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16. Abstract

Performance-based pavement marking maintenance contracts (PBPMMCs) are one of the latest mechanisms used to maintain adequate pavement marking performance levels. TxDOT has issued two PBPMMCs, but the effectiveness of these contracts as compared to other contracting mechanisms from a risk management, cost, performance, or safety perspective has not been evaluated.

This project gathered information to evaluate the effectiveness of PBPMMCs by evaluating the delivered pavement marking performance, safety performance, potential cost savings, and the most suitable performance measures and measurement protocols for inclusion into the PBPMMCs.

The evaluations found inconclusive evidence as to the benefit of the PBPMMC from a safety, marking performance, or cost-effectiveness standpoint. Recommendations are provided to improve future PBPMMCs.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

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CHAPTER 1: OVERVIEW

Pavement markings play a vital role in the safe and efficient movement of traffic on the Texas Department of Transportation's (TxDOT's) roadways. In 2010, the Federal Highway Administration (FHWA) started rulemaking to adopt minimum pavement marking retroreflectivity levels. These minimum levels will require that pavement markings of adequate visibility are present on the nation's roadways. Performance-based pavement marking maintenance contracts (PBPMMCs) are one of the latest mechanisms used to maintain adequate pavement marking performance and to share the risk of maintaining minimum performance levels. TxDOT has issued two PBPMMCs, but the effectiveness of these contracts as compared to other contracting mechanisms (annual district-wide, warranty, or hybrid contracts) from a risk management, cost, performance, or safety perspective has not been evaluated.

This project gathered information to evaluate the effectiveness of PBPMMCs by addressing the following objectives:

- What is the delivered pavement marking performance resulting from PBPMMCs?
- What is the safety performance of roadways under PBPMMCs?
- What are the potential cost savings of PBPMMCs?
- What performance measures and measurement protocols are most suitable for inclusion in PBPMMCs?

In addition to directly meeting these objectives, the research team surveyed TxDOT districts to get a better understanding of their pavement marking practices. Using all the information gathered in the project, the research team made recommendations as to the future use of PBPMMCs.

CHAPTER 2: STATE OF THE PRACTICE

The topic areas discussed in this chapter are pavement markings and safety, pavement marking performance measures and measurement protocols, pavement marking contracting and specifications, and a discussion on performance-based contract experiences. The goal of this chapter is to provide a background on areas of concern to this research project.

PAVEMENT MARKINGS AND SAFETY

Several studies have investigated the effects of pavement marking improvements on traffic safety using before-after studies and cross-sectional studies. The main consensus across all the studies is that the presence of markings can positively improve safety. However, there is no conclusive evidence with respect to safety effects of retroreflectivity levels regardless of types of markings. This section provides a literature review on the relationship between pavement markings and safety.

Safety Effects of Width and Presence of Pavement Markings

A study sponsored by FHWA in 1981 evaluated the safety effectiveness of pavement marking improvements such as the addition of a center line and edge line, center line only, and edge line only (*1*). The study found that adding edge lines to roads with center lines was the most cost-effective pavement marking improvement to reduce fatal and injury crashes that occur at night.

Al-Masaeid and Sinha (*2*) used a Bayesian before-after study to evaluate the safety effectiveness of center line and edge line pavement marking improvements. The authors did not clearly define improvements in the paper but did mention that the objective of the improvement was to improve the visibility, which can be construed as equivalent to restriping those markings that had poor visibility. The authors found that the pavement marking improvements had no significant influence on total crashes. However, when they considered only high-crash locations, the study found a statistically significant reduction of 13.5 percent in the total crash frequency. Recently, Tsyganov et al. (*3*) investigated the safety benefits of edge line additions and found that the frequency of roadway departure crashes is 11percent higher on highways without edge lines than with edge lines.

Two studies have evaluated the effects of wide edge lines on roadway departure crashes and found that wide edge lines do not have a significant effect on the frequency of these types of crashes (*4,5*). Conversely, a study conducted for the FHWA using a multistate retrospective crash analysis found evidence that suggests that the use of 6-inch edge lines does result in a reduction in several crash types on rural two-lane two-way roads, as compared to 4-inch edge lines (*6*).

Safety and Pavement Markers

Few studies have specifically investigated the safety effects of pavement markers. The markers are not typically measured by retroreflectivity as in the case of pavement markings and, therefore, are frequently excluded from the scope of the studies. Bahar et al. (*7*) evaluated the safety effects of permanent raised pavement markers in four states. They found the impact of the retroreflective markers on nighttime crashes to differ based on annual average daily traffic (AADT) and degree of curvature. Table 1 shows the crash modification factors (CMFs) from the analysis for nighttime crashes. The results indicate that the markers are actually detrimental to safety in some circumstances. The authors attributed this finding to the higher operating speeds resulting from increased visibility that the retroreflective raised pavement markers (RRPMs) provide.

Table 1. RRPM Before-After Nighttime Crash Analysis Results (*7*).

AADT (veh/day)	CMF when Degree of Curve ≤3.5 (Radius ≥1637 ft)	CMF when Degree of Curve >3.5 (Radius <1637 ft)
0–5000	1.16	1.43
5001–15,000	0.99	1.26
15,001–20,000	0.76	1.03

Safety and Retroreflectivity

Pavement markings are unlike many other engineering safety treatments in that the treatments effectiveness is continuously changing over time (i.e., decaying retroreflectivity). One common challenge that researchers face when attempting to address the degradation is how to capture these visibility changes over time and properly synchronize them with crash occurrences for safety evaluation purposes. Typically, as pavement markings age their retroreflectivity, and subsequently their visibility, degrades. The rate of degradation is dependent on many factors that are not easily accounted for such as: age of the marking, marking material type, bead type, marking color, traffic conditions, roadway surface type, installation quality, initial retroreflectivity level, winter maintenance, and environmental conditions.

Research Findings That Show Some Evidence of a Safety Relationship

Migletz et al. (*8,9*) used a before-after evaluation to determine the effects of pavement marking retroreflectivity on safety. The time when pavement marking restriping occurred was considered as the “after” period. Pavement marking restriping was considered when the retroreflectivity level fell below a minimum level. The study considered daylight and nighttime crashes separately, with nighttime crashes including dawn and dusk crashes. In addition, dry and wet crashes were examined separately to assess the safety of all-weather pavement markings. The study used a paired sign evaluation and a yoked-comparison evaluation for analyzing the safety effect. The paired sign evaluation did not provide any statistically significant conclusions. The yoked-comparison evaluation found that all-weather markings may be effective overall in reducing the number of crashes, however the result is not statistically significant. The authors concluded that, under dry pavement conditions, the crash frequency is expected to decrease by about 11 percent. Under wet pavement conditions, the crash frequency is expected to increase by 15 percent, although statistically insignificant.

Abboud and Bowman (*10*) conducted a study in Alabama to establish a relationship between retroreflectivity and crashes and to identify the minimum retroreflectivity value that corresponds to a maximum allowable crash rate. In this study, researchers collected retroreflectivity readings on 520 miles of rural highways over a 4-year period and developed a linear regression between crash rate and line visibility. The target crashes considered are all crashes other than the following types; rear-end and angle type crashes; drug/alcohol, animal, and pedestrian-related crashes; crashes occurring in rain, fog, snow, ice, sleet, and hail; crashes occurring when the road was icy; and daytime crashes. Based on the critical crash rate, the study determined a minimum retroreflectivity threshold of 150 mcd/m^2/lux for white pavement markings. Bahar et al. (*11*) pointed out that the expected crash frequency is not linearly proportional to traffic volume and the conclusions of the Abboud and Bowman (*10*) study may not be true. Bahar et al. (*11*) also pointed out that this study did not address seasonal effects or apply any analysis methods that could minimize a seasonal bias.

A research study of “pavement markings and safety” was conducted by Smadi et al. (*12*) for the Iowa Department of Transportation. This study investigated the correlation between pavement marking retroreflectivity and corresponding crash and traffic data on all state primary roads. To quantify a relationship between crash occurrence probability and pavement marking retroreflectivity, logistic regression analyses were conducted using crash occurrence as a dependent variable and road type, line type, retroreflectivity, and traffic (vehicle miles traveled) as independent variables. The analysis was sub-divided into road type, retroreflectivity measurement source, high crash routes, retroreflectivity range, and line types. The study found that the retroreflectivity levels have a significant correlation with crash occurrence probability for four data subsets—interstate, white edge line, yellow edge line, and yellow center line data. For white edge line and yellow center line data, crash occurrence probability was found to increase by decreasing values of retroreflectivity. The study also suggested the drivers may compensate for the risk by adjusting their driving behavior (e.g., reducing speed) if the markings have low visibility.

Research Findings That Show No Evidence of a Safety Relationship

In 1999, Lee et al. (*13*) conducted a study to develop a correlation between pavement marking retroreflectivity and nighttime crashes using data from four different geographic areas in Michigan. The target crashes considered in this study are crash types such as miscellaneous, overturning vehicle, fixed object collision, other object collision, and head-on crash; crashes occurring in dawn, dusk, and dark conditions; and on highway-area type of non-intersection and non-interchange. A linear regression analysis in this research found no evidence of the relationship between retroreflectivity and nighttime crash frequency. Lee et al. (*13*) also suggested that part of the reason was the insufficient variation of the observed retroreflectivity values in the database and limited sample size of the nighttime accidents used in the analysis. The authors also suggested that a larger sample of nighttime accidents may allow the identification of a relationship between pavement marking retroreflectivity and nighttime accidents.

In 2001, Cottrell and Hanson conducted a before–after evaluation in Virginia to determine the impact of white pavement marking materials on crashes (*14*). The target crashes were sideswipe-in-the-same-direction and run-off-the-road crashes during nighttime, and crashes in daytime were used for comparison. The study found inconclusive evidence of the relationship between crashes and retroreflectivity because some sites showed an increase in crash frequency, while others exhibited a decrease in the crash frequency.

The National Cooperative Highway Research Program (NCHRP) 17-28 research by Bahar et al. (*11*) evaluated the safety effects of longitudinal pavement markings and markers over time using retroreflectivity data collected in California for multilane freeways, multilane highways, and two-lane highways. Researchers considered several factors in their study of the relationship between safety and visibility of pavement marking as measured by retroreflectivity including:

- Road type – multilane freeways, multilane highways, and two-lane highways.
- Time of day – non-daylight crashes.
- Crash type – non-intersection crashes.
- Crash severity – all crashes combined, fatal, and non-fatal injury crashes.
- Pavement markings and markers – markings only, markings and markers.
- Pavement – surface material type.
- Climate region – as a function of precipitation and temperature.
- Snow removal – historical snowfall is used as a proxy measure for the amount of snow removal.
- Traffic volume.

Seasonal multipliers were developed for the three road types to account for seasonal crash variation. The target crashes considered are non-daylight and non-intersection. Retroreflectivity models were applied to relate pavement marking installation date data into pavement marking retroreflectivity estimates. The study found no evidence of a relationship between safety and pavement marking retroreflectivity for all roads that are maintained at the level implemented by California. The authors noted that California implemented a pavement marking management system that resulted in a very few segments having retroreflectivity dropping below 100 mcd/m^2/lux.

Masliah et al. (*15*) applied a time series methodology to identify the relationship between retroreflectivity of pavement markings and crashes. The time series methodology involves simultaneously solving multipliers for seasonal effect and for multipliers that represent the change in the expected number of crashes as a function of pavement marking retroreflectivity.

The data used by Bahar et al. (*11*) were also used in this study. The results of the study showed that, when the roadways are maintained at a minimum level of pavement marking retroreflectivity, the retroreflectivity levels have from no effect to a small effect on the safety performance.

Smadi et al. (*16*) attempted to model the correlation between retroreflectivity levels and the crash probability. The study analyzed three sets of data: the complete database, records for two-lane roads, and records with retroreflectivity values less than or equal to 200 mcd/m2/lux only. For the complete dataset and the two-lane roads, the authors found that there is no correlation between poor pavement marking retroreflectivity and a higher crash probability. At the same time, for records with retroreflectivity values of 200 mcd/m2/lux or less, a statistically significant, albeit weak, relationship was determined. Smadi et al. (*16*) cautioned that increased visibility may cause drivers to feel too comfortable during nighttime conditions, and drivers may then pay less attention, operate their vehicles at unsafe speeds, or both.

Donnell et al. (*17*) performed an exploratory analysis to determine the relationship between pavement marking retroreflectivity and crash frequency. Initially, a neural network was used to develop a pavement marking degradation model using data from a mobile retroreflectometer. Later on, the authors linked the monthly estimates of pavement marking retroreflectivity levels to roadway inventory and crash frequency. To overcome the correlation, generalized estimating equations were used to model monthly crash frequency. The results of the study showed that the yellow and white edge line pavement markings have no statistically significant relation with the two-lane highway nighttime target crash frequency. For multilane highways, the retroreflectivity parameter estimates for the white pavement marking were negative, whereas for the yellow pavement marking, they were positive.

Retroreflectivity Models

The retroreflectivity of pavement markings deteriorates over time and varies with traffic volume, locations, environmental conditions, and other factors, and thus complicates the safety evaluation. This characteristic is unlike other engineering treatments that remain relatively unchanged over time. In addition, markings and markers are restriped or re-marked on a regular or irregular basis, which results in a cyclical pattern for the measured retroreflectivity. This characteristic requires target crash be associated with retroreflectivity readings not only spatially but also temporally. Several researchers have therefore developed and calibrated retroreflectivity models for estimating retroreflectivity values for use in safety modeling, but these models do not necessarily apply to all markings or at all locations.

For example, Bahar et al. (*11*) examined the following factors for retroreflectivity modeling of pavement markings:

- Age.
- Color.
- Material type – waterborne, thermoplastic, epoxy, and solvent represent about 95 percent of the materials tested by the National Transportation Product Evaluation Program (NTPEP).
- Traffic volume.
- Pavement surface.
- Climate region.
- Snow removal.

Finally, Bahar et al. (*11*) proposed the nonlinear retroreflectivity models of the following form:

$$R = \frac{1}{\beta_0 + \beta_1 \cdot Age + \beta_2 \cdot Age^2} \quad (0)$$

For the purpose of safety modeling, it is possible that the researchers may consider alternative measures as a potential model variable to address the shortcoming of standard retroreflectivity modeling. For example, a variable representing integrated retroreflectivity values over time could be considered. This represents the area under the curve of retroreflectivity plotted over time, which is equivalent to the amount of retroreflectivity exposure for a specific highway segment.

Safety Summary

In summary, several studies have examined the relationship between safety and retroreflectivity, which at best yielded inconclusive evidence of such relationship. Also, those findings are not directly applicable to Texas. Further, previous research has not produced results directly related to the safety performance of performance-based pavement marking maintenance contracts). Therefore, a safety evaluation study is needed to determine if there exists a statistically reliable relationship between safety performance and the PBPMMCs.

PAVEMENT MARKING PERFORMANCE MEASURES AND MEASUREMENT PROTOCOLS

Performance Measures

Pavement markings must perform adequately to be able to convey their meaning to drivers. Markings must be easily visible during the day and night and not confusing to drivers. The most common performance measures for pavement markings are the presence of the markings and the markings' retroreflectivity. Pavement marking presence is how much of the marking is remaining on the roadway. Does the marking visually look good or is it worn away so much it is difficult to distinguish it from the surrounding pavement? Pavement marking presence is typically rated by a subjective visual inspection only. The color of the marking and any crack seal or other materials on the marking may impact the presence rating of a marking, as they can impact how visible the marking appears.

Pavement marking retroreflected luminance, RL (which is typically referred to as retroreflectivity) is an important characteristic of pavement markings because it is a surrogate measure of the nighttime visibility. Pavement markings with higher retroreflectivity are assumed to provide higher levels of visibility during nighttime conditions. Retroreflectivity is typically measured with a handheld or mobile retroreflectometer. These devices give a numeric value as to how well the marking reflects light back toward the light source. The FHWA does not currently have minimum maintained pavement marking retroreflectivity levels, though these values are being developed (*18*). Table 2 presents the FHWA proposed minimum maintained retroreflectivity levels for pavement markings. As can be seen in the table, there are several factors that affect what retroreflectivity level will be required by the markings. In areas where there are effective RRPMs or overhead lighting, the pavement marking retroreflectivity levels would not be applicable. In areas without overhead lighting or maintained RRPMs, the required retroreflectivity level would depend on striping pattern and the posted speed limit. The retroreflectivity values listed would be the minimum that the markings could fall to. Any restriping plans or performance-based contracts would need to maintain retroreflectivity values above these levels at all times.

Table 2. Minimum Maintained Retroreflectivity Levels for Longitudinal Pavement Markings (*18*).

	Posted Speed (mph)		
	≤ 30	35–50	≥ 55
Two-lane roads with centerline markings only[2]	n/a	100	250
All other roads[2]	n/a	50	100

1. Measured at standard 30 m geometry in units of mcd/m^2/lux
2. Exceptions

A. When RRPMs supplement or substitute for a longitudinal line (see Section 3B.13 and 3B.14), minimum pavement marking retroreflectivity levels are not applicable as long as the RRPMs are maintained so that at least 3 are visible from any position along that line during nighttime conditions.

B. When continuous roadway lighting assures that the markings are visible, minimum pavement marking retroreflectivity levels are not applicable.

TxDOT currently does not have a minimum maintained pavement marking retroreflectivity level outside of the performance-based pavement marking maintenance contracts. TxDOT may require minimum initial retroreflectivity levels depending on if a special specification is used (*19,20*). These special specifications are for reflectorized pavement markings with retroreflective requirements and for high-performance pavement markings with retroreflective requirements. The retroreflectivity requirements for standard thermoplastic markings are 250 mcd/m^2/lux and 175 mcd/m^2/lux for white and yellow markings, respectively. These retroreflectivity values are to be measured between 3 and 10 days after application. The retroreflectivity requirements for the high-performance thermoplastic markings are 400 mcd/m^2/lux and 250 mcd/m^2/lux for white and yellow markings, respectively. These retroreflectivity values are to be measured between 30 and 40 days after application. These retroreflectivity values are useful in that they can help determine if the markings are initially acceptable, but the long-term performance of the markings may not necessarily correlate well with these initial retroreflectivity values.

Measurement Protocols

Collecting pavement marking retroreflectivity data using a handheld retroreflectometer can be conducted in many ways, but a well-designed data collection plan is necessary to properly evaluate the markings. The ASTM standard practice for evaluating retroreflective pavement markings using portable hand-operated instruments provides several methods to evaluate the retroreflectivity of pavement marking sections (*21*). These methods include a nighttime visual inspection as a base process to identify areas of concern that can later be evaluated with a retroreflectometer. The other methods are the standard evaluation protocol and the referee evaluation protocol, which use a handheld retroreflectometer and a prescribed data collection plan to evaluate the marking's retroreflectivity level with statistical confidence. Currently there is not an ASTM standard practice for mobile retroreflectivity evaluation.

TxDOT does have a special specification dedicated to mobile retroreflectivity data collection (*22*). Special Specification 8094 covers mobile retroreflectivity data collection for pavement markings. The specification covers the formatting of the data that are to be submitted and the process of verifying that the data collected are accurate. A key element of the specification is the requirement that the operators be certified by the Texas A&M Transportation Institute (TTI) mobile retroreflectometer certification program. The mobile retroreflectometer certification program is used to ensure that the operators have the ability to collect accurate data and are able to provide it in the format specified by TxDOT. TxDOT still needs to actively inspect mobile retroreflectivity data collection to ensure that the data collected in the field are within the accuracy specifications. In addition to the special specification and the certification program, TxDOT has conducted research that is used to assist contractors and the DOT with mobile retroreflectivity data collection (*23,24*). This research yielded a best practice handbook for mobile retroreflectivity that can be used to improve the accuracy of the mobile data collection (*24*).

TxDOT's current system for evaluating the quality and effectiveness of its roadway system assets is the Texas Maintenance Assessment Program (TxMAP). TxMAP rates 23 highway elements in three categories on a 1–5 scale, with 5 being the best and 1 the worst. Approximately 10 percent of interstate highways and 5 percent of all other roads are assessed each year. The two TxMAP elements of interest to pavement markings/markers are in the traffic operations category. Table 3 provides the scoring system for markers and striping. The TxMAP system is a subjective way of evaluating the assets. The system has pros and cons, but overall will give a general idea of how well an asset is performing.

Table 3. TxDOT TxMAP Scoring System for Markers and Striping.

Traffic Operations	5	4	3	2	1
Raised Pavement Markers	Markers like new with none missing. Placed on standard placement.	Most in place, may have a few missing or obviously non-reflective, cracked or pressed into adhesive.	Most in place, maximum of 10% missing or obviously non-reflective, cracked or pressed into adhesive or adhesive over reflective face.	Many missing, maximum of <25% missing or obviously non-reflective, cracked or pressed into adhesive or adhesive over reflective face.	Most >25% missing or non-reflective or no markers installed.
Striping, Graphics	New or like new. All required graphics are in place and like new.	Stripes in very good shape with no obvious loss of reflectivity. All required graphics are in good condition.	Stripes in acceptable shape with some cracking or minor loss of reflectivity. May have crack seal slightly obscuring some stripe. Required graphics are present.	Stripes unacceptable with cracking, fading, or severely worn. May be substantially covered with crack seal material. Needs to be replaced. Graphics are missing.	Stripes totally unacceptable with severe cracking, fading or severely worn. Major loss of reflectivity. ANY road without a stripe.

Previous research has studied issues related to measuring pavement marking retroreflectivity, factors related to pavement marking performance, subjective qualitative marking evaluation processes, best practices for using mobile retroreflectometers, and methods of sampling pavement markings (*23,25*). The research indicated that tests conducted to assess subjective evaluation showed inconsistency in subjective retroreflectivity evaluation when compared between different evaluations, marking colors, and retroreflectivity levels. To ensure markings are adequately evaluated, any subjective rankings should be supplemented with quantitative retroreflectivity measurements. The research also evaluated the ability of the Laserlux mobile retroreflectometer to accurately measure the retroreflectivity of pavement markings. To accomplish this, researchers compared measurements with the mobile retroreflectometer to measurements with a handheld retroreflectometer on pavement markings with a range of retroreflectivity levels, and on various road surfaces. Overall, the comparison of the mobile and handheld retroreflectivity data provided very similar results, indicating that a properly calibrated mobile device can produce accurate results for both white and yellow pavement markings on a variety of road surfaces and across a variety of typical retroreflectivity levels.

PAVEMENT MARKING CONTRACTING AND SPECIFICATIONS

There are several types of pavement marking contracting mechanisms. The standard method is an annual district-wide striping contract, where the district decides which roads or how many miles of road need to be striped and puts them out for bid. In these contracts the type and characteristics of the striping system to be applied are defined; this would be a recipe or component-type marking specification (26). Additionally, these annual contracts may require that the newly applied marking meet some minimum level of initial performance. In this type of contract the agency knows what type of marking it will be getting and possibly an initial performance level.

Warranty contracts take these annual contracts a step further by requiring that the markings perform at a defined level for a given amount of time, with penalties for markings that do not meet these requirements. These contract types may specify the characteristics of the striping system to be used and initial performance criteria, but not all do. The goal is that the marking provided lasts at least as long as specified and at least meets the minimum performance levels. This type of contracting and the specified performance criteria can be beneficial in that the agency knows the performance (from a durability and visibility perspective) of the markings that it will be getting.

In addition to these types of contracts, TxDOT has recently begun to use the performance-based pavement marking contract. This contracting mechanism requires that the contractor installs markings that meet or exceed certain performance levels, without specifying the particular marking materials to be used. This performance-based specification is in direct contrast to the recipe type specification. In the case of some contracts they are not only performance based initially but performance based over time. These performance-based pavement marking maintenance contracts (PBPMMCs) require that the contractor installs and maintains markings that meet a predetermined level of performance for a given number of years. In the PBPMMC the contractor is free to choose the striping system to apply, but is also required to monitor and report the performance to the issuing agency at regular intervals. Markings that no longer meet the performance requirements need to be restriped to meet the performance requirements.

A 2007 survey investigated the use of performance-based specifications across state transportation departments (*27*). A total of 23 responses were received, and 13 indicated the use of some type of performance-based specification. Initial retroreflectivity was the typical performance metric used in the contracts. Of the 23 states that responded, 5 indicated that they use a performance specification across all marking types.

Procurement of Services and Risk Allocation

Procurement of goods/products and services is all about design of financial compensation mechanisms and allocation of product performance risks. In general, there are two types of compensation mechanisms for procuring services: 1) fixed upfront or incremental, in which a provider is paid for the services that are executed based on prescriptive specifications (e.g., install this type of marking, using this type of application, at these rates and you will get paid per unit, or when the service is completed), and 2) performance contracts, in which payment mechanisms are linked to some observable outcomes during or at the end of the contract tenure (e.g., install a marking that meets or exceeds these performance criteria—the type of marking, installation method, and rates do not matter as long as the performance criteria are met—and you will get paid). In cost-reimbursable contracts the risk of substandard performance is allocated to the purchaser of the services, while in performance-based contracts, as long as this observable outcome clearly relates to a true need of the service/product purchaser, it is the opposite—the performance risk is held by the service providers. There is an associated risk still held by the owner of the asset, i.e., if the asset fails, public perception will not be good, but the cost of the poor performance falls onto the service provider.

Recently there has been an increase in the use of performance-based contracting, ranging from engineering to social services. For example, in delivering built facilities, the contractor's compensation is linked to specific quality tests that relate to ultimate customer satisfaction (e.g., smoothness of the road), not to a technical parameter that may (or may not) relate to that ultimate customer satisfaction (e.g., pavement stiffness). This is the fundamental difference between performance-based and performance-related contracts. The former focuses on a specific technical outcome or a process (that may [or may not] relate to the mission), while the latter clearly focuses on mission. As it is sometimes difficult to measure product performance outcomes to the mission, products and services are fragmented into a number of performance-related outputs—using performance-related contracts.

There are, however, at least two types of problems that plague performance-based contracts:

- If contract tenure is short, the outcomes can be very specific and only loosely related to the real performance outcomes, and in some cases even negatively related with the overall outcomes. The root problem is: how to define the outcomes that matter and how to measure it (them)? A rule of thumb of performance contracting states: *Be careful how you define the outcomes, as you'll get only what you incentivize, and nothing else*. For example, if the performance outcome is pavement stiffness, the contractor may provide a very stiff pavement structure that may not provide long-term smoothness of the ride to users. The problem is further amplified by having a number of specialized contract interventions that are disconnected. For example, one performance contract could address soil and sub-grade layer properties, other pavement properties, some traffic utilization, etc. In the end, we end up with a system optimized for component functions, not for the system function(s).
- Performance targets are specified as conditions for payment while still keeping the constraints on what a provider needs to do (a prescription). This "setting the outcome without providing flexibility" can prevent performance contracts from being effective because specifying performance outcomes must be accompanied by increasing flexibility to use different methods to achieve them. For example, if I am to be held liable for some performance outcomes, I must have the freedom to use the methods that I think are best suited to achieve those outcomes.

Table 4 shows the typical methods of procuring a product or service and the allocation of risks, opportunities, requirements, and responsibilities. The most typical method for procuring a product or a service is to purchase it from the supplier (Type I). The owner pays for it upfront and is fully responsible for the product operations (i.e., management and maintenance) including taking all risks and opportunities (i.e., product better-than-expected performance, or underperformance). Depending if the sale object is a product or a service, the contracts will differ. In general, vendors and contractors have only limited downside risk exposure, and only if they provide warranties (i.e., if the product fails they will correct the problem over the warranty period). Sometimes vendors and contractors can provide financing in a form of lease sale with or without warranties. This is a Type II contract that is identical to Type I in all other aspects except funding requirement and compensation mechanism. The third and fourth types of contracts are based on the performance of a product or a service (as previously discussed). Type III relates to outputs (i.e., technical parameters of the product or service), while Type IV relates to outcomes (i.e., bottom line outcome to the owner such as total satisfaction, profit, and others).

Table 4. How Procurement Type Impacts Various Factors.

	Performance Risk (Downside)	**Performance Risk (Upside)**	**Funding Requirements**	**Operations Responsibilities**	**Compensation Type**
Type I: Sale of Product or Service					
Owner	High	High	Full	High	Upfront fixed
Vendor / Service Provider	Low	None	None	None	X
Type II: Lease or Lease Sale of Product or Services					
Owner	High	High	Partial upfront	High	Incremental fixed
Vendor / Service Provider	Low	None	Provides lease financing	None	X
Type III: Performance-related Sale					
Owner	Medium	High	Partial upfront	Low	Incremental performance-related
Vendor / Service Provider	Medium	None	Provides sale financing	High	X
Type IV: Performance-based Sale					
Owner	Low	Medium	Partial upfront	None	Incremental performance-based
Vendor / Service Provider	High	Medium	Provides sale financing	High	X

Pavement Markings

Pavement markings represent a component of a larger highway system that is designed to provide safe and economical service to the traveling public. Hence, their performance is heavily influenced by other supply components (e.g., pavement surface type, roadway geometry) and highway demand components (e.g., type of vehicles, traffic patterns). However, pavement markings performance is clearly observable. We either see the marking in day or night, or we do not. Sometimes we see them but without enough clarity. In other words, this product provides a service to the system and the traveling public, and the outcomes are clearly observable. The question here is: how good (visible) should pavement markings be so that the overall system performance is not affected or safety jeopardized?

Pavement markings are typically procured as a product that is installed by a contractor, where TxDOT pays a lump sum amount. They are designed to last X years before their outcomes start affecting system performance (condition fails minimum visibility criteria). Due to poor installation, quality of the product, or more-than-expected traffic demand, their life span may be shorter. As TxDOT has already paid the contractor, it will bear the risk of poor performance. To signal good quality, some manufacturers provide a product warranty. This warranty now provides protection to TxDOT against product failure (i.e., markings are not clearly visible). When that happens, the contractors come and repair or replace it. The compensation scheme is the same, where TxDOT pays an upfront lump sum amount (often larger than for the product without warranty as the warranty provider has more risks).

However, as markings provide service to the overall highway system, they do not have to be procured as a product only; alternatively, they can be procured as a service. TxDOT needs pavement markings to be above minimal performance/safety standards all the time. There is no need to own markings. What is needed is just the service that they provide. Hence, markings can be procured as a service using two types of contracts, depending on how each side takes the performance risks: a) lease (pay $X over Y years without monitoring performance; TxDOT takes the performance risks), or b) performance contracts (pay $X over Y years only if the performance standards are met; contractor takes the performance risk. Note that service-based contracts (Types II, III, and IV) provide financing as opposed to traditional contracts. Note that in Type IV contracts, the contractor has some upside risk (opportunity). We noted before that pavement markings are just a component of the overall system. What surrounds them is the environment, which could be more or less forgiving. So, in some cases, the contractor can use lower quality markings material and hope that the environment is favorable (lower traffic levels, favorable weather, etc.).

PERFORMANCE-BASED CONTRACT EXPERIENCES

This section reviews studies related to the cost-effectiveness of the performance-based contracts (PBCs), particularly those related to roadway maintenance work. Performance-based maintenance contracts (PBMCs), also referred to as performance-specified maintenance contracts (PSMCs), transfer the long-term responsibility for planning and executing maintenance work from agencies to contractors for a fixed premium cost. In such contractual settings, the agencies are able to obtain better budget estimates, hedge the performance-related risk, and reduce the overall cost of conducting maintenance, while the contractors are able to implement innovative construction methods and management techniques to make profit.

Overview of PBCs

A PBC may cover either only individual assets (e.g., markings, signs, bridges) or all roadway assets within a corridor. The level of complexity of a PBC depends on the number of assets and range of services included. Performance standards guide the desired result expected by the contractor, while the contractor selects the manner in which the work is to be performed. Performance monitoring is critical to the PBC success (*28*).

While benefits of PBC have been widely acknowledged, transportation agencies and contractors have also expressed a number of concerns with their implementation. One of the most important concerns is how to estimate the value of these contracts in terms of the cost agencies are transferring to the contractors.

In Australia, after two successful implementations of short-term pilot contracts, Sydney highway officials let the first long-term contract in 1995. This contract had a 10-year duration period, covered 450 km (279.6 miles) of urban roads, and resulted in a significant reduction in the cost of managing the network (*29*), including an increase in asset condition. This outcome indicates that the cost savings were not the result of cheaper designs, but due to more efficient designs and timely application of rehabilitation actions. In other words, the private sector was able to achieve savings and earn profit by managing pavements more efficiently. While in prescribed outsourcing contracts, payments to the contractor are based on the amount and type of work specified by the agency (*30*), payments under PBCs are contingent on the contractor maintaining the road to the specified service level. Since there is no schedule or quantity of work outlined at the onset of the contract, difficulties arise in predicting the costs the contractor will incur in meeting this obligation.

The lack of guidelines and methodologies for evaluating performance specifications present an obstacle in their implementation in the highway sector. Issues like quality over a pavement life span, maintenance costs, and levels of service and user costs need to be further investigated to enable a comprehensive evaluation of the benefits of performance specifications. While there are published reports on operational aspects of contracts, such as implementing performance-based contracts in the service sector (*31*), and optimal management strategies in maintenance contracts (*32*), there are very few reported guidelines on how to choose between performance and method specifications. Reports discussing the ranking of different levels of performance specifications in relation to the existing fully developed method-based specification are scarce.

The benefits of adopting performance-based contracts have been reported for procurement of government services and products. Although this is an important topic, when addressing the effect of implementing performance specifications on highway projects, it does not directly aid in evaluating the value from applying these specifications. The Office of Federal Procurement Policy (*31*) reports the results and findings of a government-wide pilot project to implement performance-based service contracting (PBSC) methods on contracts for recurring services, and to measure PBSC impact. Even though the entities involved in the study were not closely involved in road construction projects, their experiences and findings are valuable in anticipating the value of implementing performance specifications in the highway industry. This government-sponsored research started in October 1994 when the officials of 27 various government agencies agreed to implement PBSC and measure its effects on certain types of contracts. Four industry associations representing over 1000 companies endorsed the project. The research team on the PBSC study evaluated the before-and-after effects of adopting PBSC with regard to variables like contract price, agency satisfaction with contractor performance, type of work performed, type of contract, competition, procurement lead-time, and audit workload. The report concludes that the results strongly validate PBSC and support its use as a preferred acquisition methodology. Furthermore, the resulting data showed that PBSC, when fully and properly applied, enables agencies to obtain significantly improved performance at significantly reduced prices (*33*).

While the information presented in previous studies is useful in developing recommendations for application of performance specifications, they do not address the specific and measurable value from implementing these specifications and incorporating them at different project phases with proper delivery methods and for specific project characteristics.

Agencies' Experiences and Assessment of PBCs

Gransberg and Scheepbouwer (*34*) reviewed the PBC experience in the United States and compared it to the experience abroad. They found that the major difference is the U.S. distinction between construction and maintenance versus the international approach of treating the process as a holistic procedure with no divisions of service. They also suggested that a hybrid PBC model in use in New Zealand is very similar to construction manager/general contractor project delivery in the U.S. and appears to furnish an attractive structure to pilot a U.S. project that bridges the construction and maintenance line.

Several state departments of transportation have employed PBCs, including the following (*33,35,36*):

- District of Columbia.
- Florida.
- Oklahoma.
- Massachusetts.
- New Mexico.
- Texas.
- Utah.
- Virginia.
- Washington.
- North Carolina.

North Carolina Department of Transportation (NCDOT) began PBC contracting with a pilot project in 2005. The project includes routine maintenance and operations for 700 lane miles of interstates, exclusive of resurfacing. In order to verify the contractor's performance, performance targets and semi-annual condition assessments were performed. The contractor's payment is based on how closely they adhere to the targets (*35*). Pavement markings and markers were also part of the NCDOT's PBC. The condition assessment was conducted at 6-month intervals. The ratings after the first-year implementation indicated that the performance improves over time but still did not reach the required target. Pavement markers and sign lighting were among the lowest rated components with 42 percent meeting the required conditions. NCDOT completed the first year of their initial contract in 2008. The contractor did not satisfy performance requirements; therefore, the monthly payment of $482,976 was reduced to $90,000 until the next assessment (*37*).

Following the completion of the first outsourced highway maintenance contract by the Virginia Department of Transportation, Ozbek (*38*) suggested that the contract terms were allowing the contractor to maintain the network at the minimum service level required by applying less expensive measures with a shorter life span. As the contract was written, the contractor was not responsible for any failure or defects that might be discovered after the end of the contract term, even those that might occur immediately afterward. To transfer long-term risk to the contractor—the party with the most control over pavement quality and performance—Ozbek proposed that the contract include a warranty clause to guarantee the work of the contractor beyond the expiration of the contract. This would encourage the contractor to maintain the network to a higher-than-minimum standard and improve long-term conditions to avoid warranty claims later. Similarly, Kim et al. (*32*) suggested that PBMC should use long-term contracts with disincentive clauses and showed that if such contracts were considered, the contractor's optimal maintenance strategy includes actions that substantially add to the structural capacity of a pavement, such as thick overlays, rather than actions that only cover surface distresses.

Manion and Tighe (*39*) studied the effectiveness of the PSMCs in New Zealand from the perspective of social cost of crashes. Originally, these contracts concentrated on the physical attributes of the network. However, as the contracts matured, a reduction in the crash rates was observed. As a result, the contract now includes provisions to adjust the contract payments based on the safety performance. The contractor's performance is measured on the social cost of crashes that occur on the network regardless of crash causes. Under the PSMC model, the marking retroreflectivity must be maintained to a specified level. The contracts also require that the contractor conduct a preliminary accident investigation at all fatal and selected serious injury crash sites. The contractor must make an assessment of the retroreflectivity as part of the crash investigation. Two PSMCs (3-year and 7-year) were evaluated in the study. There was an appreciable improvement in the network condition. The reduction in the social cost of crashes on the network was compared to national trends on the remainder of the national highway network and the improvement was found to be significantly better than the corresponding national figures.

In Canada, the government started using PBCs between the 1980s and 1990s. British Columbia was one of the first places in which these contracts were tested. Alberta province let lump-sum performance-based contracts for 10-year performance periods. While some studies concluded that the level of service (LOS) improved and the cost decreased, other research showed the opposite—increased cost. A regression analysis suggested that the overall cost of the project actually increased. The cost increase was reported for all jurisdictions composing British Columbia (*40*).

Anastasopoulos et al. (*28*) proposed a methodology to estimate the likelihood and the amount of cost savings associated with the application of PBC for highway maintenance operations. Models were developed using data sources from maintenance contracts around the world. The explanatory variables include contract duration, activity type, and contract size. The characteristics that favor PBC are large projects with strong competition, long duration and extension periods, long outsourced road sections that incorporate crack sealing, pothole repair, illumination repair/maintenance, and mowing activities.

The authors noted that the cost savings from PBC typically reported as the difference of PBC final cost and the engineer's estimate should not be considered as actual cost savings. Rather, it would be more accurate to compute the difference of PBC cost and the in-house cost of a contract with similar characteristics (e.g., length, duration, number, and type of activities). Percentages of cost savings relative to the cost of in-house specific maintenance activities were computed to account for the varying cost sizes of the contracts.

The authors employed a series of modeling methods in that study (*28*). First, they used a mixed logit model to investigate the factors that influence the likelihood of whether a contract will incur cost savings. Then, they developed a tobit model for the contracts that are likely to incur cost savings, and used a linear regression model for the contracts that are likely to incur loss. Specifically for PBCs, a binary probit model was calibrated to estimate the factors that affect the likelihood of cost savings and then regression was applied to estimate the corresponding amount.

McCullouch and Anastasopoulos (*37*) suggest that a cost analysis requires all comparison factors to be similar or equal. This can be very difficult when comparing PBCs with in-house costs. Factors such as varying LOS, activities included and excluded, the way agencies keep record and track costs, and overhead costs can complicate cost comparisons. The authors also concluded that PBC will not save money in most cases except for specific areas such as rest areas, movable bridges, and security contracts. This is partly because PBC will require development time, new organization, capabilities, resources, and training. They further suggested that an agency should consider a hybrid approach where in-house forces are supplemented through subcontracts with private contractors.

Some unit costs associated with PBC versus in-house contracts reported in the literature are summarized in Table 5 (*37*).

Table 5. Example of Unit Cost Comparison.

Agency	In-House	PBC
INDOT	$4,500 per lane mile on interstates; includes snow and ice control (estimated subcontract costs at $300/lane-mile) $3,747 per lane mile on interstates; does not include snow and ice control	
NCDOT	$3,800 per lane mile on interstates; includes snow and ice control	$7,200 per lane mile; does not include snow and ice control
FDOT		$5,000 per lane mile; does not include snow and ice control
VDOT		$10,000 to $18,000 per lane mile; includes snow and ice control

The reported cost savings from PBCs are inconclusive from literature (*34*). Significant cost savings were reported in Florida (15.7 percent), Massachusetts (21 percent), and Virginia (12 percent). An Oklahoma project ended in court with both sides suing for the breach of contract. The Texas experience, on the other hand, was considered successful. The sticking point appears to be the political issue of outsourcing and loss of jobs historically performed by public employees rather than the viability of PBC itself.

Anastasopoulos et al. (*41*) investigated the impact of factors that influence the duration and cost of different contract types. Factors examined include number of and specific constituent activities of highway maintenance and rehabilitation contracts, as well as project physical size (length). The interrelationships between these contract characteristics were explored using a three-stage least-square (3SLS) simultaneous equation model. The results suggested that the choice of appropriate contract type for a roadway maintenance project is influenced by characteristics such as the number of constituent maintenance activities in the contract, the expected/specified contract characteristics (duration, cost, and length), and type of roadway asset in question.

The results from the SHRP 2 study state that the cost savings of PBC come from four different sources:

- Inefficient budgeting in the public sector, or lack of efficient resource allocation in the public sector.
- Quality control enforcement, or poor quality control mechanisms.
- Opportunity for innovation, or the lack of innovation incentive and general risk averseness of the agencies' project executives.
- Objective misalignment or the lack of uniformity of project objectives across the stakeholders.

To fully utilize the savings from inefficient budgeting and innovation, it is essential that the performance-based contracts are long-term. Both better budgeting efficiency and innovation cannot produce significant payoffs if the contract time period is short. In other words, only longer term contracts provide efficiency. This is also true from the perspective of the project size. Only larger size projects can produce significant savings that can be passed to the owner. Figure 1 illustrates this concept. In this figure, the level of flexibility is represented as the sum of two economic drivers in projects: 1) design and construction flexibility (contractors have flexibility in choosing designs and products), and 2) contract size/duration. As can be observed, the amount of savings from flexibility is amplified by the size of projects. In other words, relative increase in savings increases as a transition occurs from small size projects to larger size projects ($S_{BC} >> S_{AB} > S_{OA}$). In fact, there is anecdotal evidence that the relationship is highly nonlinear; the larger the contracts, the larger the savings (in percentages). It is important to note that agencies can bundle projects together to achieve the needed size.

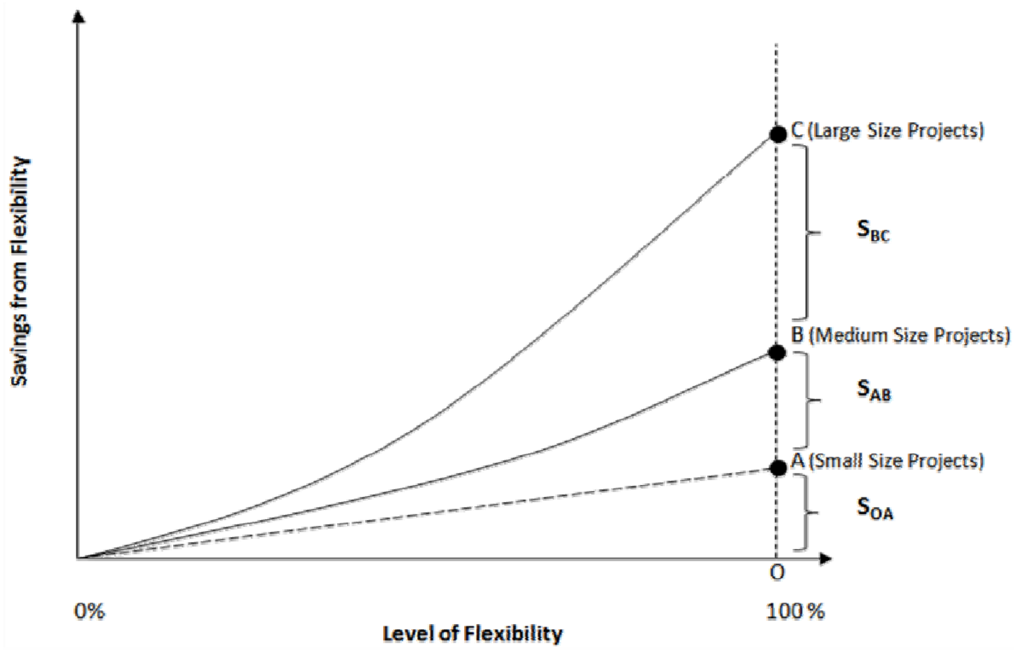

Figure 1. Savings from Flexibility.

In a synthesis report on performance-based contracting for maintenance, Hyman reviewed literature and conducted a survey (*42*). The study found that the most frequent approach to payment in a PBMC is a lump-sum with deductions for failing to meet performance standards. The literature reviewed and responses to the surveys suggest that a more balanced approach including both incentives and disincentives is a better approach and enhances partnering (*42*). Other conclusions from the synthesis are the following: 1) that evidence suggests that PBMCs result in better outcomes at lower cost with less risk and more financial predictability for highway agencies; 2) PBMCs are more likely to succeed when both risks and rewards are shared between the contracting agency and the contractor; and 3) many performance-based maintenance contracts are hybrids and include performance and method specifications, payments based on both lump-sum and unit prices, maintenance and rehabilitation work, and different phases of a facility (assets) life (*42*).

The DNER of Brazil, the equivalent of the DOT in the United States, had to terminate performance-based contracts due to the high bidding prices (*43*). The DNER anticipated much lower proposals and chose not to carry out the contracts. According to studies, these unexpected high amounts are attributed to the high risk perceived by the bidders that the government might not pay them fully for their services. A more balanced distribution of risk might have been a solution for this particular case.

The United States is not exempt from disappointing performance-based contracts. In 2001, the Oklahoma Department of Transportation decided to enter into two lump-sum PBC contracts with periods of 5 years renewed each year with a combined value of approximately $36 million. The contracts focused on the maintenance of five counties in the Tulsa and Oklahoma City areas. Approximately 7 months after the contracts were awarded, the contracts were canceled. Upon post-ante-analysis experts suggested that the main reason for the termination of the contractual agreement was defects in the contract itself. The ambiguity in some parts of the document, especially the ones regarding the performance requirements, triggered actions that resulted in discomfort from both sides, which resulted in the cessation of work from the contractors (*44*).

Benefits, Costs, and Risks

There is a tradeoff between risk/responsibility and construction/design flexibility, in other words, contractual responsibility implies flexibility. One of the key concepts in application of performance specifications through appropriate delivery methods is the tradeoff between the risk to contractors and flexibility to make design and construction decisions. This implies that the more an agency moves toward prescriptive methods, the contractors should bear less risk, and vice versa. The fundamental axiom of risk management states that the risk should be allocated to the entity that is able to control it. Failure to follow this axiom leads to increased costs.

The tradeoff between project cost and project quality mandates a positive correlation between the level of responsibility/risk and the level of control over design. For example, if contractors are given too much design freedom without the responsibility, the facility may experience lower quality as the contractors are not incentivized to provide a higher quality product. On the other hand, if contractors are assigned too much risk without having control over the design, they will price this non-controllable risk accordingly. Note that non-controllable risks are always overpriced.

The benefits from using performance-based specifications come from four different sources: 1) inefficient budgeting, or lack of efficient resource allocation in the public sector; 2) quality control enforcement, or poor quality control mechanisms; 3) opportunity for innovation, or lack of innovation incentive and general risk averseness of the agencies' project executives; and 4) objectives misalignment, or lack of uniformity of project objectives across the stakeholders. To fully utilize the savings from inefficient budgeting and innovation, it is essential that the performance-based contracts are long-term. Both better budgeting efficiency and innovation cannot produce significant payoffs if the contract time period is short. In other words, only longer term contracts provide efficiency. This is also true from the perspective of the project size. Only larger size projects can produce significant savings that can be passed to the owner. It is important to note that agencies can bundle projects together to achieve the needed size as in the case of pavement markings and markers contracts.

While performance specifications provide opportunity for savings, they are also associated with increased cost—higher bids. This cost increase comes from added performance premiums. As contractors are liable for performance, they will price this risk. Risk can be typically divided into two large categories, that is, supply and demand. For highway facilities, supply risks relate to premature failure, while demand risks relate to excessive loading. Short-term warranties are typically used to cover against premature failure, while design-build-maintain (DBM) delivery methods under performance specs provide full protection including the protection against demand risks. However, there is an upside risk potential (opportunity) in DBM contracts. The contractors can engage in stage-based construction to act once the uncertainty in future traffic loading is resolved. This can be a substantial source of savings. Note also that risks can be further decoupled by specifying warranties on utilization volume (traffic count) rather than on time period.

Performance-based contracts are lump sum contracts. Hence, there is a significant risk of increased bid prices if the agency does not provide enough information to describe the current condition so that the contractors can develop reliable scopes and projections of future performance. Uncertainty implies risk, which in turn inflates the prices.

CHAPTER 3: STATEWIDE SURVEY

The topic areas discussed in this chapter are the results of the pavement marking survey that was distributed to each TxDOT district and the outcome of the meetings held with the two districts utilizing performance-based pavement marking maintenance contracts.

DISTRICT-WIDE PAVEMENT MARKING SURVEY

One of the first steps used to determine the effectiveness of PBPMMCs was to survey each TxDOT district to learn more about their pavement marking practices. The goal of the survey was to collect as much information as possible about all aspects of the pavement marking practices of each district. This information would then be combined to further the understanding of TxDOT's pavement marking practices and be used in several other areas of this research project.

The research team designed a survey questionnaire to cover all areas of pavement markings from planning and contracting, to costs, quantities, and inspection. The draft survey was reviewed by the project panel and revised prior to distribution. The survey was distributed to each district via e-mail. The e-mail requested participation in the survey by one of three means: 1) telephone interview, 2) e-mail questionnaire, or 3) web-based questionnaire. Attached to the e-mail was the questionnaire containing all of the survey questions that could be reviewed prior to participating in the survey. The e-mail also contained a link for the web-based questionnaire and the research team's contact information for the phone survey. The final survey can be found in Appendix A.

The survey was distributed to at least one person in each district. Typically, researchers sent two people the survey to hopefully increase the response rate. In general, the survey was distributed to the director of operations/traffic operations, and/or the director of maintenance at each district. The survey was also distributed to district personnel who were known to have knowledge of the district's pavement marking practices.

Request for participation in the survey occurred three times. There was approximately 1 month allowed for response prior to redistributing the survey to the non-responding districts. In total 15 districts responded to the survey questionnaire. Of the 15 responses, 3 were only partially filled out resulting in a limited set of collected information. About half of the responses were through the web-based survey and the other half through the e-mail questionnaire. There were separate on-site interviews with the San Antonio and Dallas Districts to obtain detailed information about their PBPMMCs; therefore, a response to the survey was not needed from these districts. Figure 2 provides a map showing the location of the responding districts. The survey questions and responses will be discussed in the following sections.

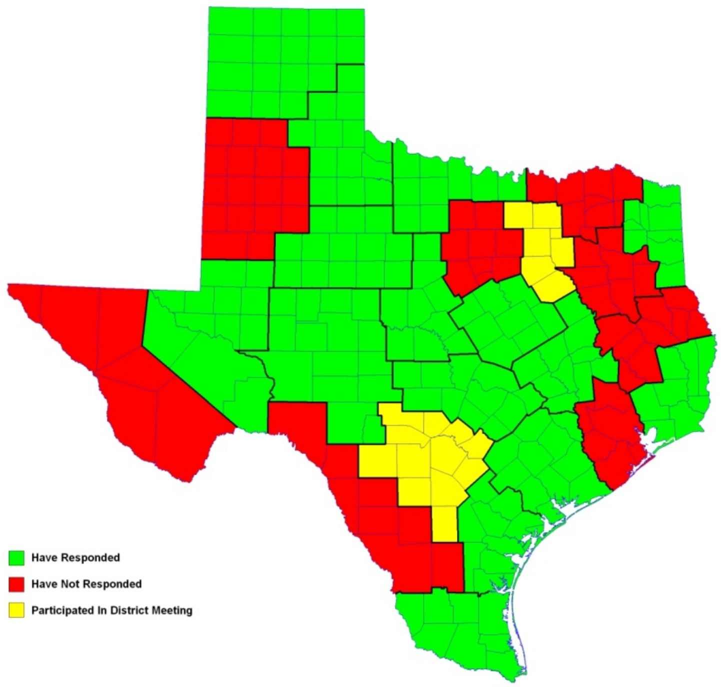

Figure 2. TxDOT Survey Response.

District Contracting

The first part of the survey gathered information about how the districts handle contracting of pavement markings and markers. The first questions asked which types of pavement marking contracts had been used by the district. Most of the districts used a combination of annual district-wide, on-call, and individual projects or roads as their contracting types (see Figure 3). Of the responding districts 85 percent indicated they had used more than one type in the past. When asked of a preference toward a specific type of contracts, on-call contracts seemed to be preferred due to the easiness of use. It was noted by some respondents that all contracting types had their own special purposes, therefore none were really preferred over another.

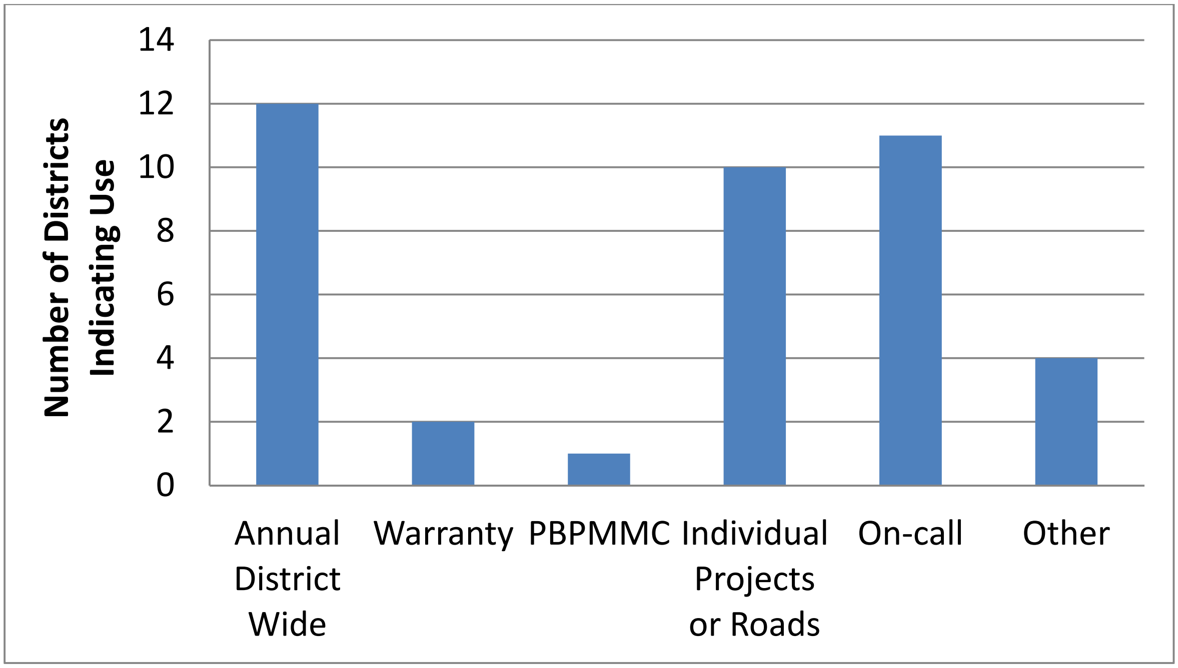

Figure 3. Types of Pavement Marking Contracts.

When asked if long and short lines are contracted together, 57 percent of the responding districts indicated they were contracted together, 29 percent indicated they are contracted sometimes together sometimes separate, and 14 percent indicated they are contracted separately. When asked if markers and markings were bid together or in separate contracts, 53 percent of the responding districts indicated they are contracted sometimes together sometimes separate, 27 percent indicated they are contracted separately, and 20 percent indicated they were contracted together. When asked if center and edge lines on a road are replaced at the same time (within the same striping season), 67 percent of the responding districts indicated that most of the time they are replaced at the same time, 20 percent indicated they are always replaced at the same time, and 13 percent indicated that they are sometimes replaced together.

When asked if any of the contracts include incentive/penalty clauses, 2 of the 15 respondents indicated that they were included. A penalty would be assessed for liquidated damages if the contract is not completed on time. Of the 13 districts not using incentive/penalty clauses, three districts replied incentive/penalty clauses may be beneficial, two districts replied it may not be beneficial, and the rest did not know or did not respond. When asked who makes the decision on pavement marking material to be applied, all 15 respondents indicated that TxDOT was the decision-maker for pavement marking type.

District Pavement Marking Information

The second part of the survey gathered information about the cost, quantity, and management of the district's pavement markings and markers. The first question asked about the total cost of pavement markings for the district over the last several years. The question also asked what materials were applied, how many miles were striped, and what the contracting mechanism was for the work. Table 6 shows the summary of total annual pavement marking costs and quantities collected from 12 of the responding districts. The districts are not specifically identified in this section, as it is not necessary for the summary of the survey.

From Table 6 it is evident there is a wide range of annual cost for pavement marking application. Not all of the responding districts included material quantities or the associated material type that was applied, but enough were included to help gain an understanding of the unit costs for the various districts. The costs and quantities summarized in Table 6 cover all of the marking material types installed in each district.

Table 6. Total Annual Pavement Marking Costs and Quantities.

Respondent	Year, Cost ($), Quantity (miles)						Average Annual Cost
	2007	2008	2009	2010	2011	2012	
1	-	-	-	-	$1,123,800 (795)	-	$1,123,800
2	-	$2,100,000 (490)	$900,000 (470)	$750,000 (300)	$2,040,000 (453)	-	$1,447,500
3	-	-	$1,298,997 (472)	$1,810,448 (722)	$1,567,855 (190)	$334,761 (140)	$1,253,015
4	-	$450,000 (100)	$2,806,000 (556)	$670,000 (200)	$940,000 (300)	$994,000 (300)	$1,172,000
5	$1,349,777 (1306)	$1,108,618 (1226)	$845,153 (884)	$613,576 (657)	$985,391 (993)	-	$980,503
6	$1,589,504 (1818)	$2,234,614 (3076)	$1,348,014 (1636)	$1,769,893 (2044)	$1,589,504 (1818)	-	$1,706,306
7	$207,619	$306,823	$27,615	$63,700	$73,287	-	$135,809
8	$2,000,000	$2,000,000	$2,000,000	$2,000,000	$2,000,000	-	$2,000,000
9	-	-	-	-	$1,193,474	-	$1,193,474
10	-	$901,952 (321)	$576,311 (191)	$133,018 (27)	$363,490 (204)	$770,640 (280)	$549,082
11	$3,000,000	$3,000,000	$3,000,000	$3,000,000	$3,000,000	-	$3,000,000
12	$2,724,372	$2,355,565	$1,518,957	$1,607,832	$1,788,974	-	$1,999,140

Table 7 and Figure 4 provide a summary of the types of pavement marking materials used by each responding district. From Table 7 it is clear that most districts use more than one type of pavement marking material to suit their various needs. Waterborne paint and sprayed thermoplastic were the two most popular, as shown in Figure 4. All the responding districts use sprayed thermoplastic. The three districts responding to the other category all indicated the use of prefabricated thermoplastic markings for stop bars, cross walks, and symbols. Each of these different pavement marking materials have varying costs and life expectancies. The performance of the markings throughout their life also varies by the marking material type and the quality of the marking installation. Selecting the most appropriate pavement marking material considering roadway conditions, cost, life expectancy, and performance can be a daunting task. The use of various pavement marking materials within a single district may be the best way to maximize cost-effectiveness for various situations.

Table 7. Types of Striping Materials Used in the Texas Districts.

Respondent	Water-borne Paint	High-Build Paint	Sprayed Thermo-plastic	Extruded Thermo-plastic	Tape	Epoxy/ Polyurea/ Other Multi-Polymer Plural Component	Other
1	X		X				
2	X		X		X		
3		X	X	X	X		
4			X				X
5	X		X				
6	X		X			X	
7	X		X				
8			X	X			X
9	X		X				
10			X				
11			X				
12	X		X			X	
13	X		X		X	X	X

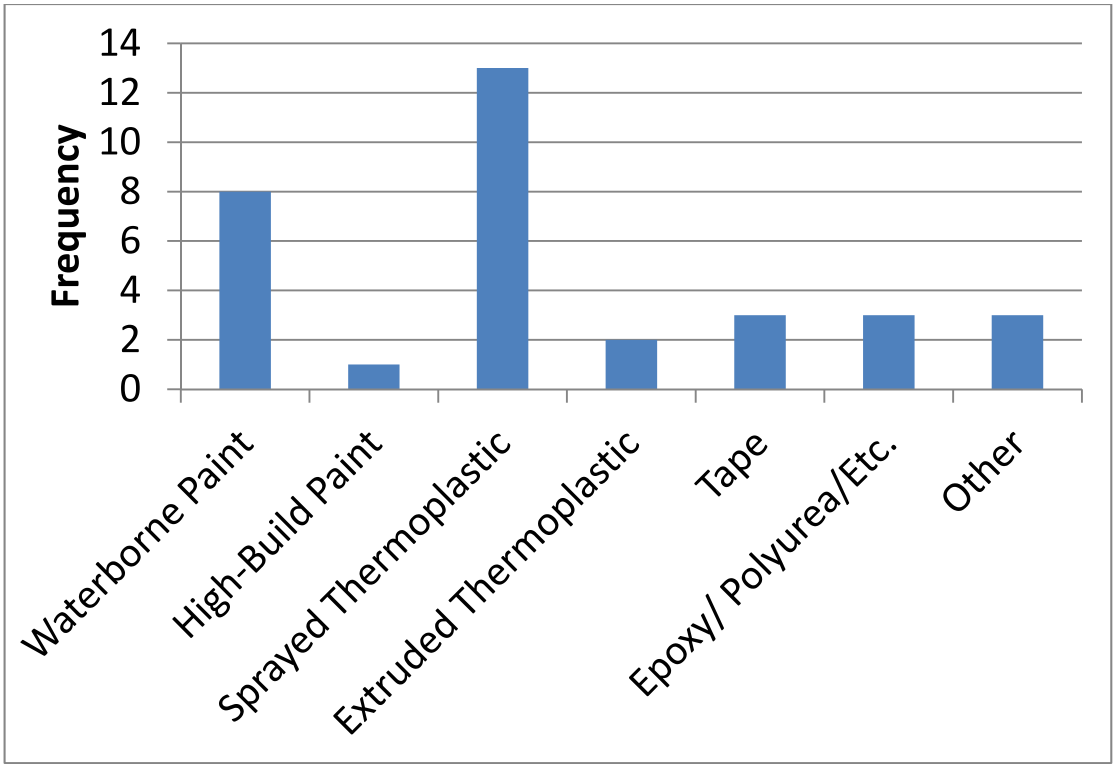

Figure 4. Frequency of Striping Material Usages from the Texas Districts.

Table 8 shows the summary of annual pavement marker costs and the average number of markers installed each year for the nine districts responding to this question. The costs per year are dependent on the amount and type of pavement marker work contracted. The cost of the markers along with the cost of the markings make up the majority of the costs associated with maintenance of markings and markers. Using this information along with other information about the districts from the survey will allow researchers to better understand which districts may be able to benefit from utilization of PBPMMCs.

Table 8. Total Annual Pavement Marker Costs.

Respondent	2007	2008	2009	2010	2011	2012	Average Annual Cost	Average Number of Markers Replaced per Year
1	-	-	-	$280,244	$277,223	$285,726	$281,064	169,899
2	-	$72,500	$96,000	$97,500	$119,000	$370,000	$151,000	47,200
3	$159,521	$2,977	$215,604	$82,383	-	-	$115,121	30,114
4	$394,384	$656,870	$540,108	$378,347	$397,513	-	$473,444	170,427
5	$300,000	$300,000	$300,000	$300,000	$300,000	-	$300,000	100,000
6	-	-	-	-	$100,000	-	$100,000	30,000
7	-	$67,928	$55,103	-	$14,935	$42,112	$45,020	17,402
8	$280,000	$280,000	$280,000	$280,000	$280,000	-	$280,000	130,000
9	$273,829	$284,812	$175,362	$227,472	$122,541	-	$216,803	71,368

To better understand the number of miles of striping in each district, the survey asked for the number of centerline miles and lane miles of roadway that each district maintains. Figure 5 provides a graphical summary of the response from the 11 responding districts. This information coupled with the quantity of markings and markers applied annually will allow researchers to better understand the frequency of maintenance of these traffic control devices. This information will also allow the researchers to see what percent of district roadways are receiving new markings or markers each year. This information can be compared to the frequency of maintenance and quantity of new materials applied annually in districts utilizing PBPMMCs.

When asked if the district keeps maintenance logs of last restriping/marking of roads, about 60 percent of the responding districts answered yes, while about 40 percent of the districts responded no. The survey participants were asked what the burden (time and effort) on the district was as far as managing their pavement marking/marker assets. The responses varied for this open-ended question depending on how the respondent interpreted what was being asked. Table 9 provides the responses to the question. These comments can be compared with the comments on the burden of a PBPMMC (topic of discussion during meeting with PBPMMC districts) to see if the burden on TxDOT is changed as far as managing the contract or managing the assets.

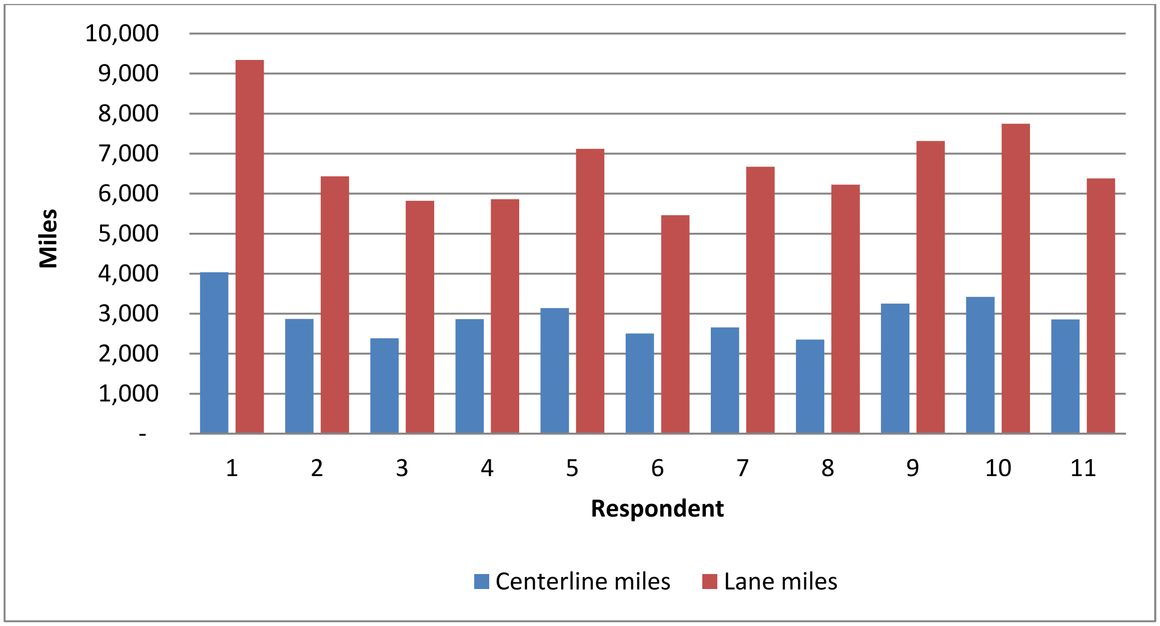

Figure 5. Roadway Miles Maintained by the Districts.

Table 9. Burden (Time and Effort) Managing Marking/Marker Assets.

Response
About 150 hours of field work and 160 hours of plan prep and management
Two employees in Traffic Engineering 40%, and 4-man crew in our special jobs section 20%
Getting contractor to start and finish contract on time
Area office record keeper and one full time inspector
Keeping up with the pavement markings that have been removed or covered up
Maintenance Supervisors add the management of the pavement marking/markers to their 3-year maintenance plan
One full-time inspector for each specific contract
500 man-hours
It takes a great deal of time to put together the contracts and administer them. We let a retroreflectivity contract each year to determine what our needs are for the following year. I have 2 inspectors that spend the majority of their time inspecting our maintenance contract and seal coat contract striping each year.
We have multiple people working on it during the year. It will probably equal 2 FTEs during the year.

District Pavement Marking Performance and Inspection

The third part of the survey gathered information about the performance, evaluation, and inspection of the district's pavement markings and markers. The respondents were asked to indicate which performance measures their district used to evaluate pavement markings. The respondents were also asked to rank order of the performance measures if they selected more than one. The responding districts indicated that general visual inspections (day/night) are used with high importance, followed by handheld retroreflectivity and mobile retroreflectivity measurements (see Table 10). The presence and color of the markings as a performance measure were used slightly less. Some districts indicated that they are not using mobile retroreflectivity or handheld retroreflectivity measurements at all. This may be due to a lack of access to the equipment by district personnel and/or not contracting retroreflectivity measurements.

Table 10. Performance Measures of the Pavement Markings and Their Ranks of Importance.

Performance Measure	Rank 1 (Most Important)	Rank 2	Rank 3	Rank 4	Not Used
Handheld Retroreflectivity	4	2	1	0	1
Mobile Retroreflectivity	4	0	1	0	3
Presence	3	0	2	2	0
Color	3	0	2	2	1
General Visual Appearance (Day)	5	3	2	2	0
General Visual Appearance (Night)	6	3	2	1	0
Other	0	1	0	0	0

The next question asked about the district's expectations of the markings' initial retroreflectivity and service life. The responding districts indicated varied expectations based on color, material, and locations where the markings are installed. Overall, the initial retroreflectivity of yellow waterborne markings are expected to be 100 mdc/m^2/lux, while yellow thermoplastic markings range from 175 to 250 mdc/m^2/lux. White markings are expected to have higher initial retro values than yellow markings. Initial retroreflectivity values for white waterborne markings are expected to be 175 mdc/m^2/lux, and white thermoplastic markings range from 250 to 350 mdc/m^2/lux. Several respondents indicated the markings just need to meet the specifications used as far as retroreflectivity is concerned. The expected service life of waterborne markings is expected to range from 12–24 months while thermoplastic markings range from 36–60 months. It was indicated that tape markings can have a warranty for up to 60 months, and the expected life of high-build waterborne paint is up to 36 months.

When asked what happens if newly applied markings do not meet the required specifications, all the districts responded that they require the contractor to replace the markings at the contractor's expense. The respondents also indicated that, on average, 2 percent (from 0 to 5 percent) of the new markings do not meet the initial requirements.

Regarding inspectors' presence during marking installation, the districts indicated that approximately 70 percent of the time new markings are applied with the presence of an inspector. Figure 6 provides detailed information in terms of number of responses from the districts for each percentage group of miles. The respondents indicated that the inspectors check for many things prior to, during, and after the installation of the pavement markings. The inspectors check retroreflectivity, thickness and width of materials, alignments, visual appearance, uniformity, bead distributions, quantity of beads, speed of application, and application temperatures.

The respondents were asked how their district determines when to restripe a roadway. Most districts indicated the use of visual (day and night) inspections (see Table 11). In addition to the visual inspection, several respondents also indicated the use of mobile or handheld retroreflectometers. Two respondents indicated the use of predetermined striping cycles. One respondent indicated available funding also plays a role in the quantity of roads that can be restriped. Similarly, researchers asked the respondents how their districts determine when their roadways need new markers. Again, most districts indicated the use of visual inspections to determine the need for marker replacement. Four respondents indicated the use of predetermined cycles for marker replacement. Three respondents also indicated that winter weather activities may require the placement of new markers. One respondent indicated available funding also plays a role in determining what roadways can get new markers.

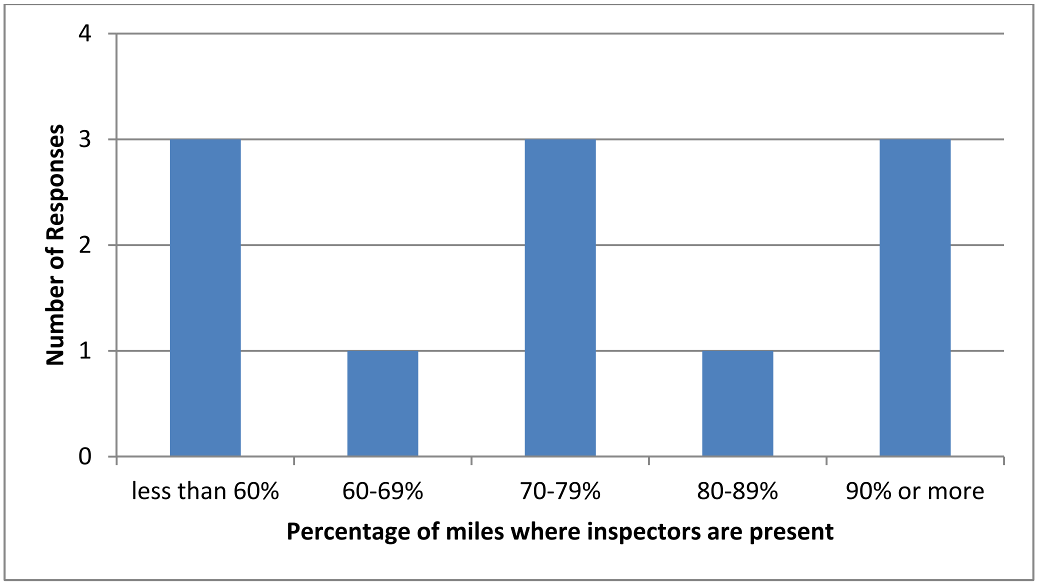

Figure 6. Percentage of Miles Where Inspectors Are Present for Marking Application.

Table 11. Methods for Determining Roadway Restriping.

Respondent	Predetermined Cycle	Handheld Retro-reflectivity Measurements	Mobile Retro-reflectivity Measurements	Day Visual Inspection	Night Visual Inspection
1			X		
2				X	X
3			X	X	X
4	X	X		X	X
5		X		X	X
6				X	X
7	X	X		X	X
8				X	X
9				X	X
10				X	X
11			X	X	X

When asked if their district has contracted mobile retroreflectivity measurements to help in determining which roads to restripe, three of the 12 respondents answered yes. One respondent indicated that all roads except those receiving new markings or a new seal coat that year were measured under a mobile retroreflectivity contract. Another respondent indicated that mobile retroreflectivity measurements were used to help with nighttime inspections and that the program would be expanded to include all roads. The mobile retroreflectivity data were also measured at night so that video of the data collection could be reviewed to determine the presence of pavement markers. The third respondent indicated that contracts have been let for mobile retroreflectivity measurements the last few years and that they are used to help determine which roads to restripe.

PBPMMC-Specific Questions

The fourth part of the survey asked specific questions about the current, past, and future usage of PBPMMCs. Each responding district indicated it had not used a PBPMMC in the past and that they are not currently using one. Each responding district also answered that they are not currently considering using a PBPMMC. There were several responses as to why they are not currently considering the use of a PBPMMC. These responses mostly indicated they were happy with the performance of their current methods and that the cost of a PBPMMC may be prohibitive.

MEETINGS WITH THE PBPMMC DISTRICTS

In addition to distributing the survey to each district, the research team met with the Dallas and San Antonio Districts. These two districts were unique compared to the other districts in that each was utilizing a PBPMMC. The research team asked a series of questions about the PBPMMC to the district personnel that were at the meetings. The research team also had a list of requested information that was sought from each district that would be of use to the research project. The meetings with the two districts utilizing the PBPMMCs are described in this section.

Several members of the research team participated in the meetings with each district. The districts were represented by personnel who regularly took part in managing the contract or carrying out work required in the contract. These representatives provided direct insight as to how the contracts are handled and the positives and negatives that TxDOT has experienced. The general questions/topics for discussion with the districts were as follows:

- Why decide to implement the PBPMMC in the first place?
- How was the contract designed, and how were the evaluation and performance criteria set?
- Why was the contract set for only certain areas and for the length of time in the contract?
- How many bids were received?

- Did the assessment ever fall below 3, resulting in a lower payment to the contractor? If so, how often, total penalties?
- Performance evaluation/inspection process:
  - Who does performance evaluations/inspections? What is the frequency? Random inspection or planned inspection (known section(s) and time periods)?
  - Is the performance evaluation or inspection process more or less burdensome than standard contracts?
    - Is any inspection conducted at the time of installation, or just performance evaluations on all markings at fixed time intervals?
    - Any noticeable difference in marking quality from markings installed under the PBPMMC vs., standard contracts?
- Is there any concern regarding the type of material used by the contractor in the last year of the contract?
- If the district decided to go back to traditional contract types, is there any concern about the old marking removal/restriping preparation cost if markings are incompatible?
- What are some areas within the contract that could use improvement?

Each of these questions/topics for discussion resulted in additional questions relating to the responses. The responses from TxDOT were recorded and later summarized. In addition to the discussion, the research team also requested information from each district. This information is critical to the research project as it will allow the research team to evaluate the costs and benefits of the contract. The requested information from the districts was as follows:

- Copy of executed contract.
- Copies of all bids.
- Copies of monthly work logs (activity reports).
- Copies of performance data collected by the contractor and DOT.
- Copies of annual striping plans.
- Copies of annual expenses.
- Copies of work plans.
- Information on district pavement marking contracting prior to and during the PBPMMC.

San Antonio District Meeting

The San Antonio (SAT) District meeting was the first of the two district meetings. San Antonio was unique in that it had recently finished a 5-year PBPMMC and was just starting its second PBPMMC. The meeting went well, with the district personnel and research team engaging in a productive dialogue exchange. The district was able to answer most of the questions and respond to the varying topics of discussion. At the time of the meeting, the district had some of the requested information available and provided it to the research team. Subsequent e-mail exchanges with the district yielded the rest of the requested information. A summary of bulleted points from the meeting is provided below.

Overview

- Two PBPMMCs have been implemented in SAT so far.
- SAT District uses mostly thermo and some tapes.
- Would like to have a better understanding of the shared risks and benefits of this type of contracting mechanism.
- Tried a total maintenance contract years ago and ended it quickly.
- Generally $4–5 million in markings for the district.
  - 1st PBPMMC was $24 million for three counties for five years.
  - 2nd PBPMMC was $14 million for one county for three years, rest of the counties $1.3 million per year.
  - Majority of the district's work is in Bexar County, which is in both contracts.

First Contract

- Five years covering three counties (Bexar, Guadalupe, and Comal).
- Allowed one year without deduct to bring the markings up to standard. This was too long, it was reduced to three months for the second contract, which may have been to short based on the initial condition of the markings.
- Not renewed in the 5th year. The contractor was notified the 2-year extension would not be implemented.
- In the first four months, TxDOT still needed to tell the contractor what to do.

- Requires personnel who understand striping work to do scheduling.
- Problems with scheduling too many major roads at the same time.
- No dedicated resource/guidance for scheduling work.
- Deducts occurred for performance deficiencies more than 70% of the time (condition rating < 3.0).
- Most deducts based on marker performance.
- Callout work was awarded as part of the PBPMMC. Callout work was paid additional money. TxDOT felt the contractor prioritized the callout work over what was required in the PBPMMC.
- District felt the markings were in no better shape after the first contract than when it started.
- District calculated approximately $4.5 million more paid for PBPMMC based on work done vs. work at standard prices.
- Dissatisfied with markings in the final year, paint applied over thermo.

Second Contract

- Reduced to three years and includes only Bexar County. The shorter contract allows TxDOT to get out of the contract sooner if they are not happy with it. Only one county because it is easier to manage, greatly reduced costs, and most of the work is in this county anyway.
- Criteria in new contract set to get better product. Higher minimum retroreflectivity levels, and stripe with 30-days where needed.
- Marker failure level reduced from 50 percent to 20 percent missing at the time of evaluation.
- Estimated work—All roads in Bexar County striped at least once during the contract. May be more on high-volume roads.
- Need to provide readings within 30 days.
- Deduct could have been assessed the first three months of the new contract as the assessments were below three, deducts were assessed months four and five as the markings and markers were not up to the required specifications.

- Decided to not allow Type II markings (paint) on high- exposure roads.
- Did away with low-exposure roads.
- Marker installation was subbed out by the contractor.

TxDOT Burden and Needs

- Data: readings, condition assessment, quarterly reports. Lots of paperwork associated with the contract and daily activities.
- Amount of work required from TxDOT personnel at the beginning of the contract is about 50% of the day.
- More burdensome for assessments, but less burdensome for installation inspection.
- Conducted some day assessments to make sure work was done and to check quantities reported.
- Need to have the submitted data in a more usable format—useful for planning work and verify public complaints. Retroreflectivity readings and condition assessments were pretty much unusable. The amount of data was a nightmare. The old specification for data collection hurt data quality when submitted (original PBPMMC was bid using the old mobile retroreflectivity specification).
- It is difficult to address public complaints with PBPMMC. Lots of negative comments about markings/markers during first contract.
- TxDOT currently feels that deduct is not severe enough. The contractor would chance failed sections not being part of the random sampling as the cost to replace outweighed the chance it would be assessed and the deduct they would face.
- Need to get after contractor to put down stripes.
- Need a dedicated inspector for PBPMMC.
- Typical budget for markings: $4–$5 million a year for the district.
- Estimated cost: $1960/lane-mile/year for the first contract.
- Random sampling five percent of the road for assessment conducted at night using visual assessment only.
- Assessment takes 8–10 hours for Bexar County and 16 hours for all 3 counties.
- Two-person crew is needed for inspection.

- No lane rental fee charged for either contract.
- Rural work is more manageable and predictable. PBPMMC seems to be better suited for urban areas where there are uncertainties, high traffic volumes, and variable product life.

Suggested Improvements

- TxDOT feels that the contractor does a better job and is more responsive in the second contract.
- The next PBC should raise the standards, be more specific, shorten the time required before assessing deducts (some implemented in 2nd contract).
- Higher deducts for poor performance.
- No water-based paint on high-exposure roads (implemented in 2nd contract).
- Feel they can get a better product with a traditional contract. They can control the work and inspect application better. Retro readings can be contracted separately.

Dallas District Meeting

The Dallas District meeting was the second of the two district meetings. The Dallas District was half way through their first PBPMMC at the time of the meeting. The meeting went well, with the district personnel and research team engaging in a productive dialogue exchange. The district was able to answer most of the questions and respond to the varying topics of discussion. Questions that were not answered during the meeting were answered through e-mail after the meeting. At the time of the meeting, the district had some of the requested information available and provided it to the research team. Subsequent e-mail exchanges and an additional visit to the district yielded the rest of the requested information in electronic format. A summary of bulleted points from the meeting is provided below.

General Comments

- Used the San Antonio contract as a starting point and made some revisions to it to suit their needs and conditions. They have plowing and more wintery conditions compared to San Antonio.
- At the time of the meeting, 2.5 years into the 5-year contract.

- Received five bids on the contract.
- Mostly thermoplastic pavement markings applied.
- Do not like epoxy because of the thickness (20–30 mils), incompatible with thermo, and poor performance when wet. Good on concrete though.

Why PBPMMC?

- No time and resource to monitor the current striping and quality of contractor's work.
- To minimize complaints from the public.
- PBPMMC requires less workforce and staff time to monitor stripes.
- To maintain minimum retro levels, they wanted markings that were always at an acceptable level.
- Innovative technique to try, so they started with just 1 county.

Contract Changes from SAT's PBPMMC.

- Percent of lane miles that need to be restriped.
- Minimum retro requirement in the first year.
- The way the contractor is bonded is different.
- Special Provision 7465-001: Minimum work required for first six months—100 miles for high-exposure roads and 50 miles for medium-exposure roads (must meet the above monthly values averaged over two consecutive months).
    - Allows for some flexibility in wintertime (difficult to put down markings).

Contract Information

- Charge lane rental fee only if the work is performed outside the time window. Never had to though.
- Next contract may include Collin and Denton Counties. Dallas County selected for the initial test because it is the hardest for striping.
- May renew the current contract, but working on new contract including the other two counties.

- The contractor is unhappy with the bond requirement. The longer period will tie up the bond longer, thus restricting the capacity of the contractor to bid on other projects.
- Not much inspection during marking install, the only inspection is the random monthly assessments.
- Sampling five percent of roadways for assessment. If the samples fall within the construction project, then move to adjacent segments. If no adjacent segment is available, then use alternate.
- Currently relies only on visual inspection. Call contractor if there is a concern to get a handheld retro.
- Assessment penalty fee probably not enough.
- The contractor has been very accommodating to requests.
- The contractor is given 14 days to keep up with the callout work. The contractor does well in general (missing the 14-day window only once so far). Callout work is moved into the striping schedule as it arises.
- Feels that PBPMMC is more burdensome or at least the same as traditional contract, because it requires more attention, but they are hoping for better results.
- No Type II (paint) is allowed and therefore less concern in the final year of the contract.

Suggested Changes for the Next PBPMMC

- Change the amount of time required for the contractor to keep all the marking up to the standard (prefer one year). Currently three years and start deducting after one year.
- Would like to have the option to stop payment if not up to the standard by year three.
- Better reporting of intersection production.
- Contractor deals with line-miles rather than lane-miles so change from lane-miles to line-miles.

Other Comments

- Do not require the contractor to enter operational modification/callout work in the maintenance management information system (MMIS). Currently launching new function code for entering PB information in the MMIS.
- The annual cost of markings to TxDOT before PBPMMC is less than with PBPMMC.
- When the contract started ¾ of striping was below standard.
- The contractor has elected to spread out the work over the first three years to get the markings up to standard when required. The contractor did this instead of getting all the markings up to standard in the first year and avoiding possible penalties.

SUMMARY

This chapter described the distribution of a survey on pavement marking practices to each TxDOT district and two meetings conducted with districts currently utilizing a PBPMMC. The district meetings yielded many comments on the pros and cons of their PBPMMCs. The district meetings also yielded a large quantity of cost and production data pertaining to the PBPMMCs. This information coupled with the district discussions and the survey responses provided much of the information needed for the rest of the work on this project.

CHAPTER 4: SAFETY EVALUATION

This chapter presents the results of the safety evaluation to assess the safety performance of roadways under performance-based pavement marking maintenance contracts. These contracts have stipulated retroreflectivity and presence requirements that the contractor should maintain for existing and new markings/markers. This type of contract is considered relatively new as opposed to traditional pavement-marking contracting mechanisms. The agency will generally sample a percentage (e.g., 5 percent) of centerline miles under contract to conduct a performance assessment. The assessment process will produce a monthly score that will then be used in a formula which determines actual monthly payment to the contractor. This type of contract may include a no-penalty period in the initial year of the contract for the contractor to bring the markings up to the required conditions. At the time of this research, the San Antonio and Dallas Districts are the two districts within TxDOT that have issued PBPMMCs. Crash data gathered from these two districts before and after the implementation of PBPMMCs were used to evaluate the safety effectiveness of such contracts.

A before-after study with a comparison group defined as “crashes that occurred during daytime conditions” was used to evaluate the safety performance of the contracts. This practice is based on the premise that retroreflectivity levels of pavement markings may correlate with crash potential. This type of target crashes was also used in previous studies by Bahar et al. (*11*) and Smadi et al. (*12*). The comparison group method attempts to consider unrecognized factors, which cannot be modeled easily. The key assumption for comparison group methodologies is that the ratio of before-to-after target crashes is the same for treatment and comparison groups (in the absence of the treatment). This suggests that unobserved changes, such as driving population, traffic, weather, etc., affect the target crashes in the same way as crashes in the comparison group.

This chapter consists of three parts. The first part describes the methodology used for safety analysis. The second part documents the procedure for the development of the database. The third part presents the modeling results and summarizes the analysis findings.

METHODOLOGY

Crash frequency counts on roadway segments were combined within each control section to determine the effectiveness that the PBPMMCs had on safety within the Dallas and San Antonio Districts. The two districts were also combined in order to develop an overall estimate of safety effectiveness of the contracts.

Step 1. Define the Target Crashes

The "target" crashes were used as the absolute measure of safety. The target crashes are defined as those types of crashes that are likely influenced by poor pavement marking visibility (e.g., non-intersection non-daylight crashes). The team combined the findings from a comprehensive literature review and our expertise with Texas crash databases to form a viable definition of target crashes that was used to assess the safety performance of PBPMMCs. In general, the target crashes include: 1) collision with fixed object such as bridge/bridge rails/overpass, underpass/structure support, culvert, ditch/embankment, curb/island/raised median, guardrail, concrete barrier (median or right side), tree, poles (utility, light, etc.), sign post, mailbox, impact attenuator, other fixed object; 2) non-collision events: overturn/rollover, jackknife, other non-collision; and 3) collision with parked motor vehicle.

Table 12 shows the criteria of target crashes used in this study.

Table 12. Criteria of Target Crash Selection.

Variable	Filtered by
Intersection-related	Non-intersection Non-driveway
Lighting condition	Dark
Surface condition	Dry
Collision type	Single vehicle run-off-the-road Head-on
Harmful event	No pedestrian No train No pedacyclist No animal

Step 2. Define the Comparison Group

The comparison group represents those crashes that are not associated with pavement marking retroreflectivity. The purpose of the comparison group is to estimate the change in crash frequency that would have occurred at the sites if they were not maintained under PBPMMCs. This is because the markings would be visible during daytime regardless of retroreflectivity levels. Each of the following incidents describes crashes that are not associated with poor pavement visibility, even though the crash may still fit the above-mentioned criteria.

- Driver's alcohol or drug use.
- Carelessness, fatigue.
- Defective equipment.
- Lost control due to shifting load.
- Skidding.

Step 3. Predict the Expected Number of Crashes and Variances for the After Period

Predicting expected crashes and variances in the after period is necessary in order to account for influences that affect safety other than the treatment itself. Since other factors may cause an effect, predicting after-period crash frequency and variances that are either not measured or produce an influence on safety, the factors must be considered. The analytical procedure used in this study was described in detail by Hauer (*45*). The expected number of after-period crashes and their variances for site *i* (note: site *i* represents a group of roadway segments on a control section) had the treatment not been implemented at the treated site is given as:

$$\hat{\pi} = \hat{r}_T K \text{ and } V\hat{A}R(\hat{\pi}) = \hat{\pi}^2\left(1/K + V\hat{A}R\{\hat{r}_T\}/r_T{}^2\right) \quad (2)$$

$$\text{with, } \hat{r}_T = (N/M)/(1+1/M) \text{ and } V\hat{A}R\{\hat{r}_T\}/r_T{}^2 \cong 1/M + 1/N$$

where,

K = Total crash counts during the before period in treated group.

M = Total crash counts during the before period in comparison group.

N = Total crash counts during the after period in comparison group.

If there were no crashes (zero) recorded on a control section in either a treatment or comparison group, then an adjustment factor of 0.5 crashes was evenly made within the control section.

Step 4. Compute the Sum of the Predicted Crashes over All Treated Sites and Its Variance

It is widely recognized that the safety effect of a treatment varies from one site to another. Thus, instead of a single site, the average safety effect of the treatment for a group of sites must be calculated. To account for this, the expected number of after-period crashes and their variances for a group of sites had the treatment not been implemented at the treated sites is given as:

$$\hat{\pi} = \sum_{i=1}^{N} \hat{\pi}_i \text{ and } Var(\hat{\pi}) = \sum_{i=1}^{N} Var(\hat{\pi}_i) \tag{3}$$

where,

N = Total number of sites in the treatment group.

$\hat{\pi}$ = The expected after-period crashes at all treated sites had there been no treatment.

Step 5. Compute the Sum of the Actual Crashes over All Treated Sites

For a treated site, crashes in the after period are influenced by the implementation of the treatment. The safety effectiveness of a treatment is known by comparing the actual crashes with the treatment to the expected crashes without the treatment. The actual number of after-period crashes for a group of treated sites is given as:

$$\hat{\lambda} = \sum_{i=1}^{N} L_i \tag{4}$$

where,

L_i = Total crash counts during the after period at site *i*.

Step 6. Compute the Unbiased Estimate of Safety-Effectiveness of the Treatment and Its Variance

The 'index of effectiveness (θ)' is defined as the ratio of what safety was with the treatment to what it would have been without the treatment.

The parameter θ gives the overall safety effect of the treatment and is given by:

$$\hat{\theta} = \frac{\left(\frac{\lambda}{\pi}\right)}{\left(1 + \frac{Var(\hat{\pi})}{\hat{\pi}^2}\right)} \tag{5}$$

The percent change in the number of target crashes due to the treatment is calculated by $100(1-\hat{\theta})$ percent. If $\hat{\theta}$ is less than 1, then the treatment has a positive safety effect. The estimated variance and standard error of the estimated safety effectiveness are given by:

$$Var(\hat{\theta}) = \hat{\theta}^2 \frac{\left(1/L + Var(\hat{\pi})/\hat{\pi}^2\right)}{\left(1 + Var(\hat{\pi})/\hat{\pi}^2\right)^2} \tag{6}$$

$$s.e.(\hat{\theta}) = \sqrt{Var(\hat{\theta})} \tag{7}$$

The approximate 95 percent confidence interval for θ is given by adding and subtracting $1.96 \times s.e.(\hat{\theta})$ from $\hat{\theta}$. If the confidence interval contains the value 1, then no significant effect has been observed.

DATABASE DEVELOPMENT

This section briefly describes the data assembly and reduction activities that were undertaken to develop a database for conducting the safety analysis.

Roadway Data

The database assembly activities consist of processing the roadway data under PBPMMCs acquired from the TxDOT Dallas and San Antonio Districts. This activity includes the following tasks:

- Rename variables for consistency across two districts.
- Convert data for common variables to a common format for consistency.

- Verify that the facility component has not undergone major physical changes during the analysis years.
- Verify that there was no construction work during the analysis years.
- Remove segments near the interchanges and intersections.
- Verify that the facility has been under active PBPMMCs.

Computer code was developed using the Statistical Analysis System (SAS) to perform the first two tasks mentioned above. Information provided by the districts was used to perform the other activities.

TxDOT has issued 5-year PBPMMCs in the San Antonio District beginning in September 2006 and in the Dallas District beginning in September 2009. The exact location of the roads under the PBPMMCs was identified with the input of TxDOT personnel contacted as part of the research project.

For San Antonio, the sites were obtained from a list of roadways that the agency had maintained for conducting sampling for monthly assessment. The data provided by the San Antonio District consisted of information related to county, control section number, highway number, Texas reference markers (TRMs), and the road type. The district also provided the information related to the construction projects that were planned during the period the PBPMMC was active. However, the construction projects data consisted of the street names for the starting and ending limits, but the TRMs were not provided. The research team used the aerial photography to obtain the TRMs of each road segment under construction. The team used the TRM Point (P-HINI) database for this purpose. The P-HINI database contains attributes about point-specific features of the roadway such as driveways, intersections, and interchanges.

The Dallas District provided the data related to the roadways under PBPMMC and also information about the construction that was being planned on those roadways when the contract was active. However, the data that the Dallas District provided do not contain TRMs. As such, the research team had to identify TRMs manually using aerial photography cross referenced with P-HINI data. Similar to the San Antonio District, the Dallas District gave the starting and ending of construction limits by the street names and thus the research team had to manually find the TRMs using Google Earth® and the P-HINI data. The research team had difficulties in identifying some of the roadway segments, so not all segments were included in this analysis. Thus, it is important to note that the mileage presented here may not represent the actual total mileage under PBPMMC. Table 13 gives the mileage by road class for the highways under PBPMMC in both the districts considered in this study for conducting the safety analyses.

The segments under PBPMMCs that fall within the construction limits were excluded from the crash analysis regardless of the construction time. This is because the construction project dates provided were planned schedules, which makes it difficult to verify when they actually took place. Further, the PBPMMCs also have a provision that relieve the contractor of its duties when the construction projects meet certain criteria.

Table 13. Mileage by Road Class Considered for the Safety Analyses.

Road Class	Road Part	San Antonio				Dallas
		Bexar	Comal	Guadalupe	Total	
IH	Main Lanes	161.138	21.377	38.748	221.263	153.701
	Frontage Roads	135.83	20.932	18.114	174.876	80.71
US	Main Lanes	70.329	15.677	23.198	109.204	50.188
	Frontage Roads	15.066	0.000	0.000	15.066	49.287
SH	Main Lanes	52.92	33.367	49.345	135.632	112.883
	Frontage Roads	11.508	0.000	0.000	11.508	24.25
SL	Main Lanes	144.394	3.029	0.773	148.196	49.719
	Frontage Roads	18.556	0.000	0.000	18.556	8.981
FM	Main Lanes	187.627	127.26	213.805	528.692	19.077
Others	Main Lanes	43.649	39.616	25.505	108.77	24.994
	Frontage Roads	0.000	0.000	0.000	0.000	1.663
Total		841.017	261.258	369.488	1471.763	575.453

Crash Data

The research team collected the crash data from TxDOT's Crash Records Information System (CRIS) maintained by the Traffic Operations Division (TRF). Three types of information are available in the CRIS database: 1) accident, 2) vehicle and driver, and 3) causing factor (causality) information. The accident file contains detailed information on the highway area type, accident type, location, severity, lighting and weather condition, time of crash, and crash contributing factors, among others. The vehicle and driver data include information about vehicle type, vehicle model, driver age, gender, and so forth. The causality file contains data on the accident-causing factors such as driving under the influence, fatigue, and driver vision defects.

These three types of information were used to filter out crashes that are influenced by pavement marking retroreflectivity. The first contract for the San Antonio District was conducted from September 2006 to August 2011, while the contract for the Dallas District ran from September 2009 through the study period. However, the districts indicated that they did not start charging any penalties until after the first year of each contract and, thus, a period of one year after the start of the contract was not considered in the analysis. These no-penalty periods allow the contractor in both contracts to conduct the initial striping work required to bring the pavement markings up to the conditions set forth in the contract agreement.

For the San Antonio District, crash data were retrieved from January 2003 through August 2006 for the before period and from September 2007 through August 2011 for the after period. For the Dallas District, crash data were retrieved from January 2007 through August 2009 for the before period and from September 2010 through December 2012 for the after period. The daytime and nighttime crashes were used as control and treatment groups, respectively. Table 14 and Table 15 summarize the crash frequency for the control and treatment groups for the before and after periods (i.e., without and with PBPMMC) for San Antonio and Dallas Districts, respectively.

Table 14. San Antonio Crash Data Summary.

Periods		**Control (Daytime)**	**Treatment (Nighttime)**	**Grand Total**
After PBPMMC	Total	1245	572	1817
	Sep 2007–Dec 2007	70	49	119
	Jan 2008–Dec 2008	355	147	502
	Jan 2009–Dec 2009	294	149	443
	Jan 2010–Dec 2010	304	136	440
	Jan 2011–Aug 2011	222	91	313
Before PBPMMC	Total	963	436	1399
	Jan 2003–Dec 2003	215	116	331
	Jan 2004–Dec 2004	255	118	373
	Jan 2005–Dec 2005	298	131	329
	Jan 2006–Aug 2006	195	71	266
Grand Total		2208	1008	3216

Table 15. Dallas Crash Data Summary.

Periods		Control (Daytime)	Treatment (Nighttime)	Grand Total
After PBPMMC	Total	820	160	980
	Sep 2010–Dec 2010	116	18	134
	Jan 2011–Dec 2011	352	61	413
	Jan 2012–Dec 2012	352	81	433
Before PBPMMC	Total	729	196	925
	Jan 2007–Dec 2007	234	78	312
	Jan2008–Dec 2008	298	66	364
	Jan 2009–Aug 2009	197	52	249
Grand Total		1549	356	1905

The collected data were assembled into a database with spatial and temporal cross reference across crash, traffic, and geometric records. The control section numbers and the TRMs were used for this purpose.

ANALYSIS RESULTS

This section of the report provides the evaluation results of safety effectiveness of PBPMMCs. Table 16 presents the average safety effect of the PBPMMCs by location in Texas. The analysis was conducted by combining the two districts together and also by analyzing each district separately. This table shows that overall there are about 790 crashes reported during the after study period. The analysis results suggest that if the treatment had not been installed, the expected number of crashes would have been about 833 crashes during the after study period. Thus, the results suggest that there is a positive safety effect, and one can expect to see a decrease in crashes by 5.77 percent with the implementation of PBPMMCs. The standard deviation of this estimate of average safety effect is 8 percent. At a 95 percent confidence interval, this result is statistically insignificant. This means that the reduction in crashes may not be due to the contracts but might have just happened randomly.

Table 16 also shows the safety effect of PBPMMCs by each district separately. In the San Antonio District, the analysis results suggest that the number of crashes increased by 3.95 percent; however, the standard deviation of the estimate is 11 percent, and thus this result is highly insignificant at a 95 percent confidence level. At the same time, the before-after analysis of the PBPMMCs in the Dallas District suggests a decrease in the number of crashes by

26.6 percent with a standard deviation of 9 percent. Although this result is statistically significant, the decrease in crashes may not be completely attributed to the performance-based contracts. Some part of the reduction in crashes may have occurred due to the other countermeasures that were implemented during the same period or it may have occurred just by chance. In summary, the overall effect of the PBPMMCs is inconclusive, although the Dallas District showed a positive effect on safety.

Table 16. Average Safety Effect of PBPMMCs by Location.

Measure	Description	Location		
		Overall	San Antonio District	Dallas District
$\hat{\lambda}$	Number of crashes observed during the after period[1]	789.5	607.0	180.5
$\hat{\pi}$	Expected number of crashes during after period if PBPMMC not implemented	833.4	578.8	243.2
$Var(\hat{\pi})$	Variance of $\hat{\pi}$	3695.5	3001.2	663.7
$\hat{\theta}$	Unbiased estimate of index of effectiveness	0.942	1.039	0.734
$\sigma(\hat{\theta})$	Standard error of $\hat{\theta}$	0.08	0.11	0.09
$100(1-\hat{\theta})$	Percent decrease in the number of crashes[2]	5.77%	−3.95%	26.6%
$(\theta_{lower}, \theta_{upper})$	95% confidence interval for θ	(0.793, 1.091)	(0.832, 1.247)	(0.550, 0.918)
Significance	Statistically significant at 95% confidence level	No	No	Yes

[1]Adjusted by 0.5 when zero crashes were recorded on a road segment.
[2]Negative sign means increase in crashes.

This finding is consistent with the findings from several past studies, which indicated inconclusive evidence of relationship between safety and pavement marking retroreflectivity. While several previous studies indicated that the presence of markings can positively improve the safety (*1,2,46*), the effects of varying range of retroreflectivity of different types of markings on safety performance have been inconclusive.

Previous NCHRP 17-28 research found no evidence of a relationship between safety and pavement marking retroreflectivity (*11*). This study evaluated the safety effect of retroreflectivity of longitudinal pavement markings and markers over time on non-intersection locations during non-daylight conditions. The study also suggested the drivers may compensate for the risk by adjusting their driving behavior (e.g., reducing speed) in the absence of or the poor visibility of pavement markings. Lee et al. (*13*) conducted a similar study using Michigan data and found no evidence of the relationship between retroreflectivity and nighttime crash frequency. Lee et al. suggested that part of the reason was the insufficient variation of the observed retroreflectivity values in the database and limited sample size of the nighttime accidents used in the analysis. Cottrell and Hanson (*14*) conducted a before-after evaluation to determine the impact of white pavement marking materials on crashes. The target crashes were sideswipe-in-the-same-direction and run-off-the-road crashes during nighttime. The study also found inconclusive evidence of crashes and retroreflectivity.

The research team conducted further analysis by including the wet-weather crashes, assuming that the PBPMMC may also influence the crashes under wet weather conditions. Table 17 presents the average safety effect of the PBPMMCs in Texas when wet-weather crashes are included. Except a small difference, the percentage change in the crashes after the implementation of the PBPMMCs is very similar to that of the results in Table 16. Thus, irrespective of the weather conditions, it can be concluded that the PBPMMCs have insignificant effect on safety.

In addition to the overall effect, it is important to understand the average safety effects that performance-based contracts have on different crash severities. The following five crash severity levels were considered:

- Fatal (K).
- Incapacitating injury (A).
- Non-incapacitating injury (B).
- Minor injury (C).
- Property damage only (PDO).

Table 17. Average Safety Effect of PBPMMCs by Location w/ Wet Crashes.

Measure	Description	Location		
		Overall	San Antonio District	Dallas District
$\hat{\lambda}$	Number of crashes observed during the after period[1]	940.0	744.5	195.5
$\hat{\pi}$	Expected number of crashes during after period if PBPMMC not implemented	936.7	639.9	242.8
$Var(\hat{\pi})$	Variance of $\hat{\pi}$	4020.6	3505.3	515.3
$\hat{\theta}$	Unbiased estimate of index of effectiveness	0.999	1.065	0.798
$\sigma(\hat{\theta})$	Standard error of $\hat{\theta}$	0.07	0.10	0.09
$100(1-\hat{\theta})$	Percent decrease in the number of crashes[2]	0.10%	−6.52%	20.2%
$(\theta_{lower}, \theta_{upper})$	95% confidence interval for θ	(0.853, 1.145)	(0.873, 1.258)	(0.616, 0.981)
Significance	Statistically significant at 95% confidence level	No	No	Yes

[1]Adjusted by 0.5 when zero crashes were recorded on a road segment.
[2]Negative sign means increase in crashes.

As a first step, the research team conducted the analysis by each severity level separately. However, due to the small number of reported crashes, these analyses did not provide any meaningful results. To obtain statistically reliable estimates, fatal crashes were combined with the other injury types. The analysis was conducted using two different severity categories: 1) fatal plus serious injury crashes (KAB), and 2) fatal plus all injury crashes (KABC).

Table 18 presents the average safety effect of PBPMMCs by severity. The results shows that KAB crashes increased by 2.7 percent, whereas KABC crashes decreased by 4.9 percent. Statistically, these changes are highly insignificant at a 95 percent confidence level, which means the safety effect of performance-based contracts on these severity categories is inconclusive.

The researchers further conducted the analysis by classifying the highways into different subgroups based on the roadway class as shown in Table 19. The examination by these subgroup combinations will identify the subgroups that are potentially influenced by PBPMMCs. The roadway classes examined in this study include interstates, U.S. and state highways, state loops and spurs, and farm-to-market roads. The other road classes, such as business routes and frontage roads, were considered but not reported here because of unreliable estimates that occurred as a result of small sample size. The estimates in Table 19 suggest that the performance-based contracts have almost no effect on U.S. and state highways and a negative effect (increase in crashes) on state loops and spurs, and farm-to-market roads, although the results are statistically insignificant. The examination of performance-based contracts on interstate highways showed a significant positive effect. It is estimated that the crashes on interstates are reduced by 33.5 percent with a standard deviation of 8 percent. Although this result is statistically significant, the decrease in crashes may not be completely attributed to the performance-based contracts. Some part of the reduction in crashes may have occurred due to the other countermeasures that were implemented during the same period, or it may have occurred just by chance.

It should be noted that the Iowa study found that retroreflectivity has a statistically significant effect on crash occurrence probability for four data subsets—interstate, white edge line, yellow edge line, and yellow center line data (*12*). Their findings on statistically significant effects on crashes on interstate highways are consistent with our findings in this study.

Table 18. Average Safety Effect of PBPMMCs by Severity.

Measure	**Description**	**Crash Severity**	
		Fatal plus Serious Injury (KAB)	**Fatal plus All Injury (KABC)**
$\hat{\lambda}$	Number of crashes observed during the after period[1]	221.5	306.0
$\hat{\pi}$	Expected number of crashes during after period if PBPMMC not implemented	210.7	315.6
$Var(\hat{\pi})$	Variance of $\hat{\pi}$	1025.7	1898.2
$\hat{\theta}$	Unbiased estimate of index of effectiveness	1.027	0.951
$\sigma(\hat{\theta})$	Standard error of $\hat{\theta}$	0.17	0.14
$100(1-\hat{\theta})$	Percent decrease in the number of crashes[2]	−2.7%	4.9%
$(\theta_{lower}, \theta_{upper})$	95% confidence interval for θ	(0.700, 1.354)	(0.678, 1.225)
Significance	Statistically significant at 95% confidence level	No	No

[1]Adjusted by 0.5 when zero crashes were recorded on a road segment.
[2]Negative sign means increase in crashes.

Table 19. Average Safety Effect of PBPMMCs by Road Class.

Measure	Description	Road Class			
		Interstate Highways	US and State Highways	State Loops and Spurs	Farm-to-Market Roads
$\hat{\lambda}$	Number of crashes observed during the after period[1]	166.5	177.5	98.5	195.0
$\hat{\pi}$	Expected number of crashes during after period if PBPMMC not implemented	248.1	176.2	85.7	184.6
$Var(\hat{\pi})$	Variance of $\hat{\pi}$	570.1	526.6	199.2	599.8
$\hat{\theta}$	Unbiased estimate of index of effectiveness	0.665	0.990	1.119	1.038
$\sigma(\hat{\theta})$	Standard error of $\hat{\theta}$	0.08	0.15	0.21	0.15
$100(1-\hat{\theta})$	Percent decrease in the number of crashes[2]	33.5%	1.0%	−11.9%	-3.8%
$(\theta_{lower}, \theta_{upper})$	95% confidence interval for θ	(0.505, 0.825)	(0.703, 1.277)	(0.707, 1.531)	(0.737, 1.340)
Significance	Statistically significant at 95% confidence level	Yes	No	No	No

[1]Adjusted by 0.5 when zero crashes were recorded on a road segment.
[2]Negative sign means increase in crashes.

FINDINGS

This chapter has presented the results of the before-after analyses conducted to evaluate the effect of PBPMMCs on traffic safety. The findings of this investigation provide inconclusive evidence that performance-based pavement marking maintenance contracts are an effective safety countermeasure that aid in reducing crashes. The before-after analysis showed that the PBPMMCs decrease crashes on an average by an estimated 0.1 percent, and the result is not significant at a 95 percent confidence level. Further analysis by each district separately showed that the performance-based contracts have no significant change in safety in the San Antonio District, whereas a statistically significant positive effect in the Dallas District was found.

When evaluating the crashes by severity, the study results showed inconclusive evidence about the change in safety. The analysis by roadway class showed that PBPMMCs have no statistically significant effect on crashes occurring on U.S. and state highways, state loops and spurs, and farm-to-market roads. However, the performance-based contracts have a significant positive effect on safety of interstate highways. It is important to note that there could be some other countermeasures implemented during the same period that might have affected the nighttime crashes, and it is difficult to isolate the effect of the performance-based contracts.

CHAPTER 5: PERFORMANCE EVALUATION

This chapter describes the evaluation of the retroreflectivity performance of the pavement markings maintained under the PBPMMCs. The methodology used to collect the pavement marking retroreflectivity data, the data that were collected, and analysis of newly applied marking retroreflectivity as well as a retroreflectivity decay analysis is presented. In addition, the research team compared their retroreflectivity readings with those of the PBPMMC contractor for the second San Antonio contract.

METHODOLOGY

The research team developed a data collection plan to evaluate the performance of pavement markings in three districts. In addition to measuring markings applied under a PBPMMC, markings applied under traditional contracting techniques were also measured for comparison purposes. This section of the chapter documents the equipment used and the pavement marking retroreflectivity data collection plan.

Data Collection Equipment

The two key pieces of equipment used by the research team were a handheld and a mobile pavement marking retroreflectometer (see Figure 7). The image on the left is a handheld retroreflectometer. The handheld retroreflectometer must be placed by the user on a pavement marking to take a measurement. The handheld retroreflectometer is simple to use and provides accurate results, but it cannot be used to collect large quantities of data and cannot safely be used in high traffic locations without traffic control. The research team used the handheld retroreflectometer to help calibrate the mobile retroreflectometer and to perform spot checks throughout the data collection process to ensure accuracy of the mobile retroreflectivity measurements.

The image on the right of Figure 7 is the TTI mobile pavement marking retroreflectometer. The mobile retroreflectometer is used to collect pavement marking retroreflectivity while traveling in the data collection van at highway speeds. This device does not require lane closures, improves safety for the data collectors, and results in minimal delay to other motorists. The mobile retroreflectometer is connected to a computer inside the van that operates the device and logs the data collected. The data collection team monitored the retroreflectivity data as it was collected to ensure proper operation. Both the handheld and mobile retroreflectometers were properly calibrated at the beginning of each day of data collection. At times throughout the day the accuracy of the mobile retroreflectometer was checked by taking several handheld comparison measurements.

Figure 7. Data Collection Equipment.

Data Collection Plan

To meet the research objectives, the data collection plan needed to consider many aspects of the pavement markings. The most important factors to consider for this research project were the following:

- Pavement marking contracting type (PBPMMC, standard contract).
- Pavement marking application date (age).
- Roadway characteristics (AADT, classification, road surface).
- Line type (center, lane line, edge).

Considering these factors, the research team developed a data collection plan to collect pavement marking retroreflectivity data on a variety of markings in three TxDOT districts. The Bryan, Dallas, and San Antonio Districts were used as the pavement marking retroreflectivity data collection districts. Both the San Antonio and Dallas Districts were using a PBPMMC in one county of each district at the time of the data collection. The PBPMMC was being used in Dallas County (Dallas District) and Bexar County (San Antonio District). The Bryan District was selected due to the data collection team being located in that district and to serve as a comparison district that was using only the standard pavement marking contracting. The Bryan District also served as a smaller district compared to the two larger urban areas.

Two data collection trips were planned to each district, one in each fiscal year of the research project. These two trips would allow the research team to measure newly applied markings in year one, and to evaluate their retroreflectivity degradation by measuring the same marking sections in year two. The research team was also interested in measuring markings that were nearing their end of life to evaluate if the markings were being restriped at appropriate times.

The research team worked with each PBPMMC district to get the recent and planned striping schedules for the roads under the contract. This allowed the research team to specifically target road segments that had recently been striped or were soon to be restriped. In addition to these segments, the research team also measured a variety of roads that ran across county lines. This would allow for a comparison of the markings maintained by the same district, but by different contracting mechanisms. In the Bryan District the research team measured roadways that were newly striped and other roadways that had been used for mobile retroreflectivity data collection in the past. Within each district, roadway segments to measure were selected to give a variety of roadway characteristics.

In addition to the data the research team collected, retroreflectivity data collected by the contractors as part of the PBPMMC was also requested. These data will be compared to the research team's data collected on the roadways within a similar time frame. These data will be used to help determine if measurement protocols need to be revised to ensure accurate results.

DATA SUMMARY

The next several pages of this report document the pavement marking retroreflectivity data collected by the research team during this project. The data summaries are separated by the data collection district. In total, over 1600 miles of pavement marking retroreflectivity data were collected. The retroreflectivity data are presented in two ways: 1) summary tables, and 2) plots on a map with color coded retroreflectivity levels.

The summary tables provide the average retroreflectivity for the entire length of the section measured for each year. The summary tables indicate the roadway measured, line type, marking color, direction of travel, and the length of the segment measured. The shading on the summary tables represents recently striped markings (yellow shading), or markings scheduled to be restriped (blue shading). Sections of roadway that crossed into a non-PBPMMC county are indicated in the notes column by "Non PB County." The sections of road were summarized separately by PBPMMC and non-PBPMMC.

To offer a visual representation, the data were also plotted on Google Earth® maps. The mobile pavement marking retroreflectivity data output is summarized every 0.1 miles and is accompanied by global positioning system (GPS) coordinates indicating where the measurements were taken as the measurements progress down the road. Each of the 0.1 mile segments on the maps are color coded based on the average retroreflectivity value reported for that segment. The data plotted on the maps in this report represent one marking, for one direction, for each color on each segment.

The colors on the maps represent the retroreflectivity values indicated in Table 20. These retroreflectivity ranges are based on the requirements of the PBPMMCs (see Table 21).

Table 21 shows that all three PBPMMCs in Texas have required the contractor to maintain the white and yellow markings above a minimum level. The second (current) San Antonio contract also requires that newly applied markings meet an initial retroreflectivity requirement 30 days after installation. These 30-day minimum initial retroreflectivity values were used as the green threshold. All retroreflectivity values indicated by green would meet the 30-day initial retroreflectivity values. The minimum maintained values were used as the red threshold. All retroreflectivity values under these minimum maintained values will be indicated by red. All values between the minimum initial and minimum maintained are indicated by yellow. Black segments on the maps indicate no recorded data.

Table 20. Pavement Marking Map Color Legend.

White Marking Map Color Legend	Yellow Marking Map Color Legend
Green >250 mcd/m^2/lux	Green >175 mcd/m^2/lux
Yellow 175–250 mcd/m^2/lux	Yellow 125–175 mcd/m^2/lux
Red <175 mcd/m^2/lux	Red <125 mcd/m^2/lux

Table 21. PBPMMC Retroreflectivity Requirements.

	All 3 PBPMMC Minimum Maintained Retroreflectivity Level	Second San Antonio PBPMMC 30-Day Initial Minimum Retroreflectivity Requirement
White Pavement Markings	175 mcd/m^2/lux	250 mcd/m^2/lux
Yellow Pavement Markings	125 mcd/m^2/lux	175 mcd/m^2/lux

San Antonio District

Data were collected in the San Antonio District in May 2012 and May 2013. Approximately 800 miles of mobile pavement marking retroreflectivity data were collected. Data were collected on interstate highways, U.S. routes, state highways, farm-to-market roads, spurs, and loops. All markings measured were thermoplastic markings; most were spray applied, but some were extruded.

Several sections of newly applied markings were measured each year of the data collection. In the first year several sections scheduled to be restriped after our data collection were also evaluated to determine if these sections were truly in need of new pavement markings. Several other sections of markings that were at various stages of their life were also evaluated. These sections tended to cross the county lines out of the PBPMMC county into surrounding counties operating under standard pavement marking contracts.

Table 22 provides the summary data from the San Antonio data collection. Figure 8 and Figure 9 display the mapped data for the white pavement markings in 2012 and 2013. Figure 10 and Figure 11 display the mapped data for the yellow pavement markings in 2012 and 2013.

From the data it is evident that the markings scheduled to be restriped are in need of new markings as the average values are below the minimum maintained level that is required. It is also evident that the newly installed markings meet the 30-day initial retroreflectivity requirements. For both years of data, and especially evident for the white 2013 data, the PBPMMC county has better performing markings than the adjoining counties.

Table 22. San Antonio Data Summary.

Road	Line Type	Color	Direction	Length	2012		2013		Notes
					Avg R_L	Stdev	Avg R_L	Stdev	
FM143	Edge	W	EB	0.8	104	19	328	67	Chip sealed after our measurements
FM143	Edge	W	WB	0.8	94	20	317	90	Chip sealed after our measurements
FM143	Centerline	Y	EB	0.8	154	53	-	-	Chip sealed the day we were to measure in 2013 (low 100s from handheld)
FM143	Centerline	Y	WB	0.8	179	61	-	-	Chip sealed the day we were to measure
I10a	Edge	W	EB	4.2	264	58	307	78	
I10a	Edge	W	EB	4.7	171	29	132	24	Non PB County
I10a	Edge	W	WB	4.0	129	36	167	43	
I10a	Edge	W	WB	6.3	204	41	112	23	Non PB County
I10a	Skip	W	WB	4.1	273	71	328	80	
I10a	Skip	W	WB	4.3	146	52	103	24	Non PB County
I10b	Edge	Y	WB	11.1	223	29	232	36	
I10b	Edge	Y	WB	3.2	204	35	329	36	Non PB County
I10b	Edge	Y	EB	2.7	168	27	219	27	
I10b	Edge	Y	EB	11.1	193	39	274	43	Non PB County
FM327	Edge	W	SB	2.3	86	16	408	82	
FM471	Edge	W	EB	5.2	157	21	417	84	
FM471	Edge	W	EB	5.7	175	25	181	34	Non PB County
FM471	Edge	W	WB	6.6	141	25	339	63	
FM471	Edge	W	WB	7.2	168	26	164	33	Non PB County
FM471	Centerline	Y	EB	4.8	-	-	202	56	
FM471	Centerline	Y	EB	5.4	-	-	194	41	Non PB County
FM471	Centerline	Y	WB	4.7	-	-	183	54	
FM471	Centerline	Y	WB	5.3	-	-	187	43	Non PB County

Table 22. San Antonio Data Summary (cont).

Road	Line Type	Color	Direction	Length	2012		2013		Notes
					Avg RL	Stdev	Avg RL	Stdev	
FM1957	Skip	W	EB	5.4	371	116	318	95	
FM1957	Skip	W	WB	4.6	348	132	354	92	
FM1957	Edge	Y	EB	4.6	268	51	194	49	
FM1957	Edge	Y	WB	4.6	267	49	202	51	
US90	Edge	W	EB	6.0	236	49	375	67	
US90	Edge	W	EB	3.2	114	19	121	22	Non PB County
US90	Edge	W	WB	5.7	242	48	195	61	
US90	Edge	W	WB	3.0	187	22	194	31	Non PB County
US90	Skip	W	EB	6.0	271	87	365	109	
US90	Skip	W	EB	3.2	138	39	126	29	Non PB County
US90	Skip	W	WB	5.7	280	89	219	70	
US90	Skip	W	WB	3.0	200	44	197	52	Non PB County
US90	Edge	Y	EB	5.2	210	36	157	26	
US90	Edge	Y	EB	2.6	197	31	143	26	Non PB County
US90	Edge	Y	WB	5.0	220	38	137	35	
US90	Edge	Y	WB	3.0	259	50	144	31	Non PB County
Loop1604b	Edge	W	WB	5.4	124	22	182	40	
I35a	Edge	W	SB	17.4	-	-	202	84	Whole section
I35a1	Edge	W	SB	5.4	-	-	341	131	First part of the section (recently striped)
I35a2	Edge	W	SB	12.0	-	-	138	62	Second part of the section (set to be restriped)
I35a	Edge	W	NB	13.7	-	-	134	53	Set to be restriped
I35b	Edge	W	NB	1.6	131	28	102	75	
I35b	Edge	W	NB	11.5	143	36	136	37	Non PB County
I35c	Edge	Y	SB	3.5	229	49	135	25	
I410a	Edge	W	EB	6.4	269	84	342	95	
I410b	Edge	W	SB	7.7	257	73	256	95	
Loop13	Skip	W	WB	13.8	299	112	145	66	

Table 22. San Antonio Data Summary (cont).

Road	Line Type	Color	Direction	Length	2012		2013		Notes
					Avg RL	Stdev	Avg RL	Stdev	
SH16	Edge	W	WB	11.3	-	-	236	97	
SH16	Edge	W	WB	7.6	-	-	214	61	Non PB County
SH16	Edge	W	EB	11.3	-	-	268	100	
SH16	Edge	W	EB	7.6	-	-	170	46	Non PB County
SH16	Centerline	Y	WB	11.3	-	-	173	36	
SH16	Centerline	Y	WB	7.5	-	-	146	38	Non PB County
SH16	Centerline	Y	EB	11.3	-	-	230	46	
SH16	Centerline	Y	EB	7.7	-	-	119	32	Non PB County
Spur422	Edge	W	NB	1.5	390	57	313	92	
Spur422	Edge	W	SB	1.5	434	76	250	85	
Spur422	Skip	W	NB	1.7	372	147	314	124	
Spur422	Skip	W	SB	1.7	389	135	302	132	
Spur422	Edge	Y	NB	1.7	227	45	189	31	
Spur422	Edge	Y	SB	1.7	269	44	189	26	
FM78	Edge	W	EB	2.0	-	-	287	71	
FM78	Edge	W	WB	2.0	-	-	197	40	
FM78	Skip	W	WB	2.0	-	-	278	93	
FM1516	Edge	W	NB	3.0	-	-	387	61	
FM1516	Edge	W	SB	3.0	-	-	321	59	
FM1518	Edge	W	NB	5.2	-	-	287	54	
FM2252	Edge	W	NB	1.1	408	80	506	72	Verified with handheld, extrude
FM2252	Edge	W	NB	1.6	168	47	107	26	Non PB County
FM2252	Edge	W	SB	1.1	424	68	415	72	
FM2252	Edge	W	SB	1.6	164	47	114	41	Non PB County
FM2252	Skip	W	NB	4.0	399	131	336	109	
FM2252	Skip	W	SB	4.0	405	115	324	113	
FM2538	Edge	W	NB	6.0	-	-	479	71	
FM2538	Edge	W	SB	6.0	-	-	448	72	

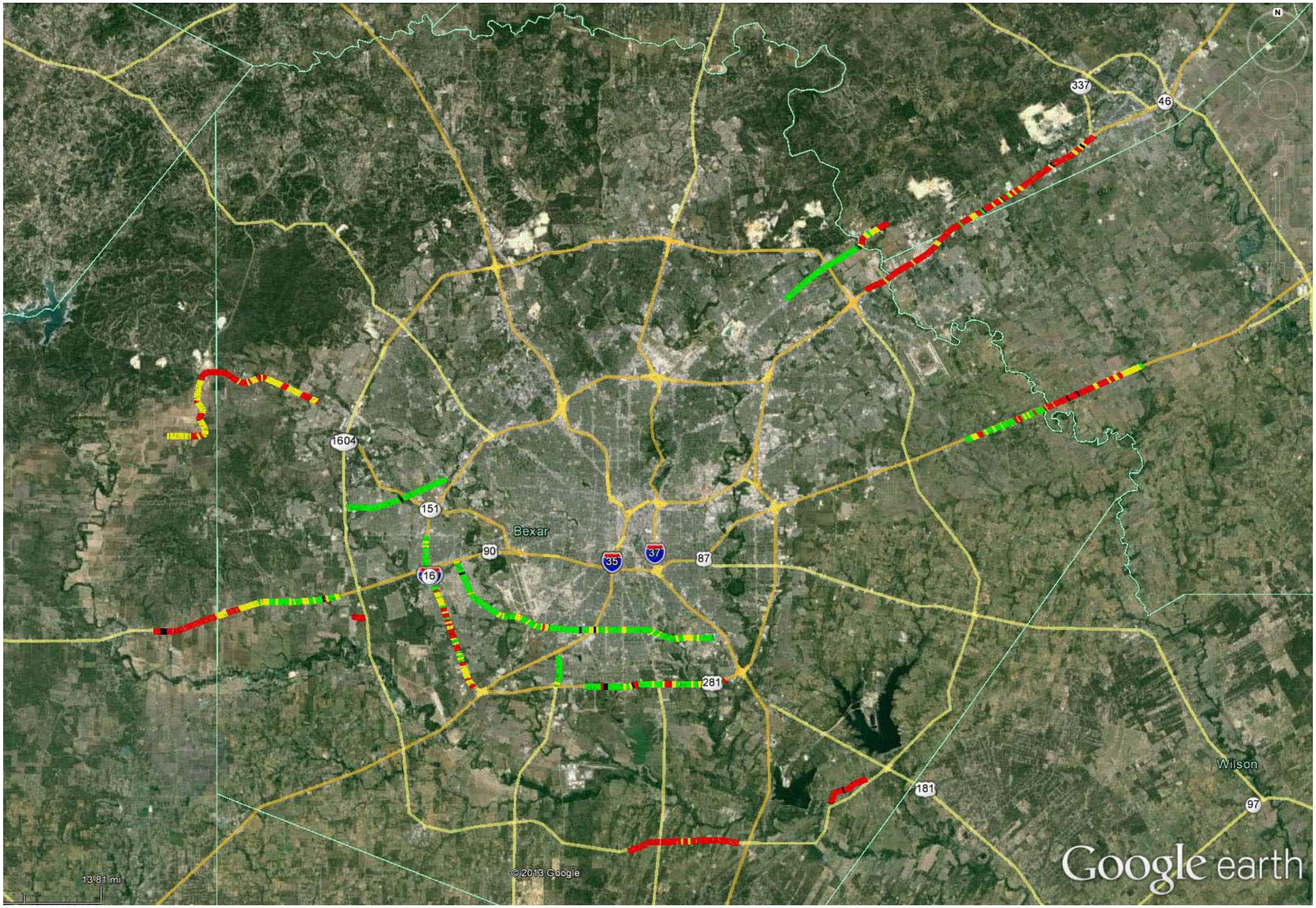

Figure 8. San Antonio 2012 White Data.

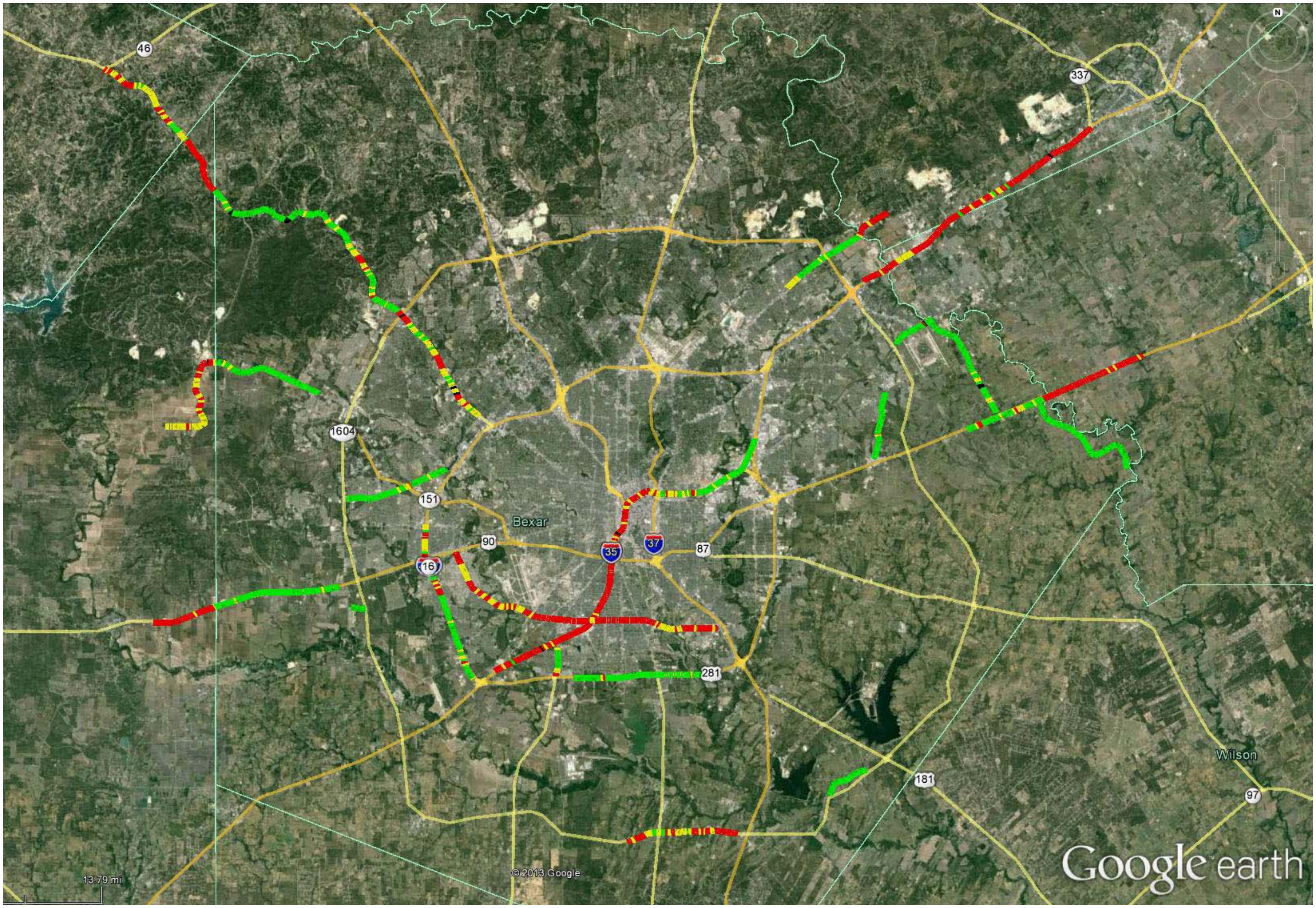

Figure 9. San Antonio 2013 White Data.

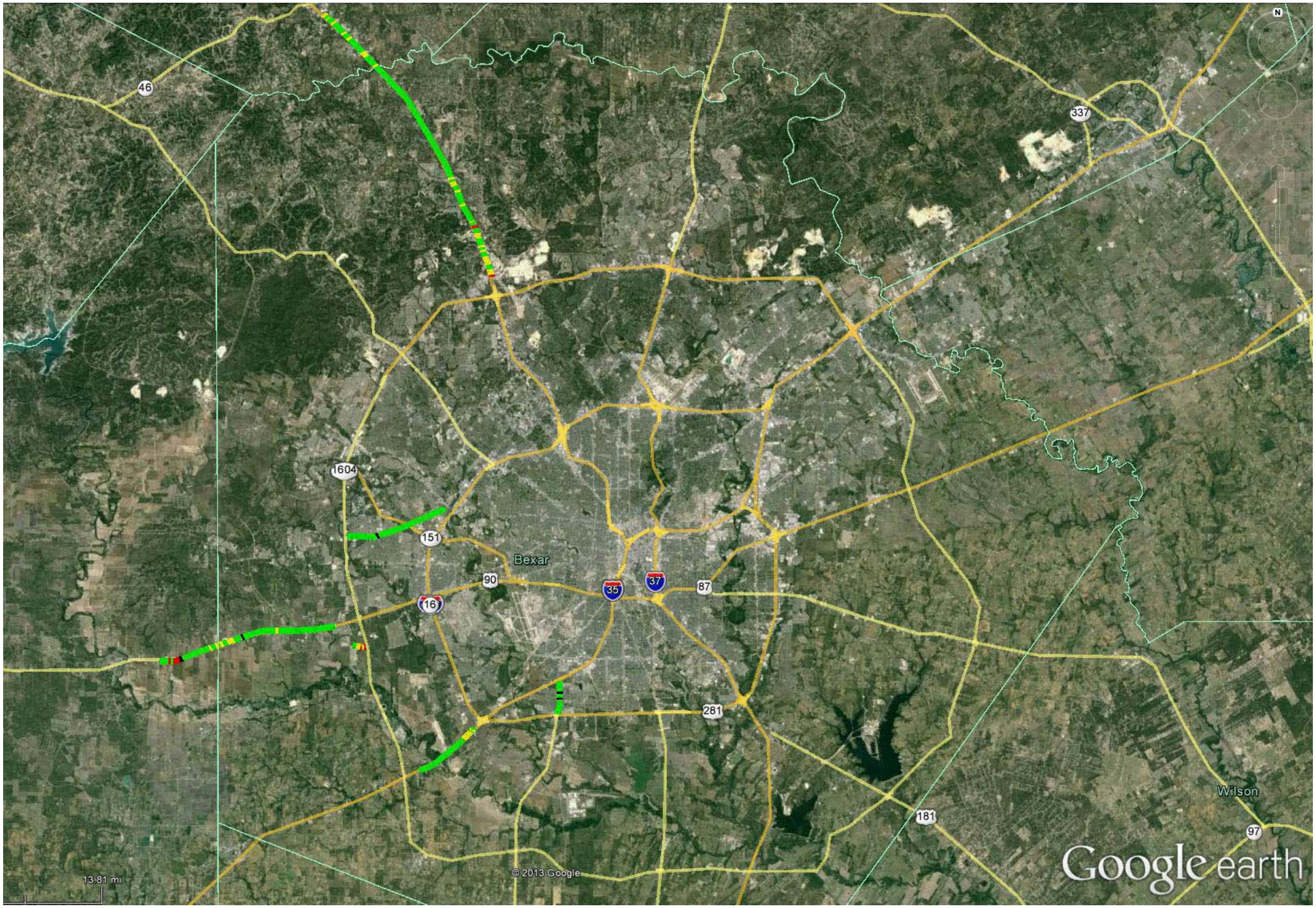

Figure 10. San Antonio 2012 Yellow Data.

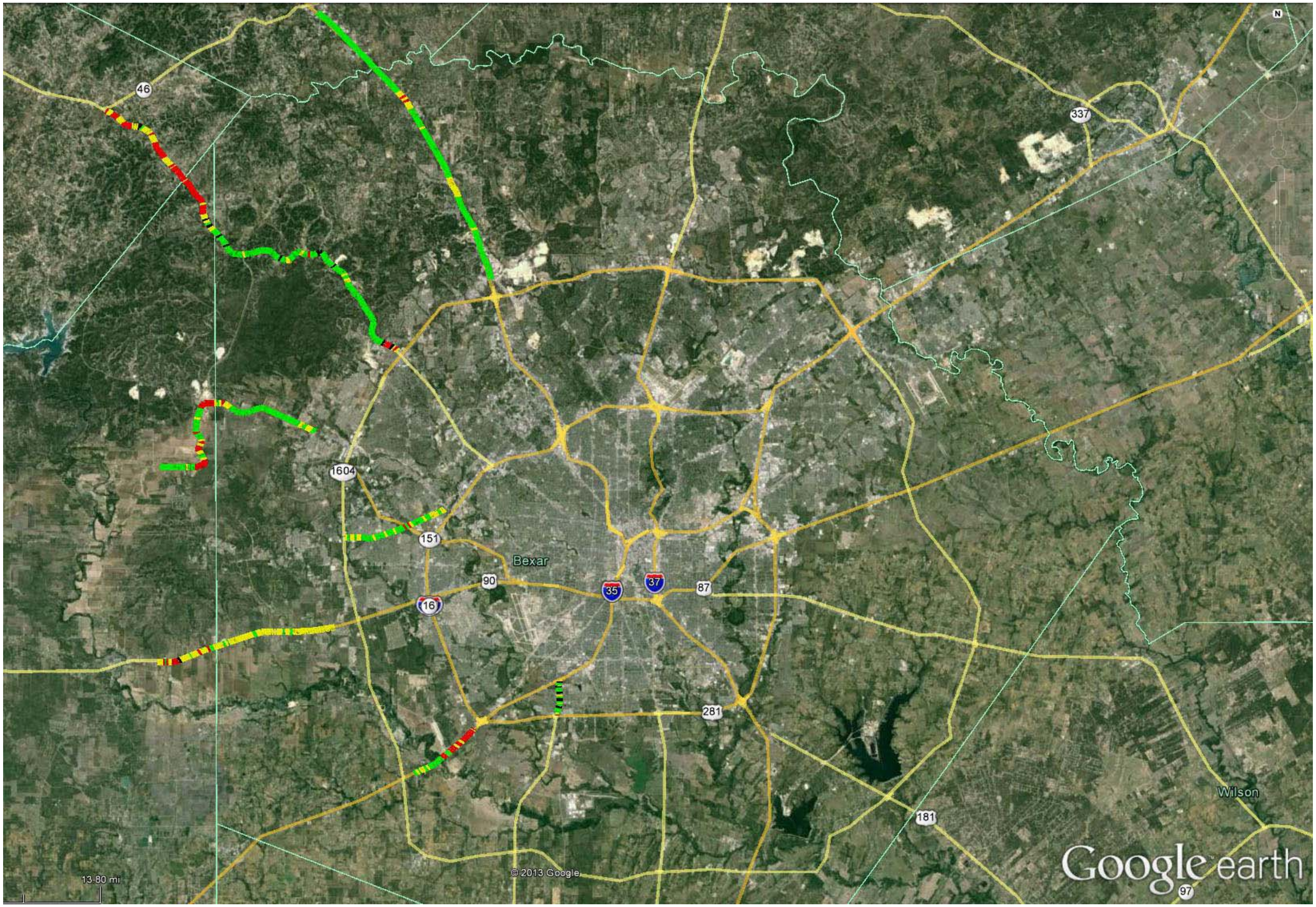

Figure 11. San Antonio 2013 Yellow Data.

Dallas District

Data were collected in the Dallas District in June of 2012 and June of 2013. Approximately 660 miles of mobile pavement marking retroreflectivity data were collected. Data were collected on interstate highways, U.S. routes, state highways, spurs, and loops. A combination of spray/extruded thermoplastic and epoxy markings were measured.

Several sections of newly applied markings were measured each year of the data collection. In the first year one section scheduled to be restriped after our data collection was also evaluated to determine if that section was truly in need of new pavement markings. Several other sections of markings that were at various stages of their life were also evaluated. These sections tended to cross the county lines out of the PBPMMC county into surrounding counties operating under standard pavement marking contracts.

Table 23 provides the summary data from the Dallas data collection. Figure 12 and Figure 13 display the mapped date for the white pavement markings in 2012 and 2013. Figure 14 and Figure 15 display the mapped data for the yellow pavement markings in 2012 and 2013.

From the data it is evident that the markings scheduled to be restriped are in need of new markings as the average values are below the minimum maintained level that is required. It is also evident that the newly installed markings meet the 30-day initial retroreflectivity requirements. The PBPMMC county had similar performance to the surrounding counties on the roadways measured in 2012. US67 was in need of being restriped and was restriped between the 2012 and 2013 readings in the PBPMMC county, but not in the adjoining county.

Table 23. Dallas Data Summary.

Road	Line Type	Color	Direction	Length	2012		2013		Notes
					Avg RL	Stdev	Avg RL	Stdev	
I20a	Edge	W	EB	6.1	489	80	365	86	
I20a	Edge	W	EB	3.5	336	93	383	68	Non PB County
I20a	Skip	W	WB	5.5	478	168	464	118	
I20a	Skip	W	WB	3.5	197	43	207	38	Non PB County
I20bFR	Edge	Y	EB	1.2	-	-	417	48	
I35	Edge	W	NB	4.3	-	-	332	64	
I35	Edge	W	NB	2.5	-	-	491	98	Non PB County
I35	Edge	W	SB	5.3	-	-	365	70	
I35	Edge	W	SB	2.3	-	-	460	94	Non PB County
I45	Edge	W	SB	8.2	422	91	311	65	
I45	Edge	W	SB	4.5	376	95	266	70	Non PB County
I45	Skip	W	NB	8.5	244	54	198	52	
I45	Skip	W	NB	7.4	216	54	226	41	Non PB County
I45	Edge	Y	SB	8.3	379	38	313	36	
I45	Edge	Y	SB	66.4	285	38	283	39	Non PB County
I635	Edge	W	EB	6.1	453	121	375	93	
I635	Edge	W	WB	5.6	445	101	348	84	
I635	Skip	W	EB	5.4	404	158	354	122	
I635	Skip	W	WB	5.1	460	167	370	98	
I635	Edge	Y	EB	6.2	376	61	352	56	
I635	Edge	Y	WB	5.5	383	74	329	63	
SH66	Edge	W	WB	5.8	-	-	341	77	
SH66	Edge	W	WB	3.1	-	-	167	34	Non PB County
SH66	Edge	W	EB	5.9	-	-	370	77	
SH66	Edge	W	EB	3.3	-	-	245	60	Non PB County

Table 23. Dallas Data Summary (cont).

Road	Line Type	Color	Direction	Length	2012		2013		Notes
					Avg RL	Stdev	Avg RL	Stdev	
SH78	Skip	W	NB	6.4	309	128	339	121	Striping parts during first year data collection, construction during second year in areas
SH78	Skip	W	SB	5.3	250	77	302	92	Striping parts during first year msts
Loop12all	Edge	W	SB	8.1	318	73	264	61	
Loop12a	Edge	W	SB	1.8	145	26	134	24	
Loop12b	Edge	W	SB	7.2	422	101	300	71	
Loop12all	Skip	W	NB	8.7	394	128	280	69	
Loop12a	Skip	W	NB	2.4	172	73	105	25	
Loop12b	Skip	W	NB	6.1	486	149	327	80	
Loop12	Edge	Y	SB	12.7	336	51	304	52	
SH342	Edge	W	NB	10.3	229	65	208	53	Edge and skips
SH342	Edge	W	SB	10.1	252	61	214	47	Edge and skips
SH356	Edge	W	WB	4.4	418	120	350	110	
SH356	Skip	W	EB	4.5	404	145	385	105	
Storey Road	Edge	W	NB	1.1	506	95	373	68	
US67	Edge	W	SB	8.3	148	35	408	70	
US67	Edge	W	SB	3.4	230	55	149	26	Non PB County
US67a	Skip	W	NB	2.5	398	92	355	97	Restriped whole section
US67b	Skip	W	NB	7.7	150	35	355	97	One bad area a mile long before end
US67c	Skip	W	NB	4.6	230	42	163	30	Non PB County
US67	Edge	Y	SB	9.8	142	26	279	53	
US67	Edge	Y	SB	2.1	224	46	168	31	Non PB County, some areas with missing line near the end in 2012 (about a 0.5-mile section)
US67	Edge	Y	NB	8.5	121	29	345	53	
US67	Edge	Y	NB	3.2	305	56	221	43	Non PB County
Spur348	Edge	Y	EB	2.7	-	-	346	54	
Spur348	Edge	Y	WB	2.7	-	-	305	52	

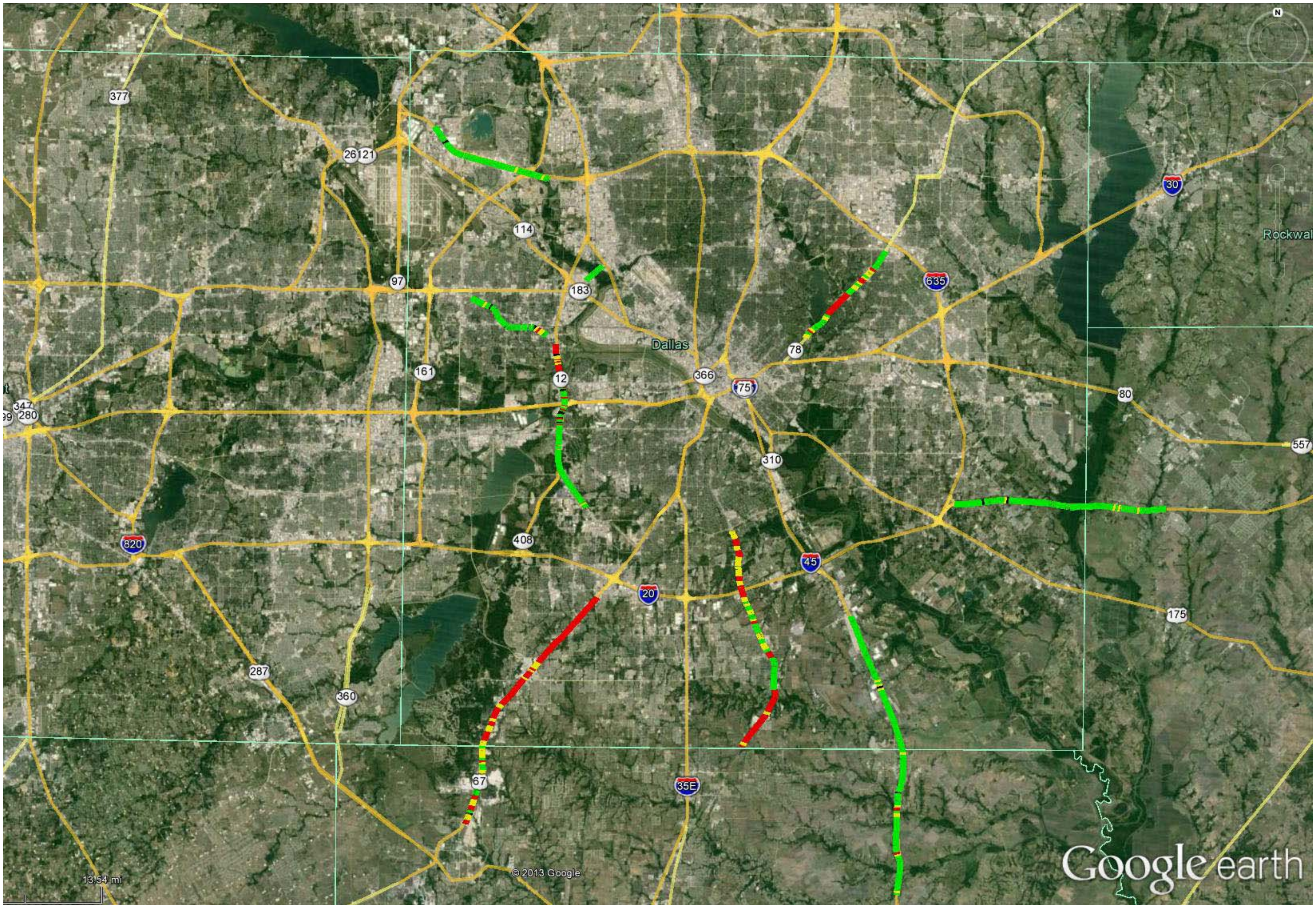

Figure 12. Dallas 2012 White Data.

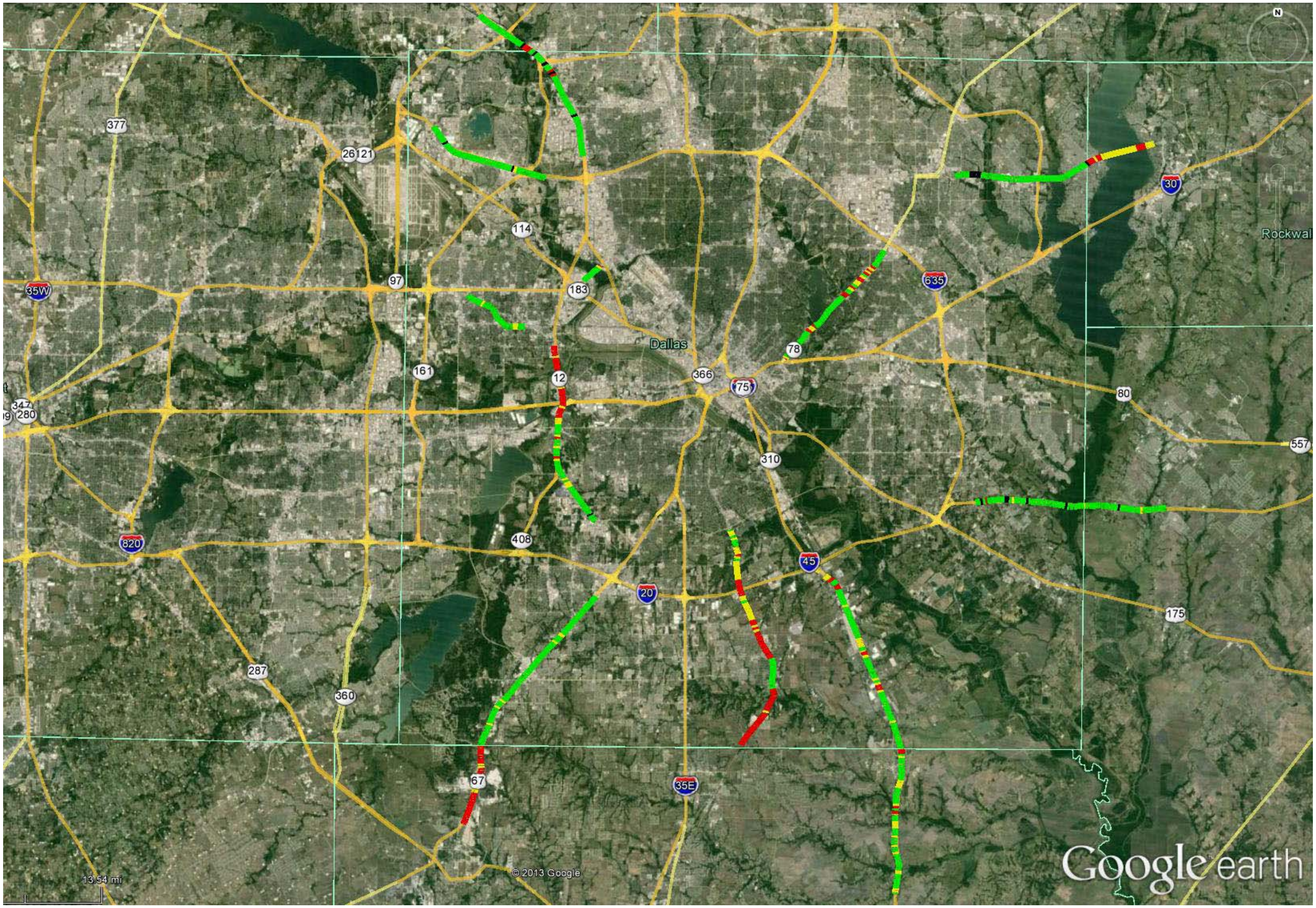

Figure 13. Dallas 2013 White Data.

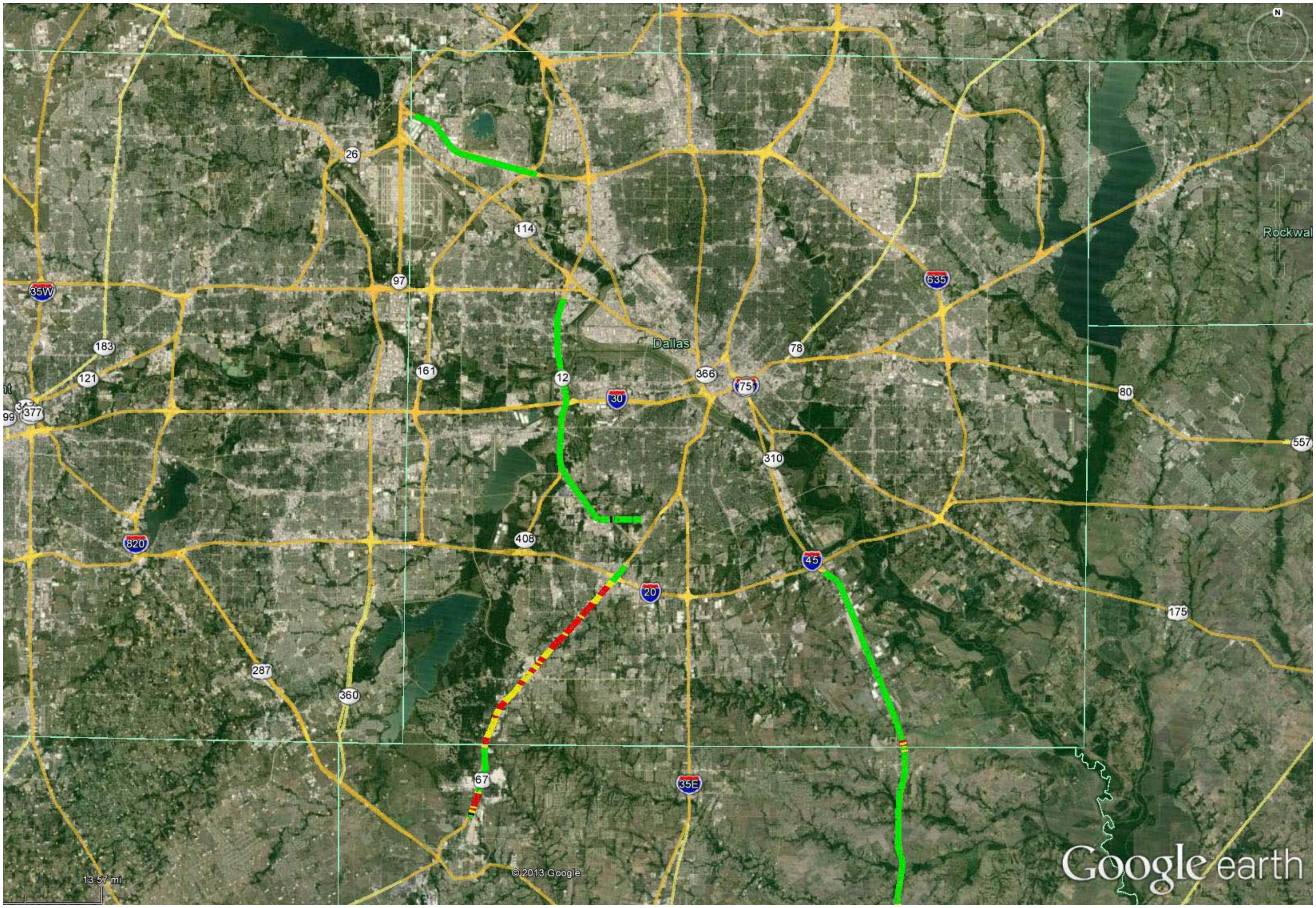

Figure 14. Dallas 2012 Yellow Data.

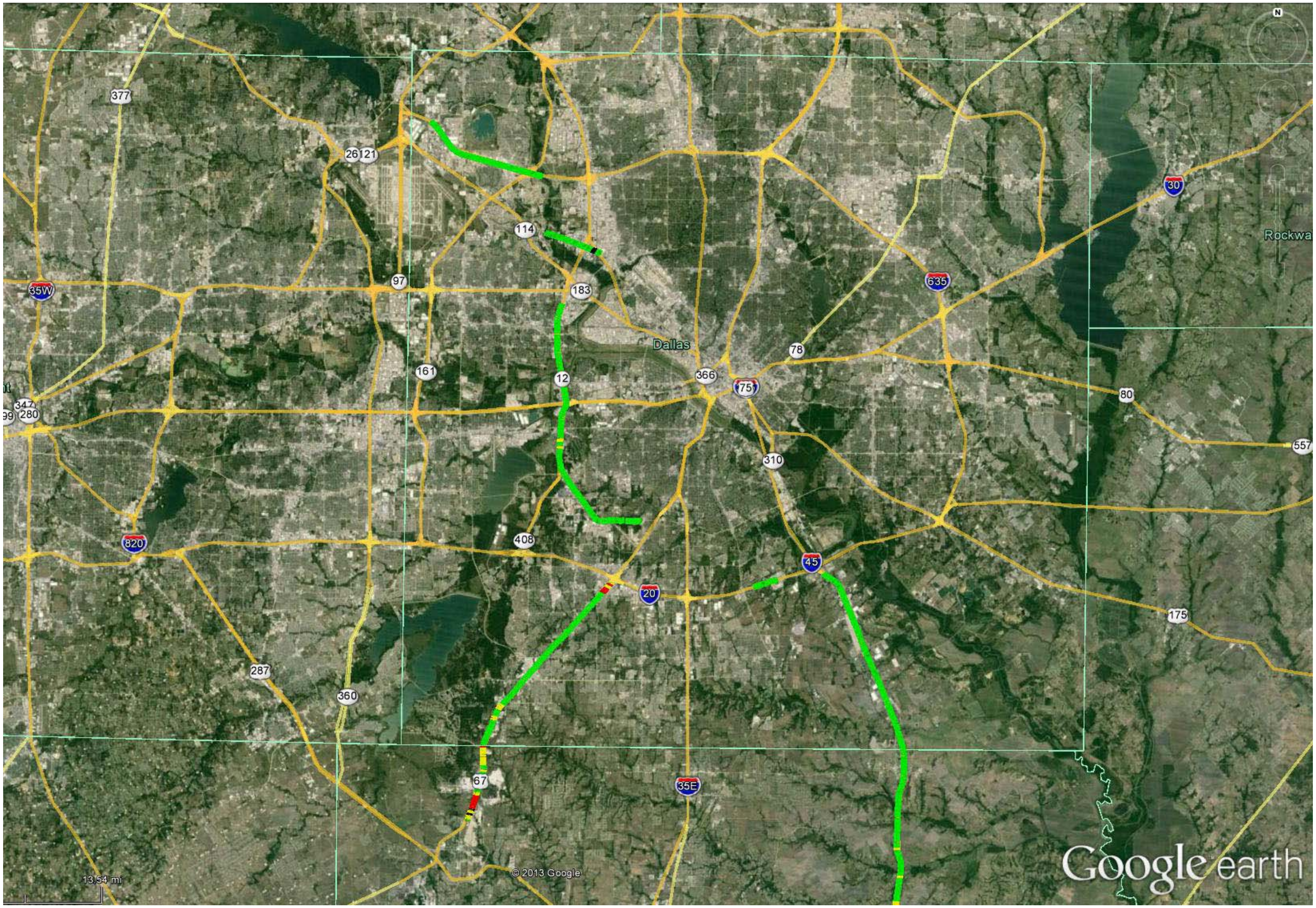

Figure 15. Dallas 2013 Yellow Data.

Bryan District

Data were collected in the Bryan District in August of 2012 and June of 2013. Approximately 200 miles of mobile pavement marking retroreflectivity data were collected. Data were collected on state highways and farm-to-market roads. All markings measured were sprayed thermoplastic.

Several sections of newly applied markings were measured in the first year of the data collection. In the first year several sections with older markings were also measured to determine the maintained retroreflectivity level and retroreflectivity degradation in a non-PBPMMC district. Though the Bryan District is not as big as San Antonio or Dallas, it does relate to many other districts in the state. The comparison of the Bryan data to the PBPMMC districts may allow for the results to be applied to most districts across the state.

Table 24 provides the summary data from the Bryan data collection. Figure 16 and Figure 17 display the mapped data for the white pavement markings in 2012 and 2013. Figure 18 and Figure 19 display the mapped data for the yellow pavement markings in 2012 and 2013.

From the data it is evident that the markings that were below the PBPMMC minimum maintained level did not get restriped in the year between the retroreflectivity measurements. The level of maintained retroreflectivity (there is no requirement), available funding, or inefficiencies in prioritizing areas to be restriped may be some reasons for these roadways not receiving new markings. It is also evident that the newly installed markings meet the 30-day initial retroreflectivity requirements.

Table 24. Bryan Data Summary.

Road	Line Type	Color	Direction	Length	2012		2013		Notes
					Avg RL	Stdev	Avg RL	Stdev	
SH47	Edge	W	NB	3.0	406	53	358	43	
SH47	Edge	W	SB	3.0	412	50	317	35	
SH47	Skip	W	NB	3.0	350	124	329	80	
SH47	Skip	W	SB	3.2	320	122	328	99	
SH47	Edge	Y	NB	3.2	289	31	232	29	
SH47	Edge	Y	SB	3.2	270	29	217	28	
FM60	Edge	W	EB	2.4	468	43	216	48	Large decrease
FM60	Edge	W	WB	2.3	431	35	463	44	
FM60	Skip	W	EB	2.4	453	130	188	68	Large decrease
FM60	Skip	W	WB	2.3	395	135	393	132	
FM60	Edge	Y	EB	2.6	268	32	270	27	
FM60	Edge	Y	WB	2.6	288	40	251	27	
OSR	Edge	W	EB	4.0	275	49	152	27	
OSR	Edge	W	WB	4.0	309	71	161	32	
OSR	Centerline	Y	EB	4.0	100	26	74	27	
OSR	Centerline	Y	WB	4.0	119	28	78	24	
SH6	Edge	W	NB	4.0	253	66	175	43	
SH6	Edge	Y	NB	4.8	185	28	134	22	
SH30	Edge	W	EB	3.3	264	38	167	29	
SH30	Edge	W	WB	3.2	250	37	173	28	
SH30	Skip	W	EB	2.9	290	80	127	68	
SH30	Skip	W	WB	3.2	280	81	143	62	
SH30	Edge	Y	EB	3.0	143	43	86	23	
SH30	Edge	Y	WB	3.0	139	43	88	21	
SH40	Edge	W	NB	2.1	404	59	321	61	
SH40	Edge	W	SB	2.0	396	49	349	55	
SH40	Skip	W	NB	1.5	376	137	334	91	
SH40	Skip	W	SB	2.1	400	120	350	98	
SH40	Edge	Y	NB	2.1	270	38	217	26	
SH40	Edge	Y	SB	2.1	251	36	203	35	
University Dr.	Skip	W	WB	2.5	391	121	207	47	Left skip
University Dr.	Skip	W	EB	2.3	355	82	206	48	Left skip
University Dr.	Skip	W	WB	2.5	353	85	204	47	Right skip
Villa Maria	Edge	W	EB	1.4	118	32	100	30	
Villa Maria	Edge	W	WB	1.4	87	25	77	24	
Villa Maria	Centerline	Y	EB	2.1	77	24	58	19	
Villa Maria	Centerline	Y	WB	2.1	81	25	57	17	

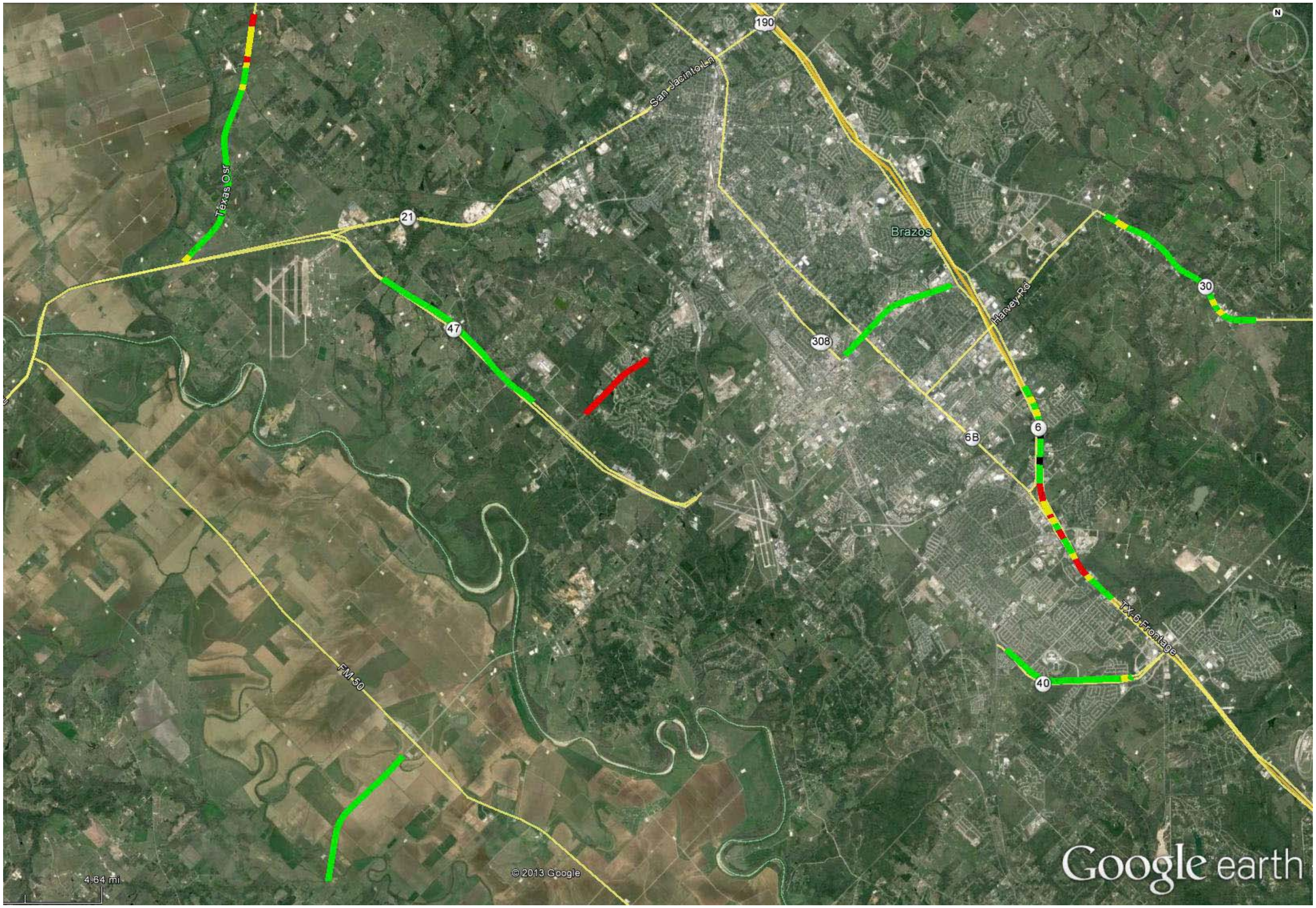

Figure 16. Bryan 2012 White Data.

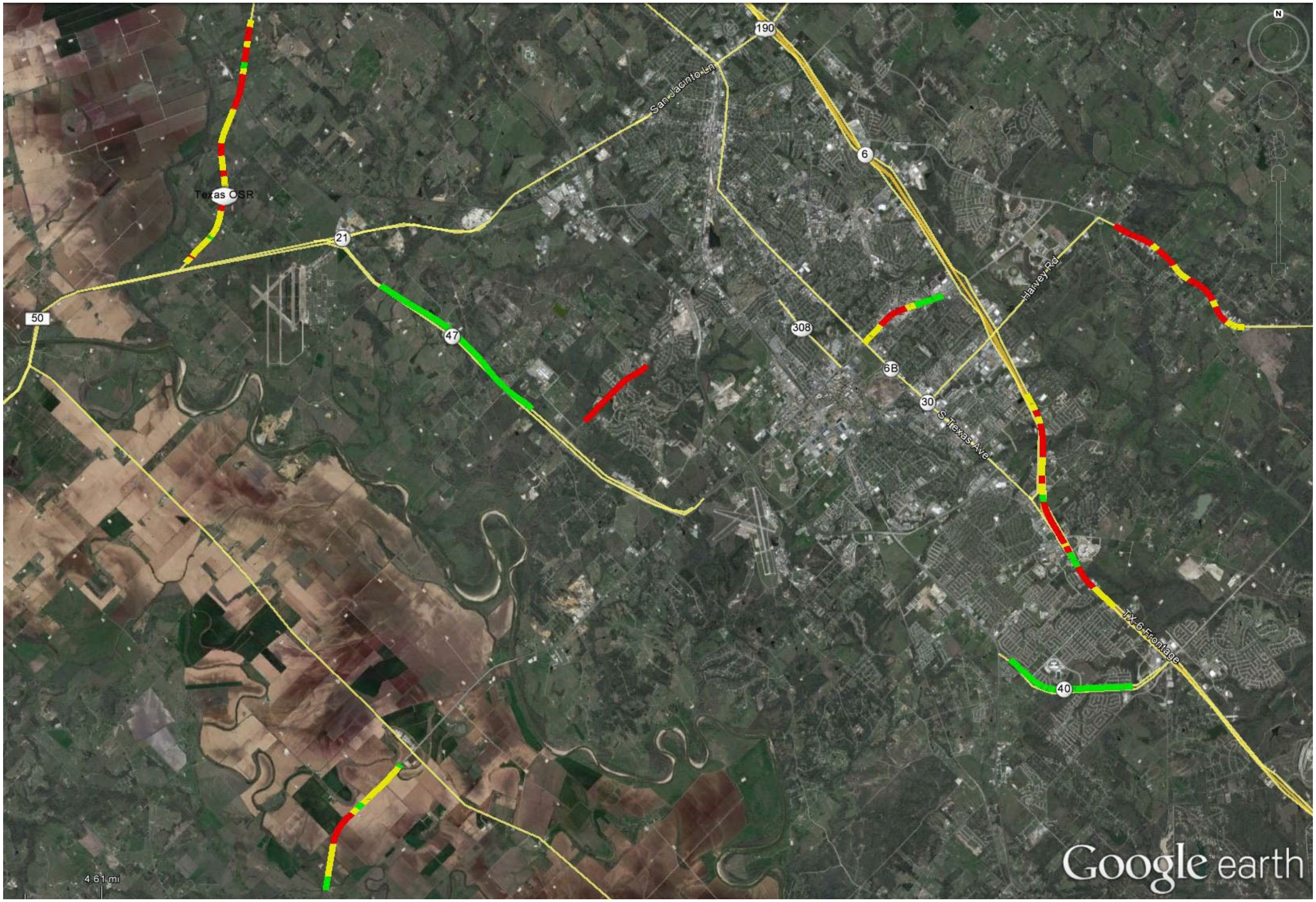

Figure 17. Bryan 2013 White Data.

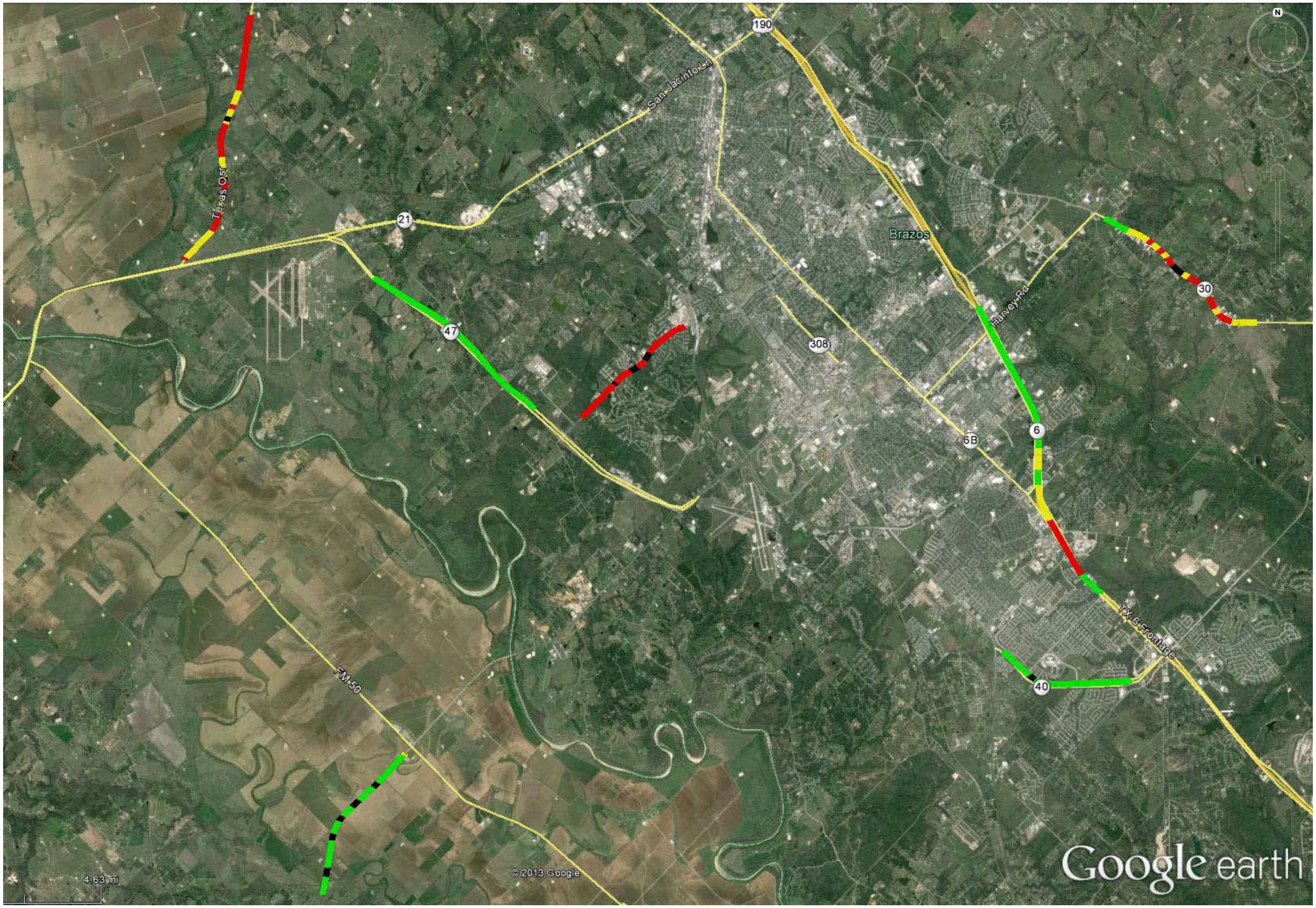

Figure 18. Bryan 2012 Yellow Data.

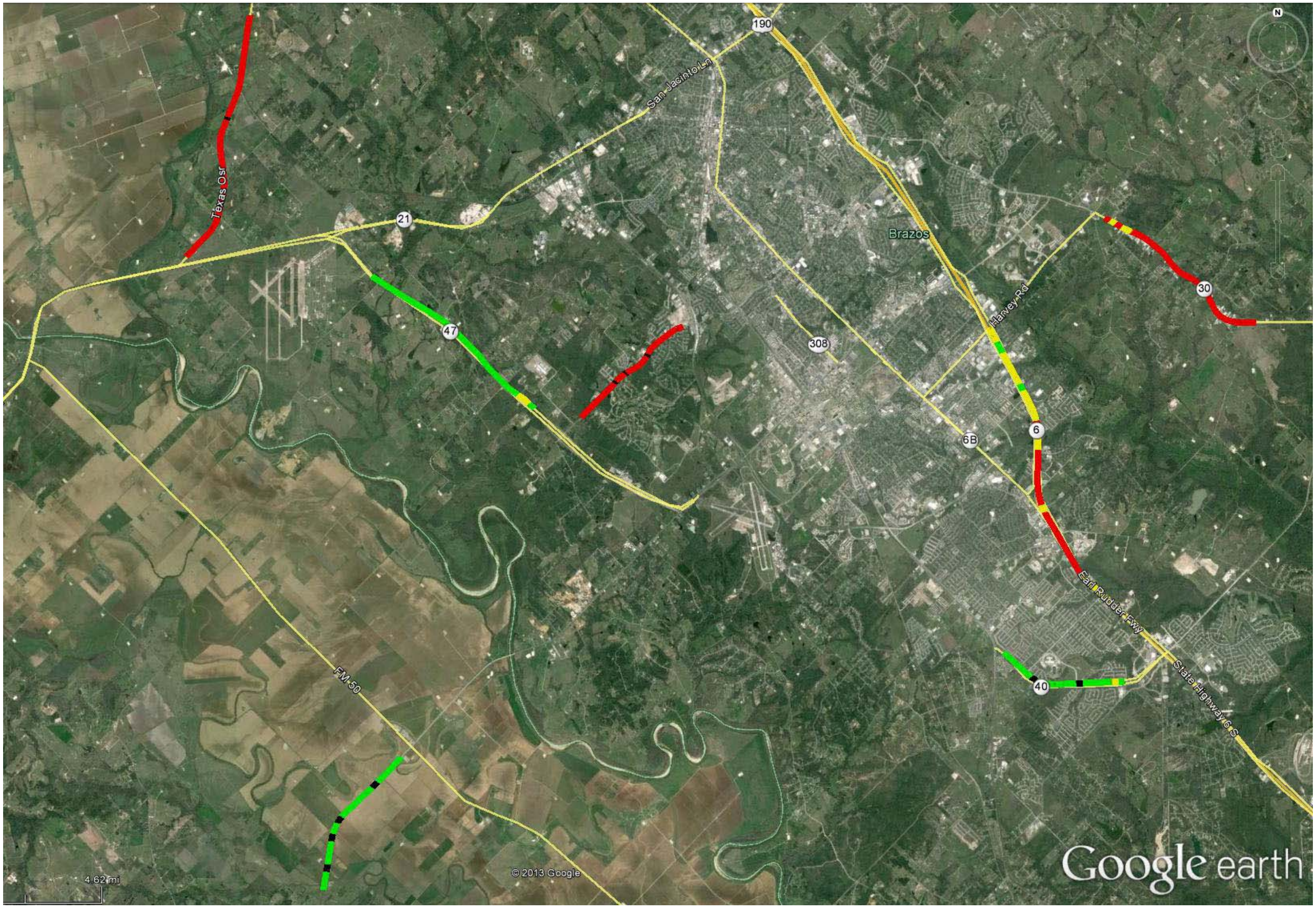

Figure 19. Bryan 2013 Yellow Data.

DATA ANALYSIS

The researchers conducted three types of analysis in this study:

1. Retroreflectivity of New Markings – This analysis determines if there are any differences in the retroreflectivity levels of the new markings installed under the PBPMMC versus non-PBPMMC contracts.
2. Decay Analysis of Retroreflectivity – This analysis quantifies the magnitude of average decay in retroreflectivity levels measured on different road segments and determines if there are any differences between PBPMMC and non-PBPMMC districts.
3. Analysis of 30-day Contractor Readings – This analysis examines whether the retroreflectivity readings on new markings provided by the PBPMMC contractor as stipulated in the contract are the same as the readings conducted by the TTI team.

The three districts included in these analyses are: Bryan (BRY), San Antonio (SAT), and Dallas (DAL). The Bryan District is the non-PBPMMC district.

RETROREFLECTIVITY ANALYSIS OF NEW MARKINGS

The researchers considered the markings that are 6 months old or less as new markings. Figure 20 shows the readings of new markings for each district by color and age of the marking at the time it was measured. The figure may include multiple marking segments in each month of data. There was no noticeable decay trend for markings within the first 6 months for the Dallas or Bryan Districts. The San Antonio District appeared to show some degradation in the first 6 months, assuming all markings were applied at a similar initial retroreflectivity level.

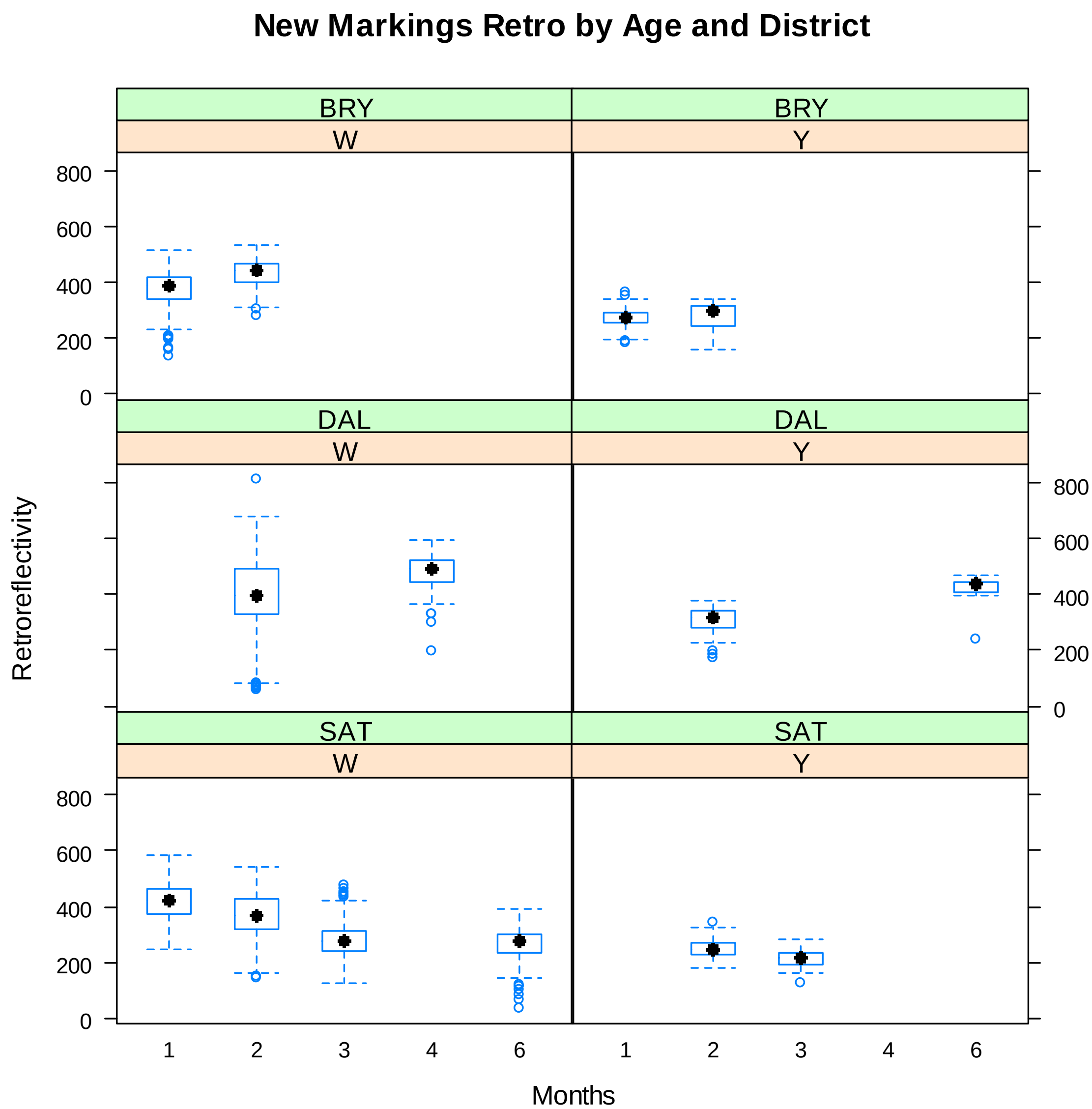

Figure 20. New Markings by Age.

Table 25 shows the retroreflectivity levels of new markings by districts. The retroreflectivity of yellow markings is generally lower than that for the white markings. The box plots in Figure 21 show the variation in retroreflectivity levels of new markings for both white and yellow markings. The Dallas District has the highest average reflectivity levels of new markings, while the San Antonio District has the lowest values of new markings. The analysis of variance (ANOVA) performed on the retroreflectivity of new markings shows that the differences observed among districts are statistically significant at a 95 percent confidence level.

Table 25. Retroreflectivity of New Markings by District.

District	White Markings		Yellow Markings	
	Mean	Standard Deviation	Mean	Standard Deviation
Bryan	391	70	274	37
Dallas	417	121	328	64
San Antonio	354	89	233	35

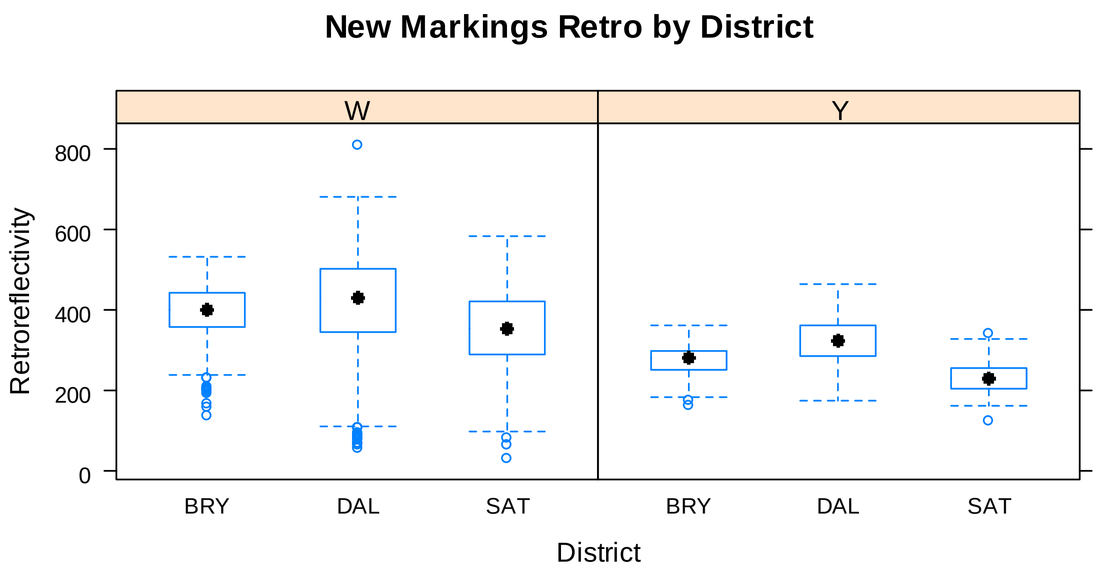

Figure 21. New Markings by District.

Table 26 summarizes the retroreflectivity levels measured for new markings for each roadway. Figure 22, Figure 23, and Figure 24 provide the box plot of each of the roadways by district. There was a significant variation in average retroreflectivity values of new markings ranging from 256 to 483 mcd/m^2/lux for white markings and 215 to 417 for yellow markings. All new markings regardless of contract type exceeded the second San Antonio contract's 30-day initial minimum retroreflectivity requirements of 250 mcd/m^2/lux for white markings and 175 mcd/m^2/lux for yellow markings.

Table 26. Retroreflectivity of New Markings by Roadways.

District	Road	White Line		Yellow Line	
		Mean	SD	Mean	SD
BRY	FM60	436.7	48.0	278.1	46.9
	SH40	395.6	42.5	261.1	31.0
	SH47	369.8	67.6	280.0	31.6
	University Drive	367.6	91.2	-	-
DAL	I20a	483.3	64.1	-	-
	I20bFR	-	-	416.5	58.5
	I35	349.7	79.5	-	-
	Loop12b	438.9	149.1	-	-
	SH66	356.6	56.3	-	-
	Spur348	-	-	307.9	46.1
SAT	FM1516	356.9	61.3	-	-
	FM1518	287.6	34.4	-	-
	FM1957	360.3	54.0	246.2	32.0
	FM2252	405.1	69.7	-	-
	FM2538	463.9	46.1	-	-
	FM78	255.8	78.7	-	-
	Loop13	299.1	58.8	-	-
	Loop1604a	412.4	62.6	-	-
	Spur422	391.8	66.9	248.3	36.6
	US90	293.6	73.5	214.6	28.8

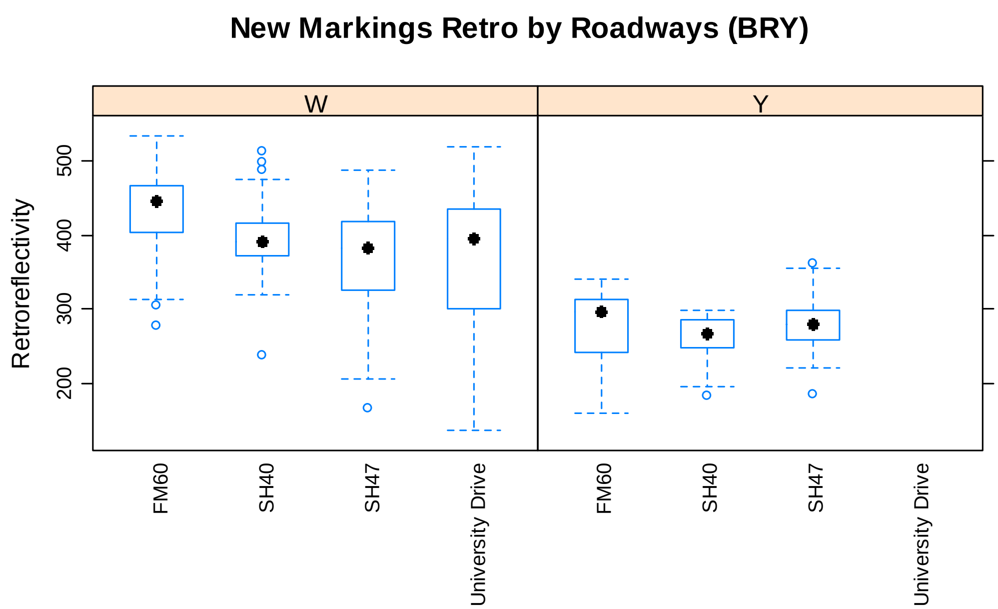

Figure 22. New Markings by Roadways (BRY).

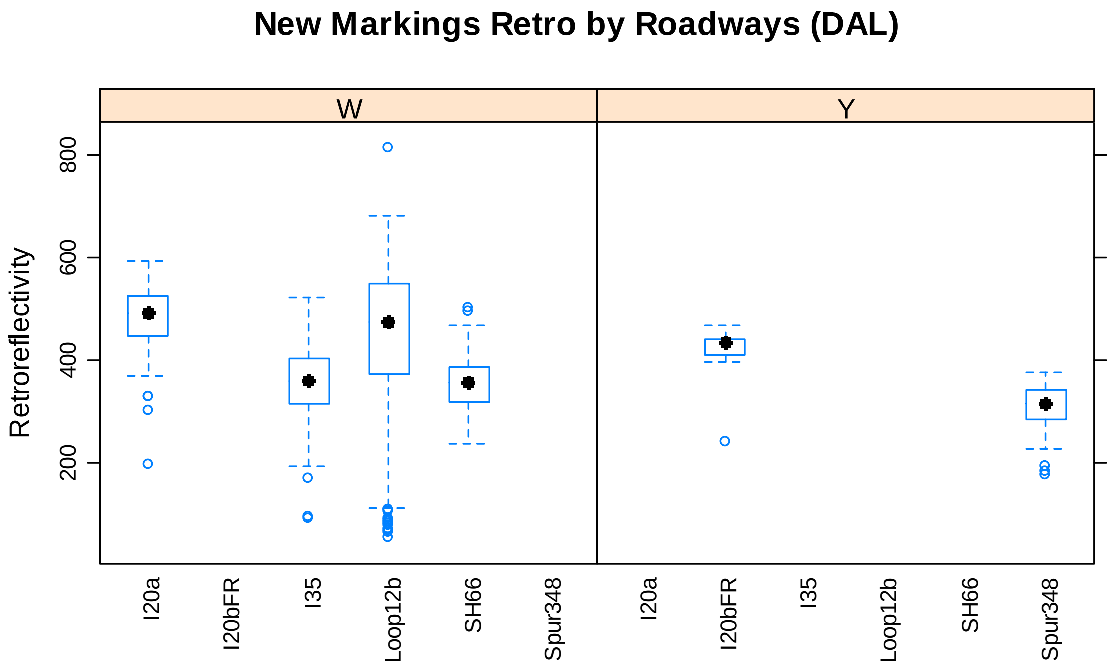

Figure 23. New Markings by Roadways (DAL).

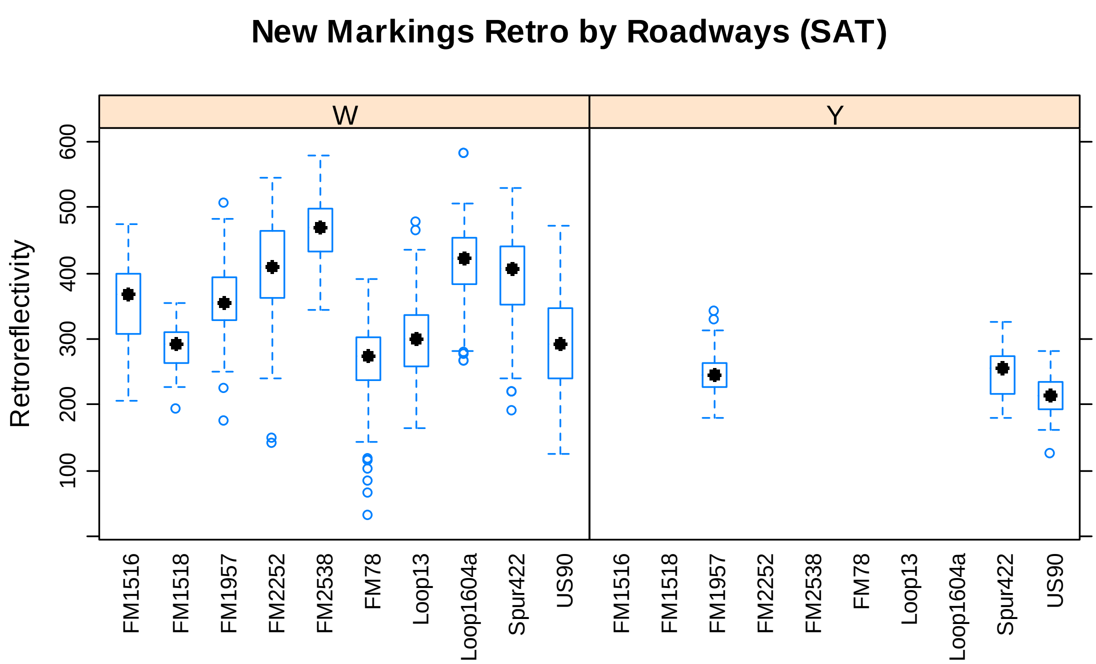

Figure 24. New Markings by Roadways (SAT).

Table 27 shows the observed percentile statistics of retroreflectivity values of new markings by districts. These values look at each individual 0.1-mile segment on each of the roadways measured. The previous section looked at the average retroreflectivity value for each roadway; this analysis breaks down each section even further to see how many areas within each section may fall below the required levels. For example, in the San Antonio District, the 10th percentile value indicated that 90 percent of all the new white 0.1-mile segments of the markings measured were greater than 239 mcd/m^2/lux. This table indicates that almost 90 percent of new white marking segments and at least 95 percent of the new yellow marking segments will meet or exceed the current 30-day initial minimum retroreflectivity requirement of the PBPMMC.

Table 27. Percentile of Retroreflectivity Values of New Markings.

District	Retroreflectivity of New Markings					
	White Markings			Yellow Markings		
	5th	10th	15th	5th	10th	15th
Bryan	250	296	320	207	221	238
Dallas	179	265	309	231	247	277
San Antonio	211	239	259	180	187	194

The San Antonio and Dallas Districts have implemented PBPMMCs, while the Bryan District has not. From our analysis, there are statistically significant differences in retroreflectivity levels of new markings among districts but there are no observable patterns either in white or yellow markings between PBPMMC and non-PBPMMC districts.

DECAY ANALYSIS

Figure 25 and Figure 26 respectively show the white marking and yellow marking decay measured approximately 10–12 months apart in 2012 and 2013. Retroreflectivity levels consistently decrease across all roadways measured in 2013. Overall, there is a slightly greater variation in the 2013 data due to varying degrees of degradation within a roadway.

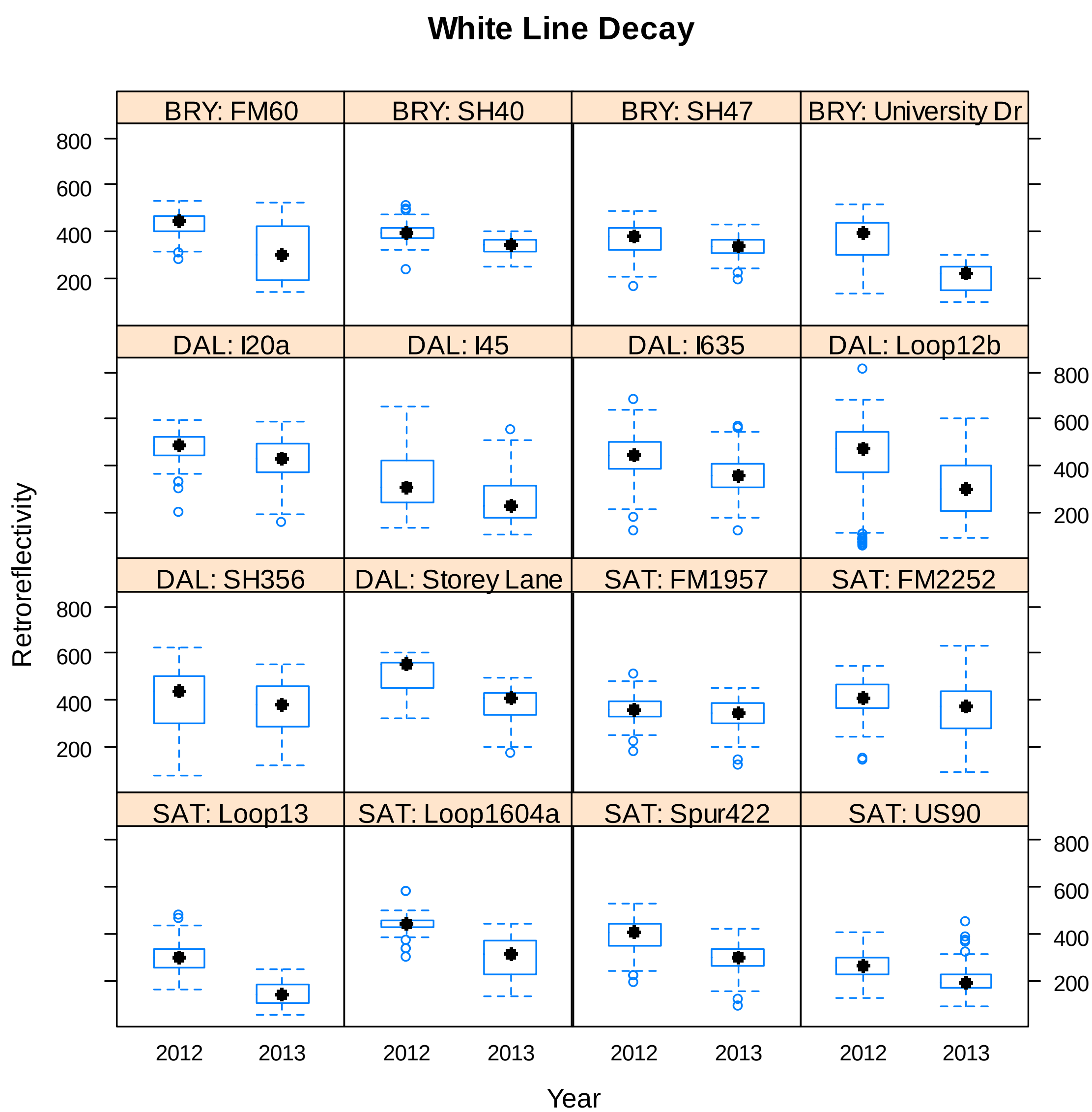

Figure 25. White Marking Decay by Roadways.

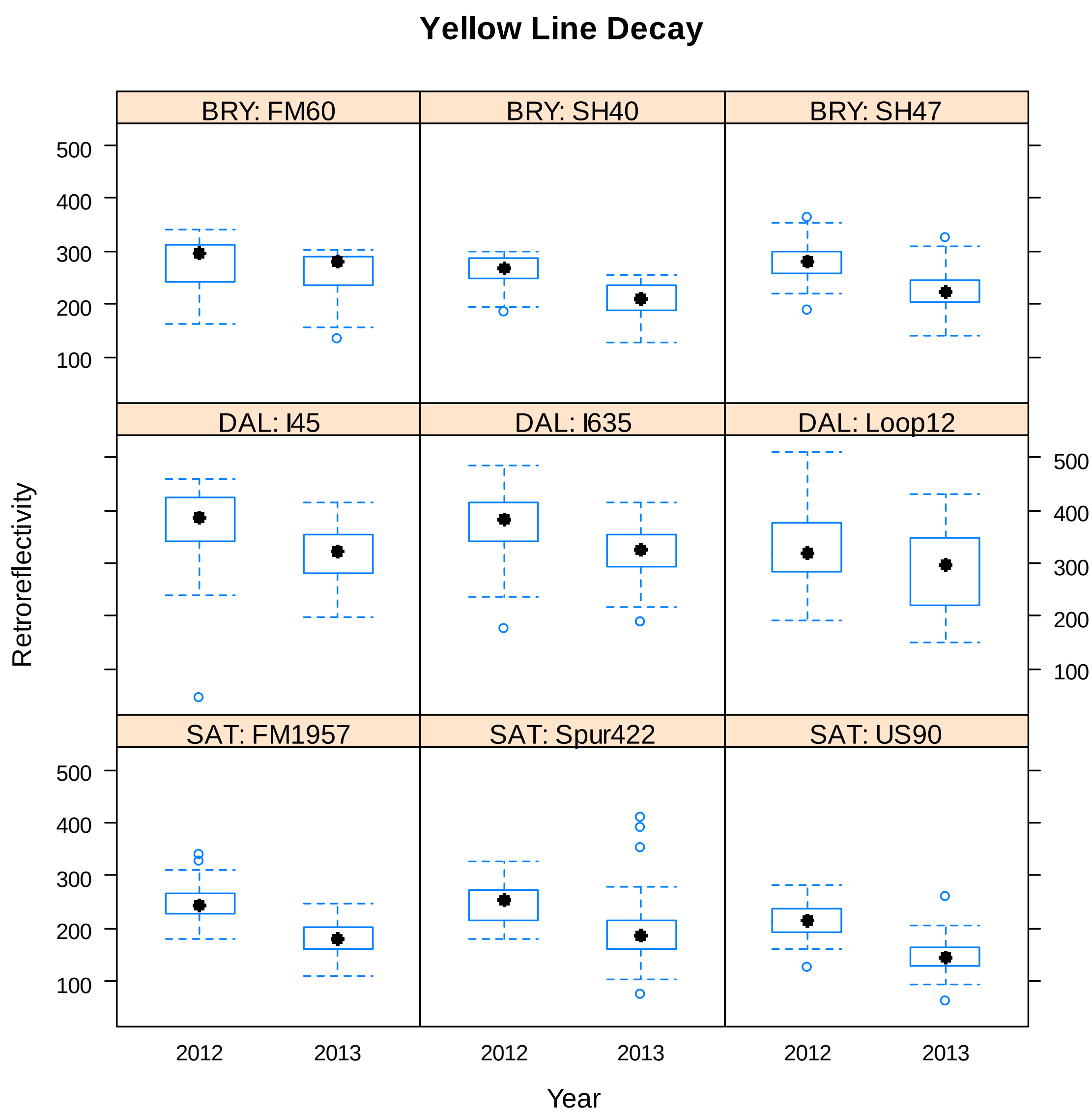

Figure 26. Yellow Marking Decay by Roadways.

Figure 27 shows the retroreflectivity levels measured for different ages of markings. The ages are grouped for every 3 months in the first year, 6 months in the second year, and every 12 months every year thereafter. The oldest markings in the data set were at 38 months. The decay trend is noticeable with a longer time frame particularly on white markings in the Dallas District where the measurement data span across several age groups.

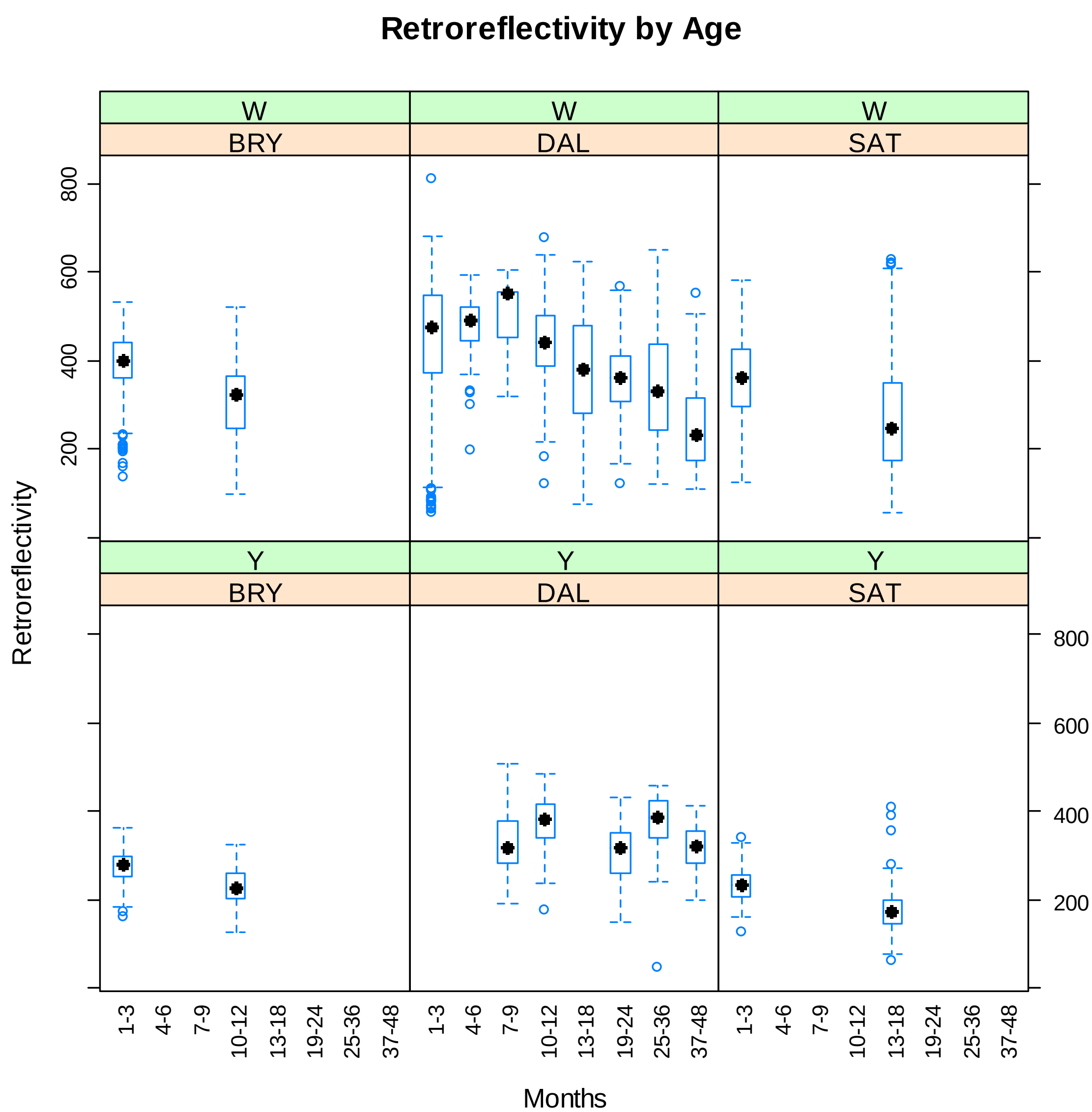

Figure 27. Retroreflectivity Decay by Age Group.

Table 28 summarized the average decay observed by roadways in each district. The percentage of the decay ranges from 3 to 44 percent for the white markings and 6 to 32 percent for the yellow markings. The magnitude of the reduction on average for the white markings is slightly larger than for the yellow markings. The traffic volumes corresponding to each roadway are also noted in the table. The measured roadways in Bryan have low to moderate ADT levels (5000–35,000), while the ones in the Dallas and San Antonio Districts have moderate to high ADT levels. The effects of ADT on average decay in white and yellow markings were examined in Figure 28 and Figure 29, respectively. There does not appear to be a strong correlation between decay of the markings measured with the ADT levels of the corresponding roadways.

Table 28. Decay in Retroreflectivity by Roadways.

District	Road	ADT	Measurement in 2012		Measurement in 2013		Reduction (2012-2013)	% Decrease
			Mean	SD	Mean	SD		
White Line								
BRY	FM60	6750	436.7	48.0	312.4	127.3	124.3	28.5%
	SH40	5000	395.6	42.5	337.7	35.5	57.9	14.6%
	SH47	6700	369.8	67.6	333.7	43.0	36.1	9.8%
	University Drive	35000	367.6	91.2	205.9	55.4	161.7	44.0%
	Average	***13363***	***392.4***	***62.3***	***297.4***	***65.3***	***95.0***	***24.2%***
DAL	I20a	32000	483.3	64.1	424.3	95.1	59.0	12.2%
	I45	62000	330.5	116.5	254.5	97.8	76.0	23.0%
	I635	115000	441.0	84.7	362.1	75.4	78.9	17.9%
	Loop12b	58000	438.9	149.1	311.4	125.9	127.4	29.0%
	SH356	25000	410.9	122.0	365.1	115.7	45.8	11.1%
	Storey Lane	41000	506.3	92.3	372.9	108.5	133.4	26.4%
	Average	***55500***	***435.1***	***104.8***	***348.4***	***103.1***	***86.8***	***19.9%***
SAT	FM1957	22000	360.3	54.0	334.8	63.0	25.5	7.1%
	FM2252	20000	404.5	59.1	392.6	114.2	12.0	3.0%
	Loop13	25000	299.1	58.8	144.8	45.3	154.2	51.6%
	Loop1604a	132000	442.5	48.8	299.1	82.0	143.4	32.4%
	Spur422	25000	391.8	66.9	295.0	70.7	96.7	24.7%
	US90	30000	261.3	60.6	205.3	59.1	55.9	21.4%
	Average	***42333***	***359.9***	***58.0***	***278.6***	***72.4***	***81.3***	***23.4%***
Yellow Line								
BRY	FM60	6750	278.1	46.9	260.9	41.2	17.2	6.2%
	SH40	5000	261.1	31.0	210.2	31.3	50.9	19.5%
	SH47	6700	280.0	31.6	225.0	37.1	55.0	19.6%
	Average	***6150***	***273.1***	***36.5***	***232.0***	***36.6***	***41.0***	***15.1%***
DAL	I45	62000	374.4	63.4	313.6	52.3	60.8	16.2%
	I635	115000	379.3	53.9	323.4	47.5	55.9	14.7%
	Loop12	50000	335.8	69.3	288.9	70.1	46.9	14.0%
	Average	***75667***	***363.2***	***62.2***	***308.6***	***56.6***	***54.5***	***15.0%***
SAT	FM1957	22000	246.2	32.0	178.6	29.2	67.5	27.4%
	Spur422	25000	248.3	36.6	188.8	45.2	59.5	24.0%
	US90	30000	214.6	28.8	146.2	27.2	68.5	31.9%
	Average	***25667***	***236.4***	***32.5***	***171.2***	***33.8***	***65.2***	***27.8%***

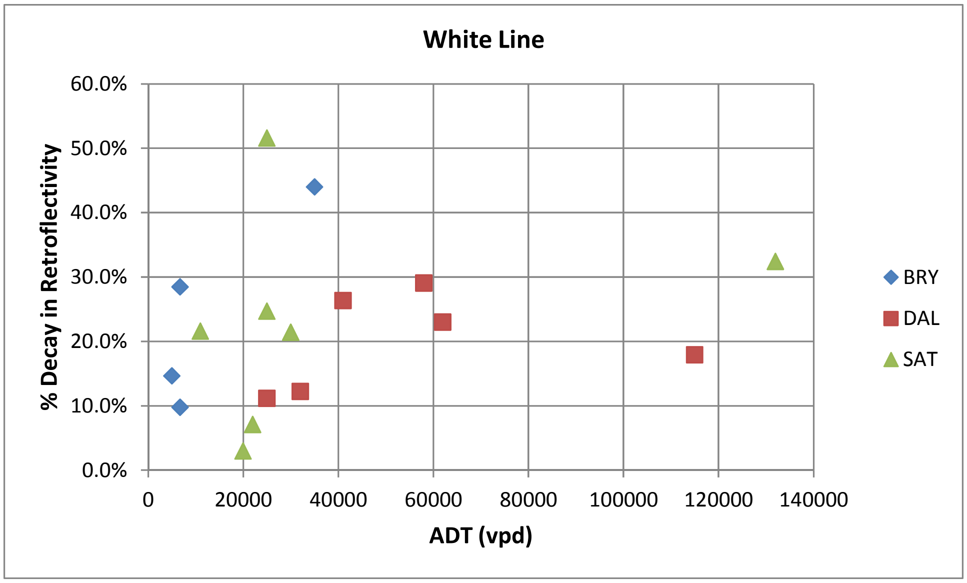

Figure 28. White Marking Average Decay by Roadways and ADT.

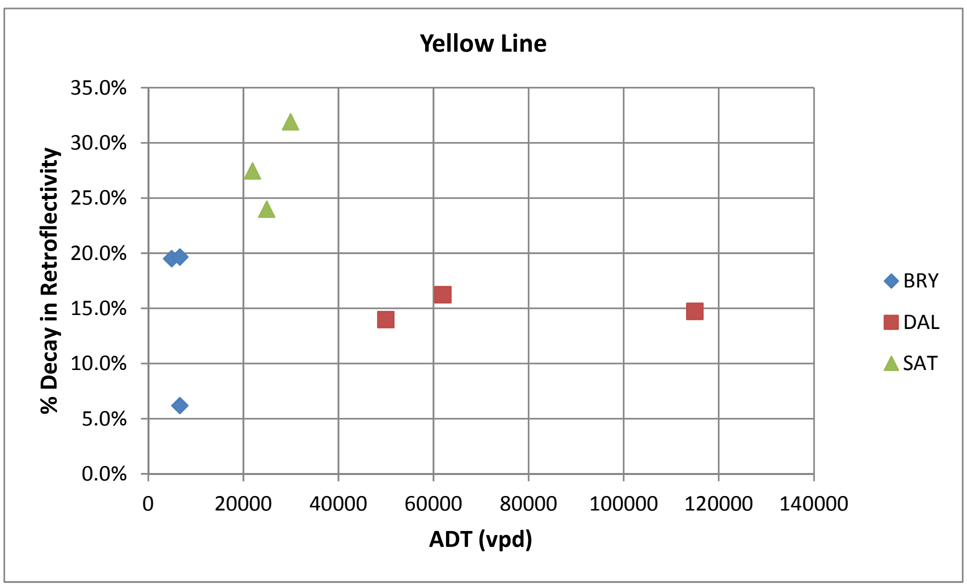

Figure 29. Yellow Marking Average Decay by Roadways and ADT.

To further examine the retroreflectivity decay rates of PBPMMC (SAT and DAL) versus non-PBPMMC (BRY) districts, the researchers utilized linear mixed effect regression models to examine the decay differences between the districts. The measured retroreflectivity was defined as a response variable. The districts and the measurement periods (before and after) were included as fixed effects. The effects of ADT and age of markings were also tested as fixed effects. Each measured segment in both the before and after periods was recognized as a random effect as it directly contributes to the levels of retroreflectivity but is not our primary interest.

The logarithm of the ADT was found to be a significant fixed effect for white markings but not for yellow marking models. The age of the markings was subsequently excluded because the differences in retroreflectivity attributed to the ages are already captured in the roadway segments (random effect).

Two models were calibrated for each marking color. The first model includes districts, measurement periods, and the interaction terms between districts and measurement periods. The interaction terms were designed to capture any differences in decay among different districts in the after period (second measurement). The second model is similar to the first model except that the interaction terms were dropped. The log-likelihood ratio test can then be used to test between the two models whether the interaction term is statistically significant. The significance of the interaction terms indicates that the decays between the two measurement periods are different among districts (i.e., with and without PBPMMCs).

Table 29 shows the two mixed effects models estimated for the white markings. The results indicated that on average white marking retroreflectivity varies among districts. From the estimated model coefficients, Dallas District has the highest white marking retroreflectivity values in the first measurement. The fixed-effect estimates also indicated that the difference in the first measurement of the white marking values between the San Antonio and Bryan Districts is not statistically significant. The average decay between two measurement periods regardless of the districts was 86 mcd/m^2/lux. The differences in the decay when considering the district differences are within ±1 mcd/m^2/lux. The log-likelihood ratio test between the two white marking models indicates that the variables that capture the differences among the districts in the after period are not statistically significant at a 95 percent confidence level (p-value > 0.05).

Table 30 shows the estimated models for the yellow marking. The results indicated that, on average, the yellow marking retroreflectivity is also the highest for the Dallas District, but followed by the Bryan District and then the San Antonio District. The overall decay average regardless of the district was 56 mcd/m^2/lux, which is smaller than the white marking average. However, the average decay varies among the districts more than that for the white markings. In this case, the log-likelihood ratio test between the two yellow marking models indicated that the differences among the districts in the decay of yellow markings are statistically significant at a 95 percent confidence level.

In summary, the analysis results indicated that there are differences in retroreflectivity decay among districts in yellow markings but not for white markings. The differences, however, may not be directly attributed to the practice of PBPMMCs. The decay in yellow marking is larger for the PBPMMC districts (DAL and SAT) than the non-PBPMMC district (BRY), but this could be due to the higher traffic volume expected in the urban districts. The researchers attempted to include the ADT effect into the yellow marking models but it was not significant. The smaller sample size of yellow markings could also contribute to the inability to detect any differences. Overall, this analysis concludes that there is no statistical evidence of whether PBPMMC contracts yields better pavement markings in terms of retroreflectivity.

Table 29. White Marking Mixed Effects Retroreflectivity Models.

White Marking Model 1

```
Linear mixed model fit by REML
Formula: Retroreflectivity ~ log(ADT) + District + Period + District:Period +
(1 | Segment)
   Data: sel.dat
 Subset: Color == "W"
   AIC   BIC logLik deviance REMLdev
 40594 40649 -20288    40620   40576
Random effects:
 Groups   Name        Variance Std.Dev.
 Segment  (Intercept) 3186.6   56.450
 Residual             7275.1   85.294
Number of obs: 3451, groups: Segment, 43

Fixed effects:
                        Estimate Std. Error t value
(Intercept)             591.2372   124.4230   4.752
log(ADT)                -21.9497    13.6222  -1.611
DistrictDAL              82.8110    33.8196   2.449
DistrictSAT              17.2544    26.8700   0.642
PeriodAfter             -85.5781     6.4295 -13.310
DistrictDAL:PeriodAfter  -0.6583     7.8554  -0.084
DistrictSAT:PeriodAfter   0.2244     8.1681   0.027
```

White Marking Model 2

```
Linear mixed model fit by REML
Formula: Retroreflectivity ~ log(ADT) + District + Period + (1 | Segment)
   Data: sel.dat
 Subset: Color == "W"
   AIC   BIC logLik deviance REMLdev
 40601 40644 -20294    40620   40587
Random effects:
 Groups   Name        Variance Std.Dev.
 Segment  (Intercept) 3187.0   56.453
 Residual             7270.8   85.269
Number of obs: 3451, groups: Segment, 43

Fixed effects:
            Estimate Std. Error t value
(Intercept)  591.304    124.372   4.754
log(ADT)     -21.946     13.622  -1.611
DistrictDAL   82.493     33.628   2.453
DistrictSAT   17.352     26.610   0.652
PeriodAfter  -85.786      2.978 -28.807
```

Table 30. Yellow Marking Mixed Effects Retroreflectivity Models.

```
Yellow Marking Model 1
Linear mixed model fit by REML
Formula: Retroreflectivity ~ District * Period + (1 | Segment)
   Data: sel.dat
 Subset: Color == "Y"
   AIC   BIC logLik deviance REMLdev
 15945 15987  -7964    15961   15929
Random effects:
 Groups   Name        Variance Std.Dev.
 Segment    (Intercept)  311.22  17.641
 Residual             2261.04  47.550
Number of obs: 1508, groups: Segment, 16

Fixed effects:
                        Estimate Std. Error t value
(Intercept)              273.700      8.202   33.37
DistrictDAL               92.596     12.356    7.49
DistrictSAT              -36.470     11.407   -3.20
PeriodAfter              -42.828      5.558   -7.71
DistrictDAL:PeriodAfter  -10.863      6.750   -1.61
DistrictSAT:PeriodAfter  -22.654      7.026   -3.22

Yellow Marking Model 2
Linear mixed model fit by REML
Formula: Retroreflectivity ~ District + Period + (1 | Segment)
   Data: sel.dat
 Subset: Color == "Y"
   AIC   BIC logLik deviance REMLdev
 15962 15994  -7975    15972   15950
Random effects:
 Groups   Name        Variance Std.Dev.
 Segment    (Intercept)  293.75  17.139
 Residual             2275.40  47.701
Number of obs: 1508, groups: Segment, 16

Fixed effects:
            Estimate Std. Error t value
(Intercept)  279.941      7.651   36.59
DistrictDAL   87.255     11.593    7.53
DistrictSAT  -48.925     10.481   -4.67
PeriodAfter  -55.534      2.550  -21.78
```

ANALYSIS OF 30-DAY CONTRACTOR READINGS

Under the second San Antonio PBPMMC, the contractor is required to provide the retroreflectivity readings of the new markings within 30 days of the installation. The TTI team also conducted separate measurements on these new markings. This analysis compares the 30-day readings provided by the contractor with the TTI measurements of the same segments conducted within 3 months of the marking installation date. Only the data from the San Antonio District are available for this analysis.

Table 31 compares TTI's versus the contractor's readings of new markings for all segments. On average, the contractor's readings are 5.5 and 18.2 percent greater than TTI's for the white and yellow markings, respectively. The variations in the measurements as measured by the standard deviation are of the same magnitude for both measurement sources.

Table 31. TTI's versus Contractor's Overall Readings.

Color	TTI Readings		Contractor Readings		Contractor - TTI	
	Mean	SD	Mean	SD	Difference	%
White	359	88	379	84	20	5.5%
Yellow	233	35	275	40	42	18.2%

The researchers conducted Welch's two-sample t-test on white and yellow marking readings between the contractor's and TTI's. The results indicated that the two sources of measurements are not equal for both colors at a 95 percent confidence level. The contractor's retroreflectivity readings are greater than TTI's for both colors. For the white markings, the 95 percent confidence interval of the difference is between 8.7 and 30.6 mcd/m^2/lux. The difference is larger for the yellow markings with the 95 percent confidence interval ranges from 33.3 to 51.2 mcd/m^2/lux.

Table 32 presents retroreflectivity readings of new markings by measurement sources, roadways, and marking colors. Figure 30 and Figure 31 show the box plots of the readings from both TTI and the contractor for white and yellow markings, respectively. The contractor's readings were generally higher than TTI's for most of the roadways. The largest differences in percentages were on US90 where the contractor's readings were 20 and 24 percent higher for white and yellow markings, respectively.

Table 32. TTI's versus Contractor's Readings by Roadways.

Color	Road	TTI		Contractor		Contractor - TTI	
		Mean	SD	Mean	SD	Difference	%
W	FM1516	356.9	61.3	398.1	44.9	41.1	11.5%
	FM1518	287.6	34.4	308.0	89.3	20.3	7.1%
	FM1957	360.3	54.0	349.7	43.5	-10.6	-3.0%
	FM2252	405.1	69.7	347.5	65.3	-57.6	-14.2%
	FM2538	463.9	46.1	506.3	83.6	42.4	9.1%
	Spur422	391.8	66.9	372.2	42.7	-19.5	-5.0%
	US90	293.6	73.5	352.5	49.4	59.0	20.1%
Y	FM1957	246.2	32.0	290.7	43.6	44.5	18.1%
	Spur422	248.3	36.6	252.5	24.6	4.2	1.7%
	US90	214.6	28.8	267.0	33.7	52.4	24.4%

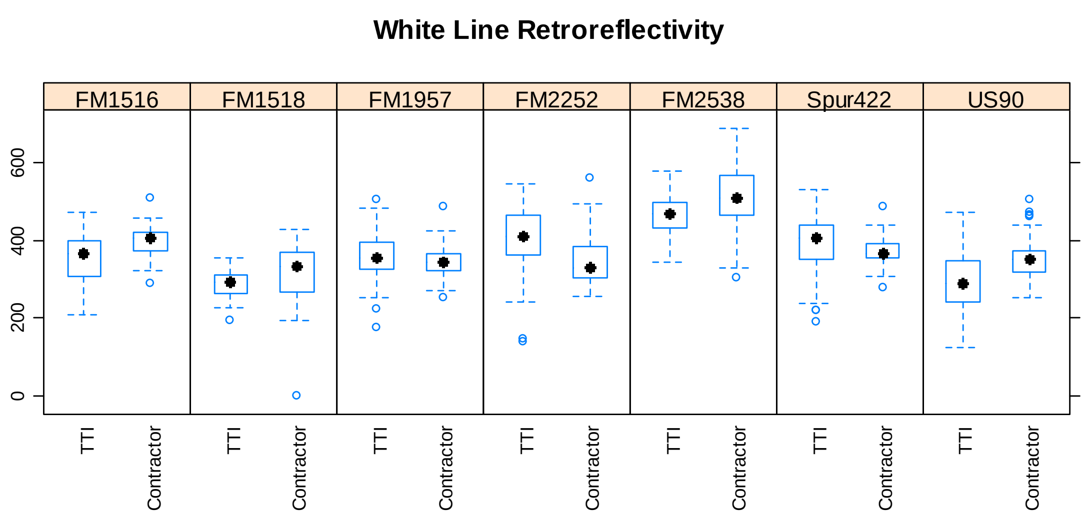

Figure 30. Comparison of White Marking Readings.

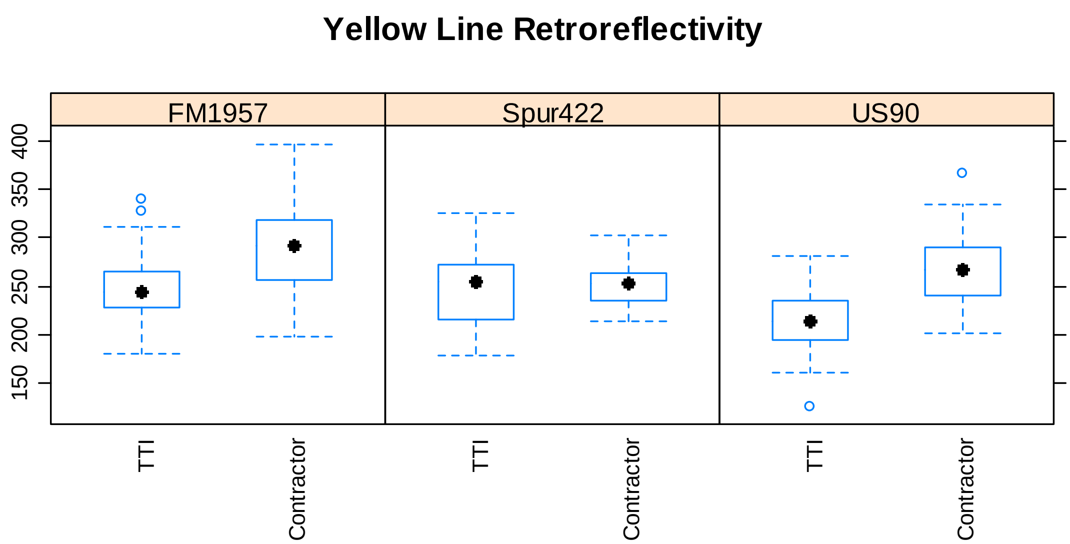

Figure 31. Comparison Readings of Yellow Marking Readings.

To further examine the sources of the differences, the researchers examined the effects of age of the markings at the time of measurement on the retroreflectivity. The TTI measurements were performed within 3 months of the marking installation while the contractor's was usually conducted within the first month. Figure 32 shows that there is a noticeable degradation of the retroreflectivity even within the first few months, which indicates that the age may contribute to the differences in the measurements noted earlier.

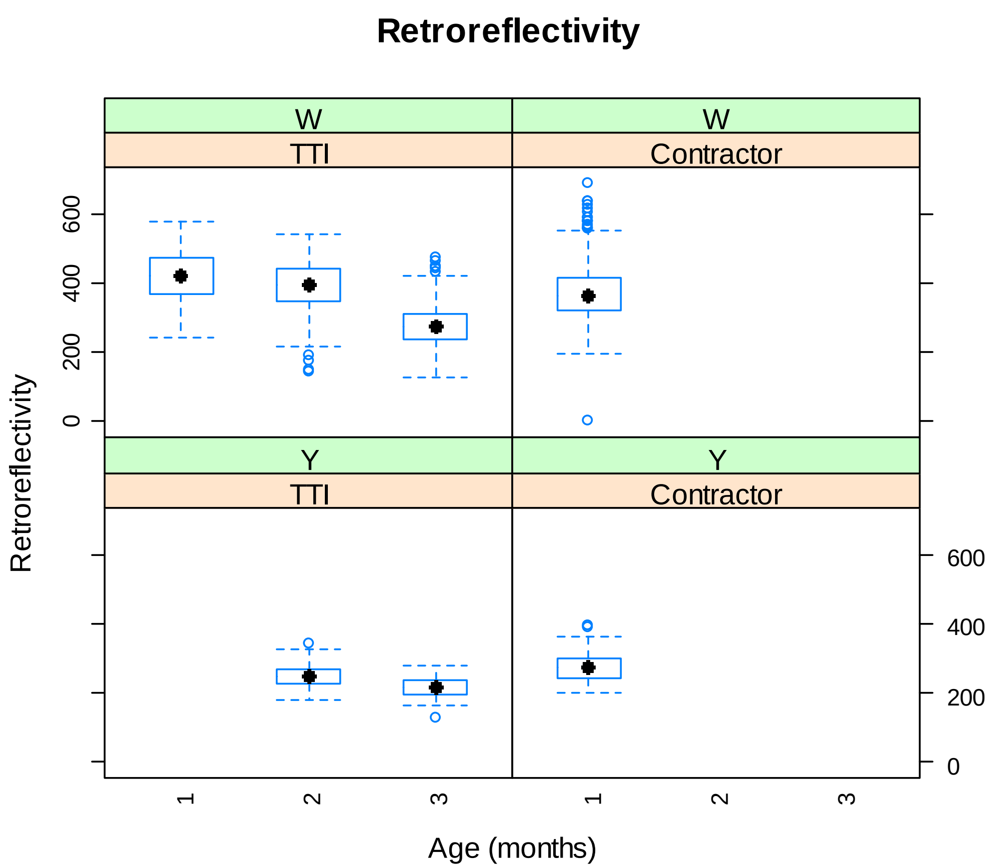

Figure 32. Measurement Comparison by Source and Marking Age.

The researchers conducted the ANOVA analysis to determine the sources of variations in the retroreflectivity readings. The analysis confirmed that the roadway, marking age at the time of the measurement, and the measurement sources all contributed to the measurement variations of the white markings at a 95 percent confidence level. However, for the yellow markings, the difference between the measurement sources was not statistically significant at a 95 percent confidence level. However, the sample size of the yellow markings (6 segments) is somewhat smaller than that of the white markings (19 segments).

Finally, the researchers calibrated the linear mixed effect models to quantify the magnitude of the differences between TTI's and the contractor's readings. The models were estimated separately for the white markings (Table 33) and yellow markings (Table 34). The response variable was the retroreflectivity readings. The fixed effect was the measurement sources (i.e., TTI and contractor). The random effect was the measured segments. The logarithm of age was used in a random effect to account for the nonlinear degradation of the retroreflectivity in each segment. In this way, the model can capture the magnitude of the differences in the measurement source using fixed effect while recognizing the variability of the readings of new markings due to ages and locations.

The modeling results indicated that the contractor's readings are generally higher than TTI's for both white and yellow markings. However, the differences between the two sources were found to be statistically significant only for the yellow markings. The contractor's white marking readings are 7.6 mcd/m^2/lux or 2.1 percent higher, while the corresponding figures for the yellow markings are 30.6 mcd/m^2/lux or 12.8 percent. The differences were less than the observed overall averages discussed in Table 31 when the effects of roadways and ages are properly accounted for.

Table 33. Linear Mixed Model Results for White Markings.

```
Linear mixed model fit by REML
Formula: Left.Peak.Average ~ Source + (log(Age) | Segment)
   Data: both.dat
 Subset: Color == "W"
   AIC   BIC logLik deviance REMLdev
 14234 14265  -7111    14234   14222
Random effects:
 Groups   Name        Variance Std.Dev. Corr
 Segment  (Intercept) 2175.8   46.645
          log(Age)    5633.5   75.056   -0.421
 Residual             3248.2   56.993
Number of obs: 1293, groups: Segment, 19

Fixed effects:
                 Estimate Std. Error t value
(Intercept)       368.950     10.691   34.51
SourceContractor    7.631      6.281    1.21
```

Table 34. Linear Mixed Model Results for Yellow Markings.

```
Linear mixed model fit by REML
Formula: Left.Peak.Average ~ Source + (log(Age) | Segment)
   Data: both.dat
 Subset: Color == "Y"
  AIC  BIC logLik deviance REMLdev
 3176 3199  -1582     3176    3164
Random effects:
 Groups   Name        Variance Std.Dev. Corr
 Segment  (Intercept)  316.83  17.800
          log(Age)     700.85  26.474   -0.541
 Residual             1045.99  32.342
Number of obs: 322, groups: Segment, 6

Fixed effects:
                 Estimate Std. Error t value
(Intercept)       239.918      8.076  29.708
SourceContractor   30.593      9.552   3.203
```

Overall, the contractor's readings were found to be consistent with TTI's measurements. There was no statistical evidence of a significant difference for the white markings. The contractor's readings were found to be higher for the yellow markings but the sample size was much smaller than that for the white markings in this study and the research team's readings were typically after those of the contractor.

CHAPTER 6: COST EVALUATION

This chapter presents the results from the cost-effectiveness comparison analysis. The cost and the effectiveness of performance-based pavement markings and markers contracts were compared to the traditional unit-based method of procurement. The data set available for the analysis included installation report quantities, reimbursement reports, and markings and markers condition assessment from 2006 to 2011 for the San Antonio District. The Dallas District data included records from 2010 through the termination of the contract; however, the data set did not include as many items in the reported quantities of work. Therefore, the Dallas data were not explored as in-depth as the San Antonio data set. The analysis of the Dallas data set is provided in Appendix B.

RESEARCH APPROACH

The research approach adopted in this study is based on statistical analysis of data collected during TXDOT's first San Antonio District PBPMMC. More specifically, it involves three steps:

1. Data set assembly, where a number of different data sources were pulled together.
2. Data analysis, where three research questions were formulated and the appropriate statistical method of analysis was selected.
3. The interpretation of the results in context of defined research questions.

Figure 33 illustrates this process, and discussion of each step follows.

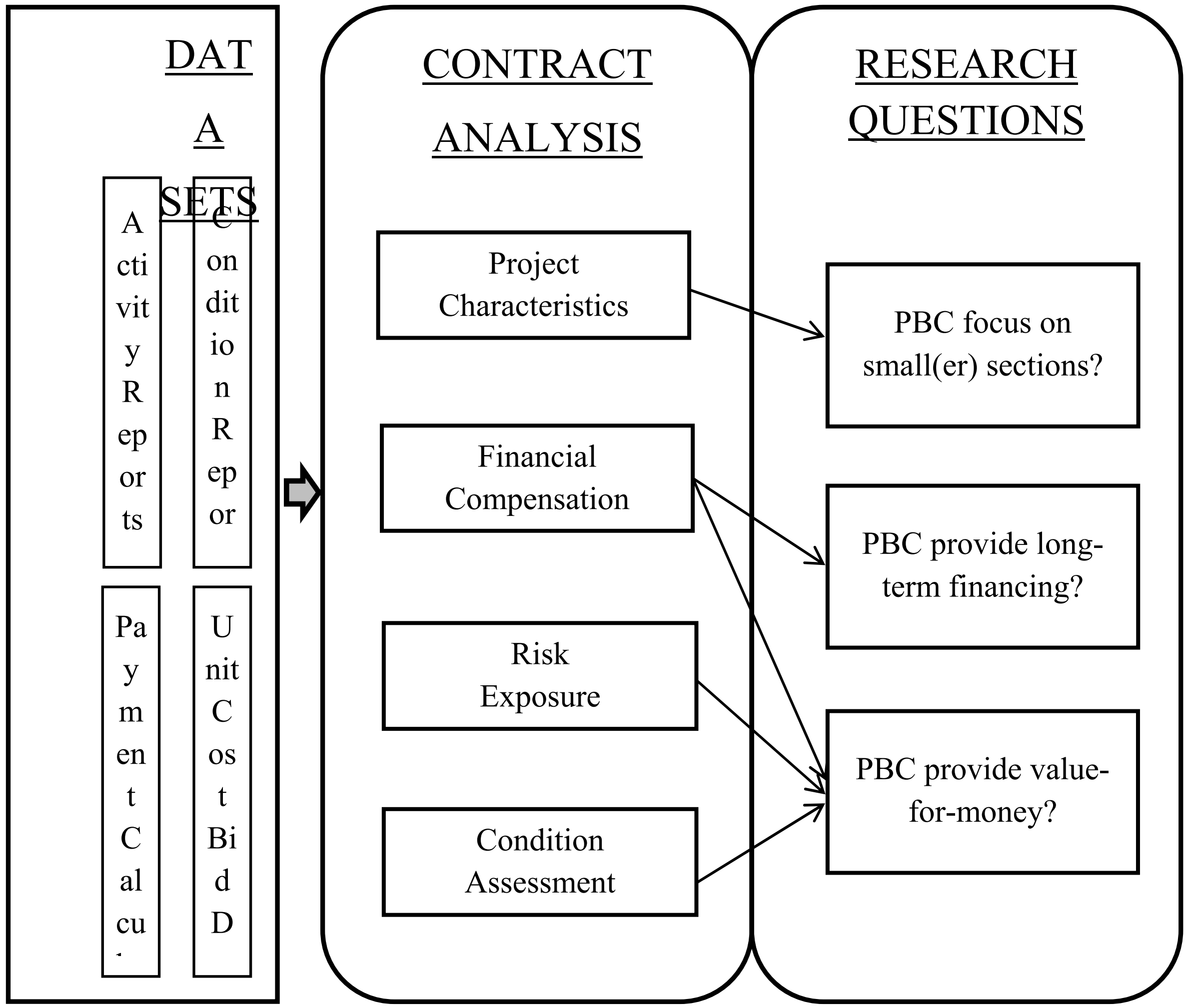

Figure 33. Research Approach.

Data Sets

Four data sources were pulled together to provide the analysis data set. TxDOT's unit bid item codes were used to link the reported quantities on bid items and the cost from TxDOT's maintenance bid database, while control-section-job (CSJ) with beginning and ending reference markers were used to identify unique projects spanning multiple months. Data from monthly payment calculators, i.e., payments and deductions including operational modifications and callout work, were then linked to activity reports and condition assessment reports.

TxDOT condition assessment samples were obtained on a monthly basis. The procedure included generating a random sample of 60 sections from the managed network. Each section then received a grade ranging from 5 (excellent) to 1 (failed) for the following performance measures: a) reflectivity, presence, width, and standard for markings; and b) reflectivity and standard for markers. The scores for all measures were then averaged independently for markings and markers, leaving 60 section scores. Finally, an average of 60 sections produced the network condition score that was used to determine if deductions should be assessed for that assessment period.

Unit cost bid data for unit items included prices from fiscal year (FY) 2005 and 2012. Note that the cost data are for traditional contracting methods, not the performance-based contracts. Full cost data from the beginning of the contract in September 2006 until September 2011 was unavailable to the research team. To overcome this difficulty, the team has created two cost bounds (upper and lower), one from the beginning of the contract (2005) and one from the end of the contract (2012). Note that the prices in 2012 were significantly higher than in 2005.

In addition, complete contract documents were available to the research team. This included network plans and roadway locations, planned construction work, cost reimbursement, and deduction formulas, as well as other typical contract items.

Research Questions

The available data provided means to investigate the characteristics of projects undertaken by the contractor, dynamics of financial transactions between TXDOT and the contractor, network condition improvement, and project risk exposure from the contractor's perspective. The research team used these contract analysis elements to answer the following research questions: 1) Are the management strategies in this PBPMMC any different than in traditional contracts? In other words, is there evidence that the contractors in long-term performance contracts tend to focus on smaller sections? 2) Did the PBPMMC provide financing? In other words, did the contractor provide more work in the early years of the contract and get compensated for that work in later years? and 3) Do PBCs for pavement markings and markers provide value-for-money? The intention is that the answers to these questions would guide future implementation of performance-based contracts in Texas.

Assumptions

The analysis was conducted using several assumptions including two key assumptions. First, reported quantities are the actual quantities; this implies that self-reports of the work done by the contractor are factual. The research team had no evidence to suspect that the contractor has not reported the actual quantities. Second, the scope of work was determined by the contractor, not imposed by the agency. Note that TxDOT provided a list of projects that needed to be done in the first year. There were no such requirements for the followings four years.

The research team did not analyze the burden of the contract on TxDOT as far as man hours required compared to traditional contracting. This was due to TxDOT indicating that their burden was similar if not slightly more for the PBPMMC compared to the standard contracts.

DATA ANALYSIS

Management Strategy Analysis

One of the most important elements of the contract performance is the analysis of the contractor's management strategies. Anecdotal evidence from literature suggests that contractors are able to exploit efficiency by focusing on smaller sections, i.e., only on the parts of the network that are failing the condition, regardless of their size. Figure 34 shows the distribution of the long-line projects' sizes in linear feet during the contract duration. A total of 850 unique projects were identified, with nearly 35 percent of them below 3000 feet. Also, it can be observed from the figure that almost 80 percent of unique projects are less than 40,000 linear feet, with more than 50 percent being less than 10,000 linear feet.

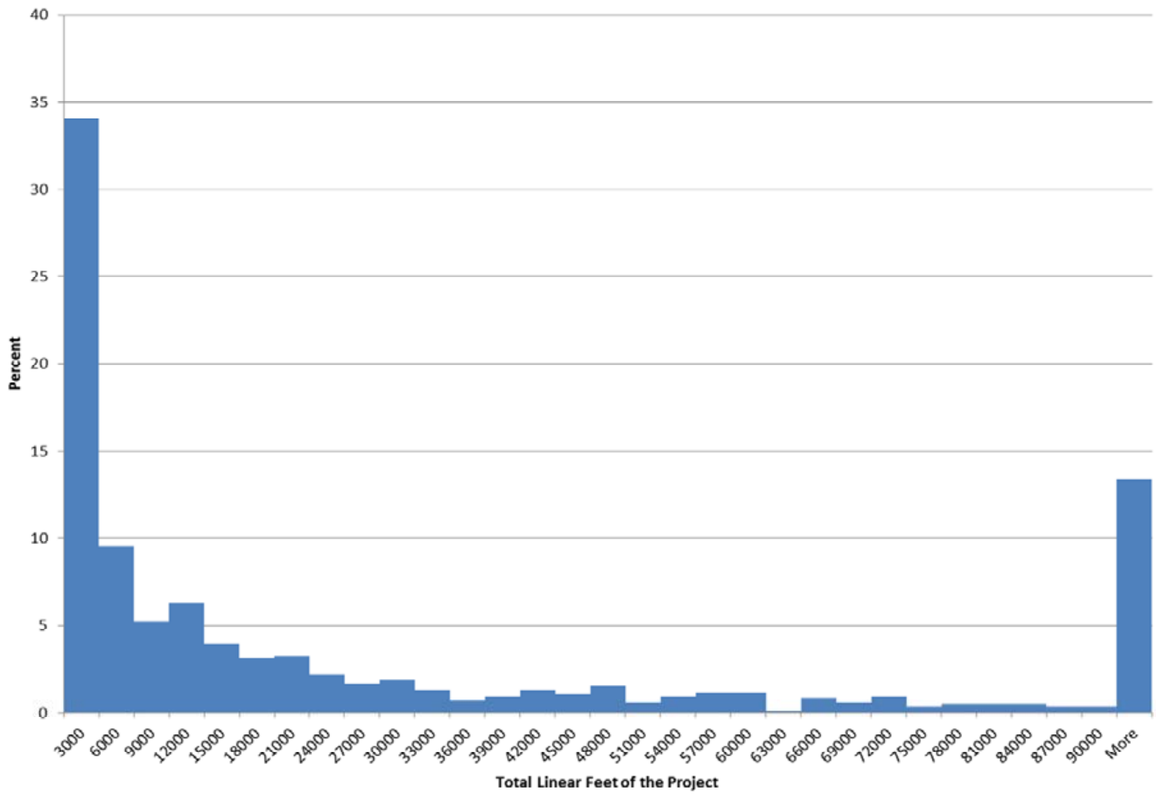

Figure 34. Histogram of Long-line Project Sizes.

The next interesting factor in analyzing the contract was the dynamics of the work done. Theoretically, the PBPMMC should not stipulate the timing of the work. However, in many instances the agencies assign specific projects that need to be completed in the contract's early years. Figure 35 shows the project dynamics during the five-year contract. The projects are classified into two categories: 1) "0" projects that include markers and short-line work, and 2) long-line projects. It can be observed from the figure that the peak in project frequency occurred during the third year of the contract. Notably, the first year did not bring the increased number of projects as one would expect, especially considering this contract had stipulations of work that was required in the first year. One thing to consider is that in the first year of the project, performance deductions were not actually assessed to the contractor. The contract gave the contractor one year to get the system up to the performance requirements, so there was no need for the contractor to rush to bring the system up to the required standards (assuming the system was below standards to begin with).

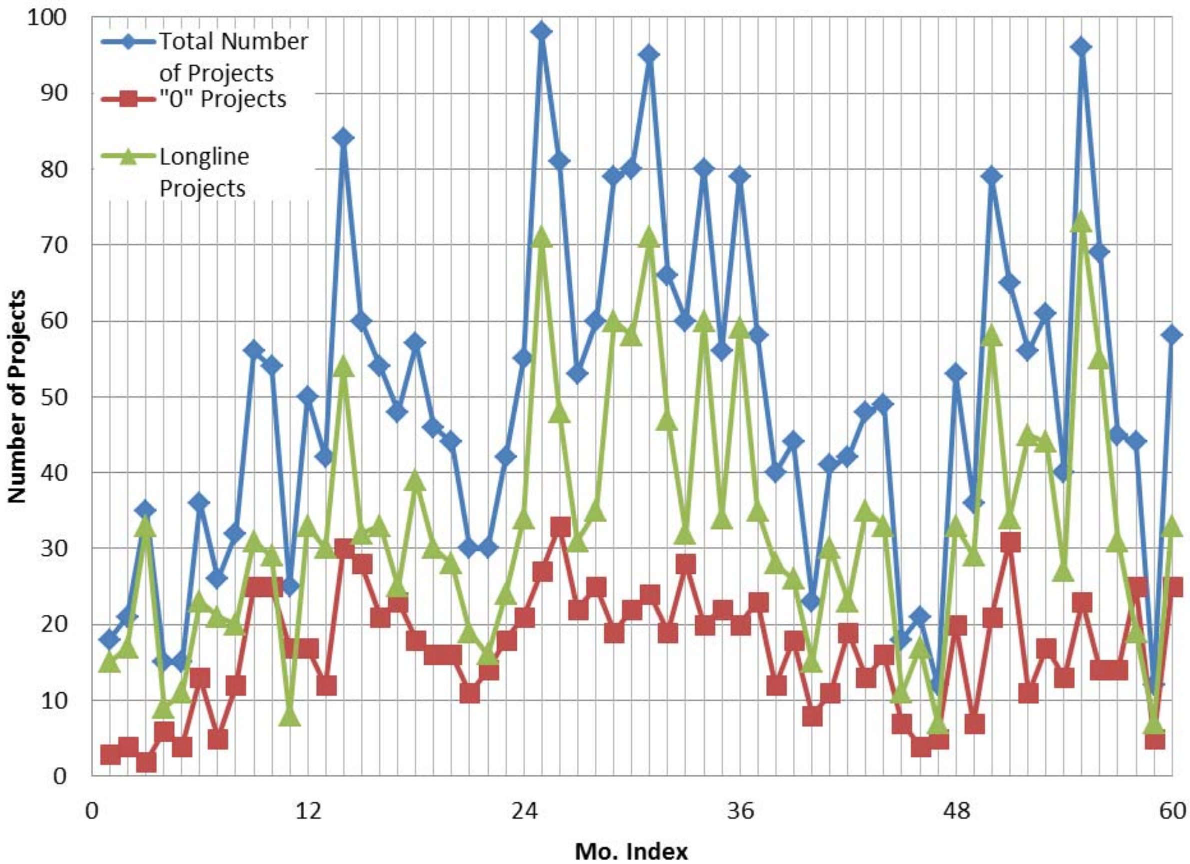

Figure 35. Project Work Dynamics (San Antonio District).

Value of Work Assessment

The financial compensation provided to the contractor compared to the work produced was of great interest to the research team. This section provides analysis of the cost of the first San Antonio contract verses the work performed. Table 35 shows the overall summary of the value of the work done, calculated using reported quantities and corresponding unit prices from two different years, 2005 and 2012. The table also includes data on callout and operational modification (OM) work, as well as "contracted" non-callout work. Note that the winning contractor's bid was $23,381,391.32 and the engineering estimate was $25,000,000.

Figure 36 shows a) the base payment distribution from the contract and the payment calculators without consideration of any other extra work, such as callout or operational modification, and b) value of the work calculated using the bid prices from 2005. It can be observed from the figure that the contractor did not provide financing during the early stages of the contact. The variance in cost over time may reflect the nature of the contract and scheduling of the work to respond to condition assessments.

Table 35. Value of Work Performed.

Contract (Bid Prices Used)	Callout Work	Non-callout Work	Operational Modifications (Reported)	Total Value of Work Performed
San Antonio (2005)	$1,300,674.73	$17,043,756.30	$1,065,000.00	$19,409,431.03
San Antonio (2012)	$1,767,601.26	$22,591,685.94	$1,065,000.00	$25,424,287.20

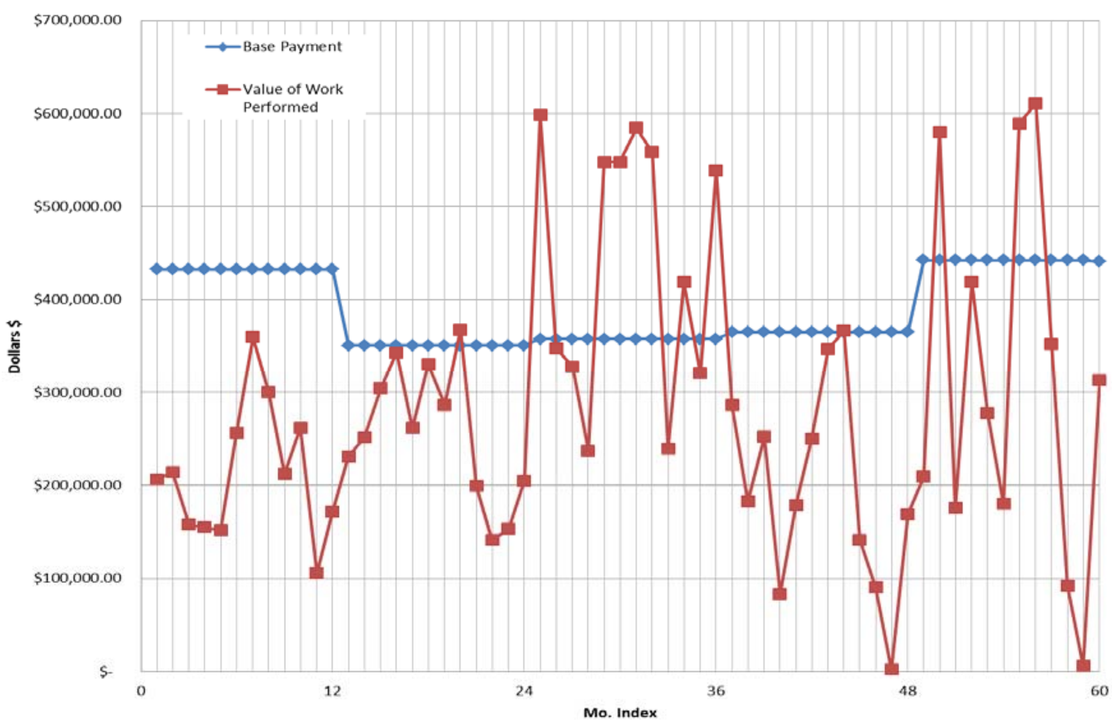

Figure 36. Contract's Monthly Payments and Value Analysis.

The sum of the OM and the callout work for each month are presented in Figure 37. These data reflect the amount of money spent on projects that were not scheduled. The peak for operational modification and callout work occurs at the ninth month, and it accounts for almost $90,000. There was a total of $2,266,001.82 spent for non-scheduled items. Note that the contractor who was awarded the PBPMMC was given this additional work and, thus, could count on this work to supplement the regular payments over the contract period.

Figure 38 shows the sum of the performance deductions for each month. These deductions are based on monthly assessments, quarterly reviews, and other liquidated damages. The first year accounts for some of the largest deductions. This can be attributed to the fact that the contractor was not able to restripe all the roads that needed immediate attention. Note that for the first year, the assessment score deductions were not actually enforced, so there was little incentive to get the markings up to standard early in the contract.

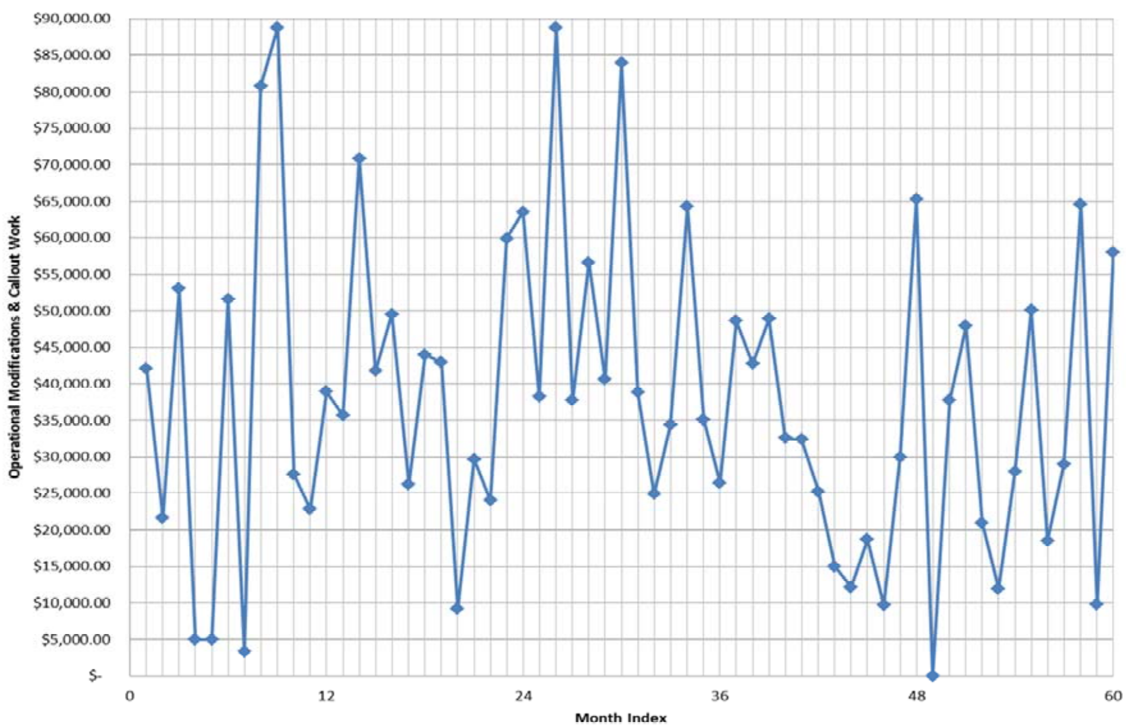

Figure 37. Operational Modifications and Callout Work.

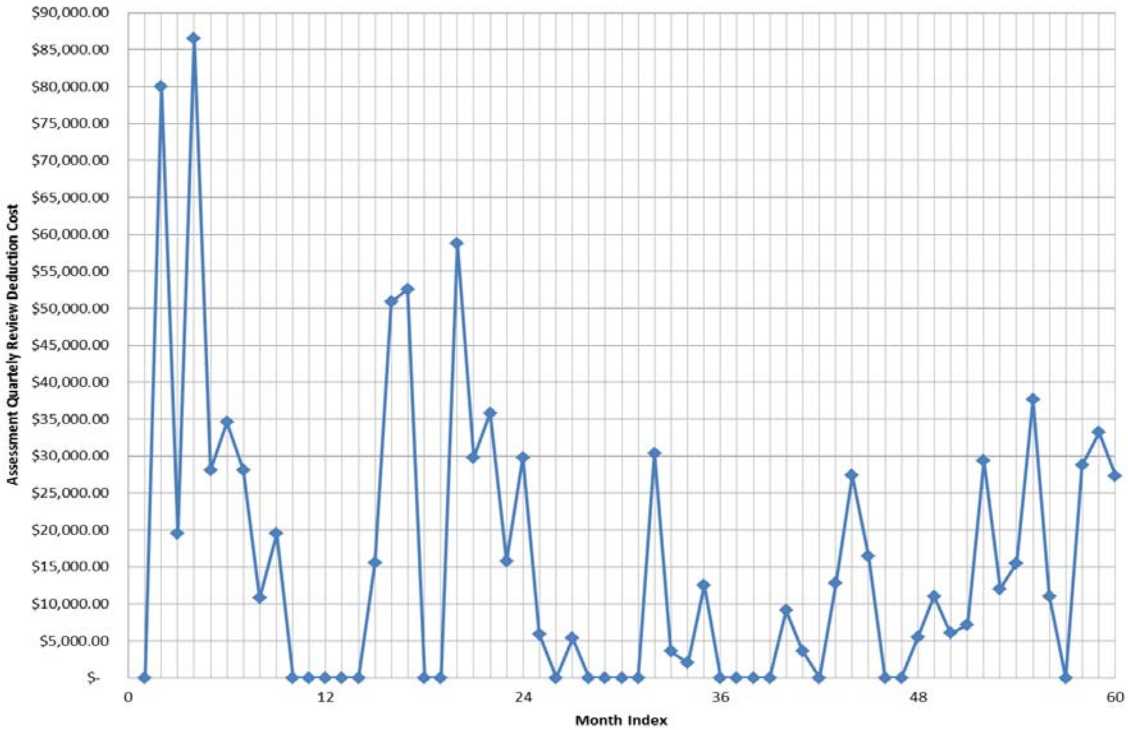

Figure 38. Monthly Deductions.

Table 36 summarizes the contractor's financial reimbursements on different accounts. In total, the contractor was paid $23,953,844.62, and the value of the work performed was estimated to be between $19,409,431.03 and $25,424,287.20. Being that those values are based on bid prices from the start and end of the contract, the average value of $22,416,859.12 is a reasonable value of the work performed over the course of the contract. This would indicate the contractor was paid approximately $1.5 million more than the value of the pavement marking and marker work performed over the length of the contract. The district estimated the contractor was paid approximately $4.5 million more than the value of the work performed. This would be the case considering all the work was performed using the statewide 2005 bid prices for the entire project. These values do not take into account additional managerial requirements that the PBPMMC required nor do they account for the performance monitoring the contractor was required to conduct.

Table 36. Summary of Payments and Deductions.

Base Payments	Assessment Deductions	Other Deductions	O&M	Callout Work
$23,381,391.41	$889,408.29	$804,140.32	$1,065,000.00	$1,201,001.82

Condition Assessment Analysis

An important aspect of the analysis of performance-based contracts is condition assessment, or whether the network condition has improved, remained the same, or worsened. As previously discussed, the assessment factor is an average measure of several indicators including reflectivity and presence. In other words, in performance-based contracts, the assessment factor represents a number that determines the quality of work performed. In fact, the contract deductions are made based on this number. The assessment scores over 3.0 did not trigger any deductions.

Figure 39 represents the monthly assessment factors (blue line) and a 3-month moving average (green line). This was done to account for monthly sample-to-sample variability of the scores. Note that there was assessment data missing for two of the months. The variability in the assessments from month to month is likely an indication of too small of a sample size to adequately assess the system. By comparing the assessment factors and the moving average it can be seen that there is limited variation of the assessment scores over the course of the contract. The scale on the left side of the figure is less than one assessment point. The difference between the highest and lowest assessment scores is less than 0.75 when looking at the individual month average, and less than 0.55 when looking at the 3-month moving average. The 3-month moving average started at about 2.7 and ended at about 2.9, a 0.2 increase. Being that the system began in a condition below the deduction level and month-to-month rating assessments varied by up to almost 0.5 points, it is difficult to say there was great improvement to the markers and markings maintained under the contract.

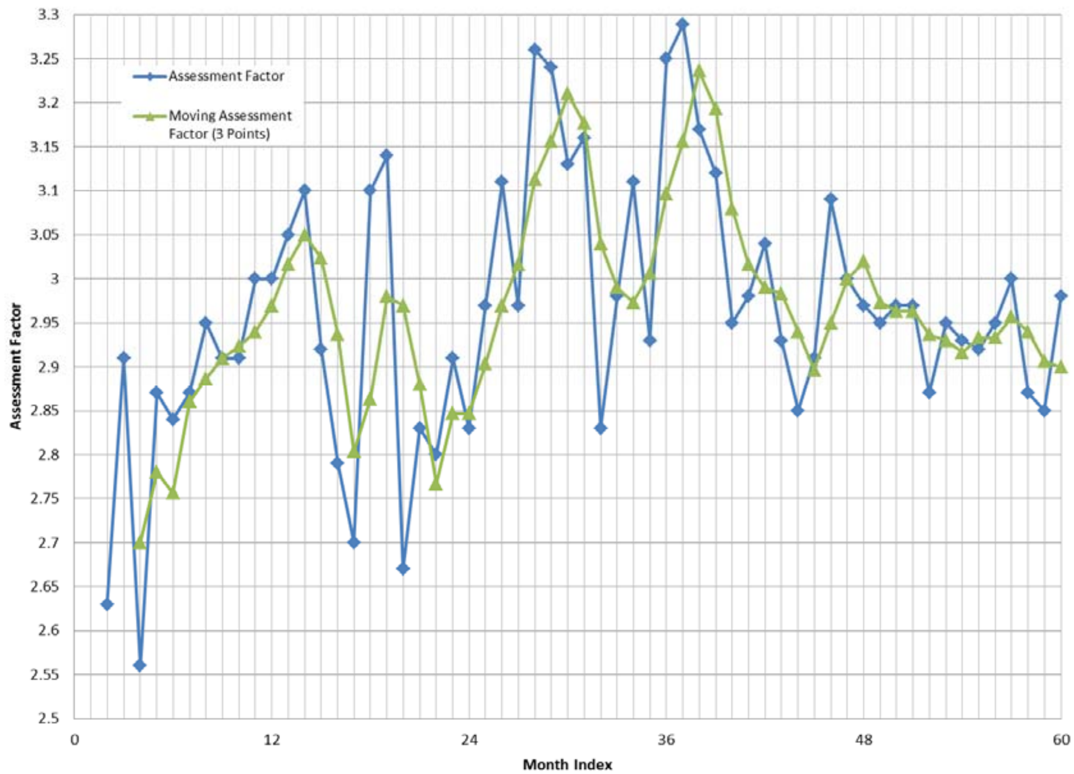

Figure 39. Assessment Score Dynamics.

Next, monthly man hours were compared to the assessment scores. The man hours were added in pairs (two consecutive months) and then divided by 4000 in order to scale it properly for the visual comparison with the 3-month moving average of assessment scores (Figure 40). The researchers expected to see to some level of positive correlations—the more work, the better the score. The correlation coefficient for normalized values for 2-month cumulative man hours and 3-month moving average for assessment scores was 0.183525413, confirming the positive correlation hypothesis.

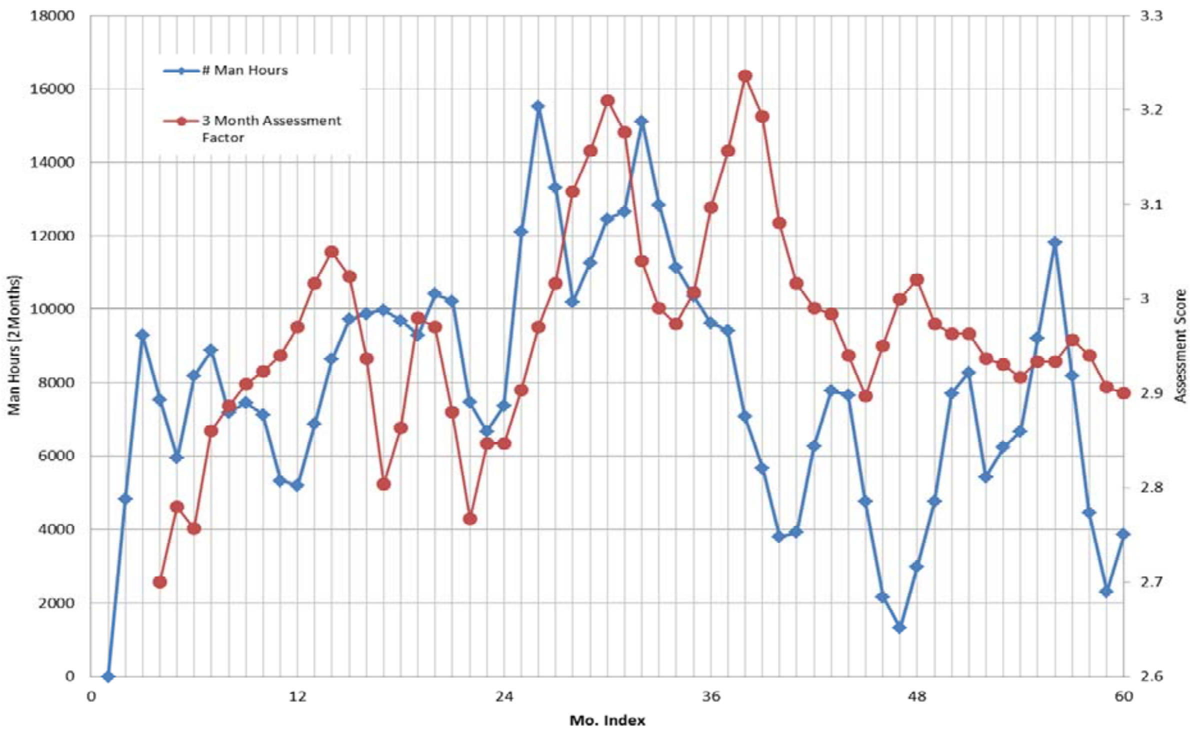

Figure 40. Man Hours – Condition Relationship.

Finally, a Monte Carlo simulation was conducted to assess the level of performance based financial risk that was allocated to the contractor. This simulation was done by estimating the distribution of potential losses, i.e., deductions from base payment of the contract under no improvement/work scenario. Under such a scenario the assessment score was calculated using a function: $f(x) = 2.5 - Slope*X$, where 2.5 was the initial condition, and the slope represents the degradation rate. To obtain this rate, a random sample from uniform distribution was used. The deductions were then calculated using the contract formula. Figure 41 shows the distribution of monthly deductions. Here, it is interesting to observe the relationship between risk and reward. It seems that the contractor had a limited amount of risk; even under a no-work scenario, the payments would exceed the deductions. In other words, the contractor did not carry much risk and the prices should not have been inflated to account for risk, as is typical in lump-sum contracts.

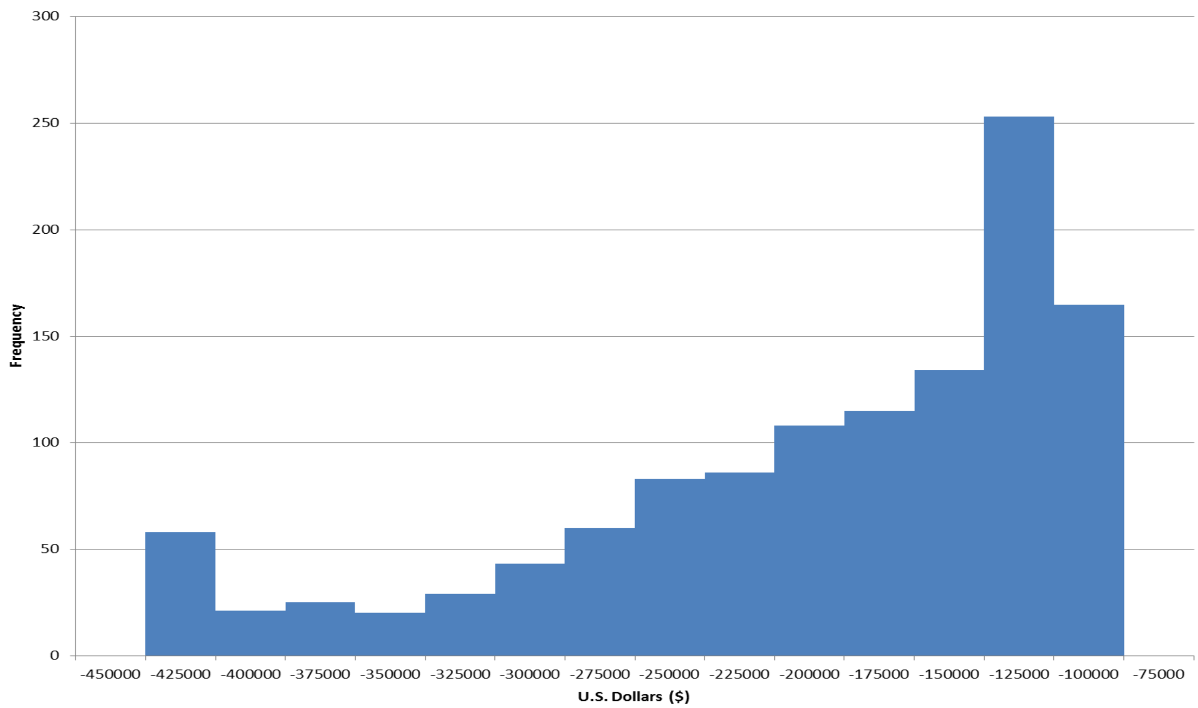

Figure 41. Distribution of Monthly Deductions from Monte Carlo Simulation.

FINDINGS AND IMPLICATIONS

The first research question was whether the contractor under the first PBPMMC in San Antonio utilized smaller management sections. Based on data from the contract, we can conclude that the private sector utilizes smaller sections to address only the parts of the roadways that actually need work. This benefit is a bit harder to transfer to traditional contracts—if the section is too small, there will be no interested bidders, and if the section is too big, there will be portions of the section that do not need the work. This holds for all types of linear distributed structures where failure is typically localized.

The second research question was whether the contract provided financing. The answer to this question is no. In the first San Antonio contract, the contractor has done less value of work than it was compensated for in the first year of the project. More suitable contract types for obtaining a long-term financing are public private partnerships (PPP) with availability fee compensation and performance requirements.

Finally, the third research question was whether the first San Antonio contract provided value-for-money. Here, the answer again is likely no. At best, the value of the work provided by the contractor matches the cost of doing the work using the traditional perspective contracting, and the condition of the system was not greatly improved. Note that this does not imply that all performance contracts do not provide value for money; just this one does not appear to. Before implementation the agencies should know answers to the following questions:

1. What is the level of unacceptable condition and, more importantly, how to try and assess the impact of operating under such condition?
2. What is the current state of the network? Providing details on the current condition reduces the uncertainty in scope, which typically implies higher premium.

SUMMARY AND CONCLUSIONS

This chapter provides an analysis of the effectiveness of the first San Antonio performance-based pavement marking maintenance contract. The analysis of the contract from the Dallas District was limited by availability of data and is summarized in Appendix B of this report. The overall emphasis of the analyses was given to providing a better understanding of how such contracts function, and more specifically what were the contractor's management strategies, what was risk allocation arrangement, how was the performance assessed, and how was the contractor compensated. The overall finding from this study indicates that this particular contract did not provide some of the key benefits of performance-based contracting. While not providing these benefits, the contract results were likely similar to contracting the work with a traditional contract.

CHAPTER 7: SPECIFICATION EVALUATION

This chapter uses the results from the previous chapters to determine if developing revised performance measures and measurement protocols for pavement markings by roadway type is warranted for inclusion in future PBPMMCs. In addition to evaluating revised performance measures and measurement protocols, the research team evaluated modifications to the performance-based pavement marking maintenance special specification to reflect the revised performance measures, measurement protocols, and any other areas where modifications may be beneficial to future contracts. Key differences between the three PBPMMCs issued in Texas are also noted.

EVALUATE PERFORMANCE MEASURES

Both the first San Antonio (*47*) and Dallas (*48*) PBPMMCs had the same performance measures for markings and markers. The colors of the markings need to meet specific chromaticity requirements, but the specification requires only visual assessment of the color. The specification does note that non-uniform color will be assessed as failing by the engineer.

The longitudinal markings are required to maintain at least the minimum retroreflectivity performance values indicated in Table 37. Transverse markings do not have to meet the retroreflectivity requirements, but they must meet presence requirements.

The second San Antonio contract (*49*) added a minimum initial retroreflectivity requirement. The initial retroreflectivity is to be measured 30 days after installation and must meet the values indicated in Table 37. Under the table in the performance-based specification it indicates that, "Readings must be within 10 percent of the minimum required lowest acceptable value." This would indicate that the markings do not need to actually meet the values listed, but that they only need to be within 10 percent of the values. To make things even more convoluted, the deductions for initial retroreflectivity readings refer to another percentage as follows, "For failing readings (readings that are more than 5 percent below the lowest acceptable value…) contractor will be allowed re-stripe once within a 30 day period of the original placement of the marking. If failed readings still exist, a deduction of up to 10 percent of the monthly payment will be assessed." This is likely oversight in writing the specification as it seems it is referring to the 10 percent previously noted.

Table 37. PBPMMC Retroreflectivity Requirements.

Pavement Marking Type	All 3 PBPMMC Minimum Maintained Retroreflectivity Level	Second San Antonio PBPMMC 30-Day Initial Minimum Retroreflectivity Requirement
White Pavement Markings	175 mcd/m^2/lux	250 mcd/m^2/lux
Yellow Pavement Markings	125 mcd/m^2/lux	175 mcd/m^2/lux

Being a performance-based maintenance contract, setting requirements for initial performance is an additional factor the contractors need to consider and will price accordingly (i.e., increased price). It is not typical for this type of contract to have initial requirements; the maintenance of the asset above a minimum level is typically the only performance metric of concern. In general, the numbers given are not difficult to achieve with good pavement markings and a good installation. The area where trouble would possibly be expected is the yellow requirement on a two-lane two-way chip seal roadway. It is typically more difficult to achieve high retroreflectivity values with this type of marking application. The measurements from the research team and the 30-day readings from the contractor indicate that the minimum initial readings are being met.

The minimum maintained retroreflectivity values are above what is expected to be the minimum values that would be established by the FHWA. When the markings are supplemented with adequate RRPMs, there may not even be minimum FHWA retroreflectivity requirements. The research team feels these are acceptable levels for this type of contract as they do not put excessive burden on the contractor to continually restripe (increased costs), and the retroreflectivity levels will still provide adequate guidance. As shown within the Chapter 5 data collection and analysis, the contractors are restriping the roads when they are near or below the minimum maintained values. The first San Antonio and Dallas contracts directed the contractors to schedule restriping when the markings reached the minimum maintained values. The second San Antonio contract directed the contractor to restripe within 30 days when the minimum maintained levels were reached. Because the minimum maintained values are above what is expected to be the minimum values that would be established by the FHWA, the practice of striping after they reach these levels is acceptable.

One issue that may arise is the frequency of retroreflectivity measurement compared to the degradation of the markings' retroreflectivity. Measurement frequency is annually on all roadways in the second San Antonio contract. Measurement frequency is 6 months for high exposure and 12 months for medium and low exposure on the other two contracts. With annual measurement of the markings, some markings that are just above the minimum values during one measurement period may not get restriped until more than a year later when they are next measured. At that point they have likely fallen below the minimum. It is worth considering adding in additional retroreflectivity readings at 6 months for roads that measured below a given value (e.g., 200 white, 150 yellow), but above the minimum, during the annual measurements. This will result in less lag time between when the marking falls below the minimum maintained level and when the restriping actually occurs. Requiring restriping within 30 days of failed measurements is a good measure to take to make sure a roadway with failing markings does not go several months before it can be fit into the striping schedule. The second San Antonio contract does require the contractor to visually assess each roadway quarterly, but there are no defined performance measurements that are required. The requirement is to visually assess the roadways and bring deficient sections up to standard within 90 days. It may be beneficial to use the monthly DOT assessments to determine which roadways the contractor should focus on, or to at least supplement the contractor-conducted visual observations.

A visual assessment of the presence of the markings is to ensure the markings maintain day- and nighttime visibility, length, width, shape, size, and configuration. The current specification requires that no more than 5 percent of longitudinal markings, by each separate line, be deficient in any 1-mile distance and that no more than 10 percent of transverse markings be deficient at each separate placement location (placement location is defined as an intersection or a lane movement area). These requirements equate to 4 out of 5 for the presence condition assessment criteria. Greater than 20 percent longitudinal and 30 percent transverse is considered a failed condition, equal to a 1 out of 5 condition assessment. The current presence assessment criteria are appropriate for the contract.

Raised reflectorized pavement markers are also to be maintained as part of the PBPMMC. The current specification indicates that performance is to be measured during nighttime visual retroreflectivity evaluations using a passenger vehicle with the headlights on low beam. The markers within the range of the headlights must appear reflective and meet the following criteria per line of markers: four markers must be reflective when placed on an 80-foot spacing, or eight markers must be reflective when placed on a 40-foot spacing; less than

10 percent, over a 1-mile distance, can be non-reflective or missing, with no more than three consecutive markers missing or non-reflective.

The condition assessments for the markers were the same for the first San Antonio and Dallas contracts. The second San Antonio contract lowered the percent missing for the fair and failing levels, see Table 38. The RRPMs were considered an area that needed improvement after the first San Antonio contract. Lowering the thresholds will result in more failing sections that would have previously been considered fair. This will result in lower assessment scores and possible deductions if the RRPMs are not maintained to at least standard conditions. The research team feels lowering these thresholds is a good decision to improve the quality of the roadway delineation, even though it may result in a slightly higher cost.

Table 38. RRPM Presence and Retroreflectivity Condition Assessment Criteria.

Contract	Excellent (5)	Good (4)	Standard (3)	Fair (2)	Fail (1)
First San Antonio and Dallas	100% in place and reflective	Less than or equal to 5% missing or non-reflective.	Greater than 5% and less than or equal to 10% missing or non-reflective.	Greater than 10% and less than or equal to 49% missing or non-reflective.	Greater than 49% missing, non-reflective fail.
Second San Antonio	100% in place and reflective	Less than or equal to 5% missing or non-reflective.	Greater than 5% and less than or equal to 10% missing or non-reflective.	Greater than 10% and less than or equal to 20% missing or non-reflective.	Greater than 20% missing, non-reflective fail.

The second San Antonio contract included additional information on the department evaluation of the contractor performance pertaining to the evaluation of RRPMs. A table was created to assist with the percentage of missing RRPMs depending on the number missing and the spacing of the RRPMs (see Table 39).

Table 39. Percentages of Raised Pavement Markers Based on Spacing.

Percentage	40' Spacing	80" Spacing
5%	7–12 ea.	3–6 ea.
10%	13–25 ea.	7–12 ea.
20%	26 ea. or more	13 ea. or more

EVALUATE MEASUREMENT PROTOCOLS

The protocols to evaluate the performance of the markings and markers have remained relatively unchanged for the three PBPMMCs. One significant change was the inclusion of Special Specification 8094, "Mobile Retroreflectivity Data Collection for Pavement Markings" (*22*). This special specification was finalized after the first San Antonio contract was let for bid and, thus, was not included. The special specification made many improvements over its predecessor that was included in the first San Antonio contract. The improvements included modifications to required summary information, and the inclusion of mapped retroreflectivity based on color-coded retroreflectivity levels.

Many aspects of the measurement protocols were described in the performance measures section. Additional information will be provided below to expand on what has already been discussed. The pavement markings are required to be measured using a certified mobile retroreflectometer; the exception is low-exposure roads where a visual inspection is adequate (no low-exposure roads were included in the second San Antonio contract). The contracts provide the reporting format to be used when evaluating the performance of the markings. Retroreflectivity values of longitudinal pavement markings are to be summarized ever 0.25 miles. A visual assessment of raised reflectorized pavement markings, marking color, and marking presence are the other current means of contractor evaluation in the measurement protocol. The research team feels that the 0.25-mile length for the averaging of the pavement marking retroreflectivity and the visual observations of other performance measures is acceptable. Anything other than visual observations for the other performance measures would be time consuming (increased cost), and the benefit would likely be small if any.

To help ensure that the contractor is properly monitoring the markings and providing accurate data, TxDOT conducts an evaluation of the contractor performance. The current levels of performance monitoring are as follows. Samples will be selected randomly from contract roadbed centerline miles and will be based on 1-mile segments. For interstate and divided highways, the mile samples will include only one direction of travel. Frontage road roadbed centerline miles will be considered separately. For all other highways, with one roadbed, the assessment will include both directions of travel. Sample sizes, unless otherwise indicated on the plans, will be 5 percent of the centerline miles for each exposure; the first intersections within the 1-mile segment for each exposure will be evaluated, and a minimum of two roadways for each exposure will be evaluated at night, unless otherwise indicated on the plans. These parameters have not changed in the three contracts.

To conduct the district evaluations, the district would create a monthly list of roadways to evaluate. Using the performance measures they would rate the markings and markers along each section. The overall condition for each section would be averaged. The averages of each individual section would then be averaged to give the final monthly condition assessment score. This condition assessment score is used to issue deductions based on the performance of the markings and markers. The research team feels that averaging a group of averages will result in undervaluing poor-performing sections. Failing sections will bring down the overall average slightly, but the goal of the contract and marking maintenance in general is to not have any failing sections. Additional deductions or maintenance requirements for failing sections should be implemented. The first San Antonio contract showed some large variations in the monthly assessments and a slight improvement overall. Reducing the number of failing segments will yield the largest gains in improving the overall score. Additional deductions or requirements for immediate or very near future maintenance on failing sections will increase the cost of the contract, but will go a long way toward improving the overall performance of the marking and marker assets.

REVISE SPECIAL SPECIFICATION FOR PERFORMANCE-BASED PAVEMENT MARKING MAINTENANCE

The special specifications for performance-based pavement marking maintenance have undergone several changes since the issuance of the first PBPMMC in Texas (*47,48,49*). Many of these changes have already been discussed. The remaining changes will be discussed in this section, as well as other changes that may be beneficial to the special specification. The special specification saw minor changes between the first contract in San Antonio and the contract in Dallas. There were three notable changes. The first was the inclusion of Special Specification 8094, which related to the mobile measurement of the marking retroreflectivity. The second was minimum amounts of striping required during the first 6 months and the duration of the contract based on lane line miles. A minimum of 50 lane line miles of high exposure and 50 lane line miles of medium exposure were required to be striped during the first 6 months. The duration of the contract required 100 lane line miles per exposure level. The first San Antonio contract required the placement of pavement markings on 10 centerline miles per exposure level for the first 6 months of the contract. The third change was excluding Type II markings for transverse markings and on high- and medium-exposure roadways. The first San Antonio contract did not exclude Type II markings on medium-exposure roadways.

The second San Antonio contract had many more changes, as the district was able to learn from the first contract and implement changes that would be beneficial. The requirements for the quantity of striping covered the whole contract and were 100 lane line miles per month. Putting requirements on the minimum amount of striping to conduct per month can be a good and a bad thing as far as the bid price of the work goes. It gives the contractor a defined amount of work that they will do no matter what, which may increase the cost of the bid if they think they would not need to strip that much; but at the same time it gives them a target amount of striping that will need to be performed so their bid may be more accurate because some uncertainty is removed.

The second San Antonio contract reduced the length and scope of the contract compared to the previous two contracts. The length was reduced from 5 to 3 years. The scope removed the low-exposure roadways, and compared to the first San Antonio contract, removed two counties that were previously included. The contract also removed operational modification and callout work. This work would be let for bid in the same manner as normal contracts. In the previous San Antonio contract the contractor who won the PBPMMC also did all of the callout and operational modification work. This work was done for an additional fee and may have been more of a priority for the contractor than the main contract since it provided additional revenue. Exclusions for areas of department projects were also modified. The second contract relieved the contractor from having to work on markings in areas where a project of 6 months of longer was occurring. The other contracts did not specify a necessary time frame of work that would relieve the contractor from maintaining the markings.

The second San Antonio contract also modified the payment schedule to the same rate each month, instead of varying the rate annually. This can be beneficial to the DOT as the previous contracts paid a higher rate the first year of the contract. The cost analysis research showed that during the first San Antonio contract there was no need to pay more during the first year as there was actually less work done than in any of the other years so this is a good change. In addition to modifying the payment schedule, the amount of time the contractor would not face deducts was also reduced. The second San Antonio contract reduced the no deduct time to 3 months, whereas it was 1 year in the other two contracts. This reduction forces the contractor to improve the marking quality faster, which is especially needed with the shorter contract length. The shorter period before deducts occur should result in slightly higher bid prices due to the additional risk that the contractor will face.

Work scheduling was also changed in the second San Antonio contract. Weekly scheduling as well as quarterly evaluations are required on top of the 1-year and monthly plans. The initial 6-month plan was removed from the contract. The contractor's condition evaluation scheduling also changed. Initial reports were required within 3 months of the start of the contract, and annually on September 1 each year after for both high- and medium-exposure roadways. The other contracts required the initial reports within 6 months. High-exposure roads were to be evaluated every 6 months with annual evaluations for medium- and low-exposure roadways.

The first San Antonio contract was not extended because it was determined that a new contract could yield a better value, and that there may have been issues with the first contractor's performance. There were not parameters listed in the first San Antonio contract for granting the 2-year extension. The second San Antonio contract listed a parameter that the contractor must meet an average monthly assessment score of 2.7 over the course of the contract to be eligible for the 2-year extension. The research team feels that a score of 2.7 is too low to be eligible for an extension. The first San Antonio contract only had three monthly assessment scores below 2.7 over the 5-year contract. An average score of 3.0 over the course of the contract would be a better option; this would mean on average there would have been no deductions, and that the contractor had maintained the markings to an adequate level.

There are several other areas of the special specification that the research team feels could use clarification or additional information. The retroreflectivity performance requirements do not state how the measurement sections are to be selected and what constitutes failing. Further clarification is needed to determine what constitutes the area to be measured. Should it be the entire length of the road, the length between two points, or by control section? With whatever section is selected is it the average of the entire section or are shorter sections within the section analyzed? If the section is 5 miles long and the overall average is passing but the first half is failing and the second half is good, what should happen? Restripe the first half, restripe the whole section, or do not restripe at all?

Another area that would be beneficial is to explicitly state in the specification the naming convention of data and map files and how they are to be submitted. The measurement protocols result in a large amount of data that may be very difficult to manage if the data cannot be organized. Proper data management and organization will ensure the roads that need to be restriped are restriped in a timely manner. Summary retroreflectivity files and map files should be tied to the monthly/quarterly/annual reports by some form of identifier. All data for a given road section should be included in a single folder with the road name and the identifier.

An area the research team believes may be a concern is the performance in the final year of the contract. The contractor may choose to let the markings deteriorate in the final year, leaving the markings in a bad condition at the end of the contract. The contractor may also install lower quality markings late in the contract just to maintain performance until the end of the contract. The research team feels some safeguards should be implemented in the final year of the contract to ensure markings are not allowed to excessively deteriorate and that inferior markings are not used. These safe guards could include a combination of higher performance deductions in the final year, extension of the contract directly tied to overall and final year performance, and require the contractor and TxDOT to provide an end-of-contract performance assessment that may result in additional deductions or bonuses. The research team feels that the deductions throughout the contract are too low. The deductions need to be large enough to deter the contractor from letting markings fail, but not so large as to greatly increase the cost of the contract. There needs to be an appropriate balance, which seems to be in the contractor’s favor at this point based on the results of chapter 6.

Both the San Antonio and the Dallas Districts have used one-time use special specifications for performance-based pavement marking maintenance. Some modifications have been made with each subsequent issuance of a PBPMMC. Other districts may need to modify measures and protocols that are more suited to their own needs.

SUMMARY

The research team, using information gathered during the project and an investigation of the changes of the three PBPMMCs, provided recommendations to benefit the development of future PBPMMCs. Recommendations cover revised performance measures, revised measurement protocols, and revisions to the special specification for performance-based pavement marking maintenance.

CHAPTER 8: FINDINGS AND RECOMMENDATIONS

This chapter presents a summary of the findings and recommendations from the research. These findings and recommendations can be used by TxDOT to improve the performance-based pavement marking maintenance contracting mechanism. As with any contracting technique the costs and benefits of any changes need to be analyzed and understood. Increasing performance requirements will generally result in an increased price to the DOT. Reducing the flexibility of the contractor will also generally result in an increased price to the DOT.

The results of the before-after analyses conducted to evaluate the effect of PBPMMCs on traffic safety provide inconclusive evidence that performance-based pavement marking maintenance contracts are an effective safety countermeasure that aid in reducing crashes. The before-after analysis showed that the PBPMMCs decrease crashes on an average by an estimated 0.1 percent, and the result is not significant at a 95 percent confidence level. Further analysis by each district separately showed that the performance-based contracts have no significant change in safety in the San Antonio District, whereas a statistically significant positive effect in the Dallas District was found.

When evaluating the crashes by severity, the study results showed inconclusive evidence about the change in safety. The analysis by roadway class showed that PBPMMCs have no statistically significant effect on crashes occurring on U.S. and state highways, state loops and spurs, and farm-to-market roads. However, the performance-based contracts have a significant positive effect on safety of interstate highways. It is important to note that there could be some other countermeasures implemented during the same period that might have affected the nighttime crashes, and it is difficult to isolate the effect of the performance-based contracts. Overall, the safety study indicated that PBPMMCs have no negative impacts on traffic safety and could potentially improve safety under certain conditions.

The retroreflectivity performance evaluation found that there are statistically significant differences in retroreflectivity levels of new markings among districts, but there are no observable patterns either in white or yellow markings between PBPMMC and non-PBPMMC districts. The analysis results indicated that there are differences in retroreflectivity decay among districts in yellow markings but not for white markings. The differences, however, may not be directly attributed to the practice of PBPMMCs. The decay in yellow markings is larger for the

PBPMMC districts (Dallas and San Antonio) than the non-PBPMMC district (Bryan), but this could be due to the higher traffic volume expected in the urban districts. Overall, the retroreflectivity performance analysis concludes that there is no statistical evidence of whether a PBPMMC yields better pavement markings in terms of retroreflectivity.

The analysis conducted to compare the contractor retroreflectivity readings to the research team's readings indicated that there was no statistical evidence of a difference for the white pavement markings evaluated. The contractor's readings were found to be higher for yellow markings; however, the sample size was much smaller than the white markings in this study and the research team's readings were typically obtained after those of the contractor for yellow, but in a more similar time frame for white. Overall the contractor's readings could be considered consistent with the readings taken by the research team.

The cost analysis of the PBPMMC indicated that neither contract provided financing to the districts. In both the San Antonio and Dallas contracts, the contractor has done less value of work than it was compensated for in the first year of the project. Overall the value-for-money of the PBPMMC was about even. At best, the value of the work provided by the contractor matches the cost of doing the work using the traditional perspective contracting, and the condition of the system was not greatly improved based on the DOT-conducted performance assessments. From an overall cost and performance standpoint the first San Antonio contract did not provide many of the key benefits of performance-based contracting.

Chapter 7 of this research report documents numerous recommendations that cover revising the performance measures, revising the measurement protocols, and revisions to the special specification for performance-based pavement marking maintenance. These recommendations are provided to improve future PBPMMCs while making the DOT aware of the possible consequences (typically higher costs) that may occur if implemented. The DOT needs to establish what the goals of the PBPMMC are in order to determine the best performance measures, measurement protocols, and the consequences that the contractor will face if the PBPMMC goals are not met.

The results from both safety and retroreflectivity performance evaluations indicate that the agencies' choice of contracting mechanism, whether it is traditional contract or PBPMMC, will not affect either safety or retroreflectivity performance of the facilities. The agencies can select the contract type based on their experience, the cost-effectiveness, and the availability of local contractors.

Overall, the PBPMMC is a contracting mechanism that may serve a purpose for any district. Based on the research, it is likely to have the best results in a larger district that has access to local competent contractors and has markings and markers that are difficult to maintain with standard contracts. A district is also likely to benefit from PBPMMC if there are a number of smaller marking/marker projects to manage within the jurisdiction. Limiting the contract to specific roadways or counties is a means to control costs while addressing the markings and markers of highest concern. As with most types of contracts, the larger the contract in scope or length will typically provide a better value to the DOT than a small, short contract.

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APPENDIX A: PAVEMENT MARKING MAINTENANCE SURVEY

The Texas Transportation Institute is currently working on TxDOT project 0-6705 to determine the Effectiveness of Performance Based Pavement Marking Maintenance Contracts (PBPMMC). One of the first steps of the study is to gather information about the pavement marking contracting practices in each TxDOT district. We are gathering this information via a web survey, telephone interviews and/or e-mail questionnaires from each individual TxDOT district.

The survey should take approximately 20 minutes (plus some time to look up cost and quantity information) and will cover a variety of questions regarding pavement marking maintenance practices. If a phone interview is not convenient for you please fill out the attached questionnaire and return via e-mail or fax, or complete the web based survey. Please answer the questions honestly to the best of your knowledge. If you cannot respond to a question please indicate so or leave it blank. We are looking to get a general district opinion on the questions that do not have defined answers. Please note that participation in the study is confidential and the records of this study will be kept private; responses used in the research will not be linked to individual respondents. Our goal is to get at least some form of a response from all 25 districts for our research purposes so that TxDOT can better understand the pavement marking practices around the state.

If you have any questions regarding this study, please feel free to contact Adam Pike using the contact information located at the end of the survey. Your support of this important research study is greatly appreciated! If possible please schedule a telephone interview and/or return the questionnaire within 20 working days. We look forward to hearing back from you.

RESPONDENT CONTACT INFORMATION

Contact Person: ____

TxDOT District: ____________________ Position: ____________________________

Telephone Number: ____

E-mail: ____

District Contracting:

1. What types of pavement marking contracts has your district used?
   ____Annual District Wide
   ____Warranty [Pay up front, marking must maintain a given level of performance over a given number of years or be replaced]
   ____Performance Based Pavement Marking Maintenance Contract (PBPMMC) [Pay over time with payments based on marking performance, all markings must maintain a given level of performance over a given number of years or be replaced]
   ____Individual Projects or Roads
   ____On-call
   ____Other, *Specify* ____________________________________

2. If your district has used more than one type of contract in the past does your district have any preference towards a specific type and why?

3. Are long and short lines contracted together or in separate contracts?
   ____Together ____Separate ____Sometimes together, sometimes separate

4. Are markers and markings bid together or in separate contracts?
   ____Together ____Separate ____Sometimes together, sometimes separate

5. Are center and edge lines on a road replaced at the same time (within the same striping season)?
   ____Always ____Most of the time ____Sometimes ____Never

6. Do any of these contracts include incentive/penalty clauses?
   ____Yes ____No
   If yes, which contract type and how often does the district exercise this clause? If, no does your district feel they may be beneficial?

7. Who makes the decision on pavement marking material type to be applied?
   ____TxDOT
   ____Contractor
   ____Depends on Contract Type

District Pavement Marking Information:

8. What are the districts total annual pavement marking costs (materials, labor and equipment, and others) for the last 5 years? Approximate numbers by year would be appreciated.(Year; Contract Type; Marking Type (new, restripe, on-call); Number of Miles; Cost ($); More or Less than Initial Estimate)
   (For example) 2011; District Wide; Restripe; 1,500 miles; $2,500,000; Less

   We will take any form of a response, if you have an easier way of getting the research team your costs and quantities information. This information can be included in this survey, faxed or e-mailed. We are just looking for overall costs and quantities of pavement markings in your district.

Year	Contract Type	Marking Type	Number of Miles	Cost in Dollars	How is the actual cost comparable to estimated costs?

9. What striping materials are used in your district?
   ____Waterborne Paint ____High-Build Paint
   ____Sprayed Thermoplastic ____Extruded Thermoplastic
   ____Tape ____Epoxy/Polyurea/Other Multi-Polymer Plural Component
   ____Other, *Specify* ____

10. What are the districts total annual marker costs (materials, labor and equipment, and others) for the last 5 years? Approximate numbers by year would be appreciated.
    (Year; Contract Type; Number of Markers; Cost ($); More or Less than Initial Estimate):
    (For example) 2011; District Wide; Replace; 200,000; $500,000; Less

    We will take any form of a response, if you have an easier way of getting the research team your costs and quantities information. This information can be included in this survey, faxed or e-mailed. We are just looking for overall costs and quantities of pavement markers in your district.

Year	Contract Type	Number of Markers	Cost in Dollars	How is the actual cost comparable to estimated costs?

11. How many miles of State maintained roadways are in your district?

Centerline miles______________________

Lane miles___________________________

12. Does your district keep maintenance logs of when the roads were last restriped/remarked?

____Yes ____No

13. What is the burden (time and effort) on your district as far as managing the pavement marking/marker assets?

District Pavement Marking Performance and Inspection:

14. What performance measures does your district use to judge initial performance and/or end of life of the markings (if a combination is used, please rank the importance of each criterion)?

____Handheld Retroreflectivity
____Mobile Retroreflectivity
____Presence
____Color
____General Visual Appearance Day
____General Visual Appearance Night
____Other, *Specify* ________________

15. What are your district's expectations on the performance of the pavements markings? If these expectations vary by marking type please indicate so.

Initial Retroreflectivity__________________$mcd/m^2/lux$

Service Life____________________________months

16. What happens when newly applied markings do not meet the required state or district specifications?

17. Approximately what percentages of new markings in your district do not meet the required initial specifications?

18. Approximately what percentage of miles are inspectors present when markings are being applied?

19. What do the inspectors check for when present?

20. How does your district determine when to restripe a road?
____Predetermined Cycle
____Handheld Retroreflectivity Measurements
____Mobile Retroreflectivity Measurements
____Day Visual Inspection
____Night Visual Inspection
____Other, *Specify* ______________________________________

21. Has your district contracted for mobile retroreflectivity measurements to assist with determining which roads to restripe? If yes, please indicate project dates and scope of work.
____Yes ____No

22. How does your district determine when a road needs new markers?

PBPMMC Specific Questions:

23. Is your district currently using a PBPMMC?
____Yes ____No

If YES,
When did it start?____
When does it end?____
On what roads?____
Why did your district elect to use this form of contracting? _______________________________________
From your district's experience what are the pros and cons of this contracting type? *Pros*:____
____
Cons:____
Are there areas (in your district or elsewhere) or roads that this contract type may be more or less beneficial?____
Does your district feel this contracting mechanism is worthwhile? ____Yes ____No
How is the actual cost comparable to the expected cost? ____more ____less ____same
How was the contract handled? ____more burdensome ____less burdensome ____as expected
How was the burden compared to typical contracts? ____more ____less ____same
Does your district have maintenance logs of when the roadways were restriped/ remarked by the contractors under this type of contract? ____Yes ____No

If Yes or NO,

Has your district used a PBPMMC in the past? ____Yes ____No

If YES,

When did it start?____

When did it end?____

On what roads?____

Why did your district elect to use this form of contracting? _____________________________

From your district's experience what are the pros and cons of this contracting type?

Pros:____

Cons:____

Are there areas (in your district or elsewhere) or roads that this contract type may be more or less beneficial?____

Does your district feel this contracting mechanism is worthwhile? ____Yes ____No

How is the actual cost comparable to the expected cost? ____more ____less ____same

How was the contract handled? ____more burdensome ____less burdensome ____as expected

How was the burden compared to typical contracts? ____more ____less ____same

Does your district have maintenance logs of when the roadways were restriped/ remarked by the contractors under this type of contract? ____Yes ____No

If Yes or NO,

Is your district currently considering using a PBPMMC? ____Yes ____No

If Yes, why?____

If No, does your district have any specific reasons?___________________________________

APPENDIX B: DALLAS DISTRICT COST ANALYSIS

This appendix presents the results from the Dallas District's contract for which a full data set required for rigorous cost comparison analysis was not available. The callout and non-callout work for Dallas is shown in Table B1. The table was created by compiling the total quantities for each month. Such totals are then classified as either the callout or non-callout work. The total cost of the work performed by the contractors was calculated by using the work reported in the monthly work logs. The average bid prices of each item were obtained from 2005 and 2012 statewide average bid prices. The average bid prices were multiplied by the quantity of each item to obtain the total value of work performed for each month and, subsequently, the contract.

Table B1. Callout vs. Non-callout Comparison (Dallas Contract).

Contract (bid prices used)	Callout Work	Non-Callout Work	Total Value of Work Performed
Dallas (2005)	$121,263.95	$8,668,565.24	$8,789,829.19
Dallas (2012)	$190,606.59	$13,140,383.30	$13,330,989.89

Figure B1, Figure B2, and Figure B3 illustrate the costs associated with the work performed under the PBPMMC in an equivalent unit cost environment. Figure B1 shows the reported callout work, the extra work that is unplanned and conducted by the contractor at the request of TxDOT for an additional fee. The contractor is fully reimbursed for this work. Figure B2 shows the monthly value of the non-callout work performed over the period of study for each contract. Figure B3 provides a comparison of the monthly base payments compared to the value of the work performed.

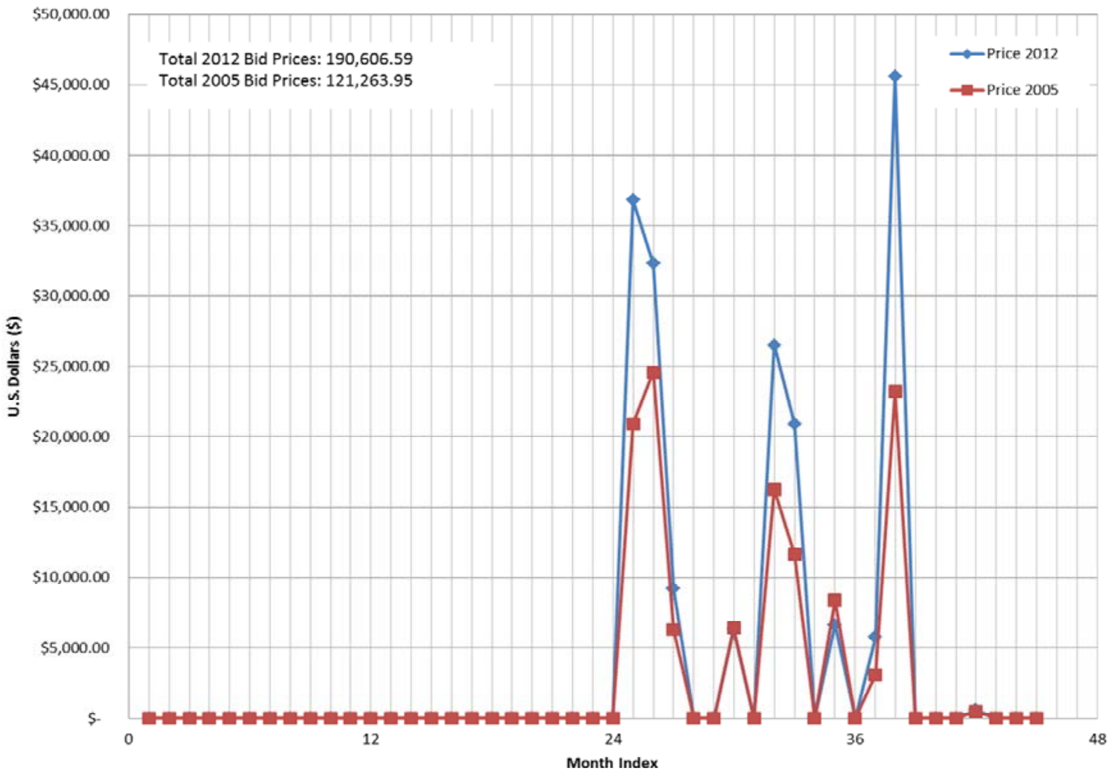

Figure B1. Value of Callout Monthly Work (Dallas Contract).

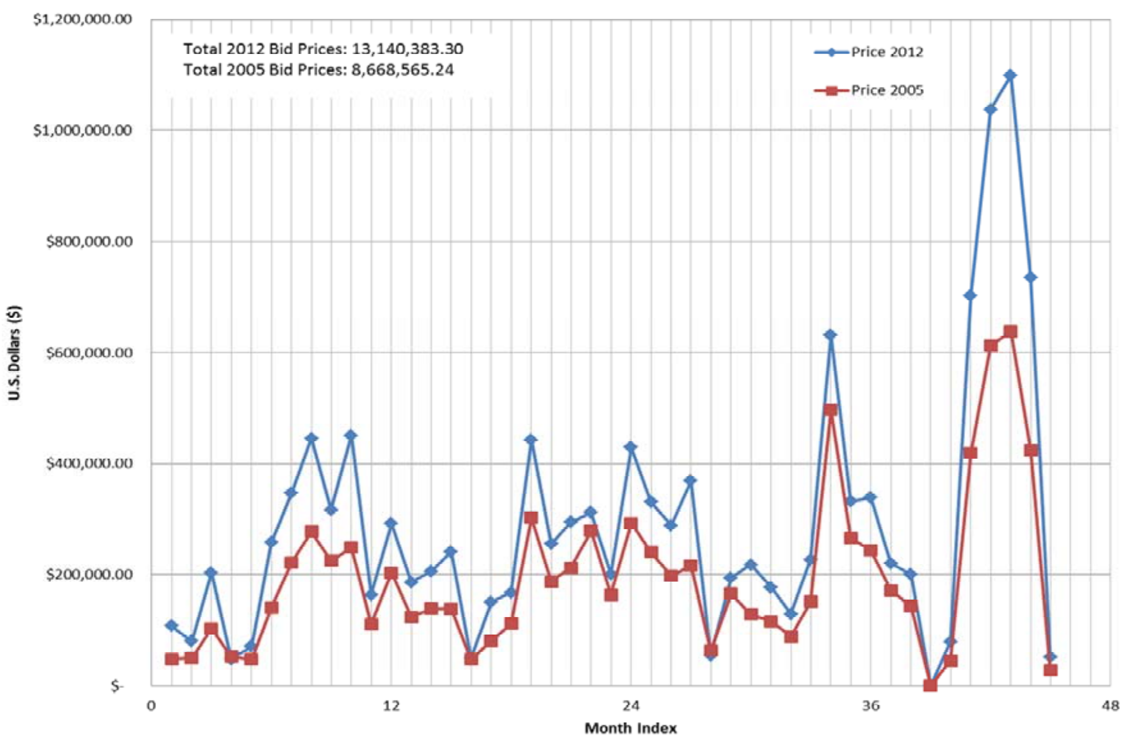

Figure B2. Value of Non-callout Monthly Work (Dallas Contract).

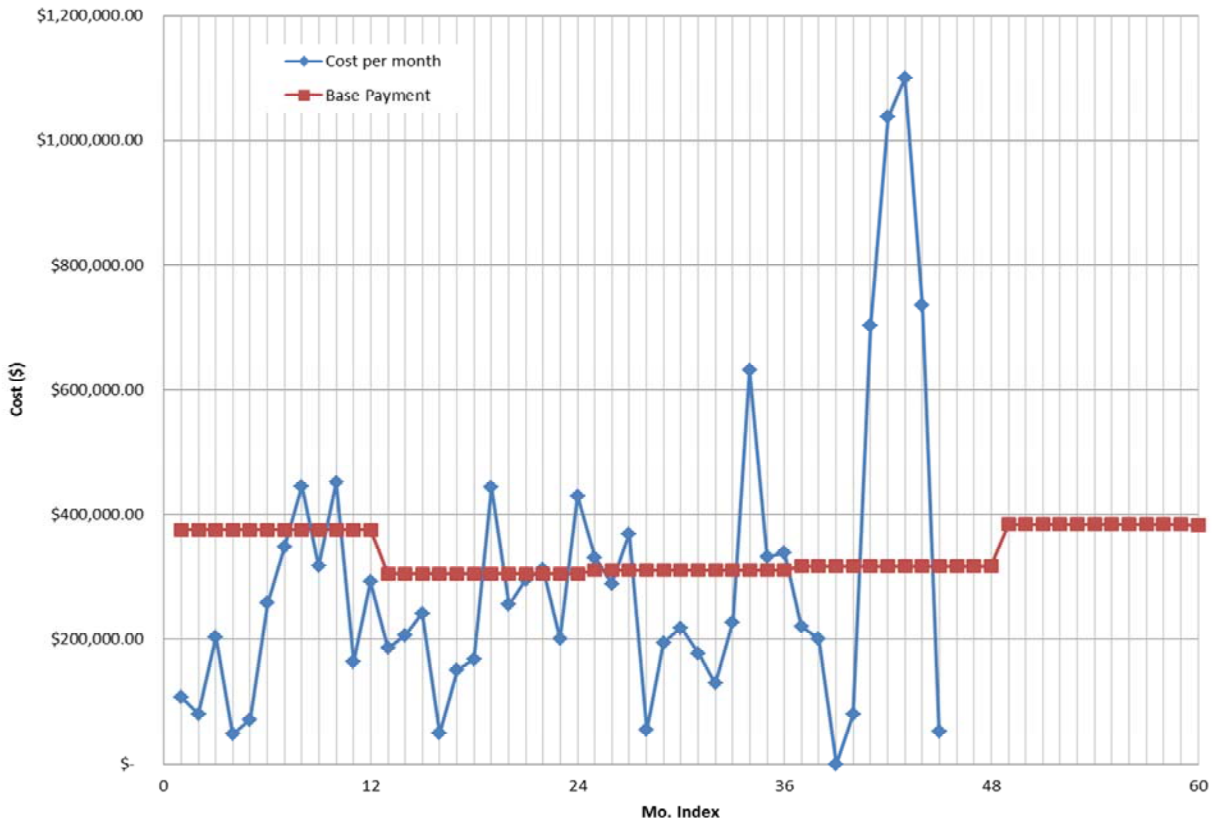

Figure B3. Value of Non-callout Monthly Work and the Base Payment (Dallas Contract).

Note that the values of the non-callout item do not include removal items. These data were not provided by TxDOT. To determine the value of such work, a study from San Antonio was used to estimate the proportion of the value of removal work (approximately 10 percent of the total value of the work). The assessment scores were used to calculate a 3-month moving average as seen in Figure B4.

Overall, the performance assessment and value of work performed in Dallas appear to be similar to what was found in San Antonio. The best way to get a fair comparison between the value of the work performed as compared to standard contracting mechanisms is to require adequate documentation of work performed.

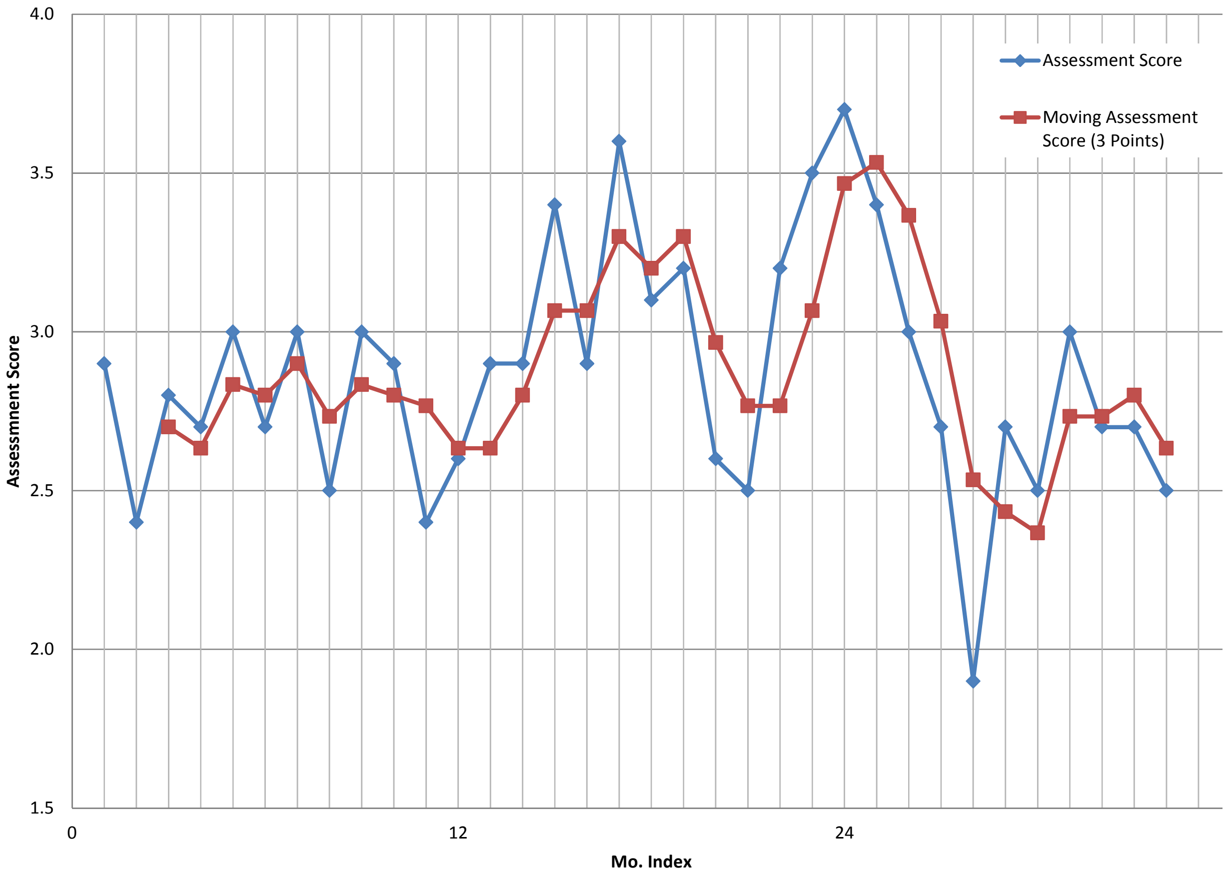

Figure B4. Assessment Scores (Dallas Contract).