows the half width (*h*) for a 95% confidence interval. The third column shows the lower bound, which is obtained by subtracting the half width from the mean number of signs (*mean - h)*. The fourth column shows the upper bound, which is obtained by adding the half width to the mean number of signs (*mean + h)*. The fifth and sixth columns show the NC sign data used to run the simulation. The annual damage rate is 4.04% (fifth column), which results in 404 out 10,000 signs (sixth column). As the table below shows, the expected number of signs that are annually damaged in NC (for each 10,000 signs) is 404 and is within the 95% confidence interval (396 to 408 signs). Thus, the research team verified that the Sign Damage Sub-Model is generating the correct number of signs that are annually damaged.

Table 12.3 Verification of Number of Signs That Are Annually Damaged

Simulation Results – Number of Signs				NC Sign Data		Verified
Mean	Half Width	Lower Bound	Upper Bound	(%)	Expected Number of Signs	
402	6	396	408	4.04	404	Yes

12.6.2.2 Effective Annual Number of Damaged Signs

The second step of the output measure analysis was to verify the annual effective number of damaged signs in the system. When the Sign Damage Sub-Model is verified by itself (no link with other sub-models), damaged signs are not replaced by the simple fact that there is no replacement sub-model in this system. Thus, the number of damaged signs increases over the years. One might think that the effective annual number of damaged signs in the system is an arithmetic progression function of the annual damage rate (4.04% of all signs in NC). If that was correct, the effective number of damaged signs in Year 1 would be 4.04%, Year 2 would be 8.08%, Year 3 would be 12.12%, and so on. That would be true if signs could be damaged only once throughout the years. However, the real system is more complex than a simple arithmetic progression due to the possibility of the same sign being damaged more than once throughout the years (e.g., a sign is damaged in Year 2 and again in Year 8).

To calculate the effective annual number of damaged signs, other variables besides damage rate shall be considered. The first variable is number of damaged signs at the beginning of the year (BOY), which represents the signs that were already damaged in previous years. The second variable is number of signs that are damaged in that year and that is a function of the annual damage rate. The third variable is number of signs that were already damaged in beginning of the year and that are damaged again that year (referred to as duplicated damaged number). The relationship among these variables is described in the equation below.

$$Effective\ Damaged\ = BOY\ Damaged\ + Annual\ Damaged\ - Duplicated\ Damaged \qquad \text{Eq.(1)}$$

To verify if the Sign Damage Sub-Model is obtaining the correct effective number of damaged signs, the research team ran one replication of 10,000 during a period of 50 years. The input parameters used here are the same as the input parameters shown in Table 12.2. The reason for running only one replication is that the research team desired to verify whether or not the sub-model was accounting for the fact that a sign may be damaged more than once in different years, which has implications in the effective annual number of damaged signs. Note that the intention here was not to check whether or not the effective annual number of damaged signs is within a confidence interval.

Table 12.4 shows partial results obtained from the simulation. The first column of the table refers to the year simulated. The second column shows the number of damaged signs at the beginning of the year. The third column shows the number of signs that are annually damaged. The fourth column shows the number of signs that were already damaged from previous years and were damaged again in that year (duplicated damaged number). The second row of the table numbers the columns and, in some cases, shows the relationship among the variables.

The simulation results demonstrate that the Sign Damage Sub-Model is working properly in calculating the effective number of damaged signs. For instance, consider Year 2 in Table 12.4. Year 2 started with 395 damaged signs that were damaged in Year 1. Then, a total of 364 signs were damaged in Year 2 (see third column). From those 364 damaged signs, 10 signs (see fourth column) were already damaged from Year 1 and were again damaged in Year 2. Thus, the effective number of damaged signs can be calculated by Equation (1) as follows.

$$Effective\ Damaged\ = BOY\ Damaged\ + Annual\ Damaged\ - Duplicated\ Damaged \qquad \text{Eq.(1)}$$
$$Effective\ Damaged\ = 395\ + 364\ - 10$$
$$Effective\ Damaged\ = 749$$

The effective number of damaged signs obtained from Equation (1) is the same as the number obtained from the simulation and that is shown in the fifth column of Table 12.4. The same verification was made for the other years. Therefore, the research team verified that the Sign Damage Sub-Model is working properly in calculating the effective number of damaged signs in the system.

Table 12.4 Verification of Effective Annual Number of Damaged Signs

Simulation Year	BOY Damaged Number	Annual Damaged Number	Annual Duplicated Damaged Number	Effective Annual Damaged Number	Effective Annual Damaged Percent
(1)	**(2)**	**(3)**	**(4)**	**(5) = (2) + (3) – (4)**	**(6) = (5) / 10,000**
1	0	395	0	395	3.95%
2	395	364	10	749	7.49%
3	749	402	34	1,117	11.17%
4	1,117	386	51	1,452	14.52%
5	1,452	376	61	1,767	17.67%
6	1,767	393	75	2,085	20.85%
7	2,085	409	84	2,410	24.10%
8	2,410	386	97	2,699	26.99%
9	2,699	428	110	3,017	30.17%
10	3,017	393	120	3,290	32.90%
11	3,290	401	129	3,562	35.62%
…	…	…	…	…	…
50	8,686	397	337	8,746	87.46%

12.6.3 <u>Spot Replacement Sub-Model</u>

The Spot Replacement Sub-Model has two processes. The first process is to select the correct number of damaged signs that are reported. The second process is the spot replacement itself in which a damaged sign is disposed of and a new sign is installed in its place. The objective here is to verify these two processes through animation observation and output measure analysis, which is detailed next.

Animation was used as one of the methods to verify the Spot Replacement Sub-Model. By simply observing the simulation animation, it was possible to check whether or not all signs that are entering the sub-model are damaged. In addition, those damaged signs that are spot replaced should have their picture also replaced: what was before represented by the picture of a damaged sign should now leave the system with the picture of an undamaged sign. Figure 12.15 illustrates an example of a damaged red sign that was spotted and reported. This sign follows to the spot replacement server. When the red sign leaves the replacement server, it should be represented by the picture of an undamaged sign as shown in the figure below. If a damaged sign passes by the spot replacement server and its remains the same as before, that means something went wrong in the replacement process.

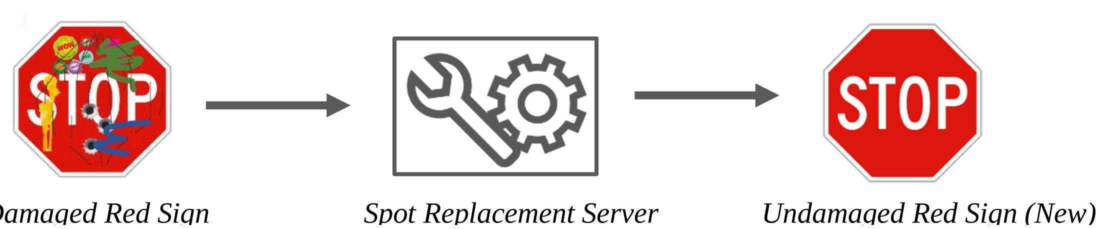


Figure 12.15 Pictures of a Damaged Red Sign Before and After Spot Replacement

The analysis of output measures for this sub-model was conducted in two steps. The first step was to verify if this sub-model was selecting the correct number of damaged signs that are spotted and reported based on the spot replacement rate. The second step was to verify if the spot replacement process was working properly (further explained in this section). Both steps are described below.

12.6.3.1 Number of Damaged Signs That Are Reported

The first step of the Spot Replacement Sub-Model is to randomly select damaged signs that are reported (out of inspection) as being damaged to a transportation agency. The number of signs reported is based on an input parameter referred as spot replacement rate. The objective here is to check whether or not the simulation is selecting the correct number of signs reported based on the input parameter.

Thus, the research team ran 30 replications of 10,000 sign each and collected the output measures with a 95% confidence interval. NC data was used as input parameter, which included an annual damage rate of 4.04% of all signs and an annual spot replacement rate of 41.09% of damaged signs. The input parameters used in this scenario are shown in Table 12.5. Considering the information shown in Table 12.5, the expected number of damaged signs in the system is 404 (10,000 signs x 4.04% damage rate) and the expected number of reported damaged signs is 166 (404 damaged signs x 41.09% spot replacement rate).

Table 12.5 Input Parameters

Input Parameters	Scenario
Number of years simulated	1 year
Number of signs simulated	10,000 signs
Annual damage rate	4.04%
Annual spot replacement rate	41.09% *
Blanket replacement cycle	NA
Grace period	NA
Daytime inspection cycle	NA
Daytime inspection replacement priority	NA

Note: NA - Not Applicable
* 41.09% of damaged signs

Table 12.6 shows the simulation results as well for number of signs damaged and signs reported. The 95% confidence interval for the number of damaged signs ranges from 399 and 413 *(mean ± h)*, which includes the expected number of damaged signs, which is 404. The same is true for the expected number of damaged signs reported, which is 166 and is within the 95% confidence interval that ranges from 163 and 171 *(mean ± h)*. Hence, the research team verified that the Spot Replacement Sub-Model is working properly and generating the correct number of damaged signs that are reported.

Table 12.6 Verification of the Annual Number of Damaged Signs That Are Reported

Input Parameters	Simulation Results Number of Signs				NC Sign Data	
	Mean	Half Width	Lower Bound	Upper Bound	%	Expected Number of Signs
Damaged Signs	406	7	399	413	4.04%	404
Damaged Signs Reported	167	4	163	171	41.09%	166

12.6.3.2 Spot Replacement Process

The second step of the Spot Replacement Sub-Model is to replace the damaged signs that were reported (during the first step). For this case, the research team needed to ensure that the all signs that passed by the spot replacement server were replaced and that the new signs had the same features (color, road class, replacement priority, etc.) as the signs that they are replacing. To do so, the research team ran one replication of 10,000 during a period of 50 years. The input parameters shown in Table 12.5 were used in this scenario, in which the difference was that instead of simulating only 1 year, this scenario simulated 50 years. This verification does not require multiple replications because the objective here was not to check whether or not the confidence levels included the input parameter entered by the user (as this was done in the first step of this sub-model).

During the spot replacement process, data from replaced signs is stored in a table. In addition, as soon as a new sign is created, and its features are assigned to it, the data of the new sign is also stored in that table. With this data is possible to check if the number of signs being replaced is the same as the number of new signs. Additional factors that can be checked by analyzing the data obtained from the simulation are as follow.

- In which year a sign was replaced
- Age in which a damaged sign was replaced
- That all signs replaced were damaged
- That all news signs should be 1 year old
- That all new signs should be undamaged

Table 12.7 shows some of the damaged sign that were spot replaced in Year 7 of the simulation. The first column of the table indicates the simulation Year. The second column shows the sign ID (identifier), which is unique for each sign and it is generated automatically by the simulation software. The sign attributes are shown in the middle of the table (sign color, road class, replacement priority that ranges from 1 to 3 and depends on the sign color). The sixth column shows sign age. Note that all new signs are 1 year old. The seventh column shows whether or not the sign was damaged. All replaced signs should appear as damaged in this table while all new signs should be undamaged. The last column indicated whether that specific sign was replaced or if it was a new sign that was just installed.

To facilitate the understanding of Table 12.7, a pair of rows were highlighted in gray to distinguish signs involved in one replacement. Each pair contains a sign that was replaced and a new sign with the same attributes as the replaced sign. For instance, consider the second and third rows of the table. Sign number 11830 was a 2 year old damaged yellow sign located on a secondary road with a replacement priority of 2. This damaged sign (11830) was replaced by a new sign (11871) that had the same features (yellow, located on a secondary road, and replacement priority 2). The new sign was 1 year old and undamaged, as expected.

Table 12.7 Partial Simulation Results of the Spot Replacement

Simulation Year	Sign ID	Sign Attributes			Sign Age	Sign Damaged	Replaced or New
		Sign Color	Road Class	Replacement Priority			
7	EntSign.11830	Yellow	Secondary	2	2	Yes	Replaced
7	EntSign.11871	Yellow	Secondary	2	1	No	New
7	EntSign.11806	Yellow	Primary	2	2	Yes	Replaced
7	EntSign.11872	Yellow	Primary	2	1	No	New
7	EntSign.11804	Yellow	Secondary	2	2	Yes	Replaced
7	EntSign.11873	Yellow	Secondary	2	1	No	New
7	EntSign.11759	White	Primary	3	2	Yes	Replaced
7	EntSign.11874	White	Primary	3	1	No	New
7	EntSign.11483	Yellow	Secondary	2	3	Yes	Replaced
7	EntSign.12230	Yellow	Secondary	2	1	No	New
7	EntSign.10814	Green	Primary	3	5	Yes	Replaced
7	EntSign.12084	Green	Primary	3	1	No	New
7	EntSign.10377	Red	Primary	1	6	Yes	Replaced
7	EntSign.12129	Red	Primary	1	1	No	New
7	EntSign.1237	Yellow	Secondary	2	7	Yes	Replaced
7	EntSign.11889	Yellow	Secondary	2	1	No	New

An additional verification was made to ensure that the number of replaced signs (by color and road class) is the same as the number of new signs. Using the table obtained from the simulation, it was possible to calculate the number of replaced and new signs and verify whether or not they matched. As Table 12.8 shows, the number of signs replaced is the same as the number of new signs. For instance, consider white signs located on primary roads. A total of 3,211 damaged white signs located on primary roads were spot replaced through a period of 50 years. And exactly the same number (3,211) of new white signs located on primary roads were created by the Spot Replacement Sub-Model. Therefore, the research team verified that the spot replacement process is working as expected.

Table 12.8 Verification of the Number of Signs Spot Replaced and New Signs

Road Class	Primary		Secondary	
Sign Color	Replaced	New	Replaced	New
White	3,211	3,211	4,748	4,748
Yellow	1,865	1,865	5,797	5,797
Green	637	637	533	533
Red	347	347	1,177	1,177

12.6.4 Blanket Replacement Sub-Model

The Blanket Replacement Sub-Model is the most complex and is the sub-model that contains the most processes, which include replacement cycles, replacement itself, and grace period. The objective here is to verify these three processes through animation observation and output measure analysis, which is detailed next.

Animation was used as one of the methods to verify the Blanket Replacement Sub-Model. By simply observing the simulation animation, it was possible to check some aspects of this sub-model. For example, red signs do not pass by grace period process, which is shown in Figure 12.16. Note that all red signs go directly to the blanket replacement process (which is the replacement itself). All the other colors (white, green, and yellow) pass by the grace period process. If the research team noticed a red sign entering the grace period process, that would have indicated something wrong in the logic of the sub-model. Another verification that was possible by observing the animation was to check all signs that left the blanket replacement process (and therefore, new signs) were represented by the picture of an undamaged sign (similar to what occurs in the spot replacement server).

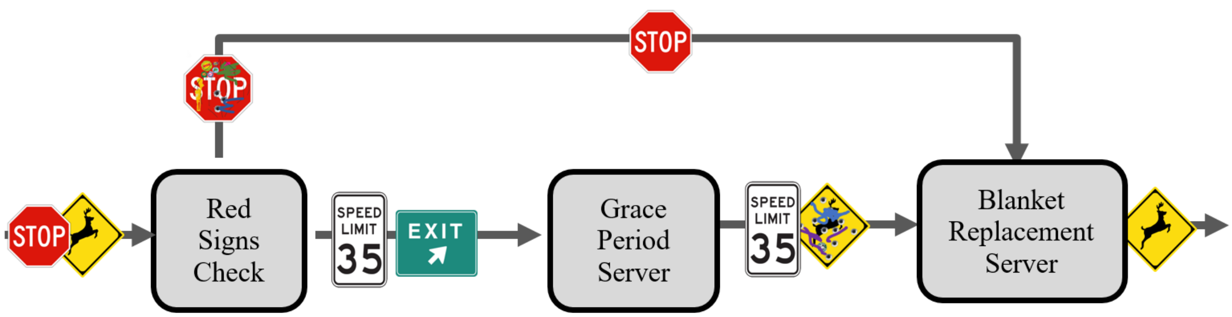


Figure 12.16 Red Signs Skip the Grace Period Server

Other verifications were conducted by analyzing output measures. The first step was to check if the Blanket Replacement Sub-Model was properly defining the years of blanket replacement. For example, if the blanket replacement cycle is 10 years, then there should be blanket replacement in Years 1, 11, 21, 31, and so on. The second step was to verify if the blanket replacement process was working properly in replacing signs and creating new signs, which is similar to the verification conducted for the spot replacement process. The third verification step was to check if the grace period process was also working properly when the scenario considered it. For example, if a scenario considers a grace period, not all signs are blanket replaced; undamaged signs that are the same age as the grace period or younger than it remain in the field (i.e., those signs are not replaced). The three steps are described below.

12.6.4.1 Blanket Replacement Cycles

The first verification step was to check if the Blanket Replacement Sub-Model was properly defining the years of blanket replacement. The research team verified the replacement cycles by analyzing the outcome measures of one replication of 10,000 during a period of 50 years for three different replacement cycles (10, 12, and 15 years). The reason for running only one replication per scenario is that the research team desired to verify the results year by year to check if signs were being replaced as expected through the years and also to determine how many signs were annually replaced. The input parameters used in the three scenarios are shown in Table 12.9.

Table 12.9 Input Parameters

Input Parameters	Scenario 1	Scenario 2	Scenario 3
Number of years simulated	50 year	50 year	50 year
Number of signs simulated	10,000 signs	10,000 signs	10,000 signs
Annual damage rate	4.04%	4.04%	4.04%
Annual spot replacement rate	NA	NA	NA
Blanket replacement cycle	10 years	12 years	15 years
Grace period	NA	NA	NA
Daytime inspection cycle	NA	NA	NA
Daytime inspection replacement priority	NA	NA	NA

Table 12.10 shows part of the results for the three scenarios. The first column indicates the simulation year. The second column shows the signs replaced considering a blanket replacement cycle of 10 years. Note that the signs are replaced every 10 years (Years 1, 11, 21, 31, and so on). The third column shows the results for a blanket replacement cycle of 12 years. In this scenario, signs are replaced in Years 1, 13, 26, and so on. The last column of the table shows the results for a blanket replacement cycle of 15 years. In this case, signs are replaced in Years 1, 16, 31, and so on. By analyzing those results, the research team verified that the Blanket Replacement Sub-Model was correctly identifying the years of blanket replacement based on the replacement cycle entered as input parameter.

Table 12.10 Verification of the Blanket Replacement Cycles

Simulation Year	Number of Signs Blanket Replaced		
	10 Year Cycle	12 Year Cycle	15 Year Cycle
1	10,000	10,000	10,000
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	10,000	0	0
12	0	0	0
13	0	10,000	0
14	0	0	0
15	0	0	0
16	0	0	10,000
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0
21	10,000	0	0

Simulation Year	Number of Signs Blanket Replaced		
	10 Year Cycle	12 Year Cycle	15 Year Cycle
22	0	0	0
23	0	0	0
24	0	0	0
25	0	10,000	0
26	0	0	0
27	0	0	0
28	0	0	0
29	0	0	0
30	0	0	0
31	10,000	0	10,000
…	…	…	…
50	0	0	0

12.6.4.2 Blanket Replacement Process

The second verification step was to check if the blanket replacement process was working properly. The research team ran a 10 year replacement cycle scenario (Scenario 1 from Table 12.9) and analyzed output measures in a very similar manner to how it was done with the spot replacement process. The objective here was to verify if the blanket replacement process was creating new signs that contained the same features as the replaced signs.

During the blanket replacement process, data from replaced signs was stored on a table. In addition, as soon as a new sign was created, and its features were assigned to it, the data of the new sign was also stored in that same table. Table 12.9 shows a portion of the results obtained from the simulation. As blanket replacement occurs only in specific years, it was necessary to choose results that corresponded to a replacement year to populate Table 12.11. For exemplification purpose, Year 11 was chosen.

Table 12.11shows signs that were blanket replaced in Year 11 of the simulation. The first column of the table indicates the year simulated. The second column shows the sign ID. The sign attributes are shown in the middle of the table (sign color, road class, and replacement priority). The sixth column shows sign age. Note that all new signs are 1 year old. The seventh column shows whether or not the sign was damaged. All new signs should be undamaged. The last column indicated whether that specific sign was replaced or was a new sign that was just created.

To facilitate the understanding of Table 12.11, some rows were highlighted in gray to distinguish the pairs involved in one replacement. Each pair contains a sign that was replaced and a new sign with the same attributes as the replaced sign. For instance, consider the second and third rows of the table. Sign number 10516 was an 11 year old damaged red sign located on a secondary road with a replacement priority of 1. This sign (10516) was replaced by a new sign (20182) that had the same features (red, located on a secondary road, and replacement priority 1). The new sign is 1 year old and undamaged, as expected. By analyzing the partial results shown in Table 12.11, it was possible to verify that the blanket replacement process is working as expected.

Table 12.11 Partial Simulation Results of the Blanket Replacement Output Table

Simulation Year	Sign ID	Sign Attributes			Sign Age	Sign Damaged	Replaced or New
		Sign Color	Road Class	Replacement Priority			
11	EntSign.10516	Red	Secondary	1	11	Yes	Replaced
11	EntSign.20182	Red	Secondary	1	1	No	New
11	EntSign.10172	Yellow	Secondary	2	11	No	Replaced
11	EntSign.20183	Yellow	Secondary	2	1	No	New
11	EntSign.10580	Green	Secondary	3	11	Yes	Replaced
11	EntSign.20184	Green	Secondary	3	1	No	New
11	EntSign.10173	Yellow	Secondary	2	11	No	Replaced
11	EntSign.20185	Yellow	Secondary	2	1	No	New
11	EntSign.10683	White	Secondary	3	11	Yes	Replaced
11	EntSign.20186	White	Secondary	3	1	No	New
11	EntSign.10174	Yellow	Secondary	2	11	No	Replaced
11	EntSign.20187	Yellow	Secondary	2	1	No	New
11	EntSign.10177	White	Primary	3	11	Yes	Replaced
11	EntSign.20188	White	Primary	3	1	No	New
11	EntSign.10714	Green	Secondary	3	11	Yes	Replaced
11	EntSign.20189	Green	Secondary	3	1	No	New

An additional verification (similar to the one conducted in the spot replacement process) was made to ensure that the number of replaced signs (by color and road class) are the same as the number of new signs. Using the table obtained from the simulation, it was possible to calculate the number of replaced and new signs and verify whether or not they matched. As Table 12.12 shows, the number of signs replaced, by color and road class, was the same as the number of new signs. For instance, consider yellow signs located on secondary roads. A total of 16,205 yellow signs located on secondary roads were blanket replaced through a period of 50 years. And exactly the same number (16,205) of new yellow signs located on primary roads were installed during the blanket replacement process. Therefore, the research team concluded that this process is working as expected.

Table 12.12 Verification of the Number of Signs Blanket Replaced and New Signs

Road Class	Primary		Secondary	
Sign Color	**Replaced**	**New**	**Replaced**	**New**
White	8,875	8,875	12,560	12,560
Yellow	4,865	4,865	16,205	16,205
Green	1,665	1,665	1,460	1,460
Red	1,100	1,100	3,270	3,270

12.6.4.3 Grace Period Process

The third verification step was to check if the grace period process was also working properly. For this purpose, the research team ran a scenario that considers a blanket replacement cycle of 10 years and a grace period of 3 years as shown in Table 12.13. It was also necessary to consider a spot replacement rate of 41.09% of damaged signs, based on NC sign data. Otherwise, the grace period would not be applicable to any sign because all of them would be 10 years old at the moment of blanket replacement, and therefore, older than a specified grace period. Readers should be aware that the signs that are spared (not replaced) due to the grace period process are those signs that were spot replaced in previous years, and therefore, the same age as or younger than the specified grace period.

Table 12.13 Input Parameters

Input Parameters	Scenario
Number of years simulated	50 year
Number of signs simulated	10,000 signs
Annual damage rate	4.04%
Annual spot replacement rate	41.09% *
Blanket replacement cycle	10 years
Grace period	3 years
Daytime inspection cycle	NA
Daytime inspection replacement priority	NA

Note: * 41.09% of damaged signs

Table 12.14 shows a portion of the results from the simulation. The first column of the table shows the simulation year. The second column shows the number of undamaged signs that were 3 years or younger and, therefore, not replaced. The last column shows how many of the 10,000 signs simulated were blanket replaced. In Year 11, for example, 968 signs (second column) were undamaged and 3 years old or less. Thus, those signs were not replaced. If there were a total of 10,000 signs and 968 of there were not replaced because they met the grace period criteria, that means that 9,032 signs were blanket replaced in Year 11 (10,000 – 968), which matches the results shown in the last column of Table 12.14. The analysis of the output measures shown in Table 12.14 indicates that the grace period process is working properly.

Table 12.14 Verification of the Grace Period Process

Simulation Year	Number of Signs	
	Undamaged Signs 3 Years Older or Younger (Not Replaced)	Blanket Replaced
(1)	(2)	(3) = 10,000 – (2)
1	0	10000
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	968	9,032
12	0	0

Simulation Year	Number of Signs	
	Undamaged Signs 3 Years Older or Younger (Not Replaced)	Blanket Replaced
(1)	**(2)**	**(3) = 10,000 – (2)**
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	1,032	8,968
22	0	0
…	…	…
50	0	0

An additional verification was conducted for the grace period process. The research team checked if the signs were replaced, did indeed not meet the grace period criteria. A replaced sign should fit one of the following categories.

- Red signs (they are replaced no matter what)
- White, yellow, and green signs older than grace period and undamaged
- White, yellow, and green signs older than grace period and damaged
- White, yellow, and green signs at the same age or younger than grace period and damaged

To do so, the research team analyzed the features of the signs that were replaced. Table 12.15 shows a small sample size of all replaced signs for illustration purpose. The table contains some signs that were replaced in Years 11 and 21. The first column of the table lists the row numbers, which are later used to reference data in the table. The second column indicates the simulation year. The third column shows the sign ID. The sign attributes are shown in the middle of the table (sign color, road class, and replacement priority). The seventh column shows sign age. And the last column shows whether or not the replaced sign was damaged.

There are some important observations that can be made from Table 12.15. For instance, consider the data from row 1. Observe that an undamaged 2 years old red sign was replaced. Although the sign was younger than the grace period and undamaged, it was still a red sign and grace period does not apply to red signs. In other words, red signs are always replaced in a blanket replacement year. Rows 2 and 3 of the table show two non-red signs that were replaced even though they were within the grace period. In these cases, both signs were replaced because they were damaged. That means that independent of sign age, a sign will be replaced if it is damaged. Rows 4 and 5 of the table show two non-red signs that were replaced even thought they were not damaged. In these cases, the signs were older than the grace period (sign age greater than 3 years); thus, they were replaced.

Note that the sign shown in row 5 (Table 12.15) is 13 years old at the moment of replacement in Year 21. One might wonder how a sign can be older than the replacement cycle (in this case, 10 years). That is possible when a grace period practice is adopted. To make it easier to understand, imagine an undamaged 3 year old yellow sign in Year 11. This sign will not be replaced in Year 11 because it is undamaged and within the grace period. As a result, this sign will be 13 years old at the next blanket replacement cycle (Year 21), when it will be finally replaced.

After analyzing the results shown in Tables 12.14 and 12.15, the research team verified that the grace period process is working properly.

Table 12.15 Partial Simulation Results of the Blanket Replacement (With Grace Period)

Row No.	Simulation Year	Sign ID	Sign Attributes			Sign Age	Sign Damaged
			Sign Color	Road Class	Replacement Priority		
1	11	EntSign.22973	Red	Secondary	1	2	No
2	11	EntSign.23283	White	Secondary	3	2	Yes
3	11	EntSign.22704	Yellow	Secondary	2	3	Yes
4	21	EntSign.24851	Green	Secondary	3	11	No
5	21	EntSign.22621	Yellow	Secondary	2	13	No

12.6.5 Daytime Inspection Sub-Model

The Daytime Inspection Sub-Model has three processes. The first process identifies which years daytime inspection are conducted based on the daytime inspection cycle entered as an input parameter. The second process is the replacement itself (resulting from the daytime inspection) in which a damaged sign is disposed and a new sign is installed in its place. The third process is the replacement by sign priority. For example, due to budget constraints, a transportation agency may opt to replace only red signs, which has priority 1. The objective here is to verify these three processes through animation observation and output measure analysis, which is detailed next.

Animation was used as one of the methods to verify the Daytime Inspection Sub-Model. For example, signs should pass by this sub-model only on a year of daytime inspection. In a year of daytime inspection, all signs are inspected, but only those that are damaged are replaced. Thus, if the research team observed any undamaged sign going to the daytime inspection replacement process, that would have indicated something wrong in the logic of the sub-model.

Other verifications were conducted by analyzing output measures. The first step was to check if this sub-model was properly defining the years of daytime inspections. The second step was to verify if the inspection replacement process was working properly in a similar manner as was done in the verification of the spot replacement and blanket replacement processes. The third and last verification step was to check if the replacement by sign priority process was working properly.

12.6.5.1 Daytime Inspection Cycles

The first verification step was to check if the Daytime Inspection Sub-Model was properly defining the years of daytime inspections. To do so, the research team analyzed the output measures of one replication of 10,000 signs during a period of 50 years for two different daytime inspection cycles (5 and 6 years). Blanket replacement was not considered in these scenarios. The reason for running only one replication per scenario is that the research team desired to verify the results year by year to check if inspections were being conducted as expected through the years. The input parameters used in the two scenarios are shown in Table 12.16.

Table 12.16 Input Parameters

Input Parameters	Scenario 1	Scenario 2
Number of years simulated	50 year	50 year
Number of signs simulated	10,000 signs	10,000 signs
Annual damage rate	4.04%	4.04%
Annual spot replacement rate	NA	NA
Blanket replacement cycle	NA	NA
Grace period	NA	NA
Daytime inspection cycle	5 years	6 years
Daytime inspection replacement priority	NA	NA

Table 12.17 shows part of the simulation results for the two scenarios. The first column of the table indicates the simulation year. The second column shows the number of signs inspected considering an inspection cycle of 5 years. Note that all signs are inspected every 5 years (Years 6, 11, 16, and so on). The last column shows the results for a daytime inspection cycle of 6 years. In this scenario, signs are inspected in Years 7, 13, 19, and so on. By analyzing those results, the research team verified that the Daytime Inspection Sub-Model was correctly identifying the years of inspection based on the inspection cycles entered as input parameter.

Table 12.17 Verification of the Daytime Inspection Cycles

Simulation Year	Number of Signs Inspected	
	5 Year Cycle	6 Year Cycle
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	10,000	0
7	0	10,000
8	0	0
9	0	0
10	0	0
11	10,000	0
12	0	0
13	0	10,000
14	0	0
15	0	0
16	10,000	0
17	0	0
…	…	…
50	0	0

As was mentioned before, the two scenarios analyzed in Table 12.17 did not consider blanket replacement. However, sign management programs may consider both blanket replacement and daytime inspection practices. When both practices are adopted, it is common (and reasonable) to not conduct daytime inspection in a year of blanket replacement by the simple fact that all signs are already scheduled to be replaced in that year. As a result, there is no need for daytime inspection. Based on this, the research team also verified that daytime inspections were skipped in a year of blanket replacement. To do so, the research ran one replication of 10,000 during a period of 50 years considering a daytime inspection cycle of 5 years and a blanket replacement cycle of 10 years. The input parameters used in the this scenarios are shown in Table 12.18.

Table 12.18 Input Parameters

Input Parameters	Scenario 3
Number of years simulated	50 year
Number of signs simulated	10,000 signs
Annual damage rate	4.04%
Annual spot replacement rate	NA
Blanket replacement cycle	10 year
Grace period	NA
Daytime inspection cycle	5 years
Daytime inspection replacement priority	NA

Table 12.19 shows partial results of the simulation for the scenario described above. As expected, daytime inspections were not conducted in years of blanket replacement (e.g., Years 11, 21, and so on.). These results verified that the daytime inspections are occurring according to the inspection cycles entered as input parameters and that they are not conducted in years of blanket replacement.

Table 12.19 Verification of the Interaction Between Daytime Inspections and blanket Replacement Cycles

Simulation Year	Number of Signs Blanket Replaced	Number of Signs Inspected
1	10,000	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	10,000
7	0	0
8	0	0
9	0	0
10	0	0
11	10,000	0
12	0	0
13	0	0
14	0	0
15	0	0
16	0	10,000
17	0	0
…	…	…
50	0	0

12.6.5.2 Daytime Inspection Replacement Process

The second verification step was to check if the daytime inspection replacement process was working properly. The research team ran a 5 year daytime inspection cycle scenario (Scenario 1 of Table 12.16) and analyzed the output measures in a very similar manner as was done with the spot replacement and blanket replacement processes. The objective here was to verify if the daytime inspection replacement process was replacing only damaged signs and if the new created signs contained the same features as the ones that they replaced.

Table 12.20 shows the results of the simulation. The reader should be aware that the number of signs replaced during daytime inspections depends on the number of damaged signs in the system. Therefore, Table 12.20 shows the number of damaged before inspections (effective number of damaged signs; see second column), number of signs replaced during the inspections (third column), and number of signs damaged after inspections (also referred as end of year number of damaged signs; see fourth column). The highlighted rows indicate the years of daytime inspections. The first inspection was conducted in Year 6. Note that all damaged signs are replaced during the daytime inspections. As a result, the number of damaged signs after inspections is zero. Based on these results presented in Table 12.20, it was possible to verify that the Daytime Inspection Sub-Model was replacing only the damaged signs as expected.

Table 12.20 Number of Damaged Signs and Signs Replaced During Daytime Inspections

Simulation Year	Number of Signs		
	Damaged Signs Before Inspections	Signs Replaced During Daytime Inspections	Damaged Signs After Inspections
1	402	0	402
2	805	0	805
3	1,137	0	1137
4	1,463	0	1463
5	1,815	0	1815
6	2,131	2,131	0
7	386	0	386
8	792	0	792
9	1,134	0	1134
10	1,499	0	1499
11	1,839	1,839	0
12	377	0	377
13	770	0	770
14	1,137	0	1137
15	1,477	0	1477
16	1,825	1,825	0
…	…	…	…
50	1,505	0	1505

An additional verification (similar to the one conducted in the spot replacement and blanket replacement processes) was made to ensure that the number of replaced signs (by color and road class) are the same as the number of new signs. Thus, Table 12.21 shows some of the damaged sign that were replaced during the daytime inspections in Year 6. The first column of the table indicates the simulation year. The second column shows the sign ID. The sign attributes are shown in the middle of the table (sign color, road class, and replacement priority). The sixth column shows sign age. Note that because this scenario did not consider spot replacement, all replaced signs are the same age (6 years old). In addition, all new signs are 1 year old. The seventh column shows whether or not the sign was damaged. While the replaced signs were all damaged, new signs are always undamaged. The last column indicated whether that specific sign was replaced or is a new sign that was just installed during the replacement process.

Each highlighted pair in Table 12.21 contains a sign that was replaced and a new sign with the same attributes as the replaced sign. By analyzing the partial results shown in the table below, it was possible to verify that the daytime inspection replacement process was working as expected.

Table 12.21 Partial Simulation Results of the Daytime Inspection Replacement Output Table

Simulation Year	Sign ID	Sign Attributes			Sign Age	Sign Damaged	Replaced or New
		Sign Color	Road Class	Replacement Priority			
6	EntSign.10062	Yellow	Secondary	2	6	Yes	Replaced
6	EntSign.10155	Yellow	Secondary	2	1	No	New
6	EntSign.10061	Yellow	Primary	2	6	Yes	Replaced
6	EntSign.10156	Yellow	Primary	2	1	No	New
6	EntSign.10036	Green	Primary	3	6	Yes	Replaced
6	EntSign.10157	Green	Primary	3	1	No	New
6	EntSign.10012	White	Secondary	3	6	Yes	Replaced
6	EntSign.10158	White	Secondary	3	1	No	New
6	EntSign.9981	Green	Primary	3	6	Yes	Replaced
6	EntSign.10159	Green	Primary	3	1	No	New

In addition, the research team also verified that the number of replaced signs (by color and road class) is the same as the number of new signs. Using the table obtained from the simulation and partially shown in Table 12.22, it was possible to calculate the number of signs replaced and new and verify whether or not they match. Table 12.22 shows the results for the simulation Scenario 1 of Table 12.16. As Table 12.22 shows, the number of signs replaced, by color and road class, is the same as the number of new signs. Therefore, the research team concluded that this sub-model is working as expected.

Table 12.22 Verification of the Number of Signs Replaced and New Signs During Inspections

Road Class	Primary		Secondary	
Sign Color	Replaced	New	Replaced	New
White	2,972	2,972	4,323	4,323
Yellow	1,610	1,610	5,376	5,376
Green	617	617	534	534
Red	397	397	1,078	1,078

12.6.5.3 *Daytime Inspection Replacement by Sign Priority Process*

The third verification step was to check if the replacement priority process was working properly. Therefore, the research team ran three scenarios with different replacement priority. One scenario considered that only Priority 1 (red) signs were replaced during daytime inspection. The second scenario considered that Priorities 1 and 2 (red and yellow) signs were replaced. The last scenario considered that Priorities 1, 2, and 3 (all colors) signs were replaced. The input parameters used in these three scenarios are shown in Table 12.23.

Table 12.23 Input Parameters

Input Parameters	Scenario 4	Scenario 5	Scenario 6
Number of years simulated	50 year	50 year	50 year
Number of signs simulated	10,000 signs	10,000 signs	10,000 signs
Annual damage rate	4.04%	4.04%	4.04%
Annual spot replacement rate	NA	NA	NA
Blanket replacement cycle	NA	NA	NA
Grace period	NA	NA	NA
Daytime inspection cycle	5 years	5 years	5 years
Daytime inspection replacement priority	Priority 1	Priorities 1 and 2	Priorities 1, 2, and 3

The results are shown in Table 12.24. The table shows the number of signs that were damaged before the inspections, the number of signs replaced during the inspections, and the number of signs damaged after inspections. By analyzing these output measures from the simulation, the research team can verify the effect that replacement by priority may have on the annual number of damaged signs of a system. The highlighted rows indicate the years of daytime inspection.

As it can be noted in the results shown from the second to fourth columns of Table 12.24, when only Priority 1 signs are replaced, that results in a significant number of damaged signs at the end of the year. When Priorities 1 and 2 are replaced (fifth to seventh columns), the number of damaged signs at the end of the year reduced by almost 50%. And finally, when all damaged signs are replaced (Priorities 1, 2, and 3; see last three columns), there are no damaged signs at the end of the year.

Analysis of the results shown in Table 12.24 proved that the daytime inspection replacement by sign priority process works as expected. In addition, it is possible to note the impact that a management decision (e.g., which signs replace during inspection) can have on the annual number of damaged signs.

Table 12.24 Verification of the Daytime Inspection Replacement By Sign Priority Process

Simulation Year	Number of Damaged Signs								
	Priority 1 (Red Signs)			Priorities 1 and 2 (Red and Yellow Signs)			Priorities 1, 2, and 3 (All Signs)		
	Before	Replaced	After	Before	Replaced	After	Before	Replaced	After
1	402	0	402	402	0	402	402	0	402
2	805	0	805	805	0	805	805	0	805
3	1,137	0	1,137	1,137	0	1,137	1,137	0	1,137
4	1,463	0	1,463	1,463	0	1,463	1,463	0	1,463
5	1,815	0	1,815	1,815	0	1,815	1,815	0	1,815
6	2,131	181	1,950	2,131	1,045	1,086	2,131	2,131	0
7	2,262	0	2,262	1,429	0	1,429	386	0	386
8	2,586	0	2,586	1,790	0	1,790	792	0	792
9	2,873	0	2,873	2,103	0	2,103	1,134	0	1,134
10	3,159	0	3,159	2,427	0	2,427	1,499	0	1,499
11	3,435	144	3,291	2,737	911	1,826	1,839	1,839	0
12	3,543	0	3,543	2,147	0	2,147	377	0	377
13	3,799	0	3,799	2,472	0	2,472	770	0	770
14	4,031	0	4,031	2,785	0	2,785	1,137	0	1,137
15	4,268	0	4,268	3,069	0	3,069	1,477	0	1,477
16	4,515	153	4,362	3,340	941	2,399	1,825	1,825	0
17	4,594	0	4,594	2,722	0	2,722	428	0	428
18	4,815	0	4,815	3,018	0	3,018	827	0	827
19	5,024	0	5,024	3,297	0	3,297	1,187	0	1,187
20	5,234	0	5,234	3,587	0	3,587	1,559	0	1,559
21	5,423	160	5,263	3,845	953	2,892	1,899	1,899	0
22	5,456	0	5,456	3,160	0	3,160	387	0	387
…	…	…	…	…	…	…	…	…	…
50	8,152	0	8,152	5,063	0	5,063	1,505	0	1,505

12.7 Simulation Transient Period, Length, and Replications

Before running all the strategies of interest, it was necessary to define three aspects of the simulation, which are transient removal, simulation length (stopping criteria), and number of replications. Transient removal consists of removing from the data analysis the observations collected during the transient interval, which is the period when the simulation is warming up and that precedes the steady-state. As described by Obaidat and Papadimitriou (2003), removing the transient interval from the results and analysis is essential in any simulation study. The simulation length can be determined by using a stopping criteria that determines how long it is necessary to run the simulation to obtain a desired half width (h). In addition, it was necessary to define the number of replications necessary to obtain an acceptable error of ± 5% as described in Chapter 7 (Section 7.7).

To conduct those analysis, the research team ran 10 replications of two pilot strategies to identify and determine the transient interval, simulation length (stopping criteria), and number of replications necessary to obtain an acceptable error of ± 5%. One of the pilot strategies was Strategy 4 because it is one of the most critical, containing the shortest blanket replacement cycle (10 years), the shortest grace period different from zero (3 years), and considering daytime inspections. In addition, the Strategy 24 was also selected as a pilot strategy because it contains the longest blanket replacement cycle (20 years), the longest grace period (5 years), and considers daytime inspections.

Table 12.25 shows the input parameters (fixed and control variables) used in the two pilot strategies, which are represented by Strategies 4 (third column of the table) and 24 (fourth column). Note that the fixed input parameters are the same because they represent the NC sign data. The only values changing based on the strategy are the control variables, the daytime inspection is the same for both strategies.

To determine the transient removal, stopping criteria, and number of replications necessary, two output measures were analyzed: number of unsatisfactory signs and strategy cost. Those measures were selected for being good estimators of the overall sign replacement strategy. For instance, the number of unsatisfactory signs depends on the number of damaged, noncompliant, and replaced signs while the total strategy cost depends on the replacement and inspection costs.

Table 12.25 Input Parameters Pilot Strategy

Input Parameter	Unit	Pilot Strategy 4	Pilot Strategy 24
Sign Replacement Cycle	Years	10	20
Grace Period	Years	3	5
Daytime Inspection (Presence)	Years	5	5
Number of signs simulated	Signs	10,000	
Period simulated	Years	50	
Annual damage rate	%	4.04	
Annual spot replacement rate	%	41.09	
Average sign replacement cost	$	81.31	
Average sign inspection cost	$	0.35	
Percent white signs on primary roads *	%	17.65	
Percent white signs on secondary roads *	%	20.05	
Percent yellow signs on primary roads *	%	9.69	
Percent yellow signs on secondary roads *	%	32.43	
Percent green signs on primary roads *	%	3.44	
Percent green signs on secondary roads *	%	3.17	
Percent red signs on primary roads *	%	2.08	
Percent red signs on secondary roads *	%	6.49	
Retroreflectivity deterioration model for white signs	$cd/lx/m^2$	304.089 – 4.815 Age	
Retroreflectivity deterioration model for yellow signs	$cd/lx/m^2$	193.01 + 5.644 Age – 0.552 Age^2	
Retroreflectivity deterioration model for red signs	$cd/lx/m^2$	59.632 – 2.658 Age	
Retroreflectivity deterioration model for green signs	$cd/lx/m^2$	53.386 – 1.345 Age	

Note: * The sum of the percentage of signs on primary and secondary roads should add up 100%.

12.7.1 Transient Period (Removal)

In this study, the first years simulated have incomplete data because the initial sign condition is unknown. Therefore, the research team is interested only on the results collected when the simulation is stabilized (steady-state). To consider steady-state results, it was necessary to identify the transient period (simulation warm up) and remove its observations from the simulation results. The literature listed some heuristic approaches that can be used to remove the transient period. Some of the heuristic techniques cited in the literature are long run, proper initialization, truncation, initial data deletion, moving average of independent replications (Obaidat and Papadimitriou, 2003; Obaidat and Boudriga, 2010).

Considering that the first simulation years contain incomplete data, the research team selected the initial data deletion technique, which consists of identifying the transient period and removing it from the results and data analysis. When using this technique, it is recommended to average the observations across a number of replications rather than only one replication with the objective of reducing the variability of the steady-state (Obaidat and Boudriga, 2010).

The authors followed the steps described by Obaidat and Boudriga (2010) to use the initial data deletion technique, which is listed in Table 12.26. The first column describes the steps. The second column shows the equations (if any) used in each step. The last column describes the variables used in the equations.

As shown in Table 12.26, the first step calculates the mean of a year (j^{th} year) by averaging all replications, which in this case is ten (m=10). The second step calculates overall mean ($\bar{\bar{x}}$) of all years simulated (n=50) across all replications (m=10). The third step calculates the overall mean excluding a transient state ($\bar{\bar{x}}_{n-k}$, where k refers to the transient state). A transient state is different from the transient period and varies from *k*=1 to *n*-1. For each level of k, an overall mean excluding the first *k* observations is calculated. For example, for *k*=1, the observation of the first year is deleted and an overall mean is calculated based on the remaining 49 observations (*n*-*k* = 50-1 = 49).

The fourth step calculates the relative change (*RC*) in the overall mean. The fifth step consists of varying *k* by adding one year at a time and repeating Steps 3 and 4. For example, when *k*=2, the observations of the first two years are deleted and an overall mean is calculated based on the remaining 48 observations (*n*-*k* = 50-2 = 48). This loop goes on until the value of *k* is equal to *n*-1 (*k*= *n*-1= 50-1= 49).

The sixth step plots both the overall mean excluding a transient state ($\bar{\bar{x}}_{n-k}$) and the relative change (*RC*) against the values of the transient state (*k*). Then, the last step (seventh) is to identify when the plotted curves start stabilizing. The transition from a very steep curve to a more horizontal and smooth curve is known as "knee" and it indicates the end of the transient period. Therefore, observations collected prior the knee (during the transient period) are removed from in the final data analysis.

Table 12.26 Steps, Equations, and Description of the Initial Data Deletion Technique (Transient Removal)

Steps	Equation	Description
1) Calculate the mean of the j^{th} year by averaging across replications	$\bar{x}_j = \frac{1}{m}\sum_{i=1}^{m} x_{ij}$	$\bar{x}_j$ = mean of j^{th} year across all replications (*m*) *m* = number of replications *n* = simulation length (years) *i* =1, 2, …m *j* =1, 2, …n
2) Calculate the overall mean	$\bar{\bar{x}} = \frac{1}{n}\sum_{j=1}^{n} \bar{x}_j$	$\bar{\bar{x}}$ = overall mean of all years (*n*) across all replications (*m*) *n* = simulation length (years) *j* =1, 2, …n
3) Calculate the overall mean excluding the observations of the first *k* years. Start with *k*=1	$\bar{\bar{x}}_{n-k} = \frac{1}{n-k}\sum_{j=k+1}^{n} \bar{x}_j$	$\bar{\bar{x}}_{n-k}$= overall mean excluding observations of the first *k* years across all replications (*m*) *k* = transient state (which is different from transient period) *n* = simulation length (years) *j* = k+1, …n
4) Calculate relative change (RC) in the overall mean	$RC = \frac{\bar{\bar{x}}_{n-k} - \bar{\bar{x}}}{\bar{\bar{x}}}$	$\bar{\bar{x}}$ = overall mean of all years (*n*) across all replications (*m*) $\bar{\bar{x}}_{n-k}$= overall mean excluding observations of the first *k* years across all replications (*m*)
5) Add *1* to *k* and repeat steps (3) and (4) until k = n-1	-	*k* = 1 to *n* – 1 *n* = simulation length (years)
6) Plot graphs of the overall mean and the relative change against *k* values (1 to n-1)	-	-
7) Identify for which value of *k* the overall mean and the relative change start "stabilizing." That point is known as the	-	-

knee and indicates the end of the transient period.		

The initial data deletion technique was conducted in two output measures (number of unsatisfactory signs and strategy cost) resulting from the two pilot strategies (Strategies 4 and 24) and it is discussed in the next subsections. The tables resulted from the analysis are presented in Appendix 12.8 (Transient Interval Removal Analysis).

12.7.1.1 Number of Unsatisfactory Signs

Figures 12.17 to 12.20 show the plots of the number of unsatisfactory signs of the pilot Strategy 4. Figure 12.17 shows the simulation results across all ten replications. Observe that all replications show the same trend, which seems to start stabilizing in Year 10. Figure 12.18 shows the overall mean ($\bar{\bar{x}}$) across all ten replications. Starting in Year 10, the overall mean curve became smoother when compared to the curves of individual replications (Figure 12.17).

Figure 12.19 shows the overall mean excluding the transient state ($\bar{\bar{x}}_{n-k}$) (i.e., excluding observation of the first *k* years while varying *k* from 1 to *n*-1). In this plot is possible to note that the knee is located *k*=9. This information is confirmed by the graph of relative change (*RC*) in Figure 12.20, which also shows a knee around *k*=9. Thus, it is possible to state that the number of unsatisfactory signs of Strategy 4 start stabilizing in Year 10, when *k*=9. Considering that Strategy 4 consists of a blanket replacement cycle of 10 years, it can be said that the transient period of the Strategy 4 output measure "number of unsatisfactory signs" corresponds to the first replacement cycle.

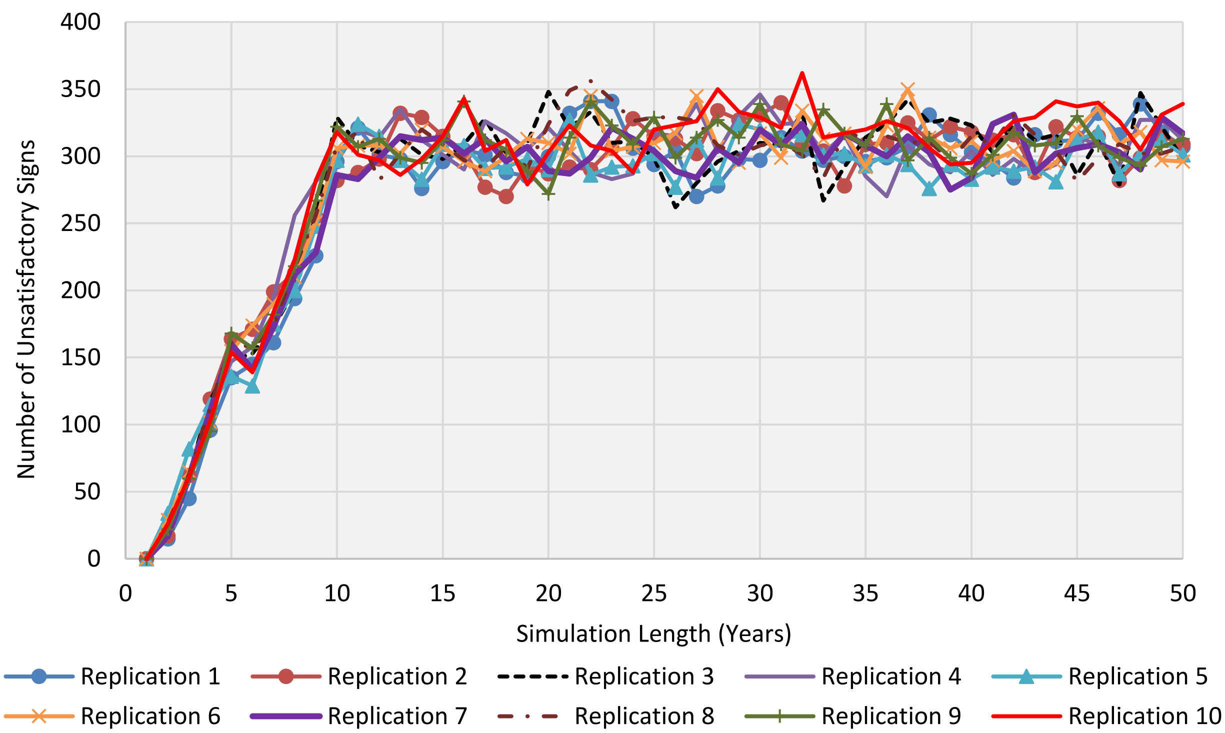


Figure 12.17 Strategy 4 Number of Unsatisfactory Signs – Individual Replications

Figure 12.18 Strategy 4 Number of Unsatisfactory Signs – Overall Mean ($\bar{\bar{x}}$) Across Replications

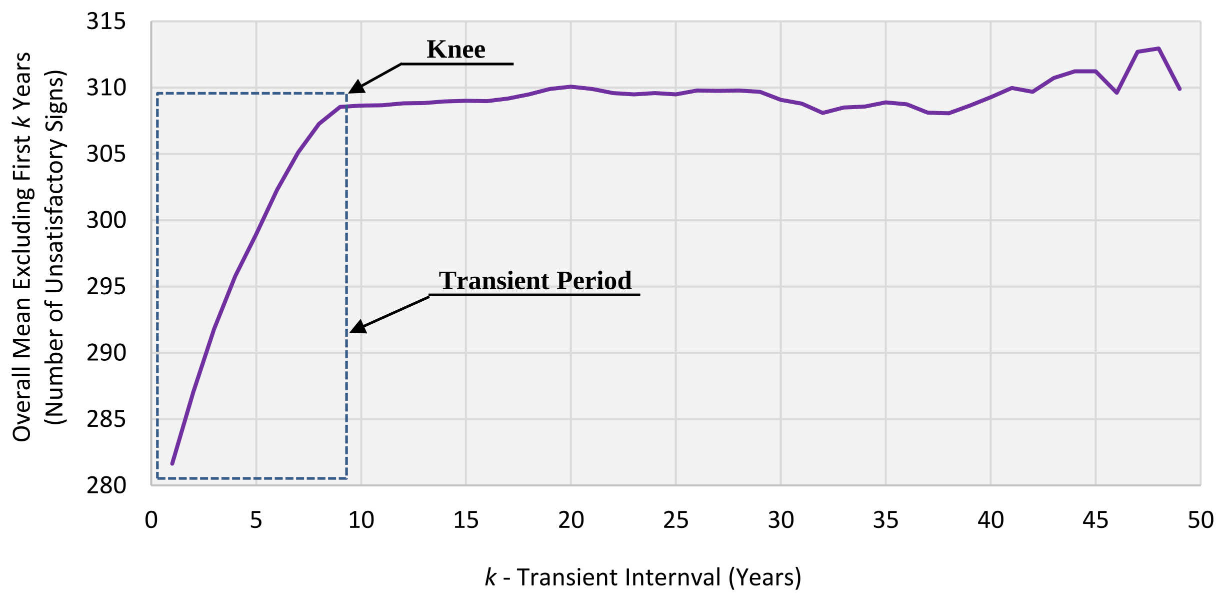


Figure 12.19 Strategy 4 Number of Unsatisfactory Signs – Overall Mean Excluding Observations of the First *k* Years Across Replications

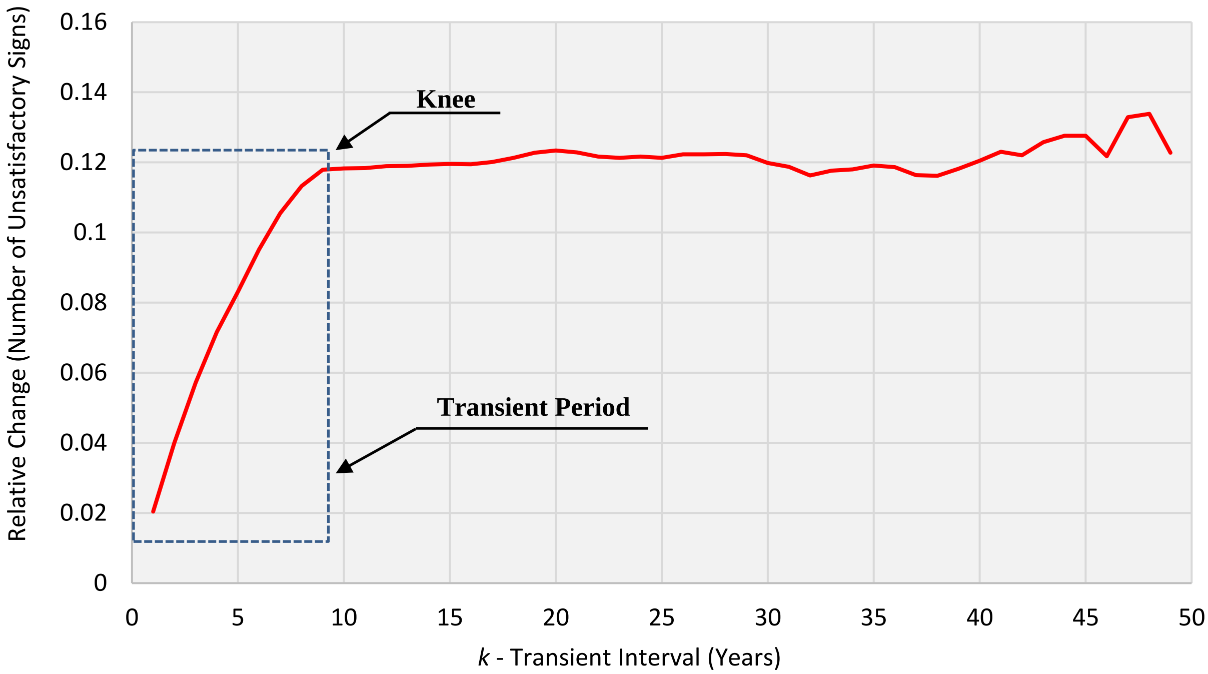


Figure 12.20 Strategy 4 Number of Unsatisfactory Signs – Relative Change (RC)

Figures 12.21 to 12.24 shows the plots of the number of unsatisfactory signs of the pilot Strategy 24. Figure 12.21 shows the simulation results across all ten replications. Observe that all replications show the same trend, which seems to start stabilizing in Year 20. Figure 12.22 shows the overall mean ($\bar{\bar{x}}$) across all ten replications. Starting in Year 20, the overall mean curve become smoother when compared to the curves of individual replications (Figure 12.21).

Figure 12.23 shows the overall mean excluding the transient state ($\bar{\bar{x}}_{n-k}$) (i.e., excluding observation of the first *k* years while varying *k* from 1 to *n*-1). In this plot is possible to note that the knee is located *k*=19. This information is confirmed by the graph of relative change (*RC*) in Figure 12.24, which also shows a knee around *k*=19. Thus, it is possible to state that the number of unsatisfactory signs of Strategy 24 start stabilizing in Year 20, when *k*=19. Considering that Strategy 24 consists of a blanket replacement cycle of 20 years, it can be said that the transient period of the Strategy 24 output measure "number of unsatisfactory signs" corresponds to the first replacement cycle.

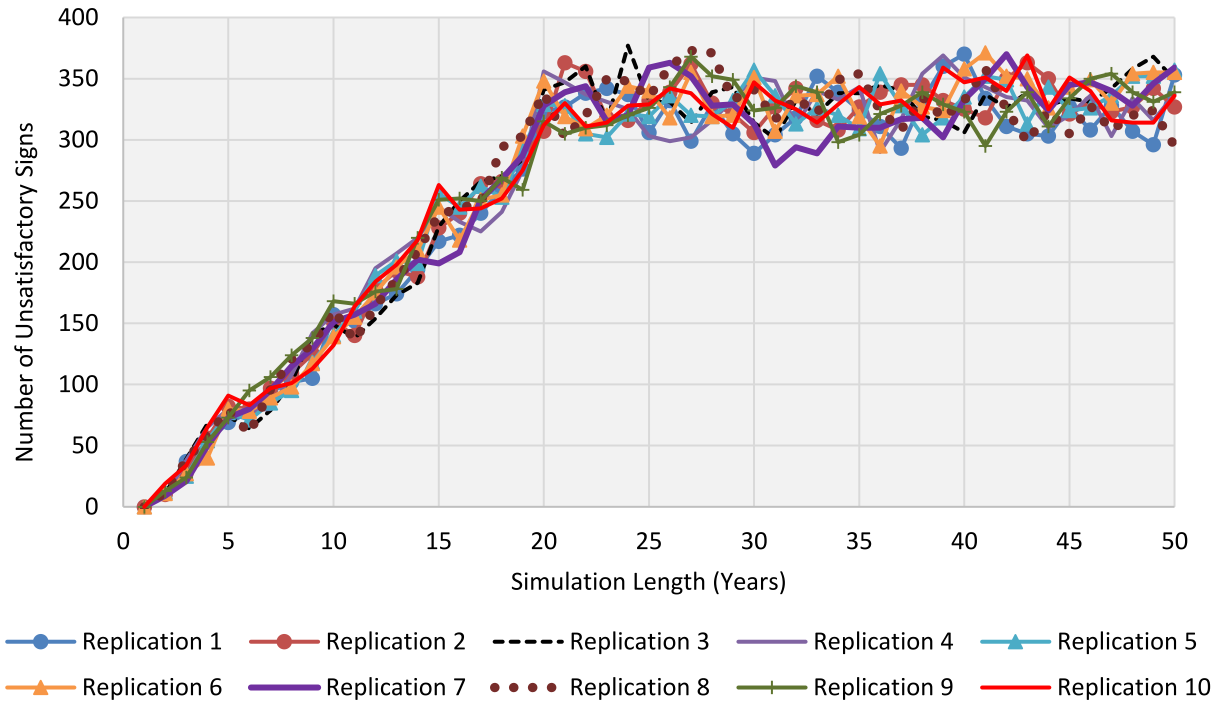


Figure 12.21 Strategy 24 Number of Unsatisfactory Signs – Individual Replications

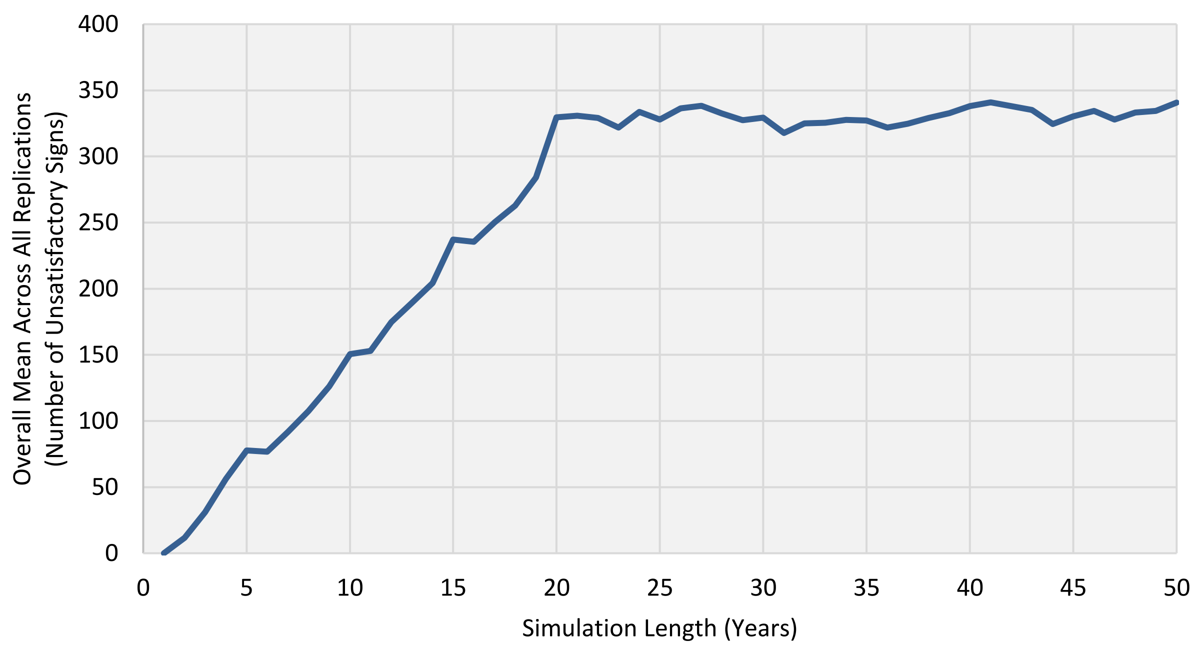


Figure 12.22 Strategy 24 Number of Unsatisfactory Signs – Overall Mean ($\bar{\bar{x}}$) Across Replications

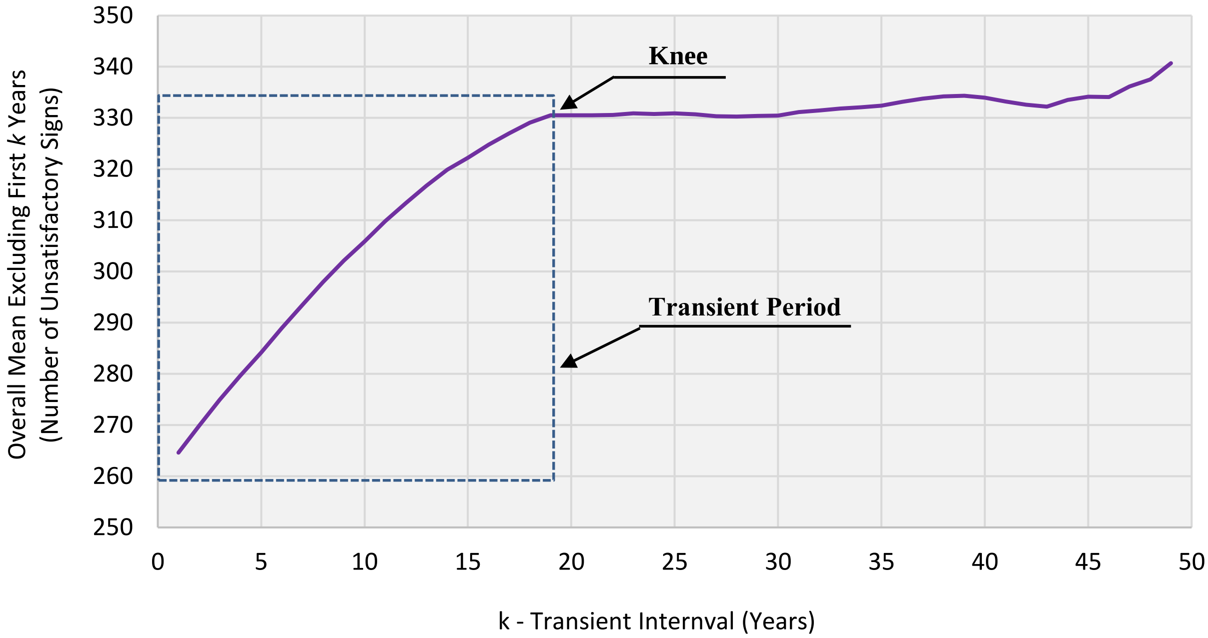


Figure 12.23 Strategy 24 Number of Unsatisfactory Signs – Overall Mean Excluding Observations of the First *k* Years Across Replications

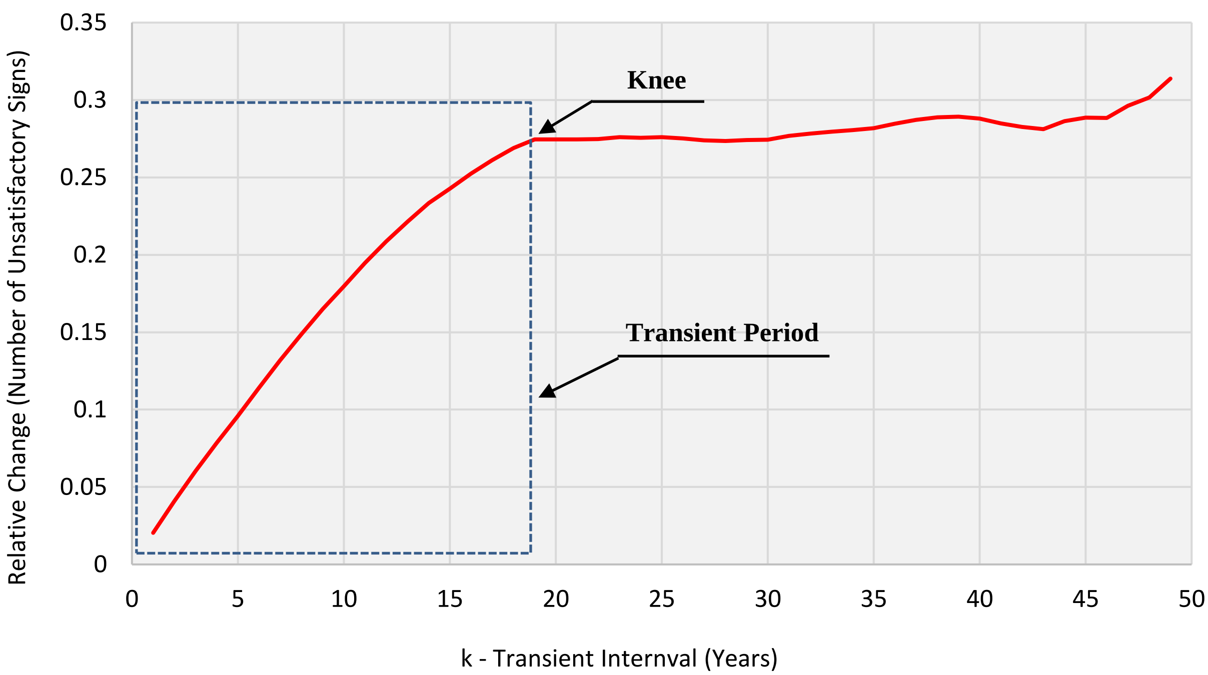


Figure 12.24 Strategy 24 Number of Unsatisfactory Signs – Relative Change (RC)

12.7.1.2 Strategy Cost

Figures 12.25 to 12.28 shows the plots of the strategy cost of the pilot Strategy 4. Figure 12.25 shows the simulation results across all ten replications. Observe that all replications show the same trend, which seems to start stabilizing in Year 11. Figure 12.26 shows the overall mean ($\bar{\bar{x}}$) across all ten replications. Starting in Year 11, the overall mean curve becomes smoother when compared to the curves of individual replications (Figure 12.25).

Figure 12.27 shows the overall mean excluding the transient state ($\bar{\bar{x}}_{n-k}$) (i.e., excluding observation of the first *k* years while varying *k* from 1 to *n*-1). In this plot is possible to note that the knee is located *k*=10. This information is confirmed by the graph of relative change (*RC*) in Figure 12.28, which also shows a knee in *k*=10. Thus, it is possible to state that the strategy cost of Strategy 4 start stabilizing in Year 11, when *k*=10. Considering that Strategy 4 consists of a blanket replacement cycle of 10 years, it can be said that the transient period of the Strategy 4 output measure "strategy cost" corresponds to the first replacement cycle.

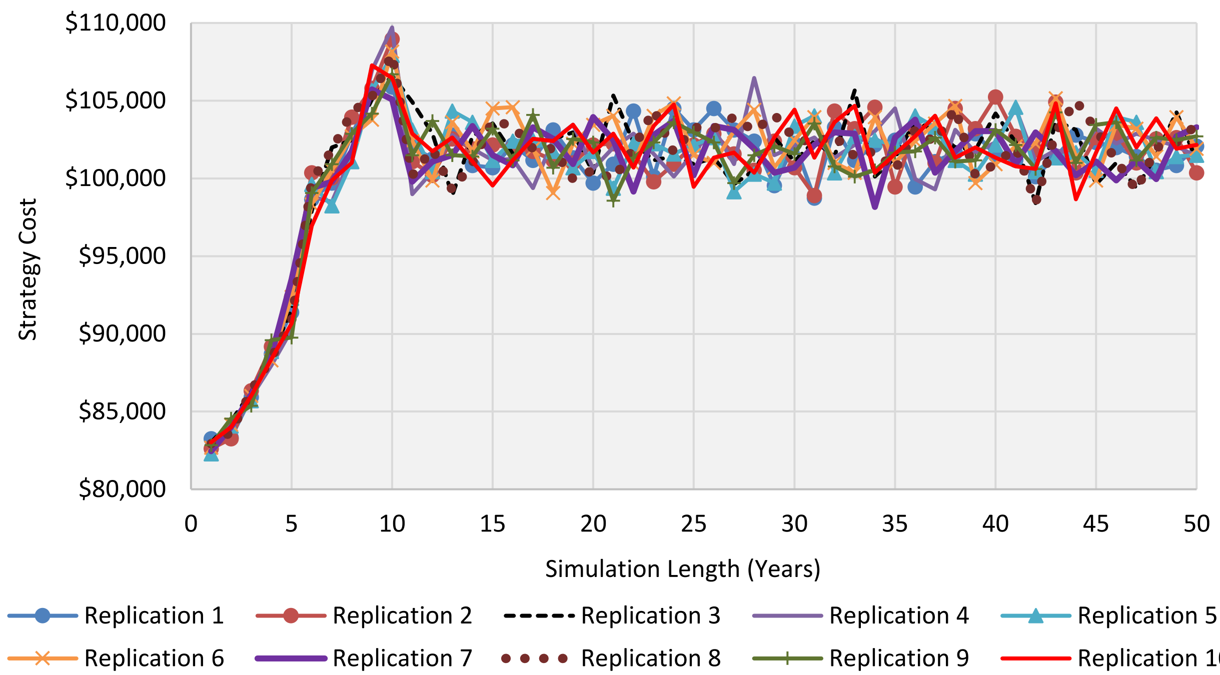


Figure 12.25 Strategy 4 Strategy Cost – Individual Replications

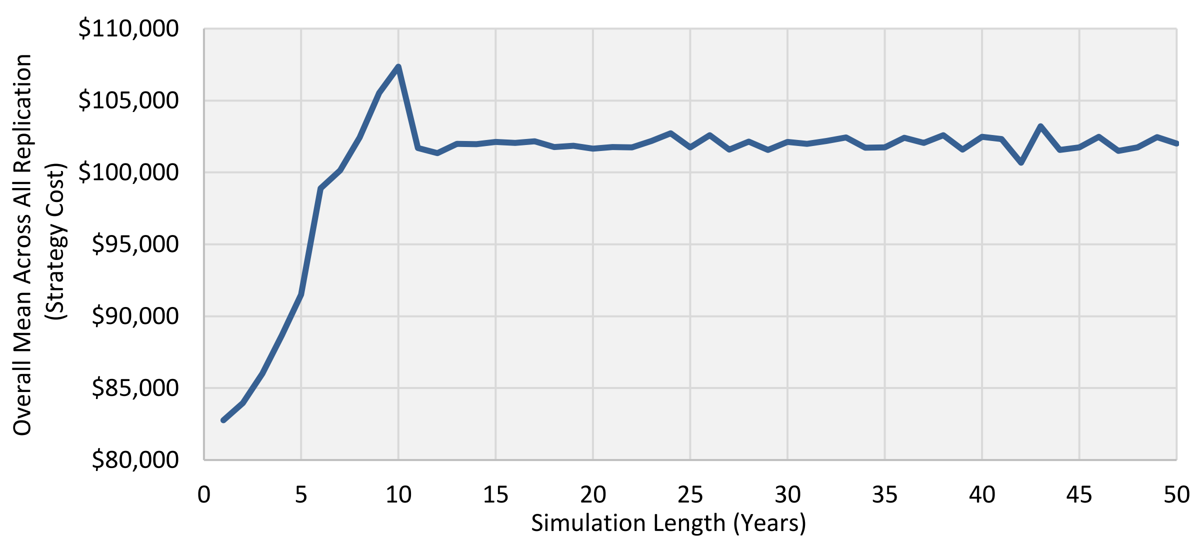


Figure 12.26 Strategy 4 Strategy Cost – Overall Mean ($\bar{\bar{x}}$) Across Replications

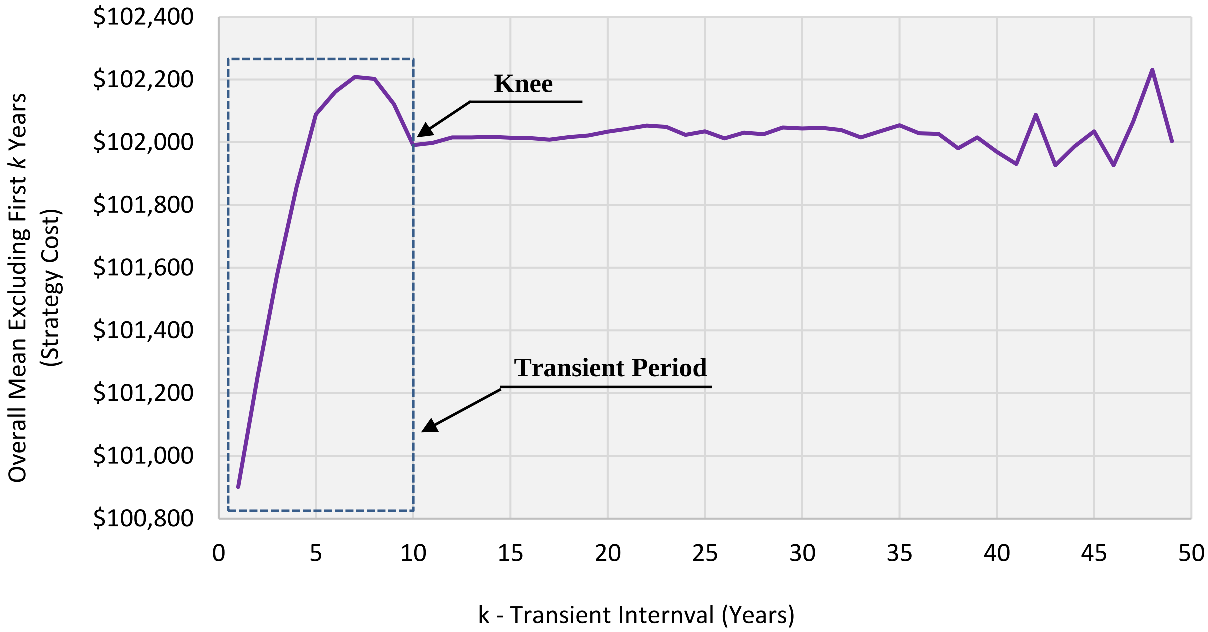


Figure 12.27 Strategy 4 Strategy Cost – Overall Mean Excluding Observations of the First *k* Years Across Replications

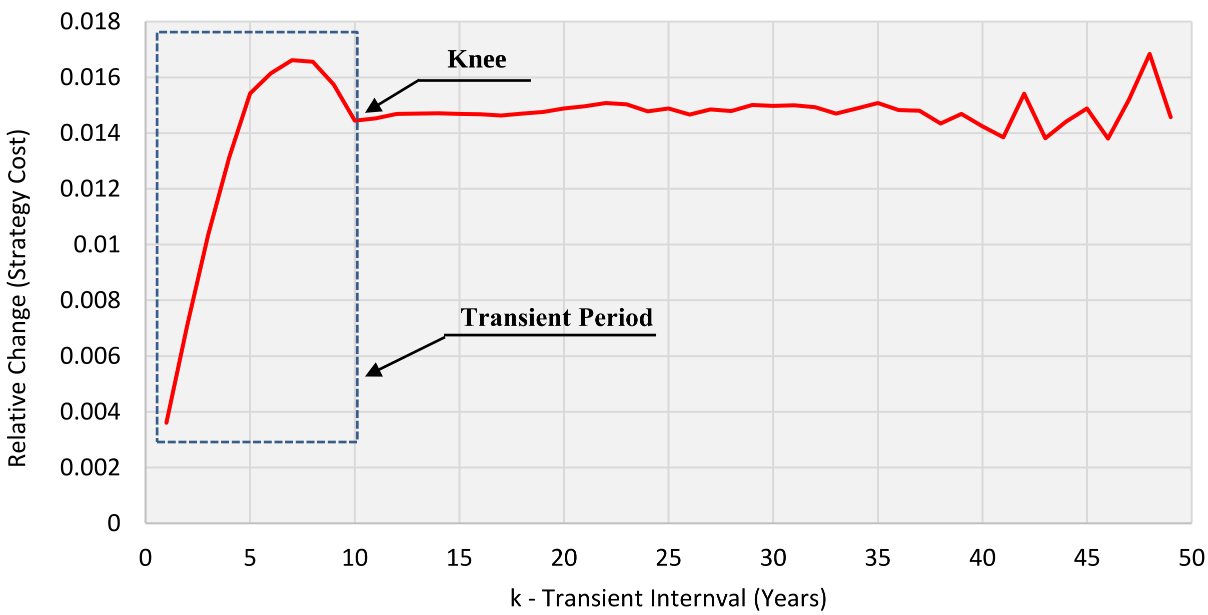


Figure 12.28 Strategy 4 Strategy Cost – Relative Change (RC)

Similarly, Figures 12.29 to 12.32 shows the plots of the strategy cost of the pilot Strategy 24. Figure 12.29 shows the simulation results across all ten replications. Observe that all replications show the same trend, which seems to start stabilizing in Year 21. Figure 12.30 shows the overall mean ($\bar{\bar{x}}$) across all ten replications. Starting in Year 21, the overall mean curve become smoother when compared to the curves of individual replications (Figure 12.29).

Figure 12.31 shows the overall mean excluding the transient state ($\bar{\bar{x}}_{n-k}$) (i.e., excluding observation of the first *k* years while varying *k* from 1 to *n*-1). In this plot is possible to note that the knee is located *k*=20. This information is confirmed by the graph of relative change (*RC*) in Figure 12.32, which also shows a knee in *k*=20. Thus, it is possible to state that the strategy cost of Strategy 24 start stabilizing in Year 21, when *k*=20. Considering that Strategy 24 consists of a blanket replacement cycle of 20 years, it can be said that the transient period of the Strategy 24 output measure "strategy cost" corresponds to the first replacement cycle.

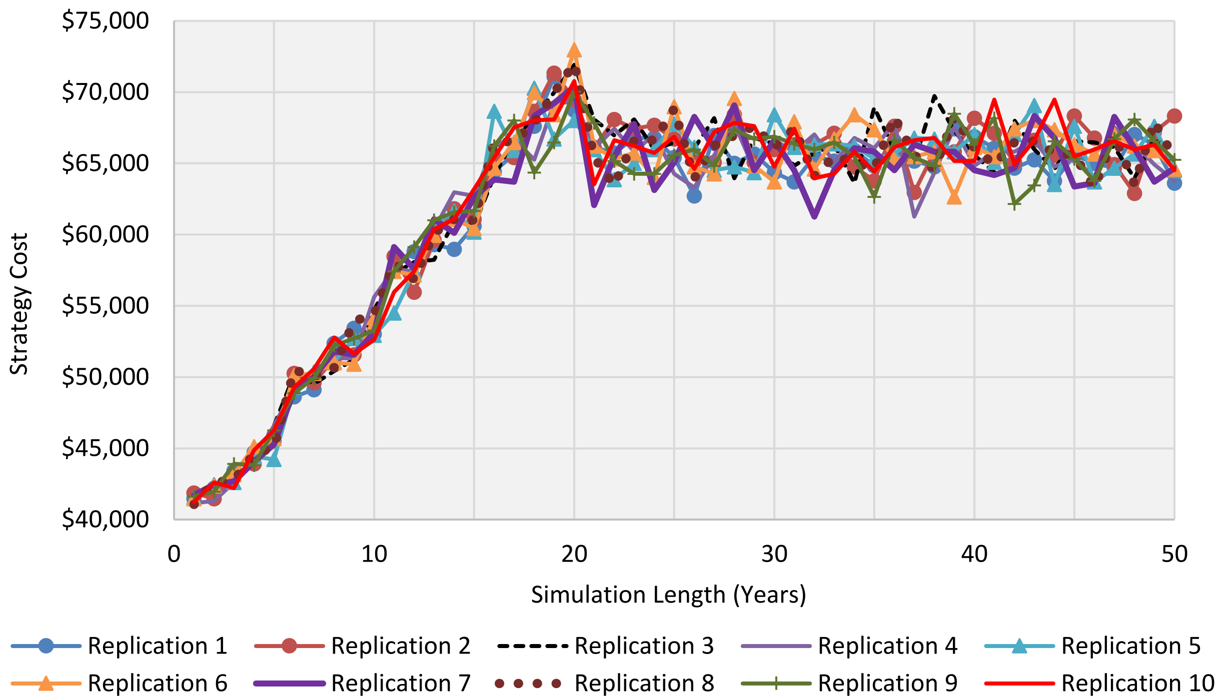


Figure 12.29 Strategy 24 Strategy Cost – Individual Replications

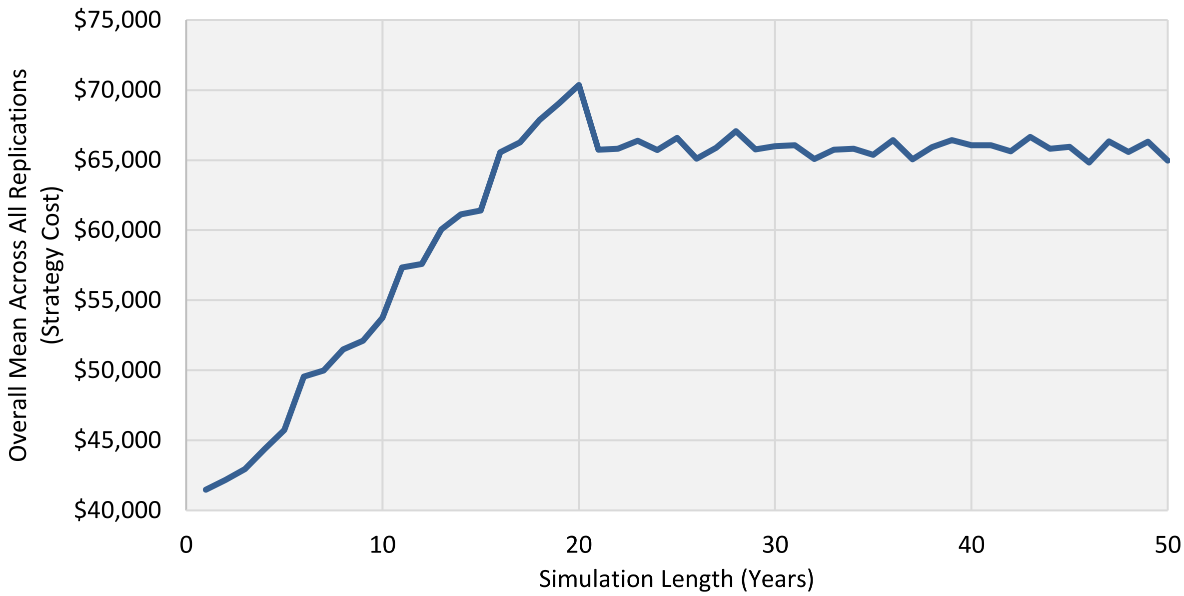


Figure 12.30 Strategy 24 Strategy Cost – Overall Mean ($\bar{\bar{x}}$) Across Replications

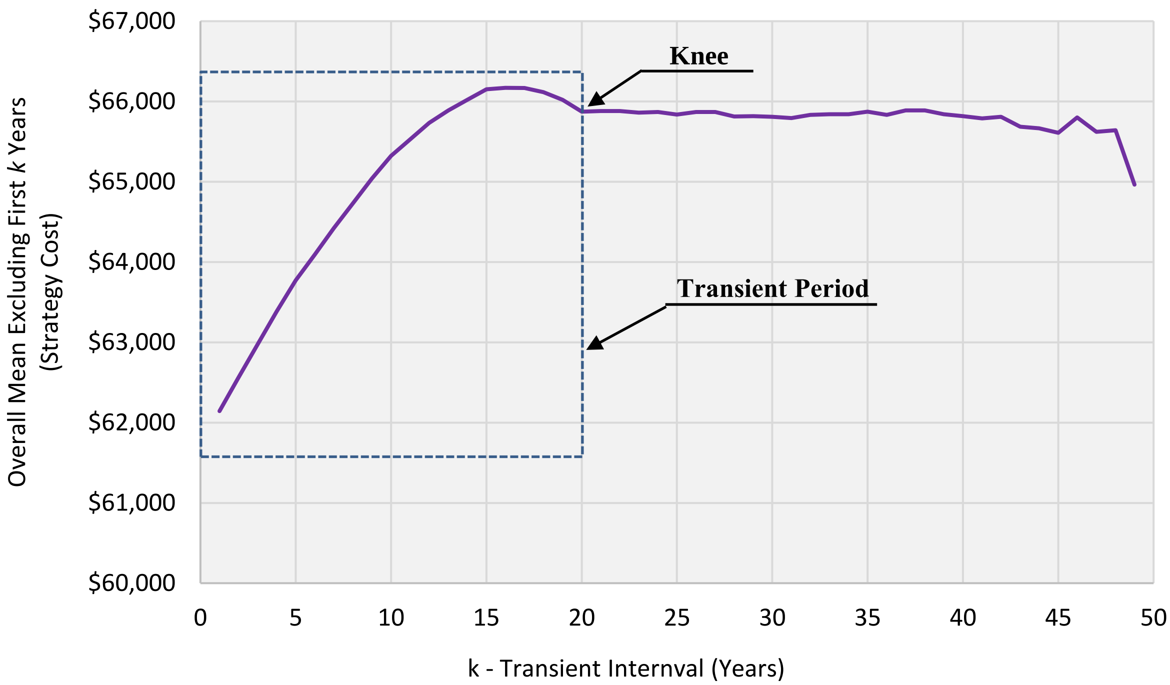


Figure 12.31 Strategy 24 Strategy Cost – Overall Mean Excluding Observations of the First *k* Years Across Replications

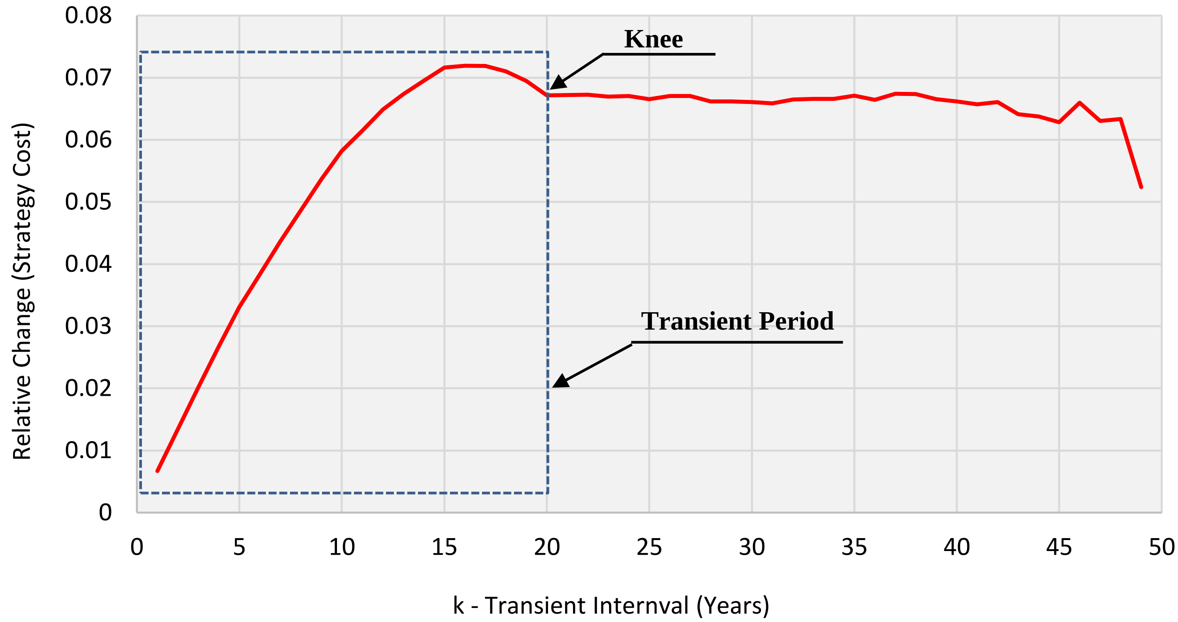


Figure 12.32 Strategy 24 Strategy Cost – Relative Change (RC)

12.7.1.3 Summary

The research team conducted initial data deletion technique to identify the transient period, which was found to be the same as the first blanket replacement cycle. The main reason for the transient period to coincide with the blanket replacement cycle is because there is incomplete data information during the first replacement cycle (see Appendix 12.9) which results in a higher variability in the output measures during this period.

That means that the transient period varies according to the blanket replacement cycle. For example, for a blanket replacement of 10 years (such as Pilot Strategy 4), the transient period is 10 years. For Pilot Strategy 24 (blanket replacement cycle of 20 years), the transient period is 20 years. To ensure that all the strategies have the same number of observations considered in the data analysis, the research team decided to remove the first 20 years of data, which corresponds to the longest transient period. Thus, the output measures of all strategies started being collected in Year 21 (after the end of the transient period).

12.7.2 <u>Simulation Length (Stopping Criteria)</u>

Obaidat and Boudriga (2010) explained that a desired and narrower half width (*h*) can be obtained by either increasing the simulation length (*n*) or increasing the number of replications (*m*). According to the literature, very short simulation length can lead to high variability, which can affect the accuracy and credibility of the simulation results On the other hand, long runs consume unnecessary amount of time and resources (Obaidat and Papadimitriou, 2003; Obaidat and Boudriga, 2010). Therefore, the need to establish a simulation length that results in a desired half width (*h*) without being too long.

To determine the simulation length, the research team used a stopping criteria known as *autonomous replications*. The research team followed the steps described by Obaidat and Boudriga (2010) to use the autonomous replications criteria, which are listed in Table 12.27. The first column describes the steps. The second column shows the equations (if any) used in each step. The last column describes the variables used in the equations.

As shown in Table 12.27, the first step calculates the mean of each replication excluding the transient period. In other words, the means are calculated considering observations from years 21 to 50. The second step calculates the overall mean ($\bar{\bar{x}}$) of steady-state (years 21 to 50) across all replications (m=10). The third step calculates the variance of replicate means ($Var(\bar{x})$). The fourth step calculates the half width (h) considering a confidence level of 95%. The fifth step verifies whether the calculated half width is within the desirable half width, which is 5% or less of the overall mean. If that shows to be true ($h \leq 5\%$), then the simulation length (excluding the transient period) is enough to obtain the desired half width. Otherwise, it is necessary to increase either the number of replications until a desired half width is obtained.

The research team conducted Steps 1 through 5 for two output measures (number of unsatisfactory signs and strategy cost) of Strategies 4 and 24. Partial results are shown in Table 12.28. With respect to number of unsatisfactory signs, the half width varied from 0.70% (Strategy 24) to 1.23% (Strategy 4) from the overall means. With respect to strategy cost, the half width varied from 0.14% (Strategy 4) to 0.29% (Strategy 24) from the overall means. Therefore, it is possible to conclude that a simulation length of 50 years is enough to obtain a half width of 5% or less from the mean.

Table 12.27 Steps, Equations, and Description of the Autonomous Replications Stopping Criteria

Steps	**Equation**	**Description**
1) Calculate the mean excluding the transient interval for each replication	$\bar{x}_i = \frac{1}{n-k} \sum_{j=k+1}^{n} x_{ji}$	$\bar{x}_i$ = mean of the observations excluding transient interval of i^{th} replication m = number of replications (10) n = simulation length (50 years) k = transient interval (20 years) i = 1, 2, …m j = k+1, k+2, …n
2) Calculate the overall mean of steady-state across all replications	$\bar{\bar{x}} = \frac{1}{m} \sum_{i=1}^{m} \bar{x}_i$	$\bar{\bar{x}}$ = overall mean of all years (n) across all replications (m) $\bar{x}_i$ = mean of the observations excluding transient interval of i^{th} replication m = number of replications (10) i = 1, 2, …m
3) Calculate variance of replicate means	$Var(\bar{x}) = \frac{1}{m-1} \sum_{i=1}^{m} (\bar{x}_i - \bar{\bar{x}})^2$	$Var(\bar{x})$ = Variance of replicate means $\bar{\bar{x}}$ = overall mean of all years (n) across all replications (m) $\bar{x}_i$ = mean of the observations excluding transient interval of i^{th} replication m = number of replications (10) i = 1, 2, …m
4) Calculate the half width (h)	$h = t_{m-1,1-\frac{\alpha}{2}} \times \sqrt{\frac{Var(\bar{x})}{m}}$	h = half width $Var(\bar{x})$ = Variance of replicate means α= confidence level (0.95) m = number of replications (10)

		$t_{m-1,1-\frac{\alpha}{2}}$: upper *1-α/2* critical point from the Student's t distribution with *m-1* degrees of *m* number of replications.
5) Verify if the half width (h) is within the desired. If not, increase simulation length and repeat steps 1 through 4	-	-

Table 12.28 Partial Results of the Autonomous Replications Stopping Criteria (Strategies 4 and 24)

Output Measure	Strategy	Step 2: Overall Mean Across All Replications * ($\bar{\bar{x}}$)	Step 3: Variance of Replicate Means ($Var(\bar{x})$)	Step 4: Half Width (h)
Number of Unsatisfactory Signs	Strategy 4	310	38.15	4.42 (1.42% of mean)
	Strategy 24	331	13.74	2.65 (0.80% of mean)
Strategy Cost	Strategy 4	$102,034	54,664.65	$167.24 (0.16% of mean)
	Strategy 24	$65,875	94,683.92	$220.11 (0.33% of mean)

Note: * Excluding observations from the transient interval

12.7.3 Number of Replications

To determine the number of replications needed to obtain an error (or half width h) within 5% of the mean value resulting from the simulation, the research team used Equation (7.12) described in Chapter 7. The initial number of replications of the pilot strategies was ten (m_0 = 10).

Table 12.29 shows the average annual (overall mean) number of unsatisfactory signs and strategy cost for Strategies 4 and 24. The first column of the table shows the output measures while the second column shows the strategies. The third column shows the initial number of replications (m_0). The fourth column shows the mean obtained from the simulation for ten replications. The fifth column shows the initial half width (h_0) while the sixth column shows the target half width (h). The last column shows the number of replication necessary to obtain an error within 5% of the mean. As the last column shows, ten replication are more than enough to obtain an error within 5%.

The mean number of unsatisfactory signs was the output measure that resulted in greater variability, and still had an error of only 1.42% (4.42/310) from the mean. Thus, the research team concluded that 10 replications were more than enough to ensure an error of 5% or less while obtaining enough data to analyze.

Table 12.29 Number of Replications Needed

Average Annual Measures	Strategy	Number of Replications Pilot (m_0)	Overall Mean *	Half Width Pilot (h_0)	Target Half Width (h) **	Number of Replications Needed (m)
Number of Unsatisfactory Signs	Strategy 4	10	310	4.42	15.5	1
	Strategy 24	10	331	2.65	16.55	0
Strategy Cost	Strategy 4	10	$102,034	$167.24	$5,101.70	0
	Strategy 24	10	$65,875	$220.11	$3,293.75	0

Note: * Excluding observations from the transient interval
** Target half width (h_0) is within 5% of the mean.

12.7.4 Conclusions

The research team ran two pilot strategies (Strategies 4 and 24 from Table 12.25) with three objectives: (1) to determine and remove the transient interval from the data analysis, (2) to determine the simulation length necessary to obtain a desired half width, and (3) to determine the number of replications necessary to obtain a desired half width. After analyzing two output measures (number of unsatisfactory signs and strategy cost) of the pilot strategies, the research team concluded the following.

- The transient period ends in Year 20. Therefore, for data analysis purpose, the authors considered observations collected from Year 21 through Year 50 (see next topic).
- A simulation length of 50 years, excluding the transient interval, was found to be enough to obtain a half width of less than 5%.
- Ten replications were found to be enough to obtain a half width less than 5%.

12.8 Transient Interval Removal Analysis Data Tables

Tables 12.30 and 12.31 show the statewide (all areas) annual number of unsatisfactory signs resulted from 10 replications of Strategy 4 (10 year blanket replacement cycle, 5 year daytime inspection cycle, and grace period of 3 years) and Strategy 24 (20 year blanket replacement cycle, 5 year daytime inspection cycle, and grace period of 5 years). Similar, Tables 12.32 to 12.33 show the statewide (all areas) annual strategy cost resulted from 10 replications of Strategies 4 and 24.

The first column of the tables shows the year simulated (Y). The intermediate columns show the results by replication (R). The last column shows the annual mean across all replications. The results show in these tables were used in the analysis of the transient interval removal and to determine the simulation length necessary to obtain a half width less than 5% (see Appendix 12.8).

Table 12.30 Strategy 4 – Annual Number of Unsatisfactory Signs by Replication and Mean Across All Replications

Y	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean
1	0	0	0	0	0	0	0	0	0	0	0
2	15	17	21	28	34	29	17	27	22	26	24
3	45	62	63	64	82	65	61	63	60	61	63
4	96	119	118	112	115	102	110	113	95	103	108
5	135	164	148	147	136	155	160	162	168	154	153
6	145	171	153	158	129	174	141	157	157	139	152
7	161	199	173	195	175	190	173	174	182	184	181
8	194	213	200	256	200	210	212	217	218	223	214
9	226	255	256	281	248	251	228	256	267	282	255
10	296	282	329	301	297	306	286	308	322	318	305
11	321	288	308	320	324	308	283	318	307	301	308
12	301	298	303	314	315	308	299	282	313	297	303
13	298	332	313	335	297	302	315	302	299	286	308
14	276	329	301	312	283	320	312	320	295	298	305
15	296	315	298	301	309	307	314	309	312	315	308
16	305	304	309	290	308	296	302	297	341	343	310
17	301	277	328	326	291	289	313	291	312	304	303
18	288	270	301	317	292	300	296	307	305	312	299
19	285	293	310	305	298	313	307	291	289	279	297
20	300	287	348	321	290	310	289	324	272	303	304
21	332	292	321	304	327	302	287	349	314	323	315
22	341	290	333	288	286	345	299	356	341	308	319
23	341	306	310	283	292	304	321	342	323	304	313
24	306	328	311	287	293	307	313	326	309	288	307
25	294	315	299	317	302	310	304	329	329	320	312
26	304	313	262	315	277	317	289	329	299	323	303
27	270	302	280	339	312	345	284	326	314	326	310
28	278	334	296	303	284	307	306	308	327	350	309
29	298	327	304	330	324	295	295	301	314	333	312
30	297	331	310	346	320	317	320	308	339	329	322
31	314	340	309	324	312	299	308	311	309	321	315
32	304	310	332	325	316	334	324	301	304	362	321
33	297	304	267	302	301	313	296	284	335	314	301
34	300	278	292	316	302	317	317	316	317	317	307
35	296	309	314	285	293	292	308	315	308	320	304
36	299	310	324	270	301	323	300	315	339	326	311
37	307	325	342	308	294	350	315	310	297	321	317
38	331	312	325	294	276	314	303	311	314	306	309
39	316	322	328	288	294	306	275	297	299	294	302
40	303	318	323	304	283	311	284	315	287	295	302
41	295	312	303	286	292	297	324	309	301	311	303
42	284	316	325	298	289	304	331	331	318	326	312
43	316	288	312	287	292	289	288	316	308	329	303
44	311	322	316	294	281	295	302	304	310	341	308
45	312	314	286	315	312	320	306	281	330	337	311
46	332	315	312	308	318	336	309	299	308	340	318
47	316	282	279	293	287	309	303	309	299	326	300
48	339	299	347	327	302	318	290	302	293	305	312
49	318	315	322	327	312	297	329	302	307	331	316
50	307	309	298	312	301	296	317	307	313	339	310

Notes: Y = Year
R = Replication
Mean = annual mean across all replications ($\bar{x}_j$ = mean of j^{th} year across all replications)

Table 12.31 Strategy 24 – Annual Number of Unsatisfactory Signs by Replication and Mean Across All Replications

Y	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean
1	0	0	0	0	0	0	0	0	0	0	0
2	11	10	11	8	12	11	9	12	13	19	12
3	37	28	39	38	25	27	21	38	24	34	31
4	53	56	68	65	54	40	50	59	53	65	56
5	69	82	74	80	77	80	73	79	73	91	78
6	77	80	64	79	71	78	80	60	95	83	77
7	94	97	79	80	85	89	95	96	106	97	92
8	102	109	102	108	95	98	115	121	124	101	108
9	105	125	141	142	118	117	129	133	138	113	126
10	157	151	149	157	140	139	151	161	168	132	151
11	152	140	138	162	160	155	157	136	166	164	153
12	166	178	154	195	189	175	166	164	176	184	175
13	174	193	173	207	201	196	186	186	178	198	189
14	194	188	183	220	199	210	202	209	220	218	204
15	217	228	229	245	256	245	199	239	251	263	237
16	222	240	250	233	245	218	208	244	252	243	236
17	240	264	266	225	262	251	251	249	250	244	250
18	260	266	270	241	253	255	268	294	269	252	263
19	276	287	284	275	292	303	287	303	259	275	284
20	323	307	341	356	329	348	328	338	315	312	330
21	327	363	347	347	328	319	339	302	305	330	331
22	338	356	360	337	305	309	344	320	310	311	329
23	342	318	314	331	302	320	315	350	312	314	322
24	337	316	377	325	321	344	320	348	320	328	334
25	306	332	331	303	319	340	359	335	326	329	328
26	332	339	331	299	336	318	363	360	343	342	336
27	299	362	314	302	320	355	352	373	368	338	338
28	329	330	339	316	319	319	328	371	352	321	332
29	305	321	343	333	332	320	329	333	349	310	328
30	289	306	314	351	357	351	313	341	324	347	329
31	304	327	301	348	336	307	279	317	326	332	318
32	318	342	332	312	313	336	294	334	344	325	325
33	352	316	321	340	326	337	289	322	339	314	326
34	339	308	338	333	320	352	311	349	298	329	328
35	324	327	338	343	309	319	310	354	304	343	327
36	311	339	345	290	354	295	310	324	321	329	322
37	293	345	340	317	328	340	317	308	328	332	325
38	332	345	319	354	304	327	318	335	339	317	329
39	360	332	316	369	318	324	302	318	329	359	333
40	370	325	306	351	335	358	333	332	323	347	338
41	334	318	337	343	352	371	350	358	295	351	341
42	311	350	326	335	349	352	370	325	323	340	338
43	305	363	339	332	313	350	343	298	339	369	335
44	303	350	328	310	343	326	324	324	311	325	324
45	327	321	334	320	324	343	345	305	334	351	330
46	308	330	331	336	326	349	347	328	350	340	335
47	328	323	342	303	336	330	340	308	354	316	328
48	307	327	358	334	352	354	328	320	339	314	333
49	296	342	368	316	352	355	346	324	331	314	334
50	353	327	349	337	357	355	359	295	339	336	341

Notes: Y = Year
R = Replication
Mean = annual mean across all replications ($\bar{x}_j$ = mean of j^{th} year across all replications)

Table 12.32 Strategy 4 – Annual Strategy Cost by Replication and Mean Across All Replications

Y	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean
1	$83.3	$82.6	$83.0	$82.5	$82.3	$82.7	$82.4	$82.9	$82.9	$83.0	$82.8
2	$83.3	$83.3	$84.4	$84.2	$84.1	$84.2	$84.0	$83.7	$84.6	$84.0	$84.0
3	$85.9	$86.4	$86.3	$85.9	$85.7	$86.0	$86.1	$86.4	$85.4	$86.0	$86.0
4	$88.7	$89.2	$88.6	$88.0	$88.9	$88.3	$88.6	$88.5	$89.6	$88.4	$88.7
5	$91.4	$92.4	$91.6	$90.3	$92.3	$92.4	$93.5	$90.8	$89.8	$90.7	$91.5
6	$98.7	$100.4	$97.9	$98.8	$99.6	$98.3	$99.4	$99.9	$99.1	$96.9	$98.9
7	$99.7	$100.0	$102.0	$98.5	$98.2	$100.5	$99.8	$101.8	$100.9	$99.9	$100.1
8	$102.8	$103.9	$102.5	$101.5	$101.1	$102.7	$101.7	$104.3	$102.9	$101.0	$102.4
9	$105.6	$105.8	$105.1	$106.9	$105.6	$103.8	$105.7	$105.2	$104.2	$107.3	$105.5
10	$105.9	$109.0	$106.6	$109.7	$107.9	$108.2	$105.1	$108.0	$106.7	$106.5	$107.4
11	$102.1	$101.1	$104.9	$99.0	$103.1	$102.4	$99.8	$100.2	$101.5	$102.9	$101.7
12	$101.3	$100.2	$102.9	$100.4	$100.4	$99.9	$101.1	$101.9	$103.7	$101.7	$101.4
13	$102.8	$102.6	$98.9	$102.8	$104.3	$103.6	$101.5	$99.2	$101.5	$102.6	$102.0
14	$100.8	$101.9	$102.7	$101.9	$103.6	$101.7	$103.4	$101.0	$101.4	$101.1	$102.0
15	$100.7	$102.2	$103.5	$101.2	$101.2	$104.5	$101.5	$103.7	$103.2	$99.5	$102.1
16	$102.2	$102.0	$101.6	$101.3	$102.4	$104.6	$100.8	$103.4	$101.2	$101.2	$102.1
17	$101.2	$101.7	$103.2	$99.4	$102.5	$101.9	$103.3	$101.9	$104.1	$102.6	$102.2
18	$103.1	$101.2	$102.6	$102.5	$101.7	$99.1	$102.6	$101.9	$100.7	$102.4	$101.8
19	$101.3	$101.0	$103.0	$103.5	$100.7	$102.2	$100.9	$100.0	$102.6	$103.5	$101.9
20	$99.7	$102.2	$100.4	$100.6	$101.7	$103.5	$103.9	$100.5	$102.3	$101.7	$101.6
21	$100.9	$102.2	$105.3	$102.0	$99.4	$104.0	$102.5	$100.0	$98.6	$102.9	$101.8
22	$104.3	$101.6	$102.3	$102.9	$102.2	$100.9	$99.1	$101.9	$101.3	$100.7	$101.7
23	$100.1	$99.8	$101.2	$101.6	$102.2	$104.0	$102.8	$104.4	$102.3	$103.4	$102.2
24	$104.5	$100.9	$101.4	$100.1	$101.6	$104.8	$103.7	$101.7	$103.6	$104.8	$102.7
25	$103.1	$102.2	$100.9	$101.7	$102.2	$101.5	$100.2	$103.3	$103.0	$99.5	$101.7
26	$104.5	$102.9	$101.3	$103.2	$102.6	$101.0	$103.4	$103.2	$102.3	$101.3	$102.6
27	$103.1	$101.6	$99.6	$100.9	$99.1	$103.0	$103.1	$103.9	$99.7	$101.7	$101.6
28	$102.4	$100.5	$100.5	$106.5	$100.3	$104.4	$101.9	$103.0	$101.5	$100.4	$102.1
29	$99.5	$102.4	$102.6	$101.5	$99.7	$100.7	$100.4	$104.1	$102.1	$102.6	$101.6
30	$102.2	$100.7	$101.1	$102.1	$103.4	$102.5	$100.7	$102.6	$101.6	$104.4	$102.1
31	$98.7	$98.9	$102.4	$102.6	$104.0	$103.9	$102.2	$102.3	$103.5	$101.3	$102.0
32	$103.3	$104.3	$101.4	$101.3	$100.4	$101.0	$103.0	$102.7	$100.8	$103.6	$102.2
33	$101.2	$103.2	$105.6	$102.2	$102.7	$100.4	$102.9	$101.4	$100.1	$104.7	$102.4
34	$102.2	$104.6	$100.1	$103.0	$102.5	$103.9	$98.2	$101.7	$100.5	$100.4	$101.7
35	$102.5	$99.5	$101.3	$104.5	$102.2	$101.0	$102.6	$100.5	$101.7	$101.6	$101.7
36	$99.5	$103.2	$103.7	$100.0	$104.0	$102.4	$103.8	$103.1	$101.7	$102.7	$102.4
37	$101.1	$101.0	$103.0	$99.3	$103.3	$103.5	$100.4	$102.3	$102.6	$104.0	$102.1
38	$101.7	$104.5	$102.0	$103.1	$101.2	$104.7	$101.7	$104.5	$101.1	$101.3	$102.6
39	$102.9	$103.2	$101.8	$101.7	$100.3	$99.7	$103.0	$100.2	$101.2	$102.0	$101.6
40	$101.5	$105.2	$104.2	$102.3	$102.2	$100.9	$103.0	$100.9	$103.1	$101.3	$102.5
41	$101.2	$102.7	$102.3	$104.5	$104.6	$102.1	$100.9	$102.0	$102.2	$100.8	$102.3
42	$100.1	$101.8	$98.4	$101.1	$100.4	$102.2	$103.0	$98.4	$100.6	$100.6	$100.7
43	$101.4	$104.9	$103.7	$101.8	$101.3	$105.2	$101.7	$103.0	$104.3	$104.8	$103.2
44	$102.8	$100.4	$103.1	$101.4	$101.7	$101.4	$100.2	$105.0	$101.0	$98.7	$101.6
45	$102.3	$102.6	$99.6	$103.2	$100.5	$99.9	$101.1	$103.1	$103.5	$101.7	$101.8
46	$102.0	$102.9	$101.0	$102.2	$103.9	$103.5	$99.9	$101.2	$103.6	$104.5	$102.5
47	$101.4	$101.0	$99.4	$102.9	$103.6	$103.2	$101.2	$99.2	$101.2	$102.0	$101.5
48	$100.5	$102.6	$101.5	$102.5	$100.4	$101.4	$100.0	$102.0	$102.6	$103.9	$101.7
49	$100.8	$102.6	$104.3	$102.1	$101.4	$103.9	$102.7	$102.3	$102.5	$101.9	$102.5
50	$102.1	$100.4	$101.2	$101.4	$101.5	$101.9	$103.3	$103.5	$102.7	$102.2	$102.0

Notes: Y = Year
R = Replication
Mean = annual mean across all replications ($\bar{x}_j$ = mean of j^{th} year across all replications)

Table 12.33 Strategy 24 – Annual Strategy Cost by Replication and Mean Across All Replications

Y	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Mean
1	$41.5	$41.9	$41.6	$41.1	$41.5	$41.5	$41.7	$41.1	$41.6	$41.2	$41.5
2	$42.2	$41.5	$42.4	$41.3	$42.4	$42.4	$42.4	$42.6	$42.0	$42.6	$42.2
3	$43.4	$43.2	$42.9	$42.6	$42.6	$43.2	$42.7	$42.8	$43.9	$42.2	$42.9
4	$44.7	$43.9	$44.2	$44.2	$44.4	$45.1	$44.1	$44.6	$43.8	$44.9	$44.4
5	$45.9	$45.5	$46.6	$46.6	$44.2	$45.7	$45.3	$45.0	$46.3	$46.3	$45.7
6	$48.6	$50.3	$50.2	$49.3	$49.3	$50.1	$49.0	$50.5	$48.9	$49.3	$49.5
7	$49.1	$49.6	$49.5	$50.5	$50.3	$50.3	$50.0	$50.0	$49.9	$50.6	$50.0
8	$52.4	$51.3	$50.4	$51.3	$51.1	$51.0	$51.8	$50.7	$52.2	$52.8	$51.5
9	$53.4	$51.6	$51.2	$51.3	$52.7	$50.9	$51.6	$53.9	$52.7	$51.6	$52.1
10	$53.0	$53.5	$54.7	$55.6	$52.9	$54.2	$53.1	$54.4	$53.3	$52.6	$53.7
11	$57.6	$58.5	$57.3	$57.6	$54.5	$57.4	$59.1	$58.0	$57.4	$56.0	$57.3
12	$58.8	$56.0	$58.1	$57.4	$57.4	$57.2	$57.6	$56.9	$59.1	$57.4	$57.6
13	$59.3	$59.6	$58.2	$60.4	$60.6	$60.0	$61.1	$60.1	$61.0	$60.4	$60.1
14	$59.0	$61.8	$60.9	$63.0	$61.7	$61.1	$60.1	$61.1	$61.6	$61.1	$61.1
15	$60.6	$61.1	$60.6	$62.7	$60.2	$60.4	$62.6	$61.0	$61.7	$63.2	$61.4
16	$64.4	$65.4	$64.1	$66.3	$68.7	$64.7	$63.9	$66.5	$66.2	$65.4	$65.6
17	$65.7	$65.4	$66.7	$66.7	$65.9	$66.5	$63.7	$66.5	$68.0	$67.5	$66.3
18	$67.6	$68.7	$68.3	$65.2	$70.3	$70.0	$68.3	$67.8	$64.4	$68.0	$67.9
19	$71.1	$71.3	$70.0	$69.2	$66.7	$68.4	$69.2	$70.0	$66.5	$68.1	$69.1
20	$68.7	$69.5	$71.9	$69.3	$68.0	$73.0	$70.4	$72.0	$70.0	$70.8	$70.4
21	$66.1	$66.1	$68.1	$66.1	$66.0	$66.2	$62.1	$65.4	$67.8	$63.5	$65.7
22	$65.7	$68.1	$67.0	$67.4	$63.9	$65.3	$65.5	$63.5	$65.2	$66.6	$65.8
23	$66.8	$67.4	$68.1	$65.8	$65.0	$65.7	$67.8	$66.6	$64.3	$66.2	$66.4
24	$66.8	$67.7	$66.0	$67.0	$66.0	$64.0	$63.1	$66.6	$64.3	$65.7	$65.7
25	$65.4	$66.7	$66.5	$64.3	$67.8	$69.0	$65.1	$68.8	$65.6	$66.9	$66.6
26	$62.7	$65.2	$66.1	$63.3	$66.1	$64.8	$68.3	$63.9	$66.0	$64.6	$65.1
27	$67.0	$65.1	$68.2	$65.6	$64.5	$64.3	$66.1	$66.2	$64.8	$67.2	$65.9
28	$65.0	$68.4	$63.9	$67.8	$64.8	$69.6	$69.1	$67.0	$67.4	$67.8	$67.1
29	$65.7	$65.1	$66.8	$64.6	$64.4	$64.8	$64.5	$67.6	$66.7	$67.6	$65.8
30	$64.4	$66.0	$66.4	$66.6	$68.4	$63.7	$66.6	$66.1	$66.9	$64.8	$66.0
31	$63.7	$66.3	$64.8	$65.8	$66.1	$67.9	$64.5	$67.4	$66.4	$67.4	$66.1
32	$65.5	$66.3	$65.7	$67.0	$66.3	$64.6	$61.3	$64.1	$66.0	$63.9	$65.1
33	$65.2	$67.1	$66.3	$65.1	$66.4	$66.7	$64.5	$65.5	$66.5	$64.3	$65.8
34	$65.9	$64.8	$63.6	$66.8	$66.2	$68.4	$66.1	$65.1	$65.5	$65.8	$65.8
35	$64.8	$63.8	$68.9	$66.1	$65.3	$67.4	$65.8	$64.6	$62.6	$64.4	$65.4
36	$66.5	$67.6	$65.9	$67.8	$65.7	$65.2	$64.5	$68.3	$66.6	$66.1	$66.4
37	$65.2	$63.0	$65.1	$61.3	$66.8	$65.5	$66.3	$65.6	$65.4	$66.6	$65.1
38	$64.8	$65.8	$69.7	$64.4	$66.7	$65.8	$65.8	$64.6	$64.8	$66.8	$65.9
39	$67.4	$65.8	$67.3	$67.5	$65.8	$62.6	$65.8	$68.3	$68.5	$65.2	$66.4
40	$66.9	$68.2	$65.6	$64.8	$67.0	$66.1	$64.5	$66.1	$66.3	$65.2	$66.1
41	$66.1	$67.1	$64.4	$65.8	$65.1	$65.5	$64.2	$64.9	$68.2	$69.5	$66.1
42	$64.7	$65.1	$68.0	$65.8	$67.0	$67.4	$64.7	$66.5	$62.2	$64.9	$65.6
43	$65.2	$66.6	$66.0	$66.6	$69.1	$68.0	$68.3	$66.5	$63.5	$66.6	$66.7
44	$63.8	$65.6	$64.6	$64.8	$63.5	$67.4	$66.8	$65.7	$66.5	$69.5	$65.8
45	$65.6	$68.3	$66.5	$65.3	$67.6	$66.3	$63.4	$65.6	$65.3	$65.5	$65.9
46	$65.0	$66.8	$66.5	$64.0	$63.7	$65.7	$63.6	$63.3	$63.8	$66.0	$64.8
47	$64.7	$64.9	$66.1	$67.5	$64.7	$67.0	$68.3	$67.0	$66.7	$66.5	$66.3
48	$67.0	$62.9	$63.9	$66.4	$65.7	$66.2	$66.1	$63.5	$68.1	$66.0	$65.6
49	$66.3	$67.2	$66.8	$64.9	$67.6	$65.9	$63.7	$67.9	$66.5	$66.3	$66.3
50	$63.6	$68.3	$65.0	$63.8	$64.5	$64.6	$64.7	$65.3	$65.2	$64.5	$65.0

Notes: Y = Year
R = Replication
Mean = annual mean across all replications ($\bar{x}_j$ = mean of j^{th} year across all replications)

12.9 Annual Output Measures Resulted from Simulation

Tables 12.34 to 12.50 show annual output measures resulted from one replication of Strategy 24 that consists of a 20 year blanket replacement cycle, 5 year daytime inspection cycle, and grace period of 5 years. This set of tables is generated for each replication of each strategy being simulated. Note that the first replacement cycle (Year 1 to Year 20) has an incomplete data set because the initial condition is unknown. As discussed in Chapter 10, annual data from the first 20 years is not considered in the data analysis.

The first column of the tables is the year simulated, which ranges from one to 50 years. The intermediate columns shows the annual output measures (e.g., number of signs damaged) by areas. Because Strategy 24 consists of a replacement cycle of 20 years, the state (or division) is divided into 20 areas. The last column of tables show the annual output measures for the entire state (or division). This total is obtained by adding the output measures of all areas for the period of a year.

Table 12.34 Strategy 24: Annual Number of Damaged Signs at the Beginning of Year (BOY)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	0																				0
2	0	0																			0
3	11	0	0																		11
4	23	14	0	0																	37
5	17	23	13	0	0																53
6	13	24	20	12	0	0															69
7	0	27	21	17	12	0	0														77
8	14	0	24	21	20	15	0	0													94
9	15	14	0	22	24	15	12	0	0												102
10	17	16	10	0	15	14	18	15	0	0											105
11	20	18	21	14	0	21	32	23	8	0	0										157
12	0	16	29	20	10	0	31	16	18	12	0	0									152
13	13	0	37	17	19	9	0	18	31	14	8	0	0								166
14	20	14	0	22	21	19	12	0	26	19	16	5	0	0							174
15	19	16	8	0	23	24	19	13	0	27	21	14	10	0	0						194
16	17	21	21	15	0	19	18	18	16	0	20	27	19	6	0	0					217
17	0	20	21	25	12	0	16	21	18	7	0	25	29	13	15	0	0				222
18	13	0	30	28	12	10	0	18	26	13	14	0	22	20	22	12	0	0			240
19	18	9	0	27	13	18	11	0	37	23	17	13	0	16	22	23	13	0	0		260
20	23	16	10	0	23	25	15	11	0	26	25	16	9	0	24	22	20	11	0	0	276
21	26	22	18	18	0	19	23	17	9	0	25	21	19	18	0	24	26	16	6	0	307
22	0	22	20	22	10	0	27	19	16	17	0	18	28	17	13	0	29	20	14	11	303
23	11	0	21	31	14	16	0	24	21	18	17	0	35	18	20	9	0	21	25	18	319
24	15	13	0	24	21	19	13	0	20	23	16	20	0	21	26	15	14	0	23	29	312
25	19	16	11	0	22	30	20	16	0	23	20	27	14	0	23	14	26	8	0	33	322
26	19	21	13	10	0	30	19	22	14	0	19	30	19	10	0	17	21	19	7	0	290
27	0	28	18	20	14	0	27	20	23	11	0	25	20	16	17	0	23	24	20	8	314
28	14	0	21	19	11	7	0	23	23	14	15	0	21	23	18	5	0	29	21	12	276
29	19	11	0	18	22	16	15	0	26	16	15	15	0	27	23	15	7	0	32	20	297
30	14	17	9	0	25	20	18	4	0	21	25	24	10	0	21	23	17	10	0	22	280
31	17	18	10	11	0	24	24	14	6	0	21	18	18	15	0	19	24	14	13	0	266
32	0	23	17	14	11	0	23	13	23	16	0	23	20	16	20	0	18	17	23	8	285
33	23	0	22	18	17	17	0	22	23	23	6	0	25	20	26	8	0	14	25	14	303
34	33	11	0	21	18	20	9	0	27	33	25	12	0	18	24	14	12	0	29	25	331
35	22	19	15	0	14	30	23	7	0	32	21	19	8	0	24	26	15	16	0	31	322
36	22	22	17	9	0	33	22	13	12	0	24	18	16	14	0	32	20	16	11	0	301
37	0	22	19	17	14	0	28	17	22	12	0	25	18	20	14	0	26	17	13	8	292
38	8	0	28	23	16	7	0	16	23	15	10	0	23	24	17	11	0	19	15	11	266
39	28	10	0	24	22	15	13	0	28	27	16	7	0	28	29	17	8	0	23	14	309

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	28	22	16	0	26	21	27	10	0	32	18	17	12	0	34	25	16	17	0	20	341
41	27	25	21	12	0	29	26	18	15	0	20	28	28	18	0	28	17	26	10	0	348
42	0	19	18	19	10	0	28	22	26	10	0	25	26	22	9	0	22	24	19	7	306
43	10	0	24	21	15	12	0	22	28	16	9	0	22	30	15	8	0	29	21	10	292
44	15	10	0	22	18	23	14	0	20	18	12	9	0	27	20	17	10	0	20	16	271
45	20	24	11	0	27	23	19	4	0	23	14	14	13	0	17	19	21	12	0	15	276
46	21	21	21	12	0	24	20	15	9	0	23	15	24	14	0	26	26	17	9	0	297
47	0	27	26	11	7	0	19	23	13	12	0	19	17	22	11	0	28	26	19	9	289
48	11	0	25	21	11	8	0	30	19	25	17	0	19	17	18	12	0	35	20	15	303
49	16	14	0	26	18	14	10	0	25	22	19	5	0	17	20	16	9	0	27	16	274
50	22	23	13	0	19	18	21	8	0	19	21	9	6	0	23	18	19	17	0	17	273

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.35 Strategy 24: Annual Number of Effective Damaged Signs

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	24																				24
2	20	17																			37
3	38	27	16																		81
4	35	38	19	27																	119
5	30	45	34	18	19																146
6	36	38	37	32	22	18															183
7	20	44	36	32	35	21	22														210
8	33	21	46	42	41	31	18	22													254
9	36	30	16	46	35	33	31	22	23												272
10	34	34	35	18	27	42	49	42	13	27											321
11	35	35	44	37	26	41	43	35	35	19	18										368
12	23	35	54	41	32	15	49	34	43	26	20	25									397
13	34	20	65	34	34	34	22	32	51	25	26	17	14								408
14	37	28	18	40	41	40	28	21	40	42	30	21	19	20							425
15	34	31	27	23	38	37	33	31	25	46	38	40	31	16	17						467
16	37	33	40	35	19	42	36	40	33	15	33	43	49	23	19	23					520
17	22	42	43	49	24	17	30	36	39	25	18	48	51	35	32	20	18				549
18	33	21	44	44	29	31	18	45	50	38	31	21	41	37	37	37	20	21			598
19	40	25	17	45	36	44	30	19	59	44	43	36	21	40	40	46	32	22	18		657
20	43	33	26	30	40	41	34	33	19	40	46	29	30	23	47	38	43	23	15	22	655
21	50	37	36	33	20	47	44	42	28	21	38	34	39	38	23	46	50	36	25	18	705
22	21	36	37	47	28	20	43	40	34	37	22	34	52	37	29	18	43	37	45	36	696
23	31	22	41	43	35	36	22	43	34	38	32	26	60	33	41	24	19	45	41	46	712
24	34	32	17	35	39	50	35	23	37	44	34	40	21	46	46	32	42	21	39	55	722
25	31	35	27	14	47	49	36	38	23	37	38	46	31	17	43	30	38	33	11	48	672
26	35	43	30	31	26	46	44	46	39	18	36	41	35	23	22	32	35	40	32	15	669
27	24	44	39	39	30	13	48	39	39	25	21	42	35	35	38	14	46	44	46	24	685
28	31	19	44	30	30	28	25	49	50	30	28	28	44	43	36	29	15	51	44	35	689
29	30	29	15	40	40	31	30	10	50	39	37	40	21	45	45	36	32	17	54	40	681
30	31	28	29	16	39	38	40	21	12	42	42	37	35	20	40	42	41	27	18	35	633
31	39	35	31	31	22	37	42	27	34	29	36	33	35	29	26	36	37	26	36	16	637
32	34	49	35	31	28	28	43	36	45	38	18	47	43	31	42	18	36	27	40	28	697
33	49	19	39	36	34	38	21	46	47	39	35	25	48	37	40	21	24	39	47	37	721
34	45	23	23	43	30	40	31	17	41	53	40	30	20	42	42	33	33	23	46	50	705
35	43	37	26	14	23	43	43	24	17	48	39	38	24	20	49	49	35	33	20	58	683
36	39	40	38	34	22	49	41	30	30	20	48	36	27	33	24	43	42	31	31	22	680
37	14	37	42	37	35	12	46	36	41	27	17	48	42	39	31	19	46	32	30	19	650
38	39	23	50	40	33	24	23	39	42	40	30	16	47	41	46	26	15	39	36	26	675
39	41	32	24	56	48	34	38	17	48	49	36	24	19	51	55	46	25	24	38	40	745

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	55	40	29	23	47	44	47	30	18	47	35	44	40	25	54	42	33	38	26	39	756
41	46	43	33	27	15	40	46	39	37	18	36	45	47	40	17	47	41	39	33	18	707
42	20	35	38	32	25	18	45	45	44	33	22	46	40	40	27	15	45	46	32	16	664
43	30	20	50	39	28	38	21	35	45	36	25	21	30	49	31	28	21	42	37	29	655
44	37	32	13	41	39	36	36	16	40	36	28	23	23	40	38	32	30	20	39	34	633
45	34	40	28	25	54	42	39	30	20	34	40	33	34	24	26	47	43	34	17	30	674
46	39	39	36	24	24	46	39	36	23	19	41	29	38	34	21	51	47	40	29	13	668
47	27	45	41	37	22	14	38	45	31	34	29	34	29	45	29	20	41	54	34	32	681
48	26	22	53	48	25	20	15	44	42	40	34	14	47	35	38	32	15	54	43	31	678
49	33	37	23	53	37	32	30	17	39	42	40	23	13	36	39	38	29	24	44	31	660
50	41	44	33	17	43	37	48	33	24	43	41	30	22	20	48	38	43	35	17	29	686

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.36 Strategy 24: Annual Number of Damaged Signs Replaced

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	24																				24
2	9	17																			26
3	15	13	16																		44
4	18	15	6	27																	66
5	17	21	14	6	19																77
6	36	11	16	15	10	18															106
7	6	44	12	11	15	6	22														116
8	18	7	46	20	17	16	6	22													152
9	19	14	6	46	20	19	13	7	23												167
10	14	16	14	4	27	21	17	19	5	27											164
11	35	19	15	17	16	41	12	19	17	7	18										216
12	10	35	17	24	13	6	49	16	12	12	12	25									231
13	14	6	65	12	13	15	10	32	25	6	10	12	14								234
14	18	12	10	40	18	16	9	8	40	15	9	7	9	20							231
15	17	10	6	8	38	18	15	13	9	46	18	13	12	10	17						250
16	37	13	19	10	7	42	20	19	15	8	33	18	20	10	4	23					298
17	9	42	13	21	12	7	30	18	13	12	4	48	29	15	10	8	18				309
18	15	12	44	17	16	13	7	45	13	15	14	8	41	21	15	14	7	21			338
19	17	9	7	45	13	19	15	8	59	18	18	20	12	40	16	24	12	11	18		381
20	17	11	8	12	40	22	11	16	10	40	21	8	11	5	47	14	17	7	9	22	348
21	50	15	16	11	10	47	17	23	12	4	38	16	11	21	10	46	21	16	11	7	402
22	10	36	16	16	14	4	43	16	13	19	5	34	17	19	9	9	43	16	20	18	377
23	16	9	41	19	14	17	9	43	14	15	16	6	60	12	15	9	5	45	18	17	400
24	15	16	6	35	17	20	15	7	37	21	14	13	7	46	23	18	16	13	39	22	400
25	12	14	14	4	47	19	17	16	9	37	19	16	12	7	43	13	17	14	4	48	382
26	35	15	12	11	12	46	17	26	16	7	36	16	15	7	5	32	12	16	12	7	355
27	10	44	18	20	19	6	48	16	16	11	6	42	14	12	20	9	46	15	25	12	409
28	12	8	44	12	8	12	10	49	24	14	13	13	44	16	13	14	8	51	12	15	392
29	16	12	6	40	15	11	12	6	50	18	12	16	11	45	24	13	15	7	54	18	401
30	14	10	19	5	39	14	16	7	6	42	21	19	17	5	40	23	17	13	5	35	367
31	39	12	14	17	11	37	19	14	11	13	36	10	15	13	6	36	19	9	13	8	352
32	11	49	13	13	11	11	43	14	22	15	12	47	18	11	16	10	36	13	15	14	394
33	16	8	39	15	16	18	12	46	20	6	10	13	48	19	16	7	12	39	18	12	390
34	23	4	8	43	16	10	8	10	41	21	19	11	12	42	18	7	18	7	46	19	383
35	21	15	9	5	23	10	21	11	5	48	15	20	8	6	49	17	15	17	9	58	382
36	39	18	19	17	8	49	13	13	8	8	48	11	9	13	10	43	16	14	18	14	388
37	6	37	14	14	19	5	46	20	18	12	7	48	19	15	14	8	46	13	15	8	384
38	11	13	50	16	11	9	10	39	14	13	14	9	47	13	17	9	7	39	13	12	366
39	13	10	8	56	22	13	11	7	48	17	18	7	7	51	21	21	9	7	38	20	404

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	28	15	8	11	47	15	21	12	3	47	15	16	12	7	54	14	16	12	16	39	408
41	46	24	15	8	5	40	18	17	11	8	36	20	21	18	8	47	19	15	14	11	401
42	10	35	14	11	10	6	45	23	16	17	13	46	18	10	12	7	45	17	11	6	372
43	15	10	50	17	10	15	7	35	25	18	13	12	30	22	11	11	11	42	17	13	384
44	17	8	2	41	12	13	17	12	40	13	14	9	10	40	21	13	9	8	39	19	357
45	13	19	7	13	54	18	19	15	11	34	17	18	10	10	26	21	17	17	8	30	377
46	39	12	10	13	17	46	20	13	10	7	41	10	21	12	10	51	19	14	10	4	379
47	16	45	16	16	11	6	38	15	12	9	12	34	10	28	11	8	41	19	14	17	378
48	10	8	53	22	7	6	5	44	17	18	15	9	47	18	18	16	6	54	16	15	404
49	11	14	10	53	18	14	9	9	39	23	19	14	7	36	16	20	10	7	44	14	387
50	12	21	10	8	43	20	19	10	8	43	12	8	9	11	48	15	16	14	5	29	361

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.37 Strategy 24: Annual Number of Damaged Signs at the End of Year (EOY)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	0																				0
2	11	0																			11
3	23	14	0																		37
4	17	23	13	0																	53
5	13	24	20	12	0																69
6	0	27	21	17	12	0															77
7	14	0	24	21	20	15	0														94
8	15	14	0	22	24	15	12	0													102
9	17	16	10	0	15	14	18	15	0												105
10	20	18	21	14	0	21	32	23	8	0											157
11	0	16	29	20	10	0	31	16	18	12	0										152
12	13	0	37	17	19	9	0	18	31	14	8	0									166
13	20	14	0	22	21	19	12	0	26	19	16	5	0								174
14	19	16	8	0	23	24	19	13	0	27	21	14	10	0							194
15	17	21	21	15	0	19	18	18	16	0	20	27	19	6	0						217
16	0	20	21	25	12	0	16	21	18	7	0	25	29	13	15	0					222
17	13	0	30	28	12	10	0	18	26	13	14	0	22	20	22	12	0				240
18	18	9	0	27	13	18	11	0	37	23	17	13	0	16	22	23	13	0			260
19	23	16	10	0	23	25	15	11	0	26	25	16	9	0	24	22	20	11	0		276
20	26	22	18	18	0	19	23	17	9	0	25	21	19	18	0	24	26	16	6	0	307
21	0	22	20	22	10	0	27	19	16	17	0	18	28	17	13	0	29	20	14	11	303
22	11	0	21	31	14	16	0	24	21	18	17	0	35	18	20	9	0	21	25	18	319
23	15	13	0	24	21	19	13	0	20	23	16	20	0	21	26	15	14	0	23	29	312
24	19	16	11	0	22	30	20	16	0	23	20	27	14	0	23	14	26	8	0	33	322
25	19	21	13	10	0	30	19	22	14	0	19	30	19	10	0	17	21	19	7	0	290
26	0	28	18	20	14	0	27	20	23	11	0	25	20	16	17	0	23	24	20	8	314
27	14	0	21	19	11	7	0	23	23	14	15	0	21	23	18	5	0	29	21	12	276
28	19	11	0	18	22	16	15	0	26	16	15	15	0	27	23	15	7	0	32	20	297
29	14	17	9	0	25	20	18	4	0	21	25	24	10	0	21	23	17	10	0	22	280
30	17	18	10	11	0	24	24	14	6	0	21	18	18	15	0	19	24	14	13	0	266
31	0	23	17	14	11	0	23	13	23	16	0	23	20	16	20	0	18	17	23	8	285
32	23	0	22	18	17	17	0	22	23	23	6	0	25	20	26	8	0	14	25	14	303
33	33	11	0	21	18	20	9	0	27	33	25	12	0	18	24	14	12	0	29	25	331
34	22	19	15	0	14	30	23	7	0	32	21	19	8	0	24	26	15	16	0	31	322
35	22	22	17	9	0	33	22	13	12	0	24	18	16	14	0	32	20	16	11	0	301
36	0	22	19	17	14	0	28	17	22	12	0	25	18	20	14	0	26	17	13	8	292
37	8	0	28	23	16	7	0	16	23	15	10	0	23	24	17	11	0	19	15	11	266
38	28	10	0	24	22	15	13	0	28	27	16	7	0	28	29	17	8	0	23	14	309
39	28	22	16	0	26	21	27	10	0	32	18	17	12	0	34	25	16	17	0	20	341

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	27	25	21	12	0	29	26	18	15	0	20	28	28	18	0	28	17	26	10	0	348
41	0	19	18	19	10	0	28	22	26	10	0	25	26	22	9	0	22	24	19	7	306
42	10	0	24	21	15	12	0	22	28	16	9	0	22	30	15	8	0	29	21	10	292
43	15	10	0	22	18	23	14	0	20	18	12	9	0	27	20	17	10	0	20	16	271
44	20	24	11	0	27	23	19	4	0	23	14	14	13	0	17	19	21	12	0	15	276
45	21	21	21	12	0	24	20	15	9	0	23	15	24	14	0	26	26	17	9	0	297
46	0	27	26	11	7	0	19	23	13	12	0	19	17	22	11	0	28	26	19	9	289
47	11	0	25	21	11	8	0	30	19	25	17	0	19	17	18	12	0	35	20	15	303
48	16	14	0	26	18	14	10	0	25	22	19	5	0	17	20	16	9	0	27	16	274
49	22	23	13	0	19	18	21	8	0	19	21	9	6	0	23	18	19	17	0	17	273
50	29	23	23	9	0	17	29	23	16	0	29	22	13	9	0	23	27	21	12	0	325

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.38 Strategy 24: Annual Number of Noncompliant (Below Minimum Retroreflectivity Levels) Signs

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	0																				0
2	0	0																			0
3	0	0	0																		0
4	0	0	0	0																	0
5	0	0	0	0	0																0
6	0	0	0	0	0	0															0
7	0	0	0	0	0	0	0														0
8	0	0	0	0	0	0	0	0													0
9	0	0	0	0	0	0	0	0	0												0
10	0	0	0	0	0	0	0	0	0	0											0
11	0	0	0	0	0	0	0	0	0	0	0										0
12	0	0	0	0	0	0	0	0	0	0	0	0									0
13	0	0	0	0	0	0	0	0	0	0	0	0	0								0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0							0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0
20	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18
21	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26
22	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19
23	0	0	0	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32
24	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
25	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
26	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	19
27	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	24
28	0	0	0	0	0	0	0	0	34	0	0	0	0	0	0	0	0	0	0	0	34
29	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	0	0	0	25
30	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0	23
31	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	21
32	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	0	0	0	16
33	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	21
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	17
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	23
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	19
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	0	0	29
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	24
39	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	20

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	19	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23
41	0	26	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28
42	0	0	17	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
43	0	0	0	35	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36
44	0	0	0	0	27	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28
45	0	0	0	0	0	32	2	0	0	0	0	0	0	0	0	0	0	0	0	0	34
46	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	20
47	0	0	0	0	0	0	0	24	2	0	0	0	0	0	0	0	0	0	0	0	26
48	0	0	0	0	0	0	0	0	32	2	0	0	0	0	0	0	0	0	0	0	34
49	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	23
50	0	0	0	0	0	0	0	0	0	0	27	3	0	0	0	0	0	0	0	0	30

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.39 Strategy 24: Annual Number of Unsatisfactory Signs

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	0																				0
2	11	0																			11
3	23	14	0																		37
4	17	23	13	0																	53
5	13	24	20	12	0																69
6	0	27	21	17	12	0															77
7	14	0	24	21	20	15	0														94
8	15	14	0	22	24	15	12	0													102
9	17	16	10	0	15	14	18	15	0												105
10	20	18	21	14	0	21	32	23	8	0											157
11	0	16	29	20	10	0	31	16	18	12	0										152
12	13	0	37	17	19	9	0	18	31	14	8	0									166
13	20	14	0	22	21	19	12	0	26	19	16	5	0								174
14	19	16	8	0	23	24	19	13	0	27	21	14	10	0							194
15	17	21	21	15	0	19	18	18	16	0	20	27	19	6	0						217
16	0	20	21	25	12	0	16	21	18	7	0	25	29	13	15	0					222
17	13	0	30	28	12	10	0	18	26	13	14	0	22	20	22	12	0				240
18	18	9	0	27	13	18	11	0	37	23	17	13	0	16	22	23	13	0			260
19	23	16	10	0	23	25	15	11	0	26	25	16	9	0	24	22	20	11	0		276
20	42	22	18	18	0	19	23	17	9	0	25	21	19	18	0	24	26	16	6	0	323
21	0	46	20	22	10	0	27	19	16	17	0	18	28	17	13	0	29	20	14	11	327
22	11	0	40	31	14	16	0	24	21	18	17	0	35	18	20	9	0	21	25	18	338
23	15	13	0	54	21	19	13	0	20	23	16	20	0	21	26	15	14	0	23	29	342
24	19	16	11	0	37	30	20	16	0	23	20	27	14	0	23	14	26	8	0	33	337
25	19	21	13	10	0	46	19	22	14	0	19	30	19	10	0	17	21	19	7	0	306
26	0	28	18	20	14	0	45	20	23	11	0	25	20	16	17	0	23	24	20	8	332
27	14	0	21	19	11	7	0	46	23	14	15	0	21	23	18	5	0	29	21	12	299
28	19	11	0	18	22	16	15	0	58	16	15	15	0	27	23	15	7	0	32	20	329
29	14	17	9	0	25	20	18	4	0	46	25	24	10	0	21	23	17	10	0	22	305
30	17	18	10	11	0	24	24	14	6	0	44	18	18	15	0	19	24	14	13	0	289
31	0	23	17	14	11	0	23	13	23	16	0	42	20	16	20	0	18	17	23	8	304
32	23	0	22	18	17	17	0	22	23	23	6	0	40	20	26	8	0	14	25	14	318
33	33	11	0	21	18	20	9	0	27	33	25	12	0	39	24	14	12	0	29	25	352
34	22	19	15	0	14	30	23	7	0	32	21	19	8	0	41	26	15	16	0	31	339
35	22	22	17	9	0	33	22	13	12	0	24	18	16	14	0	55	20	16	11	0	324
36	0	22	19	17	14	0	28	17	22	12	0	25	18	20	14	0	45	17	13	8	311
37	8	0	28	23	16	7	0	16	23	15	10	0	23	24	17	11	0	46	15	11	293
38	28	10	0	24	22	15	13	0	28	27	16	7	0	28	29	17	8	0	46	14	332
39	31	22	16	0	26	21	27	10	0	32	18	17	12	0	34	25	16	17	0	36	360

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	45	29	21	12	0	29	26	18	15	0	20	28	28	18	0	28	17	26	10	0	370
41	0	45	20	19	10	0	28	22	26	10	0	25	26	22	9	0	22	24	19	7	334
42	10	0	40	24	15	12	0	22	28	16	9	0	22	30	15	8	0	29	21	10	311
43	15	10	0	55	19	23	14	0	20	18	12	9	0	27	20	17	10	0	20	16	305
44	20	24	11	0	53	24	19	4	0	23	14	14	13	0	17	19	21	12	0	15	303
45	21	21	21	12	0	52	22	15	9	0	23	15	24	14	0	26	26	17	9	0	327
46	0	27	26	11	7	0	38	23	13	12	0	19	17	22	11	0	28	26	19	9	308
47	11	0	25	21	11	8	0	53	21	25	17	0	19	17	18	12	0	35	20	15	328
48	16	14	0	26	18	14	10	0	56	24	19	5	0	17	20	16	9	0	27	16	307
49	22	23	13	0	19	18	21	8	0	42	21	9	6	0	23	18	19	17	0	17	296
50	29	23	23	9	0	17	29	23	16	0	54	25	13	9	0	23	27	21	12	0	353

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.40 Strategy 24: Annual Number of Signs Blanket Replaced

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	500																				500
2	0	500																			500
3	0	0	500																		500
4	0	0	0	500																	500
5	0	0	0	0	500																500
6	0	0	0	0	0	500															500
7	0	0	0	0	0	0	500														500
8	0	0	0	0	0	0	0	500													500
9	0	0	0	0	0	0	0	0	500												500
10	0	0	0	0	0	0	0	0	0	500											500
11	0	0	0	0	0	0	0	0	0	0	500										500
12	0	0	0	0	0	0	0	0	0	0	0	500									500
13	0	0	0	0	0	0	0	0	0	0	0	0	500								500
14	0	0	0	0	0	0	0	0	0	0	0	0	0	500							500
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500						500
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500					500
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500				500
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500			500
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500		500
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500	500
21	425	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	425
22	0	449	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	449
23	0	0	435	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	435
24	0	0	0	437	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	437
25	0	0	0	0	442	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	442
26	0	0	0	0	0	437	0	0	0	0	0	0	0	0	0	0	0	0	0	0	437
27	0	0	0	0	0	0	436	0	0	0	0	0	0	0	0	0	0	0	0	0	436
28	0	0	0	0	0	0	0	431	0	0	0	0	0	0	0	0	0	0	0	0	431
29	0	0	0	0	0	0	0	0	430	0	0	0	0	0	0	0	0	0	0	0	430
30	0	0	0	0	0	0	0	0	0	443	0	0	0	0	0	0	0	0	0	0	443
31	0	0	0	0	0	0	0	0	0	0	450	0	0	0	0	0	0	0	0	0	450
32	0	0	0	0	0	0	0	0	0	0	0	435	0	0	0	0	0	0	0	0	435
33	0	0	0	0	0	0	0	0	0	0	0	0	429	0	0	0	0	0	0	0	429
34	0	0	0	0	0	0	0	0	0	0	0	0	0	440	0	0	0	0	0	0	440
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	434	0	0	0	0	0	434
36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	446	0	0	0	0	446
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	438	0	0	0	438
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	446	0	0	446
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	442	0	442

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	427	427
41	426	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	426
42	0	435	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	435
43	0	0	443	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	443
44	0	0	0	437	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	437
45	0	0	0	0	455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	455
46	0	0	0	0	0	444	0	0	0	0	0	0	0	0	0	0	0	0	0	0	444
47	0	0	0	0	0	0	429	0	0	0	0	0	0	0	0	0	0	0	0	0	429
48	0	0	0	0	0	0	0	433	0	0	0	0	0	0	0	0	0	0	0	0	433
49	0	0	0	0	0	0	0	0	447	0	0	0	0	0	0	0	0	0	0	0	447
50	0	0	0	0	0	0	0	0	0	439	0	0	0	0	0	0	0	0	0	0	439

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.41 Strategy 24: Annual Number of Signs Spot Replaced

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	10																				10
2	9	10																			19
3	15	13	6																		34
4	18	15	6	11																	50
5	17	21	14	6	7																65
6	15	11	16	15	10	8															75
7	6	25	12	11	15	6	8														83
8	18	7	17	20	17	16	6	12													113
9	19	14	6	18	20	19	13	7	11												127
10	14	16	14	4	9	21	17	19	5	13											132
11	12	19	15	17	16	15	12	19	17	7	6										155
12	10	9	17	24	13	6	22	16	12	12	12	13									166
13	14	6	29	12	13	15	10	10	25	6	10	12	5								167
14	18	12	10	18	18	16	9	8	21	15	9	7	9	10							180
15	17	10	6	8	17	18	15	13	9	20	18	13	12	10	8						194
16	13	13	19	10	7	19	20	19	15	8	20	18	20	10	4	11					226
17	9	24	13	21	12	7	13	18	13	12	4	17	29	15	10	8	10				235
18	15	12	15	17	16	13	7	17	13	15	14	8	21	21	15	14	7	8			248
19	17	9	7	19	13	19	15	8	17	18	18	20	12	9	16	24	12	11	5		269
20	17	11	8	12	16	22	11	16	10	15	21	8	11	5	22	14	17	7	9	13	265
21	30	15	16	11	10	17	17	23	12	4	21	16	11	21	10	22	21	16	11	7	311
22	10	12	16	16	14	4	11	16	13	19	5	16	17	19	9	9	17	16	20	18	277
23	16	9	21	19	14	17	9	12	14	15	16	6	26	12	15	9	5	20	18	17	290
24	15	16	6	13	17	20	15	7	17	21	14	13	7	18	23	18	16	13	17	22	308
25	12	14	14	4	21	19	17	16	9	19	19	16	12	7	19	13	17	14	4	22	288
26	13	15	12	11	12	19	17	26	16	7	15	16	15	7	5	13	12	16	12	7	266
27	10	19	18	20	19	6	20	16	16	11	6	15	14	12	20	9	17	15	25	12	300
28	12	8	15	12	8	12	10	19	24	14	13	13	16	16	13	14	8	19	12	15	273
29	16	12	6	13	15	11	12	6	20	18	12	16	11	19	24	13	15	7	23	18	287
30	14	10	19	5	18	14	16	7	6	17	21	19	17	5	12	23	17	13	5	18	276
31	18	12	14	17	11	14	19	14	11	13	11	10	15	13	6	9	19	9	13	8	256
32	11	11	13	13	11	11	21	14	22	15	12	17	18	11	16	10	13	13	15	14	281
33	16	8	12	15	16	18	12	19	20	6	10	13	24	19	16	7	12	19	18	12	292
34	23	4	8	18	16	10	8	10	15	21	19	11	12	23	18	7	18	7	13	19	280
35	21	15	9	5	9	10	21	11	5	17	15	20	8	6	24	17	15	17	9	25	279
36	16	18	19	17	8	22	13	13	8	8	22	11	9	13	10	21	16	14	18	14	290
37	6	19	14	14	19	5	22	20	18	12	7	21	19	15	14	8	19	13	15	8	288
38	11	13	21	16	11	9	10	19	14	13	14	9	17	13	17	9	7	17	13	12	265
39	13	10	8	22	22	13	11	7	14	17	18	7	7	21	21	21	9	7	15	20	283

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	28	15	8	11	19	15	21	12	3	20	15	16	12	7	19	14	16	12	16	20	299
41	25	24	15	8	5	19	18	17	11	8	17	20	21	18	8	18	19	15	14	11	311
42	10	17	14	11	10	6	18	23	16	17	13	19	18	10	12	7	22	17	11	6	277
43	15	10	19	17	10	15	7	16	25	18	13	12	16	22	11	11	11	20	17	13	298
44	17	8	2	25	12	13	17	12	15	13	14	9	10	19	21	13	9	8	13	19	269
45	13	19	7	13	22	18	19	15	11	13	17	18	10	10	9	21	17	17	8	14	291
46	16	12	10	13	17	16	20	13	10	7	15	10	21	12	10	22	19	14	10	4	271
47	16	18	16	16	11	6	20	15	12	9	12	15	10	28	11	8	23	19	14	17	296
48	10	8	21	22	7	6	5	25	17	18	15	9	17	18	18	16	6	20	16	15	289
49	11	14	10	20	18	14	9	9	14	23	19	14	7	16	16	20	10	7	17	14	282
50	12	21	10	8	19	20	19	10	8	19	12	8	9	11	18	15	16	14	5	13	267

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.42 Strategy 24: Annual Number of Signs Replaced During Daytime Inspections

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	0																				0
2	0	0																			0
3	0	0	0																		0
4	0	0	0	0																	0
5	0	0	0	0	0																0
6	21	0	0	0	0	0															21
7	0	19	0	0	0	0	0														19
8	0	0	29	0	0	0	0	0													29
9	0	0	0	28	0	0	0	0	0												28
10	0	0	0	0	18	0	0	0	0	0											18
11	23	0	0	0	0	26	0	0	0	0	0										49
12	0	26	0	0	0	0	27	0	0	0	0	0									53
13	0	0	36	0	0	0	0	22	0	0	0	0	0								58
14	0	0	0	22	0	0	0	0	19	0	0	0	0	0							41
15	0	0	0	0	21	0	0	0	0	26	0	0	0	0	0						47
16	24	0	0	0	0	23	0	0	0	0	13	0	0	0	0	0					60
17	0	18	0	0	0	0	17	0	0	0	0	31	0	0	0	0	0				66
18	0	0	29	0	0	0	0	28	0	0	0	0	20	0	0	0	0	0			77
19	0	0	0	26	0	0	0	0	42	0	0	0	0	31	0	0	0	0	0		99
20	0	0	0	0	24	0	0	0	0	25	0	0	0	0	25	0	0	0	0	0	74
21	0	0	0	0	0	30	0	0	0	0	17	0	0	0	0	24	0	0	0	0	71
22	0	0	0	0	0	0	32	0	0	0	0	18	0	0	0	0	26	0	0	0	76
23	0	0	0	0	0	0	0	31	0	0	0	0	34	0	0	0	0	25	0	0	90
24	0	0	0	0	0	0	0	0	20	0	0	0	0	28	0	0	0	0	22	0	70
25	0	0	0	0	0	0	0	0	0	18	0	0	0	0	24	0	0	0	0	26	68
26	22	0	0	0	0	0	0	0	0	0	21	0	0	0	0	19	0	0	0	0	62
27	0	25	0	0	0	0	0	0	0	0	0	27	0	0	0	0	29	0	0	0	81
28	0	0	29	0	0	0	0	0	0	0	0	0	28	0	0	0	0	32	0	0	89
29	0	0	0	27	0	0	0	0	0	0	0	0	0	26	0	0	0	0	31	0	84
30	0	0	0	0	21	0	0	0	0	0	0	0	0	0	28	0	0	0	0	17	66
31	21	0	0	0	0	23	0	0	0	0	0	0	0	0	0	27	0	0	0	0	71
32	0	38	0	0	0	0	22	0	0	0	0	0	0	0	0	0	23	0	0	0	83
33	0	0	27	0	0	0	0	27	0	0	0	0	0	0	0	0	0	20	0	0	74
34	0	0	0	25	0	0	0	0	26	0	0	0	0	0	0	0	0	0	33	0	84
35	0	0	0	0	14	0	0	0	0	31	0	0	0	0	0	0	0	0	0	33	78
36	23	0	0	0	0	27	0	0	0	0	26	0	0	0	0	0	0	0	0	0	76
37	0	18	0	0	0	0	24	0	0	0	0	27	0	0	0	0	0	0	0	0	69
38	0	0	29	0	0	0	0	20	0	0	0	0	30	0	0	0	0	0	0	0	79
39	0	0	0	34	0	0	0	0	34	0	0	0	0	30	0	0	0	0	0	0	98

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	0	0	0	0	28	0	0	0	0	27	0	0	0	0	35	0	0	0	0	0	90
41	0	0	0	0	0	21	0	0	0	0	19	0	0	0	0	29	0	0	0	0	69
42	0	0	0	0	0	0	27	0	0	0	0	27	0	0	0	0	23	0	0	0	77
43	0	0	0	0	0	0	0	19	0	0	0	0	14	0	0	0	0	22	0	0	55
44	0	0	0	0	0	0	0	0	25	0	0	0	0	21	0	0	0	0	26	0	72
45	0	0	0	0	0	0	0	0	0	21	0	0	0	0	17	0	0	0	0	16	54
46	23	0	0	0	0	0	0	0	0	0	26	0	0	0	0	29	0	0	0	0	78
47	0	27	0	0	0	0	0	0	0	0	0	19	0	0	0	0	18	0	0	0	64
48	0	0	32	0	0	0	0	0	0	0	0	0	30	0	0	0	0	34	0	0	96
49	0	0	0	33	0	0	0	0	0	0	0	0	0	20	0	0	0	0	27	0	80
50	0	0	0	0	24	0	0	0	0	0	0	0	0	0	30	0	0	0	0	16	70

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.43 Strategy 24: Annual Number of Signs Replaced for Any Reason (Blanket + Spot + Inspection)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	510																				510
2	9	510																			519
3	15	13	506																		534
4	18	15	6	511																	550
5	17	21	14	6	507																565
6	36	11	16	15	10	508															596
7	6	44	12	11	15	6	508														602
8	18	7	46	20	17	16	6	512													642
9	19	14	6	46	20	19	13	7	511												655
10	14	16	14	4	27	21	17	19	5	513											650
11	35	19	15	17	16	41	12	19	17	7	506										704
12	10	35	17	24	13	6	49	16	12	12	12	513									719
13	14	6	65	12	13	15	10	32	25	6	10	12	505								725
14	18	12	10	40	18	16	9	8	40	15	9	7	9	510							721
15	17	10	6	8	38	18	15	13	9	46	18	13	12	10	508						741
16	37	13	19	10	7	42	20	19	15	8	33	18	20	10	4	511					786
17	9	42	13	21	12	7	30	18	13	12	4	48	29	15	10	8	510				801
18	15	12	44	17	16	13	7	45	13	15	14	8	41	21	15	14	7	508			825
19	17	9	7	45	13	19	15	8	59	18	18	20	12	40	16	24	12	11	505		868
20	17	11	8	12	40	22	11	16	10	40	21	8	11	5	47	14	17	7	9	513	839
21	455	15	16	11	10	47	17	23	12	4	38	16	11	21	10	46	21	16	11	7	807
22	10	461	16	16	14	4	43	16	13	19	5	34	17	19	9	9	43	16	20	18	802
23	16	9	456	19	14	17	9	43	14	15	16	6	60	12	15	9	5	45	18	17	815
24	15	16	6	450	17	20	15	7	37	21	14	13	7	46	23	18	16	13	39	22	815
25	12	14	14	4	463	19	17	16	9	37	19	16	12	7	43	13	17	14	4	48	798
26	35	15	12	11	12	456	17	26	16	7	36	16	15	7	5	32	12	16	12	7	765
27	10	44	18	20	19	6	456	16	16	11	6	42	14	12	20	9	46	15	25	12	817
28	12	8	44	12	8	12	10	450	24	14	13	13	44	16	13	14	8	51	12	15	793
29	16	12	6	40	15	11	12	6	450	18	12	16	11	45	24	13	15	7	54	18	801
30	14	10	19	5	39	14	16	7	6	460	21	19	17	5	40	23	17	13	5	35	785
31	39	12	14	17	11	37	19	14	11	13	461	10	15	13	6	36	19	9	13	8	777
32	11	49	13	13	11	11	43	14	22	15	12	452	18	11	16	10	36	13	15	14	799
33	16	8	39	15	16	18	12	46	20	6	10	13	453	19	16	7	12	39	18	12	795
34	23	4	8	43	16	10	8	10	41	21	19	11	12	463	18	7	18	7	46	19	804
35	21	15	9	5	23	10	21	11	5	48	15	20	8	6	458	17	15	17	9	58	791
36	39	18	19	17	8	49	13	13	8	8	48	11	9	13	10	467	16	14	18	14	812
37	6	37	14	14	19	5	46	20	18	12	7	48	19	15	14	8	457	13	15	8	795
38	11	13	50	16	11	9	10	39	14	13	14	9	47	13	17	9	7	463	13	12	790
39	13	10	8	56	22	13	11	7	48	17	18	7	7	51	21	21	9	7	457	20	823

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	28	15	8	11	47	15	21	12	3	47	15	16	12	7	54	14	16	12	16	447	816
41	451	24	15	8	5	40	18	17	11	8	36	20	21	18	8	47	19	15	14	11	806
42	10	452	14	11	10	6	45	23	16	17	13	46	18	10	12	7	45	17	11	6	789
43	15	10	462	17	10	15	7	35	25	18	13	12	30	22	11	11	11	42	17	13	796
44	17	8	2	462	12	13	17	12	40	13	14	9	10	40	21	13	9	8	39	19	778
45	13	19	7	13	477	18	19	15	11	34	17	18	10	10	26	21	17	17	8	30	800
46	39	12	10	13	17	460	20	13	10	7	41	10	21	12	10	51	19	14	10	4	793
47	16	45	16	16	11	6	449	15	12	9	12	34	10	28	11	8	41	19	14	17	789
48	10	8	53	22	7	6	5	458	17	18	15	9	47	18	18	16	6	54	16	15	818
49	11	14	10	53	18	14	9	9	461	23	19	14	7	36	16	20	10	7	44	14	809
50	12	21	10	8	43	20	19	10	8	458	12	8	9	11	48	15	16	14	5	29	776

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.44 Strategy 24: Annual Number of Signs Inspected During Daytime Inspections

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	0																				0
2	0	0																			0
3	0	0	0																		0
4	0	0	0	0																	0
5	0	0	0	0	0																0
6	500	0	0	0	0	0															500
7	0	500	0	0	0	0	0														500
8	0	0	500	0	0	0	0	0													500
9	0	0	0	500	0	0	0	0	0												500
10	0	0	0	0	500	0	0	0	0	0											500
11	500	0	0	0	0	500	0	0	0	0	0										1000
12	0	500	0	0	0	0	500	0	0	0	0	0									1000
13	0	0	500	0	0	0	0	500	0	0	0	0	0								1000
14	0	0	0	500	0	0	0	0	500	0	0	0	0	0							1000
15	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0						1000
16	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0					1500
17	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0				1500
18	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0			1500
19	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0		1500
20	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0	1500
21	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	1500
22	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	1500
23	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	1500
24	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	1500
25	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	1500
26	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	1500
27	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	1500
28	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	1500
29	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	1500
30	0	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	1500
31	500	0	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	1500
32	0	500	0	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	1500
33	0	0	500	0	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	1500
34	0	0	0	500	0	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	1500
35	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0	0	0	0	0	500	1500
36	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0	0	0	0	0	1500
37	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0	0	0	0	1500
38	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0	0	0	1500
39	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0	0	1500

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	0	1500
41	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	0	1500
42	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	0	1500
43	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	0	1500
44	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	0	1500
45	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	500	1500
46	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	0	1500
47	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	0	1500
48	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	0	1500
49	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	0	1500
50	0	0	0	0	500	0	0	0	0	0	0	0	0	0	500	0	0	0	0	500	1500

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.45 Strategy 24: Annual Cost of Blanket Replacement (Thousand USD)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	$41																				$41
2	$0	$41																			$41
3	$0	$0	$41																		$41
4	$0	$0	$0	$41																	$41
5	$0	$0	$0	$0	$41																$41
6	$0	$0	$0	$0	$0	$41															$41
7	$0	$0	$0	$0	$0	$0	$41														$41
8	$0	$0	$0	$0	$0	$0	$0	$41													$41
9	$0	$0	$0	$0	$0	$0	$0	$0	$41												$41
10	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41											$41
11	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41										$41
12	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41									$41
13	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41								$41
14	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41							$41
15	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41						$41
16	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41					$41
17	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41				$41
18	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41			$41
19	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41		$41
20	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$41	$41
21	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
22	$0	$37	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$37
23	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
24	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
25	$0	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
26	$0	$0	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
27	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
28	$0	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
29	$0	$0	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
30	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
31	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$37	$0	$0	$0	$0	$0	$0	$0	$0	$0	$37
32	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$35
33	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$35
34	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$36
35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$35
36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$0	$0	$0	$36
37	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$0	$0	$36
38	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$0	$36
39	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$36

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35	$35
41	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
42	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
43	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
44	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
45	$0	$0	$0	$0	$37	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$37
46	$0	$0	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
47	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
48	$0	$0	$0	$0	$0	$0	$0	$35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$35
49	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36
50	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$36

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.46 Strategy 24: Annual Cost of Spot Replacement (Thousand USD)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	$1																				$1
2	$1	$1																			$2
3	$1	$1	$0																		$3
4	$1	$1	$0	$1																	$4
5	$1	$2	$1	$0	$1																$5
6	$1	$1	$1	$1	$1	$1															$6
7	$0	$2	$1	$1	$1	$0	$1														$7
8	$1	$1	$1	$2	$1	$1	$0	$1													$9
9	$2	$1	$0	$1	$2	$2	$1	$1	$1												$10
10	$1	$1	$1	$0	$1	$2	$1	$2	$0	$1											$11
11	$1	$2	$1	$1	$1	$1	$1	$2	$1	$1	$0										$13
12	$1	$1	$1	$2	$1	$0	$2	$1	$1	$1	$1	$1									$13
13	$1	$0	$2	$1	$1	$1	$1	$1	$2	$0	$1	$1	$0								$14
14	$1	$1	$1	$1	$1	$1	$1	$1	$2	$1	$1	$1	$1	$1							$15
15	$1	$1	$0	$1	$1	$1	$1	$1	$1	$2	$1	$1	$1	$1	$1						$16
16	$1	$1	$2	$1	$1	$2	$2	$2	$1	$1	$2	$1	$2	$1	$0	$1					$18
17	$1	$2	$1	$2	$1	$1	$1	$1	$1	$1	$0	$1	$2	$1	$1	$1	$1				$19
18	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$2	$2	$1	$1	$1	$1			$20
19	$1	$1	$1	$2	$1	$2	$1	$1	$1	$1	$1	$2	$1	$1	$1	$2	$1	$1	$0		$22
20	$1	$1	$1	$1	$1	$2	$1	$1	$1	$1	$2	$1	$1	$0	$2	$1	$1	$1	$1	$1	$22
21	$2	$1	$1	$1	$1	$1	$1	$2	$1	$0	$2	$1	$1	$2	$1	$2	$2	$1	$1	$1	$25
22	$1	$1	$1	$1	$1	$0	$1	$1	$1	$2	$0	$1	$1	$2	$1	$1	$1	$1	$2	$1	$23
23	$1	$1	$2	$2	$1	$1	$1	$1	$1	$1	$1	$0	$2	$1	$1	$1	$0	$2	$1	$1	$24
24	$1	$1	$0	$1	$1	$2	$1	$1	$1	$2	$1	$1	$1	$1	$2	$1	$1	$1	$1	$2	$25
25	$1	$1	$1	$0	$2	$2	$1	$1	$1	$2	$2	$1	$1	$1	$2	$1	$1	$1	$0	$2	$23
26	$1	$1	$1	$1	$1	$2	$1	$2	$1	$1	$1	$1	$1	$1	$0	$1	$1	$1	$1	$1	$22
27	$1	$2	$1	$2	$2	$0	$2	$1	$1	$1	$0	$1	$1	$1	$2	$1	$1	$1	$2	$1	$24
28	$1	$1	$1	$1	$1	$1	$1	$2	$2	$1	$1	$1	$1	$1	$1	$1	$1	$2	$1	$1	$22
29	$1	$1	$0	$1	$1	$1	$1	$0	$2	$1	$1	$1	$1	$2	$2	$1	$1	$1	$2	$1	$23
30	$1	$1	$2	$0	$1	$1	$1	$1	$0	$1	$2	$2	$1	$0	$1	$2	$1	$1	$0	$1	$22
31	$1	$1	$1	$1	$1	$1	$2	$1	$1	$1	$1	$1	$1	$1	$0	$1	$2	$1	$1	$1	$21
32	$1	$1	$1	$1	$1	$1	$2	$1	$2	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$23
33	$1	$1	$1	$1	$1	$1	$1	$2	$2	$0	$1	$1	$2	$2	$1	$1	$1	$2	$1	$1	$24
34	$2	$0	$1	$1	$1	$1	$1	$1	$1	$2	$2	$1	$1	$2	$1	$1	$1	$1	$1	$2	$23
35	$2	$1	$1	$0	$1	$1	$2	$1	$0	$1	$1	$2	$1	$0	$2	$1	$1	$1	$1	$2	$23
36	$1	$1	$2	$1	$1	$2	$1	$1	$1	$1	$2	$1	$1	$1	$1	$2	$1	$1	$1	$1	$24
37	$0	$2	$1	$1	$2	$0	$2	$2	$1	$1	$1	$2	$2	$1	$1	$1	$2	$1	$1	$1	$23
38	$1	$1	$2	$1	$1	$1	$1	$2	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$1	$22
39	$1	$1	$1	$2	$2	$1	$1	$1	$1	$1	$1	$1	$1	$2	$2	$2	$1	$1	$1	$2	$23

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	$2	$1	$1	$1	$2	$1	$2	$1	$0	$2	$1	$1	$1	$1	$2	$1	$1	$1	$1	$2	$24
41	$2	$2	$1	$1	$0	$2	$1	$1	$1	$1	$1	$2	$2	$1	$1	$1	$2	$1	$1	$1	$25
42	$1	$1	$1	$1	$1	$0	$1	$2	$1	$1	$1	$2	$1	$1	$1	$1	$2	$1	$1	$0	$23
43	$1	$1	$2	$1	$1	$1	$1	$1	$2	$1	$1	$1	$1	$2	$1	$1	$1	$2	$1	$1	$24
44	$1	$1	$0	$2	$1	$1	$1	$1	$1	$1	$1	$1	$1	$2	$2	$1	$1	$1	$1	$2	$22
45	$1	$2	$1	$1	$2	$1	$2	$1	$1	$1	$1	$1	$1	$1	$1	$2	$1	$1	$1	$1	$24
46	$1	$1	$1	$1	$1	$1	$2	$1	$1	$1	$1	$1	$2	$1	$1	$2	$2	$1	$1	$0	$22
47	$1	$1	$1	$1	$1	$0	$2	$1	$1	$1	$1	$1	$1	$2	$1	$1	$2	$2	$1	$1	$24
48	$1	$1	$2	$2	$1	$0	$0	$2	$1	$1	$1	$1	$1	$1	$1	$1	$0	$2	$1	$1	$23
49	$1	$1	$1	$2	$1	$1	$1	$1	$1	$2	$2	$1	$1	$1	$1	$2	$1	$1	$1	$1	$23
50	$1	$2	$1	$1	$2	$2	$2	$1	$1	$2	$1	$1	$1	$1	$1	$1	$1	$1	$0	$1	$22

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.47 Strategy 24: Annual Cost of Replacement during Daytime Inspections (Thousand USD)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	$0																				$0
2	$0	$0																			$0
3	$0	$0	$0																		$0
4	$0	$0	$0	$0																	$0
5	$0	$0	$0	$0	$0																$0
6	$2	$0	$0	$0	$0	$0															$2
7	$0	$2	$0	$0	$0	$0	$0														$2
8	$0	$0	$2	$0	$0	$0	$0	$0													$2
9	$0	$0	$0	$2	$0	$0	$0	$0	$0												$2
10	$0	$0	$0	$0	$1	$0	$0	$0	$0	$0											$1
11	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0										$4
12	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0									$4
13	$0	$0	$3	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0								$5
14	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0							$3
15	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0						$4
16	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$1	$0	$0	$0	$0	$0					$5
17	$0	$1	$0	$0	$0	$0	$1	$0	$0	$0	$0	$3	$0	$0	$0	$0	$0				$5
18	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0			$6
19	$0	$0	$0	$2	$0	$0	$0	$0	$3	$0	$0	$0	$0	$3	$0	$0	$0	$0	$0		$8
20	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$6
21	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$1	$0	$0	$0	$0	$2	$0	$0	$0	$0	$6
22	$0	$0	$0	$0	$0	$0	$3	$0	$0	$0	$0	$1	$0	$0	$0	$0	$2	$0	$0	$0	$6
23	$0	$0	$0	$0	$0	$0	$0	$3	$0	$0	$0	$0	$3	$0	$0	$0	$0	$2	$0	$0	$7
24	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$6
25	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$6
26	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$5
27	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$7
28	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$3	$0	$0	$7
29	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$3	$0	$7
30	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$1	$5
31	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$6
32	$0	$3	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$7
33	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$6
34	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$3	$0	$7
35	$0	$0	$0	$0	$1	$0	$0	$0	$0	$3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$3	$6
36	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$6
37	$0	$1	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$6
38	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$6
39	$0	$0	$0	$3	$0	$0	$0	$0	$3	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$8

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$3	$0	$0	$0	$0	$0	$7
41	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$6
42	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$6
43	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$1	$0	$0	$0	$0	$2	$0	$0	$4
44	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$6
45	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$1	$0	$0	$0	$0	$1	$4
46	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$0	$0	$0	$6
47	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$1	$0	$0	$0	$5
48	$0	$0	$3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$3	$0	$0	$8
49	$0	$0	$0	$3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$2	$0	$7
50	$0	$0	$0	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2	$0	$0	$0	$0	$1	$6

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.48 Strategy 24: Annual Cost of Replacement for Any Reason (Blanket + Spot + Inspection) (Thousand USD)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	$41																				$41
2	$1	$41																			$42
3	$1	$1	$41																		$43
4	$1	$1	$0	$42																	$45
5	$1	$2	$1	$0	$41																$46
6	$3	$1	$1	$1	$1	$41															$48
7	$0	$4	$1	$1	$1	$0	$41														$49
8	$1	$1	$4	$2	$1	$1	$0	$42													$52
9	$2	$1	$0	$4	$2	$2	$1	$1	$42												$53
10	$1	$1	$1	$0	$2	$2	$1	$2	$0	$42											$53
11	$3	$2	$1	$1	$1	$3	$1	$2	$1	$1	$41										$57
12	$1	$3	$1	$2	$1	$0	$4	$1	$1	$1	$1	$42									$58
13	$1	$0	$5	$1	$1	$1	$1	$3	$2	$0	$1	$1	$41								$59
14	$1	$1	$1	$3	$1	$1	$1	$1	$3	$1	$1	$1	$1	$41							$59
15	$1	$1	$0	$1	$3	$1	$1	$1	$1	$4	$1	$1	$1	$1	$41						$60
16	$3	$1	$2	$1	$1	$3	$2	$2	$1	$1	$3	$1	$2	$1	$0	$42					$64
17	$1	$3	$1	$2	$1	$1	$2	$1	$1	$1	$0	$4	$2	$1	$1	$1	$41				$65
18	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$1	$1	$3	$2	$1	$1	$1	$41			$67
19	$1	$1	$1	$4	$1	$2	$1	$1	$5	$1	$1	$2	$1	$3	$1	$2	$1	$1	$41		$71
20	$1	$1	$1	$1	$3	$2	$1	$1	$1	$3	$2	$1	$1	$0	$4	$1	$1	$1	$1	$42	$68
21	$37	$1	$1	$1	$1	$4	$1	$2	$1	$0	$3	$1	$1	$2	$1	$4	$2	$1	$1	$1	$66
22	$1	$37	$1	$1	$1	$0	$3	$1	$1	$2	$0	$3	$1	$2	$1	$1	$3	$1	$2	$1	$65
23	$1	$1	$37	$2	$1	$1	$1	$3	$1	$1	$1	$0	$5	$1	$1	$1	$0	$4	$1	$1	$66
24	$1	$1	$0	$37	$1	$2	$1	$1	$3	$2	$1	$1	$1	$4	$2	$1	$1	$1	$3	$2	$66
25	$1	$1	$1	$0	$38	$2	$1	$1	$1	$3	$2	$1	$1	$1	$3	$1	$1	$1	$0	$4	$65
26	$3	$1	$1	$1	$1	$37	$1	$2	$1	$1	$3	$1	$1	$1	$0	$3	$1	$1	$1	$1	$62
27	$1	$4	$1	$2	$2	$0	$37	$1	$1	$1	$0	$3	$1	$1	$2	$1	$4	$1	$2	$1	$66
28	$1	$1	$4	$1	$1	$1	$1	$37	$2	$1	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$64
29	$1	$1	$0	$3	$1	$1	$1	$0	$37	$1	$1	$1	$1	$4	$2	$1	$1	$1	$4	$1	$65
30	$1	$1	$2	$0	$3	$1	$1	$1	$0	$37	$2	$2	$1	$0	$3	$2	$1	$1	$0	$3	$64
31	$3	$1	$1	$1	$1	$3	$2	$1	$1	$1	$37	$1	$1	$1	$0	$3	$2	$1	$1	$1	$63
32	$1	$4	$1	$1	$1	$1	$3	$1	$2	$1	$1	$37	$1	$1	$1	$1	$3	$1	$1	$1	$65
33	$1	$1	$3	$1	$1	$1	$1	$4	$2	$0	$1	$1	$37	$2	$1	$1	$1	$3	$1	$1	$65
34	$2	$0	$1	$3	$1	$1	$1	$1	$3	$2	$2	$1	$1	$38	$1	$1	$1	$1	$4	$2	$65
35	$2	$1	$1	$0	$2	$1	$2	$1	$0	$4	$1	$2	$1	$0	$37	$1	$1	$1	$1	$5	$64
36	$3	$1	$2	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$1	$1	$38	$1	$1	$1	$1	$66
37	$0	$3	$1	$1	$2	$0	$4	$2	$1	$1	$1	$4	$2	$1	$1	$1	$37	$1	$1	$1	$65
38	$1	$1	$4	$1	$1	$1	$1	$3	$1	$1	$1	$1	$4	$1	$1	$1	$1	$38	$1	$1	$64
39	$1	$1	$1	$5	$2	$1	$1	$1	$4	$1	$1	$1	$1	$4	$2	$2	$1	$1	$37	$2	$67

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	$2	$1	$1	$1	$4	$1	$2	$1	$0	$4	$1	$1	$1	$1	$4	$1	$1	$1	$1	$36	$66
41	$37	$2	$1	$1	$0	$3	$1	$1	$1	$1	$3	$2	$2	$1	$1	$4	$2	$1	$1	$1	$66
42	$1	$37	$1	$1	$1	$0	$4	$2	$1	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$0	$64
43	$1	$1	$38	$1	$1	$1	$1	$3	$2	$1	$1	$1	$2	$2	$1	$1	$1	$3	$1	$1	$65
44	$1	$1	$0	$38	$1	$1	$1	$1	$3	$1	$1	$1	$1	$3	$2	$1	$1	$1	$3	$2	$63
45	$1	$2	$1	$1	$39	$1	$2	$1	$1	$3	$1	$1	$1	$1	$2	$2	$1	$1	$1	$2	$65
46	$3	$1	$1	$1	$1	$37	$2	$1	$1	$1	$3	$1	$2	$1	$1	$4	$2	$1	$1	$0	$64
47	$1	$4	$1	$1	$1	$0	$37	$1	$1	$1	$1	$3	$1	$2	$1	$1	$3	$2	$1	$1	$64
48	$1	$1	$4	$2	$1	$0	$0	$37	$1	$1	$1	$1	$4	$1	$1	$1	$0	$4	$1	$1	$67
49	$1	$1	$1	$4	$1	$1	$1	$1	$37	$2	$2	$1	$1	$3	$1	$2	$1	$1	$4	$1	$66
50	$1	$2	$1	$1	$3	$2	$2	$1	$1	$37	$1	$1	$1	$1	$4	$1	$1	$1	$0	$2	$63

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.49 Strategy 24: Annual Cost of Daytime Inspections (Thousand USD)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	$0																				$0
2	$0	$0																			$0
3	$0	$0	$0																		$0
4	$0	$0	$0	$0																	$0
5	$0	$0	$0	$0	$0																$0
6	$0	$0	$0	$0	$0	$0															$0
7	$0	$0	$0	$0	$0	$0	$0														$0
8	$0	$0	$0	$0	$0	$0	$0	$0													$0
9	$0	$0	$0	$0	$0	$0	$0	$0	$0												$0
10	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0											$0
11	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0										$0
12	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0									$0
13	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0								$0
14	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0							$0
15	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0						$0
16	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0					$1
17	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0				$1
18	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0			$1
19	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0		$1
20	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
21	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
22	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
23	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
24	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
25	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
26	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
27	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
28	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
29	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
30	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
31	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
32	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
33	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
34	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
35	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
36	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
37	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
38	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
39	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
41	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
42	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
43	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
44	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
45	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
46	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
47	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
48	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
49	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1
50	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)

Table 12.50 Strategy 24: Annual Strategy Cost (Cost of Replacement + Cost of Daytime Inspections) (Thousand USD)

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
1	$41																				$41
2	$1	$41																			$42
3	$1	$1	$41																		$43
4	$1	$1	$0	$42																	$45
5	$1	$2	$1	$0	$41																$46
6	$3	$1	$1	$1	$1	$41															$49
7	$0	$4	$1	$1	$1	$0	$41														$49
8	$1	$1	$4	$2	$1	$1	$0	$42													$52
9	$2	$1	$0	$4	$2	$2	$1	$1	$42												$53
10	$1	$1	$1	$0	$2	$2	$1	$2	$0	$42											$53
11	$3	$2	$1	$1	$1	$4	$1	$2	$1	$1	$41										$58
12	$1	$3	$1	$2	$1	$0	$4	$1	$1	$1	$1	$42									$59
13	$1	$0	$5	$1	$1	$1	$1	$3	$2	$0	$1	$1	$41								$59
14	$1	$1	$1	$3	$1	$1	$1	$1	$3	$1	$1	$1	$1	$41							$59
15	$1	$1	$0	$1	$3	$1	$1	$1	$1	$4	$1	$1	$1	$1	$41						$61
16	$3	$1	$2	$1	$1	$4	$2	$2	$1	$1	$3	$1	$2	$1	$0	$42					$64
17	$1	$4	$1	$2	$1	$1	$3	$1	$1	$1	$0	$4	$2	$1	$1	$1	$41				$66
18	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$1	$1	$4	$2	$1	$1	$1	$41			$68
19	$1	$1	$1	$4	$1	$2	$1	$1	$5	$1	$1	$2	$1	$3	$1	$2	$1	$1	$41		$71
20	$1	$1	$1	$1	$3	$2	$1	$1	$1	$3	$2	$1	$1	$0	$4	$1	$1	$1	$1	$42	$69
21	$37	$1	$1	$1	$1	$4	$1	$2	$1	$0	$3	$1	$1	$2	$1	$4	$2	$1	$1	$1	$66
22	$1	$37	$1	$1	$1	$0	$4	$1	$1	$2	$0	$3	$1	$2	$1	$1	$4	$1	$2	$1	$66
23	$1	$1	$37	$2	$1	$1	$1	$4	$1	$1	$1	$0	$5	$1	$1	$1	$0	$4	$1	$1	$67
24	$1	$1	$0	$37	$1	$2	$1	$1	$3	$2	$1	$1	$1	$4	$2	$1	$1	$1	$3	$2	$67
25	$1	$1	$1	$0	$38	$2	$1	$1	$1	$3	$2	$1	$1	$1	$4	$1	$1	$1	$0	$4	$65
26	$3	$1	$1	$1	$1	$37	$1	$2	$1	$1	$3	$1	$1	$1	$0	$3	$1	$1	$1	$1	$63
27	$1	$4	$1	$2	$2	$0	$37	$1	$1	$1	$0	$4	$1	$1	$2	$1	$4	$1	$2	$1	$67
28	$1	$1	$4	$1	$1	$1	$1	$37	$2	$1	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$65
29	$1	$1	$0	$3	$1	$1	$1	$0	$37	$1	$1	$1	$1	$4	$2	$1	$1	$1	$5	$1	$66
30	$1	$1	$2	$0	$3	$1	$1	$1	$0	$37	$2	$2	$1	$0	$3	$2	$1	$1	$0	$3	$64
31	$3	$1	$1	$1	$1	$3	$2	$1	$1	$1	$37	$1	$1	$1	$0	$3	$2	$1	$1	$1	$64
32	$1	$4	$1	$1	$1	$1	$4	$1	$2	$1	$1	$37	$1	$1	$1	$1	$3	$1	$1	$1	$65
33	$1	$1	$3	$1	$1	$1	$1	$4	$2	$0	$1	$1	$37	$2	$1	$1	$1	$3	$1	$1	$65
34	$2	$0	$1	$4	$1	$1	$1	$1	$4	$2	$2	$1	$1	$38	$1	$1	$1	$1	$4	$2	$66
35	$2	$1	$1	$0	$2	$1	$2	$1	$0	$4	$1	$2	$1	$0	$37	$1	$1	$1	$1	$5	$65
36	$3	$1	$2	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$1	$1	$38	$1	$1	$1	$1	$67
37	$0	$3	$1	$1	$2	$0	$4	$2	$1	$1	$1	$4	$2	$1	$1	$1	$37	$1	$1	$1	$65
38	$1	$1	$4	$1	$1	$1	$1	$3	$1	$1	$1	$1	$4	$1	$1	$1	$1	$38	$1	$1	$65
39	$1	$1	$1	$5	$2	$1	$1	$1	$4	$1	$1	$1	$1	$4	$2	$2	$1	$1	$37	$2	$67

Y	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	Total
40	$2	$1	$1	$1	$4	$1	$2	$1	$0	$4	$1	$1	$1	$1	$5	$1	$1	$1	$1	$36	$67
41	$37	$2	$1	$1	$0	$3	$1	$1	$1	$1	$3	$2	$2	$1	$1	$4	$2	$1	$1	$1	$66
42	$1	$37	$1	$1	$1	$0	$4	$2	$1	$1	$1	$4	$1	$1	$1	$1	$4	$1	$1	$0	$65
43	$1	$1	$38	$1	$1	$1	$1	$3	$2	$1	$1	$1	$3	$2	$1	$1	$1	$4	$1	$1	$65
44	$1	$1	$0	$38	$1	$1	$1	$1	$3	$1	$1	$1	$1	$3	$2	$1	$1	$1	$3	$2	$64
45	$1	$2	$1	$1	$39	$1	$2	$1	$1	$3	$1	$1	$1	$1	$2	$2	$1	$1	$1	$3	$66
46	$3	$1	$1	$1	$1	$37	$2	$1	$1	$1	$4	$1	$2	$1	$1	$4	$2	$1	$1	$0	$65
47	$1	$4	$1	$1	$1	$0	$37	$1	$1	$1	$1	$3	$1	$2	$1	$1	$4	$2	$1	$1	$65
48	$1	$1	$4	$2	$1	$0	$0	$37	$1	$1	$1	$1	$4	$1	$1	$1	$0	$5	$1	$1	$67
49	$1	$1	$1	$4	$1	$1	$1	$1	$37	$2	$2	$1	$1	$3	$1	$2	$1	$1	$4	$1	$66
50	$1	$2	$1	$1	$4	$2	$2	$1	$1	$37	$1	$1	$1	$1	$4	$1	$1	$1	$0	$3	$64

Notes: Y = Year
A = Area
Total = considering all areas (e.g., statewide)