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16. Abstract

This report describes the methodology and results of analyses performed to develop guidelines on (1) how to improve temporary traffic control at work zones in and near urban freeway interchanges, and (2) selecting appropriate pavement marking materials in work zones. Laboratory studies conducted using laptop computers and the Texas Transportation Institute (TTI) Driving Simulator indicate that continuing to use guide signs that no longer align directly over travel lanes (as often occurs during interchange reconstruction or widening) will degrade drivers' abilities to properly choose lanes and negotiate through the interchange area. The use of temporary work zone diagrammatic signing and/or pavement marking symbols to denote route destinations for the various lanes will help offset this degradation. Other findings from the laboratory studies are discussed in the report.

Monte Carlo simulation was used to model the interrelationships and variability of estimates of pavement marking material service life, project phase duration for which the marking is intended to provide service, and cost of the marking material in determining which pavement marking material would provide the lowest total expected cost for a particular work zone roadway condition. Matrices were generated of recommended pavement marking materials as a function of expected project phase duration and Annual Average Daily Traffic AADT. Additional matrices provided allow practitioners to adopt more liberal or conservative assumptions of the input variables when selecting a marking material.

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STUDIES TO IMPROVE TEMPORARY TRAFFIC CONTROL AT URBAN FREEWAY INTERCHANGES AND PAVEMENT MARKING MATERIAL SELECTION IN WORK ZONES

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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.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Gerald L. Ullman, Ph.D., P.E. #66876.

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CHAPTER 1. INTRODUCTION

STATEMENT OF THE PROBLEM

Navigating through work zones that occur within the vicinity of complex urban freeway interchanges can be particularly challenging to motorists. Numerous existing and temporary guide signs, presence of short auxiliary lane segments, multiple lane exits, high merging traffic, and other conditions in the work zones present complex driving situations and place considerable work load on drivers. Driver work load and driving complexity increases even more when temporary travel paths are in conflict with existing guide signs. Consequently, traffic control designers often find it difficult to adequately convey lane closures, lane assignments, travel paths, and other warning information using traditional temporary traffic control signs and temporary pavement markings. These difficulties are experienced at both long-term construction and short-term maintenance activities. Research was needed to identify ways to improve temporary traffic control guidelines for work zones in and around urban freeway interchanges.

At the same time, a need was identified for research on how to better select pavement marking materials for use in work zones. Lane shifts, crossovers, and other temporary changes in alignment often require the roadway into and through a work zone to be temporarily re-striped. The traffic control designer has the choice of using paint, thermoplastic, traffic buttons, or other types of material for this purpose. On the one hand, it is desirable that the material selected be durable enough to last for the duration of the temporary change in alignment. On the other hand, since the application is intended to be temporary and will eventually be removed, covered with an asphalt overlay, etc., it is desirable to use as inexpensive a material as possible whose anticipated service life for that particular application simply exceeds the temporary duration that it is needed. Therefore, an objective assessment of how to best make pavement marking selection decisions for work zones was also needed. This report describes the efforts and results of a research project that examines both of these issues.

BACKGROUND

Improved Traffic Control at Urban Freeway Interchanges

One of the underlying principles of work zone traffic control is that drivers are to be guided in a clear and positive manner while approaching and traversing a highway work zone (*1*). A system of temporary signs, channelizing devices, pavement markings, and other traffic control devices are used within and upstream of the work zone to provide this guidance. The actual series of devices to be used, and the relative location of each within and upstream of the work zone, is termed a traffic control plan.

Both research and field experience have been used to develop a number of typical traffic control plans to treat common types of work zone situations on various types of roadways (*1, 2, 3, 4, 5, 6*). Generally speaking, these typical plans work quite well in most instances and can be implemented fairly easily when the roadway section and the work activity are fairly simple. However, as the complexity of the roadway and/or the traffic control requirements of the work activity increases, the ability to apply these plans to the situation becomes more difficult. Urban freeway interchanges represent one such location where it can be difficult to effectively implement standard plans that convey appropriate path-guidance and way-finding information to motorists.

The 2003 *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) does contain some information that is used to facilitate temporary traffic control (TTC) around urban freeway interchanges (*1*). For example, Figure 1 and Figure 2, reproduced from the TMUTCD, illustrate typical traffic control set-ups for work in the vicinity of exit and entrance ramps, respectively. As long as adequate distances for the advance signing and recommended lane closure lengths are available, such layouts would be expected to provide good driver guidance through the work zones. However, space limitations in many urban areas do not lend themselves to such a layout. Furthermore, double-lane drops or additions, left-side and right-side exits in or near the same interchange, sight distance limitations, and other factors can complicate the situation significantly.

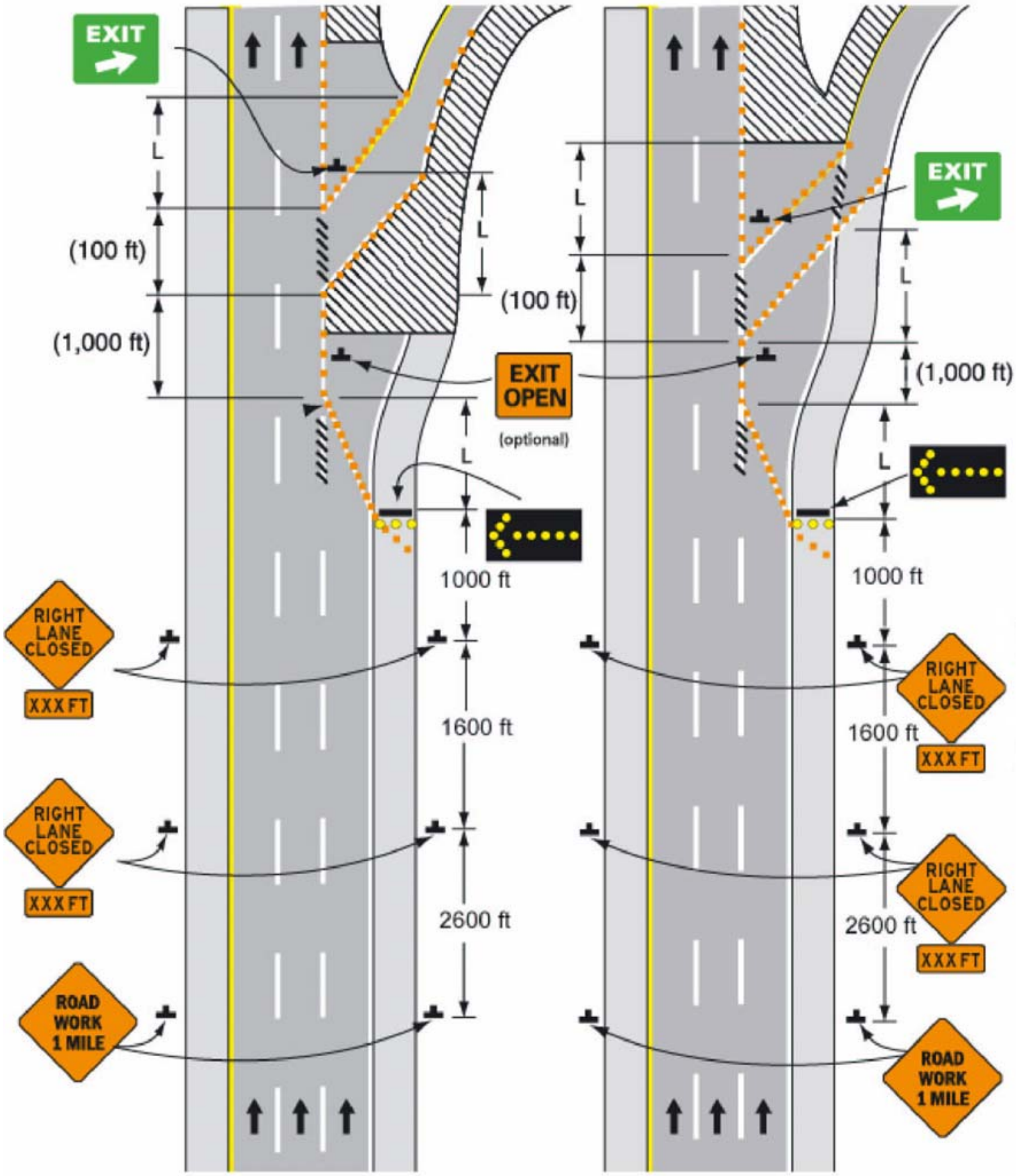


Figure 1. Typical Application 42 – Work in Vicinity of Exit Ramp (*1*).

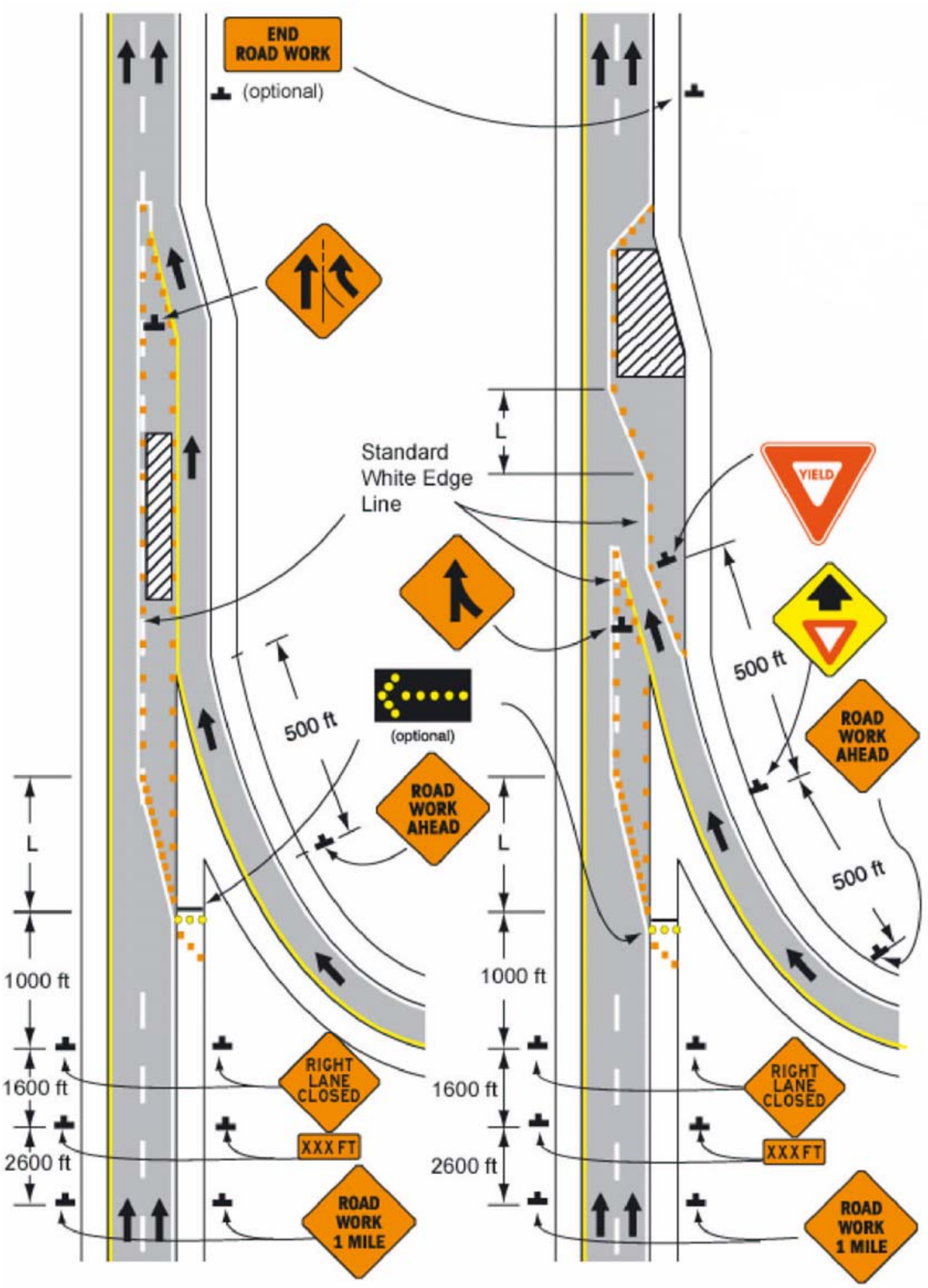


Figure 2. Typical Application 44 – Work in Vicinity of Entrance Ramp (*1*).

For long-term work zones that involve changes to roadway geometrics approaching and through the interchange (i.e., ramp closures, changes in lane assignments, etc.), the TMUTCD indicates that advance guide signing approaching the interchange should be changed as necessary. However, as noted in the manual, very little specific guidance as to when or how to make such changes is provided (*1*):

"The following guide signs should be used in TTC zones as needed:

A. Standard route markings, where temporary route changes are necessary;

B. Directional signs and street name signs; and

C. Special guide signs relating to the condition or work being done."

In addition, if special guide signs for the work zone are deemed necessary, they shall have a black legend on an orange background.

In recent field studies conducted of drivers traversing both maintenance and construction work zones through urban freeway interchanges in Texas, Helmuth identified a number of situations that can potentially create driver confusion and lead to operational and safety problems within the work zone (*7*):

- Information about freeway exits and splits (especially to the left) near where lane closures are required were difficult to convey to drivers using existing temporary traffic control advance warning signs.
- Initiating lane closures and lane shifts in the vicinity of auxiliary lanes, acceleration/deceleration lanes, or shoulder terminations can result in driver confusion about appropriate travel paths.
- Exit guide signs for construction projects that are not consistent with upstream guide sign information can confuse drivers.
- Lane shifts in areas where concrete barriers and other visual cues mislead drivers as to the actual travel paths through the interchange areas (i.e., where such cues do not follow the actual lane shifts themselves).

In summary, although some existing guidance does exist regarding temporary traffic control in and around urban freeway interchanges, a number of special challenges still exist which warrant additional focused research on this topic.

Pavement Marking Selection in Work Zones

Pavement markings are a key traffic control device available to engineers to provide positive path guidance, especially in work zones where normal travel paths must be altered temporarily to accommodate work activities. There are numerous types of pavement markings, including:

- paints (including alkyd-based, water-based latex, and epoxy-based),
- thermoplastic,
- epoxy,
- polyurea,
- polyester,
- methyl methacrylate (MMA),
- preformed tape (permanent and temporary),
- traffic buttons,
- retroreflective raised pavement markers (RRPMs), and
- thermoplastic profile markings.

In general, paint, preformed temporary tape, and a combination of RRPMs and traffic buttons are used to create temporary pavement markings in work zones. However, for long-term construction projects (i.e., those lasting longer than one year) more durable pavement markings may be needed. Unfortunately, it is difficult to know which type of pavement marking is best suited for a particular work zone situation.

Current Texas Department of Transportation (TxDOT) Departmental Material Specifications (*8*) address the use of paint (DMS-8200), thermoplastic (DMS-8220), preformed tape (DMS-8240 and DMS-8241), RRPMs (DMS-4200 and DMS-4210), and traffic buttons (DMS-4300). The other types of pavement markings listed above are either under experimental use in Texas or in other states (*9*).

Pavement Marking Performance

Pavement markings, as well as other traffic control devices, are used to guide drivers approaching and traversing a highway work zone in a clear and positive manner. However, as pavement markings get dirty or deteriorate, they lose their ability to adequately delineate the travel path through a work zone. For example, in-situ studies (*7*) found that drivers can experience difficulty traversing lane shifts due to the lack of pavement marking continuity, which can be caused by deteriorated or missing markings.

Factors Affecting Pavement Marking Performance

Many factors, including the type of pavement marking material and the manufacturer, influence the performance of pavement markings. However, the major factors can be grouped into the following three categories: roadway surface, traffic, and environmental conditions (*9*).

One of the most important factors influencing pavement marking performance is the roadway surface upon which the marking is installed (*9*). Pavement marking materials perform differently on different surface types since the surface roughness, heat sensitivity, and surface porosity vary among surfaces.

Traffic volumes also greatly influence the performance of pavement markings. In general, the service life of all pavement markings decreases as traffic volumes increase since the number of wheel hits on the marking increases. With respect to work zones, areas where there is an increase in lane changing maneuvers (e.g., lane closures, entrance/exit ramps, etc.) will increase the number of wheel hits on the pavement markings, thus further decreasing pavement marking performance (*9*).

The third key factor affecting the performance of pavement markings is the environmental conditions both when the pavement marking is placed and throughout its service life. During application the following factors should be considered: air temperature, pavement temperature, humidity, wind velocity, and surface moisture at the time of application. Year-round climate conditions affect pavement marking performance through the wearing of the material, breakdown through infiltration, and erosion of the material bond with the roadway (*9*).

Minimum Retroreflectivity Requirements of Pavement Markings

Retroreflective pavement markings redirect light back toward the light source (i.e., headlamps) making the marking visible because the driver is able to see most of the retroreflected light. For pavement markings such as paint and preformed tape, beads embedded in the marking provide the retroreflectivity performance. For RRPMs, the lens inside the marker is retroreflectorized. Although the requirement that pavement markings be retroreflective has been in the *Manual of Uniform Traffic Control Devices* (MUTCD) (*10*) for nearly forty years, there are currently no specific requirements as to the actual minimum retroreflectivity levels that must be maintained (there are requirements for color retention under daytime and nighttime viewing conditions, however (*11*)). The Federal Highway Administration (FHWA) is currently developing minimum retroreflectivity standards for pavement markings. Draft recommendations, based on research studies, have been developed for various roadway scenarios. However, at this time these draft recommendations do not constitute a standard or exist for purposes of providing guidance to agency personnel.

Traditionally, researchers (*12–23*) have attempted to determine the minimum pavement marking retroreflectivity values through two types of human factor evaluations: subject evaluations and detection distance evaluations. Table 1 summarizes the findings of these studies. As seen in Table 1, a wide range of minimum pavement marking retroreflectivity values has been suggested. Generally, the literature suggests a minimum retroreflectivity level of 100 millicandela/meter^2/lux (mcd/m^2/lux) for pavement markings. In addition, the literature is in general agreement that markings with retroreflectivity levels below 80 mcd/m^2/lux should be replaced. One must keep in mind that these studies were conducted under a variety of conditions (e.g., range of speeds, range of ambient light levels, range of subject age, etc.). In addition, for measurement purposes different viewing geometries (i.e., 30 meter versus 15 meter) may have been used. Unfortunately, retroreflectivity readings at one measurement geometry (a combination of light entrance angle and measurement observation angle relative to the marking itself) cannot be directly converted to a different geometry, nor are readings at different geometries necessarily comparable to one another.

In summary, despite an extensive amount of data previously and currently being collected on pavement marking performance and service life, it is difficult to accurately predict how a particular product will hold up in a given roadway environment. It is clear that many different variables and interactions between variables impact the overall durability of a particular product in a particular application. Manufacturers continue to strive to improve their pavement marking products, further complicating the evaluation process.

Table 1. Summary of Previous Research on Minimum Retroreflectivity.

Researcher	Recommended Minimum(s) ($mcd/m^2/lux$)
Freedman, et al. (*12*)	64-127, 100 (45 mph), 150 (50 mph)
Parker, et al. (*13*)	80-165
Allen, et al. (*14*)	90
King, et al. (*15*)	93 dry, 180 wet
Graham, et al. (*16*)	93
Ethen, et al. (*17*)	100
Henry, et al. (*18*)	100
Jacobs, et al. (*19*)	120
Loetterle, et al. (*20*)	120
Graham, et al. (*21*)	121
Zwahlen, et al. (*22*, *23*)	400-515

This is not to say that improvements cannot be made in how pavement marking materials are selected for work zone applications. Indeed, the data already available do provide at least a qualitative comparison of the relative performance amongst some of the more popular categories and some indication of the effect of traffic volumes and pavement type upon that performance. Furthermore, the work zone environment is unique in that a particular lane configuration or path is often in place for some finite period of time, after which it must be removed or obliterated so that another travel path may be identified through another application of pavement markings. Therefore, the concern is not always that of predicting the actual service life of a particular pavement marking material under a given set of conditions, but rather determining the likelihood that a particular material can provide acceptable levels of path guidance over the expected duration of the construction project (or particular phase of the construction project). In addition, the decision as to which pavement marking material to use must also consider the costs of removal, a factor which does not appear to have been systematically included in previous pavement marking selection decision processes.

CONTENTS OF THIS REPORT

This report describes the methodology and results of analyses conducted to (1) provide guidelines on how to improve temporary traffic control at work zones in and near urban freeway interchanges, and (2) provide guidelines on selecting appropriate pavement marking materials in work zones. Because of the duality in research project purpose, the report has been prepared in two distinct parts. Part 1 addresses the research tasks and results pertaining to urban freeway interchange temporary traffic control, and Part 2 addresses the work zone pavement marking material selection process tasks and results.

PART 1 – TEMPORARY TRAFFIC CONTROL AT URBAN FREEWAY INTERCHANGES

CHAPTER 2. IDENTIFICATION AND CATEGORIZATION OF TEMPORARY TRAFFIC CONTROL ISSUES AT URBAN FREEWAY INTERCHANGES

INTRODUCTION

Texas Transportation Institute (TTI) researchers conducted a series of telephone and email interviews of both TxDOT and consultant personnel involved in the design and implementation of temporary traffic control around and through urban freeway interchanges. The purpose of the interviews was to identify and characterize the types of difficulties or problems encountered with designing and implementing temporary traffic control in and around urban freeway interchanges. Interviews were conducted with personnel from the following TxDOT districts:

- Austin,
- Corpus Christi,
- Dallas,
- El Paso,
- Fort Worth,
- Houston,
- San Antonio, and
- Waco.

Topics discussed included the following:

- awareness and description of previous crashes or near misses at urban freeway interchange work zones that may have been related to driving information or path guidance deficiencies (and specifically what deficiencies may have been present);
- opinions regarding the characteristics of urban freeway interchange work zones that cause drivers the most difficulties or confusion from a path guidance and driver information standpoint;
- difficulties encountered in the past with designing and/or implementing temporary traffic control at urban freeway interchange work zones (both in general terms and for specific projects that could be recalled); and

- TTC changes or innovations implemented in response to difficulties identified with urban freeway interchange temporary traffic control and how well the changes worked in reducing those difficulties.

Researchers also conducted a positive guidance assessment of urban freeway interchanges with existing work zones, as well as those not under construction but which could have significant temporary traffic control issues should a work zone be required through the interchange. Positive guidance combines highway and traffic engineering principles with human factors considerations to assess and produce a highway information system that is matched to motorist capabilities and situational driving task demands (*24*,*25*). Key considerations in the positive guidance assessment process are the following:

- Hazard visibility – "Hazards" refer to items in the travel environment that drivers should be aware of and may need to react to in some fashion (change travel path, reduce speed, stop, etc.). Drivers should be provided adequate decision sight distance to the hazards or should receive some type of warning about them at the decision sight distance point.
- Expectancy violations – Violations of driver expectancy increase driver decision-making and reaction times, and increase the likelihood of incorrect decisions. Violations are "surprises" to drivers as they traverse a roadway section. Information that is misleading or confusing can also violate driver expectancies.
- Information needs – Research and experience have defined the type and location where drivers need information in order to make correct decisions and take appropriate driving actions. This information must be presented far enough upstream of the decision point to allow safe driving actions to be taken if necessary. Similarly, information needed for a decision point must be close enough to ensure that a driver correctly associates that information with that decision point. Information presented too far away from a decision point will increase the likelihood that a driver will forget or improperly remember that information and make incorrect decisions and/or actions.

- Information loading – Drivers have a finite capacity to perceive and process information. Locations where too much information is presented will reduce the likelihood that a driver will correctly process and react to that information. Information that is not clear will likewise increase load demands and reduce driver processing and reaction capabilities.

Researchers collected and documented field observations at 45 urban freeway interchanges at locations in Austin, Dallas, Fort Worth, Houston, and San Antonio. Of these, 18 locations had actual work zones in place somewhere within the limits of the interchange itself (the remaining 27 interchanges did not have work zones present and so were assessed with regard to potential challenges and issues that might be encountered in trying to establish temporary traffic control within the interchange). Video data were obtained from within the vehicle while traversing the various possible travel paths through the interchanges. Both daytime and nighttime video data were collected to assess whether lighting conditions (and differences in visibility) created different positive guidance issues through these interchanges. Table 2 contains a summary of the number of interchanges and movements where researchers collected data.

KEY ISSUES

Advance Guide Signing at Interchanges

One of the most pressing issues (and one raised by several survey respondents) was maintaining adequate and correct guide signing in advance of the interchange when work activities modify lane assignments, require overhead gantries to be removed, etc. These difficulties can be especially challenging at locations where exit only lanes are or have previously been in place. Maintaining adequate and correct guide signing in advance of an interchange when work activities modify lane assignments is crucial in order to provide drivers proper and clear path guidance information. From a cost-effectiveness perspective, there is typically a desire by the contractor and/or the project engineer to maintain use of the existing guide signs rather than construct new temporary signing. However, determining which existing signs can continue to be utilized, as well as determining the most appropriate and worthwhile method of temporarily modifying existing guide signs when necessary, is a challenge.

Table 2. Summary of the Positive Guidance Data Collection Efforts.

Number	District					Total
	Austin	Dallas	Fort Worth	Houston	San Antonio	
Interchanges	5	9	5	15	11	45
Interchanges with WZ	1	7	1	7	2	18
Movements – Day No WZ	31	35	53	92	43	254
Movements – Night No WZ	25	21	0	19	13	78
Movements – Day WZ	3	29	1	27	10	70
Movements – Night WZ	2	32	0	29	10	73
Total Movements	61	117	54	167	76	475

WZ – Work Zone

In many locations where lanes have been shifted out of alignment with the existing guide signs, all of the lane assignment arrows on the signs must be covered. At other locations, the modified lane assignments only necessitate that some of the lane assignment arrows be covered (typically exit only arrows). In addition to modifying existing guide signs, at several locations smaller temporary lane assignment signs (black legend on an orange background) were placed on the overhead gantry to provide motorists with information concerning the modified lane assignments. Sometimes, the mixing of temporary and existing guide signs results in a large amount of information being presented to drivers in a short period of time. Examples of these issues are illustrated in Figure 3 through Figure 5. Generally speaking, the consequences of such modifications upon driver comprehension and path following have not been evaluated.

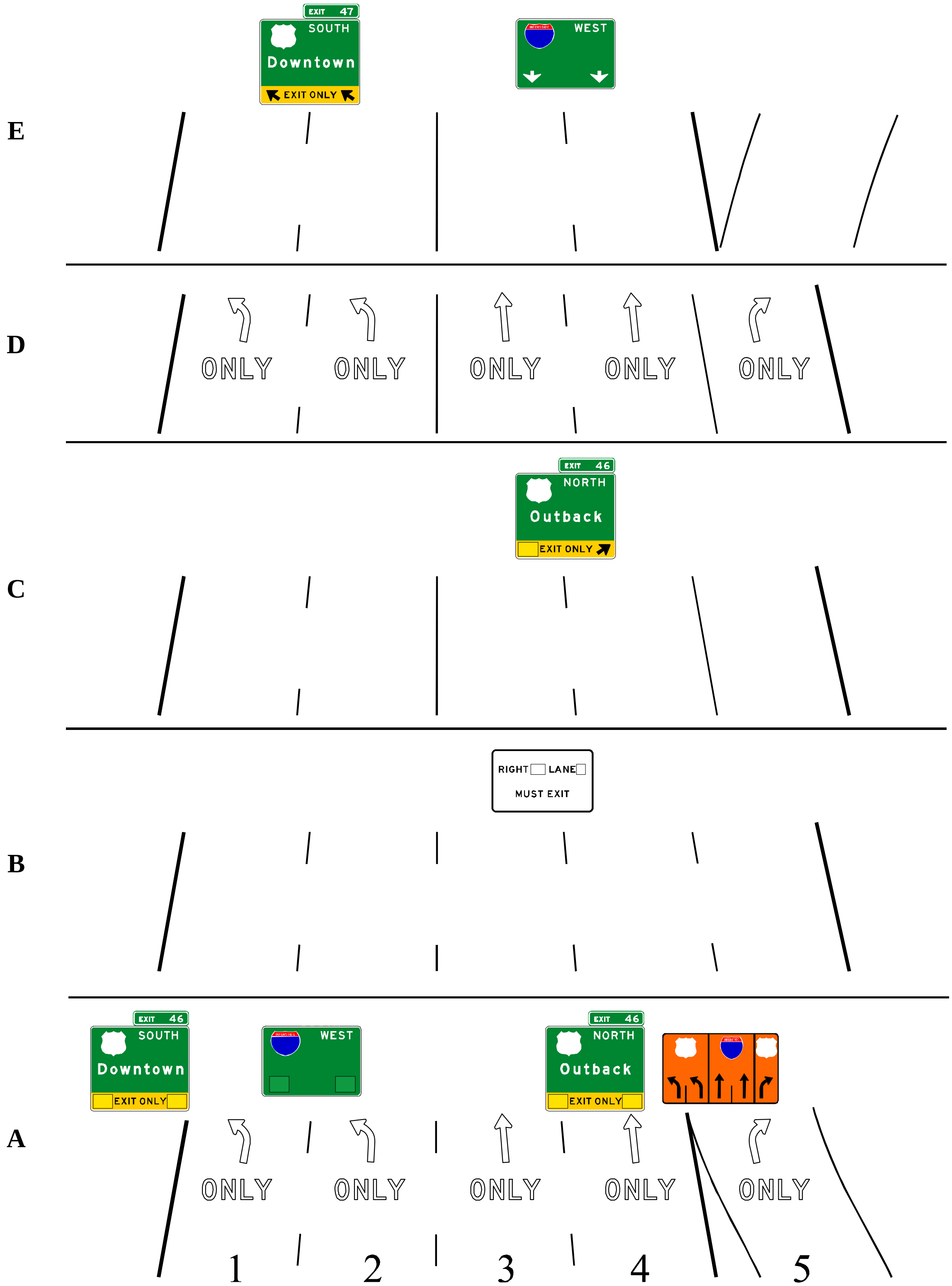


Figure 3. Modified Existing Signs and Temporary Guide Signs (Example 1).

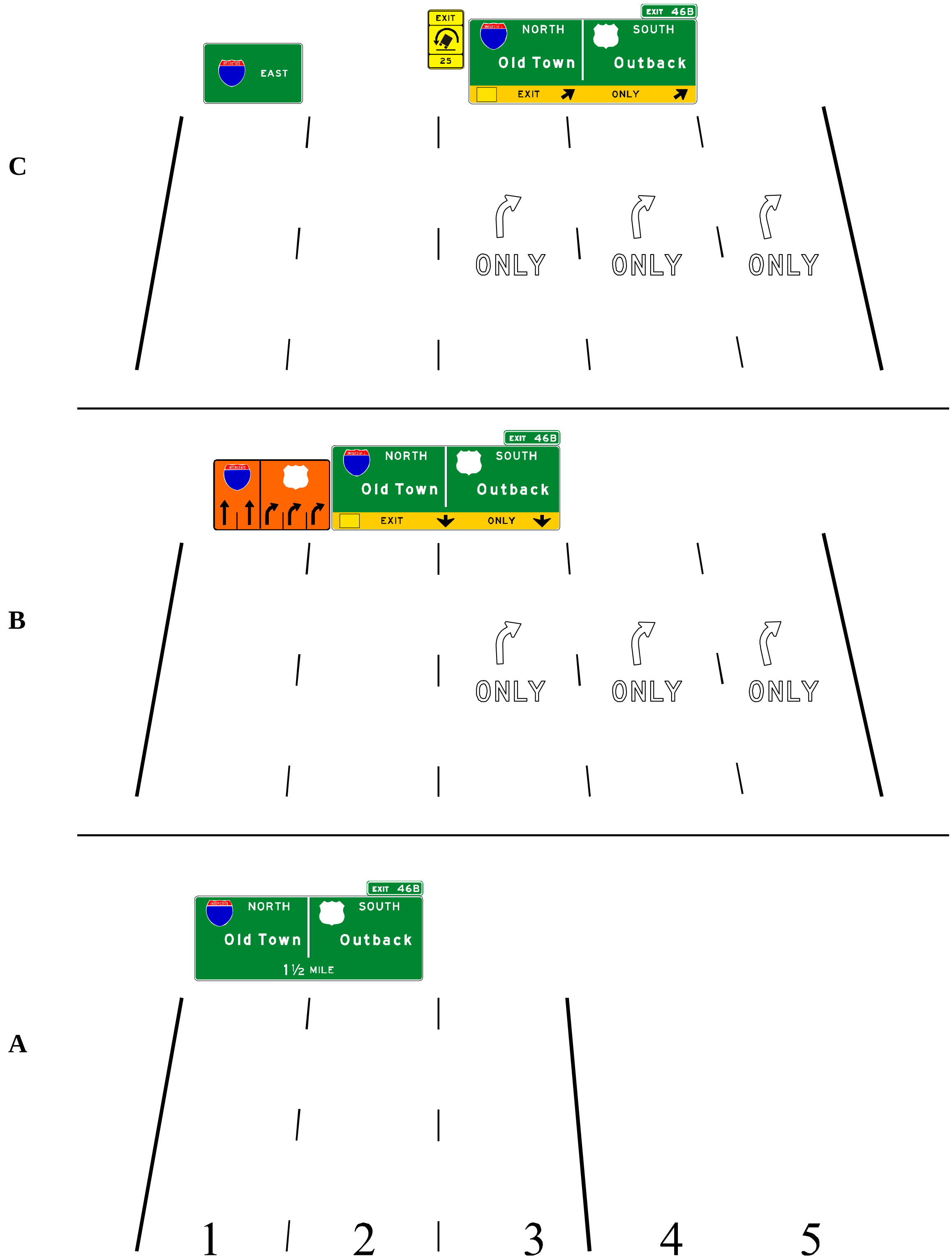


Figure 4. Modified Existing Signs and Temporary Guide Signs (Example 2).

Figure 5. Examples of Temporary Modifications to Guide Signs in the Field.

Temporary Lane Closures within the Interchange

Several difficulties exist when attempting to temporarily close one or more through lanes and/or exit lanes within an interchange. The primary challenge is in how to properly convey which lane or lanes are closed. The TMUTCD typical application for lane closures near exit ramps (shown in Figure 1) provides positive guidance, but results in a significant loss of capacity approaching the exit, especially if the exit includes one or more lane drops. As a result, substantial queuing can develop upstream along with increased turbulence and crash risk associated with such queuing. If the amount of traffic exiting is significant, it is sometimes more desirable to attempt to leave the exit only lanes open or to otherwise minimize the extent of lane closures.

During the review of temporary traffic control at urban freeway interchanges, researchers identified positive guidance issues with respect to lane closures:

- on ramps,
- near closely spaced ramps,
- on collector-distributor (C-D) roads,
- downstream of exit ramps with exit only lanes,
- downstream of multi-lane entrance ramps, and
- downstream of splits.

There were multiple sites where the advance signing for a lane closure on an exit ramp (e.g., RIGHT LANE CLOSED AHEAD) was located prior to the ramp and thus could be misleading to drivers who remain on the main lanes through the interchange. One example is shown as lane closure "A" in Figure 6. At this site, there was a RIGHT LANE CLOSED sign upstream of the eastbound freeway exit. However, the lane closure was actually past the eastbound freeway exit in the right lane of the westbound freeway exit. Similarly, at another site, there was a LEFT LANE CLOSED AHEAD sign located prior to an exit ramp to indicate a left lane closure on the ramp. Drivers could misinterpret this as a left lane closure on the main lanes. At two sites, advance signing for a lane closure on a ramp began immediately after the main exit ramp split into two ramps for each cardinal direction. This layout was most likely used to avoid signs being placed on the main lanes or main exit ramp, but resulted in a relatively short distance between the beginning of the signing and the actual lane closure.

There are also issues with lane closures near closely spaced ramps (Figure 7). Drivers need to be informed that vehicles will be entering the main lanes, that there is no acceleration lane (if applicable), and that the exit is still open. Also, as shown in Figure 7, if the distance between the entrance and exit ramp is less than two times the taper length, adequate taper lengths for the ramps cannot be provided.

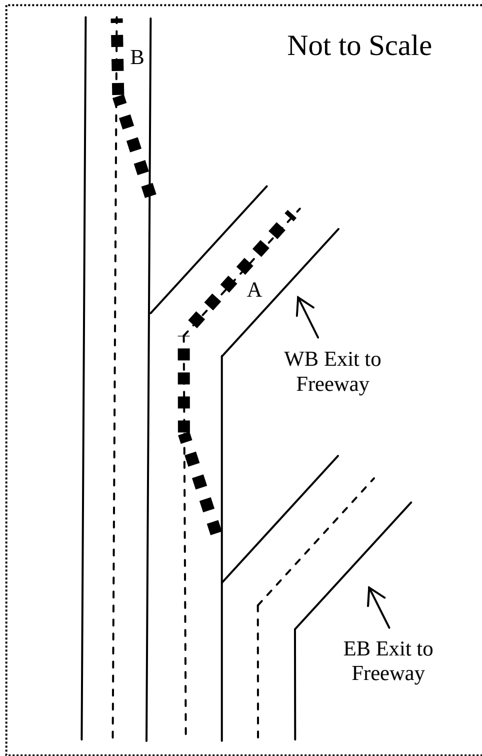


Figure 6. Examples of Lane Closures On and Downstream of Exit Ramps.

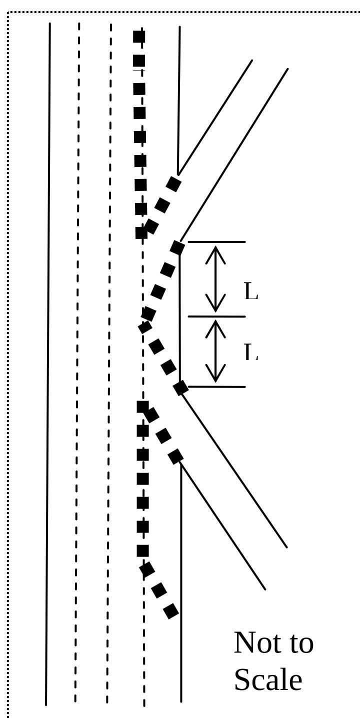


Figure 7. Example of Lane Closure near Closely Spaced Ramps.

Similar issues occur when lane closures are located on C-D roads (Figure 8). Drivers need to be informed that there is a lane closure but they can still access both directions of the freeway. However, advance signing placed upstream of the exit to the C-D road would be misleading to drivers who remain on the main lanes through the interchange.

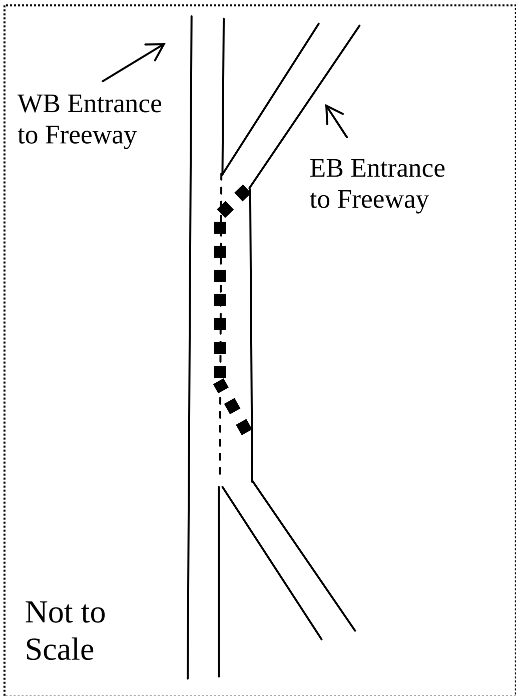


Figure 8. Example of Lane Closure on C-D Roads.

As shown in Figure 6 (lane closure "B") and Figure 9, communicating to drivers about lane closures immediately downstream of exit ramps with exit only lanes is also challenging. In both figures, a RIGHT LANE CLOSED sign prior to the exit ramps could be interpreted as a right lane closure on the ramp or on the main lanes. Signing for a left lane closure in these situations could also be misleading. Similar issues arise when lane closures are downstream of multi-lane entrance ramps (Figure 10) and splits (Figure 11).

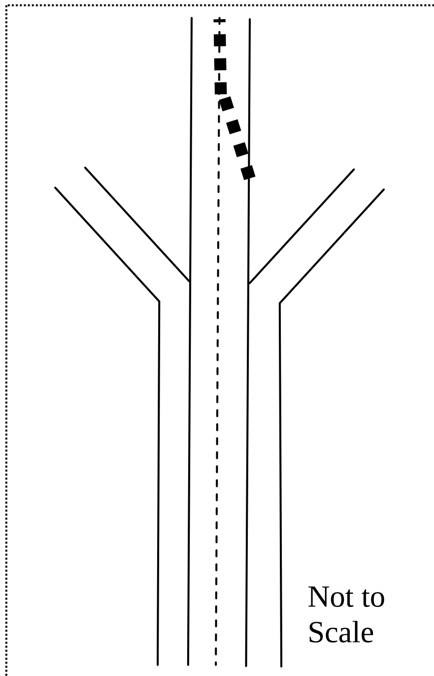


Figure 9. Example of Lane Closure Downstream of Simultaneous Left and Right Exit Only Lanes.

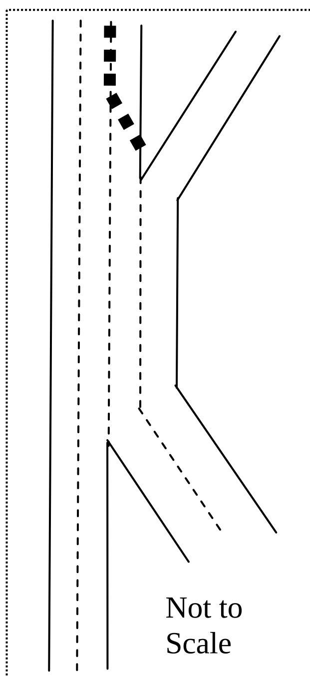


Figure 10. Example of Lane Closure Downstream of Multi-Lane Entrance Ramp.

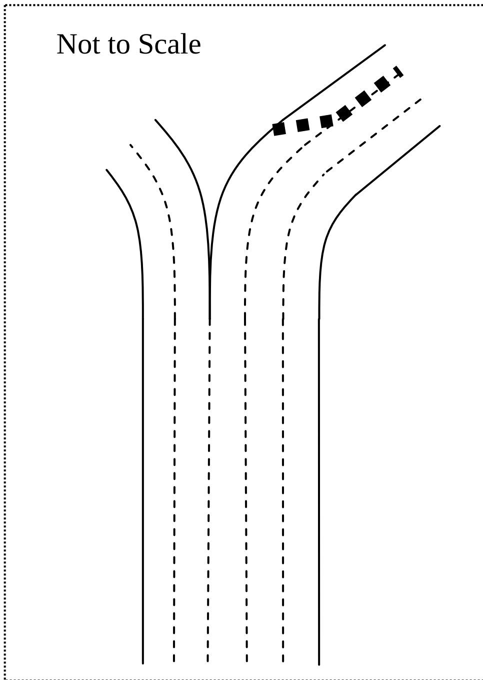


Figure 11. Example of Lane Closure Downstream of a Split.

Lane Shifts

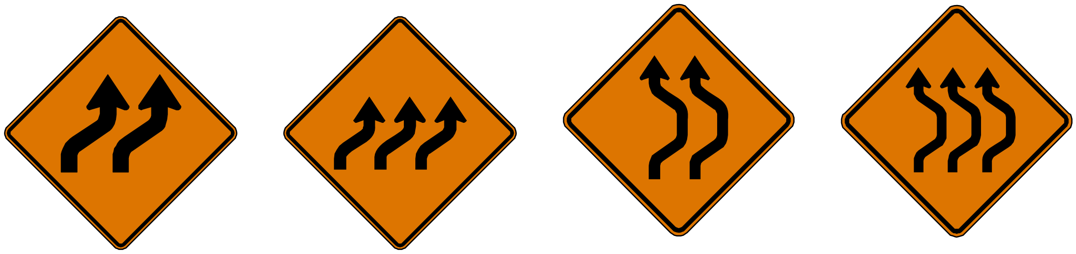
Signing for lane shifts was identified as an issue during the telephone and email interviews. According to the TMUTCD, a warning sign shall be used to show the change in alignment for lane shifts on freeways. Where the shifted section is longer than 600 ft, one set of reverse curve signs (CW1-4) should be used to show the initial shift and a second set should be used to show the return to the normal alignment (Figure 12). If the tangent distance along the temporary diversion is less than 600 ft, the double reverse curve sign should be used instead of the first reverse curve sign and the second reverse curve sign should be omitted.

CW1-4R(L)

Figure 12. Reverse Curve Sign in Texas MUTCD (*1*).

The issue is that the standard reverse curve sign contains only a single thick arrow. On freeway facilities, multiple lanes are typically shifted due to work activity. During the field investigations, researchers identified several locations where the reverse curve signs were modified such that the number of arrows on the sign matched the number of lanes (shown in Figure 13). It should also be noted that Chapter 6F of the MUTCD (*10*) includes reverse curve (W1-4b and W1-4c) and double reverse curve (W24-1a and W24-1b) signs for two or more lanes (Figure 14). While the MUTCD does not contain any language about the reverse curve signs for two or more lanes, it does state that the number of lanes illustrated on a double reverse curve sign shall be the same as the number of through lanes available to drivers. It is not clear whether there is any advantage to using reverse curve signs with multiple arrows over the single thick arrow. Furthermore, it is not clear whether a possible misapplication of a multiple arrow sign (where the number of lanes and the number of arrows were different) would create driver confusion and possible safety concerns and thus should be avoided in favor of the single thick arrow.

Figure 13. Examples of Modified Reverse Curve Signs in Texas.



W1-4b W1-4c W24-1a W24-1b

Figure 14. Reverse Curve and Double Reverse Curve Signs for Two or More Lanes (*3*).

Other Miscellaneous Issues

Sometimes getting drivers to use temporary two-lane entrance ramps back on to the freeway beyond a total freeway closure is difficult. Drivers will exit the freeway in two lanes with the proper channelization and signing. However, even when extra signing is used (i.e., TWO LEFT LANES/ENTER FREEWAY or STAY IN 2 LANES displayed on portable changeable message signs), motorists typically attempt to merge left back into a single lane prior to entering the freeway again. This creates a significant amount of turbulence and queuing on the frontage road and significantly reduces the effective capacity of the diversion route.

When traffic is diverted completely off of the freeway during a major interchange closure, sometimes there are difficulties with trailblazing signing provided. In particular, the trailblazing signs provided tended to be obscured by the large number of trucks that were present on the diversion route. In addition, it appeared that many more trailblazers should have been used because drivers quickly became anxious when they thought they had missed a turn or were on the wrong route. Part of the anxiety was believed to be due to the fact that the interchange work zone could not be seen from the diversion route, and so drivers had no way of knowing where the natural place to return to the freeway was going to be located.

When temporary lanes (e.g., shoulders or ramps) or complete diversions are used, transport of large equipment or loads must be considered, since vertical and horizontal clearances may be reduced.

Lane shifts placed on curves also appear to be confusing to motorists, as such shifts do not properly give perspective of the maneuver to be required (i.e., drivers underestimate the amount of shift they will need to make).

Another issue noted was that the removal or reduction of acceleration lane lengths for entrance ramps creates significant troubles for drivers, especially at locations with high mainlane and ramp traffic demands. The respondent noted that the proper thing to do would be to close the ramp completely if a reasonable acceleration lane length cannot be maintained. Unfortunately, political pressures often force TxDOT and the contractor to keep the lane open, even though the merging problems resulting from such a practice are evident (note the multiple impacts with the barrier in Figure 15).

Figure 15. Examples of Removal or Reductions in Acceleration Lane Lengths.

One final question raised with respect to driver guidance concerns was whether the mixing of temporary and permanent warning signing creates any confusion for the driver (see Figure 16). Although it is quite common to have both in place within the work zone, one can see how the practice could possibly raise questions with motorists (depending on the combination of signs visible) as to whether all the signs were actually relevant, which ones were most urgent, etc.

In addition, at several locations, missing pavement markings and/or "ghost" markings from previously removed pavement markings made it difficult to determine the proper travel path. This was especially a problem at exit and entrance ramps realigned during construction.

Figure 16. Combination of Permanent and Temporary Warning Signs.

Finally, in several locations, drivers on the main lanes could see temporary signs for lane closures on the frontage road and thus could have misinterpreted these signs as indicating lane closures on the main lanes.

PRIORITIZATION OF ISSUES FOR EVALUATION

Based on the surveys and field assessments of positive guidance issues in freeway interchange work zones, researchers identified four key topics to investigate further with laboratory studies in this project. The first topic for investigation was the ramification of guide sign misalignment (and elimination of down arrow to indicate lane assignments) that often occurs when temporary lane shifts, widening, and other work zone activities require lanes to be moved laterally. Key questions to be answered about this topic were as follows:

- Does a substantial misalignment between guide signs and travel lanes significantly degrade how well drivers choose lanes (either to exit or remain on the freeway) as they approach an interchange?
- Does the use of pavement marking symbols (i.e., route shields) and/or the provision of a temporary diagrammatic guide sign help reduce the adverse effects of guide sign misalignment at freeway interchange work zones?

The second topic was related to the above issue and involved questions of how best to use pavement marking symbols to help provide drivers with lane choice decisions when approaching freeway interchanges. Key questions to be answered with respect to their use in work zone applications were as follows:

- Do route shields (or, by association, text descriptions of highway numbers) provide better guidance information than pavement arrows, and does the use of pavement arrows and route shields together provide additional benefits in motorist comprehension and lane choice at the interchange?
- Do the pavement markings need to be placed across all through and exiting travel lanes, or can their use be limited to exiting lanes only?

The third topic examined in this part of the project was to determine whether portable changeable message sign (PCMS) messages could be identified to adequately convey the presence of a lane closure within a freeway interchange area, such as immediately downstream of an exit lane drop. Such a message could allow agencies to keep exit lanes open upstream of the closure to service the exiting traffic and thereby reduce the likelihood or extent of congestion developing upstream. Key questions to be answered in this investigation were the following:

- Would a text-based message (i.e., LEFT THROUGH LANE CLOSED) perform better, worse, or the same as a graphics-based message? Would either message be understood any better than a standard MUTCD LANE CLOSED warning sign?
- Would the performance of either type of PCMS message be affected by whether one lane or two lanes were being closed to traffic?

The final topic examined in this project was driver understanding of reverse curve warning signs used to convey lane shifts within freeway work zones. Specifically, the questions of interest were the following:

- Does having multiple arrows on the sign corresponding to the number of travel lanes, rather than a single thick arrow, affect driver comprehension and desired driving response to the sign?
- Will driver understanding of the sign be adversely affected if an incorrect sign is displayed where the number of arrows and the number of travel lanes do not correspond?

CHAPTER 3. DRIVING SIMULATOR STUDY OF PATH GUIDANCE INFORMATION IN ADVANCE OF COMPLEX URBAN FREEWAY INTERCHANGES

STATEMENT OF THE PROBLEM

Work activities at complex urban freeway interchanges often result in modified lane assignments; thus, it is crucial to maintain adequate and correct guide signing in advance of the interchange in order to provide drivers proper and clear path guidance information. This challenge can be especially difficult at locations where exit only lanes are or have previously been in place. From a cost-effectiveness perspective, it is typically desirable to maintain use of the existing guide signs rather than construct new temporary signing. However, determining whether existing signs can continue to be utilized, as well as determining the most appropriate and worthwhile method of temporarily modifying existing guide signs when necessary, is a challenge.

In order to use existing guide signs where they have been shifted out of alignment with the travel lanes, TxDOT typically covers the lane assignment arrows on the signs. Unfortunately, it is not known if removing the lane assignment arrows, which provide path guidance information, results in driver confusion. Smaller temporary lane assignment signs (black legend on an orange background) placed on the overhead sign gantries and/or route shield pavement markings in the travel lanes can provide modified lane assignment information and thus may be particularly helpful in work zones where overhead sign gantries have been misaligned due to work activity. As part of this project, TTI researchers designed and conducted a driving simulation study to determine the answers to these particular questions.

STUDY OBJECTIVES

The objectives of this specific study were to determine whether the location and accuracy of driver lane changes made in advance of major freeway-to-freeway interchanges were affected by the use of:

- misaligned permanent guide signing,
- temporary guide signing, and
- route shield pavement markings.

STUDY DESIGN AND PROTOCOL

Overview

Researchers developed and conducted this study with the assistance of the TTI driving simulator. For each treatment, the subject began driving on a particular three-lane freeway. Several miles down the road, the researcher gave the subject a destination (i.e., 51 north to Walker) and told the subject that they were approaching an interchange. The subject then encountered two sets of advance guide signing (one approximately one mile in advance of the tip of the exit ramp gore area and one at the tip of the exit ramp gore area). The advance guide signing indicated the current Interstate freeway and a US highway number and city name. The sign panel that presented the US highway information was positioned on the same side as the exit lanes, consistent with MUTCD requirements. In some instances, the destination given by the researcher was the US highway number, implying that the subject should exit the freeway. In other instances, the destination given by the researcher was the Interstate freeway number, implying that the subject should remain on the freeway and pass the interchange without exiting.

The treatments included the following:

- construction and non-construction conditions,
- lane assignment arrow and no lane assignment arrow conditions (first set of advance signs only),
- properly aligned and misaligned guide signs (first set of advance signs only), and
- the use of additional devices to supplement the way-finding information (i.e., temporary signing located on the first set of advance signs, route shield pavement markings between the two sets of advance signs, or both temporary signing and route shield pavement markings).

Researchers also manipulated which lane subjects were in as they approached an interchange (through or exit lanes).

After each treatment the researcher asked the subject 1) whether it was clear which lane they needed to be in to reach the specified destination, 2) which piece of information helped them the most, and 3) if there was any piece of information that was confusing. At the end of each session, each subject rated how confusing it was to determine the correct lane to be in to reach the specified destination when the guide signs were misaligned and how helpful the additional devices were at reducing any confusion. In addition, for each treatment researchers computed the following measures:

- percent of subjects making correct and incorrect maneuvers,
- percent of subjects making unnecessary lane changes, and
- the mean distance between the initiation of the final lane change and the tip of the exit ramp gore area.

Driving Simulator

The TTI driving simulator is comprised of four components: vehicle, computers, projectors, and screens. The vehicle, a complete, full-size 1995 Saturn SL automobile, is outfitted with computers, potentiometers, and torque motors connected to the accelerator, brakes, and steering. The Saturn also features full stereo audio, full instrumentation, and fully interactive vehicle components, all of which provide the realistic feel of driving. The Saturn is connected to a computer component that consists of one data-collection computer and three image-generation computers. Computer-generated driving scenes are sent to three high-resolution projectors and projected to three high-reflectance screens.

Experimental Design

As implied above, researchers developed the experimental design to determine whether the location and accuracy of driver lane changes made in advance of major freeway-to-freeway interchanges were affected by the use of:

- misaligned permanent guide signing,
- temporary guide signing, and
- route shield pavement markings.

Overall, researchers tested the six treatments shown in Table 3. Figure 17 shows an example of misaligned guide signs with no arrows and a temporary sign, while Figure 18 shows an example of the route shield pavement markings.

Researchers presented both left- and right-hand exits and varied the type of exit upon which the treatment was presented (a single exit lane drop and a single exit lane drop with an option exit/through lane). Table 4 lists the various perspectives tested. For each perspective, an exit and through maneuver was completed, so there was a total of 48 scenarios. Researchers desired to have each subject's session take about an hour to complete; thus, each subject viewed eight of the possible 48 scenarios. Table 5 identifies the sequence of perspectives for six different versions of the experiment (subject groups). Researchers randomized the order of perspectives shown in each group to control for possible learning and treatment order effects.

Table 3. Driving Simulator Study Treatments.

Treatment	Construction	Arrows on Guide Signs [a]	Sign Alignment [a]	Additional Devices
1	No	Yes	Properly aligned	None
2	Yes	No	Properly aligned	None
3	Yes	No	Misaligned [b]	None
4	Yes	No	Misaligned [b]	Temporary sign [c]
5	Yes	No	Misaligned [b]	Route shield pavement markings [d]
6	Yes	No	Misaligned [b]	Temporary sign [c] & route shield pavement markings [d]

[a] First set of advance signs only.
[b] Signs misaligned by two lanes to the right for left exits and to the left for right exits.
[c] Located at the first set of advance signs. Temporary sign placed overhead to the right or left of existing guide signs to match the exit direction.
[d] Located between the two sets of advance signs.

Figure 17. Misaligned Guide Signs with No Arrows and Temporary Signs.

Figure 18. Route Shield Pavement Markings.

For each exit type, researchers chose to use the current Texas standard guide signs on two sets of overhead sign gantries (one approximately one mile in advance of the tip of the exit ramp gore area and one at the tip of the exit ramp gore area). Since driving speed and distance is somewhat distorted in the driving simulator and researchers desired to minimize the total driving time, the first set of guide signs was actually placed two-thirds of a mile (3517 ft) from the tip of the exit ramp gore area.

Table 4. Driving Simulator Study Perspectives.

Treatment	Left Exit		Right Exit	
	1 lane drop (LLD)	2 lane optional exit (LEO)	1 lane drop (RLD)	2 lane optional exit (REO)
1	O1 I3-US98	O3 I49-US74	O4 I91-US14	O6 I66-US55
2	O7 I3-US98	O9 I49-US74	O10 I91-US14	O12 I66-US55
3	O13 I3-US98	O15 I49-US74	O16 I91-US14	O18 I66-US55
4	O19 I18-US31	O21 I98-US57	O22 I48-US81	O24 I51-US32
5	O25 I18-US31	O27 I98-US57	O28 I48-US81	O30 I51-US32
6	O31 I18-US31	O33 I98-US57	O34 I48-US81	O36 I51-US32

Ixx = Interstate; USxx = US highway

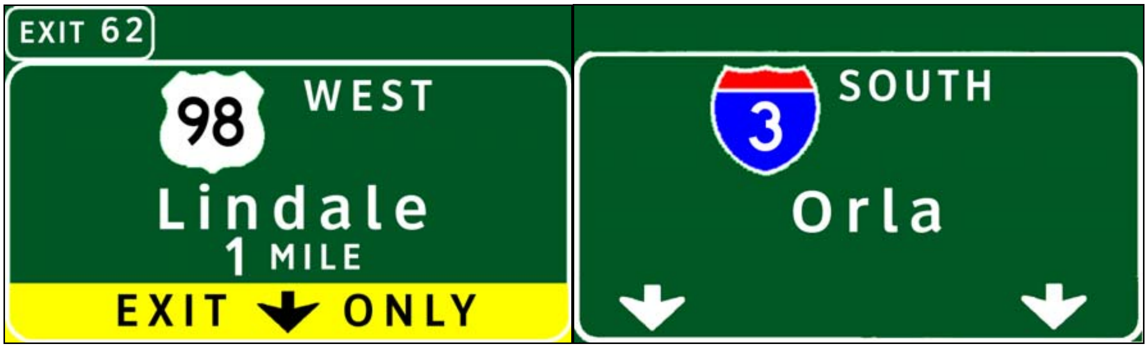
Table 5. Driving Simulator Study Treatment Order by Subject Group.

Subject Group	1	2	3	4	5	6	7	8
A1	O33E	O12T	O15T	O34T	O16E	O1T	O30E	O19E
A2	O18T	O4E	O25T	O21E	O22T	O3T	O36E	O7E
A3	O27T	O10T	O9E	O24T	O13T	O6E	O28E	O31E
B1	O34E	O19T	O1E	O15E	O33T	O16T	O30T	O12E
B2	O36T	O25E	O3E	O7T	O21T	O22E	O4T	O18E
B3	O13E	O9T	O6T	O28T	O27E	O31T	O10E	O24E

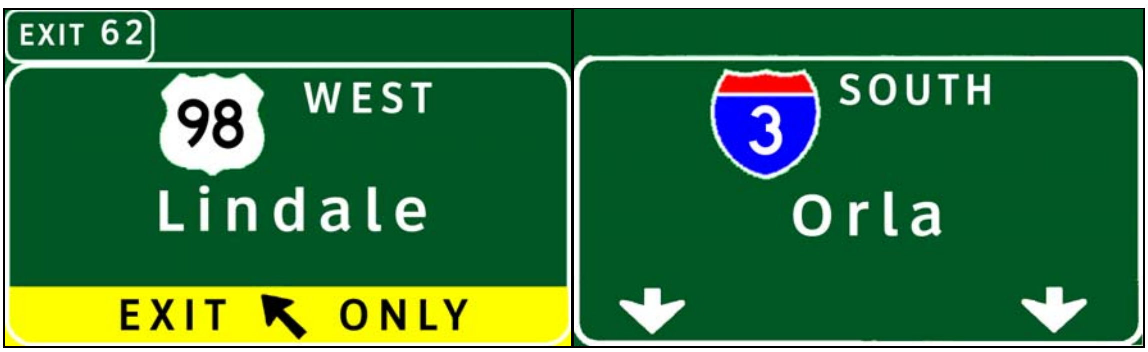
OxE = proper subject response is to exit
OxT = proper subject response is to remain on freeway (i.e., US highway number at interchange is not subject's stated destination)

For consistency, all sign sequences contained pull-through signs for the continuation of the route, as well as the exit signs. The interchange types are referred to as left lane drop (LLD), right lane drop (RLD), left exit only (LEO), and right exit only (REO). The lane drop exits begin with three lanes and either the left or right lane exits, leaving only two lanes for the through route. The exit only interchanges begin with three lanes and the exit to either the left or right consists of one lane that is forced to exit and one lane as an optional exit. This results in two lanes for the exit route and two lanes for the through route.

The overhead sign sequences tested are shown in Figure 19 through Figure 26. Each figure also contains the additional devices tested, if applicable. The temporary signs were placed on the first overhead sign gantry to the right or left of existing guide signs to match the exit direction. The route shield pavement markings appeared in the travel lanes one-third of the way between the two overhead sign gantries or 2346 ft from the tip of the exit ramp gore area. Because of limitations with the simulator software, the pavement markings were created by a fourth projector on a turntable that projected down on the roadway in front of the vehicle. A researcher maneuvered the turntable to position the pavement markings in their correct lane.

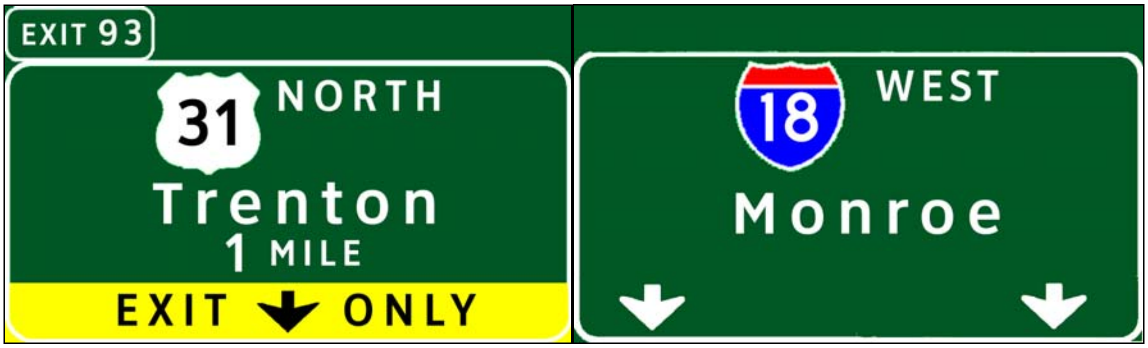


a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area

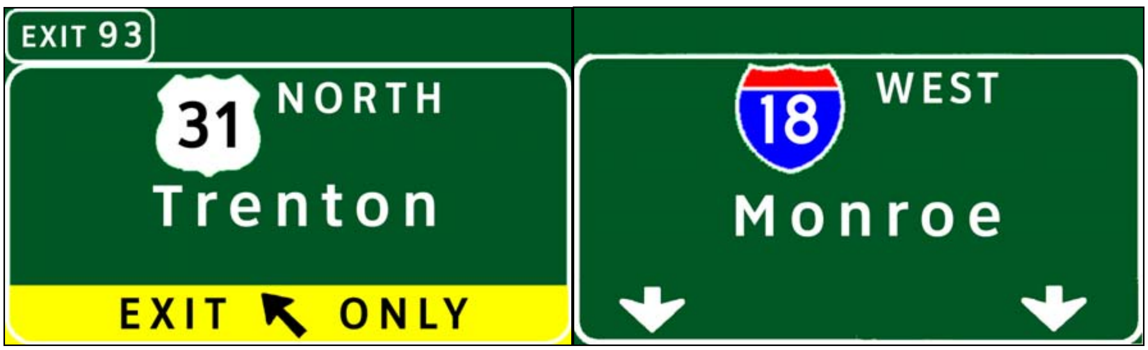


b) Guide Signs at the Exit Ramp Gore Area

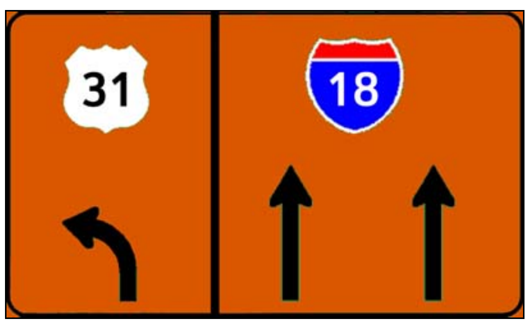
Figure 19. Simulator Sign Sequence LLD O1, O7, and O13.



a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area



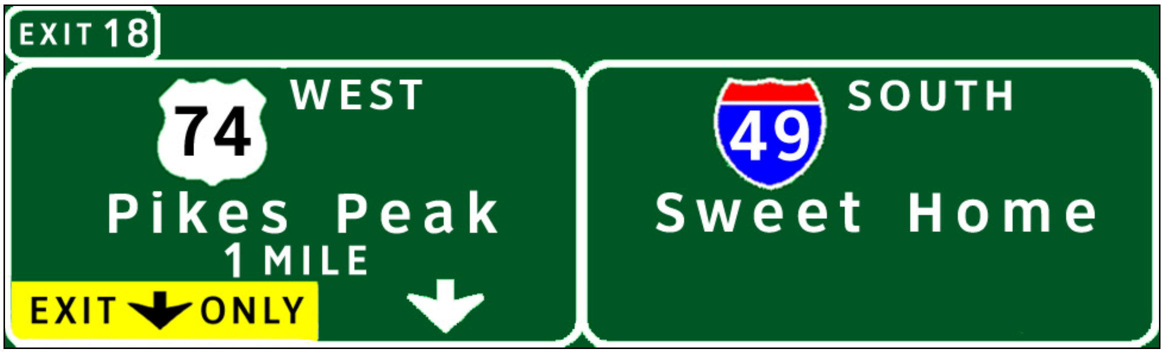
b) Guide Signs at the Exit Ramp Gore Area



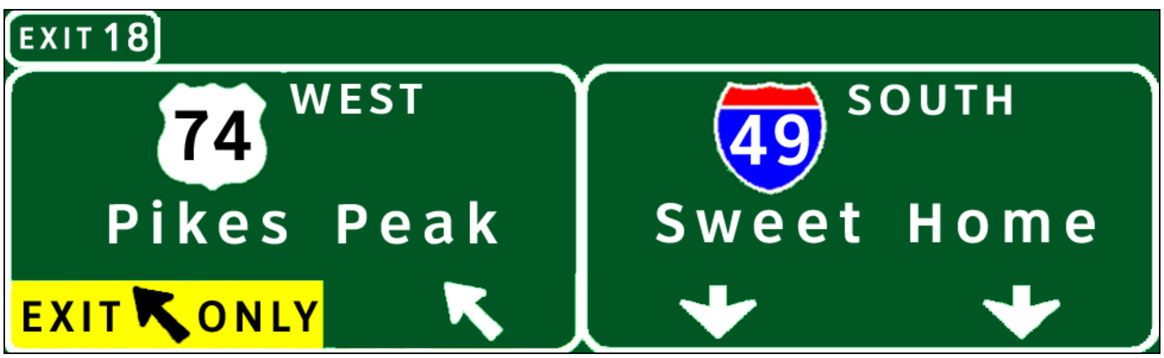
c) Temporary Sign

d) Route Shield Pavement Markings

Figure 20. Simulator Sign Sequence LLD O19, O25, and O31.

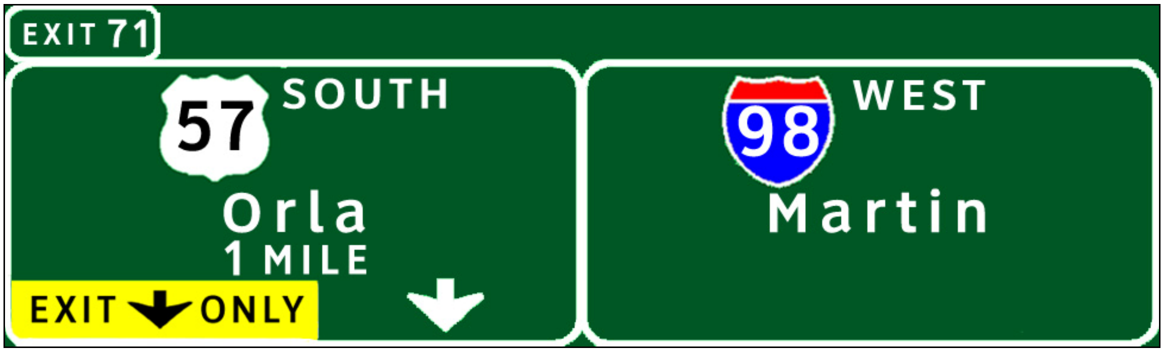


a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area

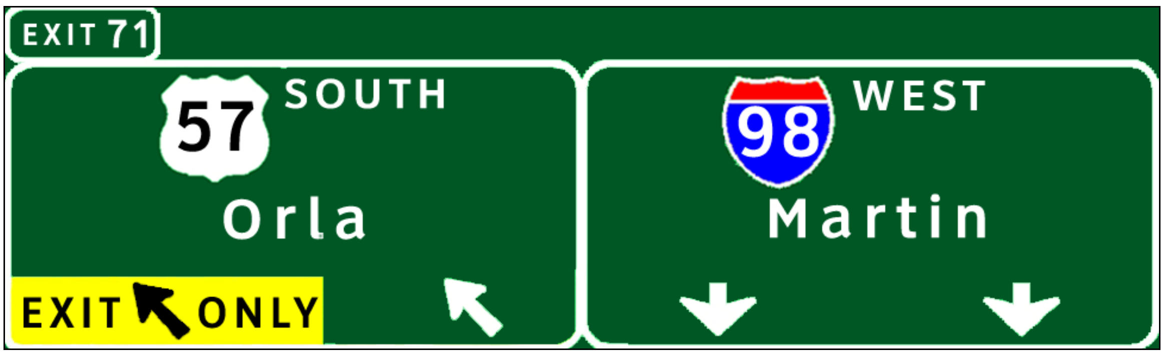


b) Guide Signs at the Exit Ramp Gore Area

Figure 21. Simulator Sign Sequence LEO O3, O9, and O15.



a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area

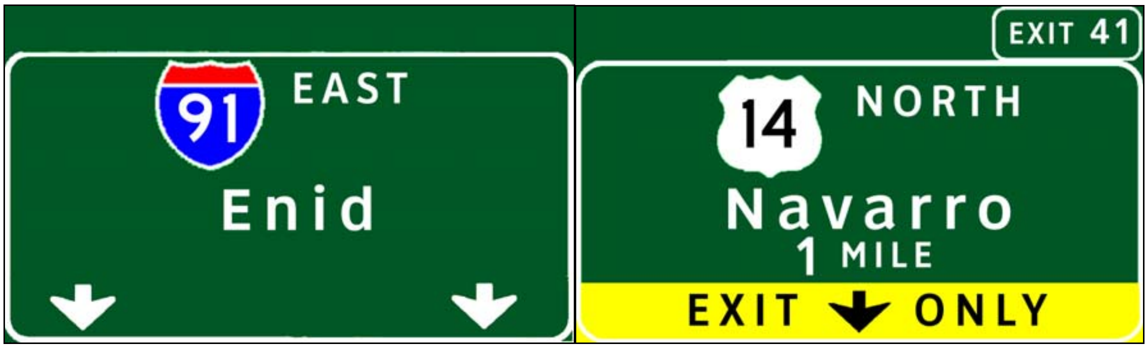


b) Guide Signs at the Exit Ramp Gore Area

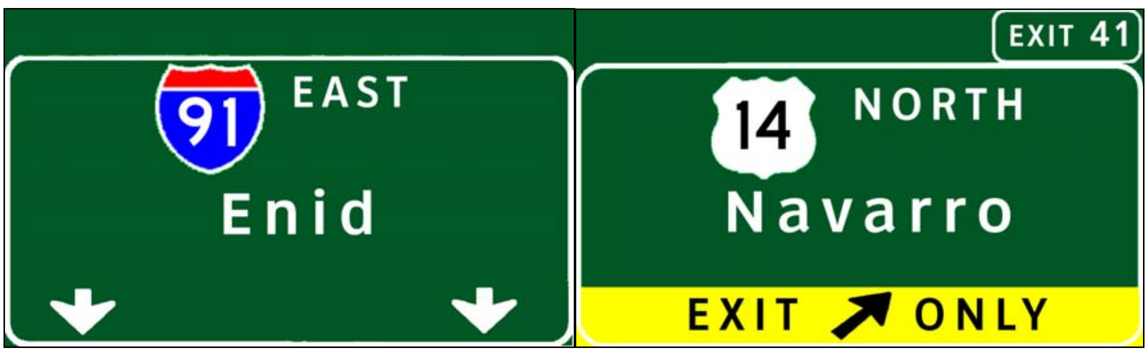
c) Temporary Sign

d) Route Shield Pavement Markings

Figure 22. Simulator Sign Sequence LEO O21, O27, and O33.

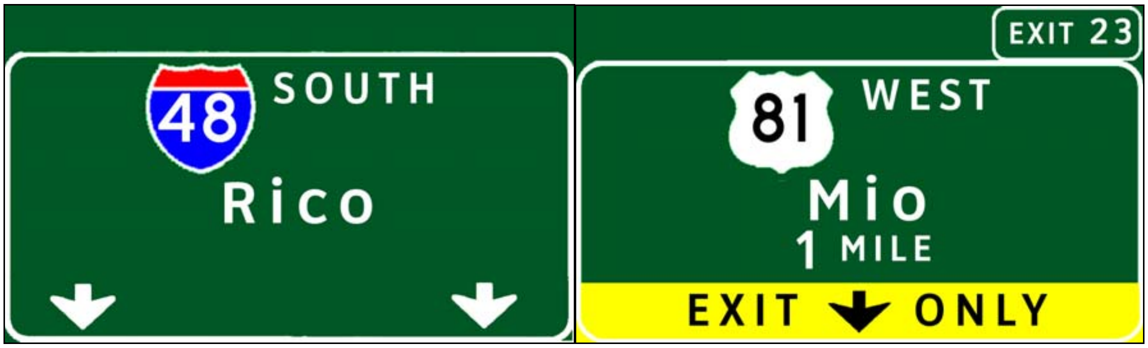


a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area

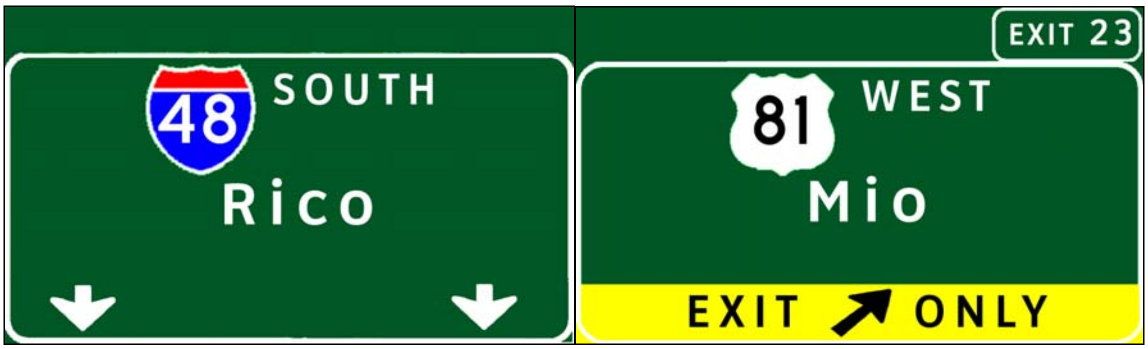


b) Guide Signs at the Exit Ramp Gore Area

Figure 23. Simulator Sign Sequence RLD O4, O10, and O16.



a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area

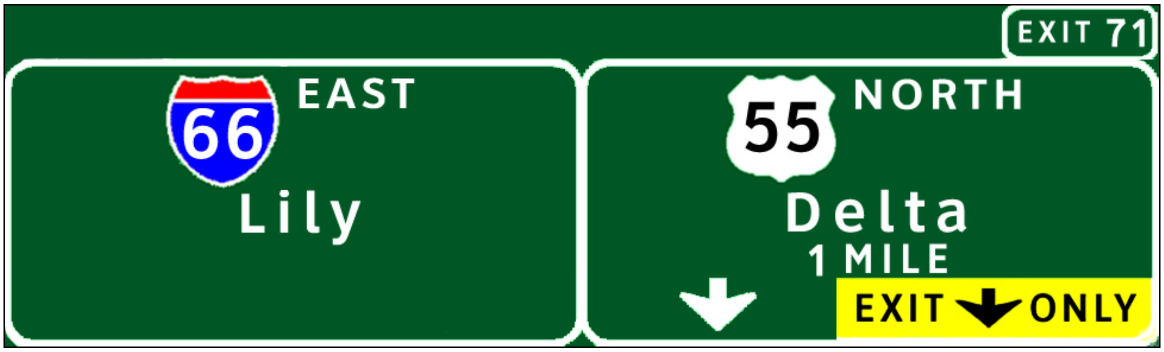


b) Guide Signs at the Exit Ramp Gore Area

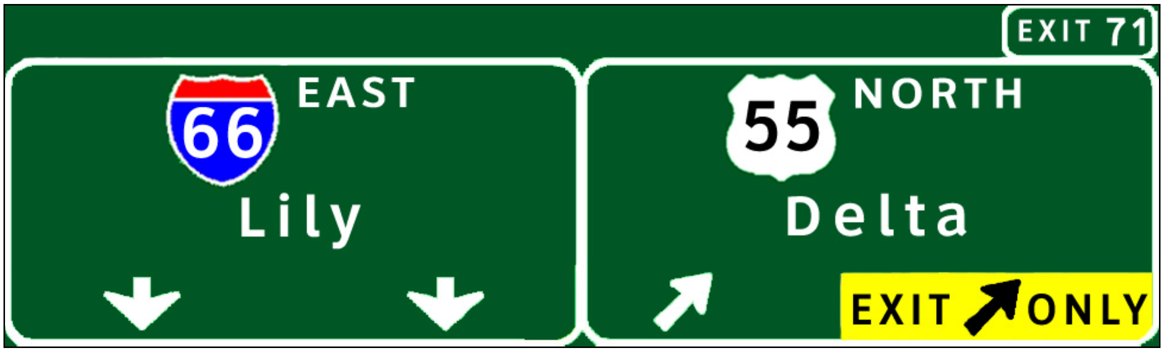
c) Temporary Sign

d) Route Shield Pavement Markings

Figure 24. Simulator Sign Sequence RLD O22, O28, and O34.

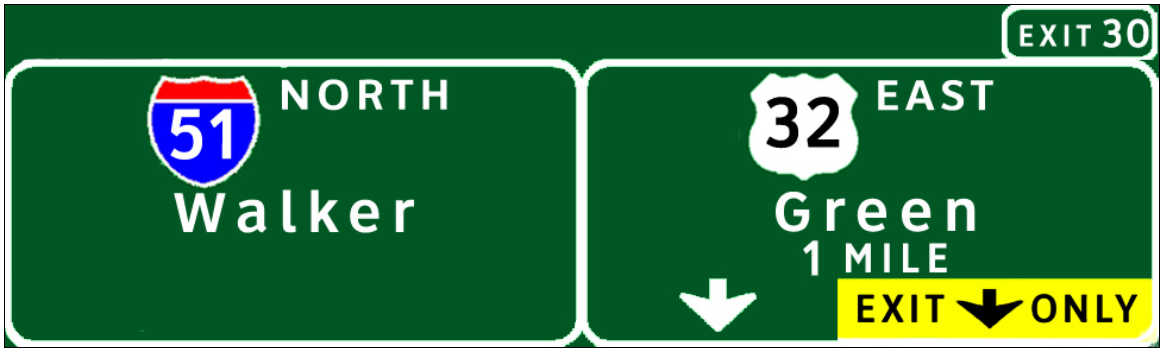


a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area

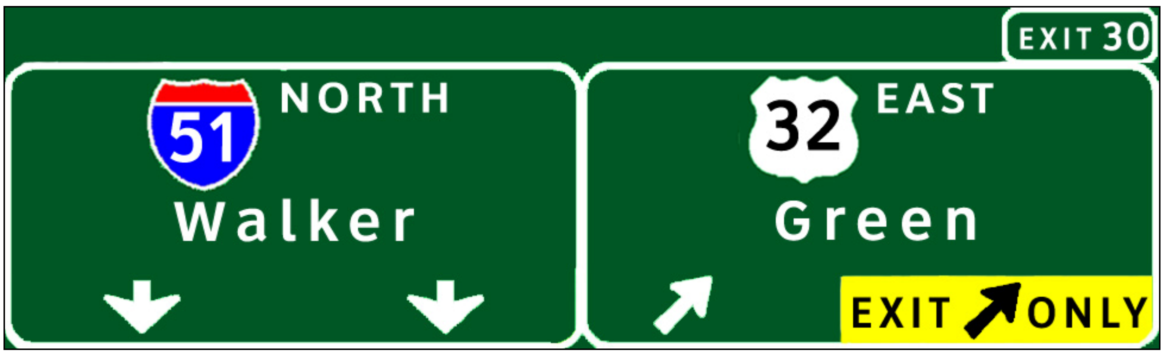


b) Guide Signs at the Exit Ramp Gore Area

Figure 25. Simulator Sign Sequence REO O6, O12, and O18.



a) Guide Signs Approximately One Mile in Advance of the Exit Ramp Gore Area



b) Guide Signs at the Exit Ramp Gore Area

c) Temporary Sign

d) Route Shield Pavement Markings

Figure 26. Simulator Sign Sequence REO O24, O30, and O36.

Test Procedure

Subject check-in and briefing took place at the TTI Gilchrist building. Upon arrival to the study location, researchers provided subjects with an explanation of the study and their driving task. Each subject then completed an introductory, practice, and experimental session. During the introductory session, subjects read and signed an informed consent document, filled out a simulator sickness questionnaire, and provided some basic demographic and driving habit information to the researcher. Before beginning the experimental session, each subject was given a chance to get accustomed to the simulator vehicle and experimental procedure by participating in a practice session.

During the experimental session, each subject viewed 8 of the 48 possible test scenarios. Researchers began each experimental session with a brief description of the overall process that was going to be followed:

"You are now about to start the experimental driving scene. When the driving scene begins, the simulator vehicle will be stopped on the side of the roadway. Place the vehicle in drive, drive onto the roadway, and proceed through the driving environment. Please drive in a normal fashion at 65 mph and obey all traffic rules.

Similar to the practice session, several miles down the road, I will give you a destination to drive to. Please repeat this information back to me so that I know that you understood the directions. Use the guide signs and pavement markings you see along the roadway to direct you to this destination. Often this will require you to make lane changes and even exits. However, we ask that you only make lane changes that are needed to reach the destination.

Similar to the practice session, I will ask you several questions concerning your lane choice and exit decision, as well as your opinion of the guide signs and pavement markings, then you will be given a new destination, and the procedure will start over again. At the end of the experiment, I will ask you to bring the vehicle to a complete stop and place it in park."

The subject then began driving on a particular three-lane freeway. At the beginning of each scenario, the researcher told the subject which lane to move into (initial lane position) and gave the subject a destination (e.g., *"Please move into the left lane. You want to drive on 57*

South to Orla."). The subject then encountered two sets of advance guide signing (one approximately one mile in advance of the tip of the exit ramp gore area and one at the tip of the exit ramp gore area). The advance guide signing indicated the current Interstate freeway and a US highway number and city name. The sign panel that presented the US highway information was positioned on the same side as the exit lanes, consistent with MUTCD requirements. In some instances, the destination given by the researcher was the US highway number, implying that the subject should exit the freeway. In other instances, the destination given by the researcher was the Interstate freeway number, implying that the subject should remain on the freeway and pass the interchange without exiting.

After each scenario the researcher asked the subject the following questions.

- Was it clear which lane you needed to be in to reach the destination? Why or why not?
- Which piece of information helped you the most to figure out where to go?
- Was there any piece of information that was confusing?

The process was repeated for each of the eight scenarios presented to the subject for a particular subject group. At the end of the experimental session, each subject rated, on a scale from one to five with one being 'not confusing' and five being 'very confusing,' how confusing it was to determine the correct lane to be in to reach the destination when the guide signs were misaligned. Each subject also rated, on a scale from one to five with one being 'very helpful' and five being 'not helpful,' how helpful the temporary signs and route shield pavement markings were at reducing any confusion. At the end of the study, each subject received $30.

Demographics

A total of 36 subjects participated in the driving simulator study. Researchers did not actively recruit to meet specific demographic criteria, but did attempt to obtain a range of participant ages and education levels. Table 6 summarizes the overall demographic distributions achieved. Overall, the subject sample consisted of slightly more males, slightly older drivers, and slightly more educated drivers than was reported for the Texas driving population as a whole. Even so, it is believed that the results obtained from this study do represent Texas drivers reasonably well overall. Seventy-eight percent of the subjects drive on urban freeways at least one to 10 days a month, while 14 percent drive on urban freeways more than 10 days a month and only 8 percent reported that they do not drive on urban freeways (three subjects who were over 50 years old).

Table 6. Subject Demographics for Driving Simulator Study.

	Gender		Age			Education [a]			
	Male	**Female**	**18-39**	**40-54**	**55+**	**< HS**	**HS Graduate**	**Some College**	**College Graduate**
Study Sample	53%	47%	33%	39%	28%	0%	14%	33%	39%
2001 Texas License Data	50%	50%	47%	29%	24%	24%	25%	27%	24%

HS – High School
[a] Study sample does not add to 100%, because five subjects (14 percent) did not provide their education level.

STUDY RESULTS

Driver Lane Choice

As described previously, in some instances the destination given by the researcher was the US highway number, implying that the subject should exit the freeway. In other instances, the destination given by the researcher was the Interstate freeway number, implying that the subject should remain on the freeway and pass the interchange without exiting. Researchers also manipulated which lane subjects were in as they approached an interchange (through or exit lanes). Thus, subjects experienced two types of trials:

- trials in which they began in a lane which would take them to their destination (a "correct" start lane), and
- trials in which they would have to change lanes to get to their destination (an "incorrect" start lane).

Researchers designed the experiment using the signal detection theory concepts shown in Figure 27. Subjects were asked to detect when a lane change was necessary (signal stimuli) and when a lane change was not necessary (noise stimuli). If a subject began a trial in a lane that would not lead them to the requested destination, they had to change lanes at some point before the gore. A trial in which a subject moved from an incorrect lane into a correct lane was scored a "hit." A trial in which the subject continued through the interchange in an incorrect lane was scored a "miss." For trials scored as "hits," researchers calculated the distance upstream of the tip of the exit ramp gore area at which the lane change occurred. If a subject changed lanes when it was not necessary, the trial was scored a "false alarm." If the subject did not change lanes in this situation, the trial was scored a "correct rejection."

		Stimuli	
		"Signal" (Incorrect Start Lane)	"Noise" (Correct Start Lane)
Responses	Lane Change Made	Hit	False Alarm
	No Lane Change Made	Miss	Correct Rejection

Figure 27. Signal Detection Concept Relating to Lane Changes.

In some trials in which the subject began in an incorrect lane, it was possible to make a second lane change that would still lead the subject to the desired destination. In this case, while the first lane change was necessary, the second lane change was unnecessary as no trial required the participant to make two lane changes to reach their destination. This second lane change was scored as a "secondary false alarm" and regarded as an unnecessary lane change.

Figure 28 displays four possible paths for the REO interchange geometry. Paths 1 and 2 are examples of primary false alarms, while paths 3 and 4 show necessary lane changes ("hits") followed by secondary false alarms. Researchers considered both primary and secondary false alarms as "unnecessary lane changes."

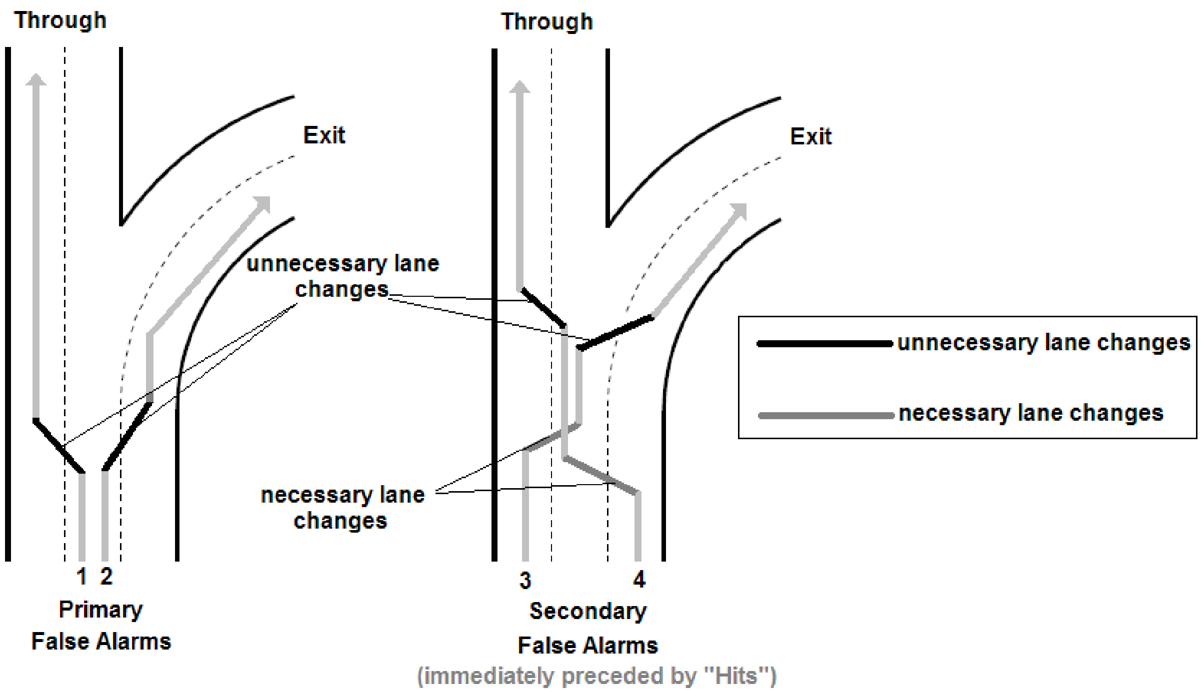


Figure 28. Primary and Secondary False Alarms Illustrated for REO Interchange Geometry.

Table 7 contains the percent of subjects who chose the correct and incorrect paths, as well as the percent of subjects who made unnecessary lane changes. All of the subjects followed the correct path (exit or remain on the freeway); thus, there were no "misses." However, for each treatment, approximately 30 percent of the subjects made unnecessary lane changes. Upon further review, the majority of unnecessary lane changes were 1) subjects moving from the center lane to either the left or right lane when they could have remained in the center lane to reach their destination and 2) subjects moving from the left lane to the right lane (across the center lane) or vice versa when they could have just moved into the center lane to reach their destination. Based on the subjects' comments to post-scenario questions, subjects made these unnecessary lane changes even though they knew they were in the correct lane in order to ensure they would be able to follow the correct path (either exit or remain on the freeway).

Table 7. Subject Path Choice.

Treatment	Percentage of Subjects Who Chose		
	Correct Path		Incorrect Path (Misses)
	Did Not Include Unnecessary Lane Changes (Hits & Correct Rejections)	Included Unnecessary Lane Changes (False Alarms)	
1	67%	33%	0%
2	71%	29%	0%
3	71%	29%	0%
4	69%	31%	0%
5	71%	29%	0%
6	73%	27%	0%

Table 8 presents the mean final lane change distance upstream of the tip of the exit ramp gore area by treatment, while Table 9 contains information on the clarity of the path guidance information. Researchers conducted an analysis of variance (ANOVA) statistical test to assess whether these mean distances are equal. Based on a 95 percent level of confidence (alpha equals 0.05), researchers could not reject the null hypothesis that the mean final lane change distances upstream of the tip of the exit ramp gore are equal. Thus, researchers did not conduct additional statistical tests (i.e., multiple comparisons).

Table 8. Mean Final Lane Change Distance Upstream of the Tip of the Exit Ramp Gore Area by Treatment.

Treatment	Mean Final Lane Change Distance Upstream of the Tip of the Exit Ramp Gore Area (ft)
1	3346
2	2834
3	2424
4	2950
5	2692
6	2947

Table 9. Subject Responses to "Was it Clear Which Lane You Needed to be in to Reach the Destination?"

Treatment	Percent of Subjects Who Chose	
	Yes	No
1	85%	15%
2	81%	19%
3	48%	52%
4	75%	25%
5	58%	42%
6	69%	31%

As expected, treatment 1 (base condition with no construction and properly aligned guide signs with lane assignment arrows) resulted in subjects changing lanes the earliest (3346 ft upstream of the tip of the exit ramp gore area or 171 ft downstream of the first set of overhead guide signs). In addition, 85 percent of the subjects thought that treatment 1 provided clear information about the lane they should be in to reach the destination. When construction was added and the lane assignment arrows were removed on the first set of overhead guide sign (treatment 2), the mean final lane change distance upstream of the exit ramp gore area decreased to 2834 ft (512 ft closer to the gore), but the percent of subjects who thought it was clear which lane they needed to be in to reach the destination remained essentially the same. The largest reduction in the mean lane change distance (922 ft) occurred with treatment 3, which contained construction, no lane assignment arrows, and misalignment of the first set of guide signs. From Table 9, it is also apparent that subjects were not as clear about which lane they needed to be in to reach the destination. Nevertheless, this scenario often occurs at complex urban freeway interchanges when lane assignments are modified and the existing guide signs have been shifted out of alignment with the travel lanes.

Through the use of additional devices (temporary sign [treatment 4], route shield pavement markings [treatment 5], or both [treatment 6]), the mean lane change distance upstream of the tip of the exit ramp gore area increased to between 2692 and 2950 ft and the percent of subjects who thought it was clear which lane to be in to reach the destination increased to between 58 and 75 percent. It should be noted that the route shield pavement markings were shown 1171 ft downstream of the temporary sign (located at the first set of overhead guide signs 3517 ft upstream of the tip of the exit ramp gore area); thus, a direct comparison between treatment 4 and treatment 5 cannot be made. Also, based on the subjects' comments the lower percentage of subjects who thought treatment 5 was "clear" (58 percent), can be attributed to the removal of the lane assignment arrows and the misalignment of the existing guide signs, not the route shield pavement markings (e.g., "signs shifted," "no arrows showing the direction of exit," and "wasn't sure until I saw the pavement markings").

Subjects' Assessment of Helpful and Confusing Information

After each scenario, the researcher asked each subject which piece of information helped them the most and was there any piece of information that was confusing. Table 10 and Table 11 contain the responses to these two questions, respectively. From Table 10 one can see that with treatment 1 the subjects relied heavily on the first set of overhead guide signs (54 percent), but once the lane assignment arrows were removed from the first set of signs (treatment 2) and these signs were misaligned with travel lanes (treatment 3) subjects depended on the second set of overhead guide signs (located at the exit ramp gore area) to determine which lane they needed to be in to reach the destination (63 and 71 percent, respectively). For the treatments that included the temporary sign, route shield pavement markings, or both of these devices, at least half of the subjects thought these devices were helpful in determining which lane they needed to be in to reach the destination. In addition, these devices reduced the need for subjects to wait and receive information from the second set of overhead guide signs.

Table 11 shows that once the lane assignment arrows were removed from the first set of signs (treatment 2) and these signs were misaligned with travel lanes (treatment 3), the first set of signs were confusing to approximately 25 percent of the subjects. In addition, 11 to 33 percent of the subjects thought that the misalignment of the first set of overhead guide signs with the travel lanes was confusing. Even though some of the subjects stated that the additional devices were confusing, the reasons provided mainly dealt with the novelty of the devices and the format of the devices (e.g., overlay of pavement markings onto simulator projection, cardinal directions not provided, two different route shield pavement markings in optional exit lane). The latter of which will be further addressed in project 0-5890, *Guidelines for the Use of Pavement Marking Symbols at Freeway Interchanges*.

Table 10. Subject Responses to "Which Piece of Information Helped You the Most to Figure Out Where to Go?"

Treatment	Percent of Subjects Who Chose					
	1st Guide Signs	2nd Guide Signs	Signs (In General)	Temporary Sign	Route Shield Pavement Markings	Other
1	54%	22%	15%	NA	NA	9%
2	14%	63%	18%	NA	NA	5%
3	10%	71%	15%	NA	NA	4%
4	0%	39%	10%	49%	NA	2%
5	9%	29%	2%	NA	51%	9%
6	7%	25%	7%	59%		2%

NA – Not Applicable

Table 11. Subject Responses to "Was There Any Piece of Information That was Confusing?"

Treatment	Percent of Subjects Who Chose					
	Nothing	1st Guide Signs	Misalignment of 1st Guide Signs	Temporary Sign	Route Shield Pavement Markings	Other
1	83%	15%	NA	NA	NA	2%
2	71%	24%	NA	NA	NA	5%
3	46%	26%	28%	NA	NA	0%
4	65%	10%	19%	4%	NA	2%
5	44%	19%	33%	NA	2%	2%
6	60%	6%	11%	19%		4%

NA – Not Applicable

At the end of each experimental session, each subject rated on a scale from one to five (with one being "not confusing" and five being "very confusing") how confusing it was to determine the correct lane to be in to reach the destination when the guide signs were misaligned.

The average rating across all subjects was 2.9 out of 5.0. This is a result of approximately 20 percent of the subjects choosing each rating.

Each subject also rated on a scale from one to five (with one being “very helpful” and 5 being “not helpful”) how helpful the temporary signs and route shield pavement markings were at reducing any confusion. The average rating across all subjects for the temporary signs and route shield pavement markings was 2.5 and 1.6 out of 5.0, respectively. Thus, the subjects rated the route shield pavement markings a little more helpful than the temporary signs.

STUDY CONCLUSIONS

This driving simulator study was conducted to determine whether the location and accuracy of driver lane changes made in advance of major freeway-to-freeway interchanges were affected by the use of:

- misaligned permanent guide signing,
- temporary guide signing, and
- route shield pavement markings.

Work activities at complex urban freeway interchanges often result in modified lane assignments and the misalignment of existing overhead guide signs with the travel lanes. However, from a cost-effectiveness perspective, it is typically desired to maintain use of the existing guide signs rather than construct new temporary signing. Thus, TxDOT typically covers the lane assignment arrows on the signs so they are no longer visible to drivers.

The results of this study indicate that when the lane assignment arrows on existing overhead guide signs are covered and the signs are misaligned with the travel lanes, drivers are not clear which lane to be in to reach their destination and thus wait to make a lane change until closer to the exit ramp gore area. At a more complex urban freeway interchange with higher traffic volumes, this may result in erratic maneuvers such as hard braking, last minute lane changes, and vehicle conflicts during merging, all of which increase the potential for crashes. Thus, additional information needs to be presented to drivers in order to provide proper and clear path guidance in advance of the interchange.

The results of this study indicate that smaller temporary lane assignment signs (black legend on an orange background) placed with the overhead guide signs and/or route shield pavement markings in the travel lanes provide modified lane assignment information. Compared to the scenario described above (misaligned guide signs with the lane assignment arrows covered) these devices resulted in drivers making their lane change further upstream of the exit ramp gore area. Thus, either of these devices or a combination of these devices should be used to provide drivers with additional path guidance information in work zones where the existing overhead guide signs are misaligned with the travel lanes due to work activity and the lane assignment arrows are covered.

CHAPTER 4. DRIVER UNDERSTANDING AND PREFERENCES OF PAVEMENT SYMBOLS FOR ROUTE DESIGNATION

STATEMENT OF THE PROBLEM

Several TxDOT districts now use pavement symbols (or words on the pavement) in advance of complex urban freeway interchanges to supplement existing guide signing. In most cases, words and arrows on the pavement are used to designate lane assignment. However, some districts also use newer route shield products. Anecdotal information indicates that these installations do improve driver understanding, lane choice, and path guidance through interchanges. It has been suggested that pavement symbols may be particularly helpful in work zones where overhead sign gantries have been removed or misaligned due to work activity. Unfortunately, it is not known whether there is a need to install the full route shields (or text equivalents) for temporary work zone situations, or whether the use of straight and turn arrows would be sufficient. It is assumed that the installation of arrows only would be quicker and less costly (and thus preferable) than full-color route shields or text descriptions of the route.

Another key question that arises with respect to pavement marking symbol applications is whether it is necessary to put markings down in all of the lanes (both through and exiting lanes), or whether putting the markings down in the exiting lanes only would be sufficient. Again, minimizing the number of markings that have to be installed would be preferable for temporary work zone situations, if driver understanding was found to be comparable. As part of this project, TTI researchers designed and conducted a laboratory study to determine the answers to these particular questions.

STUDY OBJECTIVES

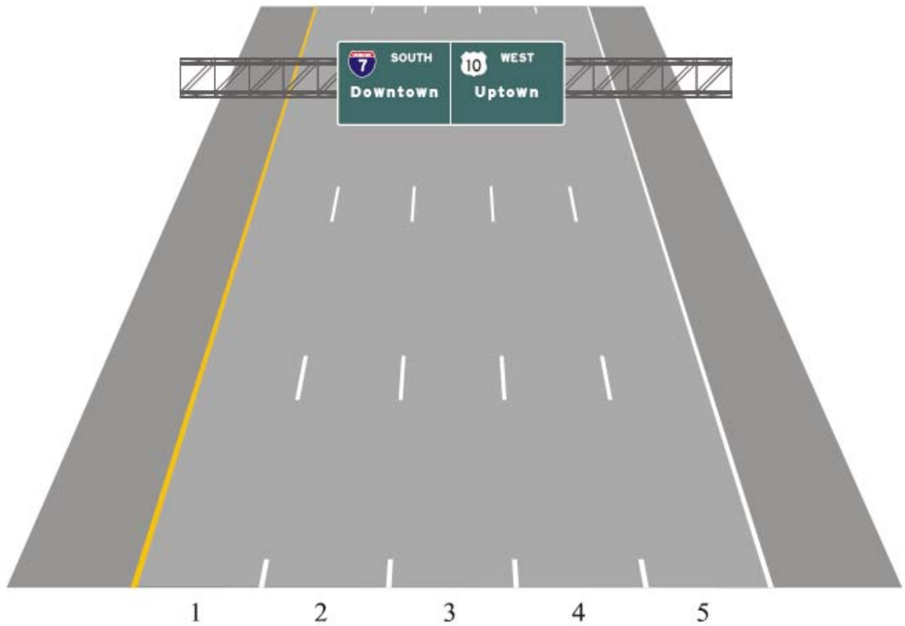
The objectives of this specific study were to determine whether the accuracy and confidence of driver lane choice selection decisions made in advance of major freeway-to-freeway interchanges are affected by:

- using markings in all lanes versus exit only lanes; and
- using route shields, arrows, or route shields and arrows combined on the lanes to indicate through and exiting lanes.

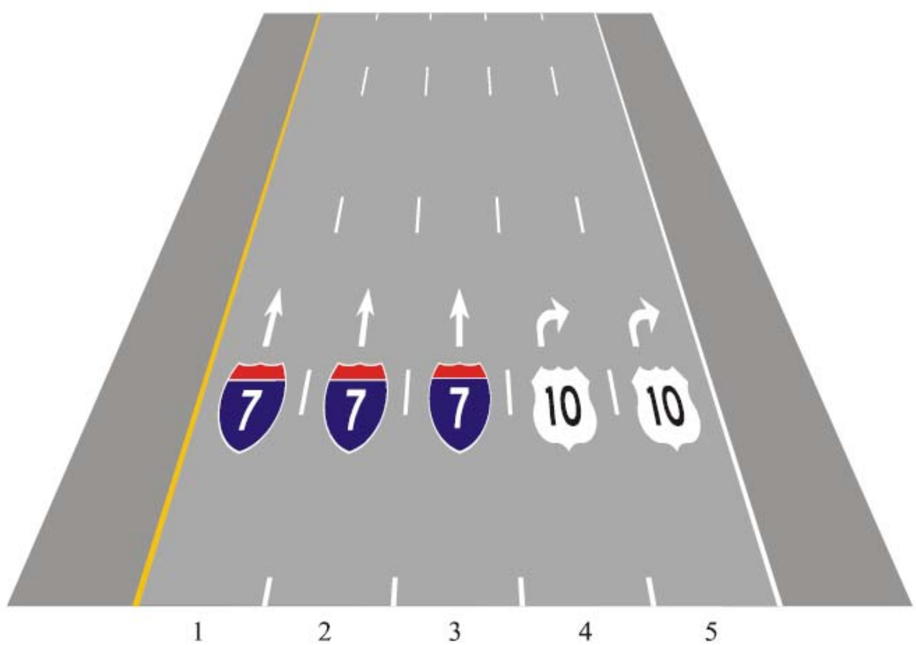
STUDY DESIGN AND PROTOCOL

Overview

Researchers developed and conducted a short survey with the assistance of a laptop computer. Researchers presented perspective views of a five-lane freeway and asked subject drivers to imagine themselves on that freeway. Researchers then instructed the subject that they were to exit at a downstream intersection US highway. Researchers then told the subject to imagine that they were approaching an interchange, and showed an advance guide sign. The guide sign would indicate the current freeway, and a US highway number and city name. No lane assignment or other arrows were used on the sign, but the sign panel that presented the US highway number and city was positioned on the same side as the exit lanes, consistent with MUTCD requirements. In some instances, the US highway number would be the same as the one researchers indicated to the subject, implying that the subject should attempt to exit the freeway. In other instances, the US highway number shown would be different than the highway number indicated earlier by the researcher, implying that the subject should remain on the freeway and pass the interchange without exiting. After a brief 3-second exposure to the advance guide sign, it would disappear and one array of pavement symbols would appear. These markings would then also disappear after 3 seconds. The researcher asked the subject to indicate 1) which lane or lanes would be acceptable to use to reach the destination they were instructed to use, 2) the specific lane they would select to reach their destination, and 3) the level of confidence they had in their answers. An example of the series of perspective views shown to subjects in this study is shown in Figure 29.



(a)



(b)

Figure 29. Illustration of Sequential Perspective Views for Pavement Symbols: Laptop Study.

Experimental Design

As implied above, researchers developed the experimental design to evaluate two principal treatment factors:

- the type of pavement marking symbol provided (route shields, arrows, both route shields and markings), and
- the number of lanes on which the pavement symbols were used (all lanes, exit lanes only).

Consequently, researchers tested six different combinations of pavement symbols and lane applications. Figure 30 through Figure 35 provide an illustration of each treatment combination. Researchers had subjects see each combination twice, once where the US highway number for the exit corresponded to the destination identified for the driver (i.e., an exit maneuver would be required), and again where the US highway number was not the intended destination (i.e., the subject would choose to remain on the freeway and pass through the interchange). Researchers presented both left- and right-hand exit perspectives to subjects in this experiment, and also varied the type of exit upon which the treatment combination was presented (a single exit lane drop, a double exit lane drop, and a single exit lane drop with an option exit/through lane).

Table 12 lists the various perspectives tested. To control for possible learning and treatment order effects, researchers developed six different versions of the experiment (subject groups). Researchers randomized the order of the perspectives shown in each group within the constraint that each version saw the six treatment combinations in both an exiting and non-exiting scenario. Table 13 identifies the sequence of perspectives for each version of the study.

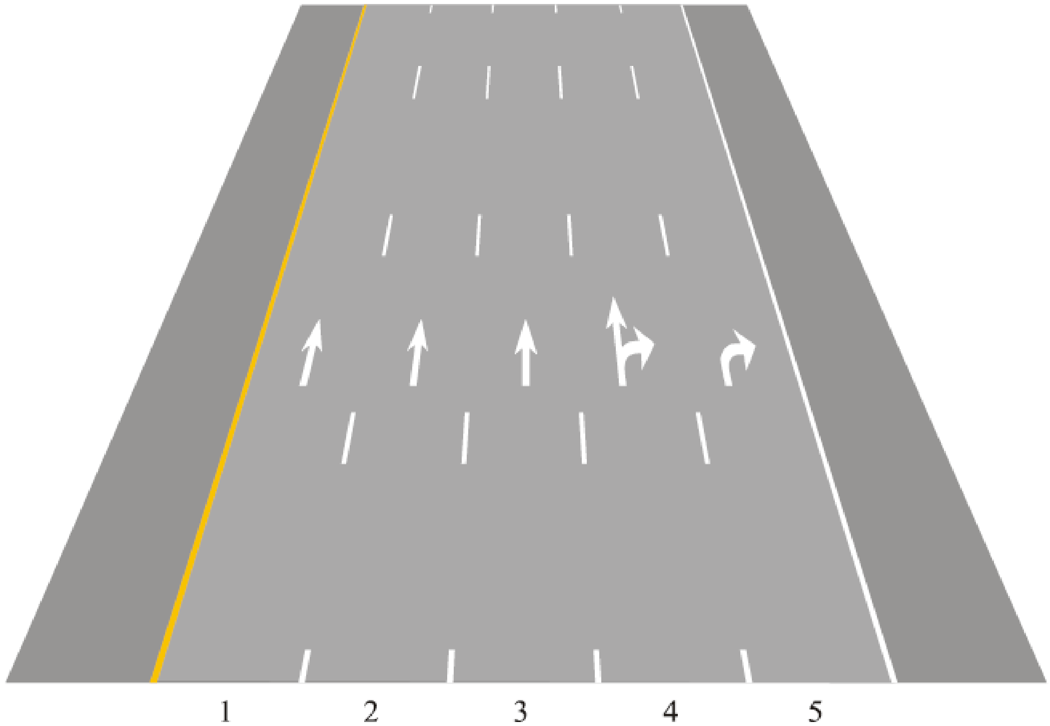


Figure 30. Arrows Shown on All Lanes (Right-Hand Optional Lane Exit).

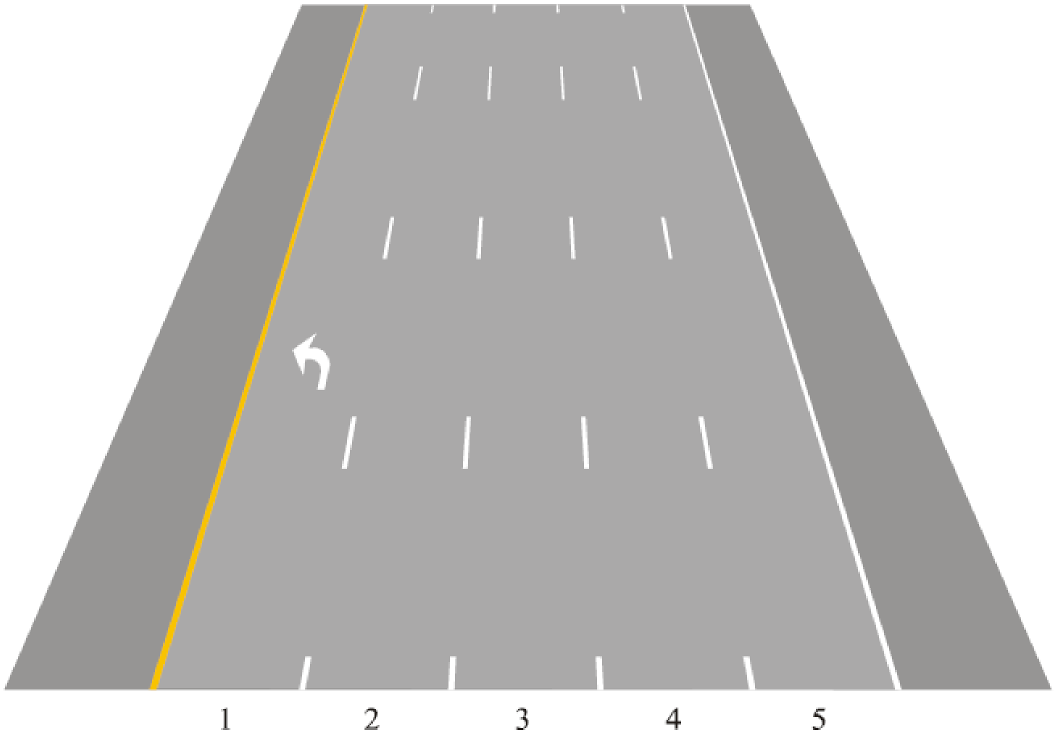


Figure 31. Arrow Shown on Exit Lanes Only (Left-Hand Single Lane Exit Drop).

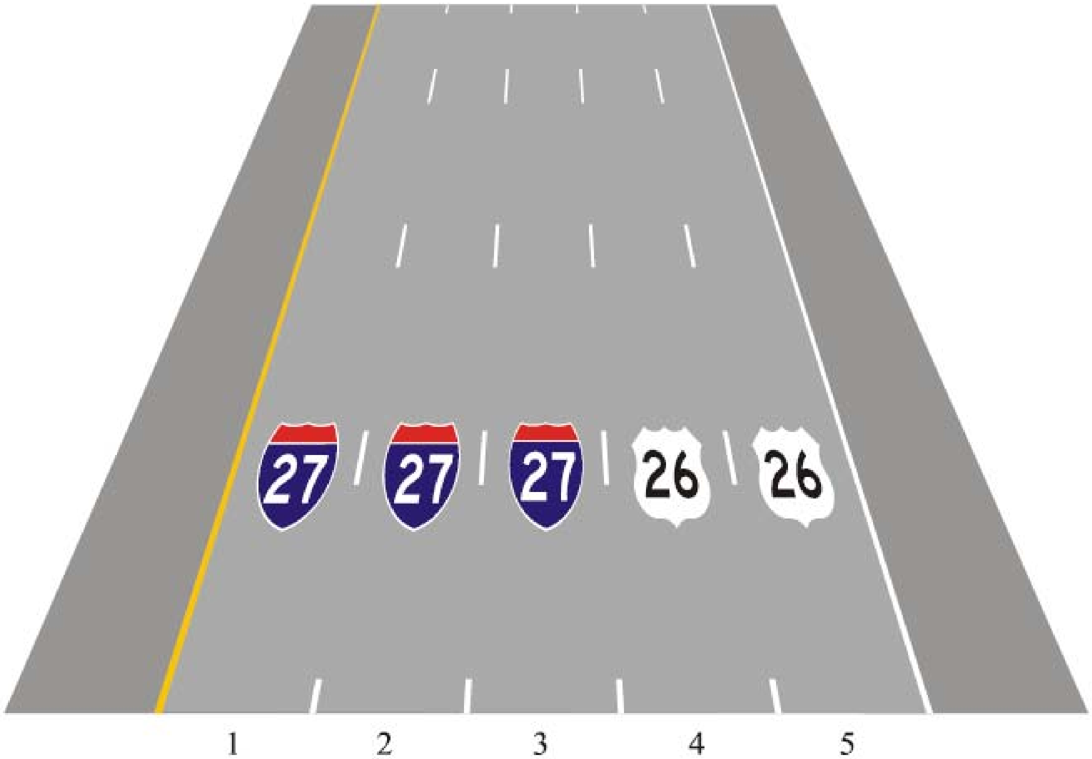


Figure 32. Route Shields Shown on All Lanes (Right-Hand Two-Lane Exit Drop).

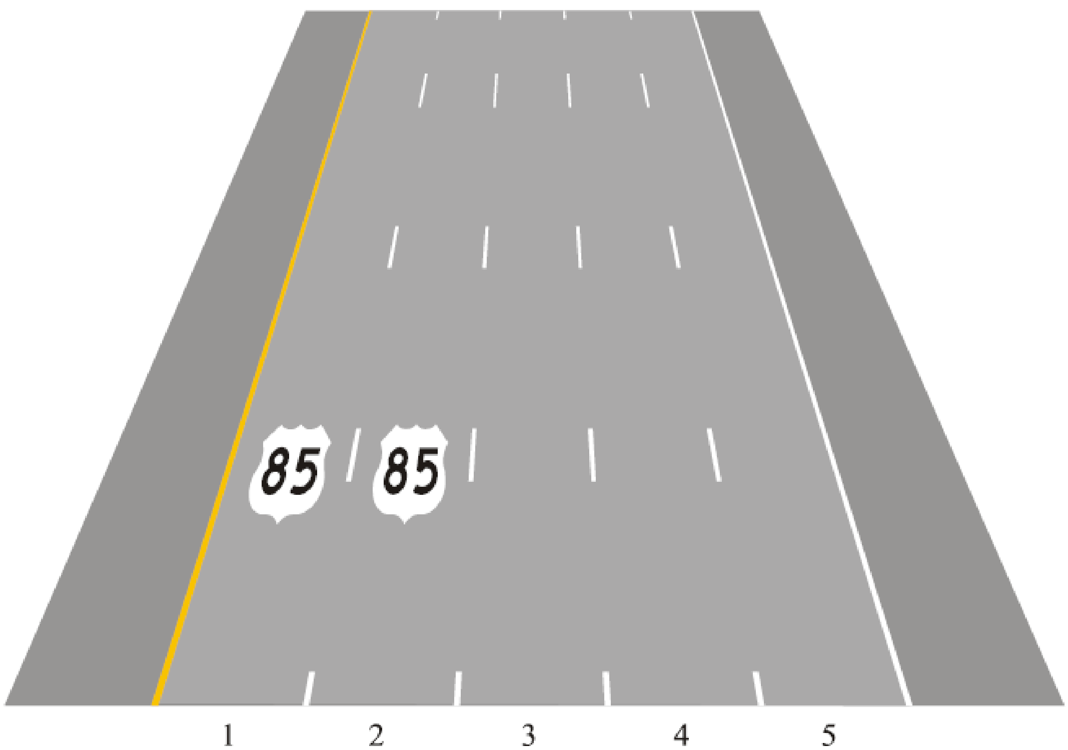


Figure 33. Route Shields Shown on Exit Lanes Only (Left-Hand Two-Lane Exit Drop).

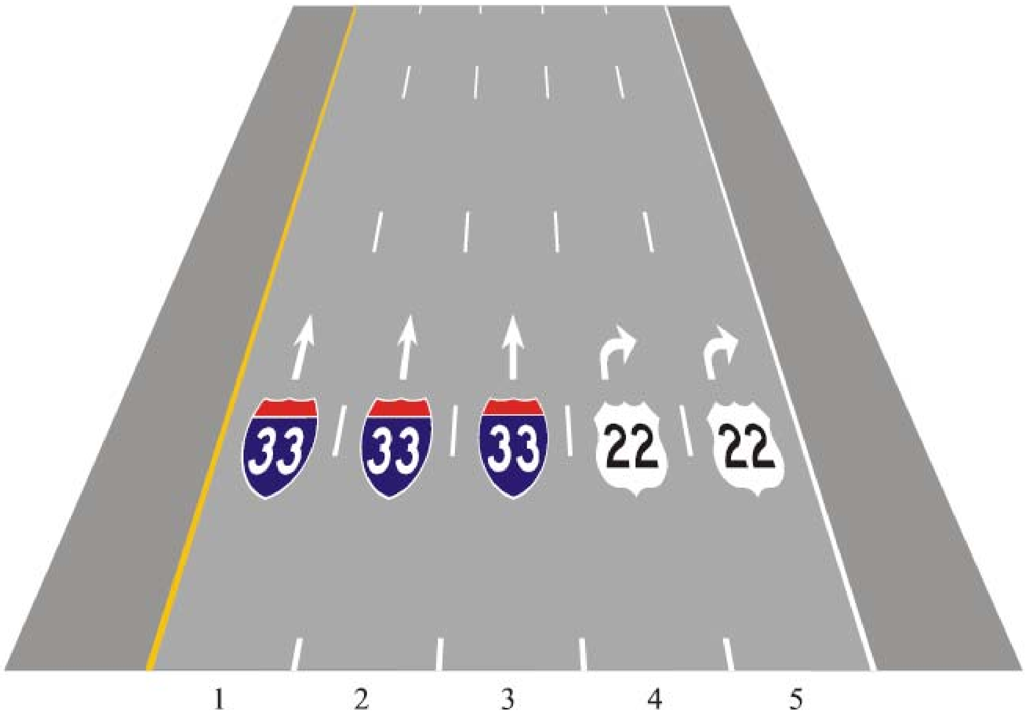


Figure 34. Both Arrows and Shields Shown on All Lanes (Right-Hand Two-Lane Exit Drop).

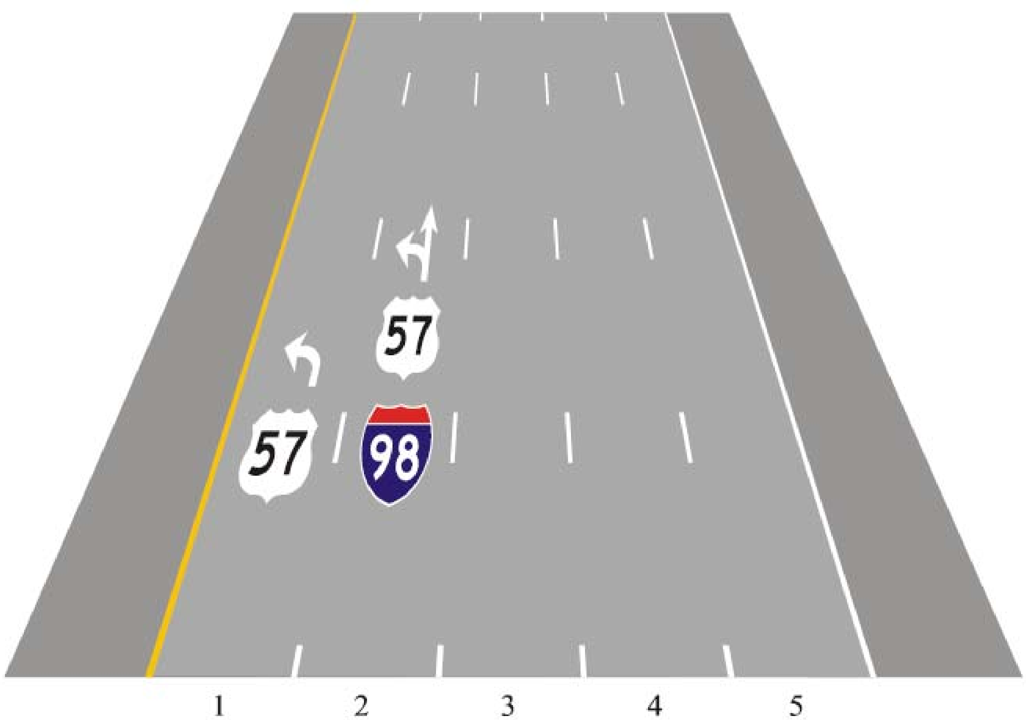


Figure 35. Both Arrows and Shields Shown on Exit Lanes Only (Left-Hand Optional Lane Exit).

Table 12. Options Tested.

	Left Exit			Right Exit		
	1 lane drop	**2 lane drop**	**2 lane Opt exit**	**1 lane drop**	**2 lane drop**	**2 lane opt exit**
Route Shields All Lanes	O1 I3-US98	O2 I36-US85	O3 I49-US74	O4 I14-US91	O5 I27-US26	O6 I66-US55
Arrows All Lanes	O7 I3-US98	O8 I36-US85	O9 I49-US74	O10 I14-US91	O11 I27-US26	O12 I66-US55
Route Shields Exit Lanes Only	O13 I3-US98	O14 I36-US85	O15 I49-US74	O16 I14-US91	O17 I27-US26	O18 I66-US55
Arrows Exit Lanes Only	O19 I18-US31	O20 I75-US52	O21 I98-US57	O22 I81-US48	O23 I33-US22	O24 I51-US32
Combined All Lanes	O25 I18-US31	O26 I75-US52	O27 I98-US57	O28 I81-US48	O29 I33-US22	O30 I51-US32
Combined Exit Lanes Only	O31 I18-US31	O32 I75-US52	O33 I98-US57	O34 I81-US48	O35 I33-US22	O36 I51-US32

Ixx = Interstate; USxx = US highway

Table 13. Treatment Order by Subject Group.

Subj Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A1	O33E	O12T	O5E	O15T	O34T	O16E	O1T	O30E	O26T	O19E	O8E	O23T
A2	O18E	O4E	O25T	O21E	O22T	O11T	O29E	O3T	O36E	O14T	O32T	O7E
A3	O27T	O35T	O10T	O17E	O9E	O24T	O13T	O6E	O28E	O20E	O2T	O31E
B1	O23E	O26E	O34E	O19T	O8T	O1E	O15E	O33T	O16T	O5T	O30T	O12E
B2	O36T	O25E	O14E	O3E	O11E	O7T	O21T	O29T	O22E	O4T	O18T	O32E
B3	O2E	O13E	O9T	O6T	O28T	O17T	O35E	O27E	O31T	O20T	O10E	O24E

OxE = proper subject response is to exit
OxT = proper subject response is to remain on freeway (i.e., US highway number at interchange is not subject's stated destination)

Test Procedure

Survey Instrument

After collecting some basic demographic information about each subject, researchers began each data collection survey with a brief description of the overall process that was going to be followed:

"Thank you for taking the time to participate in this study. This study is sponsored by the Texas Department of Transportation. The study is being done to better understand how drivers use signs and pavement markings to guide themselves on freeways throughout the state. No information is being collected which could identify you in any way. We are interested in what you think the signs and markings tell you, so there are no right or wrong answers. You are free to stop participating in this study at any time. It should take about 20 minutes to complete.

I will be using a laptop computer to show you drawings of freeway lanes like you might see as you look out of the windshield of your vehicle. I will ask you to imagine yourself driving down a particular freeway, and I will tell you what freeway exit you want to take to get to your destination. I will then tell you that you are approaching an interchange with another roadway and show you a sign over the freeway followed by some pavement markings. I will ask you to identify which lanes take you where you need to go, how certain you are about your answer, and which lane you would most likely want to be in at that point."

Researchers then followed the same general series of instructions and questions in sequence for each treatment alternative being tested. For example, as the researcher presented the perspectives shown in Figure 29, the following instructions were given and questions asked:

"Imagine you are on Interstate 7, and eventually plan to exit to US highway 10. You are approaching an interchange and see the following sign over the freeway (the first perspective that shows the guide sign is presented). You pass under the sign and eventually come upon the pavement markings shown here (the second perspective that shows the pavement symbols is presented):

- *Please tell me all of the lanes that will take you where you need to go?*
- *On a scale from 1 to 7 (with 1 being most confident and 7 least confident), how confident are you in your answer?*
- *Which of the lanes you listed above would you want to be in at this point?"*

The process was repeated for each of the 12 treatment alternatives presented to the subject for a particular subject group.

Survey Locations

Researchers conducted the surveys using laptop computers to present the various sign and pavement symbol perspectives. Researchers requested and received permission from the Texas Department of Public Safety (DPS) to conduct the surveys at driver licensing stations in six TxDOT districts:

- Dallas,
- Houston,
- Laredo,
- Paris,
- San Antonio, and
- Waco.

Demographics

In each office, researchers recruited subjects who were in line to take their driving test or who had brought someone in to take the test and were waiting for that person to finish. Researchers did not actively recruit to meet specific demographic criteria, but did attempt to obtain a range of participant ages and education levels. A total of 332 subject drivers participated in the surveys across the six district locations. Table 14 summarizes the overall demographic distributions achieved. Overall, the subject sample consisted of slightly more females, slightly younger drivers, and slightly more educated drivers than was reported for the

Texas driving population as a whole. Even so, it is believed that the results obtained from this study do represent Texas drivers reasonably well overall.

Table 14. Subject Demographics for Pavement Symbol Study.

	Gender		Age				Education			
	M	**F**	**< 25**	**26-39**	**40-54**	**55+**	**< HS**	**HS Grad**	**Some College**	**College Grad**
Study Sample	47%	53%	25%	31%	32%	12%	10%	27%	34%	29%
2001 Texas License Data	50%	50%	15%	32%	29%	24%	24%	25%	27%	24%

STUDY RESULTS

Driver Identification of Acceptable Lanes to Destinations

The first question posed to study participants for each test situation viewed was to identify each of the travel lanes that could be used to make the correct driving maneuver through the interchange (i.e., either to stay on the freeway or to exit). Researchers categorized each response as “totally correct,” “partially correct,” or “incorrect.” A “totally correct” response had all of the correct lanes identified, whereas a “partially correct” response had at least one of the correct lanes identified, but not all of them. In contrast, an “incorrect response” was one where one or more of the travel lanes selected resulted in an incorrect driving maneuver. In situations where an optional lane was shown and was selected as one of the lanes that could be used, it was assumed that the study participant intended to use the lane for the correct driving maneuver. Consequently, the participant would have had to identify another incorrect lane to be used for the driving maneuver in order for the response to be considered incorrect.

Researchers conducted statistical tests of independence to assess whether study participant response interactions existed between type of marking pattern evaluated and exit ramp configuration (single lane drop, double lane drop, single lane drop with an optional through/exit lane). Researchers found no statistically significant interactions, and so consolidated responses across these three exit ramp configurations. Table 15 presents the percent of incorrect lane identification responses for each of the pavement marking treatments evaluated. As can be seen in the table, researchers saw that displaying pavement markings in the exit lanes only yielded a slightly smaller number of incorrect lane identifications than displaying markings in all of the lanes when the participant was to make an exit maneuver. However, that trend was reversed when the correct maneuver was for the participant to remain on the freeway. For example, 15.1 percent of participants instructed to exit identified incorrect lanes when route shields were shown in all of the lanes, compared to 9.0 percent of participants when route shields were shown in the exit lanes only. In contrast, only 5.7 percent of the participants that were instructed to stay on the freeway identified an incorrect lane to use when route shields were shown in all of the lanes, compared to 8.4 percent of the participants when route shields were shown in the exit lanes only. Although these trends were fairly consistent across the different pavement marking types, they were not found to be statistically significant at a 95 percent confidence limit. In other words, participant ability to correctly identify which travel lanes could be used to make a particular driving maneuver through an interchange was not significantly affected by whether pavement markings were provided in all of the travel lanes or only in the lanes used to exit the freeway.

Table 15. Percent of Incorrect Lane Identification Choices for Each Manuever by Type of Pavement Marking and Lane Marking Configuration.

Type of Marking	Correct Maneuver = Exit		Correct Maneuver = Stay on Freeway	
	Markings in all lanes	Markings in exit lanes only	Markings in all lanes	Markings in exit lanes only
Route Shields	15.1%	9.0%	5.7%	8.4%
Arrows	20.8%	17.5%	14.2%	19.3%
Both Shields and Arrows	12.3%	6.9%	8.4%	11.8%

Next, researchers consolidated the results shown in Table 15 for the all lanes versus exit lane only marking patterns and conducted statistical tests of differences in proportions to determine whether the type of pavement marking significantly influenced participant ability to correctly identify the lanes to be used for either exiting or staying on the freeway through an interchange. These percentages are shown in Table 16. Statistical tests of proportions indicate that participant lane identification choices are essentially identical when either route shields are used alone or both arrows and route shields are used together (Z-statistics = 1.412 for exit maneuvers, 1.976 for stay-on-freeway maneuvers). However, both the route shield only and combined route shield with arrows patterns yielded significantly fewer incorrect lane identification choices than did the arrows only marking pattern (Z-statistics = 4.280 and 4.924, respectively, for exit maneuvers; Z-statistics = 5.424 and 3.525, respectively, for stay-on-freeway maneuvers).

Table 16. Percent of Incorrect Lane Identification Choices for Each Maneuver by Type of Pavement Marking.

Type of Marking	Correct Maneuver = Exit	Correct Maneuver = Stay on Freeway
Route Shields	12.0%	7.1%
Arrows	19.1%	16.7%
Both Shields and Arrows	9.6%	10.1%

Travel Lane Preferred by Drivers

Next, study participants were asked to identify the lane they would most likely want to be in for the particular test situation they were viewing to best reach their designated destination. Researchers calculated correct and incorrect lane selections in a manner similar to that used in the previous section. If the lane selected would not allow the participant to reach their designated destination, it was counted as incorrect. The percentage of incorrect lane choices by marking type and marking configuration are shown in Table 17. As expected, the route shield only and combined route shield and arrow combination patterns yielded similar small percentages of incorrect lane choices. In contrast, the arrows only pattern resulted in somewhat higher percentages of incorrect lane choices for both the exiting and the stay-on-freeway maneuvers. Again, the responses for the markings in all lanes and markings in exit lanes only patterns were similar enough to allow them to be consolidated into a comparison of marking type and maneuver type as provided in Table 18.

Table 17. Percent of Incorrect Lanes Chosen as Preferred for Each Maneuver by Type of Pavement Marking and Lane Marking Configuration.

Type of Marking	Correct Maneuver = Exit		Correct Maneuver = Stay on Freeway	
	Markings in all lanes	Markings in exit lanes only	Markings in all lanes	Markings in exit lanes only
Route Shields	8.5%	4.8%	4.8%	6.3%
Arrows	15.7%	11.7%	8.7%	16.6%
Both Shields and Arrows	6.6%	3.9%	6.3%	8.3%

As depicted in Table 17, the route shields alone and route shields with arrows marking patterns experienced very few incorrect lane choices and performed almost identically (Z-statistics = 1.048 and 1.353 for the exit and the stay-on-freeway maneuvers, respectively). Then, both the route shields only and combined route shields with arrows patterns yielded significantly fewer incorrect preferred lane choices than did the arrows only marking pattern (Z-statistics = 5.439 and 5.571 for the exit maneuvers; Z-statistics = 4.748 and 3.179 for the stay-on-freeway maneuvers, respectively).

Table 18. Percent of Incorrect Lanes Chosen as Preferred for Each Manuever by Type of Pavement Marking.

Type of Marking	Correct Maneuver = Exit	Correct Maneuver = Stay on Freeway
Route Shields	6.6%	5.6%
Arrows	13.7%	12.7%
Both Shields and Arrows	5.3%	7.4%

Study Participant Confidence in Lane Selections

As part of the selection of acceptable lanes to reach their intended destinations under the various test situations, study participants were also asked to rate their level of confidence in their answers on a standard 7-point scale (with 1 being "extremely confident"). Examination of these ratings provides insights into how well the various types of marking patterns are perceived by drivers to be clear and unambiguous (as is desired). In Table 19, researchers provide the percentage of study participants who were "extremely confident" in their lane choices under the various marking pattern and marking configuration test situations. Overall, one does see that participants were more confident with respect to choices about exiting lanes than they were about the lanes that would allow them to remain on the freeway and continue through the interchange. Interestingly, there does not appear to be a substantial difference in this trend when all lanes have pavement markings as compared to when only the exit lanes have such markings. In other words, the additional markings in the stay-on-freeway lanes do not substantially improve driver confidence in identifying which lanes exit and which continue on the freeway through the interchange.

Table 19. Percent of Participants Who Were "Most Confident" in Lanes Selected for Each Maneuver by Type of Pavement Marking and Lane Marking Configuration.

Type of Marking	Correct Maneuver = Exit		Correct Maneuver = Stay on Freeway	
	Markings in all lanes	Markings in exit lanes only	Markings in all lanes	Markings in exit lanes only
Route Shields	91.9%	86.15%	70.2%	62.3%
Arrows	78.9%	78.3%	62.3%	66.0%
Both Shields and Arrows	92.5%	87.4%	74.4%	67.2%

In Table 20, researchers consolidated the responses between the all lanes and exit lanes only marking configurations and conducted statistical tests of the differences in the percentage of "extremely confident" responses by type of marking pattern and maneuver required. Statistical tests of proportions indicate that, for exiting maneuvers, the percentage of "extremely confident" lane selections was significantly lower for the arrows marking pattern than either the route shields alone or the combined route shields with arrows marking pattern (Z-statistics = 5.118 and 5.637, respectively). However, the results were less clear for the stay-in-lane maneuvers. For these situations, the presentation of both route shields and arrows as markings yielded significantly higher percentage of extremely confident lane choices than the use of arrows alone (Z-statistic = 2.568). Meanwhile, the difference in percentages between the arrows only and route shields only pattern was not statistically significant (Z-statistic = 0.803). Likewise, the difference in percentages between the route shields only and the combined route shields and arrows marking patterns was not significantly different (Z-statistic = 1.765).

Table 20. Percent of Participants Who Were "Extremely Confident" in Lanes Selected for Each Maneuver by Type of Pavement Marking.

Type of Marking	Correct Maneuver = Exit	Correct Maneuver = Stay on Freeway
Route Shields	89.0%	66.3%
Arrows	78.6%	64.2%
Both Shields and Arrows	89.9%	70.8%

Participant Preferences

At the conclusion of the study, each participant was asked their preferences on both the types of markings preferred (route shields only, arrows only, or both route shields and arrows) and the use of such markings on all travel lanes versus only the lanes that were exiting. All total, 88 percent of the participants preferred the use of both route shields and arrows together as markings, compared to only 6 percent of participants each who preferred route shields only or arrows only. When asked why they preferred to have both types of markings shown, many participants indicated that they liked having more information shown to them and that it made it easier for them. However, participants were almost evenly divided when asked their preference for markings in all of the travel lanes versus having the markings in the exit lanes only (48 percent versus 52 percent, respectively). For both types of responses, participants often indicated that their preferred method was "less confusing" to them. Presumably, if more information was truly preferred by the majority of participants as was stated as a key reason for wanting both route shields and arrows, then one would have expected participants to prefer markings in all of the travel lanes. As previously noted, though, this was not the case, casting some degree of uncertainty on the credibility of the preference responses obtained in this effort.

STUDY CONCLUSIONS

This laptop survey was conducted to determine whether the accuracy and confidence of driver lane choice selection decisions made in advance of major freeway-to-freeway interchanges is affected by:

- using pavement symbol markings in all lanes versus exit only lanes; and
- using route shields, arrows, or route shields and arrows combined on the lanes to indicate through and exiting lanes.

The results of the study indicate that no appreciable improvement in lane selection accuracy is obtained by having markings in all lanes versus just in the lanes that exit. At the same time, there is no significant degradation in accuracy by having them in all lanes either. Consequently, both practices appear to be acceptable, and driver preferences are fairly evenly split on this topic. For temporary applications such as commonly exist in work zones near such interchanges, though, it would make sense from a cost and labor effort perspective to limit the number of markings used to only the exit lanes.

With regard to using more expensive route shields (and, by association, text that conveys the same information such as "IH-610 / NORTH") versus through and turn arrows versus both arrows and route shields, it does appear that the route shield markings perform significantly better than simply using pavement arrows in helping drivers correctly identify lanes they should use to either exit or stay on the freeway at interchange locations. The use of both route shields and arrows together did not yield appreciable improvements in lane selection accuracy, but was the highly preferred approach by drivers. Again though, from the standpoint of temporary work zone applications near interchanges, it would make more sense to limit the installation of pavement markings to only the route shields so as to minimize cost and labor installation effort.

CHAPTER 5. DRIVER UNDERSTANDING AND PREFERENCE OF ALTERNATIVE DISPLAYS ON PORTABLE CHANGEABLE MESSAGE SIGNS FOR INTERIOR LANE CLOSURES WITHIN FREEWAY INTERCHANGES

STATEMENT OF THE PROBLEM

One of the more difficult temporary traffic control situations to accommodate near freeway interchanges is the closure of an interior through travel lane downstream of exit lane drops, as depicted in Figure 36. The MUTCD indicates that the lane and the exit drop lanes be closed upstream of the ramp itself. While this is suitable and appropriate during times when traffic volumes are relatively low, doing this when higher traffic volumes are present will typically create a significant traffic queue upstream (and the resulting increase in rear end crashes that accompanies such queues). Furthermore, if the exit ramp volume is relatively high, it may be possible to avoid the creation of a queue entirely by allowing the exit lane to remain open to accommodate the exiting volume. The challenge in doing this is in using advance warning signing that properly conveys which lane is actually closed downstream. Therefore, a laptop-based laboratory study was conducted to evaluate alternative messages that could be displayed on portable changeable message signs (PCMSs) upstream of a lane closure to convey this situation.

STUDY OBJECTIVE

The objective of this laptop study was to determine driver comprehension and confidence in their interpretations of alternative advance warning messages related to interior lane closures within freeway interchanges.

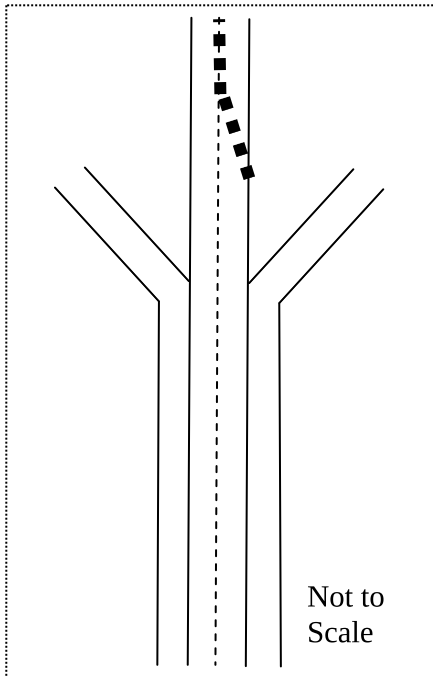
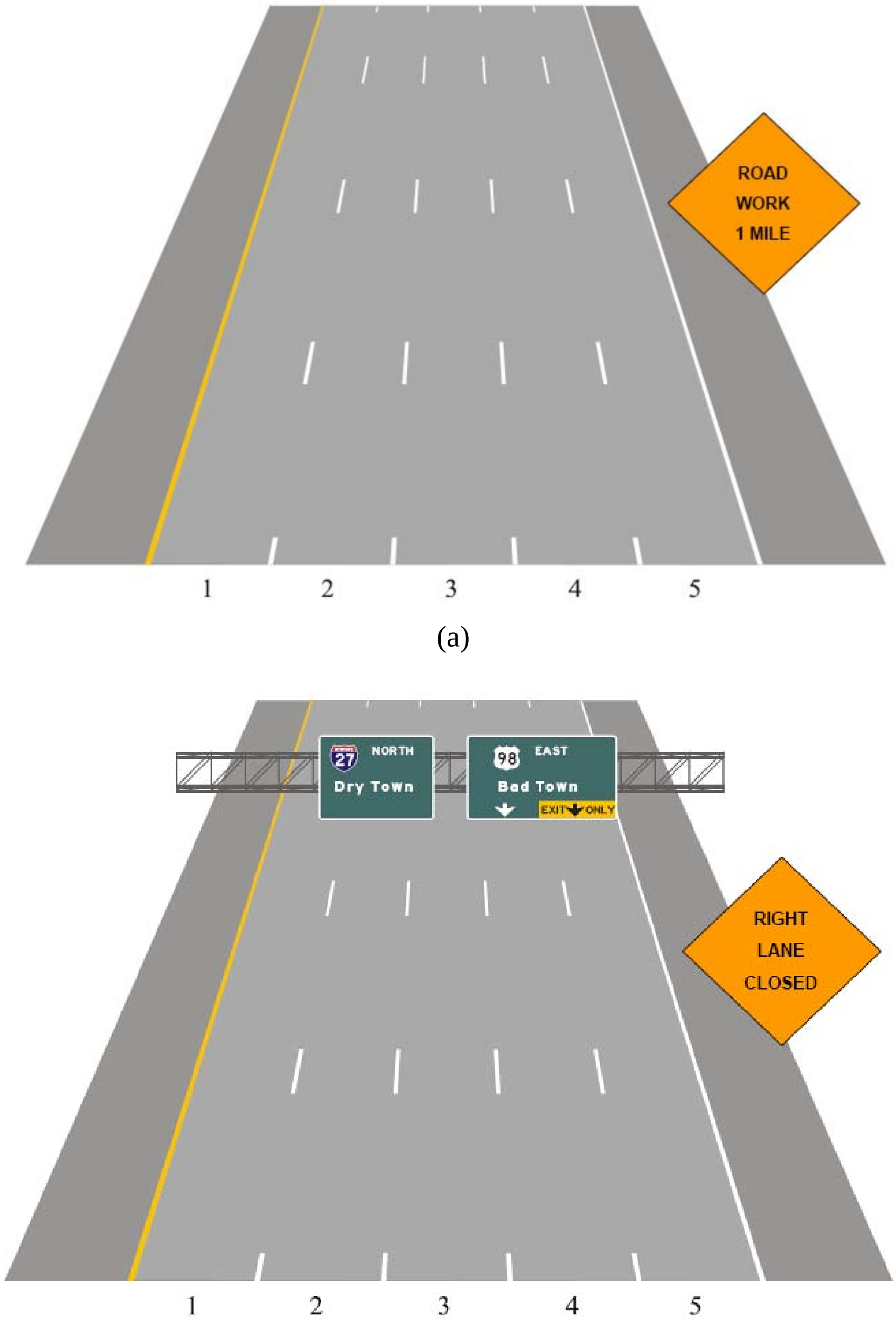


Figure 36. Example of an Interior Lane Closure Within a Freeway Interchange.

STUDY DESIGN AND PROTOCOL

Overview

Researchers developed and conducted a short survey with the assistance of a laptop computer. Researchers presented perspective views of a five-lane freeway and asked subject drivers to imagine themselves on that freeway as they approached an interchange. Subjects were then presented a sequence of images that provided an advance warning sign (ROAD WORK AHEAD), followed by a second sign that indicated that a lane was closed ahead. An overhead guide sign was located in this second perspective to provide exit lane information for the interchange. Figure 37 illustrates the sequence of images.



(a)

(b)

Figure 37. Sequence of Sign Perspectives Presented to Study Participants.

Experimental Design

In this study, the MUTCD standard lane closed sign shown in Figure 37 was compared to two types of messages that could be displayed on a full-matrix PCMS. The first message provided a text message to indicate that one or more of the through lanes at the interchange were closed, whereas the second message was a graphic depiction of through and exiting lanes with an "X" placed above the lane or lanes that were closed (both a single lane and a double lane closure condition was tested). The graphic design of the PCMS message is similar in format to the Texas lane blocked sign that has been shown to have good driver comprehension and reaction when used at work zone lane closures (*26*).

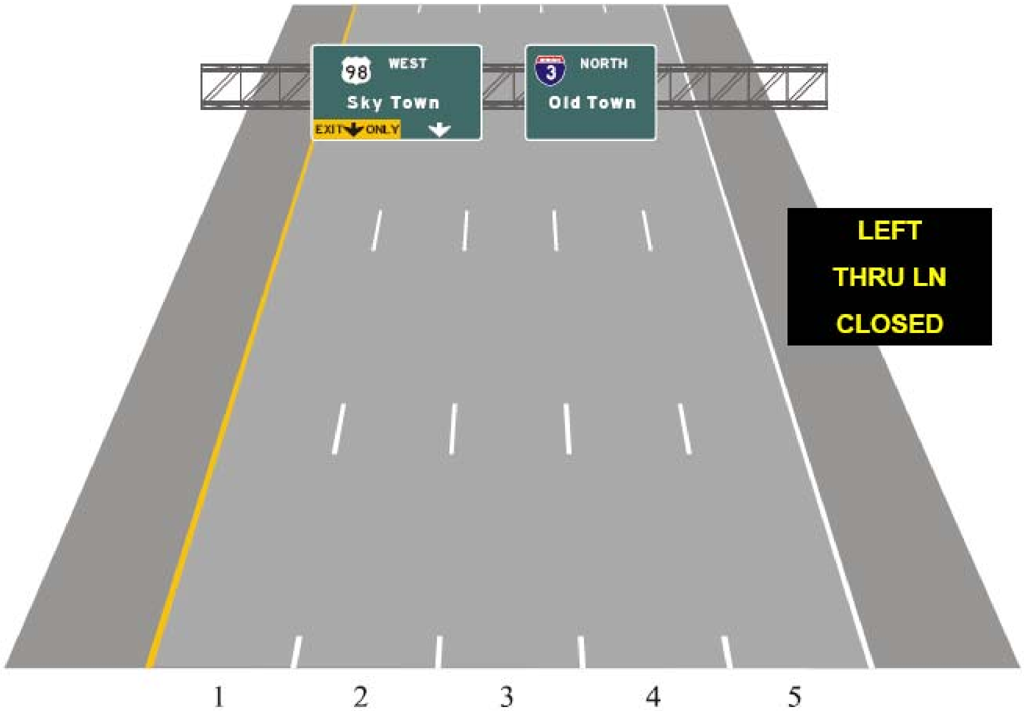
The MUTCD and two PCMS messages were tested for both left- and right-hand exit interchange configurations. Within each configuration, two types of exit lane groups were also tested: (a) a two exit lane drop, and (b) a single exit lane drop with an optional through/exit lane. Each participant would see the MUTCD, PCMS text, and PCMS graphic messages in random order, each one in a different exit lane/lane closure configuration. Figure 38 illustrates the two types of PCMS messages and different exit lane configurations tested.

Test Procedure

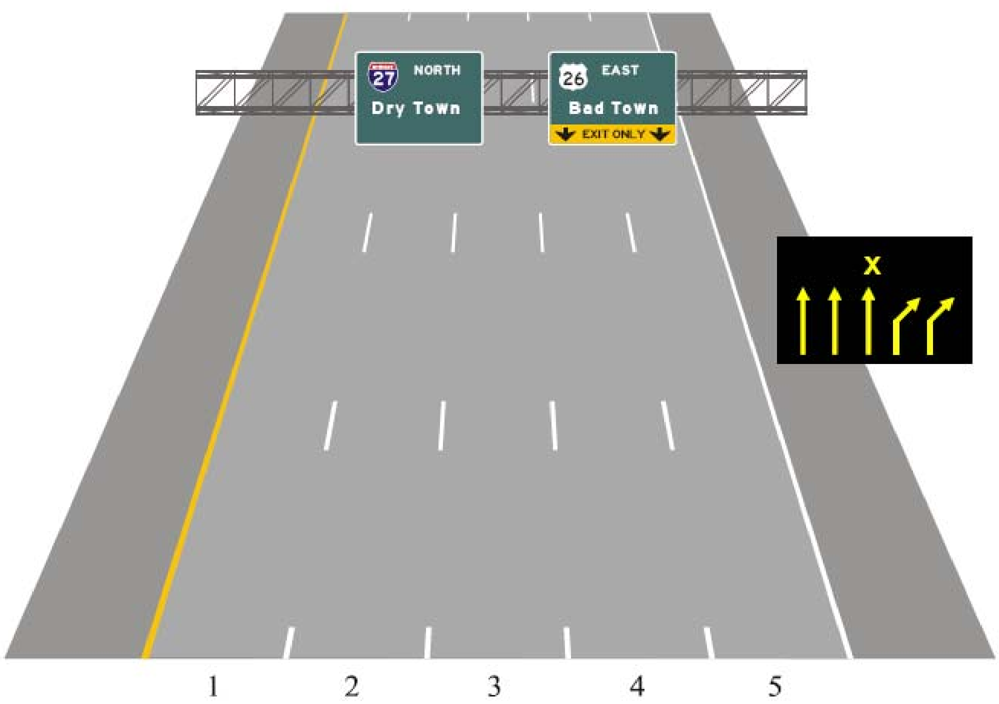
Survey Instrument

After collecting some basic demographic information about each subject, researchers began each data collection survey with a brief description of the overall process that was going to be followed:

"*Thank you for taking the time to participate in this study. This study is sponsored by the Texas Department of Transportation. The study is being done to better understand how drivers use signs to guide themselves on freeways throughout the state. No information is being collected which could identify you in any way. We are interested in what you think the signs and markings tell you, so there are no right or wrong answers. You are free to stop participating in this study at any time. It should take about 20 minutes to complete.*"



(a) PCMS Text Message



(b) PCMS Graphic Message

Figure 38. Alternative PCMS Messages Tested.

"I will be using a laptop computer to show you drawings and pictures of freeway lanes like you might see as you look out of the windshield of your vehicle. I will ask you to imagine yourself driving down a particular freeway. I will show you some signs and ask you what you think the signs mean, what lane you would try to be in if you were driving your vehicle at this location, and so on."

Researchers then followed the same general series of instructions and questions in sequence for each treatment alternative being tested. For example, as the researcher presented the perspectives shown in Figure 37 above, the following instructions were given and questions asked:

"Imagine you are on Interstate 27. You are approaching an interchange and see the following signs (the sequence of signs is presented). If you wish to continue on Interstate 27, which lanes could you travel in? If you were in lane X (the lane number was changed depending on the exit lane configuration used in the perspective), would you need to change lanes? How confident are you in your answer? If you were going to exit the freeway and were in lane XX (another lane number that varied depending on exit lane configuration used), would you need to change lanes? How confident are you in your answer?"

The process was repeated for each of the three treatment alternatives presented to study participants.

Survey Locations

Researchers conducted the surveys using laptop computers to present the various sign and pavement symbol perspectives. Researchers requested and received permission from the Texas Department of Public Safety to conduct the surveys at driver licensing stations in six TxDOT districts:

- Dallas,
- Houston,

- Laredo,
- Paris,
- San Antonio, and
- Waco.

Demographics

In each office, researchers recruited subjects who were in line to take their driving test or who had brought someone in to take the test and were waiting for that person to finish. Researchers did not actively recruit to meet specific demographic criteria, but did attempt to obtain a range of participant ages and education levels. A total of 318 subject drivers participated in the surveys across the six district locations. Table 21 summarizes the overall demographic distributions achieved. Overall, the subject sample consisted of slightly more females, slightly younger drivers, and slightly more educated drivers than was reported for the Texas driving population as a whole. Even so, it is believed that the results obtained from this study do represent Texas drivers reasonably well overall.

Table 21. Subject Demographics for PCMS Study.

	Gender		Age				Education			
	M	F	< 25	26-39	40-54	55+	< HS	HS Grad	Some College	College Grad
Study Sample	43%	57%	22%	38%	27%	13%	8%	27%	37%	24%
2001 Texas License Data	50%	50%	15%	32%	29%	24%	24%	25%	27%	24%

STUDY RESULTS

Driver Identification of Acceptable Through Lanes

After viewing one of the MUTCD or one of the PCMS messages, researchers asked study participants to indicate which of the through lanes could be used through the interchange. Table 22 presents the percentage of participants who identified one or more lanes incorrectly (i.e., the closed lane or lanes were identified as usable). Overall, the percentage of incorrect responses was quite higher, more than would be desirable from a safety and operational perspective. For the MUTCD and the PCMS text-based message, the percentage of incorrect responses was lower when only a single lane closure was being conveyed instead of a double lane closure (Z-statistics = 9.813 and 13.001, respectively). Interestingly, the percentages were approximately equal for both the single and double lane closures for the graphics-based PCMS message (Z-statistic = 0.192).

Table 22. Percent of Incorrect Lane Identification Choices by Treatment and Number of Through Lanes Closed.

Sign Tested	Number of Through Lanes Closed		Both Lanes Closed Conditions Combined
	1 Lane Closed	2 Lanes Closed	
MUTCD Lane(s) Closed	39.5%	92.9%	67.5%
Text-Based PCMS Message	18.4%	89.9%	55.9%
Graphics-Based PCMS Message	42.9%	44.0%	43.4%

Although there were significant differences in responses by number of through lanes closed being noted in the signs, some general trends were evident in terms of the performance of each of the signs tested. Referring back to Table 22, the standard MUTCD LANE CLOSED sign resulted in a higher percentage of incorrect lane choices (67.5 percent) than did either the text-based PCMS message (55.9 percent) or the graphics-based PCMS message (43.4 percent). All of these percentages were found to be statistically different from each other (Z-statistics = 3.279 for the MUTCD versus the text-based PCMS message, 3.162 for the text-based versus the graphics-based PCMS message, and 6.134 for the MUTCD versus the graphics-based PCMS message). Although the graphics-based PCMS message did not perform best for the single lane closure configuration, it was by far the most effective in conveying a double lane closure to drivers. Consequently, the overall percentage of incorrect responses was the lowest for this sign alternative. Again, however, it should be noted that none of the alternatives tested resulted in what would typically be considered acceptable levels of performance (although the text-based PCMS message did approach the 85 percent correct response rate that is the commonly used threshold for comprehension acceptability).

Driver Assessment of Need to Vacate a Closed Lane

The next question in the survey specifically examined whether drivers understood that they would have to vacate the through lane (or optional through/exit lane if they were continuing on through the interchange) that was indicated as being closed based on the information provided them via one of the three signing alternatives. Researchers summarize the percent of incorrect responses to this question in Table 23. Similar to the results reported above, the percentages differed by number of lanes indicated as closed for both the MUTCD and the text-based PCMS message (Z-statistics = 5.846 and 7.114, respectively) but not the graphics-based PCMS message (Z-statistic = 1.527). For the single lane closure condition, both the text-based and the graphics-based PCMS message resulted in essentially identical percentages of incorrect responses. For the double lane closure condition, the graphics-based PCMS message resulted in far fewer incorrect responses by participants than either the MUTCD or the text-based PCMS message. As before, the percentages of incorrect responses for all sign alternatives tested were much higher than desirable.

Although the MUTCD LANE CLOSED sign performed the least effectively in conveying which through travel lanes were available for use, study participants were found to have the most confidence in their answers to that particular question. In Table 24, researchers present the percentage of participants who were totally confident in their answer (i.e., confidence rating = 1). The number of lanes closed was not found to be a significant factor in terms of participant confidence. Overall, however, the percentage of participants who were totally confident in their answer was significantly higher for the MUTCD sign than for the text-based PMCS message (p-value =0.044) or the graphics-based PCMS message (p-value =0.091). Meanwhile, participants were equally confident in their answers between the text-based and the graphics-based PCMS messages (p-value = 0.764).

Table 23. Percent of Study Participants Who Incorrectly Believed They Could Stay in the Closed Lane Through the Interchange.

Sign Tested	Number of Through Lanes Closed		Both Lanes Closed Conditions Combined
	1 Lane Closed	2 Lanes Closed	
MUTCD Lane(s) Closed	52.0%	82.7%	68.1%
Text-Based PCMS Message	31.6%	71.4%	52.5%
Graphics-Based PCMS Message	31.8%	40.0%	35.6%

Table 24. Percent of Participants Who Were "Very Confident" In Answers about the Need to Vacate the Through Lane.

Sign Tested	Number of Through Lanes Closed		Both Lanes Closed Conditions Combined
	1 Lane Closed	2 Lanes Closed	
MUTCD Lane(s) Closed	80.7%	83.7%	82.3%
Text-Based PCMS Message	69.3%	80.7%	75.3%
Graphics-Based PCMS Message	75.9%	76.7%	76.3%

One possible reason for these contradictory results is that the MUTCD sign is the standard lane closed sign used throughout Texas whenever travel lanes are closed, whereas both types of PCMS messages are unique. Thus, it is likely that participants had actually seen the MUTCD sign in use during their travels, whereas they had not previously seen either type of PCMS message actually used. Because of these prior experiences, participants may have been more confident that they knew what the MUTCD sign was telling them, even though in reality they did not.

Driver Assessment of Need to Change Lanes if Exiting

The final series of questions for each sign configuration queried study participants on whether or not they would need to change from a specified exit lane based on the information presented on the sign. The exit lane identified varied depending on whether it was a two-lane exit or a single-lane exit with the optional exit/through lane. Participants were also asked to rate their level of confidence of their answer.

In Table 25, researchers present the percent of incorrect responses to this question (i.e., that the participant would need to change lanes if exiting when in fact they would not). For this particular question, responses for all three signing options tested varied significantly depending on whether a single lane or two lanes were indicated as closed (Z-statistics = 1.937, 2.206, and 6.564 for the MUTCD, text-based PCMS, and graphics-based PCMS signs, respectively). For all but one condition, the percentage of incorrect responses was again extremely high. The notable exception was for the graphics-based PCMS message for the one-lane closed condition, when only 20 percent of the subjects incorrectly believed they would have to change lanes if exiting. Collapsed across both lanes closed conditions tested, the graphics-based PCMS message resulted in significantly fewer incorrect responses than either the MUTCD lane(s) closed sign (Z-statistic = 7.189) or the text-based PCMS message (Z-statistic = 4.214). In turn, the text-based PCMS message performed somewhat better than the MUTCD lane(s) closed sign (Z-statistic = 3.046).

Table 25. Percent of Study Participants Who Incorrectly Believed They Would Need to Change Lanes if Exiting.

Sign Tested	Number of Through Lanes Closed		Both Lanes Closed Conditions Combined
	1 Lane Closed	2 Lanes Closed	
MUTCD Lane(s) Closed	60.5%	70.8%	65.9%
Text-Based PCMS Message	60.5%	48.2%	54.1%
Graphics-Based PCMS Message	20.0%	57.3%	37.5%

The percentages of study participants who were “very confident” in their answer as to whether they would need to change lanes if they were in an exit lane are shown in Table 26. The level of confidence was essentially the same for either the single lane or double lane closure condition for all three signing treatments tested. Overall, the MUTCD lane(s) closed sign generated a slightly higher percentage of “very confident” ratings than did the text-based PCMS message (Z-statistic = 2.166). However, it was not statistically different than the graphics-based PCMS message (Z-statistic = 1.873). Similarly, there was no appreciable difference in percentages between the text-based and graphics-based PCMS messages (Z-statistic = 0.295).

Table 26. Percent of Participants Who Were "Very Confident" In Answers about the Need to Vacate the Exit Lane.

Sign Tested	Number of Through Lanes Closed		Both Lanes Closed Conditions Combined
	1 Lane Closed	2 Lanes Closed	
MUTCD Lane(s) Closed	80.7%	83.7%	82.3%
Text-Based PCMS Message	69.3%	80.7%	75.3%
Graphics-Based PCMS Message	75.9%	76.7%	76.3%

STUDY CONCLUSIONS

This laptop laboratory study was conducted to determine driver comprehension of alternative forms of advance warning information about lane closures on through lanes just past exit lane drops at freeway interchanges. Text-based and graphics-based PCMS messages were compared against standard MUTCD lane(s) closed signing to convey this information. The results of the analysis indicate that both types of PCMS messages performed better than a standard MUTCD lane(s) closed sign in conveying which through travel lanes within the interchange were closed and that it was possible to exit the freeway from an exit lane without having to change lanes because of a lane closure. Unfortunately, the overall levels of comprehension are substantially below the minimum levels of comprehension typically desired for traffic control devices.

Based on the results of this study, the use of PCMS (either text or graphics messages) could improve safety and operations at locations where a through lane within the interchange is being closed and where it is highly desirable to keep all lanes open to the exit lane drop location because of its high traffic demand or political sensitivities. It does appear that the graphics-based PCMS may yield slightly better comprehension than the text-based PCMS message. However, these types of messages have not yet been fully evaluated from a legibility or readability standpoint in the field. Furthermore, it also appears that the potential for incorrect interpretation of either type of PCMS message is fairly high when attempting to convey that more than one through travel lane is closed. If it is necessary to close two or more through lanes past an exit, the principles of Typical Application 42 in Part VI of the MUTCD should be employed. In some instances, it may even be more effective to fully close the through lanes and route all traffic off at the exit to detour around the roadwork activities.

CHAPTER 6. DRIVER UNDERSTANDING AND PREFERENCE OF ALTERNATIVE WARNING SIGNS TO CONVEY LANE SHIFT INFORMATION

STATEMENT OF THE PROBLEM

The 2006 edition of the Texas MUTCD, the Texas Standard Highways Signs, and the TxDOT Traffic Control Standard Sheets all specify the use of a reverse curve sign (CW1-4R(L)) to designate to drivers that they are approaching a lane shift within a highway work zone (see Figure 39). This sign includes a single thick arrow and is to be used regardless of the number of travel lanes that exist in one direction at the sign and through the shift. The national MUTCD, however, allows for the display of this type of sign with multiple arrows shown, the number of arrows to correspond with the number of travel lanes that exist in that particular direction (see Figure 40). To date, concern over the misuse of the sign such that the number of arrows and number of lanes are different has kept TxDOT from officially adopting this sign for use statewide. Research was needed to determine if this concern is significant enough to warrant the continued absence of these types of signs in the Texas standards.

Figure 39. Texas MUTCD Reverse Curve Sign (CW1-4L).

Figure 40. National MUTCD Reverse Curve Sign for Multi-Lane Roadways (W1-4L).

STUDY OBJECTIVE

The objective of this laboratory study was to determine if significant differences existed in driver comprehension of the reverse curve signs when a single arrow is used or multiple arrows are used to convey the number of travel lanes shown. A secondary objective was to determine if driver comprehension is degraded if the number of arrows shown is not the same as the actual number of travel lanes that exist in that direction of travel. It should be noted that the single arrow reverse curve sign itself does not correspond to the number of travel lanes when used on a freeway or other multi-lane facility.

STUDY DESIGN AND PROTOCOL

Overview

The study approach utilized for this study relied on photographs of freeway work zone situations that consisted either of two or three lanes in the direction of travel. Study participants were instructed to envision themselves driving on the facility shown in the photograph. While viewing the photograph, the participant would be shown either a single arrow reverse curve sign (the "single arrow sign") or a multiple arrow reverse curve sign (the "multiple arrow sign"). The multiple arrow sign would either have the same number of arrows as lanes shown in the photograph, or they would differ. For example, the photograph may show a freeway with three lanes, but the sign shown would have only two arrows. Conversely, two lanes of a freeway may be depicted in the photograph, but the sign might contain three arrows. Study participants were asked what the sign meant to them and specifically whether they would have to change lanes or not. Participants were also asked their preferences between the single and multiple arrow sign designs.

Experimental Design

During the course of the study, each participant viewed one application of the single arrow sign either in conjunction with the two-lane or the three-lane freeway section photograph, and one multiple arrow sign in conjunction with the other freeway section photograph. For one-half of the participants, the number of arrows on the sign corresponded to the number of lanes shown in the photograph. For the remaining participants, the number of arrows shown on the sign was different than the number of freeway lanes shown in the photograph. Figure 41 provides an example of the two situations that one group of participants would see in this study. A total of four groups were used in the study to allow for counterbalancing of sign type and whether it agreed with the number of freeway lanes.

(a) Single arrow sign example

(b) Multiple arrow sign example

Figure 41. Example of Signs and Freeway Work Zone Photographs Viewed.

Test Procedure

Survey Instrument

After collecting some basic demographic information about each subject, researchers began each data collection survey with a brief description of the overall process that was going to be followed:

"*Thank you for taking the time to participate in this study. This study is sponsored by the Texas Department of Transportation. The study is being done to better understand how drivers use signs to guide themselves on freeways throughout the state. No information is being collected which could identify you in any way. We are interested in what you think the signs and markings tell you, so there are no right or wrong answers. You are free to stop participating in this study at any time. It should take about 20 minutes to complete.*"

"*I will be using a laptop computer to show you drawings and pictures of freeway lanes like you might see as you look out of the windshield of your vehicle. I will ask you to imagine yourself driving down a particular freeway. I will show you some signs and ask you what you think the signs mean, what lane you would try to be in if you were driving your vehicle at this location, and so on.*"

Researchers then followed the same general series of instructions and questions in sequence for each treatment alternative being tested. For example, as the researcher presented participants the perspective shown in Figure 41(a) above, the following instructions were given and questions asked:

"Imagine you are on Interstate 44 similar to the picture shown. There are two lanes going in your direction. You see the warning sign on the right. What does the sign tell you to do? If you are driving in the right lane as shown in the picture, will you be required to change lanes?"

After the participant was shown a second perspective with a multiple arrow sign and asked the same questions, the subject was asked to directly compare the single arrow and multiple arrow signs:

"If you are driving on a three-lane freeway and all the lanes are shifting to the left, is it better to show this with one thick arrow or three thinner arrows? Why?"

Survey Locations

Researchers conducted the surveys using laptop computers to present the various sign and pavement symbol perspectives. Researchers requested and received permission from the Texas Department of Public Safety to conduct the surveys at driver licensing stations in six TxDOT districts:

- Dallas,
- Houston,
- Laredo,
- Paris,
- San Antonio, and
- Waco.

Demographics

In each office, researchers recruited subjects who were in line to take their driving test or who had brought someone in to take the test and were waiting for that person to finish. Researchers did not actively recruit to meet specific demographic criteria, but did attempt to obtain a range of participant ages and education levels. A total of 332 subject drivers participated in the surveys across the six district locations. Table 27 summarizes the overall demographic distributions achieved. Overall, the subject sample consisted of slightly more females, slightly younger drivers, and slightly more educated drivers than was reported for the Texas driving population as a whole. Even so, it is believed that the results obtained from this study do represent Texas drivers reasonably well overall.

Table 27. Subject Demographics for Reverse Curve Sign Study.

	Gender		Age				Education			
	M	F	< 25	26-39	40-54	55+	< HS	HS Grad	Some College	College Grad
Study Sample	43%	57%	22%	38%	27%	13%	8%	27%	37%	24%
2001 Texas License Data	50%	50%	15%	32%	29%	24%	24%	25%	27%	24%

STUDY RESULTS

Overall, the results of the laptop study indicate good levels of comprehension of both the single arrow and the multiple arrow signs in conveying that the roadway curves or shifts ahead and that there is not a need to merge or change lanes. In Table 28, researchers present the percent of study participants who indicated that they would not need to change lanes if they were traveling in the outer lane when they viewed the sign. For the two-lane freeway section scenario, both multiple-arrow signs outperformed the single arrow sign (Z-statistics = 4.28 for the two-arrow versus single-arrow comparison, 3.78 for the three-arrow versus single-arrow comparison). This result was true even for the three-arrow sign, when the number of travel lanes shown and the number of arrows shown on the sign did not agree. For the three-lane freeway section, however, the single arrow yielded the highest percentage of "no lane change required" responses. Meanwhile, the two-arrow sign shown with this three-lane section yielded a lower percentage of correct responses. Statistically, the single-arrow sign correct response rate was significantly higher than the two-arrow sign rate (Z-statistic = 4.68), but was not significantly better than the three-arrow sign (Z-statistic = 1.75). When the results from both freeway lane conditions were computed together, no significant differences existed between any of the three signs (Z-statistics = 0.40, 1.09, and 1.50 for the single-arrow versus two-arrow comparison, single-arrow versus three-arrow comparison, and two-arrow versus three-arrow comparison). Overall, there was no clear evidence that use of multiple-arrow signs, even if the arrows and number of lanes did not match for some reason, would significantly degrade driver comprehension and interpretation of the signs.

Table 28. Percent of Study Participants Who Believed the Sign Did Not Require Them to Change Lanes.

			
2-Lane Freeway Section	76.3%	96.4%	95.1%
3-Lane Freeway Section	94.5%	66.7%	85.9%
Both Freeway Section Types Combined	85.2%	83.2%	90.4%

Note: Shaded cells indicate where number of lanes shown did not agree with number of arrows shown.

Although study participants interpreted the different signs fairly uniformly, they were fairly adamant in their preferences regarding these types of signs. In total, 72.9 percent of participants preferred the use of the multiple-arrow sign over the single-arrow sign (only 27.1 percent preferred the single-arrow sign). Many of the participants who preferred the multiple-arrow sign explicitly mentioned the fact that it shows them that all lanes continue through the curves and that it is not necessary to change lanes.

STUDY CONCLUSIONS

Based on the results of this laptop laboratory study, the use of multiple-arrow signs to indicate reverse curves and/or lane shifts within work zones on multilane facilities should be allowed. Such signs do not create undue confusion if the number of arrows and number of travel lanes do not match. Furthermore, the multiple-arrow sign is preferred by drivers, and does appear to help indicate that multiple lanes will continue through the curve or shift, so that a lane change is not required.

PART 2 – PAVEMENT MARKING MATERIAL SELECTION IN WORK ZONES

CHAPTER 7. WORK ZONE PAVEMENT MARKING MATERIAL USAGE AND PERFORMANCE ISSUES IN TEXAS

WORK ZONE PAVEMENT MARKING MATERIAL USAGE IN THE DISTRICTS

Based on the information gathered from telephone interviews, four types of pavement marking materials are currently used in work zones in Texas:

- water-based paint,
- thermoplastic,
- preformed tape, and
- traffic buttons and retroreflective raised pavement markers (RRPMs).

Table 29 shows which of these four pavement marking materials are currently installed in work zones by district. This table reveals that every district uses more than one type of pavement marking material in work zones.

Buttons and RRPMs are used by 92 percent of the districts and are most often installed on concrete and the final layer of non-concrete surfaces (i.e., asphalt and sealcoat) since they are easier to remove than other materials and generally do not leave “ghost” markings. In addition, buttons and RRPMs provide a tactile warning and improve wet weather visibility. In general, most of the districts stated that if buttons and RRPMs are applied properly they will last as long as they are needed. However, several of the urban districts cited problems with cracking and adhesion, especially on concrete.

Both water-based paint and thermoplastic are currently used by 88 and 80 percent of the districts, respectively. Water-based paint is the least expensive of the identified pavement marking materials. The durability of paint was typically reported to be six months, but in some cases (i.e. lower volume roads) it can last for a year. In general, the performance of paint is adequate under low volume conditions, but under high volume conditions paint deteriorates quickly. Based on durability concerns, seven districts either no longer use paint or very seldom use paint. Instead, six of the seven districts have decided to use thermoplastic. Thermoplastic is more expensive than paint, but its durability ranges from 1 to over 4 years. In addition, thermoplastic withstands high traffic volumes better than paint. However, several of the rural districts noted that paint was more flexible than thermoplastic, since thermoplastic is not readily available in their area.

Table 29. Types of Pavement Marking Materials Used in Work Zones by District.

District	Paint	Thermoplastic	Preformed Tape	Buttons & RRPMs
Abilene		X	X[a]	X
Amarillo	X	X[a]	X	X[a]
Atlanta	X	X[a]	X	X
Austin	X	X		X
Beaumont	X	X	X	X
Brownwood	X	X		X
Bryan	X[a]	X	X	X
Childress	X			X
Corpus Christi	X	X		X
Dallas	X[a]	X		X
El Paso	X[a]		X	
Fort Worth	X			X
Houston		X	X[a]	X
Laredo	X	X[a]	X[a]	X
Lubbock	X	X[a]		X
Lufkin		X	X	X
Odessa	X		X[a]	X[a]
Paris	X	X	X[a]	X
Pharr	X[a]	X	X[a]	X
San Angelo	X[a]	X[a]	X	
San Antonio	X	X		X
Tyler	X	X	X	X
Waco	X	X		X
Wichita Falls	X			X
Yoakum	X[a]	X	X[a]	X
Total Number	22	20	15	23
Total Percent[b]	88%	80%	60%	92%

X Denotes use.
[a] Used but not very often.
[b] Percent of the number of respondents (N=25).

Most of the districts use paint and thermoplastic on interim layers of non-concrete surfaces; thus, the markings do not have to be removed. When paint or thermoplastic is used on concrete or the final layer of a non-concrete surface, it must be removed by flailing, blasting, or milling.

Preformed tape is used by 60 percent of the districts, but half of these districts noted that it is very seldom applied. The majority of the districts reported performance issues with preformed tape. Typically, preformed tape comes up prematurely. Several districts noted that wind and rain (wet pavement) negatively impact the durability of preformed tape. The districts that use preformed tape stated that it works best under dry, hot conditions and that the surface must be very clean before application. If a good application of preformed tape is achieved, it is often difficult to remove. Several districts also noted that it is hard to apply preformed tape in a straight line. In addition, it is difficult to keep the preformed tape from getting out of alignment once it is in place. The general consensus of the districts was that preformed tape is expensive for the perceived effectiveness.

FACTORS USED TO SELECT PAVEMENT MARKING MATERIALS IN WORK ZONES

The top four factors used by the districts to select pavement marking materials in work zones were:

- traffic volume (high versus low),
- surface material (concrete versus non-concrete),
- surface layer (interim versus final), and
- duration of the application.

Other factors mentioned included:

- time of year (whether it was cold or hot and whether it was typically wet or dry),
- availability of pavement marking material,
- response time to fix problems,
- cost,

- visibility, and
- ease of removal.

ISSUES AND DIFFICULTIES WITH THE SELECTION AND MAINTENANCE OF PAVEMENT MARKING MATERIALS IN WORK ZONES

The following five main issues with the selection and maintenance of pavement marking materials in work zones were identified by the districts:

- obliteration of pavement markings,
- maintenance of pavement markings,
- credibility of temporary traffic control,
- pavement markings on milled surfaces, and
- rigidity of the temporary tab rule.

Each one is discussed in more detail below.

Obliteration of Pavement Markings

When existing pavement marking materials are removed in order to set up temporary traffic control, the removal method typically leaves "ghost" markings that may be mistaken for actual pavement markings and thus cause confusion to motorists (see Figure 42). For example, when existing thermoplastic pavement markings on concrete are removed with a rotary disk grinding machine a 1/8 to1/4 inch groove remains (Figure 43). The exposed concrete is so white that it still looks like a pavement marking. One district reports that it takes approximately six months for the newly exposed concrete to get tanned by the sun and get dirty from the vehicles' oil and tires, in order to be able to blend in with the surrounding concrete. Suggestions to combat this problem include applying a light grayish opaque paint to subdue the bright white concrete and obliterating a solid box instead of the individual letters in text markings in order to completely eradicate the message.

Figure 42. Examples of Pavement Marking Obliteration Difficulties on Concrete.

Figure 43. Pavement Marking Obliteration by Grinding.

"Ghost" markings can also occur when water-based paint or thermoplastic are removed from the final surface; however, according to the districts, they typically try to use preformed tape or buttons and RRPMs on the final surface since these materials are easier to remove and generally do not leave "ghost" marks. However, when buttons or RRPMs come up on concrete, the adhesive material is left on the roadway surface yielding black dots. Also, one district reported that the glue from the preformed tape sometimes remains on the roadway surface after the preformed tape is removed. The glue collects so much dirt and debris that it begins to look like a line.

Maintenance of Pavement Markings

As mentioned above, several of the urban districts cited problems with buttons and RRPMs on concrete, including cracking and not adhering. The missing buttons and RRPMs result in negative public response. Maintenance of pavement markings is very important; however, it is not always considered in the design of the project. Thus, it is hard to get the contractor to maintain the buttons and RRPMs. Similarly, it is sometimes difficult to get contractors to restripe water-based paint pavement markings once the markings are no longer adequately visible.

Credibility of Temporary Traffic Control

Both the maintenance of pavement markings and the complete obliteration of pavement markings are important to the credibility of the temporary traffic control. In addition, one district feels that during the day, buttons do not necessarily imply lines so they adversely affect the credibility of the temporary traffic control layout. This district feels that buttons do not provide adequate contrast during the day or at night.

Pavement Markings on Milled Surfaces

Several districts noted that there is not a good solution for milled surfaces. The consensus was that paint is not durable enough, buttons and RRPMs do not adhere well, and the roughness often "cuts" through thermoplastic over time. The districts would like to identify other types of pavement marking materials that perform better on uneven, milled surfaces.

Rigidity of Temporary Tab Rule

Currently, temporary tabs can only be used for 14 days, after which the road must be striped. Sometimes a contractor must apply a temporary pavement marking in order to meet this requirement. The temporary markings then may need to be removed prior to installing the permanent pavement markings. Some districts would like to be able to use temporary tabs for a longer period of time to reduce the need to install temporary markings. In addition, at least one district thinks it would be more cost-effective to use temporary tabs for a longer period of time, instead of striping over the markings after the limited allowable time period has expired. A couple of districts did note that it is sometimes hard to get the temporary tabs to adhere to milled and other interim surfaces.

METHODOLOGY TO ESTABLISH WORK ZONE PAVEMENT MARKING SELECTION GUIDANCE

The results of the district interviews indicate that proper pavement marking selection in work zones is a significant issue and that guidance to improve the selection process would be worthwhile. Unlike normal roadway applications, work zone pavement markings are often placed on the roadway for a limited period of time, such as during an interim phase of construction. The markings are then either covered over with a new surface treatment or removed (albeit not always very well) and reapplied in a different lane configuration. In other words, the projected duration of pavement marking use within a work zone depends on the project tasks (or combination of tasks) being completed during which the marking is required. This length of time (whether in individual phases or overall) is part of the predicted construction schedule. The challenge created from a pavement marking selection perspective is that the actual duration of a construction phase or project can actually differ quite significantly from this initial estimate. Some of the factors that impact the variability in actual marking duration requirements for a project include:

- the type and combination of tasks being completed,
- geographic location,
- project complexity,
- rainfall,
- time of year,
- crew size,
- overtime allowed, and
- traffic.

Thus, designers must consider both the expected duration for which the pavement marking will be needed, and the possibility that this estimate may be exceeded by some unknown duration. Chapter 8 provides a detailed discussion of activities undertaken to place some boundaries on the relationships between estimated and actual project phase durations, both in terms of the actual level of predictive accuracy obtained and the variability between estimated and actual durations.

Another key source of data needed for this part of the project is an estimate of pavement marking service life as a function of the key variables identified as having significant impact on current pavement marking selection (namely, traffic volume and pavement type). Many sources exist of pavement marking durability research and evaluation, covering a broad range of geographic conditions on a variety of pavement markings. Unfortunately, none of these sources focus specifically on work zone applications. Nevertheless, the sources provide the best available information on this topic upon which to base marking selections. As with the assessment of project phase duration, the variability of pavement marking performance that occurs over time was a key consideration in the analysis. A full discussion of the pavement marking performance analysis undertaken for this project is provided in Chapter 9.

The final component required to establish pavement marking selection guidance for work zones was a way to systematically assess how estimated project phase duration (and the variability of this estimate) and pavement marking performance over time (and its variability) interact. In so doing, researchers could provide a recommendations of a preferred pavement marking selection for a given work zone project or project phase duration, on a roadway of a given pavement surface type, under a given traffic demand loading. Several different mathematical formulations were considered before a decision was made to utilize Monte Carlo simulation techniques to represent these interactions directly. The selected methodology focuses on selecting the pavement marking material that results in the least total cost for the material, assuming that the material will be reapplied if the actual service life of the marking material does not meet or exceed the actual project phase duration. The description and results of the cost-effectiveness assessment are provided in Chapter 10.

CHAPTER 8. ANALYSIS OF PROJECT PHASE DURATION ESTIMATION ACCURACY AND VARIABILITY

INTRODUCTION

There are a number of factors that need to be considered when a temporary pavement marking is chosen for a work zone operation. Some of the more important factors include:

- project or project phase duration;
- pavement marking durability or service life;
- pavement surface type (e.g., concrete);
- pavement surface stage (e.g., interim or final); and
- pavement marking material and application or re-application costs.

Some of the factors listed above are static during a project or project phase that may need temporary pavement marking (e.g., pavement surface type and stage), but others are estimates that vary (e.g., phase or project duration, pavement marking service life, and material costs). The variability of these factors must be taken into account for a temporary pavement marking choice guideline or tool to be useful. The data collection and analysis activities used to define the magnitude and variability of project or project phase duration estimates are described in this chapter.

DURATION ESTIMATION EVALUATION

The most cost-effective temporary pavement marking is the material that, for the smallest cost, retains its durability and visibility for approximately the same time period it is needed (e.g., the estimated project or project phase duration). As noted, however, there are several factors that can vary and make this choice much more difficult. The magnitude and variability of three factors were quantified as part of this research project. The first factor investigated was the magnitude and variability of project or project phase duration estimates in Texas. The following tasks were completed as part of this investigation:

- review the project or project phase duration prediction or estimation tools and data currently available in Texas, and given the needs, budget, and schedule of this research project select the most appropriate data to use;
- obtain and summarize project or project phase duration estimation data from a sample of TxDOT districts with a range of rural and urban land use characteristics;
- statistically analyze the project or project phase duration data obtained and determine which of these results should be used as input to a temporary pavement marking decision tool and/or guidance; and
- provide conclusions and recommendations related to the application of these project or project phase duration estimate results.

The overall objective of this part of the research was to define, given currently available data, the typical magnitude and variability of project or project phase duration estimates for incorporation into a temporary pavement marking selection tool and/or guidelines.

EXISTING TOOLS AND DATA

The first step in the evaluation and quantification of project or project phase duration estimates in Texas was to investigate the processes and data currently available. The preferred database for this type of task would include statewide or systemwide information describing pre-contract duration estimates and also comparable post-construction times to completion. This database would also need to include information about whether each estimated time period included a work zone with temporary pavement marking(s). The literature was reviewed and discussions held with TxDOT personnel to determine whether this type of systemwide project and project phase duration estimation data were currently available and easily accessible.

The length and variability of work zone time period(s) during which temporary pavement markings are used are project specific. In fact, expected project and project phase scheduling and duration estimates are typically based on personal experience/judgment, past projects/records (e.g., historical production rates), and standard production rates (*27*). Two tools that can be used for project or project phase duration estimating have been developed in Texas. In the early 1990s TTI produced the Contract Time Determination System (CTDS). This system incorporated survey results for the production rates (including an estimate of low, average, and high rates) of more than 40 common project work items (*27*). The system was also designed so that individual TxDOT districts could use their own production rate calculations. In 2004, the Center for Transportation Research (CTR) developed the Highway Production Rate Information System (HyPRIS) for 20 critical path work items (*28*). This system was based on field data and information. It included formulas and ranges to calculate various production rates. The CTR authors concluded that HyPRIS could be used to improve the accuracy of contract time determination. These systems are helpful with project or project phase duration estimates, but do not provide the comparative data needed for this project.

A review of the literature and discussions with TxDOT Construction Division and Bryan District Construction personnel revealed that a project or project phase duration estimation database with the preferred characteristics did not exist. TxDOT personnel generally indicated that having this type of information would be useful, but could only be collected on a project-by-project basis (similar to the process followed by the CTR project described previously). The completion of a task of this scope, however, was beyond the schedule and funding of this project. An approximation of the magnitude and variability in Texas roadway construction project or project phase duration estimates was needed.

MONTHLY ESTIMATE REPORT DATA

One source of the systematic, but approximate project or project phase duration estimates in Texas is the SiteManager™ monthly estimate reports (see Figure 44 for part of this report) provided by contractors to TxDOT. Each of these documents includes the following construction reports:

- contract time statement,
- construction estimate breakdown,
- construction estimate combined,
- construction estimate distribution, and
- work performed during the given period.

The data contained in these monthly estimate reports allow the progress of a project to be tracked. They include, among other things, information about the project contract, its location, work and schedule progress, and the work items used. The duration data in the monthly estimate reports that was useful to this project include the percentage of project complete and time used. The percentage of project complete is based on the contractor estimate of the work completed. The percentage of time used, however, is simply the amount of time that has elapsed on the contract. It was concluded that the typical magnitude and variability of the difference between these two percentages was an acceptable approximation of similar measures for project or project phase duration estimates in Texas.

SiteManager

CONTRACTOR'S ESTIMATE PACKAGE

REPORT DATE: 07/05/07

CONTRACT ID:	002706050	HIGHWAY:	US 90A
PROJECT:	STP 2004(81)	DISTRICT:	12
CONTRACT:	12033210	COUNTY:	FORT BEND
CONTRACT PRICE:	$1,818,597.86	AREA ENGINEER:	Jim Hunt
ADJ. CONTRACT PRICE:	$1,836,043.18	AREA NUMBER:	061
CONTRACTOR:	DURWOOD GREENE CONSTRUCTION, L.P.		

ESTIMATE NUMBER:	0011	LETTING DATE:	12/05/2003
ESTIMATE PAID:	☑	AWARD DATE:	12/18/2003
ESTIMATE PERIOD:	09/28/2004 to 09/28/2004	NOTICE TO PROCEED DATE:	01/14/2004
ESTIMATE TYPE:	SUPP	WORK BEGIN DATE:	02/16/2004
% COMPLETE:	99.56	ACCEPTED DATE:	09/13/2004
% TIME USED:	95.56	PHYSICAL WORK COMPLETION DATE:	00/00/0000
% RETAINAGE:	0.00		

RECAPITULATION

	TOTAL TO DATE	PREV TO DATE	THIS ESTIMATE
ITEM EARNINGS	$1,828,034.75	$1,828,034.75	$0.00
PARTICIPATING	$0.00	$0.00	$0.00
NON-PARTICIPATING	$1,828,034.75	$1,828,034.75	$0.00
RETAINAGE	$0.00	$0.00	$0.00
LIQUIDATED DAMAGES	$0.00	$0.00	$0.00
INCENTIVE	$0.00	$0.00	$0.00
DISINCENTIVE	$0.00	$0.00	$0.00
OTHER ADJUSTMENTS	$3,884.00	$0.00	$3,884.00
PAID TO CONTRACTOR	$1,831,918.75	$1,828,034.75	$3,884.00

Figure 44. Example Portion of SiteManager™ Monthly Estimate Report.

Duration Data Reduction

Information from the monthly estimate reports available on October 7, 2006, were used to approximate the duration information needed for this project. More than 5,800 reports from all 25 TxDOT districts were available at that time. However, schedule and budget did not allow the summary of all these reports, and several were not relevant to this project. Therefore, the reports from a sample of four TxDOT districts were selected for further analysis. Data were used from the Corpus Christi, Houston, Paris, and San Angelo districts. These districts were selected because they represent a range of urban and rural land use characteristics. There were approximately 1,200 monthly estimate reports available for these four districts. This sample represents about 20 percent of the reports available statewide on October 7, 2006.

These monthly estimate reports from the Corpus Christi, Houston, Paris, and San Angelo districts were also reviewed for relevancy to this research project and questionable project duration data. Some of the projects summarized in the reports, for example, appeared to be ongoing "maintenance" tasks (e.g., roadside mowing) and/or not typical roadway construction (the focus of this research). One of the duration estimate items available for the ongoing "maintenance" contracts included the fact that their "percentage of project complete" may simply be an equally split percentage of the contract amount rather than an estimate of the total amount of contract work expected to be completed (which may not be known). This type of project may also be less likely to have an active or longer term work zone.

Overall, a conservative approach was taken toward the removal of any monthly estimate reports that might be unrelated to the focus of this research (i.e., roadway construction project with work zones). About 400 of the initial 1,200 reports were removed from further consideration. An additional 38 reports were also removed due to what was considered to be questionable project duration estimation data (e.g., a percentage of project work completed, but no time used on the contract). The relevant project duration data from the remaining 614 monthly estimate reports are summarized below and were used in the statistical analysis. This number of reports represents approximately 10 percent of the total available in Texas on October 7, 2006, and 51 percent of the reports available for the four sample districts.

DATA SUMMARY

Duration data from 614 SiteManager™ monthly estimate reports were used to quantify the magnitude and variability of project or project phase duration estimates in Texas. The data obtained from each monthly estimate report included, but was not limited to, the following:

- estimate period (e.g., October 1, 2006, to October 31, 2006);
- estimate type (e.g., in progress and final);
- percentage of project complete;
- current days (i.e., total number of contracted days);
- days charged to date;

- percentage of time used (i.e., days charged to date divided by current days);
- highway type (e.g., farm-to-market); and
- county and district.

District, Highway Type, and Contract Length

The projects included in the database were summarized by TxDOT district, highway type, and current days (i.e., total number of contracted days). The percentage and number of monthly estimate reports from the Corpus Christi, Houston, Paris, and San Angelo districts are shown in Figure 45. Overall, approximately 57 percent (n = 347) of the reports and data were from the Houston district, 22 percent (n = 137) were from Corpus Christi, and the remaining 21 percent of the data were split almost equally between the Paris (n = 75) and San Angelo (n = 55) districts. In addition, more than 70 percent of the projects in the database were occurring along state highways, Interstates, United States highways, or farm-to-market roadways. The remaining 30 percent of the projects in the database occurred along one or more other roadway types (e.g., ranch-to-market, loops, etc.).

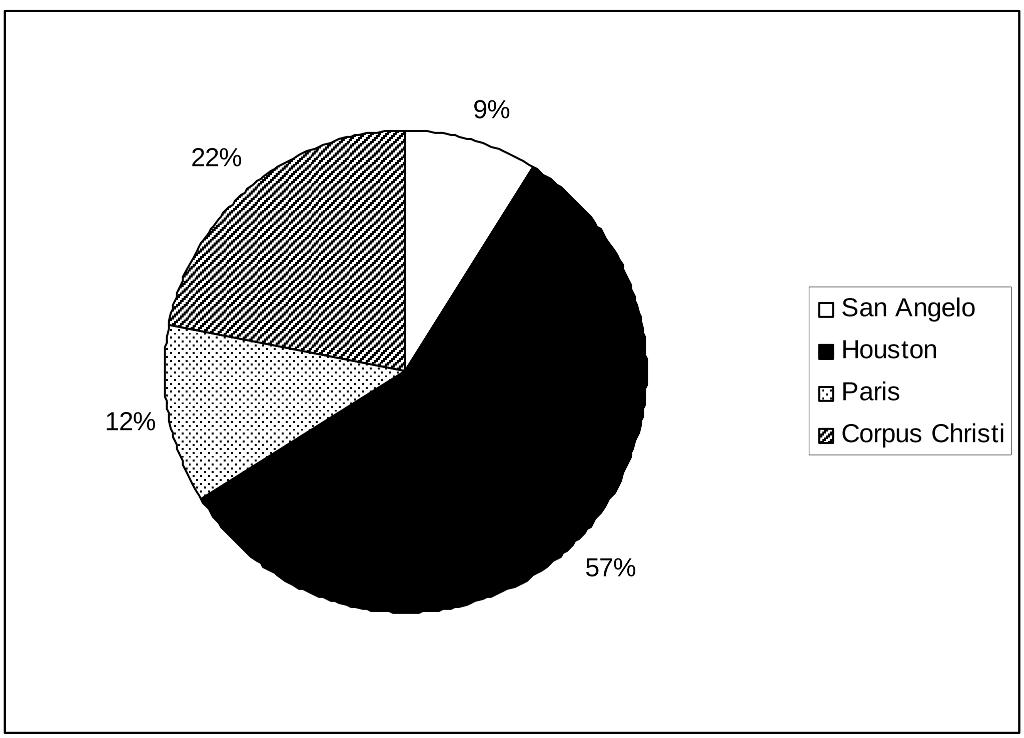


Figure 45. Percent of Monthly Estimate Reports by Texas Department of Transportation District.

The distribution of the projects in the database by total contract length is shown in Figure 46. The distribution shows that the range and variability of project contract length in the database is large. The minimum project contract length was only five days and the maximum was almost 1,500 days (about four years). The average project contract was approximately 222 days (about seven or eight months) long, but the median was only 120 days (four months). This difference between the mean and median is an indication of the relatively large variability in the data. In fact, the standard deviation in total contract length for the entire database was about 247 days. Overall, about 50 percent of the projects had total contract length at or below 120 days (four months) and 85 percent of projects had lengths at or below 401 days (about 13 months). Only 15 of the 614 projects in the database had contract lengths greater than 990 days (about 2.75 years). The monthly estimate report information in the database appears to represent a wide range of applicable TxDOT project contracts.

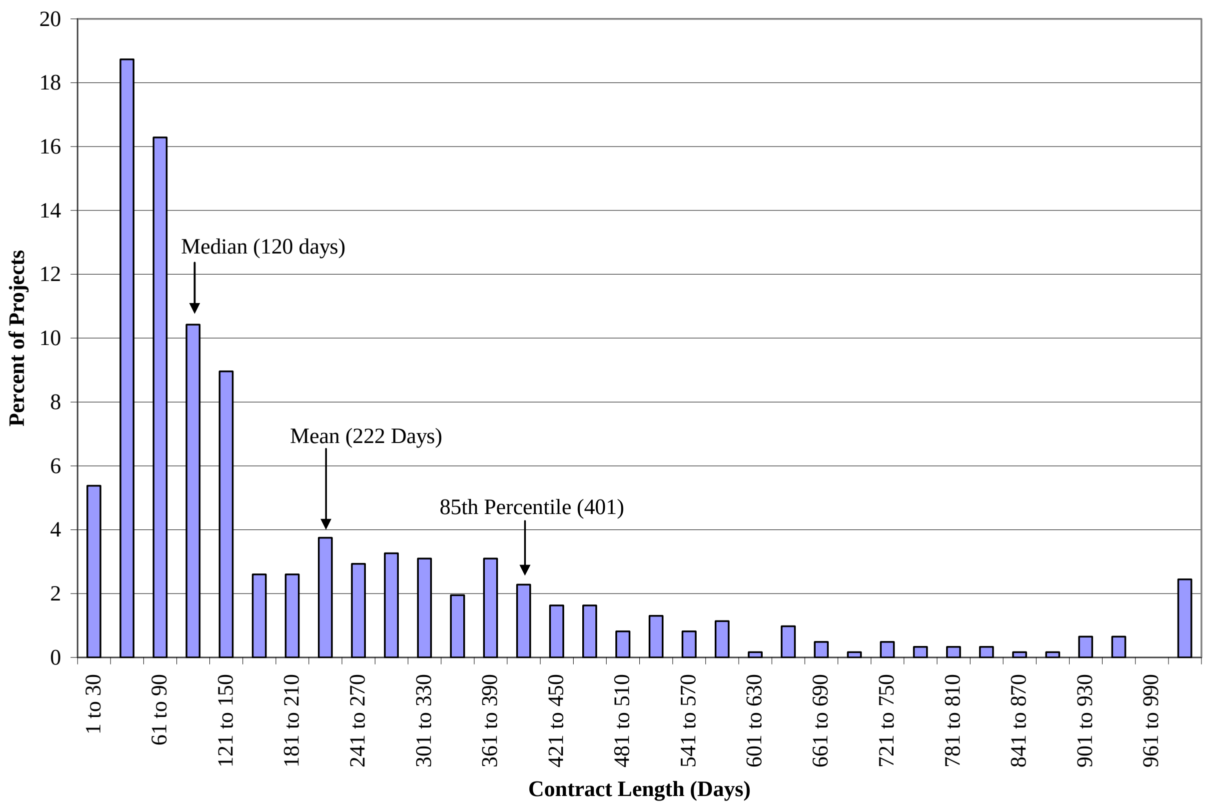


Figure 46. Distribution of Projects by Total Contract Length (n = 614).

"Percent Difference" Duration Estimates

The focus of this portion of the research project was to approximate the magnitude and variability of project or project phase duration estimates. Therefore, a "percent difference" was calculated for each of the 614 monthly estimate reports. This measure is equal to the difference between the percentage of project complete (an estimate of the project work completed) and percentage of time used in the contract. It was concluded that the descriptive statistics (e.g., mean and standard deviation) and distribution of the percent difference data could be used to approximate the magnitude and variability of the difference between actual and expected project progress (or project or project phase duration estimation capabilities).

The percent difference can be positive, negative, or equal to zero. A positive percent difference indicates that the project is generally considered ahead of schedule (i.e., the percentage of work completed is more than the contract time used), but a negative percent difference generally describes a project behind schedule (i.e., the percentage of time used in the contract is more than the percentage of work completed). A percent difference of zero, on the other hand, means that the estimate of the percentage of work completed is exactly the same percentage of days used in the contract. Approximately 60 percent (n = 371) of the 614 projects considered in this analysis were generally ahead of schedule and 29 percent (n = 177) of the projects were behind schedule. The data from 11 percent (n = 66) of the 614 projects indicated they were exactly on schedule. Of course this percent difference measure does change from month to month within a particular project due to a number of factors (e.g., work being completed, weather, crew availability, etc.). The sample of monthly estimate reports used, however, should be a good representation of TxDOT projects at different stages of completion.

The distribution of the percent difference calculated for each of the 614 projects in the database is shown in Figure 47. The typical magnitude and overall range of the data are indicated and the number of projects in each category noted. The overall average percent difference for the projects in the database was approximately 3.9 percent. In other words, on average, the percentage of work completed was 3.9 percent greater than the percentage of time used within a contract. This result is supported by the fact that the percent difference calculated for more than 70 percent of the projects was greater than or equal to zero.

The range and standard deviation of the percent difference data indicate some variability. The minimum percent difference was -90 percent and the maximum 153 percent. More specifically, in one case the percent work completed was around 90 percent behind the time used in the contract and in the other case the percent of work completed was more than 150 percent greater. The standard deviation of the percent difference data was also approximately 25.9 percent. The impact this variability might have on the ability to predict a percent difference (i.e., duration estimate) for an individual project is explained in the next section of this chapter. The descriptive statistics of the percent difference data, along with the results of the following statistical analysis, were used to create the temporary pavement marking selection tool and guidelines described in the main body of this report.

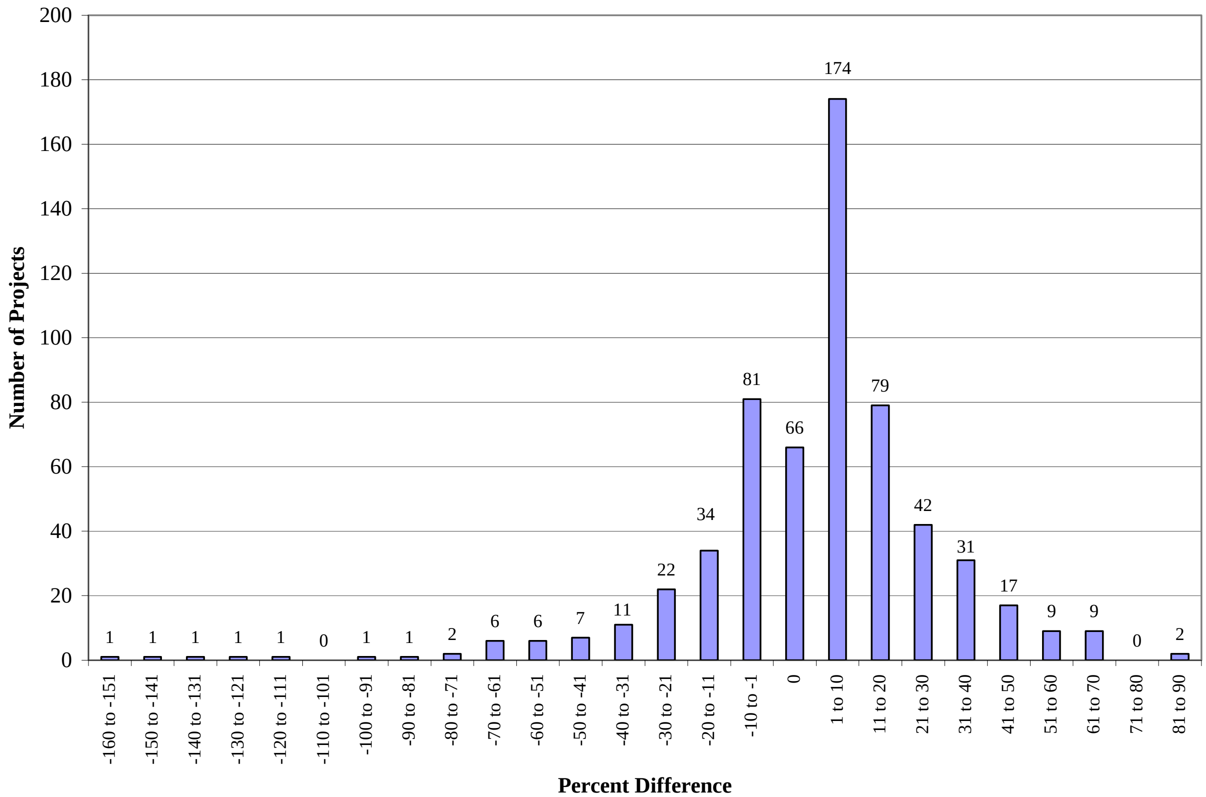


Figure 47. Distribution of the Difference Between Percent Project Complete and Percent Time Used (n = 614).

STATISTICAL ANALYSIS

The statistical analyses and calculations that focused on the percent difference data in Figure 47 were completed for two purposes. First, it was hypothesized that the ability to accurately estimate project duration (i.e., the percent difference) might change with overall project contract length. If so, the impact of this change should be taken into account within a temporary pavement marking selection tool or guidelines. Statistical tests were completed to determine if the mean percent difference of projects with varying contract lengths were significantly different. Second, measures of the variability in the percent difference data were calculated to evaluate the impacts it might have on the ability to predict this measure for an individual project.

The first step in the statistical analysis of the percent difference data was the selection of statistically defensible project categories. The normality of the percentage difference data within the categories selected also needed to be checked for the analysis tests to be valid. The project or contract duration categories selected for the analysis were 0 to 60 days (n = 148), 61 to 120 days (n = 164), 121 to 365 days (n = 183), and greater than 365 days (n = 119). These categories were selected for two reasons. First, as shown in Figure 47, there were more projects with shorter durations than long-term projects. The range of durations selected for each category results in each of them containing approximately the same number of projects. Second, the categories selected match more typical contract lengths of month and year increments. The normality of the percent difference data was checked through histogram and standard quartile plots. It was concluded that the data did not grossly violate the assumption of normality. An analysis of the data with some of the outliers removed also indicated that it was robust enough to produce acceptable statistical results even if this normality assumption was not perfectly satisfied.

Comparison of Means

The Tukey "Honestly Significantly Different" (HSD) procedure was used to determine whether the mean percent difference of the project duration categories (described above) was systematically different in some manner. The results of this test are shown in Table 30. The average difference in the means compared is shown along with its 95th percentile confidence interval. A confidence interval that contains zero generally indicates that the means compared are not likely to be significantly different. The results of the test indicate that only the duration categories with project contract lengths from 0 to 60 days and 121 to 365 days have statistically different means. The mean of the percent difference in all the "adjacent" categories (e.g., 0 to 60 days and 61 to 120 days), however, were all statistically the same. Overall, the results of this analysis did not appear to indicate a systematic or meaningful (to this project) difference in the percent difference mean by total project contract length. The percent difference mean and variability measures calculated from either the overall database or each project length category, therefore, could be used in the development of the temporary pavement marking selection methodology.

Table 30. Comparison of Means Test Results.

Project Contract Length Categories Compared (Days)	Average Difference in Means	95^{th} Percentile Confidence Interval of Diff. in Means	Significant Difference in Means?
0 to 60 and 61 to 120	6.37	-1.12 to 13.85	No
0 to 60 and 121 to 365	8.94	1.64 to 16.23	Yes
0 to 60 and > 365	3.27	-4.86 to 11.39	No
61 to 120 and 121 to 365	2.57	-4.52 to 9.67	No
61 to 120 and > 365	-3.10	-11.04 to 4.85	No
121 to 365 and > 365	-5.67	-13.44 to 2.10	No

Confidence and Prediction Intervals

The second evaluation completed as part of the statistical analysis focused on the variability of the percent difference data and its potential impacts on the development of a temporary pavement marking selection methodology. The average of the percent difference data for each project duration category is shown in Table 31. They range from approximately zero to almost 9 percent, and the overall average percent difference for the entire database is 3.9 percent. These means represent an approximation of the expected magnitude of this measure.

Confidence and prediction intervals were also calculated for the percent difference data in the entire database and within each project duration category (see Table 31). The confidence intervals in Table 31 show the range that the researchers believe, to a 95^{th} percentile level of confidence, contains the actual mean percent difference for the type of projects evaluated in this study. In this case, the confidence interval based on the mean from the overall database is 1.9 to 6.0 percent. The prediction intervals, on the other hand, represent the range within which a percent difference for a future individual project might be included. The 95^{th} percentile prediction interval calculated for the entire database ranges from -45.9 to 54.8 percent. As expected, the prediction intervals are larger than the confidence intervals. The range of these intervals was used to guide the project duration data used to develop the temporary pavement marking selection tool and guidelines.

Table 31. Confidence and Prediction Intervals.

Project Contract Length Category (Days)	Mean Percent Difference	95th Percentile Confidence Interval	95th Percentile Prediction Interval
0 to 60	8.9 (n = 148)	3.9 to 14.0	-52.4 to 70.3
61 to 120	2.6 (n = 164)	-1.6 to 6.8	-51.4 to 56.6
121 to 365	0.0 (n = 183)	-3.5 to 3.5	-47.6 to 47.6
> 365	5.7 (n = 119)	2.5 to 8.8	-28.7 to 40.0
All Categories	3.9 (n = 164)	1.9 to 6.0	-45.9 to 54.8

SUMMARY OF FINDINGS

The evaluation described in this chapter produced several findings that were used in the development of a temporary pavement marking selection tool and guidelines. These findings are summarized below. Suggestions for improvements to the project and project phase duration estimation data available in Texas are also provided.

- Currently, comparison of estimated and actual project or project phase durations can only be completed on a case-by-case basis in Texas. Information from individual project and project phase traffic control plans could be compared to actual start and end dates. The ability to compare this type of information in a systematic manner, however, would provide much more valuable insight into the accuracy of project and project phase duration estimates. It is suggested that the collection of these data be considered for TxDOT project and project phases.
- This research project used the time-related data from a sample of monthly estimate reports to approximate the magnitude and variability of project or project phase duration estimates. Data from 614 projects within four TxDOT districts (i.e., Corpus

Christi, Houston, Paris, and San Angelo) were analyzed and evaluated. These districts were selected because they represent a range of urban and rural land use characteristics. Approximately 57 percent of the projects considered were from the Houston district, and the total contract lengths ranged from less than a week to almost 2.75 years. Eighty-five percent of the projects in the database were less than 13 months long.

- The magnitude and variability of project or project phase duration estimates were approximated by the calculation of a "percent difference" for each of the 614 projects in the database. This measure was calculated from data available on the monthly estimate reports provided to TxDOT by its contractors. It is equal to the difference between the contractor's estimate of the percentage of work completed and the percentage of time used in the contract. A positive percent difference generally means that more work has been completed in the project than the percentage of time elapsed in the project contract. This measure varies from month to month during an individual contract, but the sample of projects considered in this evaluation also represents TxDOT projects at different stages of completion.
- The overall average percent difference in the database was 3.9 percent and the standard deviation was approximately 25.9 percent. In other words, on average, the projects in the database were estimated to have 3.9 percent more work completed than time used on their contracts. The variability in the percent difference data, however, was relatively large. It ranged from -90 percent to almost 150 percent. Several projects were either well behind or ahead of schedule, but on average most projects were progressing in an expected manner.
- It was hypothesized that the typical magnitude of the percent difference might be related to overall length of a contract. A statistical evaluation of the percent difference from projects of varying contract lengths, however, revealed no systematic results that were considered meaningful or relevant to the objective of this research task.
- Based on the results of activities described in this chapter, the overall average (3.9 percent) and standard deviation (25.9 percent) of the percent difference data were used to approximate the typical magnitude and variability of project and project

phase duration estimates. A normal distribution of these data was combined with similar information about pavement marking service life and cost.

CHAPTER 9. ESTIMATING THE SERVICE LIFE OF WORK ZONE PAVEMENT MARKINGS

The researchers used a two-step process to determine the pavement marking service life information. The first step in the process was determining the variability in service life of each of the pavement marking types. The second step was to determine service life of the markings based on average daily traffic (ADT) volume. The service life of the marking is considered to be the age of the marking when the retroreflectivity of the marking reaches 100 mcd/m^2/lux (i.e., when the marking no longer provides adequate nighttime delineation). The service life and its associated variability were determined for each marking type on both asphalt and concrete road surfaces.

ESTIMATING PAVEMENT MARKING SERVICE LIFE VARIABILITY

Data from the 2002 National Transportation Product Evaluation Program (NTPEP) Mississippi test deck were evaluated to determine the service life variability of the pavement markings (*29*). The Mississippi NTPEP test decks were placed on both asphalt and concrete roadways. The roads had ADTs of 24,000 and 22,000, respectively, and both were four-lane divided highways. Multiple pavement markings of each marking type were applied on each test deck.

NTPEP test decks use transverse lines that are placed across a single travel lane. The retroreflectivity of the markings is measured near the skip line and in the left wheel path. These measurements are conducted for two years except for the temporary tapes, which are evaluated for 6 months. Since the lines are transverse to the direction of travel the service life would not necessarily be expected to be representative of what longitudinal lines would provide. However, the differences between each of the various lines are believed to provide a good relative measure of variability for each marking type. The measurement near the skip line may provide some indication of service life but this has not been validated. The left wheel path measurement is intended to provide accelerated wear on the marking for comparisons between markings. A combination of the left wheel path measurements and skip area measurements may best represent the service life of a work zone pavement marking. It should also be noted that this NTPEP test deck did not include buttons or RRPMs.

A log-linear regression was fitted to the data for each pavement marking type to describe the relationship between marking service life and retroreflectivity at that particular level of traffic volume. In these regression models, marking service life and retroreflectivity represented the response and explanatory variables, respectively. A technique referred to as inverse prediction was used to make a prediction of the value of *x* which gave rise to a new observation *y* (*30*). Given a retroreflectivity of 100, the technique was used to calculate the expected service life as well as the corresponding standard error as expressed in Equations (1) and (2).

$$\hat{X} = \frac{Y^* - b_0}{b_1} \tag{1}$$

where $\hat{X}$ is a predicted service life,

Y^* is a specified retroreflectivity, and

b_0 and b_1 are parameters estimated from the log-linear regression models.

Note that different sets of parameters were obtained for asphalt and concrete data. Consequently, the corresponding estimator of standard error is:

$$s_{\hat{x}}^2 = \frac{MSE}{b_1^2}\left[1 + \frac{1}{n} + \frac{\left(\hat{X} - \bar{X}\right)^2}{\sum\left(X_i - \bar{X}^2\right)}\right] \tag{2}$$

where *MSE* is the mean square of error of the data set,

n is the sample size, and

X_i are observed retroreflectivity values.

Then, the coefficient of variation (CV) can be obtained by:

$$CV_{\hat{x}} = \frac{s_{\hat{x}}}{\hat{X}}. \tag{3}$$

The results of the analysis for the thermoplastic, paint, and temporary tape pavement markings are displayed in Table 32, Table 33, and Table 34. These tables indicate the location where retroreflectivity was measured and the resulting expected service life and variability in service life information. As expected, the skip area produces a much longer service life than the left wheel path area. The regression plots for the thermoplastic, paint, and temporary tape markings for each surface type are presented in Appendix A.

Table 32. NTPEP Thermoplastic Results.

Thermoplastic	Measurement Location	Expected Service Life (months)	Std. Error (months)	Coeff. Of Variation
Asphalt	Left Wheel Path	17.1	7.454	43.50%
	Skip Area	50.8	12.316	24.25%
	Both	28.1	12.383	44.03%
Concrete	Left Wheel Path	17.9	8.385	46.91%
	Skip Area	35.3	7.980	22.62%
	Both	25.7	10.819	42.06%

Table 33. NTPEP Paint Results.

Paint	Measurement Location	Expected Service Life (months)	Std. Error (months)	Coeff. of Variation
Asphalt	Left Wheel Path	11.0	5.512	50.04%
	Skip Area	30.7	9.579	31.15%
	Both	17.2	9.117	52.95%
Concrete	Left Wheel Path	14.1	5.959	42.23%
	Skip Area	36.4	8.777	24.13%
	Both	21.6	9.367	43.35%

Table 34. NTPEP Temporary Tape Results.

Tape	Measurement Location	Expected Service Life (months)	Std. Error (months)	Coeff. Of Variation
Asphalt	Left Wheel Path	7.8	1.995	25.53%
	Skip Area	21.4	6.520	30.50%
	Both	11.3	3.187	28.11%
Concrete	Left Wheel Path	11.2	3.131	27.92%
	Skip Area	12.9	3.153	24.47%
	Both	12.0	2.974	24.83%

RELATIONSHIP BETWEEN SERVICE LIFE AND TRAFFIC VOLUME

The service life of a pavement marking has been shown to be impacted by the traffic volume of a road. Consequently, the next step in the analysis was to develop estimates of service life (months until a marking would reach a retroreflective value of 100 mcd/m^2/lux). Five sources of data were used in this section. The NTPEP data (29) were used for comparison purposes. Thermoplastic data were obtained from the University Transportation Center for Alabama (*31*). Researchers obtained paint data from the University of Utah (*32*), and RRPM data from TxDOT (*33*) and Indiana Department of Transportation (DOT) (*34*) sources. Virtually every data source for pavement marking degradation was initially considered for this analysis, but shortfalls in much of the data (improper measurement geometry other than the standard 30 meters, major winter maintenance activities, inappropriate study designs, etc.) reduced this dataset significantly.

The University Transportation Center for Alabama conducted a study that evaluated the service life of flat thermoplastic pavement markings on asphalt roadways (*31*). Two models were fit to the data to determine the retroreflectivity decay rate (linear and exponential). These models can be seen in Equations (4) and (5), respectively. These models only apply to asphalt road surfaces. The researchers decided it was best to take the average of the two decay models to take advantage of the positive aspects of the two decay rates. Based on any given lane ADT and a minimum retroreflectivity of 100 mcd/m^2/lux, the service life of the typical thermoplastic marking can be determined by averaging the results of the two decay models. The researchers conducted this analysis for a range of lane ADT between 3000 and 25,000. The results of this analysis can be seen in Figure 48.

$$ServiceLife = \frac{(R_L - 310)}{(LaneADT * -.000031 * 30.4)} \qquad (4)$$

$$ServiceLife = \frac{Ln(\frac{R_L}{329})}{(LaneADT * -.00000016 * 30.4)} \qquad (5)$$

Since the Alabama study did not evaluate concrete roadways, an adjustment factor had to be determined to adjust for the difference in service life between the two surfaces. This factor was found by comparing the service life values from the NTPEP analysis. In the NTPEP analysis, TTI researchers found that thermoplastic provided 11.6 percent less service life on concrete as it did on asphalt (see NTPEP thermoplastic results in Table 32). Therefore, researchers multiplied the asphalt service life by 0.884 to create the service life curve for thermoplastic on concrete surfaces. The concrete service life curve for the various ADTs is also shown in Figure 48.

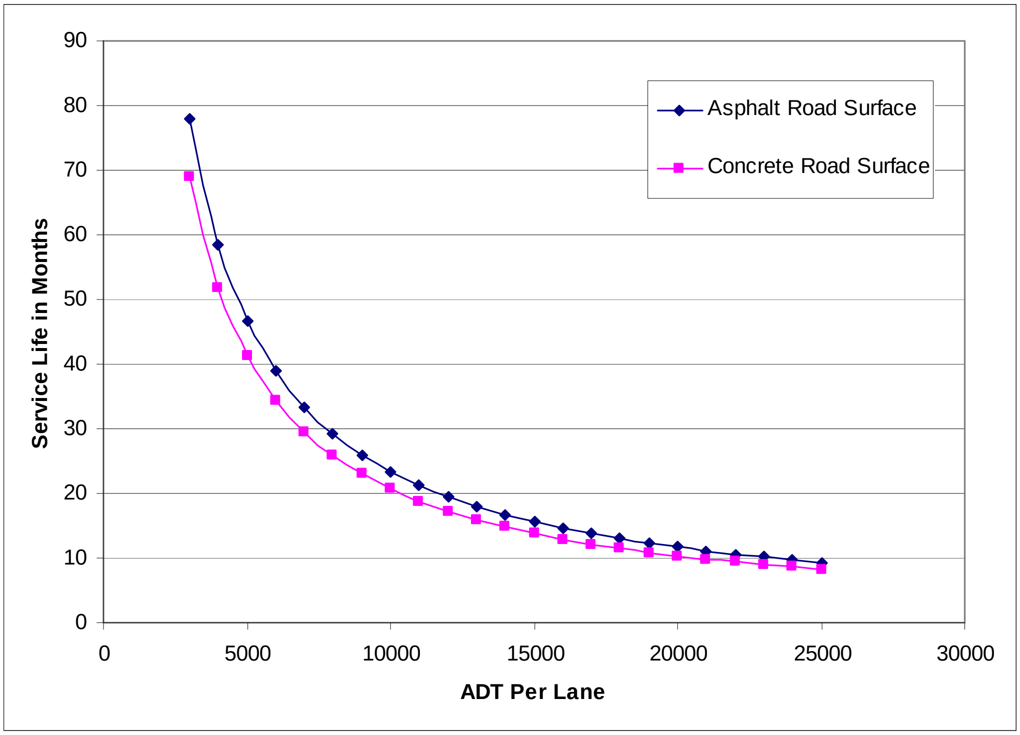


Figure 48. Service Life of Thermoplastic Based on Lane ADT.

The University of Utah conducted a study that evaluated the service life of paint pavement markings on asphalt and concrete roadways *(32)*. The resulting service life decay models for asphalt and concrete roadways are indicated in Equation (6) and Equation (7), respectively. Comparing the service life of the paint on concrete to that of the NTPEP paint data on concrete indicated that the paint-on-concrete service life based on ADT curve was approximately 18 percent higher. Therefore, the resulting service life curve from Equation 7 was reduced by 18 percent so that the NTPEP data and the Utah data paint-on-concrete had a similar service life ratio to that of the Alabama data and the Utah data on asphalt. Figure 49 displays the service life of paint on asphalt and concrete roadways based on lane ADT.

$$ServiceLife = \frac{133684}{LaneADT} \quad (6)$$

$$ServiceLife = \frac{195385}{LaneADT} \quad (7)$$

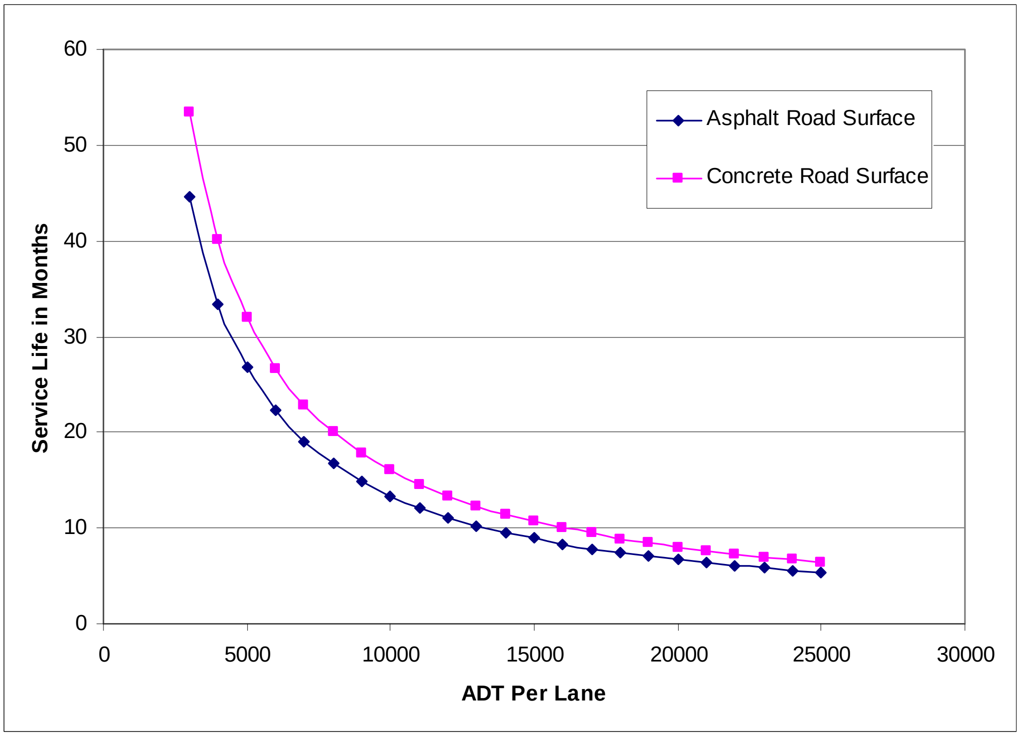


Figure 49. Service Life of Paint Based on Lane ADT.

In addition to the thermoplastic and paint analysis the researchers also evaluated temporary tape. No research was found that evaluated the service life of temporary tape on asphalt or concrete based on ADT. Again, the NTPEP data were used to determine the service life of the temporary tape. Comparing the temporary tape data to the thermoplastic data, a similar trend in service life for the skip area and left wheel path area was found. This led researchers to use the thermoplastic service life curve based on lane ADT from the Alabama study adjusted for temporary tape. Comparing the NTPEP service life values for thermoplastic and temporary tape, researchers found that an adjustment of 42.7 percent was needed for asphalt and 48.6 percent for concrete. Researchers multiplied the thermoplastic service life values by either 0.427 or 0.486 to create the service life curves for the temporary tape. Figure 50 displays the resulting curves based on a range of ADTs. The resulting curves indicate that surface type should not impact temporary tape service life.

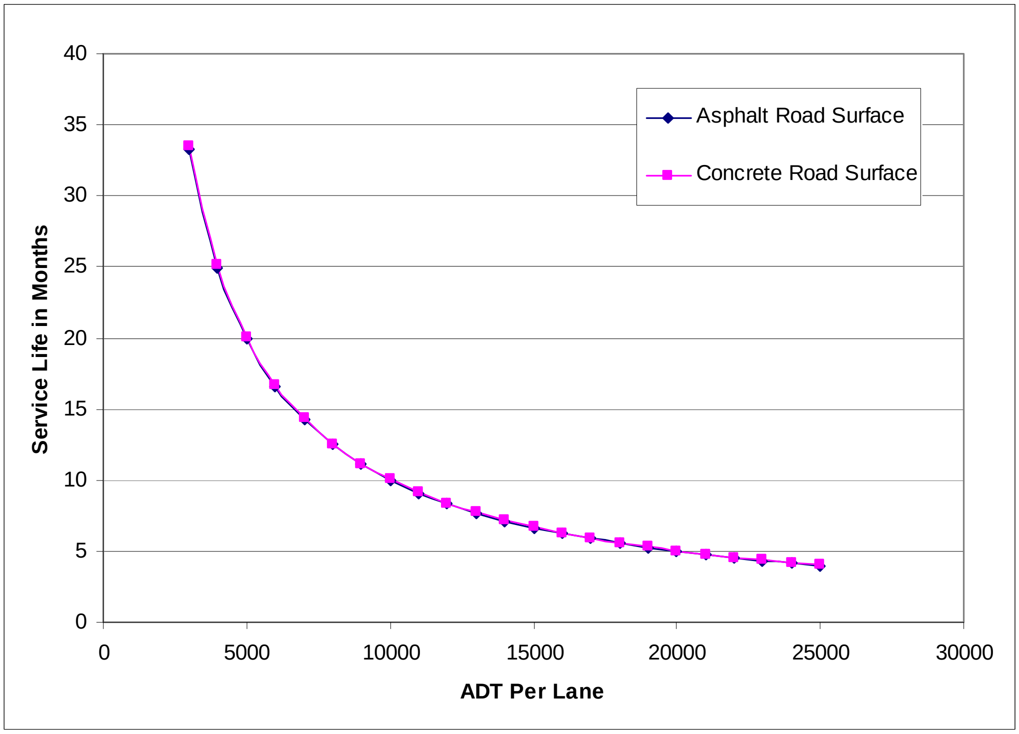


Figure 50. Service Life of Temporary Tape Based on Lane ADT.

Traffic buttons and RRPMs are two forms of raised pavement markers (RPMs). There are little data in literature that establish a service life based on ADT for RPMs. Two sources of information are the TxDOT replacement schedule that can be found in the TxDOT Pavement Marking Handbook (*33*) and the results of an Indiana DOT survey conducted by Bahar et al. (*34*). Both of these sources indicate anticipated replacement cycles for RPMs based on ADT categories. Table 35 and Table 36 contain the replacement schedules for the two data sources. Neither source differentiates between road surface types. The data contained in Table 35 and Table 36 are very similar for both states. These data were used to create the anticipated service life and service life variability curves at a range of ADTs.

Table 35. TxDOT RPM Replacement Schedule (*33*).

ADT	Replacement Cycle (years)
Less than 10000	3 to 4
10000 to 50000	2 to 3
Greater than 50000	1

Table 36. Indiana DOT RPM Replacement Schedule (*34*).

ADT	Replacement Cycle (years)
2 Lane Roads	
Less than 5000	4
5000 to 15000	3
Greater than 15000	2
4 or More Lane Roads	
Less than 10000	4
10000 to 30000	3
30000 to 75000	2
Greater than 75000	2 (inspect yearly)

Once relationships between marking materials and lane ADTs were established, researchers turned their attention back on estimating the variability in the relationships. It was assumed that the coefficient of variation was the same for all service lives predicted for the studied range of ADTs. This assumption was deemed reasonable by the researchers since the standard errors of service lives tend to increase as ADTs decrease; in other words, the variability of service life tends to be greater with low-volume conditions and vice versa. The coefficient of variation of each marking type can be found in Table 32 through Table 34. The coefficient of variation for the combination of the skip area and left wheel path (both) was the value that was used for each marking type for each road surface. The resulting standard error values for each lane ADT are provided for each marking type in Figure 51 through Figure 53. These figures display what intuitively makes sense in that the standard error is larger when service life is longer and less when service life is shorter. At higher volumes, it is the vehicle tire wear on the markings that determines how long the marking lasts. Environmental effects, which tend to be highly variable over time, do not have as much of an effect (since the markings do not last for an overly long time). At lower volume levels, the highly variable environmental effects play a much bigger role and can lead to much different readings from one location to the next even if the amount of time in place is the same.

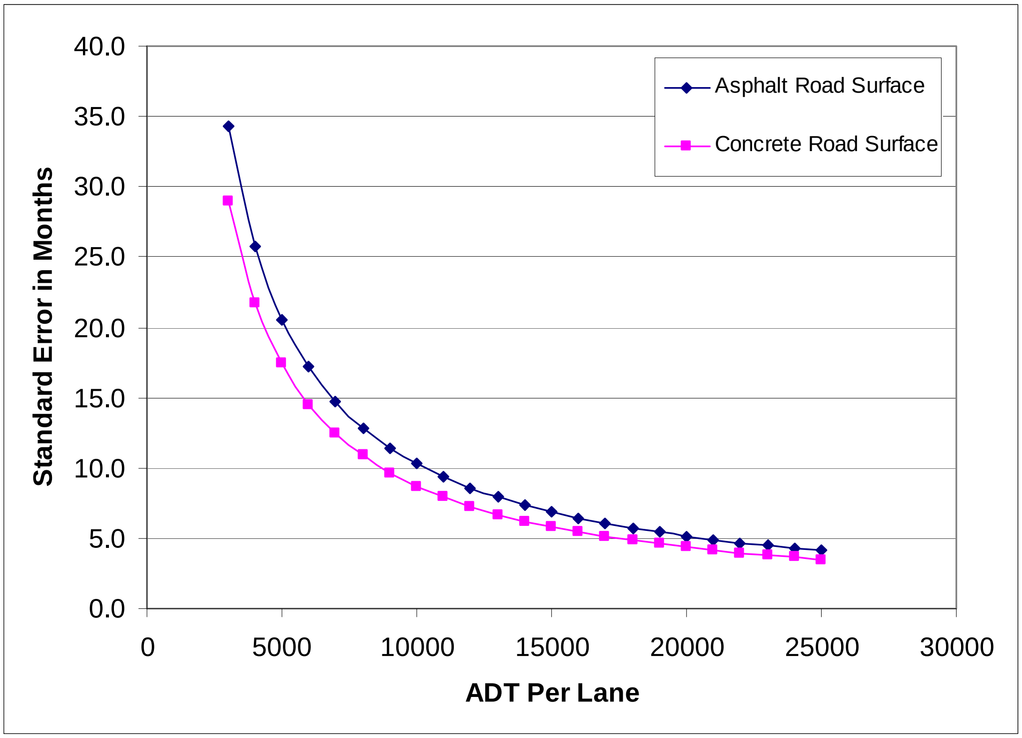


Figure 51. Standard Error of Thermoplastic Service Life Based on Lane ADT.

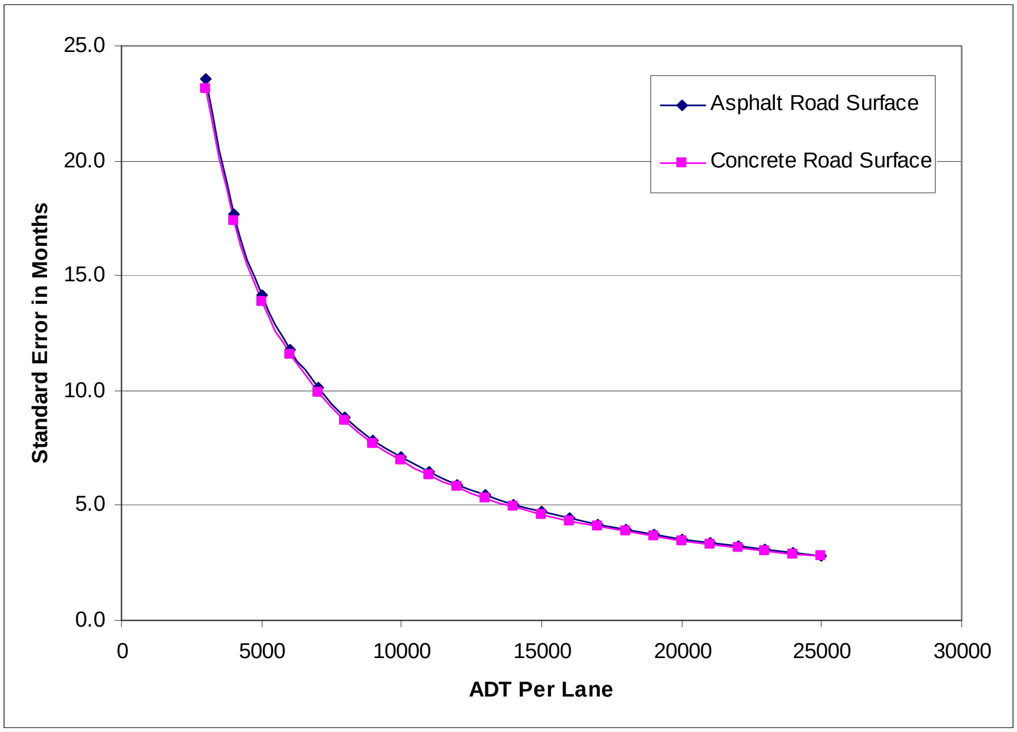


Figure 52. Standard Error of Paint Service Life Based on Lane ADT.

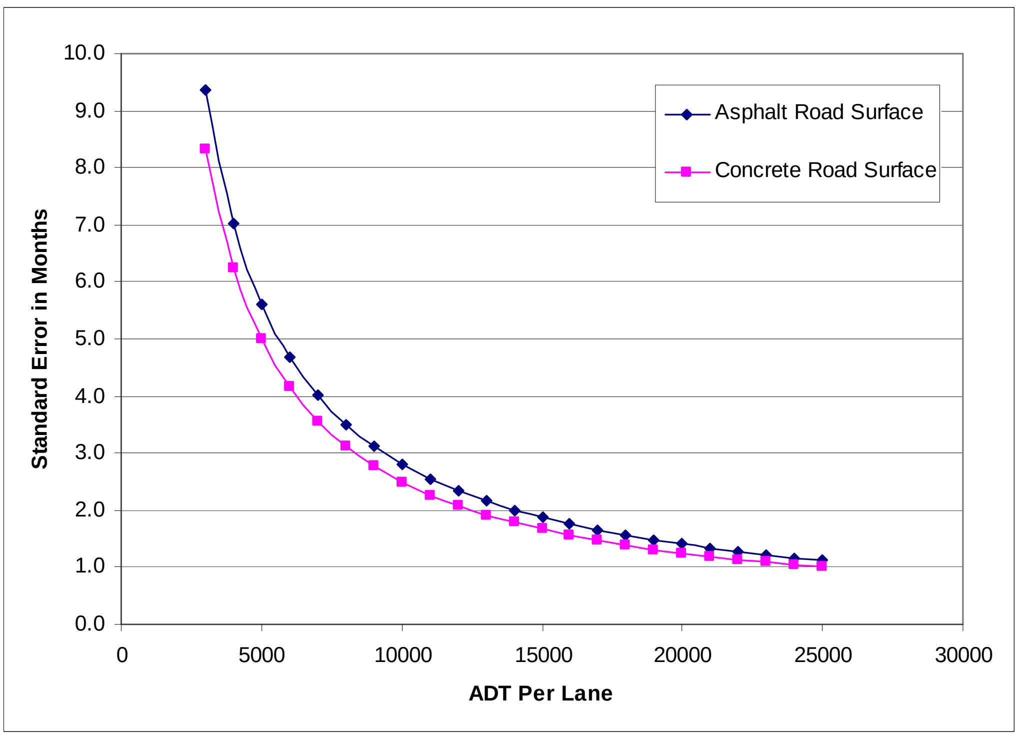


Figure 53. Standard Error of Temporary Tape Service Life Based on Lane ADT.

PAVEMENT MARKING COSTS

The researchers estimated costs for one mile of a solid white edge line. Buttons and RRPMs were assumed to be spaced at 5 ft intervals in a three-button-then-one RRPM pattern. This equates to one RRPM every 20 ft on the edge line. This spacing is the recommended spacing in the TxDOT Standard Plans for Barricade and Construction Pavement Marking Patterns.

Costs were found using the TxDOT bid sheets for statewide construction projects for the past year (i.e., August 2006 through July 2007) as well as the past month (i.e., July 2007) (*35*). The item numbers of interest used in the analysis were 6622004, 6622052, 6622060, 6622067, and 6662012. Several individual projects were also analyzed to further grasp the expected range of the marking costs. It should be understood that these costs are particularly sensitive to quantity and accessibility of the marking type.

The resulting costs from the average bid sheets and the individual project bid sheets can be found in Table 37. The costs are for one mile of a solid 4-inch edge line of white pavement marking. The costs are divided for each of the different pavement marking types. The costs listed indicate average and standard deviation of values that should be expected. Also indicated in the table are the average unit costs for each of the markings. The continuous markings unit cost is per foot and the button and RRPM cost is for each individual marking. The button and RRPM unit cost is the average cost for three buttons and one RRPM.

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Table 37. Estimated Pavement Marking Costs (Solid Line)

Pavement Marking Material	Cost per Mile ($)		Avg Unit Costs ($)	
	Average	Standard Deviation		
Paint	1056	412	0.20	per foot
Thermoplastic	1584	412	0.30	per foot
Tape	3960	1030	0.75	per foot
Buttons + RRPMs	2233	825	2.11	each

CHAPTER 10. PAVEMENT MARKING PERFORMANCE AND SERVICE LIFE ESTIMATION FOR WORK ZONES

METHODOLOGY

Researchers considered various approaches for combining pavement marking performance and work zone project phase duration data so as to establish recommendations for the best marking material to use for a particular work zone situation. Although many site-specific and work zone project-specific factors ultimately play into the final decision by the traffic control designer or contractor on which marking material to use, it is clear that the desire is to utilize the lowest-cost material that will provide satisfactory performance (i.e., maintain adequate levels of visibility, especially at night) over the duration of the project or project phase for which the material will be used. Furthermore, although it is technically feasible for a contractor to redo the markings at some point if the markings fail to last to the end of the project or phase, this is highly undesirable because of the additional traffic disruptions created, possible delays in completing other project tasks, etc. Therefore, applying a cost-based analysis approach to pavement marking material selection for work zones made the most sense.

Researchers ultimately decided to use a Monte Carlo (MC) simulation as it is the most appropriate approach to addressing the problem. The MC method is a numerical computation technique commonly used to solve mathematical problems that are not easy to solve analytically. In this application, MC simulations are used to derive the cost of selecting specific pavement materials with respect to the following factors:

- Pavement marking materials – Four types of commonly used marking materials were considered in this analysis: thermoplastic, paint, tape, and buttons.
- Surface type – Marking materials perform differently on various surface types due to different mechanical bonding characteristics. Two types of surfaces were considered in this study – asphalt and concrete.
- Annual Average Daily Traffic (AADT) – Higher traffic volume accelerates the degradation of marking materials. Researchers examined the relationships between AADT levels and marking retroreflectivity to quantify the performance of marking materials under different traffic conditions.

- Cost of material – Unit costs of marking materials were obtained from TxDOT bid sheets for use in this analysis. Unit costs may vary depending on the location and availability of qualified contractors, equipment, and materials.
- Reapplication cost – Marking reapplication is needed when the marking performance no longer meets what is selected as the minimum retroreflectivity requirement. In this analysis, a minimum retroreflectivity (MR) of 100 mcd/m^2/lux was utilized as a decision point to determine when a marking replacement would be needed.
- Project phase duration – Actual project phase completion can influence the selection of marking materials particularly when a project delay could require marking restriping. The results documented in Chapter 8 provided information on the variability of project phase length with respect to the contract length in this analysis.
- Service life – The service life of marking materials is defined as the time from when the marking was initially put on the pavement until the time when its retroreflectivity falls below the minimum requirement. As with project phase duration, marking materials that are less durable than expected could require markings to be restriped prior to the end of the project phase. Service life curves and variability of the service life estimates as a function of marking material, AADT, and pavement type were documented in Chapter 9 and were used here.

The MC simulation approach is summarized in Figure 54. The output from the MC analysis is the total cost associated with the selection of specific marking materials for a given set of factors.

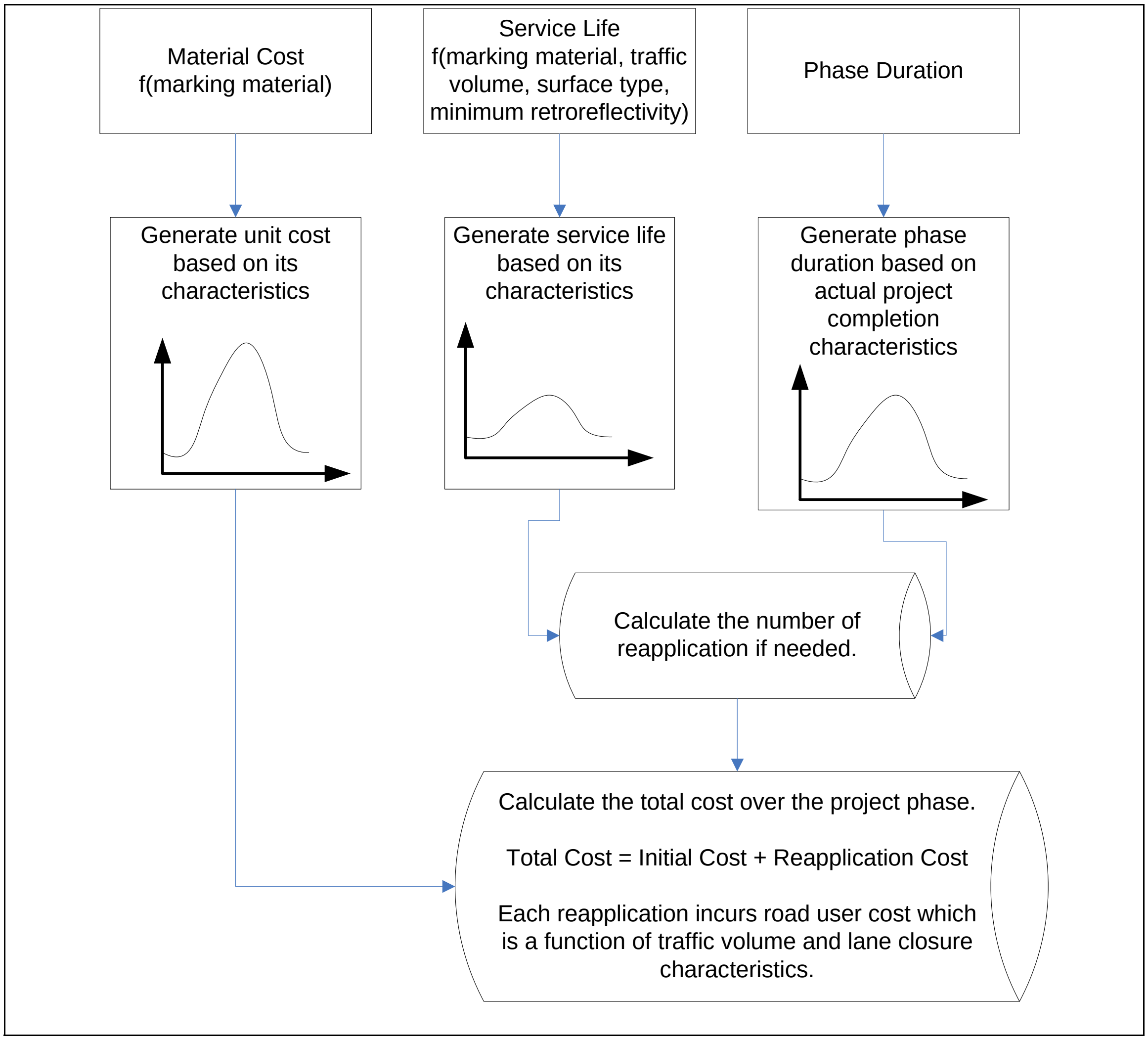


Figure 54. Overview of Monte Carlo Analytical Approach.

THE SIMULATION OBJECTIVE FUNCTION

The objective function of this analysis is the total cost of selecting and applying specific marking materials under a given set of factors. The total cost depends on how frequent markings need to be reapplied over the course of the project. The initial application of markings is always needed for every project, while the number of marking reapplication depends on actual marking service life and project phase duration.

Let N_k be the number of reapplications required for pavement marking type k. Then,

$$N_k = \lfloor P_a / S_k \rfloor \tag{8}$$

where P_a is actual phase length of the project (days) and
S_k is actual service life of marking material k.

Note that N_k is a discrete variable and equal to zero if no reapplication is needed.

Meanwhile, the total cost per unit distance of marking material k is

$$C_k = C_{k,i} + C_{k,r} \quad (9)$$

where $C_{k,i}$ is the initial application cost of marking material k and
$C_{k,r}$ is the reapplication cost of marking material k.

The reapplication cost depends on the number of reapplications needed over the course of the project at prevailing traffic volume. Reapplication is considered undesirable during the project phase since it involves equipment relocation and additional traffic disruption. This creates extra cost to the project compared to the initial application cost.

To derive the dollar equivalent amount associated with each reapplication, road user costs (RUC) from a previous TTI study *(36)* are added to the initial cost, which gives

$$C_{k,r} = N_k \cdot \left(C_{k,i} + RUC \right) \quad (10)$$

where RUC is the road user cost in $/day/mile.

RUC is estimated as a function of traffic volume and capacity reduction characteristics. In this study, the researchers used the RUC associated with work zone on four-lane and six-lane rural Interstate highways with 15 percent truck traffic. It is conservatively assumed that activities involved with marking reapplication are similar to one day of work zone activities with all lanes open with reduced capacity. The RUC figures from the 1999 report were updated to 2007 dollars using a consumer price index (CPI) multiplier of 1.251.

INPUT CHARACTERISTICS

The total cost of a particular marking material selection depends on:

- construction phase completion time,
- service life of the marking material for a given set of pavement and traffic conditions,
- unit cost of the marking material, and
- costs of reapplication of the material should it fail to last to the actual end of the project phase.

Chapters 8 and 9 provide data and relationships on the first three of these inputs that were used in this MC analysis. One of the key aspects of the analysis was the recognition that variances from the expected values of these factors were possible, and the probability of these deviations (and magnitude of such deviations) needed to be considered explicitly as a way to aid decision-makers in selecting a pavement marking material for a given set of conditions.

The analysis of the reapplication cost required consideration of road user costs associated with a restriping effort (user costs did not have to be considered for the first application as it was assumed that they would be identical for all materials). Each reapplication cost was calculated by adding a volume-dependent RUC to the initial cost for each marking material. In this manner, the analysis will tend to favor the option that requires fewer reapplications and thus lowering the total cost, particularly in a high-volume traffic condition. The RUC costs used in the analysis are provided in Table 38.

Table 38. Road User Costs Associated with Reapplication ($/Lane).

Lane ADT	RUC ($/Lane)
3000	0
6000	21
12000	75
18000	1031
24000	3103

SIMULATION PROCEDURE

The basic simulation approach utilized in this effort can be summarized as follows:

- Specify a case as a combination of marking material, pavement surface, AADT per lane, phase completion characteristics, and MR requirement.
- Generate unit cost as a random variate $C \sim N\left(\mu_C, \sigma_C^2\right)$. The values of $\left(\mu_C, \sigma_C^2\right)$ depend on the choice of marking materials.
- Generate service life as a random variate $S \sim N\left(\mu_S, \sigma_S^2\right)$. The values of μ_S and σ_S^2 depend on marking materials, surface types, AADT levels, and MR requirement. To avoid negative and unrealistic *S*, its minimum simulated value was set at 20 percent of expected service life, i.e. $S = \max\left(S, 0.2\mu_S\right)$.
- Generate percent difference between actual and contract phase length as a random variate $\Delta \sim N\left(\mu_\Delta, \sigma_\Delta^2\right)$. The values of $\left(\mu_\Delta, \sigma_\Delta^2\right)$ are assumed to follow historical data on project phase completion in Texas, i.e. mostly early or on time.
- Calculate actual phase length P_a as a function of random variate Δ.
- Calculate the number of reapplication *N* as a function of *S* and P_a.
- Calculate the total cost of marking material, which also depends on *C, S*, P_a, and *RUC* for each reapplication needed.

Since the output of the simulation depends on three random variables (cost, phase duration, and service life), the total cost estimate for the particular scenario being analyzed is itself a random variable. By repeating the simulation numerous times for a particular scenario, different total cost values will be generated until its distribution is also estimated. The simulation routine was coded in an S language, which is executable on S-Plus® statistical software platform. S language is an efficient matrix-oriented computational tool similar to MATLAB®. A total of 100,000 simulation runs for each configuration was executed to generate a resulting cost dataset that was considered robust enough upon which to base pavement marking material recommendations.

RESULTS

For each scenario, the following outputs were computed from the simulation:

- distribution of total cost ($ per mile) of each pavement marking material for a given pavement surface, AADT value, and project phase duration (the mean, standard deviation, and 15th/50th/85th/90th/95th percentile values of the total cost estimates for that particular configuration were captured and reported); and
- number of marking reapplications that would be required.

Detailed simulation results are summarized in Appendix B. An example of these simulation outputs is presented in Table 39. A graphical representation of the total cost curves as a function of AADT value is shown in Figure 55. The most cost-effective marking material on asphalt surface for a specified phase length and volume condition can be determined by selecting the alternative that gives the lowest total cost for a particular volume condition. As suggested in the figure, the lowest-cost selection changes both as the length of the project phase duration and the AADT level changes, consistent with expectations.

The results of simulation analysis showed that the distribution of estimated total costs for each marking material is heavily asymmetric, and therefore the use of arithmetic mean and standard deviations to compare between marking materials would not be appropriate. Therefore, percentile values (ordered statistics) were used to compare the total cost results of the marking materials for each scenario. The 15th, 50th (median), and 85th percentile total cost values for each marking material were selected for comparison. These three values were deemed to represent "better than expected," "expected," and "worse than expected" scenarios. For instance, the "worse than expected" would imply the case where the unit cost is higher than usual, project phase length is longer than usual, and/or the marking material degrades considerably faster than average. Stated statistically, 85 percent of the simulation estimates of total costs for that marking material under that scenario were less than this value. Similarly, the "expected" total cost of the marking material was the case where 50 percent of the simulation runs were less than this value and 50 percent were higher.

Table 39. Example of Simulation Inputs and Outputs: Asphalt Surface, Normal Phase Variability, and Project Duration of 180 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
8	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	180	3.94	1.05
28	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	180	3.94	1.05
48	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	180	3.94	1.05
68	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	180	3.94	1.05
88	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	180	3.94	1.05
6	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	180	3.94	1.05
26	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	180	3.94	1.05
46	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	180	3.94	1.05
66	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	180	3.94	1.05
86	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	180	3.94	1.05
7	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	180	3.94	1.05
27	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	180	3.94	1.05
47	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	180	3.94	1.05
67	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	180	3.94	1.05
87	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	180	3.94	1.05
5	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	180	3.94	1.05
25	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	180	3.94	1.05
45	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	180	3.94	1.05
65	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	180	3.94	1.05
85	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	180	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
8	0.0	0	0	2233	364	2234	1857	2425	2539	2610	2700	2830
28	0.0	0	0	2232	364	2232	1855	2423	2539	2609	2698	2830
48	0.0	0	0	2232	364	2232	1856	2423	2538	2609	2697	2827
68	0.0	0	0	2233	366	2233	1856	2422	2539	2610	2699	2830
88	0.0	0	0	2235	389	2232	1854	2423	2538	2610	2702	2834
6	0.0	0	0	1057	204	1057	845	1164	1229	1268	1318	1395
26	0.1	0	0	1143	372	1078	855	1200	1284	1346	1458	2009
46	0.3	0	1	1348	728	1113	869	1269	1441	1959	2445	3129
66	0.5	0	1	2182	1925	1197	902	2745	3288	3606	5283	7082
86	1.0	1	2	5124	5733	4656	960	5393	5932	9344	13275	21113
7	0.0	0	0	3956	512	3958	3427	4226	4388	4486	4610	4800
27	0.0	0	0	3999	647	3968	3433	4241	4406	4510	4640	4846
47	0.2	0	0	4576	1751	4063	3482	4414	4707	5081	7471	8508
67	0.6	1	1	7026	3303	7683	3751	8932	9466	9775	10198	11150
87	1.1	1	1	11720	4671	11108	9601	11857	12461	13250	17474	19377
5	0.0	0	0	1584	204	1585	1372	1692	1757	1796	1845	1919
25	0.0	0	0	1584	205	1583	1371	1691	1756	1796	1847	1921
45	0.1	0	0	1675	438	1598	1381	1715	1792	1844	1923	2691
65	0.1	0	0	1958	1200	1614	1386	1743	1838	1917	3552	4610
85	0.2	0	1	2689	2600	1640	1399	1797	1975	5959	6409	10162

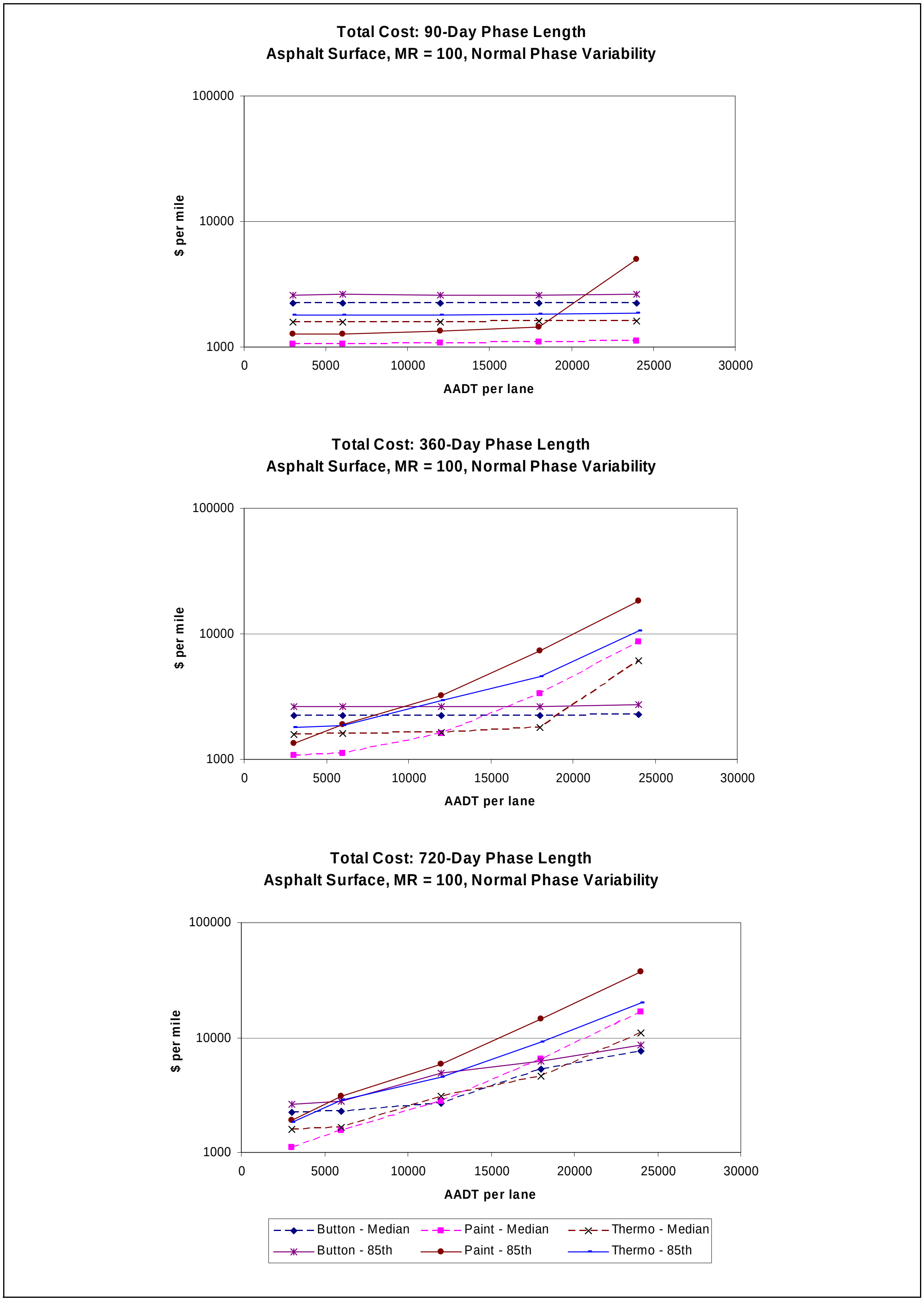


Figure 55. Example of Total Cost Curves on Asphalt Surface.

The lowest total cost marking material for the 15th, 50th, and 85th percentile total cost computations of each scenario analyzed are presented in Table 40. Scenarios in which the total costs for two marking materials were extremely close together (i.e., within 5 percent) are both shown. For example, the median total costs of thermoplastics and traffic buttons on asphalt pavements were found to be approximately equal for project phase durations of 720 days (i.e., almost two years) at AADT levels of 10,000 vehicles per day (vpd) to 19,000 vpd and so are shown in Table 40(a) as "T/B." Those scenarios where both paint and buttons are estimated to be lowest costs ("P/B") most likely reflect multiple reapplications of both materials, such that the difference in costs between the materials themselves becomes negligible.

Comparing across the 15th, median (50th), and 85th percentile recommendations in Table 40, one sees that there are many scenarios in which the choice of marking material is identical and therefore a straightforward decision. For these scenarios, the distribution of expected costs for one material is less than the others over the entire range of probabilities. This is depicted graphically in Figure 56(a) as a comparison of the cumulative probability curves of paint and thermoplastic (the values shown are for illustrative purposes only and do not correspond to any particular scenario in Table 40. In contrast, there are a few scenarios in which the lowest total cost material changes depending on the probability level being considered. These situations can be explained as conditions where there is some chance, but not necessarily a certainty, that one or more reapplications of a particular material will be required before the project phase is terminated. This reapplication may be required because the phase duration exceeded its estimate by some amount, the service life of the marking material ended up being less than expected for that particular AADT level, the cost of the materials (or the difference between them) ended up being more or less than typical, or some combination of all three of these scenarios. Graphically, this situation is depicted in Figure 56(b). Note that while paint most often is the lowest cost material, there is a small possibility in this hypothetical scenario that a reapplication of paint would be needed and thus thermoplastic would actually provide the lowest total cost. The probability of this occurring would be equal to 1-0.75 = 0.25, or the amount to the right of where the curves cross in Figure 56(b).

Table 40. Most Cost-Effective Marking Material under Normal Phase Variability.

(a) Asphalt Surface

15th Percentile Cost

Lane ADT	Phase Length (days)				
	90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	P	T/B
11000	P	P	P	P	T/B
12000	P	P	P	P	T/B
13000	P	P	P	T	T/B
14000	P	P	P	T	T/B
15000	P	P	P	T	T/B
16000	P	P	P	T	T/B
17000	P	P	T	T	T/B
18000	P	P	T	T	T/B
19000	P	P	T	B	T/B
20000	P	P	T	B	T/B
21000	P	P	T	B	T/B
22000	P	P	T	B	T/B
23000	P	P	T	B	T/B
24000	P	P	T	B	T/B

Median Cost

Lane ADT	Phase Length (days)				
	90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	T	T/B
11000	P	P	P	T	T/B
12000	P	P	T	T	T/B
13000	P	P	T	T	T/B
14000	P	P	T	B	T/B
15000	P	P	T	B	T/B
16000	P	P	T	B	T/B
17000	P	P	T	B	T/B
18000	P	P	T	B	T/B
19000	P	T	B	B	T/B
20000	P	T	B	B	B
21000	P	T	B	B	B
22000	P	T	B	B	B
23000	P	T	B	B	B
24000	P	T	B	B	B

85th Percentile Cost

Lane ADT	Phase Length (days)				
	90	180	360	540	720
3000	P	P	P	P	T
4000	P	P	P	P	T
5000	P	P	P	T	T
6000	P	P	T	T	T/B
7000	P	P	T	T	T/B
8000	P	P	T	T	T/B
9000	P	P	T	B	T/B
10000	P	P	T	B	T/B
11000	P	T	B	B	T/B
12000	P	T	B	B	T/B
13000	P	T	B	B	B
14000	P	T	B	B	B
15000	P	T	B	B	B
16000	P	T	B	B	B
17000	P	T	B	B	B
18000	P	T	B	B	B
19000	T	T	B	B	B
20000	T	B	B	B	B
21000	T	B	B	B	B
22000	T	B	B	B	B
23000	T	B	B	B	B
24000	T	B	B	B	B

(b) Concrete Surface

15th Percentile Cost

Lane ADT	Phase Length (days)				
	90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	P	P
11000	P	P	P	P	P/B
12000	P	P	P	P	P/B
13000	P	P	P	P	P/B
14000	P	P	P	P	P/B
15000	P	P	P	B	P/B
16000	P	P	P	B	P/B
17000	P	P	P	B	P/B
18000	P	P	P	B	P/B
19000	P	P	T	B	P/B
20000	P	P	T	B	P/B
21000	P	P	T	B	P/B
22000	P	P	T	B	P/B
23000	P	P	T	B	P/B
24000	P	P	T	B	P/B

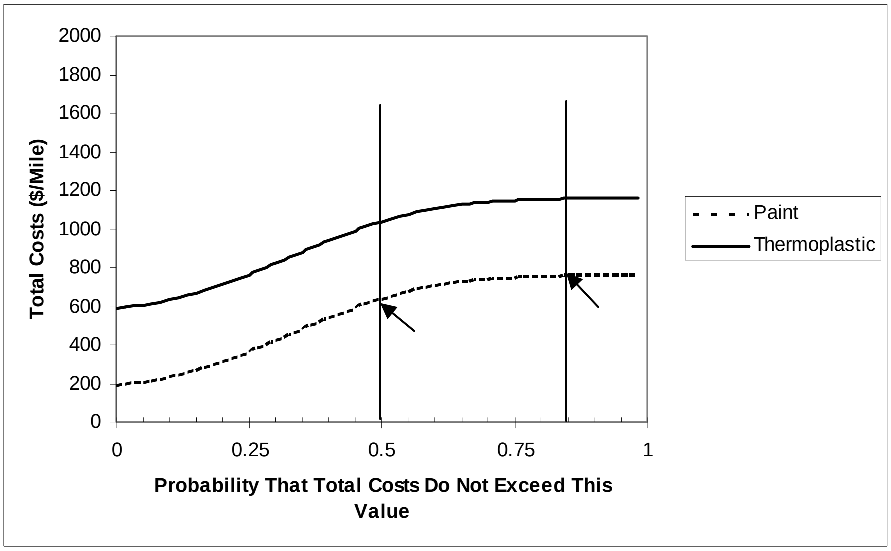
Median Cost

Lane ADT	Phase Length (days)				
	90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P	P
7000	P	P	P	P	P
8000	P	P	P	P	P
9000	P	P	P	P	P
10000	P	P	P	P	P
11000	P	P	P	P	P/B
12000	P	P	P	P	P/B
13000	P	P	P	B	P/B
14000	P	P	P	B	P/B
15000	P	P	P	B	P/B
16000	P	P	B	B	P/B
17000	P	P	B	B	P/B
18000	P	P	B	B	P/B
19000	P	P	B	B	B
20000	P	P	B	B	B
21000	P	P	B	B	B
22000	P	P	B	B	B
23000	P	P	B	B	B
24000	P	P	B	B	B

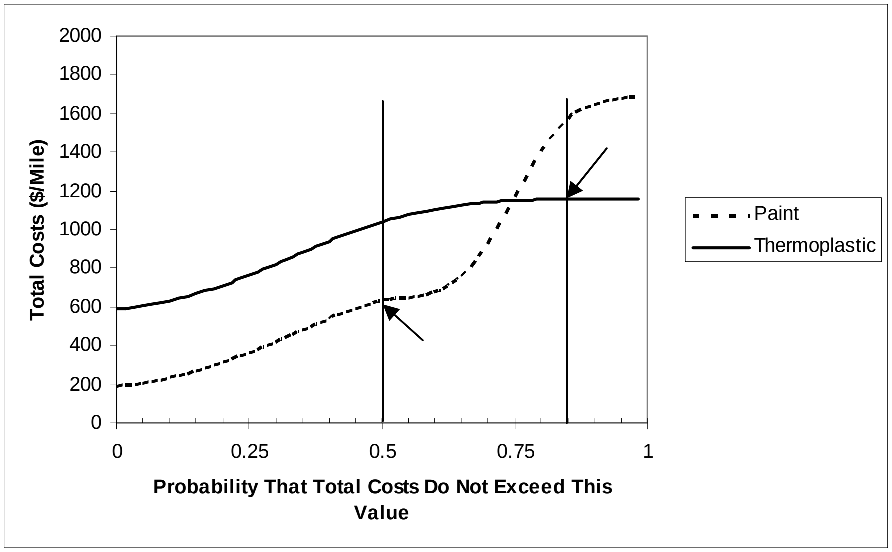
85th Percentile Cost

Lane ADT	Phase Length (days)				
	90	180	360	540	720
3000	P	P	P	P	P
4000	P	P	P	P	P
5000	P	P	P	P	P
6000	P	P	P	P/B	P/B
7000	P	P	P	P/B	P/B
8000	P	P	P	P/B	P/B
9000	P	P	P	P/B	P/B
10000	P	P	P	P/B	P/B
11000	P	P	P	P/B	P/B
12000	P	P	P	P/B	P/B
13000	P	P	B	P/B	P/B
14000	P	P	B	P/B	B
15000	P	T	B	P/B	B
16000	P	T	B	P/B	B
17000	P	T	B	P/B	B
18000	P	T	B	P/B	B
19000	P	T	B	B	B
20000	P	B	B	B	B
21000	P	B	B	B	B
22000	P	B	B	B	B
23000	P	B	B	B	B
24000	P	B	B	B	B

Notes: P = Paint, T = Thermoplastic, and B = Button



(a) Lowest Cost Material Constant across Probability Range

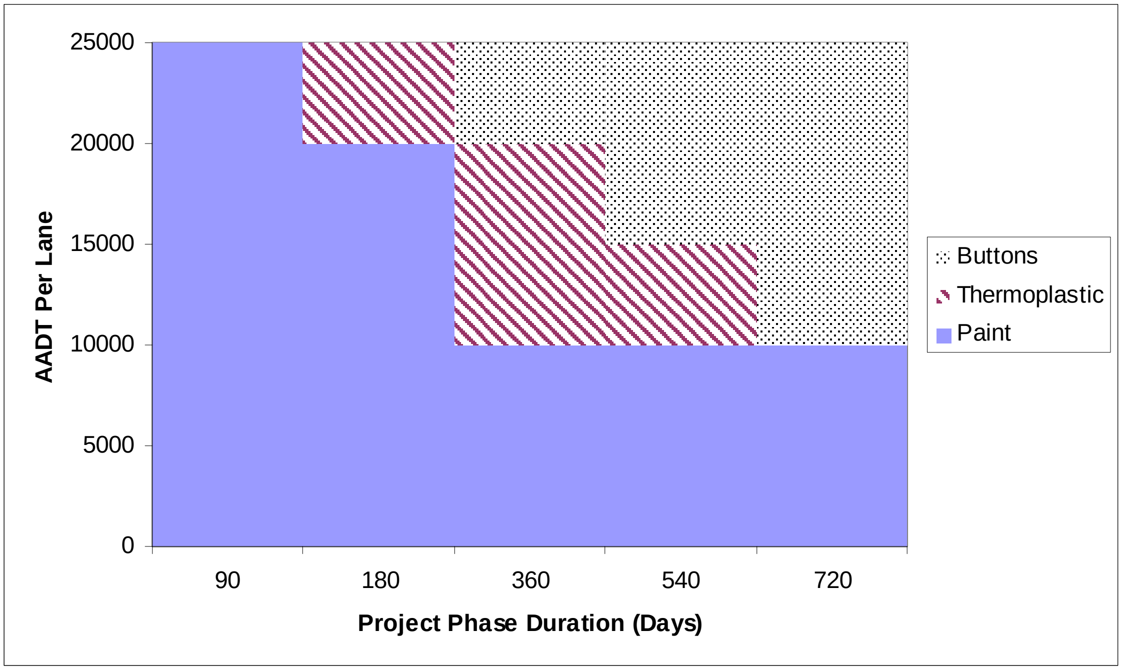


(b) Lowest Cost Material Changes across Probability Range

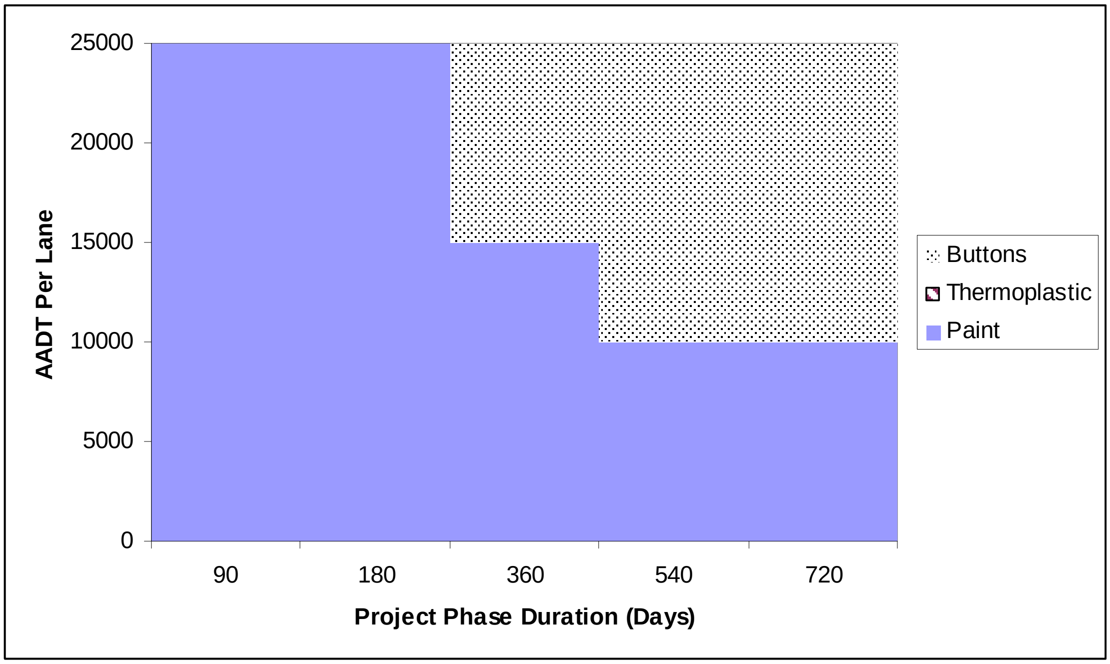
Figure 56. Lowest Cost Material Comparison.

RECOMMENDATIONS

Based on the results shown in Table 40, Figure 57 provides the research team's recommendations for pavement marking materials for a given roadway surface, estimated project duration, and estimated AADT range. Where two markings were estimated from the simulation analysis to have comparable lowest total costs, a conservative approach was taken and so the more durable marking is shown as recommended.



(a) Asphalt Pavement

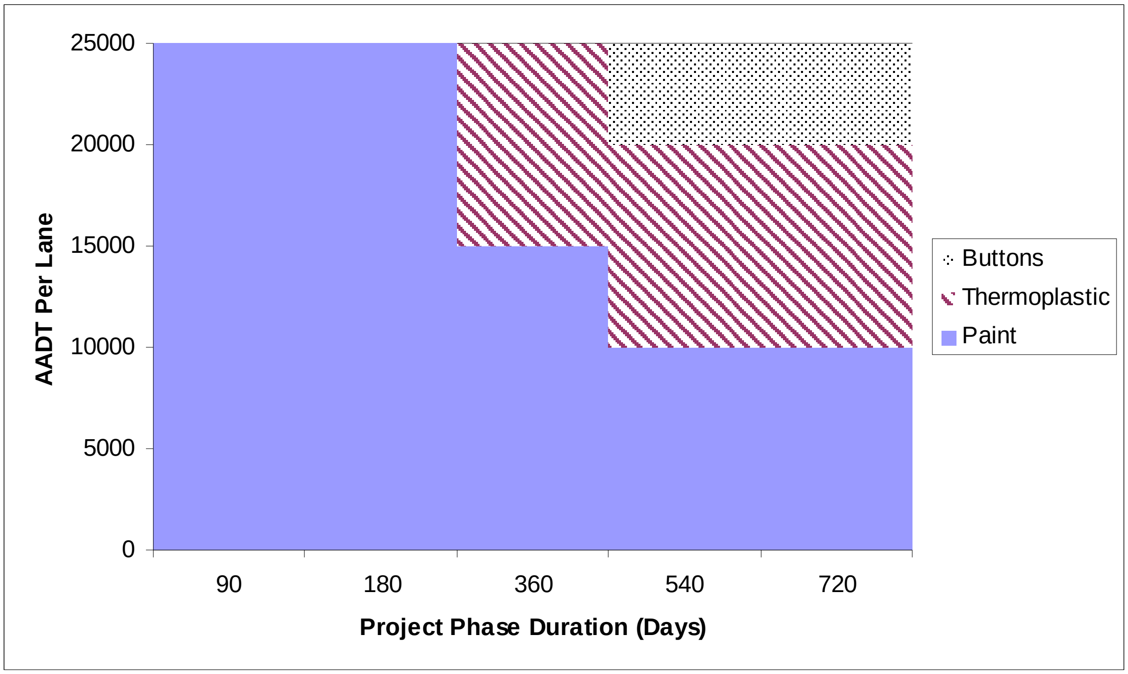


(b) Concrete Pavement

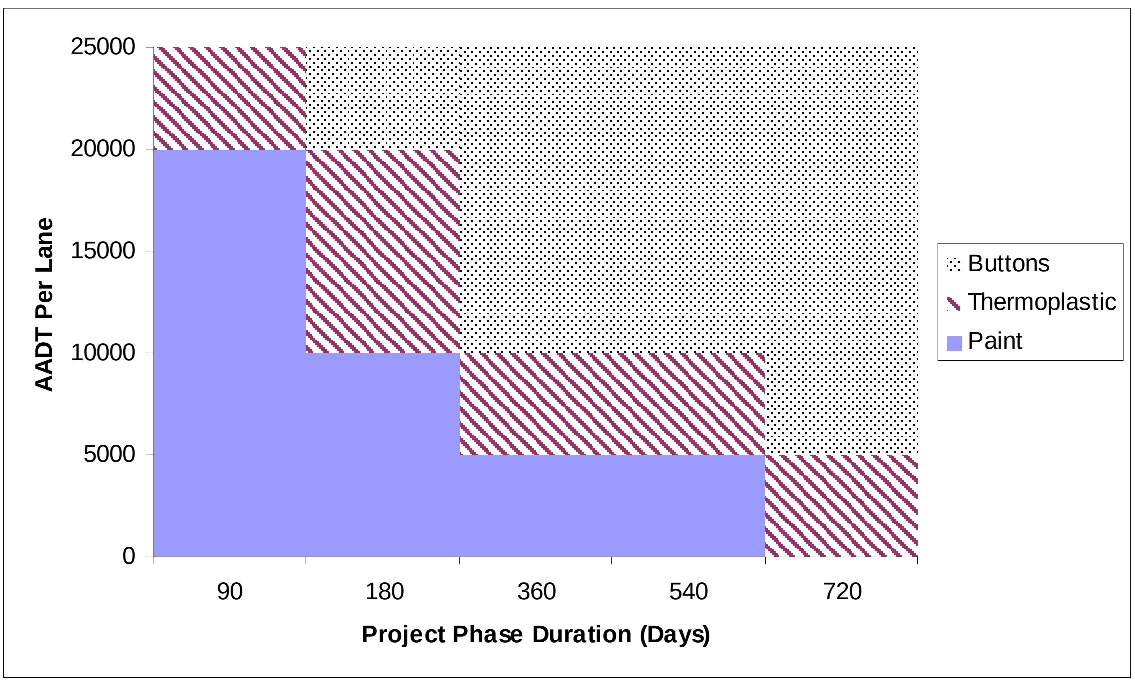
Figure 57. Pavement Marking Material Recommendations for Expected (Median Value) Conditions.

Overall, the recommended pavement marking materials tend to agree across asphalt and concrete pavement surfaces. Buttons do tend to be recommended at slightly shorter phase durations and AADT levels on concrete surfaces than on asphalt surfaces, but only slightly so. Furthermore, based on the analyses performed, researchers recommend the use of thermoplastics as the lowest cost alternative in only a few isolated conditions on asphalt pavements. For concrete surfaces, thermoplastics do not tend to wear particularly well and so do not end up as the lowest cost material in essentially any condition on concrete surfaces.

The recommendations above represent the researchers' best effort at an objective, defensible analysis framework for work zone pavement marking selection based on the best available data on the topic. Given the dearth of guidance available on this topic, these recommendations represent a significant improvement in decision-making support. Even so, it is recognized that many additional factors that could not be considered in this analysis ultimately impact pavement marking performance. Consequently, the recommendations provided must be interpreted and used in conjunction with engineering judgment and past experiences in the field with work zone pavement marking performance. To aid in that interpretation, Figure 58 and Figure 59 are provided of the 15th and 85th percentile lowest total cost comparisons. The 15th percentile recommendations imply that "better than expected" performance or conditions are expected (i.e., traffic volumes are lower than assumed, project phase duration is likely to be less than estimated, or pavement marking durability seems to last longer than typical), whereas the 85th percentile recommendations are indicative of "poorer than expected" performance or conditions. For the short duration projects and low ADT roadways, paint continues to be the recommended material under all levels of risk. As project durations and ADT levels increase, the recommended marking materials do change. At very long projects and high ADTs, the pavement marking material of choice (i.e., traffic buttons) is generally recommended regardless of the risk level considered.

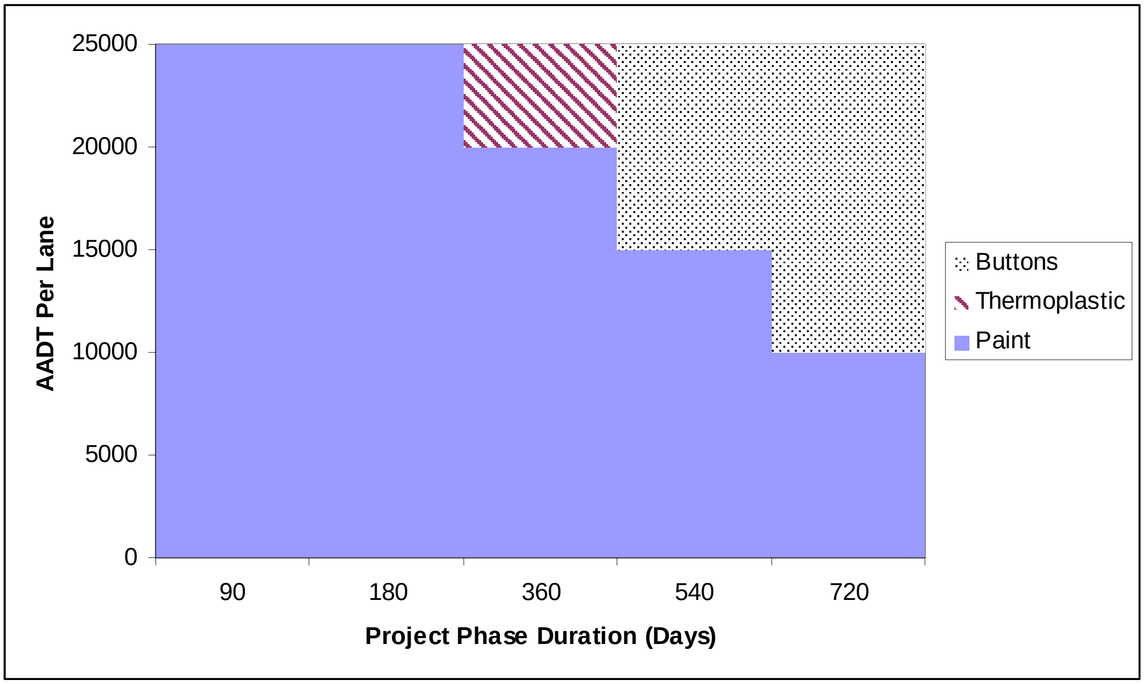


(a) Recommendations for “Better than Expected” Conditions

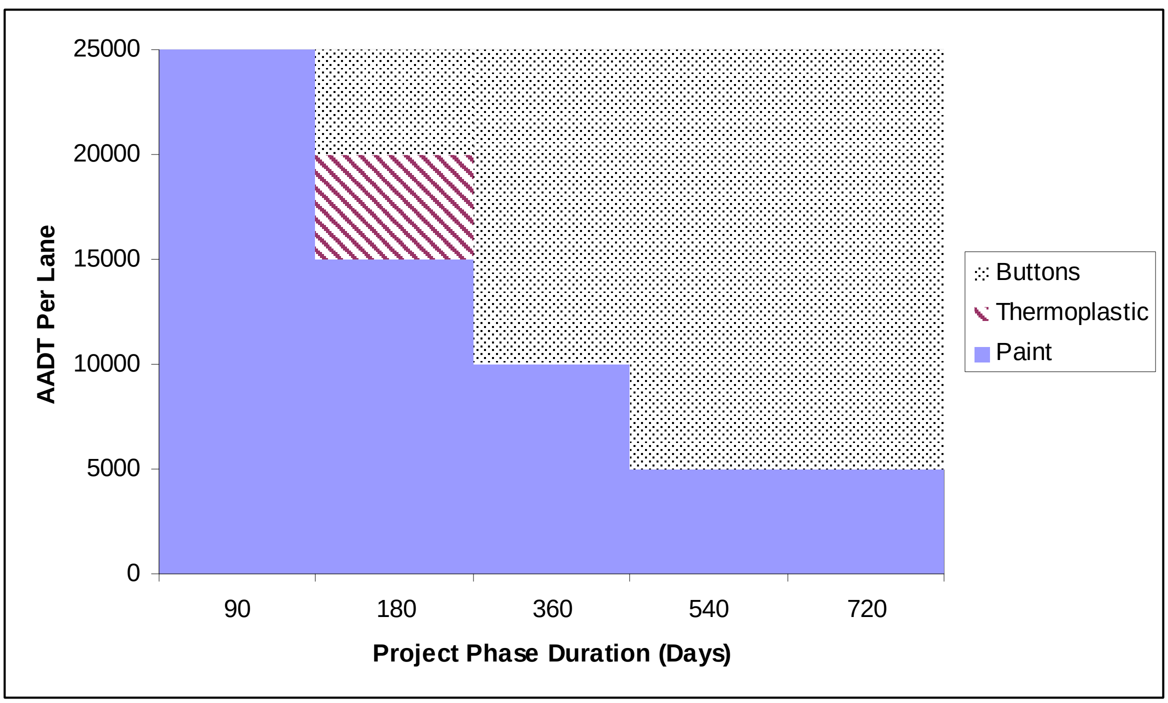


(b) Recommendations for “Worse than Expected” Conditions

Figure 58. 15th (Better Than Expected) and 85th Percentile (Worse Than Expected) Lowest Total Cost Recommendations: Asphalt Pavement.



(a) Recommendations for "Better than Expected" Conditions



(b) Recommendations for "Worse than Expected" Conditions

Figure 59. 15th (Better Than Expected) and 85th Percentile (Worse Than Expected) Lowest Total Cost Recommendations: Concrete Pavement.

CHAPTER 11. CONCLUSIONS

TEMPORARY TRAFFIC CONTROL AT AND NEAR URBAN FREEWAY INTERCHANGES

In this project, researchers have identified a number of issues and challenges surrounding the provision of temporary traffic control in and around urban freeway interchanges. Several laboratory studies were conducted to identify improvements to use to improve upon these issues and challenges. Based on the results of those studies, the following conclusions can be drawn:

- Efforts to continue to use existing guide signs by removing or covering lane assignment arrows that no longer correspond to lane positions (due to lane shifts or other temporary changes in alignment) do significantly degrade the abilities of drivers to quickly determine the appropriate lane for them to be in as they approach a freeway interchange.
- The provision of temporary diagrammatic guide signs and/or the use of pavement marking symbols designating the lanes assigned to the various routes approaching the interchange significantly improve driver lane choice abilities in such situations.
- If pavement marking symbols are to be used for this purpose, the use of route shields (or, presumably, text descriptors of the route and direction) provides better driver comprehension and lane choice decisions than simply using pavement arrows to indicate through and exiting lanes.
- The provision of pavement symbols in all lanes approaching the interchange does not significantly improve driver comprehension and lane choice decisions over simply providing the symbols in the exiting lanes only. However, if heavy traffic volumes are likely to obscure the pavement symbols for a large portion of the traffic stream, providing symbols in all lanes may be necessary to insure that all drivers receive at least some indication as to whether or not they are in their desired lane. It may also be necessary to provide more than one set of pavement symbols in advance of the interchange, although this was not evaluated explicitly in this research.
- Lane closures on through lanes immediately downstream of exit lane drops are difficult to effectively convey to drivers with current advance warning signs without

closing both the through and the exiting lanes upstream of the interchange. Such upstream closures will often create significant queues, leading to rear-end and other types of crashes. If a significant amount of approaching traffic is destined for the exit, waiting to close the through lane(s) until after the exit can sometimes reduce or eliminate such queuing. Studies done for this research suggest that the use of PCMS with the message "RIGHT/THRU LN/CLOSED" or similar text message improves driver understanding of this situation over the use of standard MUTCD lane closure signing. A graphical PCMS message based on principles of the Texas LANE BLOCKED sign may provide even better driver comprehension, but the legibility of full-matrix PCMS to portray this graphic has not been evaluated. Even with the use of PCMS, however, driver comprehension of this situation is less than typically desired for efficient traffic operations.

- On multi-lane facilities where lane shifts are required, the use of reverse curve signs that have multiple arrows (the number of arrows corresponding to the number of travel lanes) may slightly improve driver comprehension of the required driving maneuver (i.e., to stay in a lane and follow the curve) than the standard reverse curve sign with a single thick arrow. In addition, the multiple-arrow sign format is strongly preferred by drivers over the single-arrow format.

Based on these findings, guidelines on improving temporary traffic control at and near urban freeway interchanges have been prepared and are provided as Appendix C.

SELECTION OF PAVEMENT MARKING MATERIALS FOR WORK ZONES

As part of this project, researchers also investigated and developed an objective methodology for selecting the most-appropriate pavement marking material for work zone situations based on the duration of the project or project phase for which the marking is needed, type of pavement surface the marking will be placed on, and durability of the various marking materials available for use in work zone situations. The following is a listing of key findings from this part of the project:

- An analysis of time-related data from a sample of 614 monthly estimate reports indicates that the overall average percent difference between estimated and actual project progress was 3.9 percent. In other words, on average, the projects in the database were estimated to have 3.9 percent more work completed than time used on their contracts. The variability in the percent difference data, however, was relatively large. It ranged from -90 percent to almost 150 percent. Several projects were either well behind or ahead of schedule, but on average most projects were progressing in an expected manner. Statistically, this variability corresponded to standard deviation of 25.9 percent. No clear trends in these statistics were detected as a function of project duration or work type.
- Analyses of NTPEP and other data sources regarding pavement marking material performance allowed researchers to develop a series of service life performance relationships as a function of pavement surface type, lane ADT, and type of marking material. Researchers were also able to establish relationships to describe the variability of pavement marking service life as a function of these same variables.
- Researchers estimated total costs of using the various pavement marking materials considered under various pavement surface, project phase duration, and ADT levels through a Monte Carlo simulation model. Variability in project phase durations, pavement marking service life, and marking costs were considered explicitly in the analysis. Results from the analysis allowed researchers to recommend the lowest cost pavement marking material for each pavement surface/project phase duration/AADT level condition considered.
- The Monte Carlo simulation approach also allowed researchers to assess the impact of the variability of the various factors considered upon the recommended pavement marking materials. Researchers used this information to generate additional recommendations for decision-makers to consider if they prefer to take a more liberal (i.e., “better than expected” marking performance and/or project phase duration) or a more conservative (i.e., “worse than expected” marking performance and/or project phase duration) approach on pavement marking selection.
- It should be noted that temporary tapes are not recommended for any situation. This is due to the high costs and marginal performance. Temporary tapes may need to be

used in applications on final surfaces where buttons and RRPMs cannot be used and the alignment is only temporary. This is likely the only situation in which temporary tape may be the most feasible option.

A set of guidelines providing these pavement marking selection recommendations and other factors to consider are provided as Appendix D.

CHAPTER 12. REFERENCES

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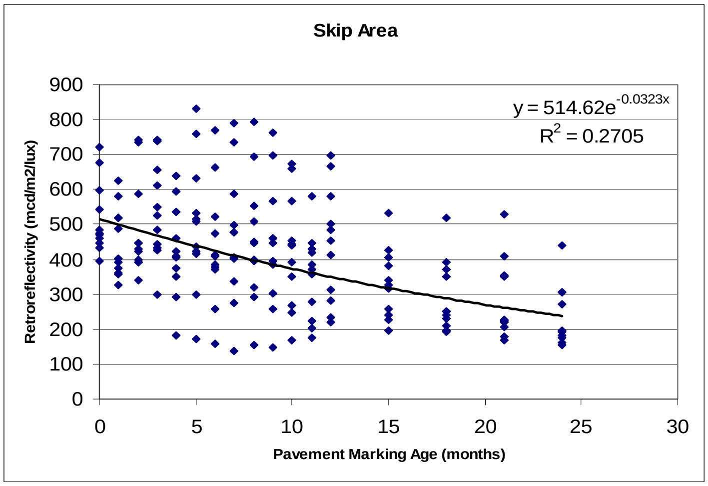
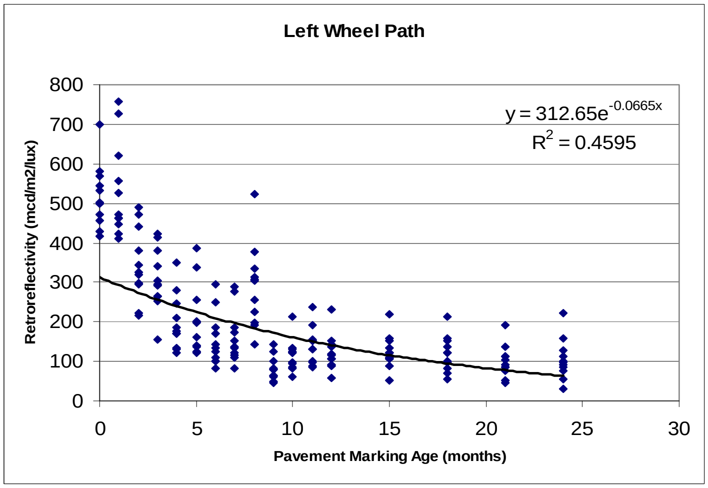
APPENDIX A. REGRESSION PLOTS FOR THE THERMOPLASTIC, PAINT, AND TEMPORARY TAPE MARKINGS





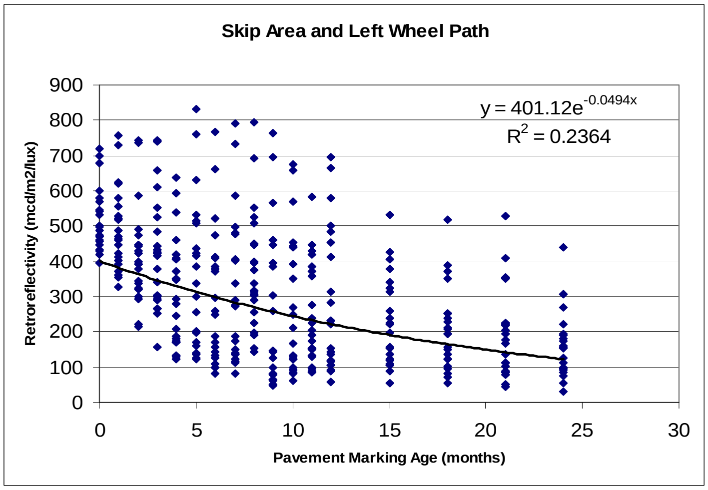


Figure A1. Thermoplastic on Asphalt (NTPEP).

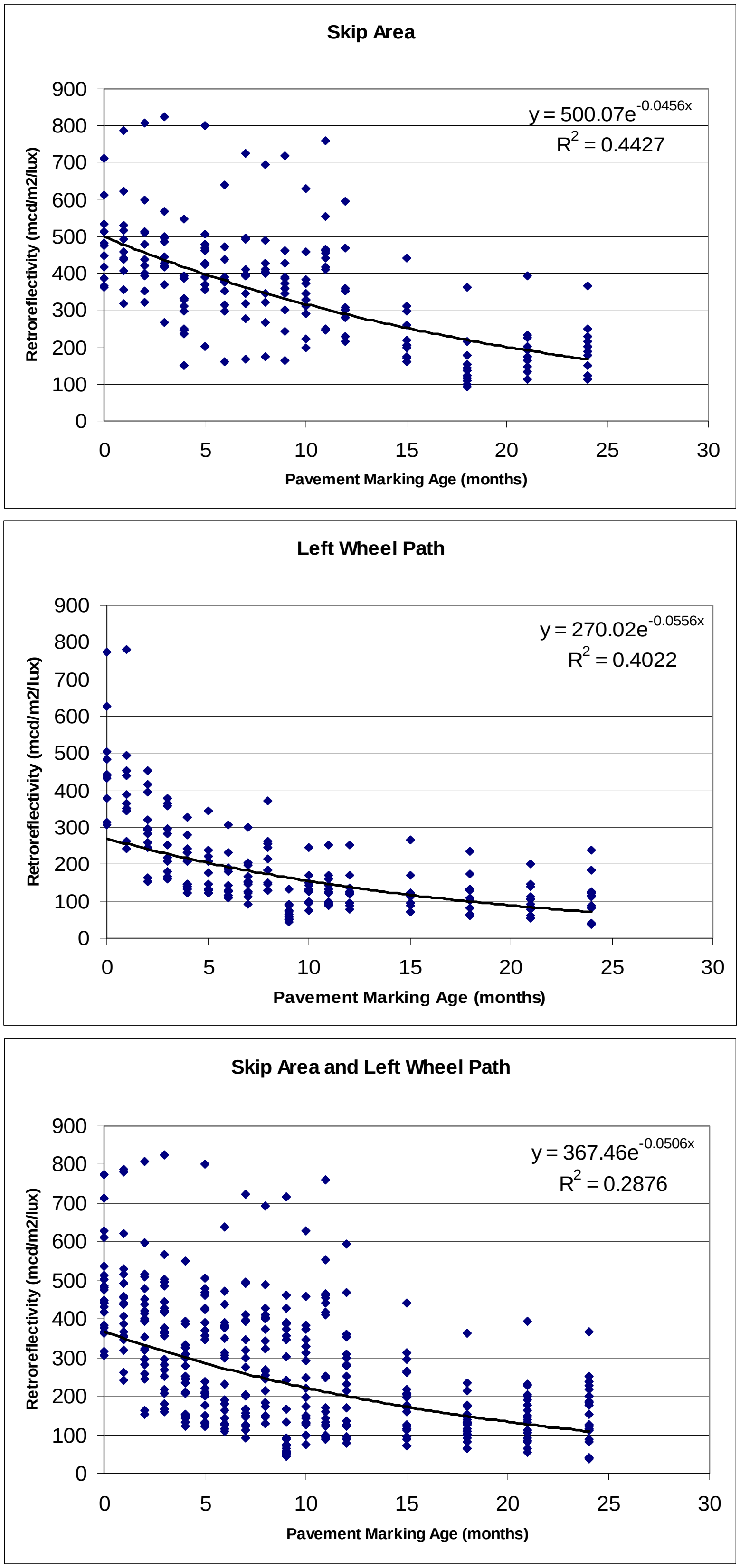


Figure A2. Thermoplastic on Concrete (NTPEP).

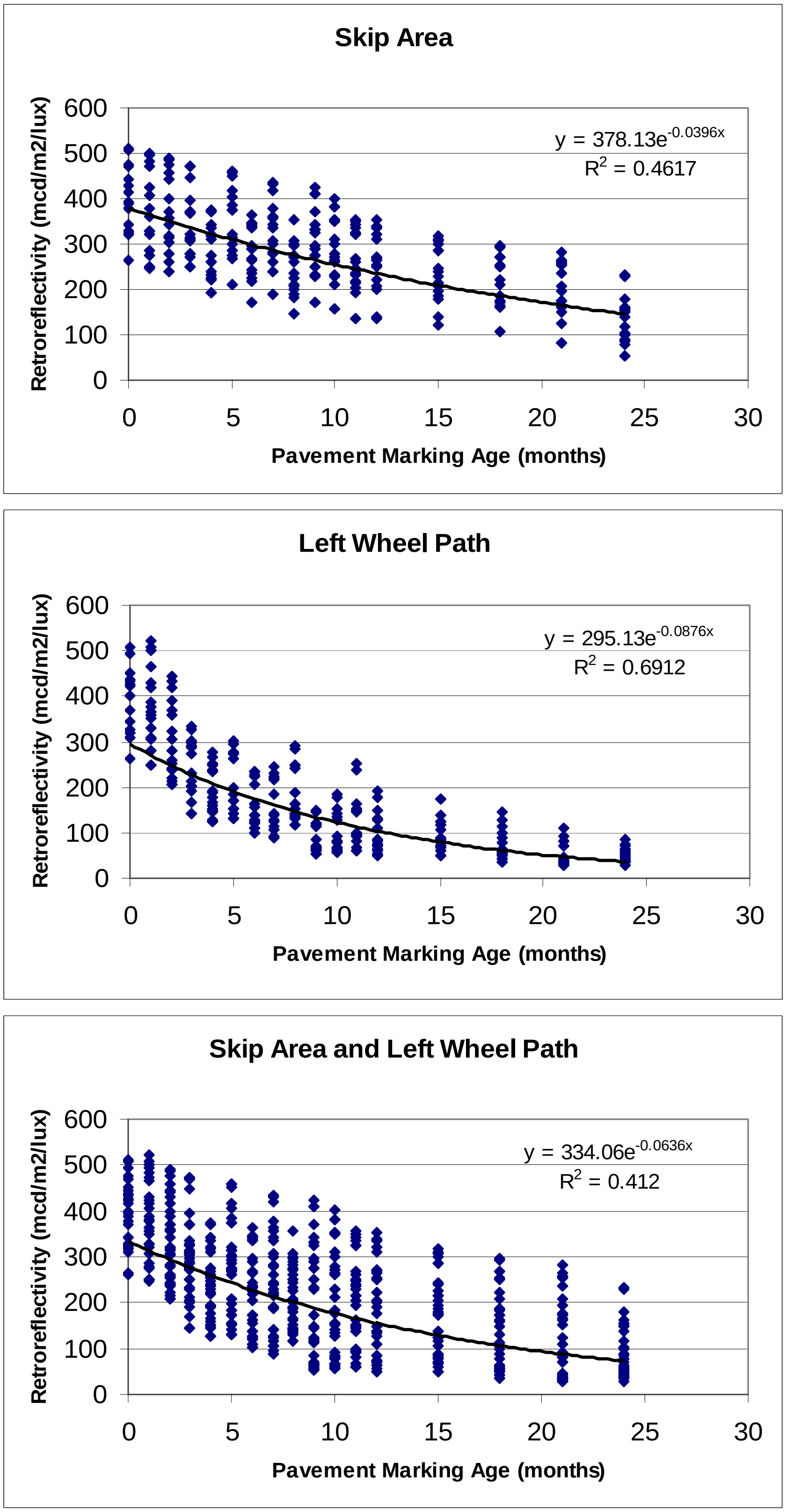


Figure A3. Paint on Asphalt (NTPEP).

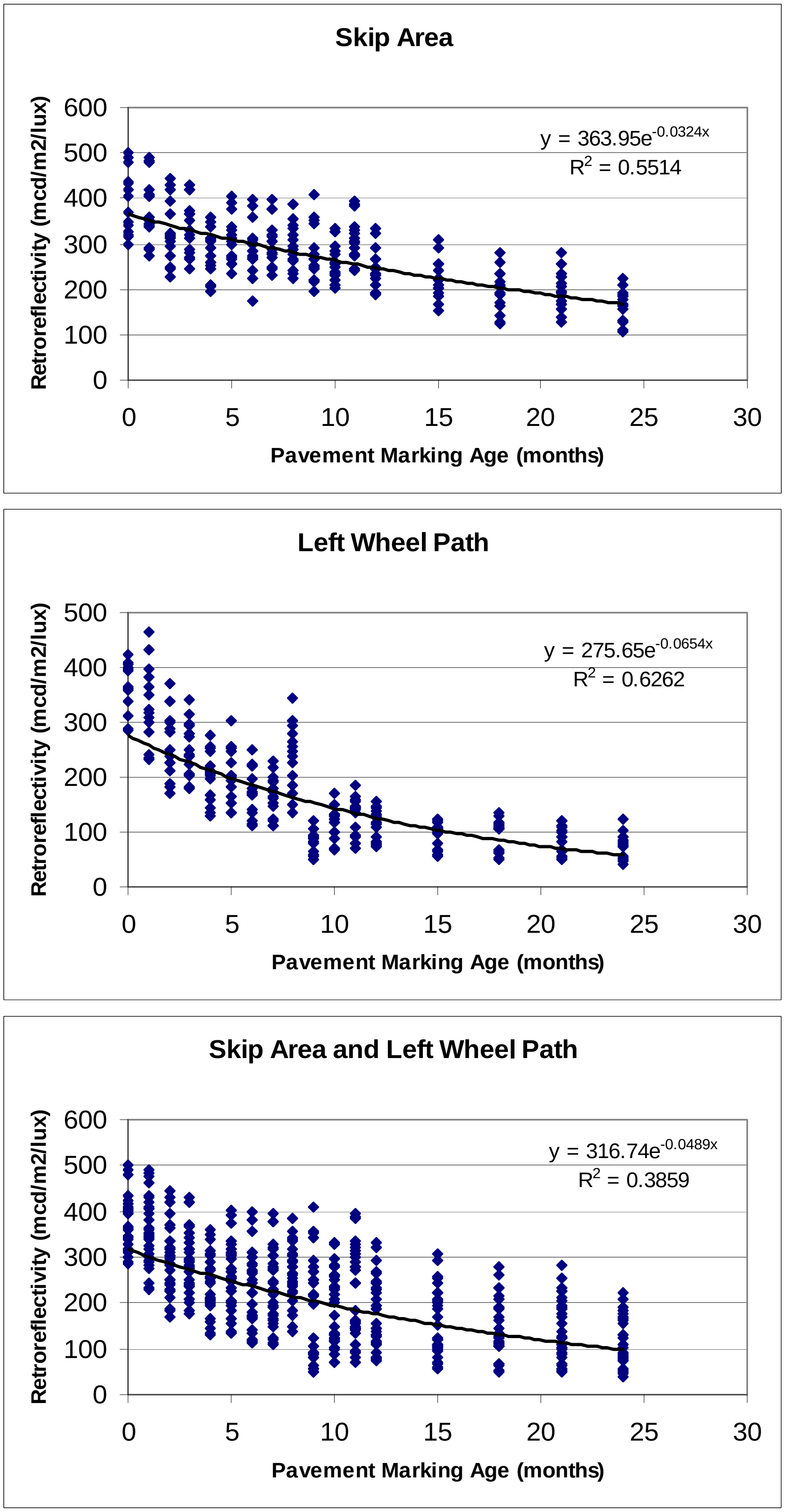


Figure A4. Paint on Concrete (NTPEP).

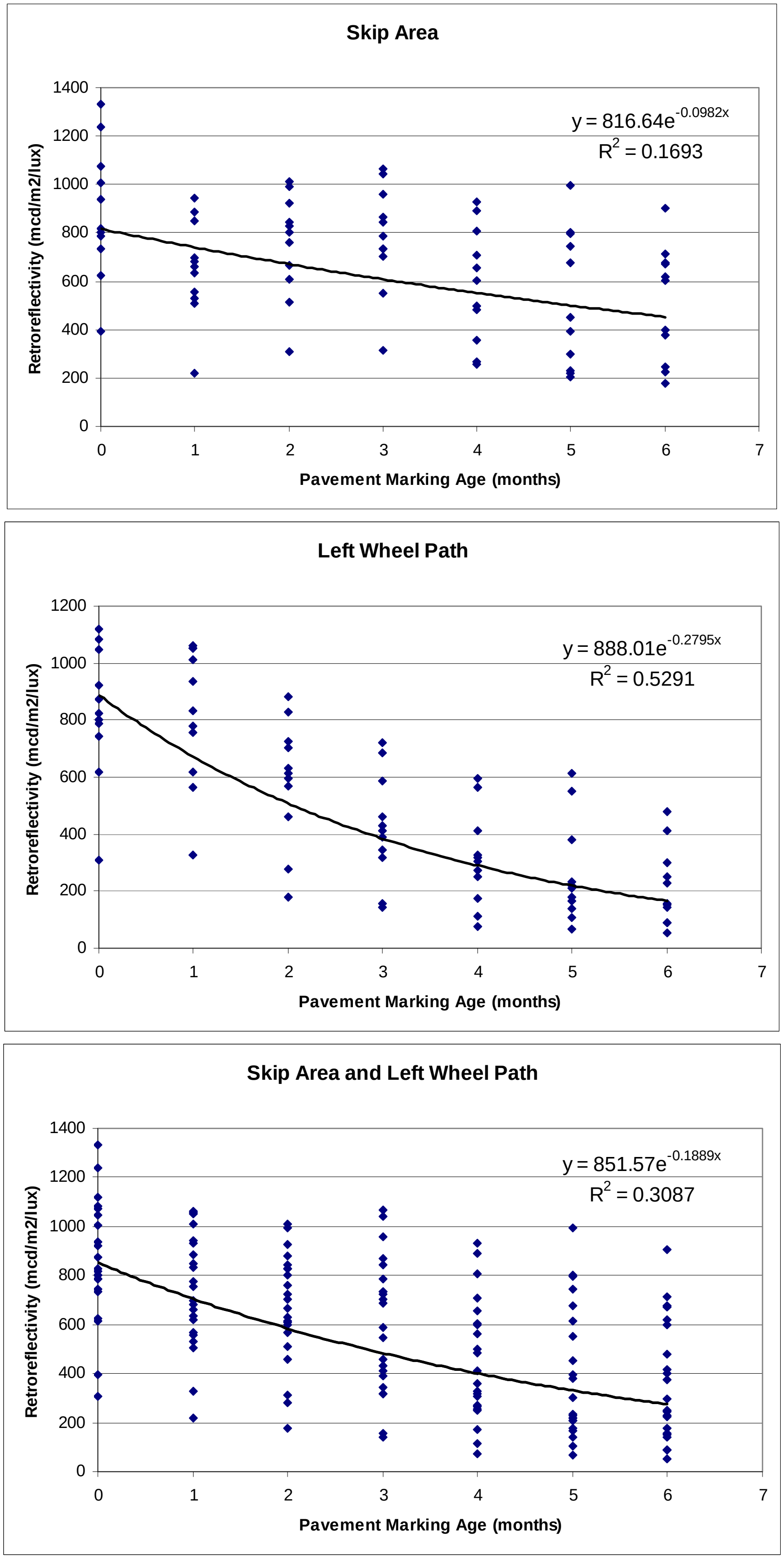
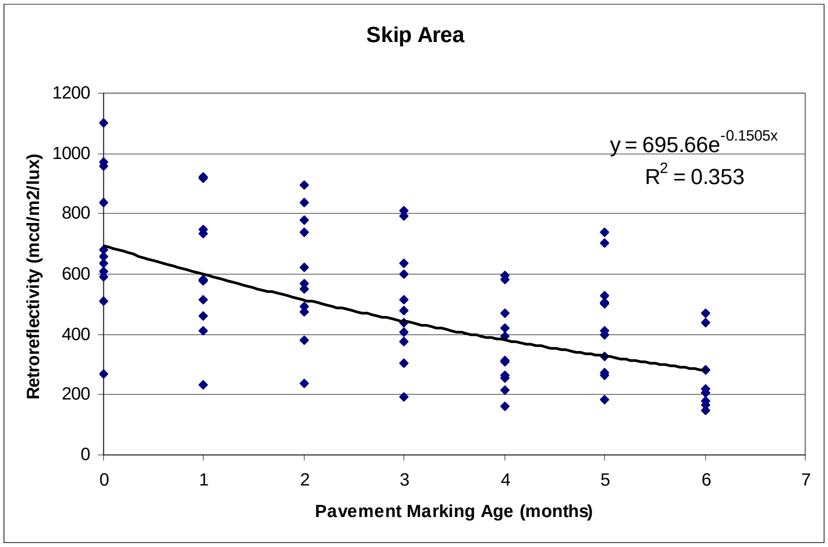
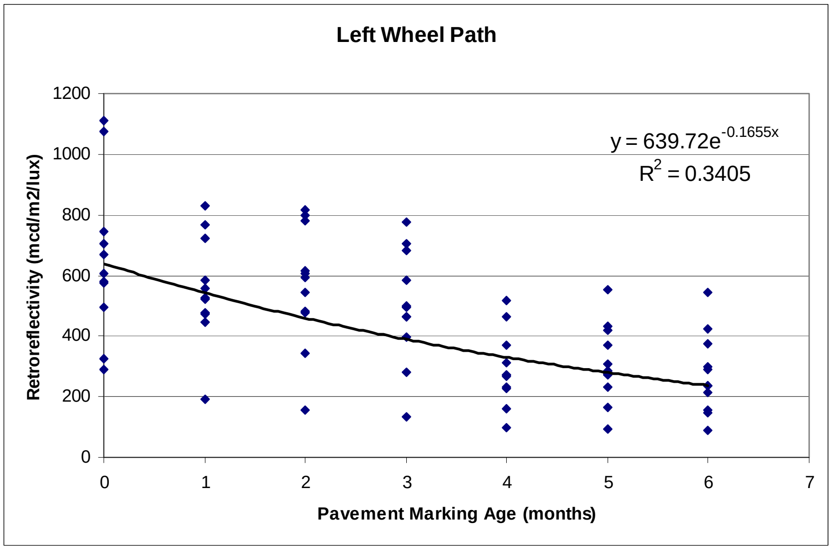


Figure A5. Temporary Tape on Asphalt (NTPEP).





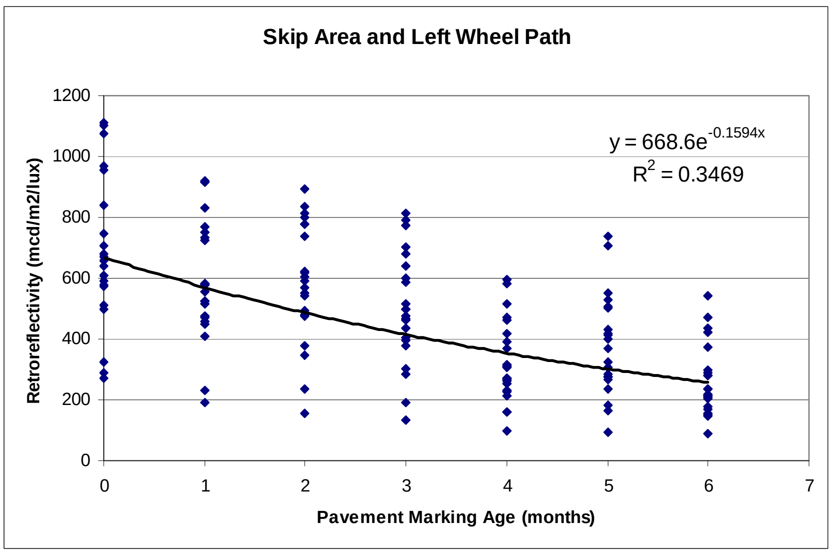


Figure A6. Temporary Tape on Concrete (NTPEP).

APPENDIX B. RESULTS OF THE MONTE CARLO SIMULATION ANALYSES

Table B1. Simulation – Asphalt Surface, Normal Phase Variability, 90 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
4	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	90	3.94	1.05
24	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	90	3.94	1.05
44	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	90	3.94	1.05
64	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	90	3.94	1.05
84	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	90	3.94	1.05
2	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	90	3.94	1.05
22	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	90	3.94	1.05
42	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	90	3.94	1.05
62	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	90	3.94	1.05
82	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	90	3.94	1.05
3	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	90	3.94	1.05
23	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	90	3.94	1.05
43	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	90	3.94	1.05
63	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	90	3.94	1.05
83	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	90	3.94	1.05
1	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	90	3.94	1.05
21	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	90	3.94	1.05
41	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	90	3.94	1.05
61	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	90	3.94	1.05
81	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	90	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
4	0.0	0	0	2233	363	2234	1856	2426	2540	2609	2696	2825
24	0.0	0	0	2234	364	2235	1856	2425	2541	2611	2700	2831
44	0.0	0	0	2231	363	2231	1854	2420	2536	2607	2697	2830
64	0.0	0	0	2233	364	2234	1856	2423	2539	2609	2697	2831
84	0.0	0	0	2234	363	2235	1857	2424	2540	2611	2700	2830
2	0.0	0	0	1056	205	1056	844	1164	1230	1269	1318	1392
22	0.0	0	0	1056	205	1056	844	1164	1230	1270	1321	1394
42	0.1	0	0	1148	383	1079	857	1203	1287	1349	1460	2060
62	0.1	0	0	1317	735	1092	861	1229	1337	1449	2804	3257
82	0.3	0	1	2142	2495	1113	871	1272	1460	4996	5574	9193
3	0.0	0	0	3958	512	3959	3426	4227	4387	4487	4612	4801
23	0.0	0	0	3959	511	3958	3430	4229	4393	4490	4613	4796
43	0.0	0	0	3999	665	3966	3430	4235	4402	4506	4640	4853
63	0.0	0	0	4196	1277	3988	3447	4273	4460	4579	4757	5218
83	0.1	0	0	5017	2890	4063	3481	4410	4701	5064	10450	11510
1	0.0	0	0	1584	205	1584	1372	1690	1756	1796	1846	1921
21	0.0	0	0	1583	204	1583	1372	1690	1755	1794	1844	1918
41	0.0	0	0	1584	205	1583	1371	1691	1756	1796	1846	1920
61	0.0	0	0	1683	542	1594	1379	1708	1779	1827	1893	2039
81	0.1	0	0	1848	1103	1599	1379	1716	1794	1847	1930	5767

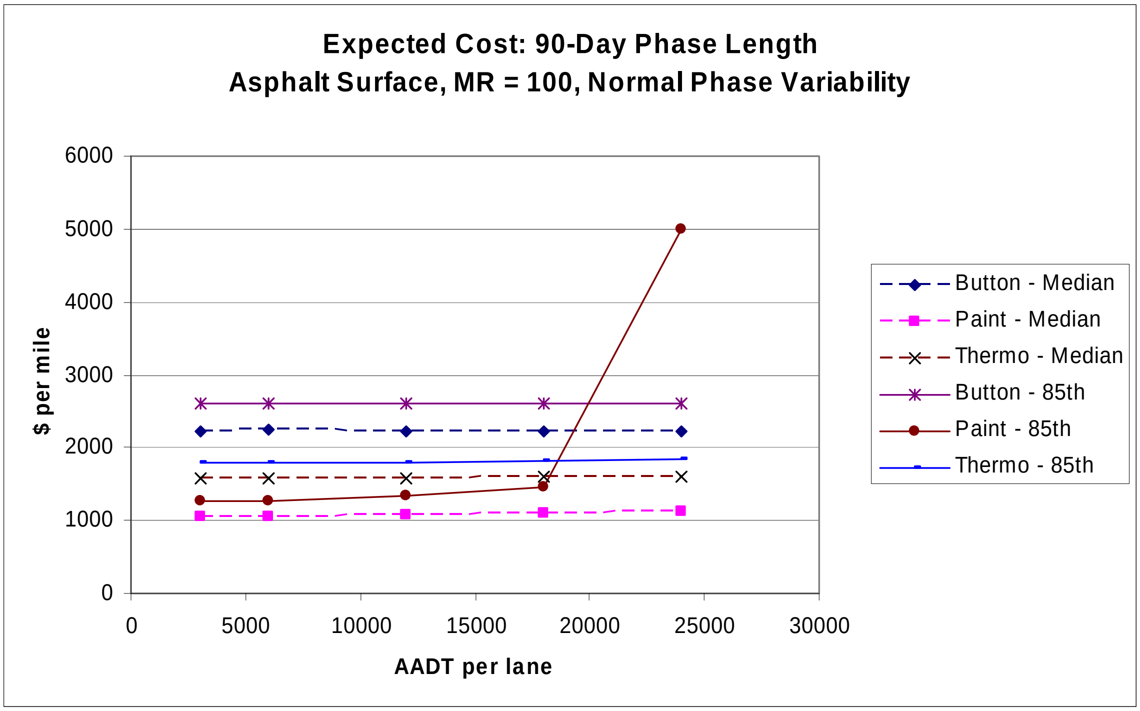


Figure B1. Total Cost – Asphalt Surface, Normal Phase Variability, 90 Days.

Table B2. Simulation – Asphalt Surface, Normal Phase Variability, 180 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
8	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	180	3.94	1.05
28	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	180	3.94	1.05
48	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	180	3.94	1.05
68	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	180	3.94	1.05
88	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	180	3.94	1.05
6	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	180	3.94	1.05
26	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	180	3.94	1.05
46	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	180	3.94	1.05
66	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	180	3.94	1.05
86	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	180	3.94	1.05
7	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	180	3.94	1.05
27	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	180	3.94	1.05
47	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	180	3.94	1.05
67	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	180	3.94	1.05
87	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	180	3.94	1.05
5	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	180	3.94	1.05
25	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	180	3.94	1.05
45	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	180	3.94	1.05
65	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	180	3.94	1.05
85	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	180	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
8	0.0	0	0	2233	364	2234	1857	2425	2539	2610	2700	2830
28	0.0	0	0	2232	364	2232	1855	2423	2539	2609	2698	2830
48	0.0	0	0	2232	364	2232	1856	2423	2538	2609	2697	2827
68	0.0	0	0	2233	366	2233	1856	2422	2539	2610	2699	2830
88	0.0	0	0	2235	389	2232	1854	2423	2538	2610	2702	2834
6	0.0	0	0	1057	204	1057	845	1164	1229	1268	1318	1395
26	0.1	0	0	1143	372	1078	855	1200	1284	1346	1458	2009
46	0.3	0	1	1348	728	1113	869	1269	1441	1959	2445	3129
66	0.5	0	1	2182	1925	1197	902	2745	3288	3606	5283	7082
86	1.0	1	2	5124	5733	4656	960	5393	5932	9344	13275	21113
7	0.0	0	0	3956	512	3958	3427	4226	4388	4486	4610	4800
27	0.0	0	0	3999	647	3968	3433	4241	4406	4510	4640	4846
47	0.2	0	0	4576	1751	4063	3482	4414	4707	5081	7471	8508
67	0.6	1	1	7026	3303	7683	3751	8932	9466	9775	10198	11150
87	1.1	1	1	11720	4671	11108	9601	11857	12461	13250	17474	19377
5	0.0	0	0	1584	204	1585	1372	1692	1757	1796	1845	1919
25	0.0	0	0	1584	205	1583	1371	1691	1756	1796	1847	1921
45	0.1	0	0	1675	438	1598	1381	1715	1792	1844	1923	2691
65	0.1	0	0	1958	1200	1614	1386	1743	1838	1917	3552	4610
85	0.2	0	1	2689	2600	1640	1399	1797	1975	5959	6409	10162

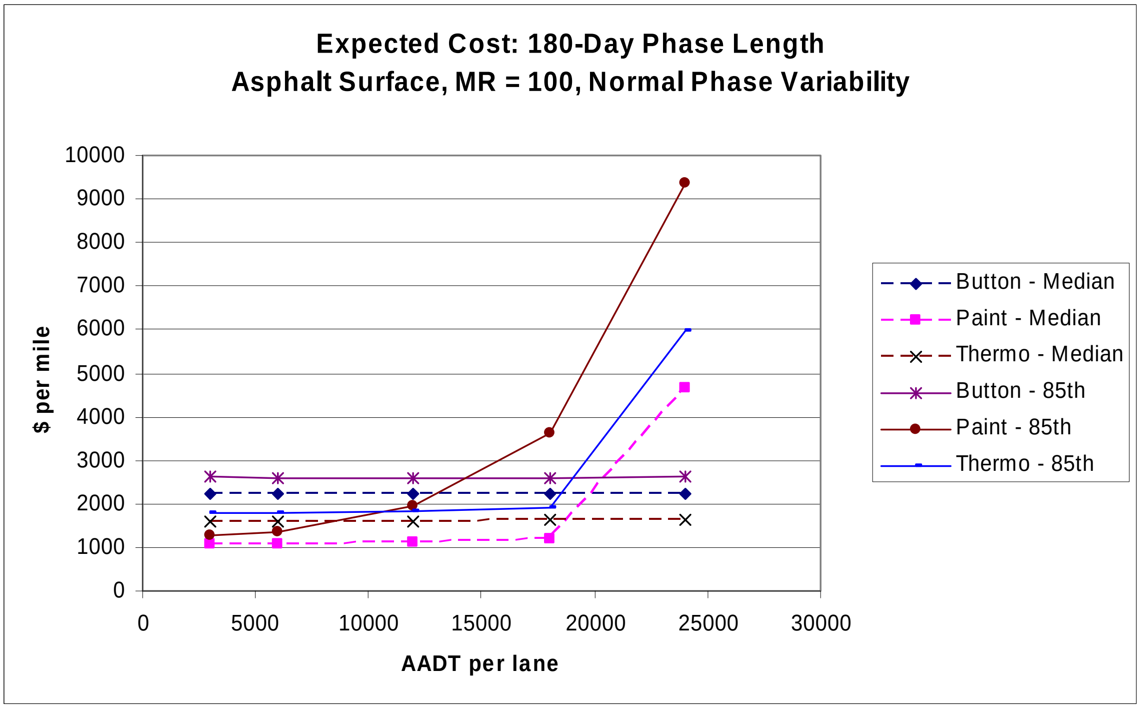


Figure B2. Total Cost – Asphalt Surface, Normal Phase Variability, 180 Days.

Table B3. Simulation – Asphalt Surface, Normal Phase Variability, 360 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
12	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	360	3.94	1.05
32	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	360	3.94	1.05
52	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	360	3.94	1.05
72	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	360	3.94	1.05
92	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	360	3.94	1.05
10	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	360	3.94	1.05
30	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	360	3.94	1.05
50	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	360	3.94	1.05
70	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	360	3.94	1.05
90	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	360	3.94	1.05
11	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	360	3.94	1.05
31	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	360	3.94	1.05
51	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	360	3.94	1.05
71	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	360	3.94	1.05
91	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	360	3.94	1.05
9	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	360	3.94	1.05
29	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	360	3.94	1.05
49	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	360	3.94	1.05
69	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	360	3.94	1.05
89	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	360	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
12	0.0	0	0	2233	365	2233	1856	2425	2539	2610	2699	2828
32	0.0	0	0	2236	369	2234	1855	2425	2540	2611	2700	2834
52	0.0	0	0	2243	404	2234	1854	2424	2543	2616	2708	2847
72	0.0	0	0	2306	615	2243	1864	2441	2564	2642	2748	2926
92	0.1	0	0	2623	1458	2269	1876	2483	2629	2735	2918	7207
10	0.1	0	0	1143	369	1079	855	1202	1287	1348	1455	1998
30	0.3	0	1	1335	700	1112	872	1268	1436	1891	2382	3045
50	1.0	1	2	2144	1610	1609	957	2337	2728	3213	4220	6118
70	1.7	1	3	4675	3831	3334	1564	4772	5872	7348	10116	14863
90	2.5	2	4	11495	10357	8569	4983	10183	14211	18113	25909	41158
11	0.0	0	0	3998	642	3968	3434	4243	4406	4509	4641	4851
31	0.2	0	0	4559	1708	4063	3480	4415	4706	5078	7375	8425
51	1.1	1	1	8390	2806	8075	6589	8808	9383	9934	11390	13234
71	1.8	2	2	12865	5271	12220	8526	14367	15470	16403	18437	21542
91	2.6	2	3	22202	9297	19378	16337	24474	26561	28219	31955	37482
9	0.0	0	0	1584	205	1584	1371	1690	1755	1795	1847	1921
29	0.1	0	0	1672	430	1599	1378	1716	1793	1845	1925	2657
49	0.2	0	1	1975	955	1640	1399	1797	1975	2938	3375	4179
69	0.6	0	1	3132	2495	1781	1445	4021	4373	4591	5688	8859
89	1.0	1	2	6387	5505	6094	1556	6542	6960	10635	11558	20092

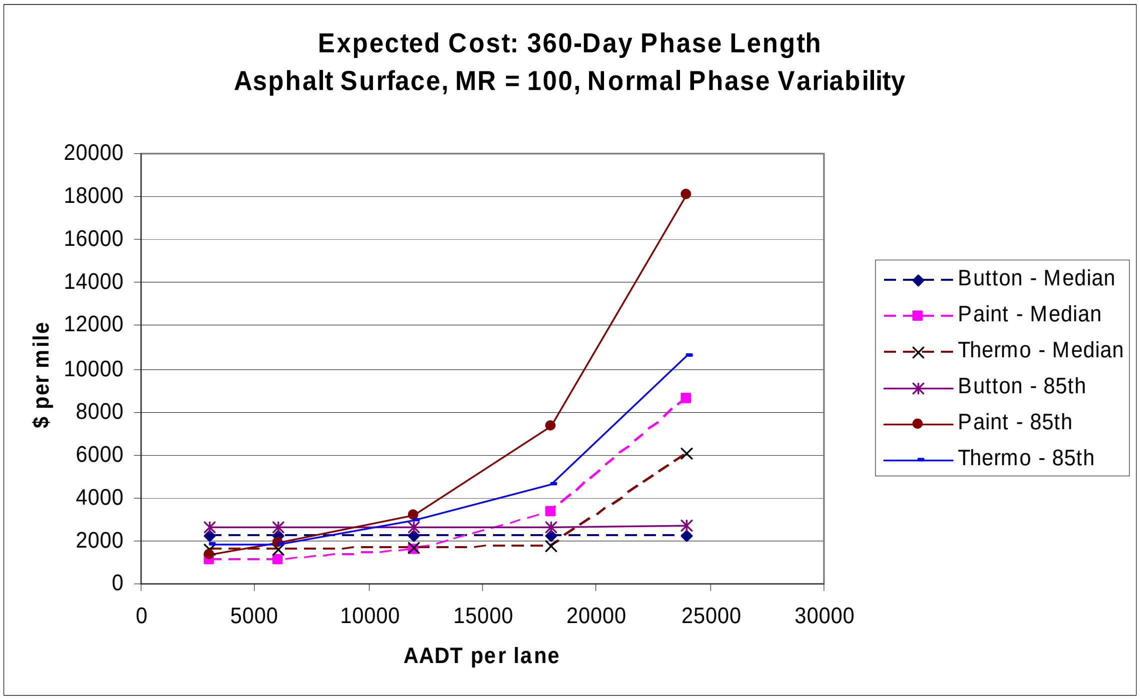


Figure B3. Total Cost – Asphalt Surface, Normal Phase Variability, 360 Days.

Table B4. Simulation – Asphalt Surface, Normal Phase Variability, 540 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
16	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	540	3.94	1.05
36	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	540	3.94	1.05
56	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	540	3.94	1.05
76	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	540	3.94	1.05
96	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	540	3.94	1.05
14	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	540	3.94	1.05
34	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	540	3.94	1.05
54	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	540	3.94	1.05
74	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	540	3.94	1.05
94	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	540	3.94	1.05
15	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	540	3.94	1.05
35	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	540	3.94	1.05
55	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	540	3.94	1.05
75	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	540	3.94	1.05
95	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	540	3.94	1.05
13	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	540	3.94	1.05
33	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	540	3.94	1.05
53	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	540	3.94	1.05
73	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	540	3.94	1.05
93	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	540	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
16	0.0	0	0	2240	384	2237	1856	2427	2544	2613	2702	2835
36	0.0	0	0	2261	453	2236	1859	2430	2549	2626	2727	2882
56	0.1	0	0	2433	773	2276	1880	2495	2649	2768	3001	4396
76	0.3	0	1	3202	1594	2433	1943	3105	5169	5489	5810	6210
96	0.6	1	1	5612	2762	6956	2144	7618	7927	8108	8328	8664
14	0.1	0	0	1188	425	1092	861	1226	1330	1426	1765	2220
34	0.5	0	1	1640	1040	1194	901	1748	2270	2545	3128	4116
54	1.7	1	3	3035	2167	2363	1379	3001	3812	4526	6000	8457
74	2.9	2	5	7052	5822	5113	3025	6935	8941	10945	15390	22807
94	4.0	3	6	17699	15514	12637	6237	17369	22392	27772	39691	61574
15	0.0	0	0	4147	1074	3986	3444	4273	4457	4580	4753	5208
35	0.6	1	1	6413	2698	6686	3744	7944	8463	8775	9181	10070
55	1.8	2	2	11166	4367	10408	7560	12430	13479	14271	15710	18353
75	3.0	3	4	18750	7521	17117	13141	20182	22326	24129	26489	31293
95	4.1	4	5	32953	13694	30133	23278	35053	39517	42485	47027	55625
13	0.0	0	0	1645	373	1592	1377	1708	1780	1828	1895	2048
33	0.1	0	0	1806	748	1613	1387	1743	1836	1913	2357	3507
53	0.6	0	1	2565	1606	1780	1445	3065	3416	3634	4155	6079
73	1.3	1	2	4858	3448	4199	1673	4645	6281	6976	8321	12948
93	1.9	1	3	10281	7902	6647	5920	10883	11724	15355	19076	29898

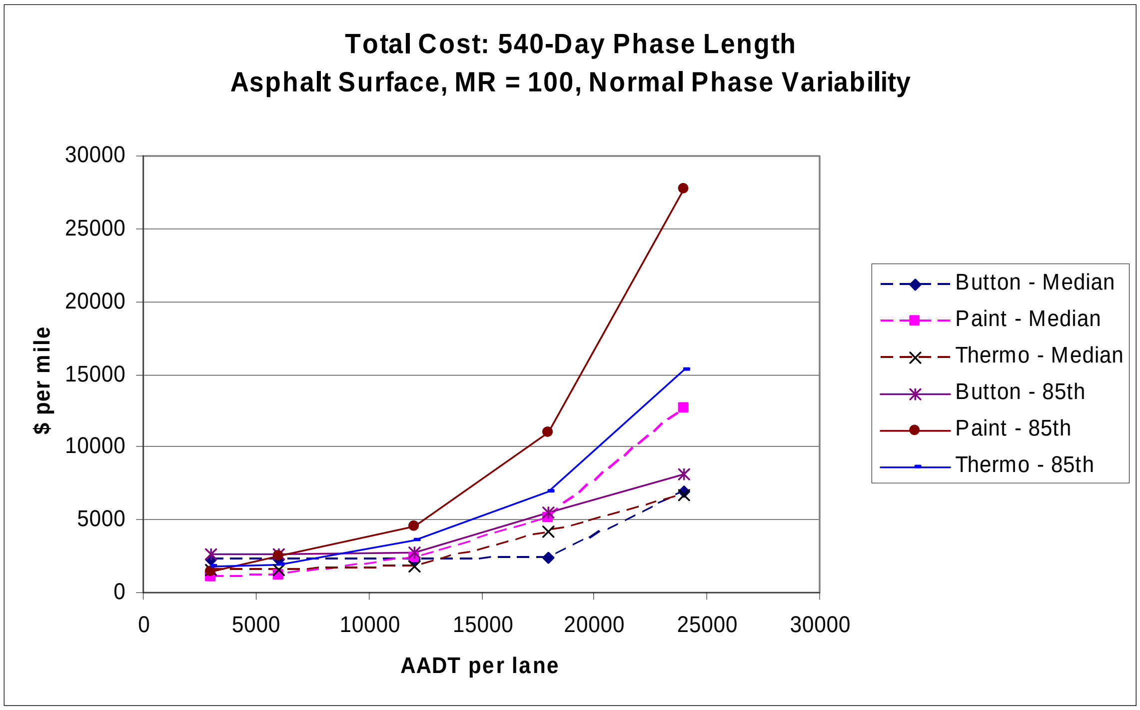


Figure B4. Total Cost – Asphalt Surface, Normal Phase Variability, 540 Days.

Table B5. Simulation – Asphalt Surface, Normal Phase Variability, 720 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
20	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	720	3.94	1.05
40	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	720	3.94	1.05
60	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	720	3.94	1.05
80	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	720	3.94	1.05
100	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	720	3.94	1.05
18	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	720	3.94	1.05
38	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	720	3.94	1.05
58	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	720	3.94	1.05
78	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	720	3.94	1.05
98	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	720	3.94	1.05
19	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	720	3.94	1.05
39	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	720	3.94	1.05
59	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	720	3.94	1.05
79	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	720	3.94	1.05
99	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	720	3.94	1.05
17	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	720	3.94	1.05
37	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	720	3.94	1.05
57	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	720	3.94	1.05
77	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	720	3.94	1.05
97	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	720	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
20	0.0	0	0	2283	500	2245	1864	2440	2562	2640	2745	2923
40	0.1	0	0	2447	787	2279	1878	2503	2664	2789	3090	4442
60	0.4	0	1	3262	1300	2680	2009	4206	4635	4855	5105	5458
80	0.8	1	1	5001	1545	5323	2619	5784	6052	6215	6438	6795
100	1.1	1	1	7874	1870	7619	6796	8058	8352	8562	8931	12357
18	0.3	0	1	1333	691	1114	872	1269	1441	1893	2366	3006
38	1.0	1	2	2092	1551	1560	956	2279	2662	3093	4042	5913
58	2.5	2	4	3907	2957	2814	1946	3858	4841	5818	7853	11472
78	4.0	3	6	9385	7812	6534	3901	9127	11864	14494	20323	30600
98	5.5	4	9	23868	20447	16712	9513	22748	30081	37074	52787	81889
19	0.1	0	0	4553	1703	4063	3479	4412	4698	5044	7338	8399
39	1.1	1	1	8330	2786	8023	6526	8755	9332	9864	11260	13090
59	2.6	2	3	14394	5602	13114	10272	15466	17238	18418	20195	23665
79	4.1	4	5	24418	9857	22242	17092	26178	29135	31352	34510	40763
99	5.6	5	7	43714	18170	39733	30403	46712	52102	56027	62048	73649
17	0.1	0	0	1672	424	1599	1379	1716	1793	1846	1925	2646
37	0.2	0	1	1961	928	1639	1397	1796	1973	2871	3316	4122
57	1.0	1	2	3278	1991	3064	1556	3508	3889	4552	5410	7831
77	1.9	1	3	6448	4463	4572	3849	6738	7591	9178	11099	17527
97	2.6	2	4	13819	10703	10909	6212	14720	16464	20189	25123	39924

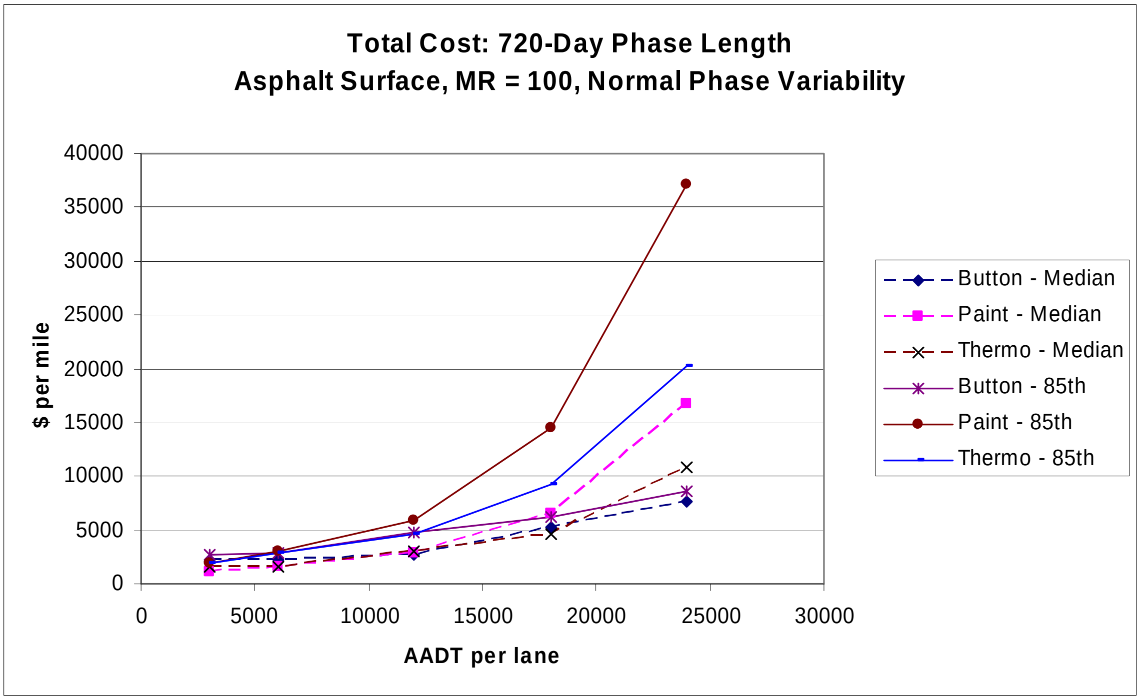


Figure B5. Total Cost – Asphalt Surface, Normal Phase Variability, 720 Days.

Table B6. Simulation – Concrete Surface, Normal Phase Variability, 90 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
4	Button	Concrete	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	90	3.94	1.05
24	Button	Concrete	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	90	3.94	1.05
44	Button	Concrete	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	90	3.94	1.05
64	Button	Concrete	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	90	3.94	1.05
84	Button	Concrete	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	90	3.94	1.05
2	Paint	Concrete	Solid Edge White	3000	100	0	100000	1056	205	53.4	23.2	90	3.94	1.05
22	Paint	Concrete	Solid Edge White	6000	100	0	100000	1056	205	26.7	11.6	90	3.94	1.05
42	Paint	Concrete	Solid Edge White	12000	100	0	100000	1056	205	13.4	5.8	90	3.94	1.05
62	Paint	Concrete	Solid Edge White	18000	100	0	100000	1056	205	8.9	3.9	90	3.94	1.05
82	Paint	Concrete	Solid Edge White	24000	100	0	100000	1056	205	6.7	2.9	90	3.94	1.05
3	Tape	Concrete	Solid Edge White	3000	100	0	100000	3960	512	33.5	8.3	90	3.94	1.05
23	Tape	Concrete	Solid Edge White	6000	100	0	100000	3960	512	16.7	4.2	90	3.94	1.05
43	Tape	Concrete	Solid Edge White	12000	100	0	100000	3960	512	8.4	2.1	90	3.94	1.05
63	Tape	Concrete	Solid Edge White	18000	100	0	100000	3960	512	5.6	1.4	90	3.94	1.05
83	Tape	Concrete	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.0	90	3.94	1.05
1	Thermo	Concrete	Solid Edge White	3000	100	0	100000	1584	205	68.9	29.0	90	3.94	1.05
21	Thermo	Concrete	Solid Edge White	6000	100	0	100000	1584	205	34.5	14.5	90	3.94	1.05
41	Thermo	Concrete	Solid Edge White	12000	100	0	100000	1584	205	17.2	7.2	90	3.94	1.05
61	Thermo	Concrete	Solid Edge White	18000	100	0	100000	1584	205	11.5	4.8	90	3.94	1.05
81	Thermo	Concrete	Solid Edge White	24000	100	0	100000	1584	205	8.6	3.6	90	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
4	0.0	0	0	2234	363	2234	1856	2425	2540	2610	2701	2831
24	0.0	0	0	2233	365	2232	1855	2424	2539	2613	2702	2836
44	0.0	0	0	2232	363	2232	1855	2423	2539	2610	2701	2830
64	0.0	0	0	2231	365	2231	1854	2421	2537	2610	2700	2832
84	0.0	0	0	2234	362	2232	1858	2423	2539	2609	2699	2833
2	0.0	0	0	1056	204	1056	846	1164	1227	1267	1318	1392
22	0.0	0	0	1055	205	1055	844	1162	1227	1267	1318	1394
42	0.0	0	0	1097	301	1067	849	1179	1252	1298	1363	1497
62	0.1	0	0	1180	542	1073	852	1191	1269	1322	1407	2735
82	0.1	0	0	1599	1800	1083	858	1208	1300	1373	1588	5492
3	0.0	0	0	3958	512	3959	3427	4227	4389	4490	4614	4802
23	0.0	0	0	3958	512	3955	3430	4227	4393	4492	4617	4805
43	0.0	0	0	3975	573	3961	3434	4228	4391	4494	4624	4823
63	0.0	0	0	4093	998	3977	3439	4257	4433	4545	4691	4958
83	0.1	0	0	4737	2411	4034	3466	4360	4600	4800	9341	11136
1	0.0	0	0	1584	205	1584	1372	1693	1758	1797	1847	1922
21	0.0	0	0	1584	204	1585	1373	1692	1756	1794	1844	1918
41	0.0	0	0	1585	205	1584	1372	1692	1759	1799	1849	1922
61	0.0	0	0	1684	545	1595	1377	1709	1781	1829	1896	2041
81	0.1	0	0	1854	1115	1599	1379	1717	1796	1849	1932	5813

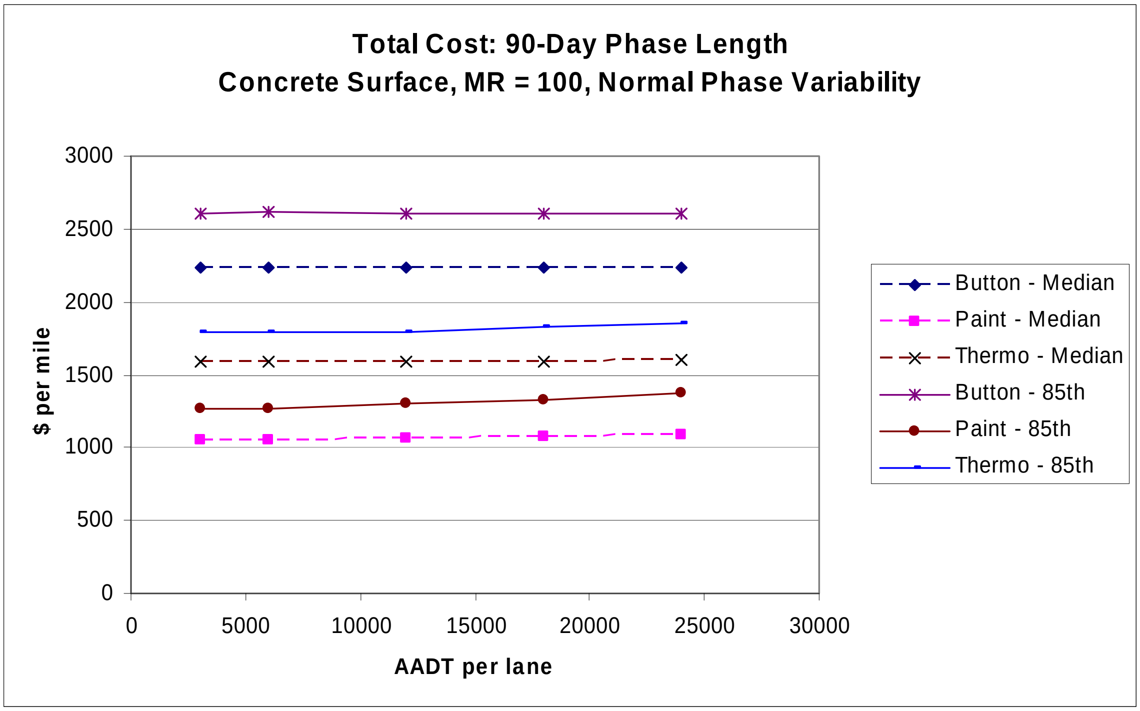


Figure B6. Total Cost – Concrete Surface, Normal Phase Variability, 90 Days.

Table B7. Simulation – Concrete Surface, Normal Phase Variability, 180 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
8	Button	Concrete	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	180	3.94	1.05
28	Button	Concrete	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	180	3.94	1.05
48	Button	Concrete	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	180	3.94	1.05
68	Button	Concrete	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	180	3.94	1.05
88	Button	Concrete	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	180	3.94	1.05
6	Paint	Concrete	Solid Edge White	3000	100	0	100000	1056	205	53.4	23.2	180	3.94	1.05
26	Paint	Concrete	Solid Edge White	6000	100	0	100000	1056	205	26.7	11.6	180	3.94	1.05
46	Paint	Concrete	Solid Edge White	12000	100	0	100000	1056	205	13.4	5.8	180	3.94	1.05
66	Paint	Concrete	Solid Edge White	18000	100	0	100000	1056	205	8.9	3.9	180	3.94	1.05
86	Paint	Concrete	Solid Edge White	24000	100	0	100000	1056	205	6.7	2.9	180	3.94	1.05
7	Tape	Concrete	Solid Edge White	3000	100	0	100000	3960	512	33.5	8.3	180	3.94	1.05
27	Tape	Concrete	Solid Edge White	6000	100	0	100000	3960	512	16.7	4.2	180	3.94	1.05
47	Tape	Concrete	Solid Edge White	12000	100	0	100000	3960	512	8.4	2.1	180	3.94	1.05
67	Tape	Concrete	Solid Edge White	18000	100	0	100000	3960	512	5.6	1.4	180	3.94	1.05
87	Tape	Concrete	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.0	180	3.94	1.05
5	Thermo	Concrete	Solid Edge White	3000	100	0	100000	1584	205	68.9	29.0	180	3.94	1.05
25	Thermo	Concrete	Solid Edge White	6000	100	0	100000	1584	205	34.5	14.5	180	3.94	1.05
45	Thermo	Concrete	Solid Edge White	12000	100	0	100000	1584	205	17.2	7.2	180	3.94	1.05
65	Thermo	Concrete	Solid Edge White	18000	100	0	100000	1584	205	11.5	4.8	180	3.94	1.05
85	Thermo	Concrete	Solid Edge White	24000	100	0	100000	1584	205	8.6	3.6	180	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
8	0.0	0	0	2232	364	2233	1856	2423	2539	2609	2697	2828
28	0.0	0	0	2234	363	2234	1857	2423	2539	2611	2700	2832
48	0.0	0	0	2233	365	2233	1855	2422	2540	2611	2698	2831
68	0.0	0	0	2235	369	2233	1858	2427	2543	2614	2704	2836
88	0.0	0	0	2234	385	2232	1854	2422	2538	2612	2702	2837
6	0.0	0	0	1056	205	1056	844	1164	1228	1270	1321	1395
26	0.0	0	0	1093	289	1066	847	1178	1250	1295	1359	1482
46	0.1	0	0	1202	544	1083	858	1208	1298	1366	1534	2399
66	0.3	0	1	1693	1473	1126	877	1303	2491	3035	3393	5085
86	0.6	0	1	3362	3853	1228	910	4956	5344	5567	6066	11976
7	0.0	0	0	3960	512	3960	3432	4225	4388	4491	4616	4804
27	0.0	0	0	3976	574	3962	3431	4231	4397	4500	4629	4826
47	0.1	0	0	4396	1447	4034	3467	4354	4591	4787	6148	8084
67	0.6	1	1	6867	2957	7629	3741	8889	9394	9684	10049	10657
87	1.1	1	1	11444	3689	11087	9718	11764	12261	12665	15640	18489
5	0.0	0	0	1585	205	1585	1372	1692	1757	1797	1848	1922
25	0.0	0	0	1584	204	1585	1373	1692	1756	1795	1846	1921
45	0.1	0	0	1680	445	1600	1381	1717	1795	1849	1932	2785
65	0.2	0	0	1994	1223	1617	1388	1751	1854	1951	3908	4638
85	0.3	0	1	3009	3178	1655	1404	1835	5740	6182	6518	10595

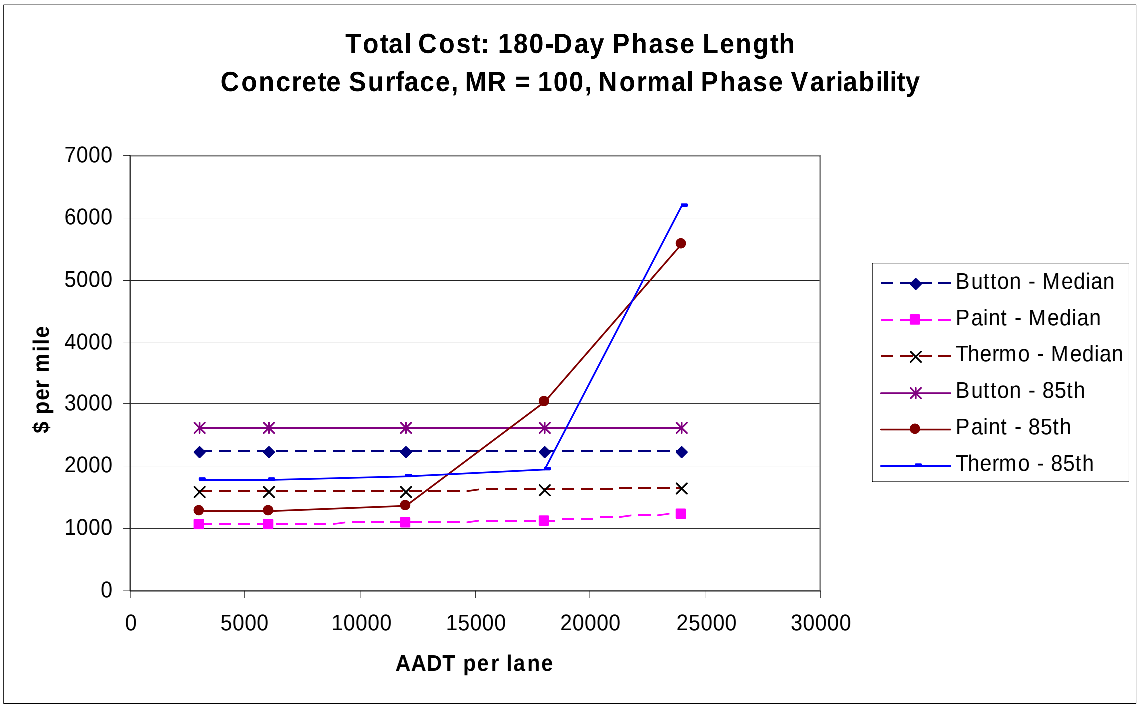


Figure B7. Total Cost – Concrete Surface, Normal Phase Variability, 180 Days.

Table B8. Simulation – Concrete Surface, Normal Phase Variability, 360 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
12	Button	Concrete	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	360	3.94	1.05
32	Button	Concrete	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	360	3.94	1.05
52	Button	Concrete	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	360	3.94	1.05
72	Button	Concrete	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	360	3.94	1.05
92	Button	Concrete	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	360	3.94	1.05
10	Paint	Concrete	Solid Edge White	3000	100	0	100000	1056	205	53.4	23.2	360	3.94	1.05
30	Paint	Concrete	Solid Edge White	6000	100	0	100000	1056	205	26.7	11.6	360	3.94	1.05
50	Paint	Concrete	Solid Edge White	12000	100	0	100000	1056	205	13.4	5.8	360	3.94	1.05
70	Paint	Concrete	Solid Edge White	18000	100	0	100000	1056	205	8.9	3.9	360	3.94	1.05
90	Paint	Concrete	Solid Edge White	24000	100	0	100000	1056	205	6.7	2.9	360	3.94	1.05
11	Tape	Concrete	Solid Edge White	3000	100	0	100000	3960	512	33.5	8.3	360	3.94	1.05
31	Tape	Concrete	Solid Edge White	6000	100	0	100000	3960	512	16.7	4.2	360	3.94	1.05
51	Tape	Concrete	Solid Edge White	12000	100	0	100000	3960	512	8.4	2.1	360	3.94	1.05
71	Tape	Concrete	Solid Edge White	18000	100	0	100000	3960	512	5.6	1.4	360	3.94	1.05
91	Tape	Concrete	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.0	360	3.94	1.05
9	Thermo	Concrete	Solid Edge White	3000	100	0	100000	1584	205	68.9	29.0	360	3.94	1.05
29	Thermo	Concrete	Solid Edge White	6000	100	0	100000	1584	205	34.5	14.5	360	3.94	1.05
49	Thermo	Concrete	Solid Edge White	12000	100	0	100000	1584	205	17.2	7.2	360	3.94	1.05
69	Thermo	Concrete	Solid Edge White	18000	100	0	100000	1584	205	11.5	4.8	360	3.94	1.05
89	Thermo	Concrete	Solid Edge White	24000	100	0	100000	1584	205	8.6	3.6	360	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
12	0.0	0	0	2232	365	2233	1854	2423	2538	2607	2696	2830
32	0.0	0	0	2233	369	2232	1855	2421	2537	2608	2699	2832
52	0.0	0	0	2244	403	2235	1854	2426	2544	2615	2709	2851
72	0.0	0	0	2306	614	2245	1863	2441	2563	2643	2747	2926
92	0.1	0	0	2623	1456	2270	1875	2485	2632	2738	2918	7197
10	0.0	0	0	1095	292	1067	850	1179	1251	1298	1364	1489
30	0.1	0	0	1195	520	1083	858	1209	1298	1366	1522	2324
50	0.6	0	1	1679	1099	1224	912	1922	2299	2503	2829	3958
70	1.2	1	2	3556	2732	3103	1111	3533	4347	5268	6185	9707
90	1.8	1	3	8423	6715	5529	4836	9135	9945	12783	14616	23854
11	0.0	0	0	3977	572	3963	3433	4234	4395	4497	4623	4819
31	0.1	0	0	4403	1450	4034	3471	4359	4598	4804	6395	8056
51	1.1	1	1	8243	2314	8053	6698	8721	9202	9574	10409	12461
71	1.7	2	2	12438	4324	12100	8514	14171	15127	15812	17039	19800
91	2.5	2	3	21470	7461	19215	16496	23818	25855	27039	29383	34140
9	0.0	0	0	1583	205	1583	1370	1691	1757	1797	1847	1921
29	0.1	0	0	1674	430	1599	1380	1717	1794	1847	1929	2689
49	0.3	0	1	2096	1162	1658	1406	1842	2756	3161	3497	4528
69	0.7	1	1	3495	2682	3147	1476	4226	4521	4759	6452	9084
89	1.2	1	2	7331	5778	6274	1696	6707	10282	11028	11953	20026

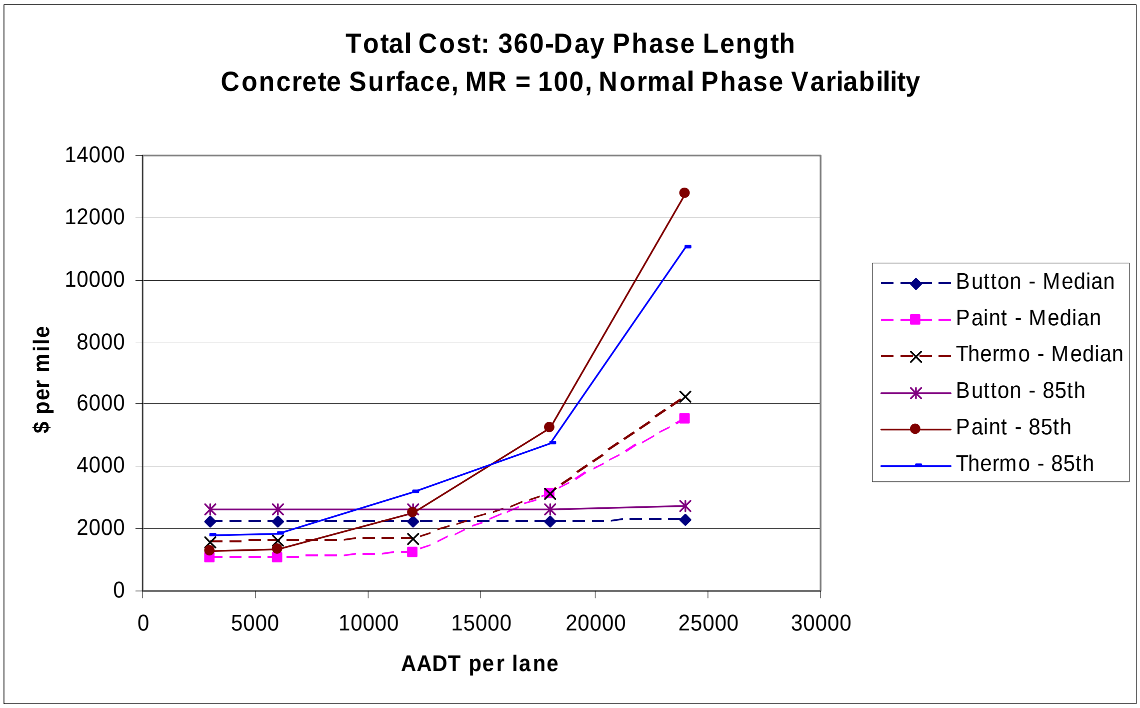


Figure B8. Total Cost – Concrete Surface, Normal Phase Variability, 360 Days.

Table B9. Simulation – Concrete Surface, Normal Phase Variability, 540 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
16	Button	Concrete	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	540	3.94	1.05
36	Button	Concrete	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	540	3.94	1.05
56	Button	Concrete	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	540	3.94	1.05
76	Button	Concrete	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	540	3.94	1.05
96	Button	Concrete	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	540	3.94	1.05
14	Paint	Concrete	Solid Edge White	3000	100	0	100000	1056	205	53.4	23.2	540	3.94	1.05
34	Paint	Concrete	Solid Edge White	6000	100	0	100000	1056	205	26.7	11.6	540	3.94	1.05
54	Paint	Concrete	Solid Edge White	12000	100	0	100000	1056	205	13.4	5.8	540	3.94	1.05
74	Paint	Concrete	Solid Edge White	18000	100	0	100000	1056	205	8.9	3.9	540	3.94	1.05
94	Paint	Concrete	Solid Edge White	24000	100	0	100000	1056	205	6.7	2.9	540	3.94	1.05
15	Tape	Concrete	Solid Edge White	3000	100	0	100000	3960	512	33.5	8.3	540	3.94	1.05
35	Tape	Concrete	Solid Edge White	6000	100	0	100000	3960	512	16.7	4.2	540	3.94	1.05
55	Tape	Concrete	Solid Edge White	12000	100	0	100000	3960	512	8.4	2.1	540	3.94	1.05
75	Tape	Concrete	Solid Edge White	18000	100	0	100000	3960	512	5.6	1.4	540	3.94	1.05
95	Tape	Concrete	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.0	540	3.94	1.05
13	Thermo	Concrete	Solid Edge White	3000	100	0	100000	1584	205	68.9	29.0	540	3.94	1.05
33	Thermo	Concrete	Solid Edge White	6000	100	0	100000	1584	205	34.5	14.5	540	3.94	1.05
53	Thermo	Concrete	Solid Edge White	12000	100	0	100000	1584	205	17.2	7.2	540	3.94	1.05
73	Thermo	Concrete	Solid Edge White	18000	100	0	100000	1584	205	11.5	4.8	540	3.94	1.05
93	Thermo	Concrete	Solid Edge White	24000	100	0	100000	1584	205	8.6	3.6	540	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
16	0.0	0	0	2238	384	2233	1857	2423	2540	2611	2703	2840
36	0.0	0	0	2260	450	2236	1860	2431	2549	2623	2721	2877
56	0.1	0	0	2434	777	2275	1877	2496	2652	2770	3003	4405
76	0.3	0	1	3200	1592	2430	1942	3097	5156	5482	5805	6203
96	0.6	1	1	5593	2769	6949	2137	7611	7922	8105	8328	8668
14	0.1	0	0	1119	333	1073	852	1190	1267	1320	1402	1716
34	0.3	0	1	1378	794	1121	875	1294	1561	2003	2349	3009
54	1.2	1	2	2403	1536	2138	1107	2540	2901	3305	3958	5651
74	2.0	1	3	5315	3835	3774	2882	5457	6465	7570	9276	14090
94	2.9	2	4	13019	10278	9642	5317	13425	16431	18433	23141	36989
15	0.0	0	0	4062	844	3977	3438	4255	4428	4540	4689	4950
35	0.6	1	1	6283	2425	6615	3742	7881	8380	8670	9036	9643
55	1.7	2	2	10819	3648	10256	7543	12240	13162	13791	14796	16973
75	2.8	3	4	18146	6046	16972	13198	19788	21498	22884	24959	28459
95	4.0	4	5	31893	10996	29842	23567	34276	37995	40521	43905	50669
13	0.0	0	0	1644	375	1593	1377	1707	1779	1827	1895	2048
33	0.2	0	0	1834	773	1618	1388	1752	1853	1950	2887	3576
53	0.7	1	1	2806	1734	2342	1479	3282	3573	3797	4547	6252
73	1.5	1	2	5426	3652	4341	3548	4950	6803	7336	9184	13132
93	2.1	2	3	11417	8665	9467	6043	11301	14881	16027	20231	30063

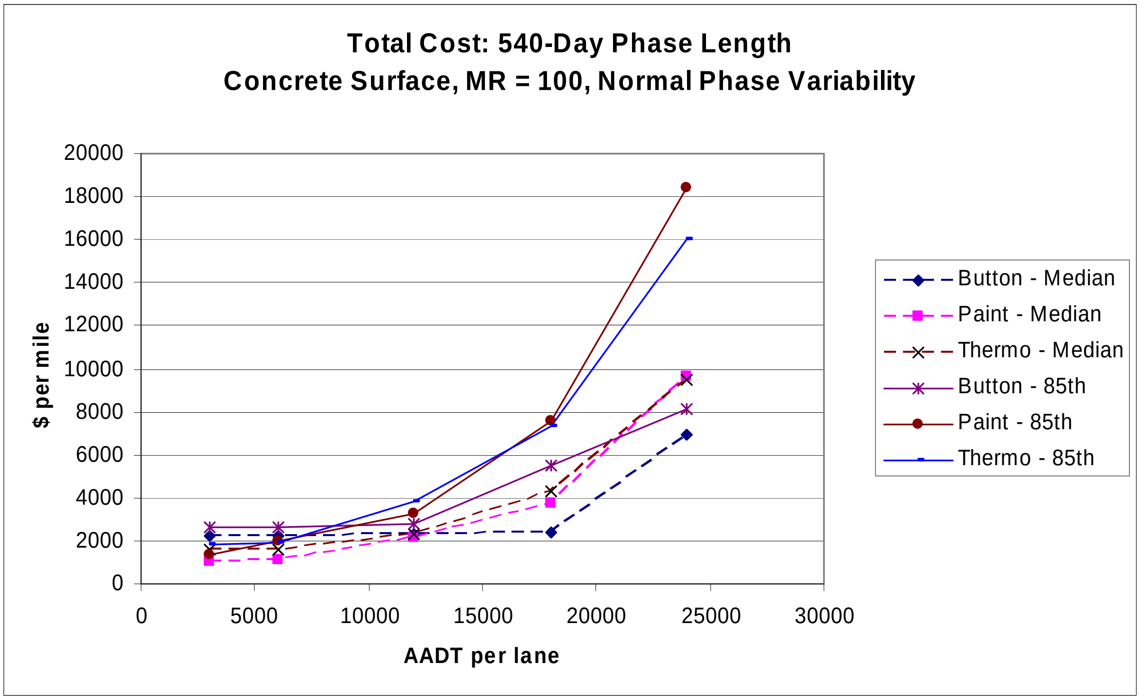


Figure B9. Total Cost – Concrete Surface, Normal Phase Variability, 540 Days.

Table B10. Simulation – Concrete Surface, Normal Phase Variability, 720 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
20	Button	Concrete	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	720	3.94	1.05
40	Button	Concrete	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	720	3.94	1.05
60	Button	Concrete	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	720	3.94	1.05
80	Button	Concrete	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	720	3.94	1.05
100	Button	Concrete	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	720	3.94	1.05
18	Paint	Concrete	Solid Edge White	3000	100	0	100000	1056	205	53.4	23.2	720	3.94	1.05
38	Paint	Concrete	Solid Edge White	6000	100	0	100000	1056	205	26.7	11.6	720	3.94	1.05
58	Paint	Concrete	Solid Edge White	12000	100	0	100000	1056	205	13.4	5.8	720	3.94	1.05
78	Paint	Concrete	Solid Edge White	18000	100	0	100000	1056	205	8.9	3.9	720	3.94	1.05
98	Paint	Concrete	Solid Edge White	24000	100	0	100000	1056	205	6.7	2.9	720	3.94	1.05
19	Tape	Concrete	Solid Edge White	3000	100	0	100000	3960	512	33.5	8.3	720	3.94	1.05
39	Tape	Concrete	Solid Edge White	6000	100	0	100000	3960	512	16.7	4.2	720	3.94	1.05
59	Tape	Concrete	Solid Edge White	12000	100	0	100000	3960	512	8.4	2.1	720	3.94	1.05
79	Tape	Concrete	Solid Edge White	18000	100	0	100000	3960	512	5.6	1.4	720	3.94	1.05
99	Tape	Concrete	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.0	720	3.94	1.05
17	Thermo	Concrete	Solid Edge White	3000	100	0	100000	1584	205	68.9	29.0	720	3.94	1.05
37	Thermo	Concrete	Solid Edge White	6000	100	0	100000	1584	205	34.5	14.5	720	3.94	1.05
57	Thermo	Concrete	Solid Edge White	12000	100	0	100000	1584	205	17.2	7.2	720	3.94	1.05
77	Thermo	Concrete	Solid Edge White	18000	100	0	100000	1584	205	11.5	4.8	720	3.94	1.05
97	Thermo	Concrete	Solid Edge White	24000	100	0	100000	1584	205	8.6	3.6	720	3.94	1.05

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
20	0.0	0	0	2283	500	2244	1863	2441	2563	2642	2743	2925
40	0.1	0	0	2446	780	2280	1879	2504	2666	2792	3084	4426
60	0.4	0	1	3251	1302	2662	2006	4189	4628	4846	5107	5454
80	0.9	1	1	5010	1538	5321	2649	5788	6052	6222	6437	6807
100	1.1	1	1	7877	1877	7626	6802	8056	8354	8566	8928	12357
18	0.1	0	0	1192	512	1083	858	1209	1298	1365	1514	2323
38	0.6	0	1	1654	1059	1223	912	1877	2255	2453	2772	3842
58	1.8	1	3	3076	1936	2473	1816	3120	3752	4212	5095	7294
78	2.9	2	4	7035	5165	5493	3252	7185	8581	9947	12265	18649
98	4.0	3	6	17812	13731	13594	9104	17796	21846	25289	31425	49485
19	0.1	0	0	4397	1439	4038	3469	4360	4600	4801	6231	8025
39	1.1	1	1	8189	2301	7998	6637	8679	9163	9540	10372	12328
59	2.5	2	3	13955	4461	13002	10447	15032	16682	17668	19066	21716
79	4.0	4	5	23687	7962	22055	17344	25601	28093	29951	32633	37442
99	5.4	5	7	42401	14544	39577	30889	45648	50216	53498	58197	67066
17	0.1	0	0	1674	426	1600	1381	1717	1794	1847	1929	2664
37	0.3	0	1	2072	1126	1655	1405	1837	2647	3095	3435	4438
57	1.2	1	2	3618	2101	3246	1696	3663	4282	4949	5695	8051
77	2.1	2	3	7068	4894	5339	3974	7141	8591	9773	11908	17547
97	2.9	2	4	15386	11530	11359	6496	15733	19436	21204	26243	39973

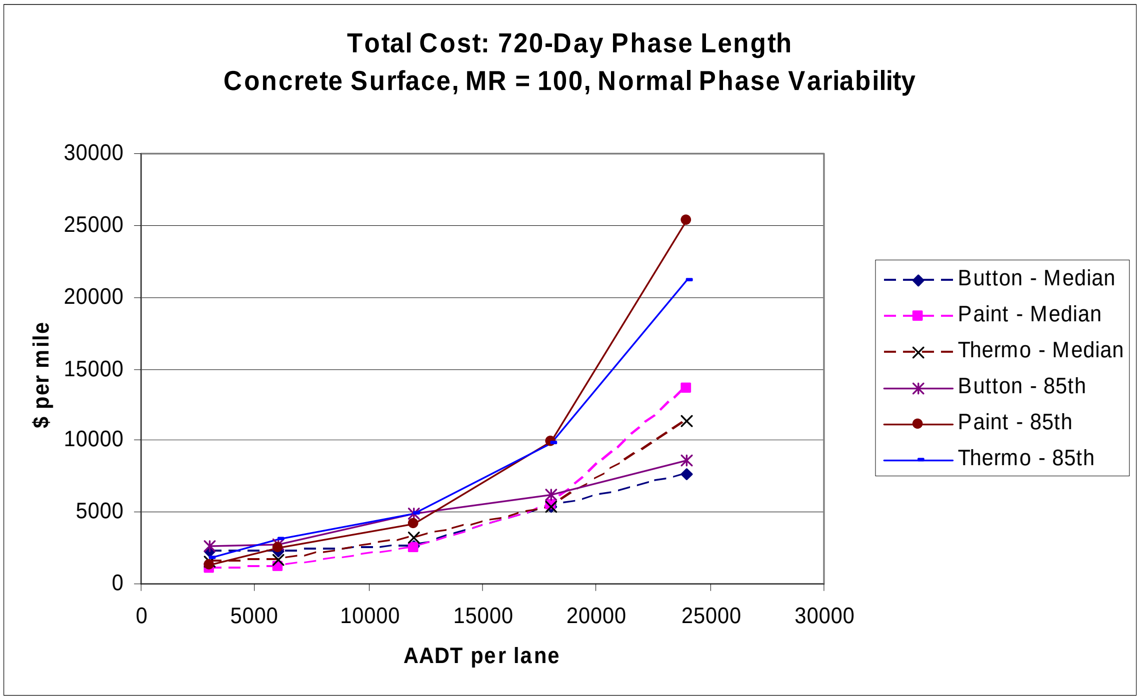


Figure B10. Total Cost – Concrete Surface, Normal Phase Variability, 720 Days.

Table B11. Simulation – Asphalt Surface, Conservative Phase Variability, 90 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
4	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	90	-10.00	2.65
24	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	90	-10.00	2.65
44	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	90	-10.00	2.65
64	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	90	-10.00	2.65
84	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	90	-10.00	2.65
2	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	90	-10.00	2.65
22	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	90	-10.00	2.65
42	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	90	-10.00	2.65
62	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	90	-10.00	2.65
82	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	90	-10.00	2.65
3	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	90	-10.00	2.65
23	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	90	-10.00	2.65
43	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	90	-10.00	2.65
63	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	90	-10.00	2.65
83	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	90	-10.00	2.65
1	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	90	-10.00	2.65
21	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	90	-10.00	2.65
41	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	90	-10.00	2.65
61	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	90	-10.00	2.65
81	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	90	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
4	0.0	0	0	2234	363	2235	1857	2425	2541	2611	2699	2830
24	0.0	0	0	2233	365	2234	1853	2423	2538	2608	2699	2832
44	0.0	0	0	2231	363	2230	1855	2421	2536	2607	2697	2830
64	0.0	0	0	2232	362	2232	1859	2421	2536	2607	2697	2830
84	0.0	0	0	2232	363	2232	1856	2422	2537	2607	2697	2828
2	0.0	0	0	1056	205	1056	845	1163	1229	1269	1319	1393
22	0.0	0	0	1056	205	1055	844	1162	1227	1269	1320	1394
42	0.1	0	0	1161	401	1082	857	1207	1296	1365	1508	2151
62	0.2	0	0	1506	1192	1101	865	1243	1369	1582	3250	4884
82	0.3	0	1	2432	2901	1129	877	1313	4795	5264	5825	9498
3	0.0	0	0	3961	511	3959	3432	4227	4390	4491	4618	4804
23	0.0	0	0	3963	522	3957	3432	4229	4393	4493	4618	4802
43	0.0	0	0	4028	749	3971	3435	4248	4418	4523	4663	4891
63	0.1	0	0	4367	1621	4006	3452	4309	4519	4668	4942	8596
83	0.3	0	1	5763	3570	4156	3518	4655	9989	10729	11322	12061
1	0.0	0	0	1583	205	1583	1371	1690	1756	1795	1846	1919
21	0.0	0	0	1585	204	1584	1374	1691	1756	1796	1846	1921
41	0.0	0	0	1585	204	1585	1373	1693	1758	1797	1847	1921
61	0.0	0	0	1701	583	1597	1378	1712	1786	1836	1906	2105
81	0.1	0	0	1894	1184	1604	1383	1724	1803	1859	1953	5973

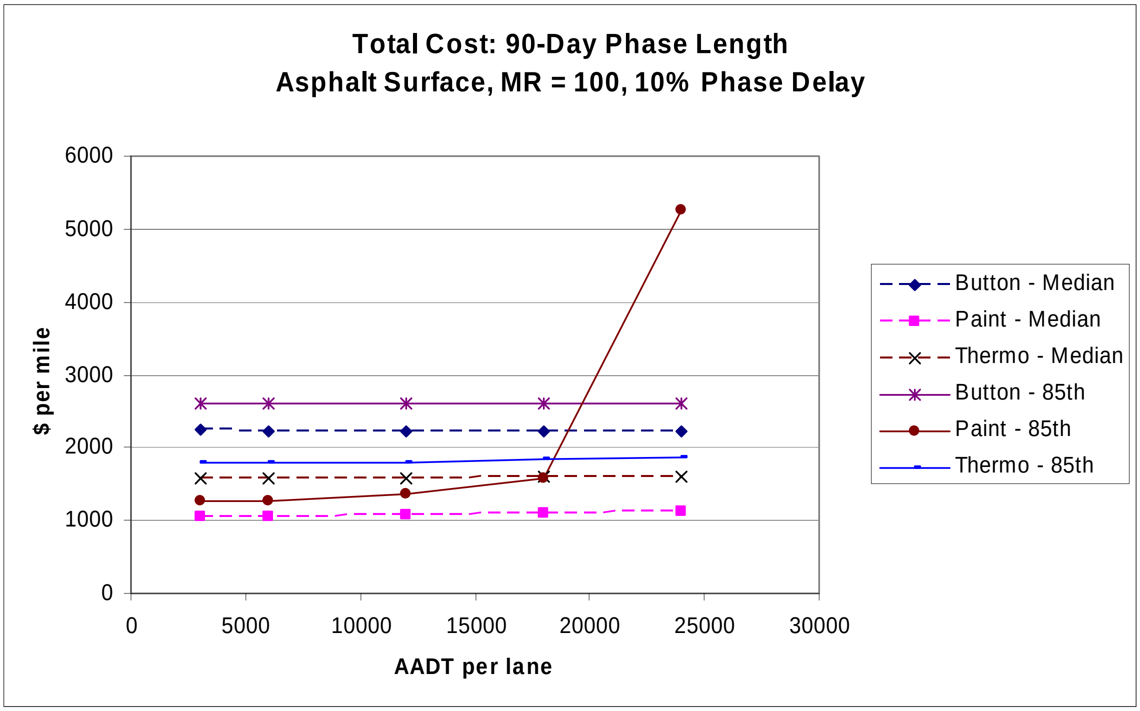


Figure B11. Total Cost – Asphalt Surface, Conservative Phase Variability, 90 Days.

Table B12. Simulation – Asphalt Surface, Conservative Phase Variability, 180 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
8	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	180	-10.00	2.65
28	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	180	-10.00	2.65
48	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	180	-10.00	2.65
68	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	180	-10.00	2.65
88	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	180	-10.00	2.65
6	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	180	-10.00	2.65
26	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	180	-10.00	2.65
46	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	180	-10.00	2.65
66	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	180	-10.00	2.65
86	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	180	-10.00	2.65
7	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	180	-10.00	2.65
27	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	180	-10.00	2.65
47	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	180	-10.00	2.65
67	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	180	-10.00	2.65
87	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	180	-10.00	2.65
5	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	180	-10.00	2.65
25	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	180	-10.00	2.65
45	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	180	-10.00	2.65
65	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	180	-10.00	2.65
85	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	180	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
8	0.0	0	0	2232	365	2233	1853	2422	2539	2609	2700	2832
28	0.0	0	0	2234	364	2233	1860	2423	2538	2609	2700	2834
48	0.0	0	0	2233	363	2233	1858	2422	2537	2608	2698	2830
68	0.0	0	0	2234	371	2233	1856	2425	2539	2609	2699	2831
88	0.0	0	0	2240	421	2232	1856	2425	2542	2613	2703	2835
6	0.0	0	0	1056	205	1056	844	1164	1229	1269	1319	1392
26	0.1	0	0	1155	386	1082	857	1207	1296	1366	1503	2084
46	0.3	0	1	1435	850	1129	878	1313	1796	2228	2650	3414
66	0.7	0	1	2567	2393	1276	922	3073	3486	3984	5797	8857
86	1.2	1	2	5913	6030	5032	1012	5573	8876	9784	14098	21681
7	0.0	0	0	3964	525	3964	3429	4231	4393	4493	4621	4811
27	0.0	0	0	4024	741	3971	3434	4248	4415	4521	4660	4884
47	0.3	0	1	4978	2094	4157	3523	4647	6937	7686	8283	9004
67	0.8	1	1	8184	3357	8596	4083	9376	9854	10189	10749	13564
87	1.3	1	2	13079	5289	11389	10070	12382	16621	17855	18936	21202
5	0.0	0	0	1584	205	1584	1370	1691	1757	1797	1848	1922
25	0.0	0	0	1584	205	1583	1371	1692	1756	1795	1846	1920
45	0.1	0	0	1697	473	1603	1381	1724	1805	1862	1957	2985
65	0.2	0	0	2039	1289	1622	1390	1759	1869	1992	4037	4821
85	0.3	0	1	3165	3371	1663	1408	1862	5911	6263	6609	11132

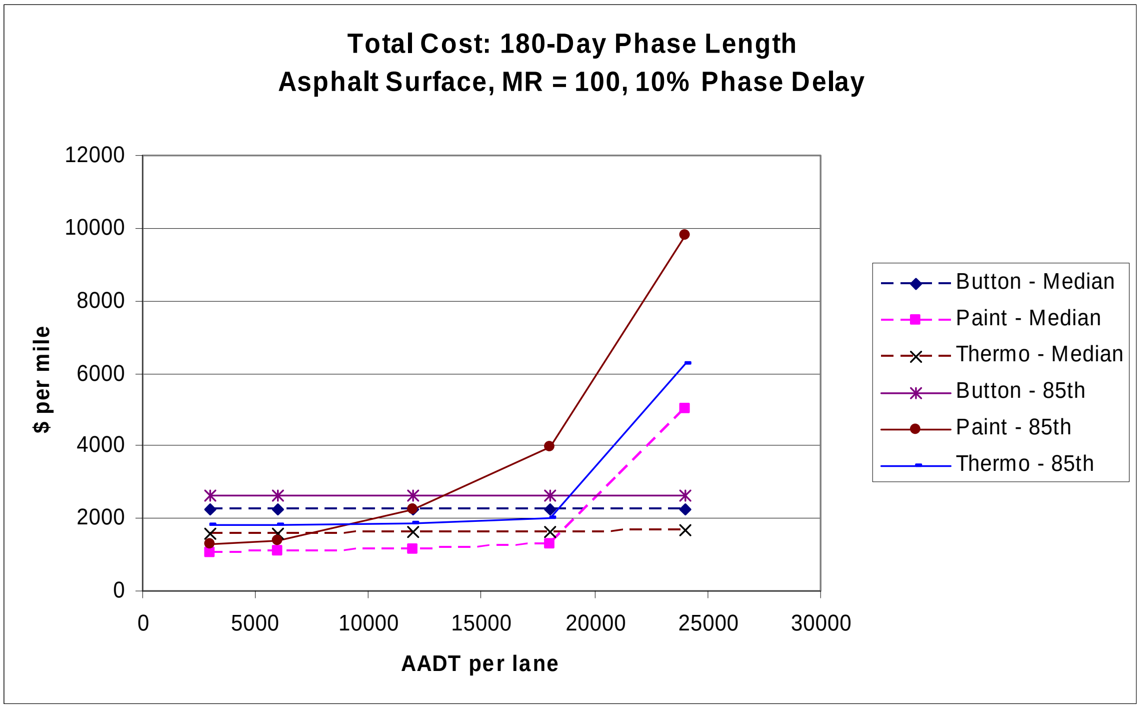


Figure B12. Total Cost – Asphalt Surface, Conservative Phase Variability, 180 Days.

Table B13. Simulation – Asphalt Surface, Conservative Phase Variability, 360 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
12	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	360	-10.00	2.65
32	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	360	-10.00	2.65
52	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	360	-10.00	2.65
72	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	360	-10.00	2.65
92	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	360	-10.00	2.65
10	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	360	-10.00	2.65
30	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	360	-10.00	2.65
50	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	360	-10.00	2.65
70	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	360	-10.00	2.65
90	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	360	-10.00	2.65
11	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	360	-10.00	2.65
31	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	360	-10.00	2.65
51	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	360	-10.00	2.65
71	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	360	-10.00	2.65
91	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	360	-10.00	2.65
9	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	360	-10.00	2.65
29	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	360	-10.00	2.65
49	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	360	-10.00	2.65
69	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	360	-10.00	2.65
89	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	360	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
12	0.0	0	0	2234	369	2233	1852	2424	2542	2614	2701	2835
32	0.0	0	0	2237	377	2234	1859	2423	2541	2612	2702	2839
52	0.0	0	0	2263	454	2239	1860	2433	2551	2626	2722	2876
72	0.1	0	0	2417	856	2260	1870	2469	2603	2699	2842	4574
92	0.2	0	1	3160	2100	2328	1900	2602	2891	6761	7427	7986
10	0.1	0	0	1154	385	1082	857	1207	1295	1362	1501	2077
30	0.3	0	1	1416	810	1130	880	1314	1734	2161	2573	3290
50	1.2	1	2	2373	1711	2001	1010	2510	2996	3609	4655	6480
70	2.1	1	3	5420	4451	3550	2723	5391	6896	8306	11655	17265
90	2.9	2	5	13233	11726	9337	5117	13264	17265	21131	29841	46044
11	0.0	0	0	4026	752	3968	3436	4242	4410	4516	4655	4887
31	0.3	0	1	4963	2074	4161	3520	4648	6850	7609	8212	8944
51	1.3	1	2	9185	3201	8355	7039	9315	10728	11830	12870	14561
71	2.1	2	3	14615	5959	13870	9195	15573	17522	19043	20716	24424
91	3.0	3	4	25234	10462	23649	17390	26845	30356	32776	35805	42631
9	0.0	0	0	1584	205	1584	1371	1691	1756	1795	1847	1921
29	0.1	0	0	1691	458	1602	1381	1722	1801	1858	1951	2912
49	0.3	0	1	2143	1223	1664	1408	1860	2896	3241	3581	4963
69	0.8	1	1	3636	2872	3487	1485	4261	4577	4882	6774	9957
89	1.3	1	2	7626	6197	6294	1705	6754	10579	11219	14889	21974

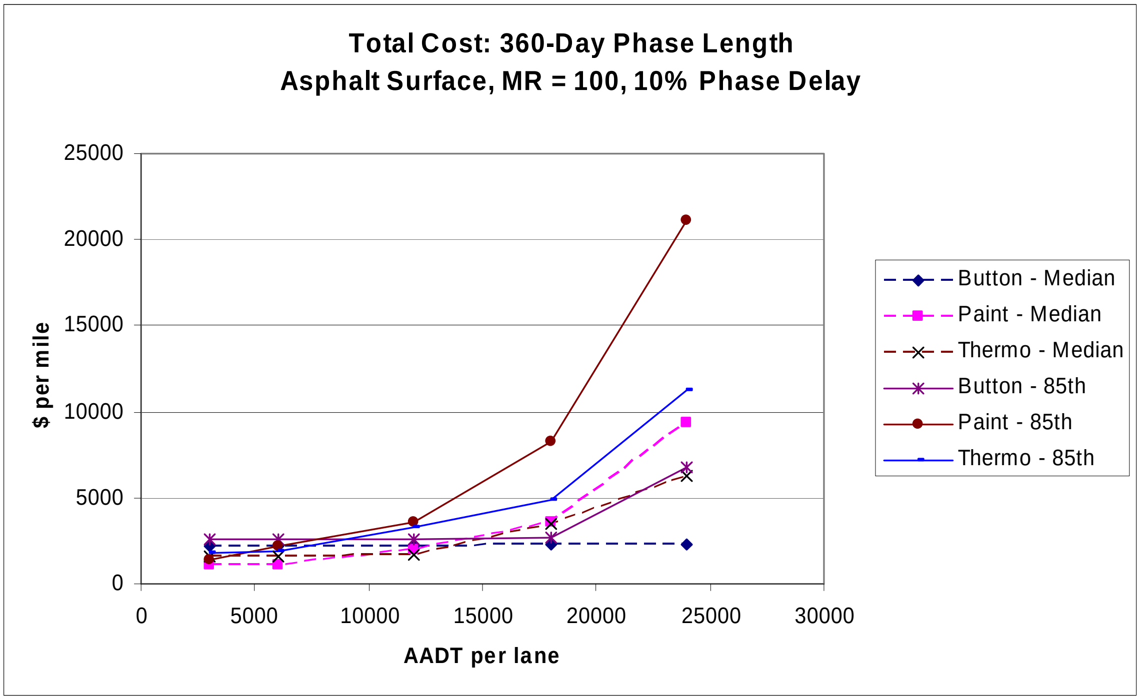


Figure B13. Total Cost – Asphalt Surface, Conservative Phase Variability, 360 Days.

Table B14. Simulation – Asphalt Surface, Conservative Phase Variability, 540 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
16	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	540	-10.00	2.65
36	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	540	-10.00	2.65
56	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	540	-10.00	2.65
76	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	540	-10.00	2.65
96	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	540	-10.00	2.65
14	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	540	-10.00	2.65
34	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	540	-10.00	2.65
54	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	540	-10.00	2.65
74	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	540	-10.00	2.65
94	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	540	-10.00	2.65
15	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	540	-10.00	2.65
35	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	540	-10.00	2.65
55	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	540	-10.00	2.65
75	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	540	-10.00	2.65
95	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	540	-10.00	2.65
13	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	540	-10.00	2.65
33	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	540	-10.00	2.65
53	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	540	-10.00	2.65
73	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	540	-10.00	2.65
93	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	540	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
16	0.0	0	0	2252	416	2237	1862	2429	2547	2619	2713	2858
36	0.0	0	0	2307	558	2249	1865	2447	2573	2656	2767	2985
56	0.2	0	1	2707	1052	2352	1909	2657	3190	4090	4567	5055
76	0.5	1	1	4027	1781	4471	2073	5401	5755	5949	6184	6522
96	0.9	1	1	6949	2265	7439	5804	7888	8156	8319	8544	8946
14	0.2	0	0	1285	650	1100	865	1241	1362	1523	2173	2896
34	0.7	0	1	1832	1287	1264	920	2050	2439	2750	3554	4954
54	2.1	1	3	3432	2509	2532	1763	3429	4272	5118	6870	9703
74	3.4	2	5	8056	6749	5617	3203	7831	10160	12442	17341	26316
94	4.6	3	7	20349	17583	13791	8998	19248	25850	31679	44931	70106
15	0.1	0	0	4286	1317	4013	3455	4320	4530	4679	4946	7557
35	0.9	1	1	7354	2753	7601	4088	8387	8854	9181	9713	11651
55	2.1	2	3	12584	4915	11949	8214	13535	14964	16209	17780	20690
75	3.5	3	5	21212	8567	19484	14252	22754	25440	27260	30090	35514
95	4.8	4	6	37704	15776	34012	25421	40403	45084	48641	53800	63620
13	0.0	0	0	1655	395	1596	1377	1711	1787	1835	1905	2105
33	0.2	0	0	1866	821	1623	1390	1760	1872	1994	3036	3750
53	0.8	1	1	2887	1847	2547	1481	3316	3623	3895	4849	6908
73	1.5	1	2	5565	3857	4358	3542	5137	6929	7536	9606	14627
93	2.2	2	3	11863	9335	9982	6050	11381	15251	16409	21038	34231

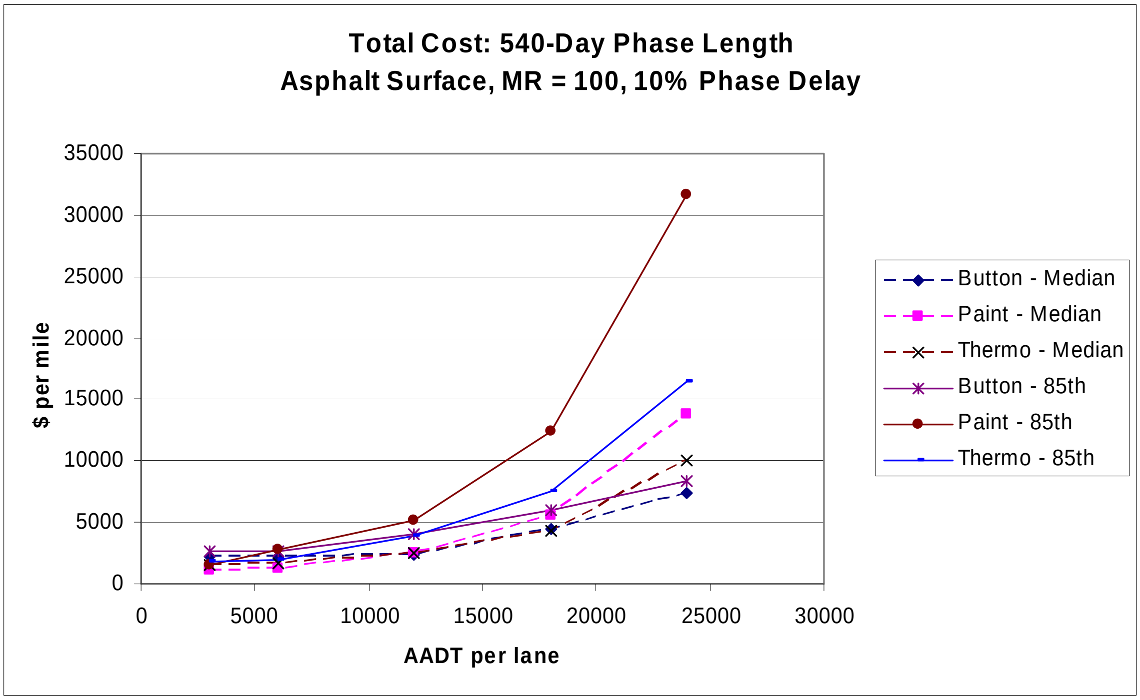


Figure B14. Total Cost – Asphalt Surface, Conservative Phase Variability, 540 Days.

Table B15. Simulation – Asphalt Surface, Conservative Phase Variability, 720 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
20	Button	Asphalt	Solid Edge White	3000	100	0	100000	2233	364	38.8	7.8	720	-10.00	2.65
40	Button	Asphalt	Solid Edge White	6000	100	0	100000	2233	364	31.3	6.3	720	-10.00	2.65
60	Button	Asphalt	Solid Edge White	12000	100	0	100000	2233	364	23.8	4.8	720	-10.00	2.65
80	Button	Asphalt	Solid Edge White	18000	100	0	100000	2233	364	19.4	3.9	720	-10.00	2.65
100	Button	Asphalt	Solid Edge White	24000	100	0	100000	2233	364	16.3	3.3	720	-10.00	2.65
18	Paint	Asphalt	Solid Edge White	3000	100	0	100000	1056	205	44.6	23.6	720	-10.00	2.65
38	Paint	Asphalt	Solid Edge White	6000	100	0	100000	1056	205	22.3	11.8	720	-10.00	2.65
58	Paint	Asphalt	Solid Edge White	12000	100	0	100000	1056	205	11.1	5.9	720	-10.00	2.65
78	Paint	Asphalt	Solid Edge White	18000	100	0	100000	1056	205	7.4	3.9	720	-10.00	2.65
98	Paint	Asphalt	Solid Edge White	24000	100	0	100000	1056	205	5.6	2.9	720	-10.00	2.65
19	Tape	Asphalt	Solid Edge White	3000	100	0	100000	3960	512	33.3	9.3	720	-10.00	2.65
39	Tape	Asphalt	Solid Edge White	6000	100	0	100000	3960	512	16.6	4.7	720	-10.00	2.65
59	Tape	Asphalt	Solid Edge White	12000	100	0	100000	3960	512	8.3	2.3	720	-10.00	2.65
79	Tape	Asphalt	Solid Edge White	18000	100	0	100000	3960	512	5.5	1.6	720	-10.00	2.65
99	Tape	Asphalt	Solid Edge White	24000	100	0	100000	3960	512	4.2	1.2	720	-10.00	2.65
17	Thermo	Asphalt	Solid Edge White	3000	100	0	100000	1584	205	77.9	34.3	720	-10.00	2.65
37	Thermo	Asphalt	Solid Edge White	6000	100	0	100000	1584	205	39.0	17.2	720	-10.00	2.65
57	Thermo	Asphalt	Solid Edge White	12000	100	0	100000	1584	205	19.5	8.6	720	-10.00	2.65
77	Thermo	Asphalt	Solid Edge White	18000	100	0	100000	1584	205	13.0	5.7	720	-10.00	2.65
97	Thermo	Asphalt	Solid Edge White	24000	100	0	100000	1584	205	9.7	4.3	720	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
20	0.1	0	0	2357	651	2259	1868	2468	2603	2697	2840	3545
40	0.2	0	1	2733	1056	2366	1917	2693	3517	4145	4570	5042
60	0.7	1	1	3900	1284	4157	2249	4696	4984	5155	5369	5700
80	1.0	1	1	5567	1297	5517	4655	5942	6216	6404	6680	7567
100	1.2	1	2	8564	2446	7763	6905	8314	8921	11759	12780	13672
18	0.3	0	1	1411	804	1130	878	1312	1720	2143	2554	3263
38	1.2	1	2	2317	1646	1950	1010	2454	2915	3493	4510	6239
58	2.9	2	5	4361	3318	3242	2069	4308	5441	6547	8765	12772
78	4.6	3	7	10747	8949	7519	4852	10367	13523	16637	23246	35035
98	6.4	4	10	27544	23503	18484	12236	26417	34845	43130	60342	94043
19	0.3	0	1	4966	2071	4163	3519	4653	6873	7616	8211	8942
39	1.3	1	2	9107	3136	8305	6993	9242	10561	11680	12731	14427
59	3.0	3	4	16128	6312	14764	11310	17420	19234	20662	22720	26603
79	4.8	4	6	27806	11292	25349	19075	29763	33169	35721	39423	46822
99	6.5	6	8	50127	20888	45410	34226	53512	59832	64490	71412	84731
17	0.1	0	0	1691	456	1603	1380	1724	1803	1861	1956	2910
37	0.3	0	1	2130	1197	1664	1409	1862	2843	3185	3532	4913
57	1.3	1	2	3716	2260	3259	1700	3702	4502	5121	6026	8930
77	2.2	2	3	7268	5168	5799	3977	7237	9000	10057	12462	19192
97	3.1	2	4	15901	12294	11403	6501	15872	19975	22166	28633	45045

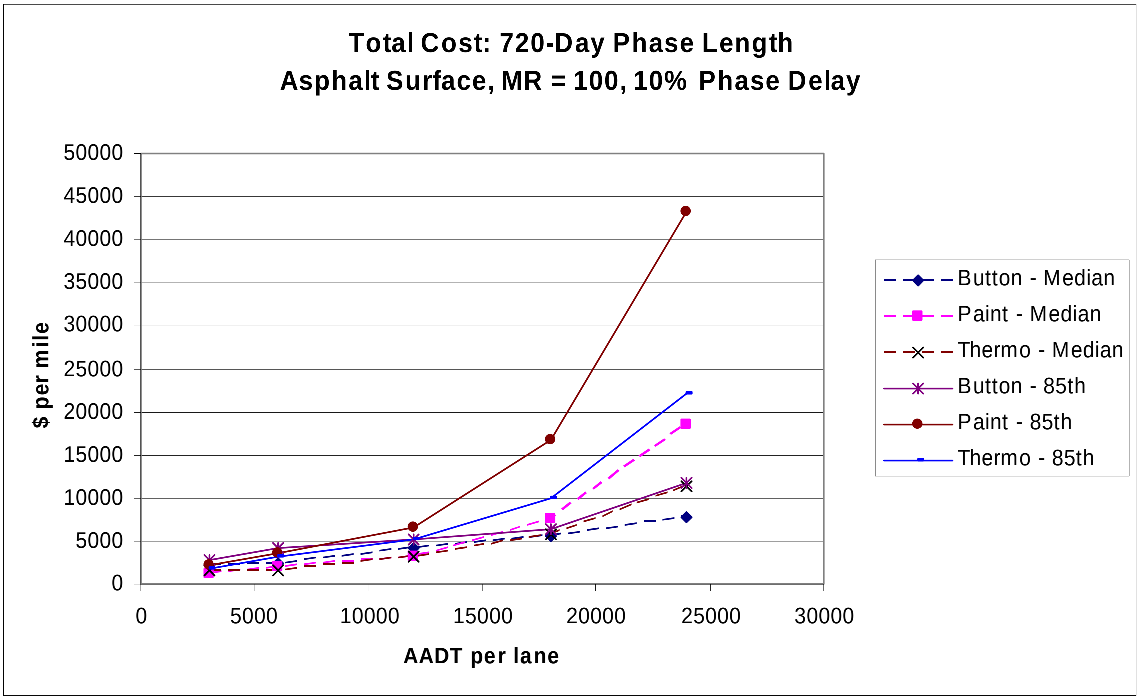


Figure B15. Total Cost – Asphalt Surface, Conservative Phase Variability, 720 Days.

Table B16. Simulation – Concrete Surface, Conservative Phase Variability, 90 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
4	Button	Concrete	Solid Edge White	3000	100	-10	100000	2233	364	38.8	7.8	90	-10.00	2.65
24	Button	Concrete	Solid Edge White	6000	100	-10	100000	2233	364	31.3	6.3	90	-10.00	2.65
44	Button	Concrete	Solid Edge White	12000	100	-10	100000	2233	364	23.8	4.8	90	-10.00	2.65
64	Button	Concrete	Solid Edge White	18000	100	-10	100000	2233	364	19.4	3.9	90	-10.00	2.65
84	Button	Concrete	Solid Edge White	24000	100	-10	100000	2233	364	16.3	3.3	90	-10.00	2.65
2	Paint	Concrete	Solid Edge White	3000	100	-10	100000	1056	205	53.4	23.2	90	-10.00	2.65
22	Paint	Concrete	Solid Edge White	6000	100	-10	100000	1056	205	26.7	11.6	90	-10.00	2.65
42	Paint	Concrete	Solid Edge White	12000	100	-10	100000	1056	205	13.4	5.8	90	-10.00	2.65
62	Paint	Concrete	Solid Edge White	18000	100	-10	100000	1056	205	8.9	3.9	90	-10.00	2.65
82	Paint	Concrete	Solid Edge White	24000	100	-10	100000	1056	205	6.7	2.9	90	-10.00	2.65
3	Tape	Concrete	Solid Edge White	3000	100	-10	100000	3960	512	33.5	8.3	90	-10.00	2.65
23	Tape	Concrete	Solid Edge White	6000	100	-10	100000	3960	512	16.7	4.2	90	-10.00	2.65
43	Tape	Concrete	Solid Edge White	12000	100	-10	100000	3960	512	8.4	2.1	90	-10.00	2.65
63	Tape	Concrete	Solid Edge White	18000	100	-10	100000	3960	512	5.6	1.4	90	-10.00	2.65
83	Tape	Concrete	Solid Edge White	24000	100	-10	100000	3960	512	4.2	1.0	90	-10.00	2.65
1	Thermo	Concrete	Solid Edge White	3000	100	-10	100000	1584	205	68.9	29.0	90	-10.00	2.65
21	Thermo	Concrete	Solid Edge White	6000	100	-10	100000	1584	205	34.5	14.5	90	-10.00	2.65
41	Thermo	Concrete	Solid Edge White	12000	100	-10	100000	1584	205	17.2	7.2	90	-10.00	2.65
61	Thermo	Concrete	Solid Edge White	18000	100	-10	100000	1584	205	11.5	4.8	90	-10.00	2.65
81	Thermo	Concrete	Solid Edge White	24000	100	-10	100000	1584	205	8.6	3.6	90	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
4	0.0	0	0	2233	363	2234	1857	2424	2539	2609	2697	2828
24	0.0	0	0	2234	365	2236	1857	2425	2540	2612	2701	2832
44	0.0	0	0	2235	364	2234	1857	2425	2542	2612	2703	2836
64	0.0	0	0	2230	363	2230	1855	2420	2535	2606	2696	2828
84	0.0	0	0	2231	364	2231	1853	2422	2537	2607	2696	2829
2	0.0	0	0	1056	205	1056	845	1163	1228	1269	1319	1392
22	0.0	0	0	1057	205	1056	844	1164	1229	1269	1321	1394
42	0.0	0	0	1104	315	1067	850	1182	1254	1303	1371	1523
62	0.1	0	0	1206	585	1075	853	1196	1279	1338	1439	2934
82	0.2	0	0	1731	1959	1092	861	1226	1332	1432	4944	5709
3	0.0	0	0	3957	512	3957	3427	4227	4388	4488	4610	4797
23	0.0	0	0	3959	515	3959	3427	4228	4393	4491	4617	4805
43	0.0	0	0	3990	631	3966	3429	4236	4400	4502	4632	4839
63	0.1	0	0	4227	1305	3996	3447	4286	4473	4603	4796	6927
83	0.2	0	1	5427	3112	4122	3504	4548	5478	10339	11046	11811
1	0.0	0	0	1585	205	1585	1373	1693	1759	1799	1848	1922
21	0.0	0	0	1584	204	1584	1371	1690	1756	1796	1845	1920
41	0.0	0	0	1585	212	1583	1371	1690	1756	1795	1847	1921
61	0.0	0	0	1703	589	1596	1378	1712	1785	1835	1907	2123
81	0.1	0	0	1928	1260	1605	1382	1726	1807	1866	1970	6066

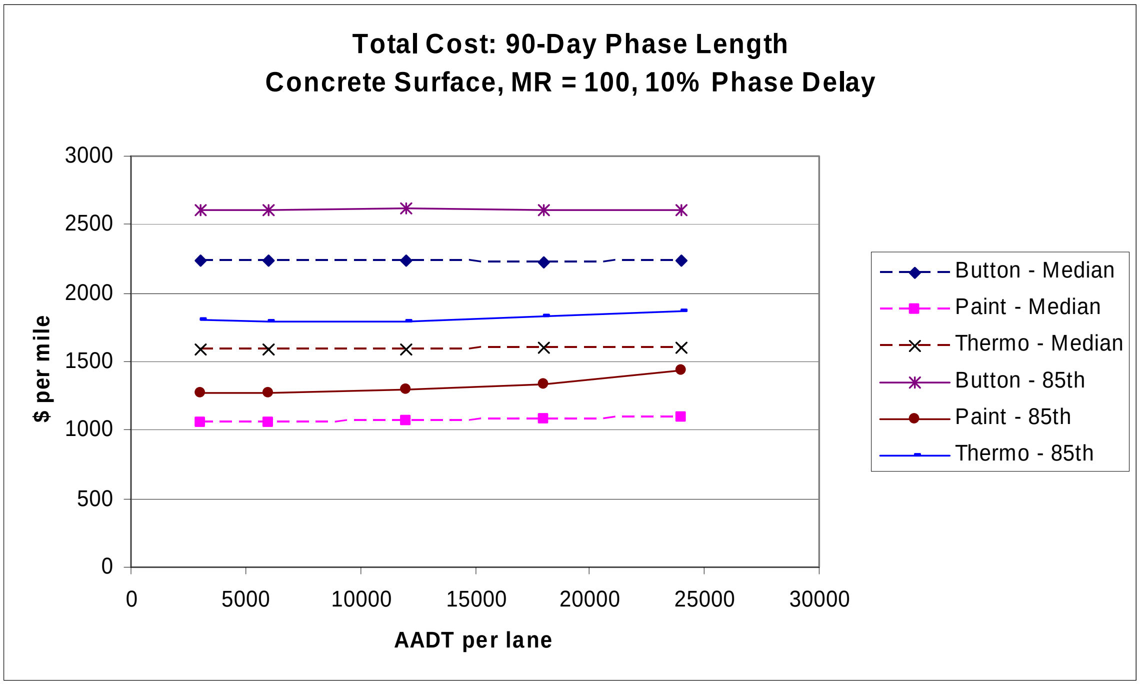


Figure B16. Total Cost – Concrete Surface, Conservative Phase Variability, 90 Days.

Table B17. Simulation – Concrete Surface, Conservative Phase Variability, 180 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
8	Button	Concrete	Solid Edge White	3000	100	-10	100000	2233	364	38.8	7.8	180	-10.00	2.65
28	Button	Concrete	Solid Edge White	6000	100	-10	100000	2233	364	31.3	6.3	180	-10.00	2.65
48	Button	Concrete	Solid Edge White	12000	100	-10	100000	2233	364	23.8	4.8	180	-10.00	2.65
68	Button	Concrete	Solid Edge White	18000	100	-10	100000	2233	364	19.4	3.9	180	-10.00	2.65
88	Button	Concrete	Solid Edge White	24000	100	-10	100000	2233	364	16.3	3.3	180	-10.00	2.65
6	Paint	Concrete	Solid Edge White	3000	100	-10	100000	1056	205	53.4	23.2	180	-10.00	2.65
26	Paint	Concrete	Solid Edge White	6000	100	-10	100000	1056	205	26.7	11.6	180	-10.00	2.65
46	Paint	Concrete	Solid Edge White	12000	100	-10	100000	1056	205	13.4	5.8	180	-10.00	2.65
66	Paint	Concrete	Solid Edge White	18000	100	-10	100000	1056	205	8.9	3.9	180	-10.00	2.65
86	Paint	Concrete	Solid Edge White	24000	100	-10	100000	1056	205	6.7	2.9	180	-10.00	2.65
7	Tape	Concrete	Solid Edge White	3000	100	-10	100000	3960	512	33.5	8.3	180	-10.00	2.65
27	Tape	Concrete	Solid Edge White	6000	100	-10	100000	3960	512	16.7	4.2	180	-10.00	2.65
47	Tape	Concrete	Solid Edge White	12000	100	-10	100000	3960	512	8.4	2.1	180	-10.00	2.65
67	Tape	Concrete	Solid Edge White	18000	100	-10	100000	3960	512	5.6	1.4	180	-10.00	2.65
87	Tape	Concrete	Solid Edge White	24000	100	-10	100000	3960	512	4.2	1.0	180	-10.00	2.65
5	Thermo	Concrete	Solid Edge White	3000	100	-10	100000	1584	205	68.9	29.0	180	-10.00	2.65
25	Thermo	Concrete	Solid Edge White	6000	100	-10	100000	1584	205	34.5	14.5	180	-10.00	2.65
45	Thermo	Concrete	Solid Edge White	12000	100	-10	100000	1584	205	17.2	7.2	180	-10.00	2.65
65	Thermo	Concrete	Solid Edge White	18000	100	-10	100000	1584	205	11.5	4.8	180	-10.00	2.65
85	Thermo	Concrete	Solid Edge White	24000	100	-10	100000	1584	205	8.6	3.6	180	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
8	0.0	0	0	2234	364	2235	1856	2426	2541	2610	2700	2832
28	0.0	0	0	2233	365	2233	1855	2424	2540	2613	2701	2833
48	0.0	0	0	2233	365	2233	1856	2423	2537	2609	2701	2829
68	0.0	0	0	2236	370	2234	1861	2424	2541	2612	2701	2832
88	0.0	0	0	2241	423	2232	1857	2423	2541	2612	2704	2841
6	0.0	0	0	1056	205	1056	844	1164	1229	1268	1317	1390
26	0.0	0	0	1100	306	1066	848	1181	1253	1303	1370	1522
46	0.2	0	0	1239	587	1092	860	1225	1328	1426	1924	2570
66	0.4	0	1	1869	1584	1156	890	1424	3002	3265	3598	5583
86	0.7	0	1	4064	4199	1477	945	5232	5542	5805	9158	13567
7	0.0	0	0	3962	515	3960	3432	4229	4393	4493	4620	4805
27	0.0	0	0	3992	625	3965	3432	4240	4408	4510	4643	4841
47	0.2	0	1	4796	1857	4118	3509	4542	5316	7315	8032	8767
67	0.8	1	1	8083	2885	8619	4145	9343	9768	10046	10433	11546
87	1.2	1	2	12641	4196	11330	10067	12181	13838	17234	18398	19839
5	0.0	0	0	1584	205	1584	1372	1692	1757	1797	1847	1922
25	0.0	0	0	1587	211	1585	1374	1693	1757	1797	1847	1922
45	0.1	0	0	1704	493	1604	1381	1725	1806	1864	1965	3042
65	0.2	0	1	2117	1353	1633	1397	1778	1918	3574	4211	4919
85	0.4	0	1	3454	3466	1692	1420	2023	6169	6409	6714	11201

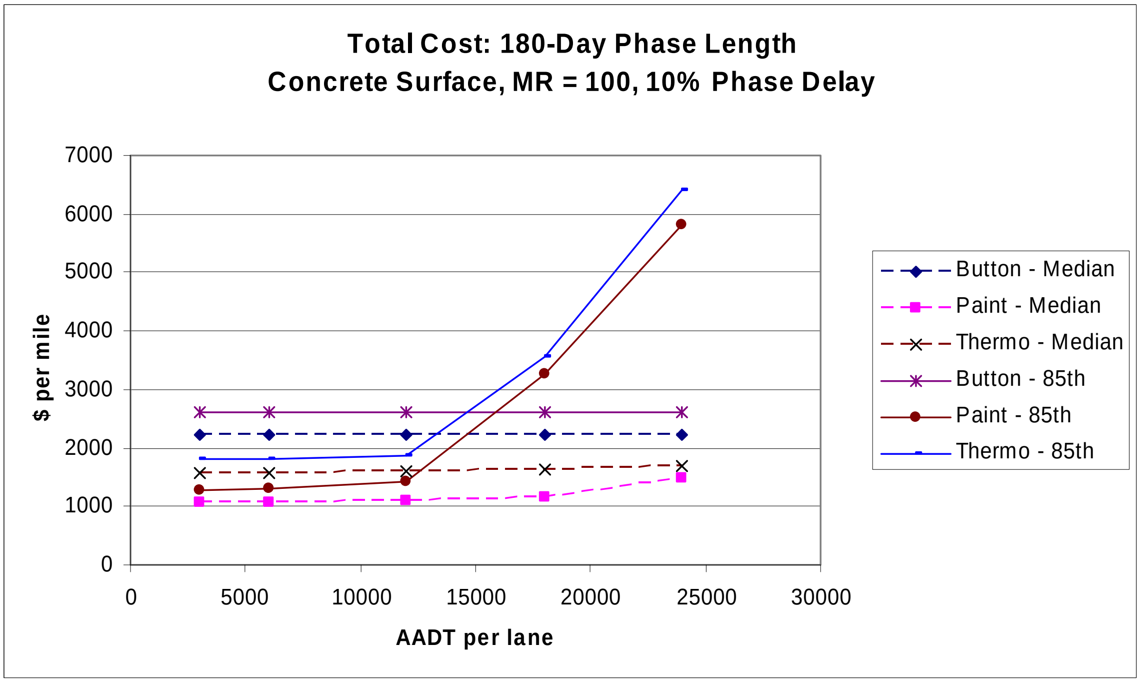


Figure B17. Total Cost – Concrete Surface, Conservative Phase Variability, 180 Days.

Table B18. Simulation – Concrete Surface, Conservative Phase Variability, 360 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
12	Button	Concrete	Solid Edge White	3000	100	-10	100000	2233	364	38.8	7.8	360	-10.00	2.65
32	Button	Concrete	Solid Edge White	6000	100	-10	100000	2233	364	31.3	6.3	360	-10.00	2.65
52	Button	Concrete	Solid Edge White	12000	100	-10	100000	2233	364	23.8	4.8	360	-10.00	2.65
72	Button	Concrete	Solid Edge White	18000	100	-10	100000	2233	364	19.4	3.9	360	-10.00	2.65
92	Button	Concrete	Solid Edge White	24000	100	-10	100000	2233	364	16.3	3.3	360	-10.00	2.65
10	Paint	Concrete	Solid Edge White	3000	100	-10	100000	1056	205	53.4	23.2	360	-10.00	2.65
30	Paint	Concrete	Solid Edge White	6000	100	-10	100000	1056	205	26.7	11.6	360	-10.00	2.65
50	Paint	Concrete	Solid Edge White	12000	100	-10	100000	1056	205	13.4	5.8	360	-10.00	2.65
70	Paint	Concrete	Solid Edge White	18000	100	-10	100000	1056	205	8.9	3.9	360	-10.00	2.65
90	Paint	Concrete	Solid Edge White	24000	100	-10	100000	1056	205	6.7	2.9	360	-10.00	2.65
11	Tape	Concrete	Solid Edge White	3000	100	-10	100000	3960	512	33.5	8.3	360	-10.00	2.65
31	Tape	Concrete	Solid Edge White	6000	100	-10	100000	3960	512	16.7	4.2	360	-10.00	2.65
51	Tape	Concrete	Solid Edge White	12000	100	-10	100000	3960	512	8.4	2.1	360	-10.00	2.65
71	Tape	Concrete	Solid Edge White	18000	100	-10	100000	3960	512	5.6	1.4	360	-10.00	2.65
91	Tape	Concrete	Solid Edge White	24000	100	-10	100000	3960	512	4.2	1.0	360	-10.00	2.65
9	Thermo	Concrete	Solid Edge White	3000	100	-10	100000	1584	205	68.9	29.0	360	-10.00	2.65
29	Thermo	Concrete	Solid Edge White	6000	100	-10	100000	1584	205	34.5	14.5	360	-10.00	2.65
49	Thermo	Concrete	Solid Edge White	12000	100	-10	100000	1584	205	17.2	7.2	360	-10.00	2.65
69	Thermo	Concrete	Solid Edge White	18000	100	-10	100000	1584	205	11.5	4.8	360	-10.00	2.65
89	Thermo	Concrete	Solid Edge White	24000	100	-10	100000	1584	205	8.6	3.6	360	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
12	0.0	0	0	2235	368	2234	1857	2424	2542	2613	2702	2833
32	0.0	0	0	2237	376	2234	1861	2423	2538	2609	2698	2832
52	0.0	0	0	2265	463	2238	1860	2433	2554	2627	2726	2883
72	0.1	0	0	2415	853	2259	1867	2469	2606	2700	2844	4572
92	0.2	0	1	3161	2102	2327	1900	2603	2896	6748	7444	7997
10	0.0	0	0	1099	303	1067	847	1181	1254	1302	1369	1514
30	0.2	0	0	1233	566	1094	864	1225	1329	1424	1877	2523
50	0.7	0	1	1878	1221	1407	943	2197	2492	2705	3165	4444
70	1.5	1	2	4127	3048	3273	2370	3847	5221	5774	7263	11004
90	2.1	1	3	9807	7835	6079	4975	9693	12796	13991	17861	28087
11	0.0	0	0	3993	628	3967	3436	4238	4404	4507	4639	4844
31	0.2	0	1	4785	1840	4119	3505	4543	5336	7251	7982	8724
51	1.2	1	2	8915	2593	8295	7044	9118	10011	11167	12321	13663
71	2.0	2	3	14165	4764	13807	9326	15272	16614	18029	19721	22152
91	2.9	3	4	24436	8452	23528	17438	26389	28794	31355	33848	39109
9	0.0	0	0	1586	211	1585	1373	1692	1757	1797	1847	1922
29	0.1	0	0	1703	481	1604	1383	1725	1808	1868	1969	2997
49	0.4	0	1	2241	1258	1692	1419	2012	3142	3381	3689	5028
69	0.9	1	2	4062	2890	3973	1540	4415	4753	5960	7065	10097
89	1.5	1	2	8603	6498	6432	5686	7125	11014	11552	15522	22092

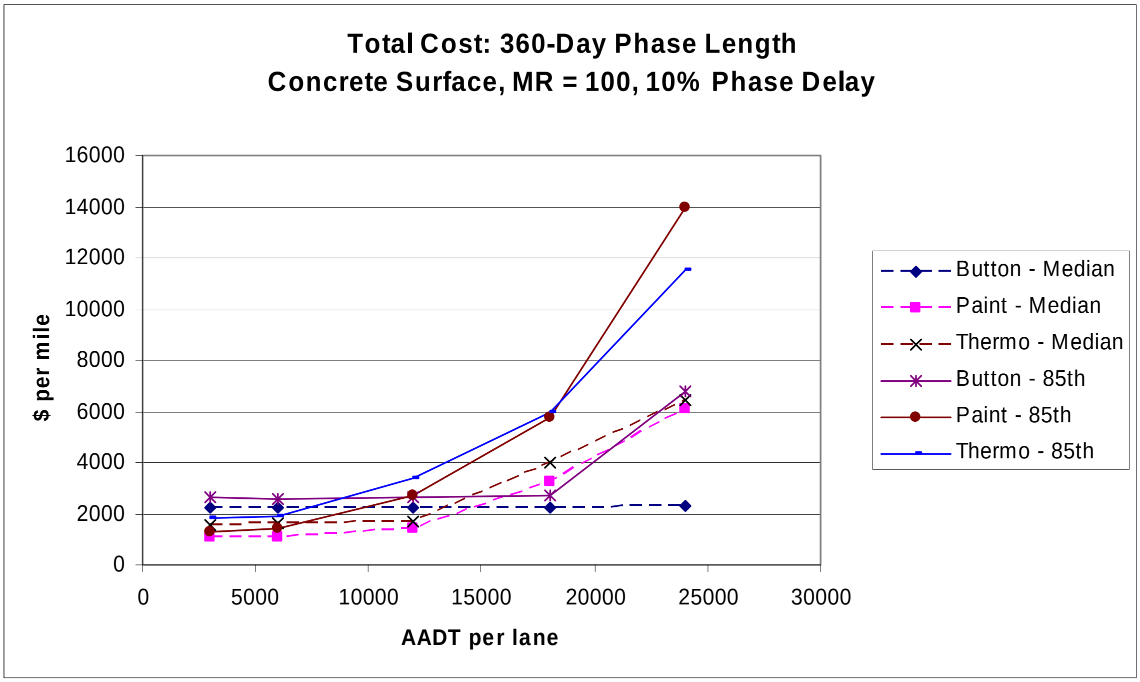


Figure B18. Total Cost – Concrete Surface, Conservative Phase Variability, 360 Days.

Table B19. Simulation – Concrete Surface, Conservative Phase Variability, 540 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
16	Button	Concrete	Solid Edge White	3000	100	-10	100000	2233	364	38.8	7.8	540	-10.00	2.65
36	Button	Concrete	Solid Edge White	6000	100	-10	100000	2233	364	31.3	6.3	540	-10.00	2.65
56	Button	Concrete	Solid Edge White	12000	100	-10	100000	2233	364	23.8	4.8	540	-10.00	2.65
76	Button	Concrete	Solid Edge White	18000	100	-10	100000	2233	364	19.4	3.9	540	-10.00	2.65
96	Button	Concrete	Solid Edge White	24000	100	-10	100000	2233	364	16.3	3.3	540	-10.00	2.65
14	Paint	Concrete	Solid Edge White	3000	100	-10	100000	1056	205	53.4	23.2	540	-10.00	2.65
34	Paint	Concrete	Solid Edge White	6000	100	-10	100000	1056	205	26.7	11.6	540	-10.00	2.65
54	Paint	Concrete	Solid Edge White	12000	100	-10	100000	1056	205	13.4	5.8	540	-10.00	2.65
74	Paint	Concrete	Solid Edge White	18000	100	-10	100000	1056	205	8.9	3.9	540	-10.00	2.65
94	Paint	Concrete	Solid Edge White	24000	100	-10	100000	1056	205	6.7	2.9	540	-10.00	2.65
15	Tape	Concrete	Solid Edge White	3000	100	-10	100000	3960	512	33.5	8.3	540	-10.00	2.65
35	Tape	Concrete	Solid Edge White	6000	100	-10	100000	3960	512	16.7	4.2	540	-10.00	2.65
55	Tape	Concrete	Solid Edge White	12000	100	-10	100000	3960	512	8.4	2.1	540	-10.00	2.65
75	Tape	Concrete	Solid Edge White	18000	100	-10	100000	3960	512	5.6	1.4	540	-10.00	2.65
95	Tape	Concrete	Solid Edge White	24000	100	-10	100000	3960	512	4.2	1.0	540	-10.00	2.65
13	Thermo	Concrete	Solid Edge White	3000	100	-10	100000	1584	205	68.9	29.0	540	-10.00	2.65
33	Thermo	Concrete	Solid Edge White	6000	100	-10	100000	1584	205	34.5	14.5	540	-10.00	2.65
53	Thermo	Concrete	Solid Edge White	12000	100	-10	100000	1584	205	17.2	7.2	540	-10.00	2.65
73	Thermo	Concrete	Solid Edge White	18000	100	-10	100000	1584	205	11.5	4.8	540	-10.00	2.65
93	Thermo	Concrete	Solid Edge White	24000	100	-10	100000	1584	205	8.6	3.6	540	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
16	0.0	0	0	2249	417	2237	1856	2428	2547	2619	2712	2855
36	0.0	0	0	2308	557	2249	1865	2451	2578	2658	2773	2994
56	0.2	0	1	2708	1057	2349	1909	2655	3216	4092	4570	5070
76	0.5	1	1	4020	1788	4443	2070	5403	5757	5947	6178	6520
96	0.9	1	1	6961	2258	7444	5883	7894	8160	8324	8542	8935
14	0.1	0	0	1134	357	1076	855	1197	1279	1337	1434	1906
34	0.4	0	1	1473	859	1154	888	1400	1992	2242	2540	3316
54	1.5	1	2	2720	1730	2298	1443	2746	3300	3760	4462	6442
74	2.4	2	4	6073	4502	4930	3005	6020	7498	8530	10589	16225
94	3.4	2	5	15103	11748	10542	8355	14528	18339	21729	26741	42189
15	0.1	0	0	4168	1082	3993	3448	4280	4469	4599	4789	5818
35	0.8	1	1	7244	2366	7601	4144	8324	8754	9025	9413	10322
55	2.1	2	3	12237	4034	11896	8334	13310	14425	15390	16798	18984
75	3.3	3	4	20534	6899	19368	14414	22156	24521	26051	28179	32192
95	4.6	4	6	36447	12466	33815	25761	39431	43191	46125	50164	57829
13	0.0	0	0	1655	391	1597	1377	1712	1787	1836	1904	2091
33	0.2	0	1	1908	852	1634	1398	1779	1913	2517	3182	3779
53	0.9	1	2	3146	1856	3016	1540	3460	3771	4184	5112	7007
73	1.7	1	3	6138	4092	4513	3830	6547	7316	8381	10108	14983
93	2.5	2	4	13088	9912	10792	6175	12062	15989	19041	22467	34625

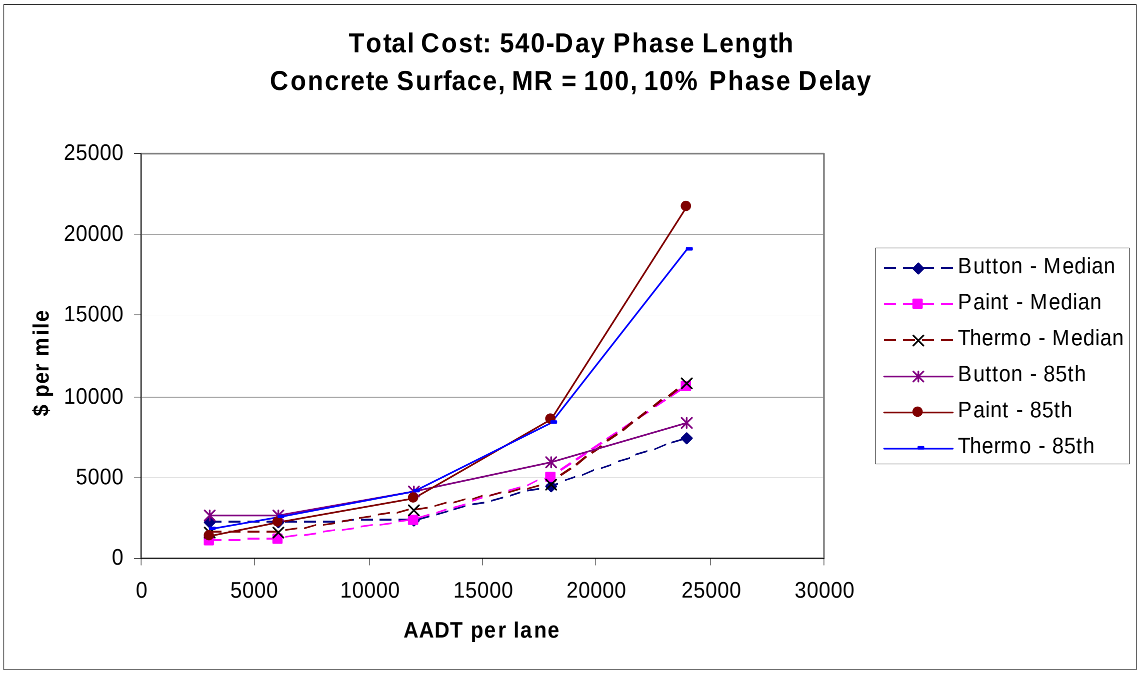


Figure B19. Total Cost – Concrete Surface, Conservative Phase Variability, 540 Days.

Table B20. Simulation – Concrete Surface, Conservative Phase Variability, 720 Days.

(a) Scenario Inputs

num	marking	pvmt.type	line.type	AADT	minR	proj.diff	nsim	cost	cost.sd	life	life.sd	contract.len	diff	diff.sd
20	Button	Concrete	Solid Edge White	3000	100	-10	100000	2233	364	38.8	7.8	720	-10.00	2.65
40	Button	Concrete	Solid Edge White	6000	100	-10	100000	2233	364	31.3	6.3	720	-10.00	2.65
60	Button	Concrete	Solid Edge White	12000	100	-10	100000	2233	364	23.8	4.8	720	-10.00	2.65
80	Button	Concrete	Solid Edge White	18000	100	-10	100000	2233	364	19.4	3.9	720	-10.00	2.65
100	Button	Concrete	Solid Edge White	24000	100	-10	100000	2233	364	16.3	3.3	720	-10.00	2.65
18	Paint	Concrete	Solid Edge White	3000	100	-10	100000	1056	205	53.4	23.2	720	-10.00	2.65
38	Paint	Concrete	Solid Edge White	6000	100	-10	100000	1056	205	26.7	11.6	720	-10.00	2.65
58	Paint	Concrete	Solid Edge White	12000	100	-10	100000	1056	205	13.4	5.8	720	-10.00	2.65
78	Paint	Concrete	Solid Edge White	18000	100	-10	100000	1056	205	8.9	3.9	720	-10.00	2.65
98	Paint	Concrete	Solid Edge White	24000	100	-10	100000	1056	205	6.7	2.9	720	-10.00	2.65
19	Tape	Concrete	Solid Edge White	3000	100	-10	100000	3960	512	33.5	8.3	720	-10.00	2.65
39	Tape	Concrete	Solid Edge White	6000	100	-10	100000	3960	512	16.7	4.2	720	-10.00	2.65
59	Tape	Concrete	Solid Edge White	12000	100	-10	100000	3960	512	8.4	2.1	720	-10.00	2.65
79	Tape	Concrete	Solid Edge White	18000	100	-10	100000	3960	512	5.6	1.4	720	-10.00	2.65
99	Tape	Concrete	Solid Edge White	24000	100	-10	100000	3960	512	4.2	1.0	720	-10.00	2.65
17	Thermo	Concrete	Solid Edge White	3000	100	-10	100000	1584	205	68.9	29.0	720	-10.00	2.65
37	Thermo	Concrete	Solid Edge White	6000	100	-10	100000	1584	205	34.5	14.5	720	-10.00	2.65
57	Thermo	Concrete	Solid Edge White	12000	100	-10	100000	1584	205	17.2	7.2	720	-10.00	2.65
77	Thermo	Concrete	Solid Edge White	18000	100	-10	100000	1584	205	11.5	4.8	720	-10.00	2.65
97	Thermo	Concrete	Solid Edge White	24000	100	-10	100000	1584	205	8.6	3.6	720	-10.00	2.65

(b) Simulation Outputs

				Total Cost ($/mile)								
num	reapp.mean	reapp.50%	reapp.85%	mean	sd	50.00%	15.00%	70.00%	80.00%	85.00%	90.00%	95.00%
20	0.1	0	0	2358	653	2261	1868	2466	2602	2697	2839	3602
40	0.2	0	1	2723	1052	2361	1914	2682	3443	4117	4555	5029
60	0.7	1	1	3899	1285	4159	2243	4701	4988	5156	5370	5691
80	1.0	1	1	5575	1294	5518	4656	5948	6228	6417	6692	7595
100	1.2	1	2	8557	2441	7757	6904	8309	8912	11751	12780	13674
18	0.2	0	0	1227	559	1092	859	1223	1327	1423	1846	2491
38	0.7	0	1	1834	1153	1400	944	2143	2436	2636	3052	4216
58	2.1	1	3	3419	2218	2698	1937	3544	4171	4714	5705	8209
78	3.4	2	5	8065	5905	6117	4191	8085	9908	11356	13956	21353
98	4.7	3	7	20520	15664	14977	9577	20580	25174	29093	36281	57262
19	0.2	0	1	4789	1848	4121	3505	4542	5354	7271	7972	8731
39	1.2	1	2	8840	2556	8246	6988	9062	9933	11008	12168	13510
59	2.9	3	4	15678	5177	14712	11359	17106	18636	19771	21481	24508
79	4.6	4	6	26845	8966	25149	19285	29019	31902	33942	36887	42222
99	6.3	6	8	48450	16514	45117	34879	52112	57422	61187	66752	76938
17	0.1	0	0	1698	475	1603	1379	1724	1807	1866	1966	2968
37	0.4	0	1	2224	1227	1692	1418	2017	3092	3328	3640	4943
57	1.5	1	2	4069	2372	3401	2656	3970	4927	5405	6415	9201
77	2.5	2	4	8028	5574	6662	4115	7915	9799	11105	13482	20090
97	3.4	3	5	17748	13084	14514	10246	17042	21277	25055	30470	45568

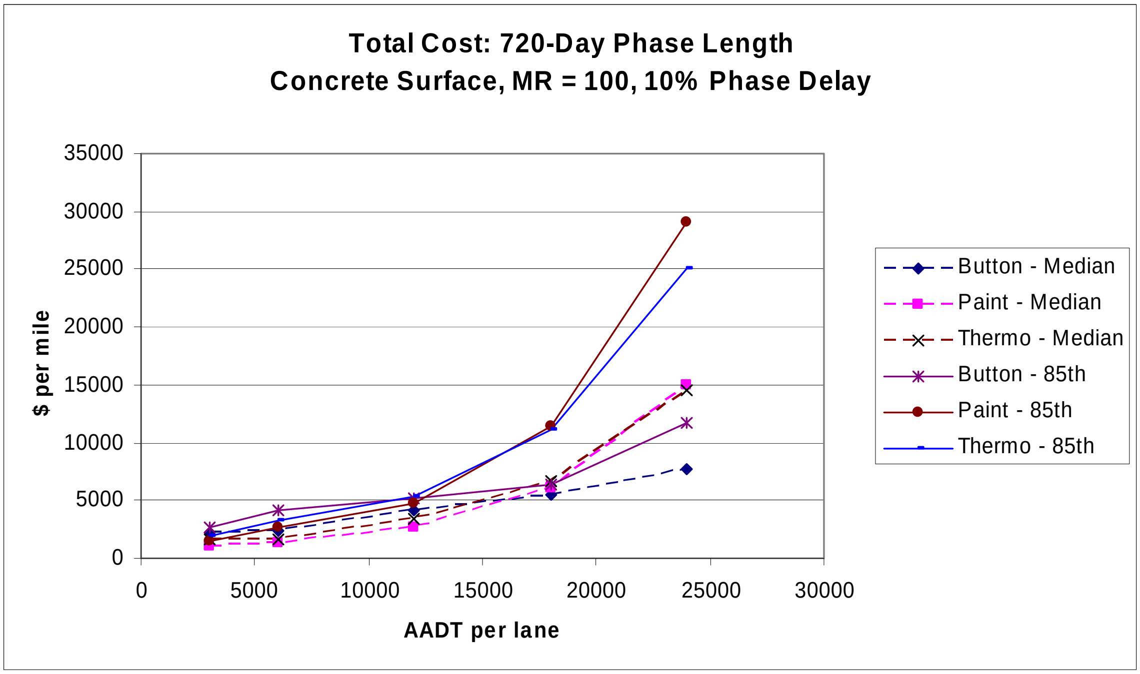


Figure B20. Total Cost – Concrete Surface, Conservative Phase Variability, 720 Days.

APPENDIX C. GUIDELINES FOR TEMPORARY TRAFFIC CONTROL AT AND NEAR URBAN FREEWAY INTERCHANGES

Navigating through work zones that occur within the vicinity of urban freeway interchanges can be particularly challenging to motorists. Numerous existing and temporary guide signs, presence of short auxiliary lane segments, multiple lane exits, high merging traffic, and other conditions in the work zones present complex driving situations and place considerable work load on drivers. Driver work load and driving complexity increases even more when temporary travel paths are in conflict with existing guide signs. The following guidelines pertain to the unique temporary traffic control needs that exist at these types of locations.

MODIFICATIONS TO EXISTING GUIDE SIGNS APPROACHING FREEWAY INTERCHANGES

Highway construction upstream of freeway interchanges often requires temporary lateral shifting of travel lanes. Depending on the construction sequencing and phasing, several lateral shifts may be required. In freeway widening projects, additional lanes may even be made available at various stages in the construction cycle. Such changes to the lane alignments can create discontinuities with the guide signing system on the approach to the interchange. Furthermore, the installation of the new guide signing system cannot typically occur until the very end of the project once the final lane alignment is obtained, support structures are completed, etc. Under these conditions, it may be necessary to modify and temporarily supplement the existing guide signing system until the new guide signs can be installed. When this does occur, the following points should be considered:

- Efforts should be made to re-position guide sign panels over the lanes they pertain to as much as possible.
- If limitations of the sign support or other factors limit the extent to which sign panels can be moved laterally over their applicable travel lanes, lane assignment arrows (pointing down) must be covered or removed from drivers' view. The covering used should be square or rectangle so that the silhouette of the downward arrow is not accidentally implied to approaching drivers.

- Removal of lane assignment arrows and offsetting of the guide signs relative to the corresponding travel lanes will degrade drivers' ability to quickly and easily understand which lane they should be in to continue through the interchange or to exit. When this is necessary, consideration should be given to the provision of supplemental diagrammatic guide signing and/or pavement route symbols (or corresponding text) designating the route to which each lane is assigned. Examples of such signing (other designs may be acceptable as well) and pavement symbols are shown below.

- If pavement symbols are provided in the travel lanes, they must be in all of the exiting lanes, as a minimum. If the facility serves a large amount of traffic and the potential exists that many drivers will not be able to see the exit lane symbols, it may be beneficial to provide pavement symbols in all lanes (through and exiting).
- For an optional exit/through lane at multi-lane exit drops, it is acceptable to provide both route symbols one after the other in the lane to indicate a shared-use condition.
- If the symbols must be removed via sandblasting, grinding, etc., a rectangular section encompassing the symbol should be blasted or ground so that a ghost marking of the symbol does not remain and potentially confuse drivers.

ACCOMODATING THE TEMPORARY CLOSURE OF THROUGH TRAVEL LANES IMMEDIATELY DOWNSTREAM OF EXIT LANE DROPS

When it is necessary to close a through travel lane immediately downstream of an exit lane drop, the MUTCD indicates that the through lane and the exit drop lanes be closed upstream of the ramp itself. While this is the preferred approach and works well during times when traffic volumes are relatively low, doing this when higher traffic volumes are present will typically create a significant traffic queue upstream (and a resulting increase in rear-end crashes that accompany such queues), even at night. Furthermore, if the exit ramp volume is relatively high, it may be possible to avoid the creation of a queue entirely by allowing the exit lane to remain open to accommodate the exiting volume. Consequently, it is sometimes desirable to set up the lane closure just downstream of the exit ramp gore and leave the exit lanes open. This creates a challenge with the advance warning sign that is required upstream of the lane closure, however. If the decision is made to not close the exit drop lanes, consideration should be given to the provision of a supplemental portable changeable message sign with the following type of message displayed (the number of lanes and the terms right or left would be changed as needed):

If used, the PCMS should be placed midway between the first sign (ROAD WORK 1 MILE, CW20-1) and the second sign (XXX LANE CLOSED XXXX FT, CW20-5) to ensure adequate motorist detection and information processing time.

OTHER GENERAL CONSIDERATIONS

In addition to the above recommendations for specific conditions common at freeway interchange work zones, the following other items are also recommended for consideration:

- When lane shifts are required on freeway facilities, the use of multi-arrow lane shift signs to warn drivers and indicate that they do not need to change lanes should be considered.
- When exit and entrance ramps are realigned during construction, ensure that ramp edge lines are fully removed (including adhesive) so as not to confuse drivers.
- Check that exit ramp closed signing is used when temporary lane closures incorporate a ramp.

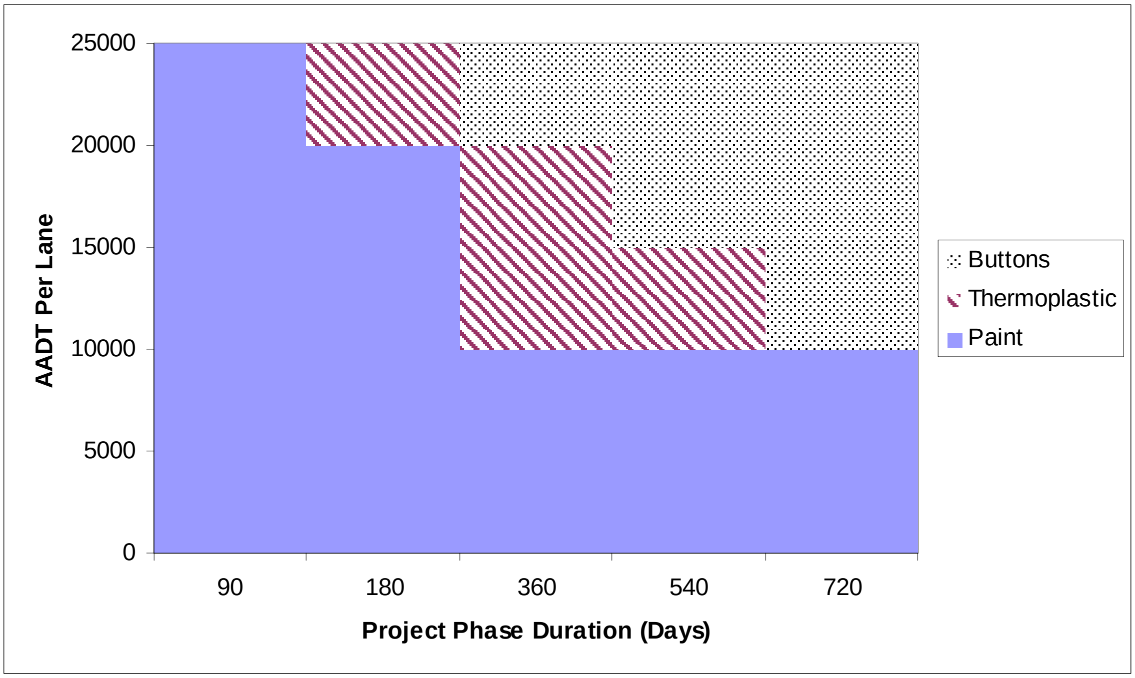
- Check the vertical and horizontal clearances available when traffic on interchange ramps is to be shifted onto the shoulder.
- Avoid starting lane closures on horizontal curves when possible (both in/near interchanges as well as between interchanges).
- When drivers are detoured far around and out of sight distance of the interchange because of construction, the use of trailblazing signs on both sides of the roadway should be considered to ensure that all traffic is able to see and verify that they are on the detoured route.

APPENDIX D. GUIDELINES FOR SELECTING PAVEMENT MARKINGS FOR WORK ZONES

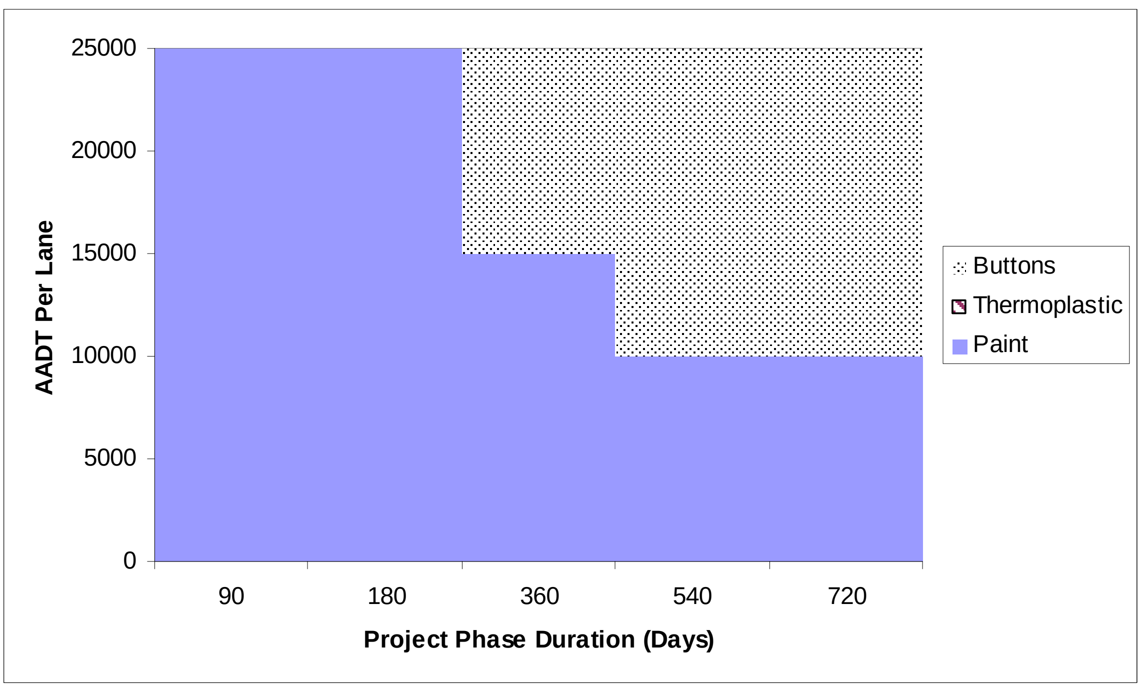
Lane shifts, crossovers, and other temporary changes in alignment often require the roadway into and through a work zone to be temporarily restriped. The traffic control designer has the choice of using paint, thermoplastic, traffic buttons, or other types of material for this purpose. On the one hand, it is desirable that the material selected be durable enough to last for the duration of the temporary change in alignment. On the other hand, since the application is intended to be temporary and will eventually be removed, covered with an asphalt overlay, etc., it is desirable to use as inexpensive a material as possible whose anticipated service life for that particular application simply exceeds the temporary duration that it is needed.

A cost-effectiveness evaluation has been performed considering the expected service life of various pavement marking materials (and the variability in expected service life), installation and reapplication costs of the various materials, traffic volume levels, type of pavement surface, and expected duration of the project or project phase for which the markings are needed. The following matrices identify the recommended marking materials under various per-lane ADT levels and project phase durations:

ASPHALT PAVEMENTS

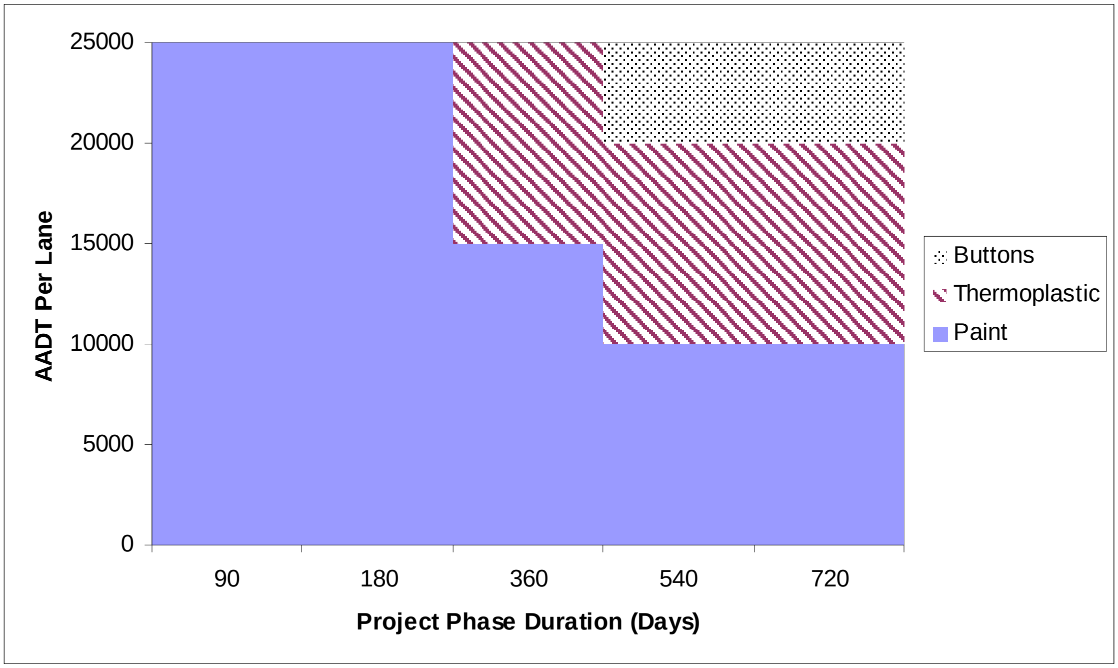


CONCRETE PAVEMENTS

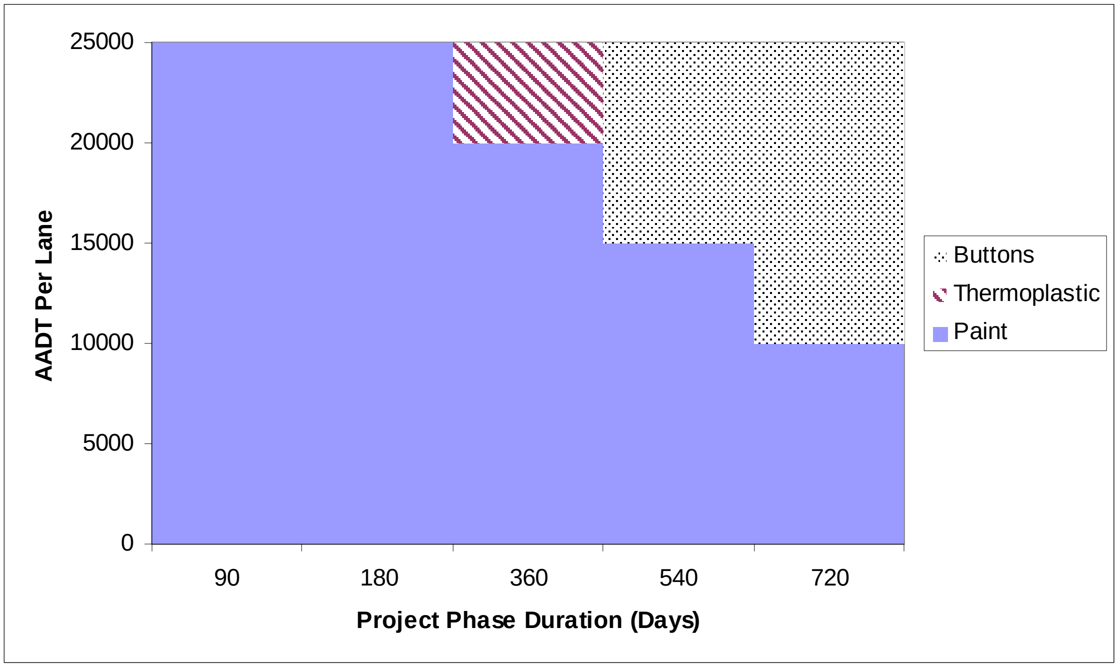


If the traffic control designer is optimistic that favorable ("better than expected") conditions affecting pavement marking performance will exist, the following matrices may be used instead:

ASPHALT PAVEMENTS

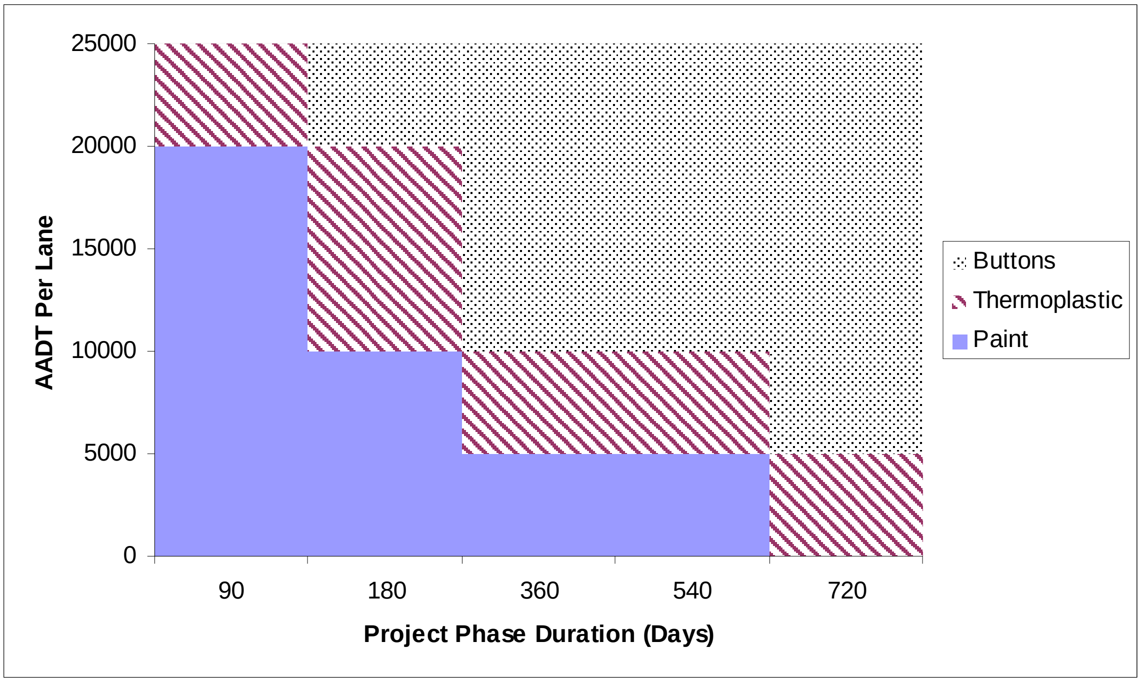


CONCRETE PAVEMENTS



If the traffic control designer believes that unfavorable ("worse than expected") conditions affecting pavement marking performance will exist, the following matrices may be used instead:

ASPHALT PAVEMENTS



CONCRETE PAVEMENTS