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The papers in this compendium report on the following topics: 1) Using Psychology to Understand Managed Lane Use; 2) Performance Characterization of Different Asphalt Binders at High Temperature: Oklahoma Case Studies; 3) Rapid Rehabilitation of Energy Impacted Roads; and 4) Benefit-Cost Analysis of Horizontal Curve Traffic Control Treatments.					
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## COMPENDIUM OF STUDENT PAPERS: 2014 UNDERGRADUATE TRANSPORTATION SCHOLARS PROGRAM



David Florence (Student), Kaitlynn Dione Simmons (Student) Dr. H. Gene Hawkins (Program Director), Nicole L. Kelly (Student) and Sam Jordan (Student)

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August 2014

#### PREFACE

The Southwest Region University Transportation Center (SWUTC), through the Transportation Scholars Program, the Texas A&M Transportation Institute (TTI), and the Zachry Department of Civil Engineering at Texas A&M University, established the Undergraduate Transportation Engineering Fellows Program in 1990. The program design allows students to interact directly with a Texas A&M University faculty member or TTI researcher in developing a research proposal, conducting valid research, and documenting the research results through oral presentations and research papers. The intent of the program is to introduce transportation engineering to students who have demonstrated outstanding academic performance, thus developing capable and qualified future transportation leaders.

In summer 2014, the following students and their faculty/staff mentors were:

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Sam Jordan University of Memphis	Dr. Maryam S. Sakhaeifar
David Florence Texas A&M University	Dr. Mark W. Burris Lisa Larsen Green, PhD.Student
Nicole L. Kelly Texas A&M University	Dr. David Bierling
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# Using Psychology to Understand Managed Lane Use

Prepared for Undergraduate Transportation Scholars Program

by

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August 8, 2014



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Additionally, the author expresses appreciation for the effort, time, and knowledge offered by his mentors, Dr. Mark Burris and Lisa Green. Other people whose assistance played a key role in the success of this project include Namoo Han and Dr. Winfred Arthur.

## SUMMARY

Managed lanes are intended to offer congestion-free travel as an alternative to the general purpose lanes, which are often congested. The goal of this project was to better understand the relationship between managed lane use and psychological characteristics of travelers. This was accomplished through development and administration of an exploratory survey and a final survey. The exploratory survey was distributed to friends and family of the researchers involved provided data that was used to finalize and analyze the list of psychological items. The results of the exploratory survey were used to better gauge which psychological questions will help to

determine a travelers use of managed lanes. The psychological items were assessed to determine if they should be kept for use in future discrete choice models that will create functions that model mode choice and allow researchers to determine the effectiveness of each variable included in the model. A thorough analysis of the exploratory survey was performed, which revealed a number of significant trends. This analysis suggested that travelers with a low sense of control are more likely to drive alone on managed lanes and that travelers with a high likelihood to rely on others are more likely to choose to carpool on the managed lanes. Additional tests showed that travelers who frequently drive alone on the managed lanes might not be choosing the managed lanes to reach their destination by a certain time. Future research in this area should include psychological constructs aimed at better understanding the reasons for this finding. The final survey is discussed in this paper, since a large portion of this research effort involved creating the survey and making sure that the survey is relevant to future respondents. Respondents will be solicited from persons who travel along corridors containing managed lanes in one of six different cities around the United States.

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## INTRODUCTION

Managed Lanes (MLs) have emerged as a useful tool in optimizing roadway usage. They are intended to offer congestion-free travel as an alternative to the general purpose lanes (GPLs), which are often congested. The Federal Highway Administration (FHWA) defines MLs as "a limited number of lanes set aside within an expressway cross section where multiple operational strategies are utilized, and actively adjusted as needed, for the purpose of achieving pre-defined performance objectives" (1). Given this fairly broad definition, various techniques can be used in structuring and implementing MLs. MLs are typically kept congestion free by travelers paying a toll or meeting a certain criteria (such as 3 or more occupants or transit). These tolls are dynamic and typically fluctuate with the time of day, or congestion level, depending on the demand for the lane (2). Although MLs are a relatively new tool, dozens of states already use MLs to ease congestion. With many other states planning on creating MLs, it is important to understand the usage of these lanes.

Recent analysis of ML use on the Katy Freeway showed that some travelers were paying a toll to use the MLs during off-peak hours, when the expected actual travel time savings are minimal or non-existent because of lack of congestion on the other lanes (3). Similar findings were reported by Burris, Nelson, Kelly, Gupta, and Cho (2012) from an analysis of I-394 in Minnesota, where the median value of travel time savings (TTS) for toll paying travelers was \$166 per hour for the entire afternoon and approximately 70 percent of paying ML travelers were paying for one minute or less of TTS (4). Devarasetty, Burris, and Shaw conclude that travel time reliability should be included in ML related studies along with travel time savings. Devarasetty et al. also note that travelers use the MLs "simply for a mental habit of doing so, and stick with their chosen lanes even when the conditions vary" (3). These findings suggest that psychological factors could play a role in ML use. Despite efforts made to understand the extent to which psychological traits can play a role in predicting ML use decisions, the extent to which the psychological traits impact traveler decisions remains unknown. With reports of the MLs becoming congested, resulting in a need to raise toll prices to detour travelers (5), the need for further investigation into the impact of psychological traits on traveler behavior in MLs is warranted.

## **BACKGROUND INFORMATION**

Burris, Arthur, Devarasetty, McDonald, and Muñoz (2012) performed preliminary research over the impact of psychological traits on ML use (2). They created psychological items that were administered in an offline survey and online survey. The psychological items, offline survey, online survey, and conclusions are discussed in the following sections.

#### **Psychological Items**

The items used by Burris et al. fell into one of six psychological constructs (or psychological characteristics, ideas, values, etc.); namely conscientiousness, locus of control, personal need for structure, risk tolerance, driving risk perceptions, and driving styles (2). Questions about carpooling preference were added to assess the participant's attitude toward carpooling, resulting in a total of six scales being used. A total of 78 questions were included in the survey, a majority

of which were to answered using a 9 point Likert scale (i.e. 1 = strongly disagree; 9 = strongly agree). In an effort to shorten the survey, the measures were broken into 20 different sets of 3 measures each. This resulted in each survey participant answering the questions associated with only three of the six scales, and a total of 20 different versions of the survey.

In addition to the psychological items, three Stated Preference (SP) questions were asked to each survey participant. These questions presented the respondent with a travel scenario on the major freeway in their respective hometown with four different modes of travel to choose from:

- Drive Alone on the General Purpose Lanes (DA-GPL).
- Carpool on the General Purpose Lanes (CP-GPL).
- Drive Alone on the Express Lanes (DA-EL or DA-ML)
- Carpool on the Express Lanes (CP-EL or CP-ML)

These questions were organized into two different surveys that were distributed in an attempt to better understand ML use. These surveys were given to Texas A&M students and advertised in four different cities selected for the ML implementation. The next two sections discuss the administration of these surveys.

## **Offline Survey**

The primary goal of the offline survey was to confirm that the individual difference measures performed as intended and to generate a dataset that could be compared to the online results (2). Two rounds of data were collected during the offline survey, once with 24 graduate students from Texas A&M University and again with 231 undergraduate students from four psychology classes at Texas A&M University who participated in exchange for course credit (2). The graduate students were asked to answer all six measures, and were also asked about their reaction to the measures in order to confirm that the survey instructions and questions were clear. The undergraduate students were also asked to answer the items from all six measures, but not asked about their reactions to the items (2). These responses were reviewed prior to completion of the online survey in order to make sure that the online survey was easy to understand.

## **Online Survey**

An online survey was posted on a Texas Transportation Institute server and made available for public access through the *www.TravelChoiceSurvey.org* website. This survey aimed to collect responses from residents of Denver, Miami, San Diego, and Seattle who use the I-25, I-95, I-15, and S.R. 167 freeways respectively. The surveys were promoted through various ads on web banners or social media websites. Incentive to take the survey was created through the presentation of VISA gift cards worth \$250 each that would be given to a randomly selected respondent in each of the four cities. The participant's information was stored separately from the responses so that the two could not be linked. A total of 1,001 responses were collected. However, only 664 of those responses were considered for further analysis either due to the respondent not completing the survey, or stating that they used a motorcycle or bus for their recent trip (2). The Seattle region only resulted in two completed surveys and was omitted from the study.

#### Conclusions

The findings of the research done by Burris et al. showed that some psychological variables had significant relationships with the SP questions (2). The best model created, which had a success rate of 43 percent, was comprised of the responses from the need for structure and risky driving style scales. ANOVAs indicated that those who consistently chose a ML option had significantly higher risk tolerance scores than those who chose the DA-GPL mode. Drivers with higher risky driving style scores were more likely to choose the ML modes, which makes sense since many of the risky driving style characteristics pertain to wanting to travel faster – which the managed lane usually allows. Additionally, respondents with higher conscientiousness scores were less likely to choose carpooling on the GPLs, which is consistent with the desire to maintain structure.

Another analysis of the same data set was completed by Larsen and Burris (2013) (6). This analysis used the responses from the surveys from the study done by Burris et al. (2) and created models using individual items, as opposed to the aggregate, scale level variables that were created and analyzed by Burris et al (2). Larsen and Burris used a base model that was created using variables found to be significant in the analysis performed by Burris et al. (2): socioeconomic and trip-type characteristics. Additional models were created in search of one that resulted in a higher percentage correctly predicted and a higher adjusted rho-squared value (which takes into account the number of variables and enforces a penalty for every additional variable) than the base model. This resulted in one model (containing personal need for structure and driving risk perception and driving style variables) that met both criteria, as well as a handful of models where one of the criteria were met and the other criteria was nearly met. This research showed that psychological items could play a role in better understanding travel behavior in MLs. Larsen and Burris conclude that a survey where every respondent answers every psychological item would address some of the limitations faced by previous studies, and that psychological items framed in the context of transportation could be a more promising tool in better understanding ML use.

## **Parent Project**

The present research largely follows the methodology presented in a dissertation proposal submitted by Larsen (7). Therefore, this effort began after the development of a new set of psychological items. The original group of items contained the significant items from psychological items used by Burris et al. (with a 90% confidence level or higher specified by specific models addressed by Larsen and Burris), and new transportation related items (2, 6, 7). This bank of psychological items was further reduced from 43 items to 32 items by having 21 respondents complete an item sort form where they grouped the items into the constructs they felt the items best fit into. The constructs included on the item sort form include the following:

- Reliance on Others
- Control of Situations and Destiny
- Desire for Predictability, Reliability, and Consistency
- Tendency to Take Risks (Transportation related)
- Tendency to Take Risks (Purely Financial)
- Analytical Tendency in Decision Making Process

The titles of the constructs are effective in describing what the construct is attempting to measure so, for the sake of brevity, they will not be explained in depth for this publication. Should the reader desire clarification for any construct, they should see Larsen's dissertation proposal (7). Furthermore, the reader should also note that as a result of the exploratory survey administered during the present project, the Desire for Predictability, Reliability, and Consistency construct was removed and the Tendency to Take Risks sub-constructs were combined for the final survey. This decision is discussed in depth in the Exploratory Survey Results section.

## **STUDY LOCATIONS**

This section discusses the administration of the exploratory survey and the properties of the eight different highways the final survey targeted. The exploratory survey targeted friends and family of the researchers involved in the present project. These respondents were contacted via email, Facebook message, or presented with a paper copy.

The eight highways for the final survey are spread across six different cities, and are listed below:

- SR 167 in Seattle, Washington
- I-15 in Salt Lake City, Utah
- I-10 in Los Angeles, California
- I-110 in Los Angeles, California
- I-495 in the Capital Beltway in the Washington D.C. area
- I-394 in Minneapolis, Minnesota
- I-35W in Minneapolis, Minnesota
- I-85 in Atlanta, Georgia

In order to create an applicable survey for each city, the toll rate, high occupancy vehicle (HOV) requirements, and wording were altered, depending on the city the respondent states they travel in. The following sections provide a brief description of each highway and any special treatment each given highway received.

#### SR 167 in Seattle, Washington

The SR 167 High Occupancy-Toll (HOT) lanes cover a 10 mile stretch between Renton and Auburn. It allows 2+ carpoolers, busses, and motorcycles to ride for free, while solo drivers can pay a toll to drive in the lane. Solo drivers have to purchase a *Good To Go!* pass in order to pay the variable electronic toll for the HOT lanes. If the HOT lanes become too full, the lanes will be switched to HOV only. The variable toll system calculates a toll (via computer program) from 50 cents to \$9 every five minutes (8). Despite the possible range, the average toll paid is as low as \$1.25 and the highest toll paid in 2012 was \$6.50 (8). Since the SP questions were allowed to reach a maximum of \$10 (for the adaptive random design) and \$9 (for the D<sub>b</sub>-efficient design), the tolls were reduced for Seattle. If the respondent claimed to travel in the Seattle area, they would receive tolls that were reduced by 15 percent (compared to Los Angeles, Washington D.C., and Atlanta). Researchers were informed that the Seattle area is more familiar with the phrase "express toll lanes" than "express lanes" when describing the SR 167 HOT lanes. The

Renton Renton SOS HOT Lanes Kent 16 18 Auburn Tacoma

survey was programed so that every instance of the phrase "express lanes" was changed to "express toll lanes". A map of the SR 167 HOT lanes is shown in Figure 1.

Figure 1. Map showing SR 167 HOT Lanes near Seattle, Washington (9)

## I-15 in Salt Lake City, Utah

I-15 in Salt Lake City, Utah has the longest and cheapest MLs of all the cities. These express lanes (ELs) cover a 62 mile stretch of roadway which is divided into 6 different zones of varying lengths (10). Travelers driving alone are charged a toll on a zone-by-zone basis ranging from 25 cents to \$1 per zone (10). Carpoolers (constituting of two or more people in the vehicle), buses, C Deal vehicles, and motorcycles are allowed to travel on the I-15 MLs free of charge (10). In order to travel in the I-15 MLs travelers need to purchase an *Express Pass*, which allows for electronic payment for the use of I-15. The *Express Pass* has a tab that travelers can pull to signify that they are riding as a carpool and should not be charged for the trip. Researchers noticed that Salt Lake City's tolling system caused the tolls to be significantly less that those seen in the more major cities. Even if a toll-paying traveler were to drive the entire length of the MLs, they would only be paying a maximum of \$6. For this reason the tolls for Salt Lake City travelers were reduced by one third, causing the maximum toll for the D<sub>b</sub>-efficient design to be \$6. The adaptive random design was still allowed to reach tolls as high as \$1 per mile, but the initial toll was reduced by one third, just like the D<sub>b</sub>-efficient design. Figure 2 shows a map of the I-15 ELs.



Figure 2. Map of I-15 express lanes in Salt Lake City, Utah (11)

#### I-10 and I-110 in Los Angeles, California

I-10 and I-110 in Los Angeles, California are the most expensive MLs in this study. The tolls range from 25 cents to \$1.40 per mile, and two person carpools have to pay a toll during peak hours, which is a percentage of the single occupancy vehicle (SOV) rate. I-10 and I-110 are approximately 14 and 11 miles long respectively (*12*, *13*). In order to pay the tolls, travelers need to purchase a *FasTrak* transponder which has three modes for travel: solo driver, 2 person carpool and 3+ person carpool Dynamic pricing is used to ensure that the ML speed does not go below 45 miles per hour. Should the lane speed drop below this threshold, additional SOVs would not be allowed to enter the MLs. Motorcycles, buses, and carpools are allowed to ride for free on both I-10 and I-110 MLs. The final survey was coded so that the respondents were asked about a 2 person carpool instead of a 3 person carpool in the SP questions. This means that each respondent that travels in Los Angeles was presented with a toll for the carpooling on MLs option. It was assumed that most travelers would be traveling during the times that the 2 person carpool needed to pay to ride (Monday to Friday from 5 am to 9 am and 4 pm to 7 pm) (*12*) and that very few travelers would be carpooling with 3 person carpool. A map showing the ELs along I-10 and I-110 and the *FasTrak* transponder can be seen in Figure 3.



Figure 3. Managed lanes in the Los Angeles area (Including I-10 and I-110) (14)

#### I-495 in the Capital Beltway in Washington D.C.

The I-495 (Capital Beltway) ELs were completed on November 17, 2012 (15) and are now open for use as long as the traveler has an *E-ZPass* mounted inside their vehicle, with the exception of motorcycles who do not need an *E-ZPass* to use the MLs. The tolls range from 20 cents to \$1.25 per mile for SOVs and 2 person carpools. Carpools with 3 or more people, motorcycles, and busses can ride for free at any time. Since 3 or more people need to be in the vehicle for a free trip, the final survey was coded so that the carpool option in the SP questions specified a 3 person carpool. A map showing the general location of the Capital Beltway ELs is presented in Figure 4.



Figure 4. Map of the I-495 express lanes in Washington D.C. area (16)

## I-394 and I-35W in Minneapolis, Minnesota

I-394 and I-35W ELs only charge a toll during peak and shoulder traffic periods. When a toll is not in effect the signs will read "OPEN" and general traffic can use the MLs free of charge (17). Otherwise only transit riders and carpoolers (two person or more) are allowed to ride free of charge. The ELs are approximately 10 and 14 miles long respectively. Solo drivers must purchase a *MnPass* transponder to pay for the tolls and should remove the transponder from the activation clip before driving as a carpool to avoid being charged. Therefore, travelers who plan on using the MLs only as a carpool do not need to purchase a *MnPass* transponder. Since the average trip in the peak period varies between \$1 and \$4, with a maximum toll of \$8, the tolls for

I-394 and I-35W were reduced by 15 percent for the final survey. Figure 5 shows a map of the 20 year plan for MnPass ELs in Minneapolis.



Existing & Planned MnPASS Express Lanes

Source: Minnesota 20-year State Highway Investment Plan: 2014-2033; Metro District 10-year Work Plan



#### I-85 in Atlanta, Georgia

Travelers on the 16 mile stretch between Chamblee Tucker Road and Old Peachtree Road have the option to use the I-85 ELs in Atlanta, Georgia. SOVs and 2 person carpools will be charged between one cent and 90 cents per mile if they drive on the MLs, depending on the demand for the MLs. In order to pay their tolls, SOV travelers must purchase a Peach Pass. Three or more person carpools, transit, motorcycles, alternative fuel vehicles, and on-call emergency vehicles are allowed to use the ELs toll-free. The final survey recognizes that travelers in Atlanta need three or more occupants to ride toll-free, so the wording is changed for some of the items. A rough sketch of the location of the I-85 ELs can be viewed in Figure 6.



Figure 6. Location of the I-85 express lanes in Atlanta (18)

On July 25, 2014 researches were informed of a customer satisfaction survey that was in preparation to be released for I-85 Express Lane users/customers in the Atlanta area. For this reason, the survey for the present research could not be advertised in the Atlanta area and was removed from the survey. The code was not altered so that Atlanta could be easily added to the survey again, since researchers were informed that the survey could be advertised in the Atlanta area during Fall of 2014.

## METHODOLOGY

The following sections explain the methodology that was used in analyzing the exploratory survey data and in generating the final survey design. Specifically, factor analysis, Cronbach's Alpha, and the Kruskal-Wallis Test are described, relative to the exploratory survey data analysis.  $D_b$ -efficient design and adaptive random—two methods of designing stated preference questions—are outlined.

## **Factor Analysis**

Factor analysis methods are useful when summarizing data so that relationships and patterns can be easily understood. These methods essentially try to group variables with similar characteristics together into clusters, termed factors, which can be used for further analysis. Factor analysis is divided into two different methods: exploratory factor analysis (EFA) and confirmatory factor analysis (CFA). As the names imply, EFA is typically used when the researcher is trying to group the variables together in order to form a construct, while CFA is used to confirm constructs that the researcher already has in mind. Since the computer software to conduct a CFA was not available, researchers used an EFA method. SPSS (the computer program being used), was forced to extract only one factor. Factor analysis is helpful in determining if a proposed scale is actually measuring and only measuring the intended dimension (19). Therefore, factor analysis was used to validate the items and constructs from data collected in a pilot survey. Review of the statistics was used to aid in the process of eliminating items that were not significant enough to include in the final survey. This allowed the final survey to be brief and have every respondent answer every psychological item, which allows for a multidimensional analysis of the data.

#### **Cronbach's Alpha**

The other statistic used to analyze items using the exploratory survey data was the Cronbach's alpha (also referred to as coefficient alpha). This value measures the first-factor saturation, or in other words, the extent to which a factor is present in all items as an index ranging from 0 to 1 (20). High Cronbach's alphas (i.e., greater than 0.7) suggest that the items measure the same construct (20). Since the Cronbach's alpha of each construct calculated from the pilot survey played a large role in the selection of the items that would be included in the scales for the final survey, the calculation for the index is shown in Equation 1 (21).

$$\boldsymbol{\alpha} = \frac{K}{K-1} \left[ \mathbf{1} - \left( \frac{\sum \sigma_k^2}{\sigma_{TOTAL}^2} \right) \right]$$
 Equation 1

Where, K = number of items

 $\sum \sigma_k^2$  = sum of the k item score variances  $\sigma_{TOTAL}^2$  = variance of the scores on the total test

The reliability calculated from Equation 1 is the lower bound of reliability of a test, meaning that the true reliability is greater than or equal to the Cronbach's alpha value (20).

## Kruskal-Wallis Test

The Kruskal-Wallis one-way analysis of variance was used to determine psychological items from the exploratory survey that had a different mean depending on mode choice. For example, this test will identify an item where respondents who chose the DA-ML choice had a different mean value from those who chose the DA-GPL choice for a specific SP question. The Kruskal-Wallis test is especially useful because it allows for the comparison of multiple samples that have different sample sizes and makes no assumptions about normality (22). The test statistic, H, is calculated using the formula presented in Equation 2 (22).

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1), \ N = \sum_{i=1}^{k} n_i$$
 Equation 2

Where,  $R_i$  = the sum of the ranks for each group i (i = 1, 2, ..., k)  $n_i$  = size of each group Using the output, items that had at least one mode choice that had a different mean from the others for each SP question were identified. The SPSS software was used to conduct the Kruskal-Wallis tests and automatically generate post hoc tests to show the pairwise comparisons between the mode choices. These comparisons were used, in part, to determine which questions were included in the final survey as well as a preliminary analysis of the psychological items.

#### **Stated Preference Question Design**

Stated preference questions reflecting the same designs and administration as those used by Burris et al. (2) were used for the final survey. These questions were designed to represent a realistic travel scenario in the respondent's respective city in relation to their most recent trip on the ML corridor. This was accomplished by gathering data regarding the distance, toll rate, average speed, and the average time savings for each highway represented in the study. Since the toll and average speed vary according to the time of day, data were gathered for different times of day and the appropriate values were used according to the time the respondent stated they began their most recent trip on the ML corridor. Using these values, appropriate hypothetical scenarios regarding toll and travel time were generated via two different design methods:  $D_b$ -efficient design and adaptive random design. The N-Gene computer program was used in the creation the  $D_b$ -efficient design used for the SP questions. These designs are meant to be compared to each other during the analysis of the final survey. Both of these designs are discussed in the following subsections.

## D<sub>b</sub>-Efficient Design

The D-efficient design is a form of Bayesian efficient design. Efficiency in design means the reduction of asymptotic standard errors and covariances of the model parameters in order to increase the asymptotic *t*-ratios of the model estimates (23). This means that a lower number of respondents are required to produce statistically significant parameter estimates (23). D-efficient designs are those that minimize the D-error (a measure of efficiency calculated as the determinate of the AVC matrix raised to the power of one over the number of parameters). D<sub>b</sub>-efficient, or Bayesian efficient, designs are created by minimizing the D<sub>b</sub>-error which can be calculated using Equation 3 (23).

$$D_{\rm b} - \text{error} = \int_{\tilde{\beta}} \det AVC \left(\tilde{\beta} | \boldsymbol{X} \right)^{1/K} \phi(\tilde{\beta} | \theta) d\tilde{\beta} \qquad \text{Equation 3}$$

Where, X =matrix of attribute levels in design

 $\tilde{\beta}$  = vector of parameter priors  $\phi(\tilde{\beta}|\theta)$  = joint distribution of the assumed parameter priors

 $\theta$  = corresponding parameters of the distribution

K = number of parameters in the model

The computation of the integral in Equation 3 is complicated and cannot be solved analytically. The integral is approximated using several methods. In this study, Halton draws are used for simulating the distributions in the same manner described by Burris et al. (2). As stated before, this design was accomplished through the use of the N-Gene computer program which used 400

Halton draws to create an efficient design. In order to run properly, N-Gene needed prior estimates for the utility functions. The mean and standard deviation of the priors used for obtaining the  $D_b$ -efficient design and the exact levels of the attributes used for each model at different times of day are shown in Table 1.

		Attribute Levels			Mean	Standard
Attribute	Attribute Time of Day			Value of	Deviation	
	Mode	Peak Hours	Shoulder Hours	<b>Off-Peak Hours</b>	Priors	of Priors
	CP-ML	0	0	0		
Toll (cents/mile)	DA-ML	45,67.5,90	22.5,33.75,45	15,22.5,30	-0.12	0.1
	<b>CP-GPL</b>	0	0	0		
	DA-GPL	0	0	0		
	CP-ML	55,60,65	55,60,65	60,65,70		
Speed (mph)	DA-ML	55,60,65	55,60,65	60,65,70	0.14*	0.64
	CP-GPL	25,35,45	30,40,50	35,45,55	-0.14*	0.04
	DA-GPL	25,35,45	30,40,50	35,45,55		

Table 1. Mean, Standard Deviation of Attribute Priors,and Attribute Levels for Different Times of Day

Note: \*Prior is the coefficient of travel time from a previous survey on managed lane use done by Burris et al. (2). Necessary transformation was performed to use it as a coefficient for speed.

The attributes gathered for Table 1 were based on data regarding ML distance, average speed, and toll rates for the eight different highways targeted for this study. These attributes were first set so that the tolls were higher to reflect the maximum range for the tolls in Los Angeles, California (12) and Washington, D.C. (24). However, the tolls were unreasonably high for a single trip on the MLs, so the tolls were lowered to allow the survey to be more reasonable for the targeted travelers. For certain cities, the tolls were reduced further to reflect the actual tolls paid that city. The toll rates used in this survey still are higher than those found in Burris et al. (2). The highest toll for the peak hours from Burris's et al. (2) study was 40 cents per mile and the highest peak toll in this study is 90 cents per mile.

Similarly, the speeds were determined by ensuring that there is time savings from using the MLs with respect to the GPLs. This was an important decision because there would be times, especially during the off-peak hours, where the GPLs would be traveling at the same speeds as the MLs. If that was the case, the SP questions would display an equal travel time for each lane, and the vast majority of respondents would choose the GPLs. For that reason, the GPLs were kept at least five miles-per-hour slower than the MLs. Notice that speed attributes are identical to those used by Burris et al. (2).

The attributes or the peak hours were coded into N-Gene and used for the design. The N-Gene code used for this study is presented in Appendix B. The relationship between the attributes for the three time periods was used to obtain the designs for the shoulder and off-peak hours based on the N-Gene results from the peak hours. The design had 15 rows divided into 5 blocks of 3 rows. Each respondent was randomly presented with all choice sets from one of the blocks. The

 $D_b$ -error for the design was found to be 0.09. As stated before, the  $D_b$ -error should be as close to zero as possible. Seeing as this  $D_b$ -error is very close to zero, the design is acceptable. The optimal  $D_b$ -efficient design found can be viewed in Table 2.

Mode	CP-ML	DA-ML		CP-GPL	DA-GPL	
Choice Situation	Speed (mph)	Speed (mph)	Toll (cents/ mile)	Speed (mph)	Speed (mph)	Block
1	60	60	90	35	35	1
2	55	55	67.5	35	35	1
3	65	65	67.5	35	35	1
4	65	65	45	25	25	2
5	55	55	45	45	45	2
6	60	60	90	45	45	2
7	55	55	45	35	35	3
8	65	65	67.5	25	25	3
9	60	60	67.5	25	25	3
10	60	60	45	45	45	4
11	55	55	90	45	45	4
12	65	65	90	25	25	4
13	55	55	67.5	45	45	5
14	60	60	45	25	25	5
15	65	65	90	35	35	5

 Table 2. D<sub>b</sub>-Efficient Design Generated Using N-Gene Software (for Peak Hours)

## Adaptive Random Design

The second design strategy for SP questions was the adaptive random attribute level generation method. As seen in Burris et al. (2), this design generated values in a range corresponding with the appropriate toll and speed based on the time of day. The choice sets for the second and third SP questions were partially dependent on the response to the previous SP question. If the respondent chose a toll option on the prior SP question the toll rates were increased by a random percentage anywhere between 15 and 75 and if the respondent chose a non-toll option the toll rate would decrease by a random percentage between 15 and 50. Notice that although the design is exactly like the one used by Burris et al. (2), the attribute levels are slightly different. The attribute for the adaptive random design are presented in Table 3.

Although the speeds used in this design are identical to the ones used by Burris et al. (2), the tolls are higher to reflect the higher tolls seen in Los Angeles, Washington D.C., and Atlanta (12, 24, 25), just like in the  $D_b$ -efficient design. The cities with lower tolls received reduced rates compared to Los Angeles, Washington D.C., and Atlanta in both designs. In order to compare the two designs, the ranges for the tolls and speeds for this design were selected to be identical to those found in the  $D_b$ -efficient design. The first question would charge between 45 and 90 cents per mile and the other two SP questions were not allowed to charge a toll greater than \$1 per

mile if the respondent chose the tolled option on the previous SP question. The minimum rate allowed in this design is 10 cents per mile.

	Attribute Levels				
Attribute		Time of Day			
	Mode	Peak Hours	<b>Shoulder Hours</b>	<b>Off-Peak Hours</b>	
	CP-ML	0	0	0	
Toll (cents/mile)	DA-ML	45+(0 to 45)	22.5+(0 to 22.5)	15+(0 to 15)	
	CP-GPL	0	0	0	
	DA-GPL	0	0	0	
Speed (mph)	CP-ML	55+(0 to 10)	55+(0 to 10)	60+(0 to 10)	
	DA-ML	55+(0 to 10)	55+(0 to 10)	60+(0 to 10)	
	CP-GPL	25+(0 to 20)	30+(0 to 20)	35+(0 to 20)	
	DA-GPL	25+(0 to 20)	30+(0 to 20)	35+(0 to 20)	

Table 3. Attribute Levels for the Adaptive Random Deign

## EXPLORATORY SURVEY RESULTS

The exploratory survey collection period began on June 9, 2014 and ended on June 16, 2014. In that time 118 responses were collected (102 filled out electronically and 16 filled out on a paper copy) from friends and family of the researchers involved in this effort. Of those responses, only 82 (69 percent) answered all the items. This is partially due to the fact that respondents were welcomed to skip an item that they could not relate to, since the target audience for this survey may not all be familiar with MLs. Another possible reason a respondent might not have answered all the items could be that the last six items were placed onto a separate page at the very end of the survey that could have been easily missed if filled out on a computer. A total of eight respondents (seven percent) failed to answer the last six items. Since the purpose of this survey was to validate the constructs defined by the item sort form, the respondents that did not answer all of the items still provided useful information. However, this led to an uneven sample size for the different analyses performed on this dataset.

#### **Scale Construction**

A scale is a term used for a group of items that are used to better understand a psychological construct. The exploratory survey was an essential step in finalizing the scales used for the data analysis regarding the final survey. In order to finalize the scales, the Cronbach's alpha and a factor analysis were used to determine the reliability and validity of the items in each construct. The finalized scales were determined by iterative elimination of the items that would increase the Cronbach's alpha the most. More specifically, every time an item was deleted from the scale, the alpha was recalculated and, if necessary, another item was removed from the group. Once all of the items that were lowering the alpha were deleted, an EFA was performed with each remaining construct where only one factor was extracted. Items with a correlation of less than 0.3 with the factor were analyzed further due to a poor fit in the factor. In this manner, an EFA

was used to validate the constructs identified by the item sort form and deemed reliable by Cronbach's alpha.

While eliminating items, the Desire for Predictability, Reliability, and Consistency construct showed very poor reliability. The maximum Cronbach's alpha reached was 0.16 with only two items. Therefore, the construct had to be removed from the study. Similarly, the Tendency to Take Risks (Transportation related) construct, with only two items, resulted in a negative alpha and a negative correlation among the items. The Tendency to Take Risks (Purely Financial) had an acceptable alpha, but the alpha was not maximized until the elimination of the majority of the items in that construct. Therefore, the two Tendency to Take Risks constructs were combined into one scale. The single Tendency to Take Risks scale performed better than the subconstructs did individually. This analysis resulted in four scales, with a total of 17 items. The four scales and the number of items in each scale are listed below.

- Reliance on Others (three items)
- Analytical Tendency in Decision Making Process (four items)
- Tendency to Take Risks (six items)
- Control of Situation and Destiny (four items)

The scale with the lowest Cronbach's alpha was Tendency to Take Risks ( $\alpha = 0.440$ ) and the highest was Reliance on Others ( $\alpha = 0.772$ ). Even though three of the scales did not meet the criteria of having an alpha above 0.7 (Control of Situation and Destiny, Analytical Tendency in Decision Making Process, and Tendency to Take Risks), the factor analyses performed showed that the items in the factor correlate well with the scale (defined by a correlation of 0.3 or higher). Since the items inside the scales that did not have a very high Cronbach's alpha had an acceptable correlation with each other, the scales with a low alpha can be interpreted as a valid scale.

#### **Comparison of Means**

A comparison of means test was conducted by running a Kruskal-Wallis one-way analysis of variance, across all the responses. The analysis was completed for the three SP items individually and once more for those respondents who chose the same mode choice for all three SP items. 19 items were identified (at 95 percent significance) as items whose means varied across the different mode choices. Eight items were significant across at least two SP question cases. These eight items are discussed in this section, according to their respective scales. Five additional items are discusses that did not fall into any particular scale. This section provides a preliminary analysis of the psychological items. Note the items are identified in this section according to their item number according to the exploratory survey (see Appendix A). The items were slightly rearranged for the final survey. Therefore, the item numbers used in this section do not necessarily apply to the item numbers in the final survey. The items were also slightly reworded for the final survey. This paper uses the wording from the exploratory survey while discussing the comparison of means in the following sections.

There were some sample size concerns worth noting in SP question two (SP2), SP question three (SP3), and the case where the respondent answered the same mode choice for all three SP

questions (SPA). SP2 only had only three respondents who chose the CP-GPL mode. SP3 only had seven respondents who chose the DA-ML mode. SPA only had three respondents in the DA-ML mode choice category. Comparisons between the mode choices listed above in the respective SP questions should be interpreted with caution.

#### Control of Situation and Destiny

Item 6 (I have often found that what is going to happen will happen) and item 9 (Whether I am involved in a traffic accident is purely a matter of fate and there is not much I can do to prevent it) are both members of the Control of Situation and Destiny scale. Item six showed significance in SP question one (SP1), SP3, and SPA. SP1 showed that DA-ML was different from DA-GPL. SP3 showed that DA-ML was different from both DA-GPL and CP-ML. SPA showed that DA-ML was different from DA-GPL. Item 9 showed significant differences in SP3 and SPA, both with a relationship between DA-GPL and DA-ML. The trend is that respondents that score higher (agree more) with these two items are more likely to choose DA-ML. It is important to specify that items in this construct were ranked so that the high scores represent a low sense of control. Furthermore, item 6 was interpreted so that higher scores correlate to respondents being unable to change their future, after they envision it. These results imply that travelers with a low sense of control over their everyday lives are more inclined to choose DA-ML. This behavior could be a compensation technique for their perceived lack of control over their lives, since DA-ML provides the most controlled trip available.

## Reliance on Others

All three items from the Reliance on Others scale had at least two significant relationships between their mode choices and responses for the SP questions. Item 8 (Carpooling makes me feel like I am at the mercy of others in the carpool to get to my destination on time) had a significant difference in SP1, SP3, and SPA. Both item 15 (The coordination involved with carpooling is more hassle than it is worth) and item 26 (I do not like relying on others for rides) showed a difference between mode choices in all four of the SP question groups. For item 8, SP1 and SP3 both show that CP-ML is different from DA-GPL and DA-ML; while SPA only shows that CP-ML is different from DA-GPL. Items 15 and 26 showed the same mode choice differences in all of the SP questions except for SP3. In SP1, items 15 and 26 showed that CP-ML was different from both DA-GPL and DA-ML. Items 15 and 26 both found a significant difference between CP-ML and DA-GPL for SP2 and SPA. As for SP3, CP-ML was different from DA-GPL and DA-ML for item 15 and CP-ML was different from just DA-GPL for item 26. These differences from the three items suggest that respondents with lower scores on these items (disagree) have a higher propensity to engage in carpools. This makes sense because if the respondent thinks that by carpooling, they can make it to their destination on time, can tolerate the hassle, and can rely on others for rides, they would engage in a carpool and use the MLs.

## Tendency to Take Risks

Two items from the Tendency to Take Risks scale showed at least two significant differences in mode choice for the SP questions. Item 13 (I cannot understand why someone would pay to use the managed lanes when the general purpose lanes are available for "free", especially when it

may or may not save time) and item 29 (Lending a friend the money needed to purchase a \$20 toll tag so they could use the managed lane) both showed significant differences in SP1 and SP3. Notice that item 13 was reverse scored for this analysis; meaning that if the respondent were to agree with the statement in item 13 they would score low as opposed to high. According to the Kruskal-Wallis test for SPA, item 13 had a significant difference between at least one of the mode choices. However, the pairwise comparison for item 13, in the same analysis, does not show any significant relationships (where the adjusted significance was less than 0.05). The pairwise comparison for SP1 showed that DA-GPL had a relationship with both CP-ML and DA-ML in item 13 and that DA-GPL had a relationship with CP-ML in item 29. SP3's pairwise comparisons reveal a relationship between DA-GPL and DA-ML for item 13 and a relationship between DA-GPL and CP-ML for item 29. These results are interesting because in each relationship, DA-GPL scores lower than either CP-ML or DA-ML. This suggests that DA-GPL is the "least risky" mode choice. That makes sense because it has no financial risk and it does not have the risks involved with carpooling. These results could be interpreted as if to say that slowdowns in the GPLs are more desirable for some than paying for ML use or carpooling.

The significant relationships found for item 13 suggest that travelers who chose the ML options are more likely to understand why someone would pay to use the MLs. This result seems to make sense. Travelers who use the MLs would value MLs more and be more likely to understand the desire to pay to travel on those lanes. A more surprising result is found in item 29. Although the item is asking about the willingness to lend a friend the money needed to purchase a transponder, the significant relationships are between DA-GPL and CP-ML, both of which do not require money. It is as if the respondents who are typically willing to participate in a carpool are also willing to lend a friend money. Regardless, lending a friend money is considered a risk, and CP-ML involves the risk of a member of the carpool failing to be prepared in a timely manner.

## Analytical Tendency in Decision Making Process

Only one item from Analytical Tendency in Decision Making Process had a significant relationship in two or more SP questions: item 20 (I tend to make the choice about which road to use based on the traffic I encounter). Item 20 had a significant relationship between DA-GPL and DA-ML in both SP1 and SPA. High scores with item 20 corresponds with respondents who are more likely to choose DA-ML, suggesting that travelers who analyze their traffic situation are more likely to use the MLs. Therefore, some of the DA-ML travelers must be selecting that mode choice in response to the congestion in the GPLs.

## Items with No Scale

Five items were found to have significant relationships between different mode choices through this analysis that were not already part of a scale. Items four and five both yielded a 0.05 significance in the Kruskal-Wallis test, but had no relationships at a 0.05 adjusted significance in the pairwise comparison test. For this reason, the relationships for items four and five were determined at an adjusted significance level of 0.1. Each of these items only had significant relationships in one of the SP questions. These items are summarized in Table 4.

Item Number	Item Text	Stated Preference Question of Significance	Significant Mode Choice Relationship(s)
2	Unless there is no traffic on the freeway, I choose the managed lane since traffic could become congested at any time.	Stated Preference 2	$DA-GPL \rightarrow CP-ML$
4	I only choose to use the managed lane if the general purpose lane seems crowded.	Stated Preference 3	$DA-GPL \rightarrow CP-ML^*$
5	When buying fuel for my car, I use the most convenient gas station and do not pay much attention to price.	Stated Preference 3	$DA-GPL \rightarrow CP-ML^*$
22	I would rather stay 30 minutes longer at work than leave during rush hour and face the possibility of being stuck in traffic for an extra 30 minutes.	Stated Preference 1	$DA$ -GPL $\rightarrow$ DA-ML
24	I generally choose to use managed lanes when I feel it is the only way I will make it to my destination on time.	Stated Preference 3	$DA-ML \rightarrow DA-GPL$ $DA-ML \rightarrow CP-ML$

Table 4. Significant Relationships Found in Psychological Items without a Scale

Note: \* Adjusted significance of less than 0.1. All others are at a significance of less than 0.05. Each significant relationship is shown from low score to high score (i.e. disagree  $\rightarrow$  agree).

The relationship found in item 2 is interesting because travelers cannot simply switch from DA-GPL to CP-ML. The respondent would have to plan for a carpool in order to switch across mode types in this manner. Nonetheless, those who agree with item 2 would be expected to choose a ML option, and those who disagree would be expected to choose DA-GPL. Item four has a similar dynamic as item two. Those who agree would be expected to prefer a ML option and those who disagree would be predicted to choose DA-GPL. The relationship for item 4 is also between DA-GPL and CP-ML. An interesting result, although not statistically significant, was that DA-ML has a lower mean rank than DA-GPL in item 4. This means that travelers who are disagreeing with item 4 are also the ones who are choosing to use the drive alone on the MLs unconditionally, supporting the theory of travelers choosing a mode choice out of habit described by Devarasetty et al. (*3*).

Even though item 5 seems to be about analytical tendencies, the item sort form identified the item as a tendency to take a financial risk. This result supports that interpretation, since the risked reliability in traveling to pick up passengers in a reasonable time seems to outweigh the travel time savings from using the MLs. Those who disagree with item 5 might be more willing to pass up a gas station since they do not want to risk another station having a lower price, correlating with a low tendency to take risk and, as a result, the DA-GPL mode choice. Special care should be used when analyzing this item because respondents could also be using the most convenient gas station because they do not want to risk running out of gasoline. Such an interpretation could drastically change their reason for selecting a high or low score.

Item 22 produces the expected relationship. A traveler who selects carpooling would likely not be able to simply choose to stay at work an extra 30 minutes since that could interfere with the others involved in the carpool. Additionally, DA-ML provides the most reliable trip, which this item is supposed to target. This relationship between DA-GPL and DA-ML suggests that the

respondents with a lower desire for a predictable trip are more likely to choose DA-GPL and those with a higher desire for predictability would choose DA-ML.

Item 24 provides some more interesting results. This item yielded relations between DA-ML and both DA-GPL and CP-ML. These relationships suggest that travelers who are more likely to choose the MLs only when they are unable to reach their destination in time are those who choose DA-GPL or CP-ML. This suggests that travelers who choose DA-ML are not necessarily choosing that particular mode in order to reach their destination by a certain time. Instead they could be choosing that mode out of habit, further supporting the suggestion by Devarasetty et al. (*3*).

## Summary

The Kruskal-Wallis one-way analysis of variance gives insight into travel behavior based on a traveler's sense of control, likelihood to depend on others, risk taking tendency, assessment of their situations, and the possibility of traveling in the MLs for more than just saving time. Travelers with a low sense of control (according to items 6 and 9) appear to be choosing DA-ML, perhaps to compensate for perceived lack of control. Respondents who were likely to rely on others (scored high in items 8, 15, and 26) were more likely to choose CP-ML, as expected. Travelers with higher likelihood to take risks, according to items 13 and 29, appear to be less likely to travel DA-GPL, suggesting that DA-GPL is interpreted as the least risky mode choice. Analytical tendencies, in item 20, appear to have a correlation between DA-GPL and DA-ML, showing that those who are more willing to change travel modes are the ones who are more likely to select DA-ML. However, findings from item 24 seem to contradict item 20. Item 24 suggests that travelers who typically do not choose the MLs to reach their destination by a certain time chose DA-ML. This implies that travelers who choose DA-ML are traveling for a reason other than to reach their destination by a certain time. Items 2, 4, and 5 each show a relationship between DA-GPL and CP-ML even though they are not part of a scale. Item 2 suggests that travelers who use the MLs to avoid congestion are more likely to choose CP-ML. Item 4 shows a positive correlation between analyzing traffic conditions and choosing CP-ML. An insignificant, although interesting, interesting finding in the analysis of item 4 is that DA-ML had a lower mean ranking than DA-GPL, suggesting that traversers who choose DA-ML might be doing so out of habit. Item 5 suggests that travelers who use the most convenient gas station are more likely to choose CP-ML. Item 22 implies that travelers who are willing to stay at work longer to avoid traffic are also willing to choose DA-ML. These relationships give insight into the potential effectiveness of each item in a discrete choice model. The analysis of the final survey will benefit from the relationships identified by the analysis of the exploratory survey data.

## PSYCHOLOGICAL ITEMS FOR THE FINAL SURVEY

The items that did not fit into a particular scale but were deemed significant by the Kruskal-Wallis test were automatically chosen for inclusion in the final survey. These items were kept to analyze as individual items for the final survey. Three additional items were kept out of pure interest to those participating in the research, which were also meant to be used as individual items for the final survey analysis. This brought the total number of items for the final survey to 25. Two TTI employees were asked to pilot test the final survey when it was completed and note any confusion or problems they encountered. The time they took to complete the survey was recorded and used to determine the approximate time the advertisements claimed the survey would take to complete.

#### FINAL SURVEY RESULTS

The final survey administered was largely an adaptation of the survey used in the research conducted by Burris et al. (2). The tool used for the administration of this survey was LimeSurvey, a free final survey website. This tool allows all data to be collected via a web-based survey. The survey was made available through the *www.TravelSurveys.org* website. This survey included the 25 remaining psychological items after the analysis conducted on the exploratory survey, questions about the respondent's most recent trip on the targeted highway, questions about their opinion of MLs, and questions regarding demographic information. Respondents were given incentive to take the survey through \$250 MasterCard gift cards that were to be given to a randomly chosen individual from one of each of the five cities, since Atlanta had to be removed from this survey. Each respondent's contact information was stored separately from their survey results. Small and large advertisements were created for each city to aid the contacts in advertising this survey. A sample add of each format is presented in Figure 7 and Figure 8, respectively.



Figure 7. Sample small advertisement (Seattle ad shown)



# Do you travel on SR-167 between Renton and Auburn?

The Texas A&M Transportation Institute is examining ways to improve traffic flow along heavily traveled freeways. We need your help with this. Take our 10 minute survey for your chance to win a **\$250 MASTERCARD GIFT CARD!** Any answers you provide will be kept anonymous.



Figure 8. Sample large advertisement (Seattle ad shown)

A slow moving review process led to a delayed release of the survey. Contacts in the cities of interest were unable to review the completed survey for several days. This time was critical because the primary form of advertisement for this survey was meant to be included in the newsletter of each contact. The survey was sent to the contacts in the six cities on July 22, 2014 for their review. During the course of this effort, the final survey was not included in any newsletters. Therefore, there were not enough responses to the final survey to conduct an analysis for this paper.

## CONCLUSION

MLs have proven to be a useful tool in reducing congestion on a major freeway, with many cities seeing improvement in the GPL traffic flow as a result of travelers choosing to use the MLs. This paper described the steps taken as the parent project transitions from a list of 32 items, grouped into constructs by an item sort form, into a functional final survey that targets eight different highways in six different cities around the United States in an attempt to understand

ML usage better. Critical steps in this process included the exploratory survey, scale construction, comparison of means, final survey design, and advertisement of the final survey. The exploratory survey yielded a data set that could be analyzed to create scales and assess the psychological items individually. Four scales were constructed with data to support the idea that each scale was valid and reliable. Individual analysis of the exploratory survey responses showed some of the relationships between mode choices. The Reliance on Others scale showed the most promising results, suggesting that travelers with a high propensity to rely on others are more likely to choose the CP-ML mode of travel. Interesting relationships were found in item 4 and item 24, implying that travelers who chose the DA-ML mode choice might be doing so out of habit rather than as a result of congestion. The analysis over the individual psychological items made in this paper should be compared to a similar analysis completed on the responses from the final survey in order to confirm that they are valid conclusions.

Future research in this field could benefit from the addition of new constructs into the survey. One construct that could produce valuable information is the desire to appear wealthy. Travelers could be choosing DA-ML in an attempt to profess their wealth to the other travelers on the road. Another possible construct could be found in the likelihood to spend or save money. Despite the fact that a small population has an enormous value of travel time savings, most of the survey responses seem to suggest that the amount of money required for a trip largely influences the traveler's decision. Perhaps using psychological items to aid modeling this behavior could be useful for future discrete choice models. A third possible construct could be patience. A traveler with little patience might be more likely to travel on the MLs. The Desire for Predictability, Reliability, and Consistency construct should be included in future research regarding ML use.

In the next research project, the exploratory survey process could be expedited by using an online format to administer the survey. This would automatically store the data into a spreadsheet and allow for easier electronic distribution of the survey to friends and family. This could be accomplished through a free online tool, such as SurveyMonkey. The next research project could also benefit from using a newer version of LimeSurvey. The present research used version 1.85 of LimeSurvey which does not have some of the useful features found in newer versions. For example, the survey used in this project was unable to be viewed by out of state contacts while the survey was inactive due to a default setting version 1.85 did not allow the user to change easily. Newer versions of LimeSurvey have a settings menu that allows the user to easily toggle this setting and allow non-administrators to test the offline survey.

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### APPENDIX A: EXPLORATORY SURVEY

# **Stated Preference Questions**

Each of the following questions will ask you to choose between two potential travel choices on a managed lane corridor. Please put an "X" in the box next to the one option that you would be most likely to choose if faced with these specific options. Remember that carpooling may require added travel time to pick up or drop off your passenger(s).

Please select one option for each question (i.e., **answer all three questions**) by putting an "X" inside the box beside your choice.

**Note:** A "managed lane" refers to a lane that can only be used by vehicles meeting certain criteria. Two common types of managed lanes include the following:

- **High Occupancy Vehicle (HOV) lanes**: Where vehicles with at least a certain number of people—for example vehicles with 2 or more occupants—can use the lane for free.
- **High Occupancy Toll (HOT) lanes**: Where vehicles with at least a certain number of people can use the lane for free, plus others can pay a toll to use the lane.



Note: General Purpose Lanes are regular freeway lanes.

#### **Question 1**

If you had the options below for your morning commute during rush hour, which would you choose?



Carpool on General Purpose Lanes
 No Toll
Travel Time: 40 minutes

	Drive Alone on Managed Lanes
_	Toll: <b>\$5.00</b>
	Travel Time: 18 minutes

Carpool on Managed Lanes
No Toll
Travel Time: 18 minutes

### **Question 2**

If you had the options below for your morning commute during rush hour, which would you choose?

	Drive Alone on General Purpose Lanes	Drive Alone on Managed Lanes
	No Toll	Toll: <b>\$2.00</b>
	Travel Time: <b>30</b> minutes	Travel Time: <b>20</b> minutes
	Carpool on General Purpose Lanes	Carpool on Managed Lanes
_	No Toll	 No Toll
	Travel Time: <b>30</b> minutes	Travel Time: <b>20</b> minutes

#### **Question 3**

If you had the options below for your morning commute during rush hour, which would you choose?

	Drive Alone on General Purpose Lanes
_	No Toll
	Travel Time: 45 minutes
	Carpool on General Purpose Lanes

No Toll	
Travel Time: <b>45</b> minutes	

Drive Alone on Managed Lanes
 Toll: <b>\$8.00</b>
Travel Time: 25 minutes
Carpool on Managed Lanes

1		υ	
	No 7	Toll	
Travel	Time:	<b>25</b> minutes	

# **Psychological Questions**

Please rate the extent to which you agree with each statement using the following scale:

Strongly disagree	Disagree	Somewhat disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7	8	9

Note: These are destined for travelers who live near managed lanes. If you can't answer managed lane questions (like #1 and #2) just skip them.

1.	It does not matter if I choose the general purpose lane or managed lane since it is just luck if the managed lane saves me time.	0 2 3 4 5 6 7 8 9
2.	Unless there is no traffic on the freeway, I choose the managed lane since traffic could become congested at any time.	0 2 3 4 5 6 7 8 9
3.	If I were listening to the radio and heard there is an accident on the road I was traveling on, but I was unsure of whether the accident is behind me or ahead of me, I would choose to continue driving on the roadway anyway rather than try a different route.	1 2 3 4 5 6 7 8 9
4.	I only choose to use the managed lane if the general purpose lane seems crowded.	023456789
5.	When buying fuel for my car, I use the most convenient gas station and do not pay much attention to price.	023456789
6.	I have often found that what is going to happen will happen.	123456789
7.	I usually choose to use the managed lane only at the last second.	003456789
8.	Carpooling makes me feel like I am at the mercy of others in the carpool to get to my destination on time.	023456789
9.	Whether I am involved in a traffic accident is purely a matter of fate and there is not much I can do to prevent it.	003456789
10.	Before purchasing a new vehicle, I spend an extensive amount of time researching potential makes, models, and prices before making a decision.	003456789
11.	If pulled over by a police officer, I do not try to talk my way out of a ticket since it will not help.	123456789
12.	If I were to carpool, my carpool partner(s) would have to be very dependable.	023456789
13.	I cannot understand why someone would pay to use the managed lanes when the general purpose lanes are available for "free", especially when it may or may not save time.	023456789
14.	I rarely complain about traffic problems because that will not help fix the problem.	003456789

Stroi disag	ngly gree	Disagree	Somewhat disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Son a	newhat gree	Agree	Strongly agree	
1		2	3	4	5	6		7	8	9	
15.	<b>15.</b> The coordination involved with carpooling is more hassle than it is worth.① ② ③ ④ ①										
16.	Wh prio	en taking or to begin	a road trip, ining the trip	I map out o.	the route I w	ill follow		000	3 4 5	6789	
17.	Get the	ting pulle wrong pla	d over for space at the wr	beeding is ong time.	simply a ma	tter of being	g at	$\bigcirc$	345	6789	
18.	I of to d	ten look u Iriving any	p information where.	on about t	he traffic con	ditions prio	or	000	3 4 5	6789	
19.	The trav GP	e travel ch vel inform S.	oices I make ation I obtai	e are large n from so	ly influenced urces like the	l by real-tim radio or m	ne y	120	345	6789	
20.	I ter traf	nd to mak fic I encou	e choices ab unter.	out which	n road to use	based on the	e	00	345	6789	
21.	I we con min	ould rathe nmute that nutes.	r consistentl t varies anyv	ly have a 2 where from	20 minute con n 10 minutes	mmute than to 30	a	12(	345	6789	
22.	I would rather stay 30 minutes longer at work than leave during rush hour and face the possibility of being stuck in traffic for an extra 30 minutes.								345	6789	
23.	Wh que	en the relistionable,	ability of tra it deters me	ansit syste from usin	em schedules ng transit.	is		$\bigcirc$	345	6789	
24.	I ge the	enerally ch only way	loose to use I will make	the managit to my d	ged lanes whe	en I feel it is time.	s	000	3 4 5	6789	
25.	I lis traf	sten to the fic.	radio while	driving so	o I can get up	dates on		00	3 4 5	6789	
26.	I do	not like 1	elying on ot	thers for r	ides.			120	3 4 5	6789	

For each of the following statements, please indicate your likelihood of engaging in each activity. Provide a rating from 1 to 9, using the following scale:

Extr unl	emely ikely	Unlikely	Somewhat unlikely	Slightly unlikely	Neither likely nor unlikely	Slightly likely	Somewhat likely		Likely	E	Extremely Likely	
	1	2	3	4	5	6		7	8		9	
27.	27.Choosing to use the managed lane, knowing there is a 50 percent chance it will not save me time.1 2 3 4 5 6 7 8 9									9		
28.	Inves	ting 10%	of your annu	ual income	e in a blue ch	nip stock.		12	345	6	78	9
29.	Lending a friend the money needed to purchase a \$20 toll tag so they could use the managed lane.									9		
30.	Taking a job where you get paid exclusively on a commission① ② ③ ④ ⑤basis.								6	78	9	
31.	Lending a friend an amount of money equivalent to one month's income.① ② ③ ④ ⑤ ⑥ ⑦ ⑧									78	9	
32.	Betti	ng a day's	income at the	he horse ra	aces.			12	3 4 5	6	78	9

### **APPENDIX B: N-GENE CODE**

```
;Design
;alts=dagl,cpgl,daml,cp2ml
:rows=15
;block=5
;eff=(rppanel,d)
;rep=1000
;rdraws=halton(400)
;cond:
if(cp2ml.spdlvl_m \Leftrightarrow daml.spdlvl_m, cp2ml.spdlvl_m = daml.spdlvl_m), if(cpgl.spdlvl_g \iff
dagl.spdlvl_g,cpgl.spdlvl_g=dagl.spdlvl_g)
;model:
U(cp2ml)=c3[-0.38]+spd[n,0.14,0.64]*spdlvl_m[55,60,65]
U(daml)=c2[-1.90]+spd*spdlvl_m+toll[n,-0.12,0.1]*tlvl[45,67.5,90]
U(cpgl)=c1[-4.25]+spd*spdlvl_g[25,35,45]
U(dagl)=spd*spdlvl_g
$
```

# Performance Characterization of Different Asphalt Binders at High Temperature: Oklahoma Case Studies

Prepared for Undergraduate Transportation Scholars Program

by

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Program Sponsored by: Oklahoma Department of Transportation Selection of Long-Lasting Rehabilitation Treatment Using Life Cycle Cost Analysis and Present Serviceability Rating Project No. 2261

08 August 2014



### STUDENT BIOGRAPHY

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Sam is actively involved with the University of Memphis student chapter of Engineers Without Borders, where he serves as chapter President. He is also the project lead for the chapter's irrigation and potable water project in Yarvicoya, Bolivia. Sam is a member of the American Society of Civil Engineers and the Society of Women Engineers. He has previously completed research on sustainable civil engineering projects in developing nations, on collaboration between engineers and anthropologists to create sustainable community

projects, and on the use of light-weight fill in freight rail embankments. After graduation, he intends to pursue a Master's degree in sustainable and renewable energy infrastructure.

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# SUMMARY

Asphalt binder characterization is fundamental to the performance and longevity of asphalt concrete. Therefore, in order to better estimate pavement life and create a maintenance and rehabilitation (M&R) program, it is imperative that we improve our understanding of asphalt binder rheology. Asphalt binder characterization is an important part of the generation of an engineering decision tool to facilitate M&R planning for the sponsor of this project, Oklahoma Department of Transportation (ODOT).

A constitutive model is one that relates two physical quantities specific to a material. The linear viscoelastic Kelvin-Voigt constitutive model was used to characterize the rheological properties of asphalt binder. This model was utilized to represent and simplify the complex case of characterizing the viscoelastic asphaltic materials.

In order to characterize and simplify asphalt binder rheology, several laboratory tests were conducted on three binders commonly used by ODOT. The rheological properties of asphalt binder are viscoelastic; its stress/strain response is dependent on temperature and rate of loading. The frequency sweep test was performed using a dynamic shear rheometer (DSR) to distill an elastic solution from a viscoelastic problem via the principle of time-temperature (t-T) superposition concept. This allowed for the reduction of input variables for the mechanistic-empirical M&R tool.

The binder's PG grade was confirmed and its ability to resist rutting was analyzed using DSR testing. These characteristics will be included in an excel-based tool for M&R planning. This tool will add the rheological characteristics of asphalt binder to the elements of mix design, category of roadway, traffic volume and rate of loading, and life cycle cost analysis with the objective of improving pavement longevity and performance while decreasing cost for the state of Oklahoma.

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Replicate
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Replicate
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#### INTRODUCTION

Asphalt concrete is a complex material consisting of aggregates, asphalt binder, and air voids. It is well-known that the mechanical response of asphalt concrete is time-, rate-, and temperaturedependent and exhibits nonlinear behavior under different loading conditions (26). The complex microstructure of the asphalt concrete along with the difference between the stiffness moduli of binder and aggregate phases induce strain/stress localization in the binder phase as the material deforms. This increase in stress/strain level in the binder phase contributes in the nonlinear behavior of binder which subsequently leads to the nonlinear mechanical response of asphalt concrete (27), (28), (29). At high temperatures, the stiffness of asphalt concrete significantly drops making the material more prone to rutting (i.e., permanent deformation) under cyclic loading conditions. On the other hand, at lower temperatures, asphalt concrete becomes more brittle and more prone to fatigue damage (i.e., evolution of micro-cracks and micro-voids). The time-dependent viscoelastic response of asphalt concrete significantly affects the evolution rate of both fatigue damage and rutting. Therefore, robust modeling of mechanical response of asphalt concrete over a wide range of temperature requires accurate characterization of the rheological properties of binder which is a key component in the asphalt concrete.

Resource scarcity and rising cost of petroleum are driving up the cost of hot mix asphalt and roadway resurfacing, and road closures for asphalt maintenance are costly and time consuming (surface treatments are still costly and require road closures, but much less than milling and replacement of the asphalt layer). So, the performance of preservation surface treatments for asphalt pavement is becoming increasingly important. The goal of sustainable pavement preservation is "keeping good roads good" instead of allowing them to deteriorate beyond the point of costly rehabilitation. Sustainable pavement preservation is being pursued by DOTs across the country and will be instrumental in addressing pavement system needs. This performance is highly dependent upon the properties of the asphaltic binders used in preservation surface treatments; the cause of many premature treatment failures can be traced back to improper binder selection (*30*). So in order to properly sustain roadway performance, the properties of asphalt binder must be carefully considered.

This project, "Performance Characterization of Different Asphalt Binders at High Temperature: Oklahoma Case Studies," is a portion of a larger, parent project entitled "*Selection of Long-Lasting Rehabilitation Treatment Using Life Cycle Cost Analysis and Present Serviceability Rating*". The objective of the parent project, sponsored by the Oklahoma Department of Transportation, is to develop an engineering decision tool that facilitates the selection of maintenance and rehabilitation activities and their timing for different types of high-volume asphalt pavement roads in the state of Oklahoma using historical data, materials characterization and performance testing, and life cycle cost analysis. The tool will require calibration due to potential differences between national and local conditions.

#### BACKGROUND

Before addressing the performance properties of asphalt binder, it is helpful to review the challenges faced in asphalt pavement design, as well as some proposed methods of addressing those problems. Because pavement condition is the focus of the parent project, we will discuss

three common—but important—modes of failure in asphalt pavement. This project is focused on the asphalt concrete layer of the roadway (Figure 9, (a)); problems arising from inadequate structural design or subgrade support are outside the scope of this project. Instead, the parent project is focused on the design of the asphalt concrete overlay, and is adopting a life-cycle cost analysis approach for the selection of the best cost-effective rehabilitation treatment based on a multiscale approach (Figure 9, (b)).



Figure 9. Roadway Cross-Section and Components of Asphalt Concrete Pavement Performance Evaluation

Asphalt binder is highly sensitive to changes in temperature (*31*). As temperature drops, asphalt hardens and contracts. When tensile forces resulting from thermally-induced strains exceed the strength of the binder, low-temperature cracking develops in the pavement's surface. This type of cracking is top-down cracking (it generally originates at the top surface of the pavement and propagates downward), and usually runs perpendicular to the flow of traffic as shown in Figure 10. These cracks may be caused by temperature drop alone, by thermal fatigue, or through some combination of thermal fatigue and loading.

Fatigue cracking indicates structural failure of the roadway. Within the asphalt pavement layer itself, there are two mechanisms for the development of fatigue cracking. First, in thin pavements, bottom-up cracking can develop. As loads pass over a section of pavement, that pavement deflects under the load; this causes an accumulation of compressive strain at the top surface of the pavement, and tensile strain at the bottom of the pavement layer. These tensile strains cause cracking that propagates upward through the layer. Second, in thick pavements, top-down cracking results from high localized stresses due to tire-pavement interaction or binder aging (binder aging will be discussed shortly). In either case, these cracks form a connected system of cracking known as "alligator cracking," as shown in Figure 11. Like low-temperature cracking, fatigue cracking is a form of brittle failure.



Figure 10. Low-Temperature Cracking



Figure 11. Alligator Cracking due to Pavement Fatigue

Rutting is the accumulation of plastic deformation due to traffic loading. Rutting may be related to improper compaction of the asphalt layer during construction or inadequate support by the underlying layers. For the purpose of this project, however, we will focus on rutting as it results from asphalt binder viscosity. When pavement temperatures increase, asphalt binders become more viscous. When this happens, asphalt pavement becomes less elastic and more plastic; it ceases to relax properly after stresses are removed. Rutting, then, occurs primarily through two mechanisms: consolidation and shear flow. In consolidation, air voids in the pavement are squeezed out, reducing the depth of the asphalt layer in the wheel path. In some cases, as shown in Figure 12, pavement uplift (shear failure) may occur along the edges of the rut; this is the result of shear flow perpendicular to the wheel path. This represents a safety hazard on the roadway, as well as diminished ride comfort. Rutting is a combination of ductile and shear failures.



Figure 12. Rutting

Asphalt binder is composed of asphaltenes, resins, and oils (32), and it ages through several distinct mechanisms (33), (34), (35) (36), two of which will be addressed here. First, in order to be used in the field, asphalt binder must be heated; this allows the material to become viscous enough to coat the aggregates and apply the pavement layer. During heating, however, some of the lighter oils in the asphalt binder are volatilized and lost; this changes the specimen rheology. As a result, freshly applied hot mix asphalt carries different binder characteristics than virgin asphalt.

The second mechanism of asphalt binder aging is oxidation. Oxidation of the binder occurs in two ways: during mixing (short term aging) and over years of exposure to the elements (long term aging). During mixing, hot asphalt binder is exposed to air as it is turned to cover the aggregate. This allows the resins in the binder to oxidize into asphaltenes, stiffening the mix. Then, as asphalt pavement is in service, it continues to oxidize, further reducing ductility. Both long-term and short-term aging must be accounted for in laboratory testing.

To address the effects of short-term aging, specimens are aged in a rolling thin film oven (RTFO) (37). In the RTFO, the asphalt specimen is heated to the approximate mix temperature and exposed to a stream of air, simulating the effects of creating HMA. To address the effects of long-term aging, binder is placed in a pressure aging vessel (PAV). The pressure aging vessel heats the binder and exposes it to high pressure, creating an environment that simulates the oxidation caused by years in the field (38).

# State of the Practice

In the past, asphalt binder was characterized by a series of index tests performed at a controlled test temperature (*Error! Reference source not found.*). These tests included the penetration test and the direct tensions test, among others. The main limitation of these tests is that they are performed at a single temperature and loading rate; the response of asphalt binders is dependent on both of these conditions. The result is that two binder samples can behave similarly under the prescribed test conditions, but very differently in other conditions. To combat these limitations, new methods of binder classification have been introduced.

#### AASHTO Superpave Specification Method

Asphalt binder is a complex material. It is viscoelastic and thermally sensitive, it sometimes behaves as a Newtonian fluid and sometimes as non-Newtonian, and supply is variable. A useful analysis of asphalt binders will help to simplify these characteristics. Superpave<sup>TM</sup> (Superior Performing Asphalt Pavements) was created by the 1987 Strategic Highway Research Program "for the development of performance based asphalt specifications to directly relate laboratory analysis with field performance" (*39*). Asphalt binders are assigned a particular grade based on temperature extremes in the regions in which they are used. This grading helps to simplify selection of appropriate asphalt binders in HMA design.

In the Superpave method, a certain level of performance is required from asphalt binders. Rather than changing the required performance for different environments, the Superpave method establishes limits for properties like ductility and viscosity, and then reports the temperature limits at which a binder specimen ceases to fall within these limits. High and low temperature limits alike are rounded toward zero in increments of six degrees centigrade. The performance grade for the binder is then reported as shown in Figure 13.



Figure 13. Superpave Performance Grading

The Superpave method introduces conservatism into pavement design in two distinct ways. First, when binder is graded, the grade is reported in increments of six degrees centigrade. This means that a binder may be able to perform up to the required level even outside of the stated temperature range. Second, when pavement is designed, the desired binder grade is bumped up; that is, the required grade is the next grade higher than the expected needed temperature range. The effect of this conservatism is that binder may be more resilient in the field than expected; this underscores the need for better empirical and mechanical inputs into a constitutive model in order to optimize life cycle cost and performance.

#### **GOALS AND OBJECTIVES**

The primary goal of this research project was to provide the information necessary to satisfy the Materials and Pavement Structure: Level 1: Material Properties input required for the parent project. To accomplish this goal, the following objectives were met:

- Verified the high temperature PG grading on each ODOT binder sample
- Performed Multiple Stress Creep Recovery (MSCR) Test for characterizing the strain recovery and high temperature performance
- Performed frequency sweep test for developing the binder master curve for each ODOT sample, including:
  - Dynamic Shear Modulus (|*G*\*|)
  - Phase Angle  $(\delta)$

#### ASPHALT BINDER SUPERPAVE SPECIFICATION

The mechanistic portion of the mechanistic-empirical model was obtained using laboratory testing and data. Tests were run using a Bohlin Instruments Dynamic Shear Rheometer (DSR). Testing was completed in compliance with ASTM and AASHTO specifications (*Error! Reference source not found.*) (*Error! Reference source not found.*) (*Error! Reference source not found.*) (*40*).

The first task was to perform PG grade verification (*Error! Reference source not found.*). ODOT provided three sample binder grades: PG 64-22, PG 70-28, and PG 76-28. Because the PG grades were already known, verifying those grades was necessary only as a failsafe measure; as such, this paper will not emphasize the procedure.

Three tests were completed on each binder sample to verify the grade: high temperature grading of the original binder, high temperature grading of the RTFO aged binder, and mid-range temperature testing of the PAV aged binder. All three binder samples passed each test at the prescribed temperatures; for simplification, only the verification data for the PG 64-22 binder is shown. Table 1 shows the results for the high temperature grading at both original and RTFO ages. At original age, the value for  $|G^*|/\sin\delta$  must be greater than 1.00 kPa; at RTFO age, the value for  $|G^*|/\sin\delta$  must be greater than 2.20 kPa. The highest temperature passed by both samples is the PG grade of the binder.

		0				
Superpave Grading Specification	PG64		PG70			
Aging Condition	Original		RTFO			
True Grade Temperature	67.15 ° C		71.3		2 °C	
Trial No.	1	2	1	2	3	
Result	Pass	Fail	Pass	Pass	Fail	
G* /sinδ (kPa)	1.44	0.722	5.24	2.58	1.25	
Phase Angle (°)	85.2	86.4	78.6	81.0	83.1	
Complex Modulus ( $ G^* $ ) (kPa)	1.43	0.72	5.14	2.55	1.24	
Temperature (°C)	63.99	69.98	63.99	69.99	76.03	
Strain (%)	12.00	11.97	10.10	9.99	9.95	
Shear Stress (Pa)	171.699	86.0643	517.997	254.11	122.625	
Frequency (rad/s)	10.03					

 Table 5. High Temperature PG Grading for PG 64-22 Binder

Mid-range temperature grading is performed on PAV aged specimens. Binder samples must have a  $|G^*|sin\delta$  value less than or equal to 5,000 kPa at a range of temperatures specified by the high PG grade. For the high grade of 64°C, the sample must pass at 31°C, 28°C, 25°C, 22°C, and 19°C. Figure 14 shows variance in  $|G^*|sin\delta$  with temperature for the PG 64-22 binder.



Figure 14. Mid-Range Temperature Testing for PG 64-22

#### Taken together,

Table **5** and Figure 14 show the data used to verify the high temperature PG grading for the PG 64-22 sample provided for the project by ODOT. Rutting is a concern only at high temperatures; therefore, the low temperature grading was outside the scope of this project. The other two binder samples were tested with similar results, but that data has been omitted for simplicity and ease of reading.

#### **Time-Temperature Superposition**

Development of the dynamic modulus master curve was completed in accordance with the AASHTO standard (*Error! Reference source not found.*) for all three binders at RTFO age using a frequency sweep at various temperatures on the DSR (shown in Table 6).

Test Temperatures (°C)	Loading Frequencies (Hz)
6	25, 17.647, 11.538, 7.8947,
10	5.3571, 3.6145, 2.459,
15	1.6667, 1.1321, 0.76923, 0.52174, 0.35419, 0.24038,
25	0.16322, 0.11082,

Table 6. Fre	quency Sweej	p Test Parameters
--------------	--------------	-------------------

40	0.075263, 0.051099,
60	0.034702, 0.023563,
$70^*$	0.010001

\**Note*: 70°C temperature was not used for PG 64-22, as this temperature is outside the working range for the sample.

The dynamic modulus master curve is a composite curve constructed at a reference temperature (20 °C) by shifting dynamic modulus ( $|G^*|$ ) data from various temperatures along the logarithmic frequency axis using the Christensen-Anderson-Marasteanu (CAM) model (41). This process provides a two-variable solution to a three-variable problem by translating both frequency and temperature variables into a single variable, the reduced frequency. Because asphalt binder is a thermorheologically simple material, a single master curve for each binder sample can be formed by horizontal translation of data along the logarithmic time axis.

In order to perform the translation from frequency and temperature into reduced frequency, two equations were used:

$$F_r = f \times a_T \tag{1}$$

$$\log a_T = \alpha_1 T^2 + \alpha_2 T + \alpha_3 \tag{2}$$

where  $F_r$  is the reduced frequency f is the test frequency  $a_T$  is the shift factor

 $\alpha_1, \alpha_2$ , and  $\alpha_3$  are parameters used to fit the shift factor to the data

To fit the master curve and phase angle to the shifted data,

$$|G^*| = \frac{10^9}{\left(1 + \left(\frac{f_c}{F_r}\right)^k\right)^{\frac{m_e}{k}}}$$
(3)

$$\delta = \frac{90m_e}{1 + \left(\frac{F_r}{f_c}\right)^k} \tag{4}$$

where  $|G^*|$  is the dynamic modulus of the binder  $F_r$  is the reduced frequency  $\delta$  is the phase angle  $f_c, m_e$ , and k are parameters used to fit the master curve to the data

Because formulae 2-4 are interdependent, the solution is iterative. Excel's Solver tool was used to minimize squared error between the original  $|G^*|$  data and the  $|G^*|$  curve. The resulting values were used to calculate the phase angle at each reduced frequency. As a result, there is a higher

error associated with phase angle than with  $|G^*|$ . Fitting parameters (unitless constants) used for each binder sample are shown in Table 7. Shift factor, complex modulus, and phase angle are shown for each material in Figures 7-9 (PG 64-22), Figures 10-12 (PG 70-28), and Figures 13-15 (PG 76-28), all in RTFO-aged condition.

Sample	$f_c$	k	$m_e$	
64-22, RTFO	4.23E-02	1.15E-01	1.32E+00	
70-28, RTFO	1.35E+04	1.72E-01	6.70E-01	
76-28, RTFO	2.62E+05	2.45E-01	5.67E-01	

**Table 7. Master Curve Fitting Parameters** 



Temperature (°C) Figure 15. Shift factor for PG 64-22 from Frequency Sweep Test



Figure 16. Dynamic Shear Modulus Mastercurve for PG 64-22 from Frequency Sweep Test



Figure 17. Phase Angle Mastercurve for PG 64-22 from Frequency Sweep Test



Figure 19. Dynamic Shear Modulus Mastercurve for PG 70-28 from Frequency Sweep Test



Figure 20. Phase Angle Mastercurve for PG 70-28 from Frequency Sweep Test





Figure 22. Dynamic Shear Modulus Mastercurve for PG 76-28 from Frequency Sweep Test



Figure 23. Phase Angle Mastercurve for PG 76-28 from Frequency Sweep Test

# Multiple Stress Creep Recovery (MSCR)

Evaluation of the creep and recovery capacity for each binder was assessed using the MSCR test on the DSR, according to the ASTM standard (42). Each replicate (two from each binder sample) underwent twenty cycles of stress and recovery—ten cycles at 100 Pa and ten cycles at 3200 Pa. These two stress levels were used to simulate behavior of the binder phase at different depths within the pavement layer while staying in the linear elastic range for the material and avoiding the introduction of damage. It is important to note that each MSCR test was performed at the high PG grade temperature for that sample; the test is designed to show strain recovery for each binder at its maximum service temperature. For each cycle, stress was applied for one second, then the specimen was allowed to rest for nine seconds. Strain responses were measured as a function of time (Figure 24, (b)).

Portions of the strain response curve can be identified according to the type of response—instant (elastic) or time-dependent (viscous). There is an elastic response at the start and end of the creep cycle ( $\varepsilon_0$  and  $\varepsilon_c$ ), and a viscous response during creep and relaxation (until  $\varepsilon_r$ ). At the end of each cycle, the difference between the starting and ending strain is the permanent deformation left in the material from that cycle. By applying repeated loading cycles, the material can be frustrated, displaying the deformation properties of the binder and of any polymer modifications. For this project, the PG 64-22 binder is unmodified, PG 70-28 has some polymer modification, and PG 76-28 is heavily polymer modified. Exploration of these responses allows comparison of the materials to a series of springs and dashpots in a constitutive model such as the Berger model



Figure 24 (a) Primary Components and (b) Schematic Picture of Input and Response of Burger Constitutive Model

(Figure 24, (a)). This evaluation generates the permanent strain,  $\varepsilon_p$ , relative to induced stress for the material via equation 5. Using this parameter, depth of rutting can be estimated using equation 6 (4318), demonstrated in Figure 25.

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_r a N_r^{\ b} \tag{5}$$

$$PD = \sum_{i=1}^{n} \varepsilon_p \times N \times h_i \tag{6}$$

where  $\varepsilon_p$  is the permanent axial strain in the material  $\varepsilon_r$  is the recoverable axial strain in the material  $\beta_r$  is a calibration coefficient  $N_r$  is the number of load repetitions *a* and *b* are non-linear regression coefficients *N* is the number of pavement sublayers  $h_i$  is the thickness of the sublayer



Figure 25. Pavement Sublayers and Stress Bulbs Due to Varied Loading

Using output data from MSCR testing on the DSR, graphs were created showing accumulated strain as a function of time for each replicate. Figure 26 shows data for each replicate of the PG 64-22 binder at each stress level. Figure 27 shows data for the PG 70-28 binder, and Figure 28 shows data for the PG 76-28 binder. To provide better scale reference, Figure 29 shows one replicate of each binder at 3200 Pa stress level.



Figure 26. PG64-22 Binder (a) 100 Pa Stress Level, (b) 3200 Pa Stress Level, (i) 1<sup>st</sup> and (ii) 2<sup>nd</sup> Replicate



Figure 27. PG70-28 Binder (a) 100 Pa Stress Level, (b) 3200 Pa Stress Level, (i) 1<sup>st</sup> and (ii) 2<sup>nd</sup> Replicate



Figure 28. PG76-28 Binder (a) 100 Pa Stress Level, (b) 3200 Pa Stress Level, (i) 1<sup>st</sup> and (ii) 2<sup>nd</sup> Replicate



Figure 29. One Replicate of Each Binder at 3200 Pa Stress Level

#### CONCLUSIONS AND RECOMMENDATIONS

Comparison of the graphs of the master curves generated by the frequency sweep tests for PG 64-22 and PG 70-28 shows that both samples reached a similar minimum G\* value (about 0.01 psi), but the PG 70-28 reached this value at a lower reduced frequency—that is, at a higher temperature. This confirms that, as expected, the higher graded binder responds better to high temperatures than the lower grade. Comparison of the master curve graphs for PG 70-28 and PG 76-28 shows that at the same low reduced frequency, the PG 76-28 has a higher minimum G\* value. These curves, taken together, demonstrate the validity of the frequency sweep test by confirming the results expected from PG grading.

Similarly, comparison of the graphs of the phase angles for these three samples shows that under the same high temperature condition, the PG 64-22 sample has a phase angle near 90°, while the PG 70-28 has a phase angle around 60° and the PG76-28 has a fitted phase angle near 50°. This shows that, under similar testing conditions, the lower grade sample has a much less elastic response than the high grade binder. The lower elastic response allows for greater shear flow in the material, and therefore a lower rutting resistance. As a result, it was expected that the higher grade binders would demonstrate more recoverable strain and less accumulated strain than the lower grade binders.

Ranking the three binder grades in order of accumulated strain shows that the highest accumulated strains—and the lowest levels of strain recovery—are found in PG 64-22, followed by PG 70-28 and PG76-28. The polymer network in the modified binders provides a much greater strain recovery rate and high-temperature stiffness than we see in the unmodified binder. Resistance to rutting is directly linked to the binder property of strain recovery. Therefore, the highly polymer modified binder is less likely to undergo rutting, even at a higher temperature that the low grade binder.

The parent project will utilize this information as one set of inputs to complement information about mix specifications, climate, and traffic loading to produce the damage vs time model for pavement life.

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# Rapid Rehabilitation of Energy Impacted Roads

Prepared for Undergraduate Transportation Scholars Program

by

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#### SUMMARY

This project identifies primary practices and associated policies used by state departments of transportation (DOT) for rapid rehabilitation of historically low-volume paved roads in response to heavy truck traffic increases that are often associated with energy development. The practices are also evaluated for efficiency in responding to the heavy truck traffic impacts. While rehabilitation issues are experienced by both local (municipal, township, and county) and state transportation agencies, this project focuses on rehabilitation of historically low volume paved roadways maintained by state DOTs. DOT officials were interviewed from multiple districts in six different states: Colorado, North Dakota, Oklahoma, Pennsylvania, Utah, and Wyoming. Practices and policies from the different districts were collected and compared to establish a synthesis of state DOT's responses to the energy development impacts through roadway rehabilitation.

Upon evaluation of the collected data, six roadway rehabilitation techniques were found to be used: mill and fill, structural overlay, cold mix in-place recycling, hot mix in-place recycling, full depth reclamation and reconstruction. The rehabilitation was not energy specific in most districts, nor was it rapid. Rehabilitation is currently being conducted as it would be on any other low volume roadway, only at a greater frequency.

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## ABBREVIATIONS AND ACRONYMS

AADT: Annual Average Daily Traffic ARRA: Asphalt Recycling and Reclaiming Association **CDOT**: Colorado Department of Transportation CIR: Cold Mix In-Place Recycling **DEP**: Department of Environmental Protection **DOT**: Department of Transportation FDR: Full Depth Reclamation FHWA: Federal Highway Administration **HIR**: Hot Mix In-Place Recycling HMA: Hot Mix Asphalt NDDOT: North Dakota Department of Transportation **ODOT**: Oklahoma Department of Transportation PennDOT: Pennsylvania Department of Transportation **RAP**: Reclaimed Asphalt Pavement **UDOT**: Utah Department of Transportation **WYDOT**: Wyoming Department of Transportation

## INTRODUCTION

Many states are involved in energy development and associated construction of oil and gas wells in an effort to grow their economies. Roadway infrastructure has played a critical role in supporting and facilitating the energy development. The roads have facilitated the moving of components during the construction and the development of energy resources and subsequently the intermediate and final products.

The construction activities that are involved in establishing and operating oil and gas wells, as well as wind turbines, can cause great fatigue on the roadways, as the heavy truck traffic loads and volumes increase during this time. Many roadways the trucks are traveling upon are neither designed nor capable of withstanding such traffic, in turn requiring extensive repairs. State departments of transportation (DOT) are tasked with the job of rehabilitating these roadways against the strains of resources like time and money during the rise of this new situation.

The intent of this project was to identify the primary practices and methods used by state DOTs for rapid rehabilitation of historically low-volume paved roads in response to heavy truck traffic increases that are often associated with energy development. Interviews were conducted with DOT representatives in six states with intensive energy development activities to identify these practices and methods. The practices and methods were analyzed for effectiveness and efficiency in their response to the heavy truck traffic damage. Because timeliness is an essential factor in effectiveness of any rehabilitation strategy, it is the main focus of the analysis for this research.

## BACKGROUND

This research project was a component of a project currently being conducted for Texas A&M Transportation Institute's Policy Research Center. The parent project is considering oil, gas and wind energy developments and is looking into how state DOTs are managing the developments impacts on roadway systems, including financial, environmental, safety and infrastructure aspects. The parent project is focused primarily on states which have had significant increases in energy development intensiveness in the past decade.

#### **Energy Development**

The shale map (Figure 1) shows plays—organically rich geographic areas—that are found throughout the Mountain West, the South, and throughout the Northeast's Appalachian Basin. The development of these shale plays not only provide natural resources but has also boosted local and state economies. The development of a well also creates traffic increases in rural areas as equipment and fluids must be brought in to construct it. For example, the Pennsylvania Department of Environmental Protection (DEP) estimates that one well requires an average of 1,000 truck trips during drilling and fracking (44). In addition, wind energy developments also can have significant truck traffic, particularly oversized/overweight trucks, although the effects of this are less extensive and more short-lived than truck traffic associated with petroleum based energy development.



**Figure 30. US Map of All Shale Plays** Source: Reference (45)

The truck traffic associated with energy development often travels over both state and local road and bridge infrastructures. Particularly for historically lower volume roadways, this traffic can cause great damage.

## Impacts on the Roadway

Roadways are public infrastructure that is being adversely impacted by energy development. Publicly borne costs for maintaining infrastructure, safety, convenience and vehicle maintenance are a major problem with the impacts on the roadways. A reliable roadway is beneficial to all associates: DOTs, energy companies and the general public.

Historically low volume, rural paved roads, can be made of flexible pavement typically Hot Mix Asphalt (HMA), or from a collection of chip seals over an old 'farm road'. A flexible pavement is comprised of layers of material, each of which receives the loads from the above layer, spread them out, and then pass them on to the layer below. The term pavement *structure* refers to the layers of the roadway as a whole. The further down in the pavement structure a layer is, the less loading in terms of force per area the layer carries.

Pavements will fail sooner than expected if:

- There are heavier loads than expected
- There are more loads than expected
- The pavement is too thin for the traffic loads
- The materials used are weaker than expected (46)

In the situation of energy development impacts on historically low volume roads, the first three out of the four conditions can be expected to occur frequently. The volumes of heavy truck traffic, as well as the loads, can increase dramatically in areas with intensive energy development. The roadways that this project considered, historically low-volume paved roads, are thin in structure. This was confirmed by the state DOT representatives who were contacted for this project. The structures of their energy impacted roadways typically consisted of a thin base, if any, and a thin surface course. Many of these roads were never 'engineered', but rather just a combination of maintenance seals and thin overlays, sometimes over poor soils.

With three or four of these conditions occurring frequently, these roadways can fail quickly. Signs of failure can include cracking, rutting, pumping, potholes and other distresses. These conditions all occur under the influence of large loads or heavy volumes of traffic. Rehabilitation must be conducted quickly to minimize impacts on the traveling public, and also avoid destruction of the road and more costly total reconstruction, or risk of the roads becoming impassible.

## **Rehabilitating a Roadway**

Rehabilitation treatments are structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capacity (47). There are multiple rehabilitation techniques available, and variances within each technique are possible. Some of the more common rehabilitation techniques are listed in Table 1. While mill-and-fill is generally considered a maintenance method it has been included in the rehabilitation techniques list for this study method as multiple districts included it within their rehabilitation techniques.

Technique	Description
Mill-and-Fill	Removing of existing pavement with milling machine. Milled pavement is hauled away and replaced with new asphalt plant mix.
Structural Overlay	Placement of hot mix asphalt over existing pavement structure.
Hot Mix In-Place Recycling (HIR)	Heating and softening of pavement which is then mixed on-site with a rejuvenator and compacted into place. Additional aggregates added as required.
Cold Mix In-Place Recycling (CIR)	A portion of the asphalt layer is crushed, mixed with asphalt emulsion or foamed asphalt binder and compacted to be used to produce a base course.
Full Depth Reclamation (FDR)	Asphalt and portions of subbase and base layers are crushed, mixed with binder, and placed with or without a stabilizer such as cement, asphalt emulsion or foamed asphalt.
Reconstruction	Removal of asphalt and portions of subbase and base layers which are replaced by new aggregates and pavement mix.

 Table 8. Common Rehabilitation Techniques

Identifying subtle differences in application of techniques can be challenging, as each DOT office may use different names or those that are quite similar to other techniques.

- Mill-and-fill goes by multiple names such as mine-and-blend or mill-and-replace, for example.
- Full depth reclamation (FDR) is very similar to reconstruction; however FDR is a recycling method whereas reconstruction is not. FDR rehabilitates the asphalt, subbase, and base like reconstruction, but rather than hauling the material away, FDR recycles the material and the reclaimed material may or may not be mixed with a stabilizing binder such as cement, asphalt emulsion or foamed asphalt. Reconstruction differs in that it removes the old material and brings in new base aggregates and asphalt mixtures.
- FDR is more closely related to cold in-place recycling (CIR), as CIR once included both partial and full depth recycling. In recent years however, the two methods have been described as distinct. The Asphalt Recycling and Reclaiming Association (ARRA) defines cold-in place recycling as a partial depth (75 to 100mm or 3 to 4") recycling of the existing pavement, and it defines full depth recycling as full depth reclamation (48).

Application of each technique also has considerations: required equipment, cost, service life, or pavement restrictions. For example, FDR is better suited than CIR for pavements with variable thickness, as FDR can rehabilitate a pavement at any depth while CIR is best for pavements that are at least five inches thick (49). Due to time and economic constraints however, DOT engineers may be required to select road rehabilitation techniques that reflect the most efficient and lowest cost option available.

# DATA COLLECTION

Qualitative data was collected through interviews with DOT officials in seven different states. These officials ranged from district engineers to construction, pavement, and materials engineers. The contact information for the DOT officials was located online through the DOT's website or through referrals from other contacts already interviewed.

Fact-based data was collected through semi-structured phone interviews, based on an interview guide developed during in the beginning phases of the project. DOT representatives from the following states were interviewed:

- Colorado (CDOT)
- North Dakota (NDDOT)
- Oklahoma (ODOT)
- Pennsylvania (PennDOT)
- Utah (UDOT)
- Wyoming (WYDOT)

These states are among the top ten most-intensive in recent energy development outside of Texas in the Continental United States, and preliminary project work had confirmed that energy development impacts were being seen on the state roadways. The goal for the project was to conduct between two and three interviews per state. This was able to be achieved for five states (Colorado, Oklahoma, Pennsylvania, Utah, and Wyoming). In the remaining state (North Dakota), interviews were able to be conducted with one representative, but attempts to contact additional interviewees within the project timeframe were not successful.

## RESULTS

Upon evaluation of the collected interview data, it was found that state DOTs generally give rehabilitation control to districts, and they do not all follow the same practices, even within the same state. This is interpreted as being primarily due to the varying nature of finance and environmental characteristics between the districts. Each district had identified the technique(s) that are best suited for them and addressing their needs.

#### **Rehabilitation Techniques**

Some districts utilized multiple rehabilitation options while others chose to only implement one technique. In total, six techniques were found to be used (Table 2), and some were more prevalent than others.

State	District*	Rehabilitation Methods					
		Mill & Fill	Structural Overlay	CIR	HIR	FDR	Reconstruction
Colorado	'A'	√				✓	
	ʻB'					✓	
North Dakota	ʻA'	✓		✓			✓
	'A'		✓				
Oblahama	ʻB'						
Oklanoma	ʻC'		✓		✓		
	'D'		✓				
	ʻA'		✓	✓			
Pennsylvania	ʻB'		✓			✓	✓
	ʻC'						
Utah	'A'	✓		✓			
	ʻB'	✓	✓	✓			
Wyoming	ʻA'	✓					
	ʻB'		✓				

 Table 9. State DOT Use of Roadway Rehabilitation Methods

\*Specific district names or identifiers are substituted with letters in this report.

#### Mill-and-Fill

Mill-and-fill is the process where the surface of the pavement is removed via cold milling, or grinding of the asphalt, with a milling machine. The old material is hauled off-site, and new asphalt is installed as an overlay, usually about 50 mm (2 in). Mill-and-fill is generally considered a maintenance method but for this research study is being included in the techniques used by the DOTs due to its prominence amongst the DOT offices' stated road rehabilitation choices. Despite many maintenance handbooks including mill-and-fill as a maintenance method, when asked which rehabilitation techniques they used, the district representatives would include mill-and-fill as one of their rehabilitation techniques.

The purpose of mill-and-fill is to correct surface issues such as roughness and surface cracking. It provides no benefits to strengthening the overall roadway structure, but does provide DOTs the opportunity to add better bonding between the new overlay and the existing structure. Mill-and-fill is chosen instead of direct overlay when additional structure is not required, vertical limitations exist and there are problems with the existing pavement materials (49).

Five DOT offices in four states indicated using mill-and-fill as a method for addressing the impacts of energy development on roads. These offices were:

- CDOT Region 'A'
- NDDOT District 'A'
- UDOT Region 'A'
- UDOT Region 'B'
- WYDOT District 'A'

These five DOT offices have chosen mill-and-fill as a viable technique either because of financial constraints, policy restrictions or other reasoning. CDOT Region 'A''s representative, for example, states they "are more likely to do minor rehabilitations, such as mill-and-fill, due to funding issues. [The road] may require FDR but funding will only allow a mill-and-fill (50)."

NDDOT District 'A' calls their process 'mine-and-blend' and has been using it for ten years now, whereas before they would just pull the material off and not reuse it. UDOT Region 'A''s mill-and-fill is 'fairly significant' with four inches of milling and three to four inches of new asphalt placed on top. This technique has been their more popular choice compared with CIR (discussed below) which has created some constructability issues. Mill-and-fill is also faster, but nonetheless UDOT Region 'A' is still considering CIR as they await the long term results on performance, such as service life and durability.

#### Structural Overlay

An overlay is a new layer of asphalt surface that is applied over an existing pavement. Overlays are often utilized in conjunction with other techniques, like mill-and-fill and reconstruction for example. Structural overlays increase the pavement's structural capacity and are generally 50 mm (2 in) or more in thickness. Pre-surface repairs are done, such as pothole patching and/or crack repair before the surface is then cleaned and a tack coat is applied. The tack coat material is sprayed down to promote bonding between layers, ensuring maximum achievement of strength in the pavement structure. Following the tack coat is the asphalt placement with either a single lift or multiple lifts to the desired thickness.

Overlays are a popular, quick treatment used by:

- ODOT Division 'A'
- ODOT Division 'C'
- ODOT Division 'D'
- PennDOT District 'A'
- PennDOT District 'B'

- UDOT Region 'B'
- WYDOT District 'B'

WYDOT District 'B' places their overlays to a depth of two inches in what is generally considered the typical overlay. Meanwhile, PennDOT District 'A' uses four inches of overlay, consisting of 2.5 in. minimum of binder course and 1.5 in. of wearing course. The wearing course is the layer directly in contact with traffic. Its purpose is to provide characteristics like friction, smoothness and drainage. The binder course is placed directly below the wearing course and provides the bulk of the pavement structure (51). Its purpose is to distribute the load to the base course, limiting fatigue. Given the significant traffic increases experienced in their district, PennDOT District 'A' has found the binder course to be the important aspect of their overlays and give it substantial depth and strength.

ODOT Division 'C' has taken the approach of gradually widening their narrow energy-impacted roads with overlays. Starting with a 24 foot wide road, they will widen about a foot or two over multiple years on each side until they have built up a three to four foot shoulder. Thus, 24 feet road widths become 26 feet and then 28 feet, and the problem of edge breakaways is mitigated. ODOT Division 'C' states that "if [they] would have had a 24 foot wide roadway the edge certainly would have had some cracking and breaking off. But now over the years [they have] been able to widen with millings and been able to widen out three or four feet and been able to cap that off with the two inch overlay (*52*)."

ODOT Division 'C' has taken up the mindset of adding structure to their thin pavements rather than milling them down, and to do so they have kept up with newer surfacing techniques like the spray paver, shown in Figure 2. This machine can place a 0.75 in. Ultrathin Bonded Wearing Course (UTBWC) or a bonded 2 in. asphalt concrete overlay.



Figure 31. Spray Paver in Use Source: Reference (53)

A spray paver combines the distributer truck with the paving machine so that trucks no longer have to back through the tack coat to get to the lay down the machine (54). In a normal overlay operation the road is tacked, the tack is allowed to break – the separation of water from the asphalt in the emulsion- and then the trucks have to back up to the lay down machine. This requires them to travel through the tack coating, picking up some of it with their tires, creating areas where the layers may not bond properly. While ODOT Division 5 says they did the normal operation with the trucks for years and it works fine, the spray paver is a better technique. The spray paver sprays tack and then applies the HMA seconds later after the tack sets. This provides a better bond between the layers and does not allow trucks to travel through tack coat. This is the new technique for the two inch overlays that ODOT Division 5 has begun using that is receiving high remarks.

Oklahoma's Division 'A' considers their overlays as maintenance, but this research has included it within the rehabilitation techniques. A two lift overlay, meaning it is done in two layers, is placed to improve ride quality. A 3/4 inch lift of S5 mix, which is a finer mix, is placed first to address minor roughness and surface defects, followed by a 1.25 in. lift of a surface course. ODOT Division 'A' believes this gives them two opportunities to improve smoothness, and with smoother roads there is greater vehicle energy efficiency and less stress on the roadways, allowing them to last longer.

According to a division representative, when they do a single overlay they can only improve the ride by 50%, in theory. That is provided that there is good workmanship and the equipment is in good condition. With two lifts, the ride could potentially be improved by 75%—50% the first time, and 50% of the remaining, leading to an overall 75% improvement (55). After tracking this process for seven years it is believed to be working very well, with great endorsement from the contractors. It has been a slow process treating all roads with this technique, however, as only 10-12 projects are completed per year, all eight miles or less in length.

ODOT Division 'D' does overlays to a depth of 1.5 inches, sometimes up to 2.0 inches. In this division they are typically installing one-lift overlays on lower volume roads, as there is not enough thickness to qualify for a two-lift overlay, as in ODOT Division 'A'. Division 'D' does conduct base work before any overlays, however, and this is the extent of any rehabilitation for them. This requires excavation down to where the base failures may be occurring. Once the spot of base failure has been located, leveling is attempted and then an overlay is applied. This is commonly referred to as base patching. Division 'D' acknowledges this is not a permanent fix, as future problems will be expected, but they've done what they could to address current problems, and with financial constraints this may be the best they can do for the time being.

## Cold In-Place Recycling

Cold in-place recycling (CIR) is defined as a rehabilitation technique in which pavement materials are reused in place without the application of heat. The reclaimed asphalt pavement (RAP) material is obtained by milling or crushing the existing pavement, normally to a depth between 50 and 100 mm (2 and 4 in). Virgin aggregate and asphalt emulsion are blended with the RAP material which is then replaced and compacted. A new surface course is then placed onto the compacted RAP. CIR is often combined with an overlay on top or at least a seal coat.

The CIR material is not capable of supporting the truck traffic for too long without a top layer. Some of the major reasons for the use of CIR are:

- the increased scarcity of materials, particularly gravel and crushed rock
- the method's high production rate
- potential of cost savings
- minimum traffic disruption
- ability to retain original profile (56)

Major benefits of in-place recycling versus traditional recycling at a central plant (called cold inplant recycling or cold-mix recycling), are time and cost savings. With traditional recycling, the RAP is removed and hauled to the central plant, where it is mixed with the asphalt emulsion, and then hauled back to the job site. Eliminating this requirement with in-place recycling is particularly helpful with secondary roads that are generally located a considerable distance away from a recycling plant.

NDDOT District 'A' and UDOT Regions 'A' and 'B' indicated that they use CIR in their rehabilitation practices. NDDOT District 'A' has switched from cold in-plant recycling to CIR after determining that they wanted to speed up their operations. One of the new accelerated construction methods was CIR as they found it more efficient to do in place recycling rather than haul material back and forth.

NDDOT District 'A' does a fair amount of CIR combined with widening. The district will grind up the existing asphalt and gravel base to utilize as a new base. Then they widen the roadway out with a grading operation and place an overlay on top. The overlay is typically in the range of six to eight inches of hot mix asphalt (HMA) on the oilfield roads. This depth provides extra structure and load carrying capacity.

Utah Department of Transportation (UDOT) classifies their roadways into two levels. 'Level 1' road ways are the higher volume roadways, above 2000 average annual daily traffic (AADT) or 500 combination trucks, which also receive federal funding. 'Level 2' roads, those with less than 2000 AADT or less than 500 combination trucks, receive state maintenance money only. When considering 'Level 1' roads, UDOT Region 'A' used CIR is some cases but has experienced issues with constructability. With such narrow roads, there is limited space to both rehabilitate the road and maintain traffic simultaneously. The roads generally have no practical detours, according to the region's representative, so a less-intensive procedure like mill-and-fill is often chosen over CIR. UDOT Region 'B' claimed to have the same technique choices as their neighbor Region 'A' but did not mention having any issues with CIR.

UDOT Region 'B' indicated using a four inch deep CIR as part of their purple book program. The purple book program is one of Utah's pavement preservation funding programs that is used for more robust rehabilitation treatments like structural overlays and pavement recycling. The purple book program states that within some CIR jobs, the surface is milled and removed first, to recycle to a deeper layer or to maintain the existing surface elevation after the overlay (57). PennDOT District 'A' uses cold recycling as well, however it is not CIR that they use. PennDOT District 'A' uses cold-mix recycling. The road is milled and removed to be replaced with three inches of the RAP mix produced cold from the mixing plant. District 'A' then tops this with a double seal coat. This method is cost effective for District 'A' and provides long-term pavement performance by increasing the structural strength. On top of that, the method is environmentally friendly as it saves aggregate and crude oil (54). Cold RAP mix recycling utilizes surplus stockpiled RAP material from other projects. This method is used to pave low volume unsurfaced roads and secondary roads, those that the energy industry seems to be using.

## Hot In-Place Recycling

Hot in-place recycling (HIR) has been described as an on-site, in-place method that rehabilitates deteriorated asphalt pavements, thereby minimizing the use of new materials. This technique softens the pavement surface with heat, removes the material, and mixes the material on site with a rejuvenating agent, binder or new mix. The material then is placed back down and compacted (58).

The advantages of hot in-place recycling are that it is comparatively economical and needs less traffic control than the other rehabilitation techniques. Hot in-place recycling is usually performed to a depth of 20 mm to 50 mm (3/4 to 2 in), with 25 mm (1 in) being a typical depth (58). The primary purpose of hot in-place recycling is to correct surface distresses not caused by structural inadequacy.

ODOT Division 'C' and a state representative within UDOT are the only contacts to classify HIR as one of their rehabilitation techniques. HIR is a new technique for Oklahoma and something they have been seeing positive results from thus far.

Within ODOT Division 'C', large propane heaters apply heat through metal plates to the pavement and the surface is milled off in layers half an inch at a time until two inches has been removed. The material is then picked up by a machine, mixed with a rejuvenating agent and then laid back down with no new aggregate added. The paving train, like the one shown in Figure 3, is about half a mile long and when the end of the train has passed the process is done and the job completed. According to a representative from ODOT Division 'C', "HIR is a pretty fast process... you can walk at a slow pace beside the train (52)." A recycled road can be completed and opened to traffic with only a few hours delay. Although the train is highly visible to the public, the process is fast and presents only a minor inconvenience to motorists (59). The finished surface can be opened to traffic after the pavement has cooled.

Contractors can use a mobile asphalt recycling system (MARS) which is customizable for each job and changing conditions. The basic setup is as follows:

- 1. The MARS process begins with two or more propane-fueled heaters.
- 2. Following is another heater equipped with grade-controlled milling drums that windrow the top desired depth of material. The milling heads are capable of milling 15 feet wide and one inch deep (59).



**Figure 32. HIR Recycling Train** Source: Reference (*60*)

- 3. The surface is then milled and heated up to three more times with milling heaters followed by tunnel heaters. Tunnel heaters follow each milling heater and begin heating the underlying pavement while maintaining the temperature of the windrow.
- 4. The last milling heater has an oil metering system that injects and mixes rejuvenating agent, which is a water-based emulsion that replaces the chemical constituents of the asphalt that have oxidized. The rejuvenating agent contains polymer-modified asphalt which further improves the flexibility. That is the final phase of the MARS process.
- 5. The windrow is then picked up with a conveyer belt after being mixed.
- 6. The paving process is performed with a conventional electronic grade control, electric-screed paver (59).
- 7. Finally the material is rolled with conventional rollers.

HIR is fast to complete, and is becoming a more economical choice for agencies. However the switch to HIR over other techniques is slow. The long term results of HIR have yet to be seen in Oklahoma but are projected by the state's DOT to be positive. HIR is, however, energy intensive and can only be used for correction of minor surface defects.

## Full Depth Reclamation

Full depth reclamation (FDR) has been defined as a recycling method where the entire asphalt pavement section and a predetermined amount of underlying materials are treated to produce a stabilized base course (61). The layers are pulverized and additives such as cement, fly ash and lime are added. The material is then shaped, compacted and a new surface course is added. This

process can be seen in Figure 4. If the in-place material is not sufficient to provide the desired depth of the treated base, new materials may be imported and included in the processing (61). This method of recycling is normally performed to a depth of 100 to 300 mm (4 to 12 in).

The main benefit of FDR is that it is the only recycling method to improve the entire structure of the pavement. Other advantages include surface restoration, that pavement widening can be accommodated in the process, and low production cost as only a thin overlay or chip seal is often needed as a surfacing. The Federal Highway Administration (FHWA) recommends FDR for pavements with deep rutting, load-associated cracks, maintenance patches, and particularly for pavements with base or subgrade problems (*58*).

CDOT Regions 'A' and 'B' both use FDR, as well as PennDOT District 'B'. CDOT Region 'A' uses FDR occasionally but due to financial constraints will typically be limited to a mill-and-fill operation instead. CDOT Region 'B' is also generally choosing minor treatments over FDR with their switch to a new 'drivability model'.



**Figure 33. Full Depth Reclamation of Distressed Road** Source: Reference (49)

With the new standards in their model and their pavement programming Region 'B' has moved to doing multiple minor treatments, like overlays and chip seals. However, when the road is in

extremely poor condition, Region 'B' will use a FDR treatment. For some roads, however this can take a while. A Region 'B' representative stated: "Sometimes those roads might not see anything; they might just get maintenance treatments for two to five years before we can get in there (62)." Once the project is set to begin, it will usually take a construction season to be completed. Conservatively, five to six miles (depth not specified) can take about 130-150 construction days (62).

PennDOT District 'B' has chosen FDR as one of their favored techniques and indicated doing more FDR than other PennDOT districts, according to the district representative. During their FDR process, the base is stabilized with cement and then given a structural overlay. District 'B' states FDR is much more efficient than reconstruction as there is no material to haul away, only material to add.

#### Reconstruction

Reconstruction becomes necessary when:

- There is no redeemable pavement life,
- Major subgrade corrections are needed,
- There are changes to roadway geometrics,
- There are planning and design changes, or
- Utility construction also takes place.

Like FDR, a great majority, if not all, of the pavement is removed. When there is a poor subgrade, the unsuitable soils are removed from the site and new fill or granular material is installed prior to the construction of new asphalt pavement (63). Reconstruction allows DOTs to engineer a road that will meet the new traffic loads and conditions as a long-term solution.

Reconstruction is not a widely used method because it is a costly and lengthy process. Out of the 14 Districts that were contacted for this project, NDDOT District 'A' and PennDOT District 'B' were the only users of this method. The North Dakota representative stated that a lot of reconstruction was needed in their district because the existing roadways were so old and the structure of the historically lower volume roadways just could not handle the impacts from the heavy truck traffic.

"If there was a more robust infrastructure we could probably get away with lower maintenance project methods, but for us unfortunately, the oilfield development happens to be along our lower volume roads, with less structure. That requires us to do a lot higher level of repairs (64)." Those repairs were reconstruction, but in NDDOT District 'A' the stabilization of the base layers was problematic as there are issues with finding local sources of aggregates. If aggregates were to be used they would need to be hauled in from long distances, making them very costly. Instead District 'A' has opted to use cement stabilized bases and subgrades.

The NDDOT District 'A' representative stated that cement stabilization has only been introduced in the past few years, and they are still waiting to see how it performs. Thus far it appears to be a good strategy for increasing the strength of the pavement and subgrade prior to pavement surface construction. PennDOT District 'B' has chosen reconstruction as one of the three techniques they use, recognizing that occasionally the entire structure needs to be upgraded. During reconstruction they excavate out the old structure, typically old seal coats and any other material that was underneath the old low volume roads, and begin rebuilding the roadway structure. The PennDOT District 'B' representative stated that on occasion rock is brought in before placing a two inch subbase, followed by a base course and a wearing course on top to complete the structure. The process provides a good, strong base and an overall good product for years to come, but it is time consuming and requires material to be hauled in and out, increasing the cost. District 'B' acknowledges that reconstruction is the least efficient technique out of their three rehabilitation choices. It is now only being done in certain areas where the soil is poor and there is a need for new materials. However, even those areas are limited to 100 to 200 foot sections. Full depth reclamation has become their chosen technique as they move away from reconstruction.

#### **Timing Considerations**

Roadway rehabilitation is a process that state DOTs in the project sample are accustomed to, but doing that process quickly is something that only few in this sample have been able to accomplish. The general methods of acceleration vary between using incentives, A+B contractor bidding, penalties or other methods they have developed on their own.

Incentives function as part of a performance-based contract. A target performance standard is established, in this case a timeline, and if contractors can excel beyond the standard an incentive is awarded, which is a financial bonus. In the case limiting project timeframes, the contractors get a bonus for finishing the project ahead of schedule. In the same aspect, there can be penalties for not completing a project on time. A contractor can end up paying the DOTs a dollar amount per day they are not finished on schedule. Six DOT districts that were interviewed for this project, shown in Table 3, use either incentives or penalties.

State	District	Incentives	Cost + Time Bidding	Penalties	<b>Extraneous Method</b>
Colorado	ʻA'	✓	✓		
	ʻB'	✓			
North Dakota	ʻA'	✓			✓
	ʻA'				
Oklahama	ʻB'	✓	✓		
Okianoma	ʻC'	√		✓	✓
	'D'				
	ʻA'				
Pennsylvania	ʻB'				✓
	ʻC'				
Utah	'A'		✓		✓
	'B'		√		✓
Wyoming	'A'			✓	
	ʻB'				✓

Table 10. Accelerated Timeline Methods by State

Cost plus time bidding, or A+B bidding, is a method of bidding that includes both cost and time in low bid determination. The 'A' is the dollar amount of work to be performed, while 'B' is the number of calendar days bid to complete the work multiplied by the dollar amount of what a day is established to be worth. The lowest sum is awarded the contract, as the aim is to bid a short timeline. This innovative contracting technique encourages contractors to develop well-thoughtout plans. Contractors become encouraged to schedule operations efficiently, work more shifts or off-peak hours, and develop their own innovative ways to accelerate construction. Four DOT Districts across three states indicated using A+B bidding: Colorado, North Dakota, and Utah. In Utah, both DOT districts that were interviewed indicated using this approach.

The six DOT districts that use extraneous methods to accelerate their rehabilitation timelines have established these within their techniques or policies.

Utah's statewide focus on working off-peak hours to limit traffic disruption and increase the chances of completing work with less distractions or problems that arise from the traveling public is established within their policy.

Oklahoma Division 'C' tries to keep momentum within its construction season so that projects can be completed quicker. Overlays are scheduled to be completed by October 31 as previous projects that lasted into the winter months tended to take longer, battling shorter work days and colder temperatures, which make heat loss a larger problem. In the summer days work can go from 8 a.m. to 7 p.m., but in the winter the days generally get reduced to 10 a.m. to 2 p.m. The shorter days correspond to more breaks in the process and more joints in the pavement.

NDDOT District 'A' has taken the approach of switching techniques to those that are faster, like switching from in-plant recycling to in-place recycling. Their accelerated construction methods also include cement stabilization rather than waiting on hauling in aggregates from long distances. NDDOT stated they would continue to look into ways to reduce the timelines of their rehabilitation methods, including contracting techniques although they have not decided to use A+B as of yet.

Pennsylvania DOT established a relationship with the oil and gas industry that has worked well for them. The industry is bonded to certain low volume roads they travel and is held responsible for maintaining them. With policies set up statewide, PennDOT can pass the timeline pressure onto the industry. If the industry is not already aware of the damage that has become a safety hazard a notice may be given by the district office. The notice lets industry know that damage has occurred due to their heavy loading, and gives them five days to begin repairs, and ten days after beginning to have the repair completed. If action is not taken and completed properly the company's permit may be suspended.

# DISCUSSION

Based on interviews conducted with DOT representatives for this project, it appears that those districts which have 'caught up' with the energy development were in 'more-proactive' states. These districts have policies and procedures that can include permitting, routing, partnerships with the industry, and financial programs. Now they have started to implement these policies to

help alleviate the impacts of heavy duty energy development truck traffic on historically low volume roads.

Some districts that are experiencing overwhelming impacts have yet to catch up, and are still rushing to fix their roads with a 'more-reactive' mindset. These districts have not established response programs, yet. This is interpreted to be the primary reason why methods did not differentiate between regular fatigued roads and those with energy development traffic active on them. These districts acknowledged their temporized state, maintaining what they have until they could 'catch a break' and decide on what to do in terms of bigger projects.

Those that have been able to get some breathing time, like NDDOT District 'A' and ODOT Division 'C', have adapted their methods to fit the energy traffic. NDDOT District 'A''s CIR increases their regular overlay depth to six to eight inches because of the energy loads. ODOT Division 'C' has determined the low volume roads with energy traffic need to all be widened out four feet to reduce edge failure.

Other states/districts have created policies for collaborating with the industry. This has been extremely beneficial for the DOTs as they now receive help, typically financially or in smaller ways like schedule coordination. Half of the states contacted had begun some level of a partnership with the energy companies in their areas. At a minimum, districts like CDOT's region 'B', NDDOT's District 'A', and WYDOT's District 'B' have been in contact with the industry to coordinate schedules, traffic control, permitting, and routing. Some districts have been able to attain greater benefits in their partnerships, though, like donations in materials and money from the industry so the DOT can continue to maintain the roads. PennDOT's partnerships have established the industry is responsible for the roadways and must either reconstruct them or maintain them. CDOT's partnership stemmed from the outreach of the energy companies when the district claimed they would be unable to maintain the necessary roads. Bonding, taxing and mutually beneficial partnerships are policies that have begun to arise in an extremely beneficial way for the DOTs.

Not all policies are helpful, however. Some policies that were established before the energy development might now be hindering DOTs. UDOT established a state wide policy on how they would choose to maintain their roads, with a two tier system. When push came to shove the 'Level 1' roads would be maintained under this system, while the 'Level 2' roads were not. The issue with this system in recent development of the energy boom is that energy-related truck traffic impacts are primarily on 'Level 2' roads. The policy is limiting the DOT's ability to help fix those roads. A reevaluation is in effect to categorize those energy impacted roads up to 'Level 1', but while they wait for the roads to shift categories the damage to them is increasing.

# LIMITATIONS

Limitations were discovered during data collection and review of collected information. An uneven sampling of data was collected in the project, as only one district was reached in one of the states, while multiple districts were reached in other states. Contacts were attempted with district representatives in all states numerous times and there was no bias in attempting contacts. The districts were too busy to participate in interviews as the construction season—the time

when this project was conducted—is one of the busiest times for the DOTs. Projects are being done out in the field and many representatives are out of their offices or do not have the time to participate in interviews. Thus, the data collection was not able to be completed for all states within the desired sampling framework given project time constraints.

Contacting only one official per district was also a limitation realized by the end of the project. A more in-depth analysis of the techniques could have been achieved had multiple representatives per district been contacted. Materials, design and procedure for example are some of the in depth analysis that could have been obtained for each technique.

As data was limited in some states, it is unclear as to the consistency of approaches that state DOTs use to conduct roadway rehabilitation. Some states were more uniform among districts while others differed extremely in their actions. With only small samplings in certain states, the data should not be considered representative of all districts within a state.

## RECOMMENDATIONS

For future research it is recommended that interviews are not conducted during construction season. It is believed that the limited number of interviews can be attributed to the busy schedules of the representatives. In one instance a representative asked if it were possible to talk in the winter rather than during July. Due to the limited timeframe of the project this was not possible and the interview could not be conducted.

The data could have been improved by contacting multiple positions within a district. Various representatives gave vague or incomplete information. Contacting multiple representatives per district could provide a more comprehensive idea of the techniques being used. For example, contacting the materials engineer and the construction engineer could provide different sides of information on the same technique. The same could be said for contacting pavement and maintenance engineers. If possible, a conference call could be made with all relevant parties needed in the district to make sure all aspects of roadway rehabilitation are recorded. Planning and organization of appointments could be a helpful avenue for future research.

This study found that further research is needed on a cost-benefit analysis of the rehabilitation methods and techniques. The literature review provided little insight on the cost requirements of each technique, and the district representatives in the interviews conducted for this project did not readily recall costs, or chose not to disclose them. Research in this specific area could establish a financial comparison among the techniques and an in-depth assessment could be beneficial in determining how great of an impact finances were to the decision of choosing a particular technique.

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# Benefit-Cost Analysis of Horizontal Curve Traffic Control Treatments

Prepared for Undergraduate Transportation Scholars Program

by

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Kaitlynn is active in the Texas A&M University Institute of Transportation Engineers as an officer. In addition, she is a member of the TAMU Concert Band and her church's choir. For the past two years she has worked for the mobility analysis division of Texas A&M Transportation Institute.

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## SUMMARY

Horizontal curves have traditionally had three times the crash rate than that of a similar straight road. To address this issue, the FHWA has updated the requirements for horizontal curves in the MUTCD. Agencies responsible for the maintenance and replacement of traffic control devices (TCDs) may benefit from a study of the economics of these recent changes and so this study produced a benefit-cost analysis of TCDs used at horizontal curves.

A survey of state DOTs was conducted in order to gather data on the unit cost and installation cost of various TCDs as well as the expected life of the devices. These devices include advance curve warning signs, arrow signs, chevrons, delineators and retroreflective raised pavement markings. From the data gathered in the survey, the total cost and the annualized cost of installation were calculated. Additionally, the benefit from installing TCDs, which is the reduction in crashes and thus monetary savings, were also calculated. The annualized benefit and annualized cost were used to find the benefit-cost ratio.

The benefit was calculated based from the weighted average cost of a crash on a horizontal curve on a two-way, two-lane road calculated as part of this report. The final value is \$190,000. Costs

of installing an appropriate device for either before or within a curve ranged from \$81 per year per curve for an advance warning sign to \$281 per year per curve for chevrons. The benefit-cost ratio ranged from 47:1 to almost 2500:1. These numbers, which are much greater than previous studies, are due in part to the \$9.2 million value of a statistical life used by FHWA in economic analyses and the longer life spans reported by the states

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## INTRODUCTION

Horizontal curves are a fundamental aspect of any road, particularly, highways. These changes in horizontal alignment allow drivers to negotiate obstacles such as historical property lines and geographical barriers that prevent a road from following a straight path. Horizontal curves, however, are not uniform. Even when the characteristics of two curves (such as the central angle, length, superelevation, radii, number of lanes, shoulder width, and advisory speed) are similar, different traffic control treatments are often used. One of the aspects that affect the application of traffic control devices (TCDs) is the surrounding roadway environment. For example, a curve within a series may require a different TCD or combination of TCDs than an isolated curve with a tangent that has a high speed.

The National Cooperative Highway Research Program (NCHRP) awarded the Texas A&M Transportation Institute Project 03-106, Traffic Control Device Guidelines for Curves to identify potential improvements to the MUTCD guidelines for the application of TCDs on curves. The team compiled data on service life cost for various horizontal curve treatments. These devices include advance warning signs (curve, turn, reverse curve, reverse turn, and winding road signs, each with or without advisory speed plaques), chevrons, post-mounted delineators, retroreflective raised pavement markers (RRPMs) and large arrow signs within the curve.

This research also performed a benefit-cost analysis of the various TCDs as part of the larger project on the overall effectiveness of combinations of TCDs. The intent of the work plan was to develop an easily used benefit-cost analysis which can be shown to reinforce the overall conclusions.

## **BACKGROUND INFORMATION**

Highway curves tend to be locations with safety concerns. While 25 percent of fatal crashes occur on curves, there is about three times as many crashes on curves than as on comparable tangents (65). Run off the road (ROR) and head-on crashes account for nearly 90 percent of fatal crashes at these sites (1). Through the years, methods have been developed to attempt to model and address these crash rates.

## **Maintenance of Traffic Control Devices**

In addition to the installation of a device, the maintenance throughout its life needs to be considered. Many studies have been conducted on the service life of TCDs. One study, concentrating on the deterioration of sign reflectivity, divided the United States into eight geographic regions based on general climate (*66*). The study found that, for signs, age had the greatest impact on sheeting deterioration and that factors such as geographic and climatological affects were minor. On the other hand, a more recent study did not find a strong linear trend between age and retroreflectivity, implying there are other factors influencing the rate of deterioration in addition to age. The authors suggest that although individual factors such as weather and measurement error cause small irregularities in the data, but collectively these factors cause notable variations in life spans (*67*).

Pavement markings also have varying life cycles and costs due to color, thickness, and internal bead type. Due to these factors, the service lives, costs, and thus life-cycle costs of pavement markings vary considerably (68).

Raised pavement markers (RPMs) are an additional type of pavement marking. RPMs come in different varieties such as reflective, non-reflective and snow-plowable. Currently, some states have ceased implementation of these devices due to their high maintenance costs, however, other states, such as Texas, continue to install them. States may maintain RPMs in different manners. Texas, for example, schedules maintenance based on a night-time vision check and replacement based on average daily traffic (ADT) (69). The life spans of RPMs vary drastically depending on external factors such as roadway type, ADT, and climate. The differences in life span range from 10 months to more than 100 months (*70*).

Maintenance treatments for deteriorating horizontal curve treatments include restriping pavement, and cutting foliage to improve sight distance and line of sight to TCDs (71). However, some departments consider replacing a sign or device as the most practical treatment for degraded devices and adjust the life span accordingly. Therefore, the largest portion of cost is the upfront installation and unit cost.

# **Traffic Control Devices at Curves**

Traffic control devices are used at curves to provide drivers information to help them safely navigate the change in alignment Within the MUTCD are guidelines regarding the use of TCDs at curves. MUTCD Table 2C-5, reproduced in Figure 1, identifies these guidelines, which are applicable for roadways with traffic volumes greater than 1,000 vpd. This table defines the recommended and required TCDs based on the geometric considerations which define the recommended navigation speed. In this table, advance warning signs include turn, curve, reverse turn, reverse curve, winding road, combination horizontal alignment/ intersection signs and advisory speed plaques (72). While devices within the curve include chevrons, one direction large arrows, exit speed and ramp speed signs. However, there are other common devices and treatments not within the table that are in use. These devices include post-mounted delineators, RRPMS, rumble strips, high friction surfaces, and wider pavement markings.

# **Calculating Crash Estimates**

Different geometries and environmental factors affect the number of crashes on a given roadway. The change in the number of crashes is estimated using two terms a safety performance function (SPF) and a crash modification function (CMF or CMFunction). The SPF is the expected number of crashes. An SPF is a function whose primary variable tend to be average annual daily traffic (AADT) volumes (73). More specifically, a SPF is used to predict the average number of crashes per year at a given location. CMFs, however, are used to adjust the SPF value for conditions other than the initial standard values. In this report, CMFunction values adjust the expected crashes to represent the crash rate after the TCDs are installed. A CMF of 1 indicates no improvement, while those less than 1 indicate a decrease in the number of crashes. The CMFs help establish the "benefit" portion of the benefit-cost analysis through estimating crash reductions due to the devices.

The solution of the second state	Difference Between Speed Limit and Advisory Speed					
Alignment Sign	5 mph	10 mph	15 mph	20 mph	25 mph or more	
Turn (W1-1), Curve (W1- 2), Reverse Turn (W1-3), Reverse Curve (W1-4), Winding Road (W1-5), and Combination Horizontal Alignment/Intersection (W10-1) (see Section 2C.07 to determine which sign to use)	Recommended	Required	Required	Required	Required	
Advisory Speed Plaque (W13-1P)	Recommended	Required	Required	Required	Required	
Chevrons (W1-8) and/or One Direction Large Arrow (W1-6)	Optional	Recommended	Required	Required	Required	
Exit Speed (W13-2) and Ramp Speed (W13-3) on exit ramp	Optional	Optional	Recommended	Required	Required	

See Section 2C.06 for roadways with less than 1,000 ADT.

Figure 34. Table 2C-5 of the 2009 MUTCD

The Highway Safety Manual (HSM) contains a number of safety performance functions (SPFs) that can be used to estimate the quantities of crashes predicted at a particular facility. The crash frequency for a rural two-lane, two-way roadway segment with the base assumptions can be estimated using the following SPF in the HSM:

$$N_{spfrs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312}$$
 (Equation 1)

Where:

 $N_{spfrs}$  = predicted total crash frequency for a roadway segment under base conditions; AADT = average annual daily traffic (vehicles per day); and L = length of roadway segment (miles).

Crash modification factors (CMFs) and a local calibration factor, (Cr), are used to obtain the final expected number of crashes for a given set of specific geometric features in a specific geographic area or territory. Using CMFs for a curve while evaluating Equation 2 can produce the expected number of crashes for a specific curve. A crash estimate for a curve would thus be:

$$N_{curve} = N_{spfrs} \times C_r \times (CMF_1 \times CMF_2 \times ... \times CMF_{12})$$
(Equation 2)

Where:

$$N_{curve}$$
 = predicted average crash frequency for an individual roadway segment for a specific year;

 $N_{spfrs}$  = predicted average crash frequency for base conditions for an individual roadway segment;

- $CMF_1 \times CMF_2 \times ... \times CMF_{12}$  = crash modification factors for rural two-lane, two-way roadway segments
- $C_r$  = calibration factor for roadway segments of a specific type developed for a particular jurisdiction or geographical area.

## Safety Analysis

The safety analysis team at Vanasse Hangen Brustlin (VHB) determined CMFunctions for the TCDs investigated in the study. This was done by examining horizontal curves at more than 500 sites across three states. Using crash frequency as the dependent variable of interest, several predictor variables were considered, including traffic volume, type and location of TCDs, and other roadway and operational characteristics.

VHB has performed a safety analysis under the assumption that treated sites have different crash statistics than untreated sites for curves with similar characteristics. During their analysis, their hypothesis was confirmed and they developed CMFunctions to describe the change. In this study, the CMFunctions used are based on VHB's work, more specifically, their equations for total reduced crashes. Their CMFunctions were split into two categories based on the placement of the treatment. The devices they studied may all be found within Table 2C-5 (Figure 1) of the MUTCD. Their two categories include advance warning signs and signs within the curve such as chevrons and large arrow signs. The equation for reducing crashes through a sign placed within a curve is:

$$CMF_{within} = e^{(0.203-0.089 \times AADT (thousand))}$$
 (Equation 3)

The equation for advance warning signs:

$$CMF_{advance} = e^{(0.710-0.11 \text{ kDegreeCurvature})}$$
 (Equation 4)

## Cost of a Crash

In an unpublished survey by Alaska DOT in 2006, the researchers found that states take varying approaches to estimate the cost of life lost in a crash. Some states directly use the FHWA costs, while others modify the FHWA cost. Very few of the responding states used identical methods. One state used a value that set a fatality at twice the value of an injury and as a result, their value of a crash was much lower than federal numbers. In 2005, FHWA published a comprehensive report on estimates for the economic cost of a crash which was used for a number of years as the basis for recommended crash costs. The numbers presented in the report are based on empirical data gathered from police reports and are split into crash severity divisions (74).

## **Benefit-Cost Analysis**

Benefit-Cost analyses are useful tools to determining future actions and have been used historically to justify changes in practice. This study considers the benefit as the economic savings due to the decrease in crashes. In order to accurately model a benefit-cost ratio, a more

complex form is used than simply dividing the raw benefit by the raw cost. Although this method is valid for single year ratios, when considering long-term capital effects, the benefit-cost ratio of a project that extends multiple years can become quite inaccurate. A basic equation for benefit-cost analysis that includes adjustments for time is as follows (75):

$$\frac{B}{C} = \frac{(\sum N \times T \times R \times C) \times (P/A, i\%, n)}{CC}$$
(Equation 5)

Where:

 $\frac{B}{C} = benefit-cost ratio$  N = annual crash frequency T = traffic volume growth factor R = proportional reduction in crashes C = average crash cost (P/A, i%, n) = uniform series present worth factor for an improvement

(P/A, i%, n) = uniform series present worth factor for an improvement service life of n years at a minimum attractive rate of return of i%

CC = installation cost per curve

For this research, however, the equation has been modified to better fit the format of the data. For example, the traffic volume growth is not taken into consideration. This report contains a benefit-cost analysis of the TCDs investigated by the parent project. It considers the cost of the materials and installation cost.

## **Previous Work/ Similar Studies**

In a study by Cost and Safety Efficient Design for rural highways in Developing Countries (CaSE), the researchers found adding reflectorized chevron boards reduced crashes within the first year by a factor of ten (76). The number of lives saved was determined through empirical data, though the savings per crash was theoretically determined. Similarly, a report from Texas Department of Transportation (DOT) used real values as the base number of crashes from which savings are estimated (77). However, the study used numbers they derived as part of the study to estimate the reduction in crashes. The cost of each crash was estimated using data from the latest statistics for costs for crashes.

A recent study on the safety effectiveness for low-cost safety strategies on horizontal curves examined the benefit-cost ratio of horizontal curve treatments (78). This project empirically explored the safety effectiveness in order to provide better support to States selecting safety improvements at horizontal curves. This was done by estimating the cost savings of preventing a crash using FHWA recommended numbers and estimating the cost to install devices by asking the states involved in the project. They determined the benefit as the product of the total crash reduction and the cost of a crash. The research supported that because the cost ratios were far greater than 2:1, the cost of installation was economically justifiable.

#### METHODOLOGY

In order to model the benefit-cost ratio of applying various TCDs at horizontal curves, cost data was gathered for this study. In addition, the benefit was estimated based on equations for the reduction in crashes at a curve due to the installation of a device. The following section is divided into three major parts, cost survey, benefit, and benefit-cost ratio.

#### **Cost Survey**

Information was collected from state departments of transportation (DOTs) in a survey that identified their costs to install TCDs and the expected life of each device. To ensure all the necessary information was obtained, the different ways a question could be interpreted were taken into consideration while formulating the questions. The survey is broken into three categories, engineering, installation, and maintenance, and each section addresses a different part of the overall cost. The engineering portion concentrates on the initial preparation work such as evaluating the curves in a jurisdiction. The second portion, the installation, contains the more traditional costs. These include cost of equipment and labor to install. The third part, however, maintenance, is not always paid for by a state DOT directly, but can be completed by a private entity. The maintenance section asks if this is the case before asking for more details on maintenance costs.

Twenty-three states responded to the survey and the returned data were organized into a table detailing the numerical responses. In order to have a more accurate number, the highest and lowest responses were removed from the pool for each category before the averages were calculated. From this data, the average unit cost, service life, mean installation and total cost were determined and then further used to determine the average cost per year which is adjusted to a present-day annualized amount. The final table presents the average life span and cost per year of each of the studied devices. The average cost/year is the number that is used in the benefit-cost analysis as it is in a comparable unit (per year) to the benefit. In addition, once the final table was constructed, the costs by geographical region were examined to look for trends.

Information on pavement markings was gathered as part of the survey and the annual cost per year per foot was calculated, but it is not within the scope of this project to identify the cost of applying and maintaining such pavement markings. For the remainder of this report, it is assumed that pavement markings are already applied at the curves as a continuation of the markings already present in the tangents.

## Benefit (SPF & CMF formulation)

Estimating the expected number of crashes based on the HSM's guidelines is the first step of calculating the benefit of a given treatment (see Equation 1 and Equation 2). The adjusted value varies for whether the TCD is found within or in advance of the curve. In the calculations that follow, several assumptions were in applying the HSM prediction models. One of the conditions was superelevation, instead of the base condition; a superelevation value of 0.06 was used in all calculations. In this study the Cr is not used because the CMFs come from a multi-state effort. The other assumptions pertained to the geometry of the curve such as the radius, length, and the

traffic volume at the curve. For this study, the radius ranged from 300 to 1,100 ft and the length from 500 to 1,300 ft, while the AADT ranged from 1,000 to 13,000 vehicles per day (vpd). 1,000 VPD is the smallest value at which the MUTCD Table 2C-5 is applicable, thus it is used as the lower threshold.

A general equation to find the expected yearly crash frequency after a device is applied is as follows:

$$N_{device} = N_{curve} \times CMFunction$$
 (Equation 6)

Where:

$N_{device} =$	expected number of crashes for a given curve once a device has been installed;
$N_{curve} =$	predicted average crash frequency for an individual roadway segment for a
	specific year (Equation 2);
CMFunction =	= CMFunction provided (Equation 3 and Equation 4)

This equation is similar to Equation 2 but is specifically for this report and the CMFunction used after all HSM CMFs have been applied.

Because the cost of one fatality can greatly increase the average cost of a crash, in order to identify a reasonable estimate for the cost of a crash, a composite method was followed. The value of a statistical life, as suggested by the USDOT, is \$9.2 million. National Highway Traffic and Safety Administration (NHTSA) General Estimates System (GES) crash records were used to determine the percentage of crashes for each of the crash severity (KABCO) levels. The ratios of crash severity were determined from crash rates meeting the following parameters: occurrence on a non-interstate two-lane, two-way roadway without an intersection or work zone and at a curve. Although rural roads could not be explicitly selected, the other parameters generally describe rural roads. The value of a PDO crash in 2013, \$3,927, was pulled from the TIGER Resource Guide (79). Next, using the crash severity percentages and factors for converting between the KABCO and abbreviated injury scale (AIS) scale, the weighted average of a crash cost on a horizontal curve was identified as \$190,000. The exact calculations are provided in Appendix C. This value is used in all of the benefit analysis.

The benefit is calculated as follows:

$$B = (N_{curve} - N_{device}) \times (AverageCost)$$
 (Equation 7)

Where:

B = Benefit in the first year  $N_{device} = expected number of crashes for a given curve once a device has been installed (Equation 6);$   $N_{curve} = predicted average crash frequency for an individual roadway segment for a specific year (Equation 2);$ 

Average Cost= weighted average of a cost of a crash (\$190,000).

The modified SPF (using the models from the HSM and the safety analysis from VHB) is dependent upon three variables: radius, curve length and AADT. The results of the benefit produced by the treatments are illustrated using these three variables. Three graphs are provided for each of the two types of treatment (advance and within-curve warnings). One graph is based on constant length (820 ft), one on constant radius (574 ft), and one based on constant AADT (6,000 vpd). A curve length of 820 ft was selected as a simple average of the curve lengths used in a separate analysis of actual curves. A radius of 574 ft represents a degree of curvature of 10°/100 ft of length, and was the threshold at which the safety results are significant. An AADT of 6,000 vpd was selected because it is also near the limit of significance from the safety study.

## **Benefit-Cost Ratio**

The benefit-cost ratio was determined using engineering economics to appropriately adjust the present day annual values to account for discount rates. The cost was divided into two sections, warning signs before the curve and signs within the curve. The cost is divided thus because the CMFunctions were based on the same division. The cost of an advance warning sign was estimated by adding the unit cost of the advance warning signs and half of the cost of advisory speed plaques, which is an assumption that half of all advance warning signs are supplemented with an advisory speed plaque. The cost of signs within a curve was estimated by taking the average cost the agencies reported to install chevrons and arrow signs. The resulting numbers were graphed in a way similar to the Benefit Analysis.

The benefit was adjusted as seen below. This transformation accounts for the growth in the VSL as well as the discount rate.

AnnualBenefit = 
$$B \times (\frac{(1-(\frac{1+g}{1+i})^n)}{(i-g)}) \times (\frac{i \times (1+i)^n}{(1+i)^n-1})$$
 (Equation 8)

Annual Benefit=
$$B \times ((1 - ((1+g)/(1+i))^n)/(i-g)) \times ((i [x(1+i)] ^n)/((1+i)^{n-1}))$$
 (8)  
Where:

B = Benefit for the first year (Equation 7) g = VSL growth factori = discount rate

n = number of years of a life span of a device

The initial benefit is transformed into the overall benefit that would be earned for the entire lifespan of the device, including the growth of the benefit. This present day value is then converted into an equal annual benefit. The discount rate is assumed to be 3 percent and the growth factor is 0.0118 as is suggested by USDOT for the growth of the VSL (80). The number of years, n, is the average life span of either the advance or within curve devices.

The cost was adjusted by converting the initial installment value into annual, uniform payments. This method accounts for the discount rate on the initial money used.

AnnualCost = 
$$P \times \frac{(i \times (1+i)^n)}{(1-i)^n - 1}$$
 (Equation 9)

Where:

	•••	
Р	=	the installation plus the unit cost of the device
i	=	discount rate
n	=	number of years of a life span of a device

The final Benefit-Cost ratio was formed by dividing the Annual Benefit by the Annual Cost.

## RESULTS

The following section discusses the results of the benefit, cost and benefit-cost ratio analyses. The section includes graphs and tables describing the results and how they relate to each other.

#### **Benefit Analysis**

When examining the effect of devices within the curve, some general trends were observed. Overall benefits increased as the length and the AADT increased and benefits increased as the radius decreased. This is logical because a percent decrease of crashes per vehicle for a curve with a larger AADT would cause a greater benefit than that of a smaller AADT. Smaller radii need greater warning and guidance than larger, easier to navigate curves. Finally, similar to AADT, the longer the length, the greater the area available to crash and thus any percent decrease has a greater effect.

The CMFunctions cannot be applied universally. Due to significance boundaries the equations for signs in advance of a curve may not be used if the radius is greater than 574 ft which is where advance warning signs become significant and the equations for signs within a curve may not be used if AADT is less than 5,500 vpd. The significant limitations are to the model and not to the application of devices to a curve.

When examining the CMFunctions it is apparent that the functions are exponential, however, the benefit graphs are linear. This is due in part to the initial SPF formed from information in the HSM but it is, in a larger part, due to the axis used to graph the information. If a different axis is used, i.e. if x-axis is radius and the different series represent different AADT, other relationships are revealed. For the given example, the new set of graphs would include four negative exponentially shaped graphs. The two non-exponential graphs would be the ones with constant radius. Radius appears to have the greatest effect on the benefit. The greatest variance in benefit was found when the radius was not constant such as in Figure 2.

The following are the graphs for given situations of the benefit. The graphs illustrate how there is variations in the benefit as the three variables through which the benefit is calculated change.

#### Advance Warning Signs

The following three figures graph the benefit for advance warning signs.

Figure 2 relates AADT and radius to benefits for curves with a length of 820 ft. This figure is for devices in advance to the curve and the applicable CMFunction is radius dependent. Curves with a degree of curvature less than 10 (radius greater than 574 ft) do not experience significant reductions; they do, however display the trend found in the significant data. The shaded in triangle and any area below the triangle is outside the bounds of significance.



Figure 35. Economic Benefit of Advance Warning Device - Constant Length

Figure 3 displays the relationship between AADT, monetary benefit, and length of roadway for curves with a radius of 574 ft. In this situation, the relationship between AADT and the Benefit is linear. As the length decreases, the slope of the benefit also decreases.



Figure 36. Economic Benefit of Advance Warning Devices - Constant Radius

In Figure 4, the change in slope between the graphed radii is due to the final CMFunction that is applied which is derived based on the various radii. The benefit becomes gradually greater as the radii decreases from 900 feet. Similar to Figure 2, the bottom line represent insignificant values that, nevertheless, follow the general trend by which the data is changing. The shaded region represents insignificant results.



Figure 37. Economic Benefit of Advance Warning Device – Constant AADT
## Signs Within Curve

The following three figures graph the benefit for signs within curves.

The benefit seen when using a constant length for a device within a curve, as in Figure 5, is a shallow exponential curve. As radius decreases, the intensity of the exponential curve increases. That is, the smallest radius increases the benefit most rapidly. The equation is based on an exponential that is related to AADT, explaining the shape of the graph. In this graph, the benefit for a radius of 300 feet and a radius of 1,100 feet is shown. The box indicates the data that is insignificant due to boundaries of the equations.



Figure 38. Benefit of Within Curve Device – Constant Length

Figure 6 also displays an exponential trend, once again, due to the CMFunction. In this graph, with constant radius, it is apparent that the benefit decreases with decreasing curve length. The overall trend is to increase with AADT. Once again, the box marks the insignificant data due to model limitations. The graphed curves are based on curve length of 500 feet and 1,300 feet.



Figure 39. Economic Benefit of Within Curve Device – Constant Radius

In Figure 7, when there is a constant AADT, the slopes are constant and the greatest benefit is found on curves with small radius (300 ft in the graph).



Figure 40. Economic Benefit of Within Curve Device – Constant AADT

## **Cost-Analysis**

The survey results provided the data necessary to complete the cost and service life components of Table 1. Within the table are also assumptions regarding the quantity that would be installed at a sample curve. These assumptions are used in calculating the total cost to install the devices at the curve and thus the yearly cost when factoring in the service life.

Device	Unit	Number/	Installation	Average	Service	Cost/
	Cost	Curve	Cost	Agency Cost/	Life	Year
				Curve		
Advance Warning	\$136	2	\$488	\$752	11.9	\$81
Advisory Speed Plaque	\$47	2	-	\$94	11.9	\$10
Chevron	\$90	12	\$1,458	\$2,488	11.1	\$281
Arrow	\$150	2	\$424	\$740	11.4	\$83
RRPM	\$6	15	\$573	\$397	4.1	\$44
Delineator	\$40	8	\$544	\$636	9.1	\$95
Pavement markings-	\$0.25/ft	N/A	\$0.25/ft	\$0.36/ft	2.5	N/A
Lower Limit						
Pavement markings-	\$0.99/ft	N/A	\$0.83	\$1.47	4.9	N/A
Higher Limit						

 Table 11: Costs of TCDs at Curves

Chevrons have the highest cost per year of any of the devices, but this is likely due to the number of chevrons per curve required as compared to the other devices. As can be expected, advisory speed plaques cost the least amount per year as they do not need individual posts. The unit costs, total costs per curve, and service lives are the average of all the survey data excluding the highest and lowest responses.

The cost data were compiled into geographic regions. It was found that the Midwest has lower than average costs for all studied devices, while Mountainous regions, have higher than average costs for advance warning and arrow signs, as well as delineators. The Mountainous region states did not respond on cost of RRPM as none of the states currently use them. The North-East had lower costs for signs and delineators but the RRPM value was much higher than average. The South region indicated a lower RRPM cost but higher sign and delineator costs. Finally, the Pacific indicated higher sign costs and lower RRPM and delineator costs.

Also included in the survey were questions that were not used in the cost-benefit analysis. One such question was the cost to asses a curve for a traffic control treatment. The majority of the states responded in cost per curve and the average of their responses is \$485 per curve. A related question asked whether or not the state kept an up-to-date database of the curves which would potentially reduce the cost to analyze the curves in a jurisdiction. The majority of states responded negatively, though many indicated they would like to create one. Finally, of the responding twenty-three states, fourteen responded saying they used other devices not listed in the MUTCD table. These devices included delineators and RRPMs but also included surface treatments and other such devices not studied in this report.

## **Benefit-Cost Analysis**

The following are the graphs for given situations of the benefit-cost analysis. The shapes and trends of the benefit-cost ratios are the same shapes and trends as the benefit graphs. This is because the ratio is directly related to the benefit, while the cost remains constant and is based on the values in Table 1. As such, when a benefit reports a negative value, so does the ratio. Any value less than one is considered as a net loss as the cost is greater than the benefit. Likewise, for values greater than one, the action is considered a net gain.

## Advance Warning Signs

The following three figures graph the benefit-cost ratio for advance warning signs.

Figure 8 relates AADT and radii to benefits by having a constant length. This figure is for devices in advance to the curve which requires a CMFunction that is radii size dependent. The bottom line is insignificant because it has greater than the maximum 574 feet radius required for significance. However, it does display the same trend found in the significant data. The shaded area represents the portion of the graph that contains insignificant data.



Figure 41. Benefit-Cost Ratios of Device Advance to Curve – Constant Length

Figure 9 displays the relationship between AADT, monetary benefit, and length of roadway when the radius is constant. In this situation, the relationship between AADT and the benefit-cost ratio is linear.



Figure 42. Benefit-Cost Ratios of Device Advance to Curve – Constant Radius

The lines in Figure 10 are not parallel due to the final CMFunction that is applied which is derived based on the various radii. The benefit becomes gradually greater as the radii decreases from 900 feet. Similar to Figure 8, the bottom line represent insignificant values that, nevertheless, follow the general trend of the data. Once again, the shaded region represents insignificant data.



Figure 43. Benefit-Cost Ratios of Device Advance to Curve – Constant AADT

Signs Within Curve

The following three figures graph the benefit-cost ratio for signs within curves.

The benefit-cost ratio seen when using a constant length for a device within a curve, as in Figure 11, is a shallow exponential curve. As radius decreases, the intensity of the exponential curve increases. That is, the smallest radius increases the benefit most rapidly. The equation is based on an exponential that is related to AADT, explaining the shape of the graph. In this graph, the benefit for a radius of 300 feet and a radius of 1,100 feet is shown. The box indicates the data that is insignificant due to limitations of the equations.



Figure 44. Benefit-Cost Ratios of Device Within Curve – Constant Length

Figure 12 also displays an exponential trend due to the CMFunction. In this graph, the radius is constant and so we are able to see the smallest length segment creates the smallest ratio. The overall trend is to increase with AADT. Once again, the box marks the insignificant data due to model limitations. The graphed curves are based on 500 feet and 1,300 feet lengths.



Figure 45. Benefit Cost Ratios of Device Within Curve – Constant Radius

In Figure 13, when there is a constant AADT, the slopes are constant and the greatest ratio is found on the smallest radius of a curve, 300 feet.



Figure 46. Benefit-Cost Ratios of Device Within Curve – Constant AADT

## CONCLUSIONS

TCDs can greatly improve the safety of a horizontal curve. The safety improvement, in turn, affects the monetary benefit as there is a direct relationship between the two. This relationship, which was the focus of this study, is used to determine the practicality of installing devices. This study presents a method to calculate the benefit of typical TCDs as well as provides basic tables for benefit and benefit-cost ratios.

Within significance and within the bounds calculated, the smallest benefit-cost ratio was 48:1 for an advance warning sign before a curve with a 574 foot radius, 500 feet long and 1,000 AADT (Table 2). This was also the smallest benefit within the significant data. The smallest benefit for signs within the curve was 85:1, which if for curves with 1,100 foot radius, 820 feet long and 6,000 AADT. These numbers which represent minimums show a large benefit to installing a device.

Advance warning signs had a maximum benefit-cost ratio of 2,517:1, occurring at curves with a radius of 300 feet, a length of 820 feet, and 1,300 AADT. The maximum benefit-cost ratio for within-curve devices was 957:1 which occurs at a curve of 575 foot radius, 1,300 foot length, and 13,000 AADT. The advance to the curve TCDs have a greater effect on the overall economic benefit of a curve though they also had a greater range in benefit.

De	vic	e:	Advance Warning Signs	Within Curve Signs
	Be	enefit	48:1-2,517:1	85:1 - 957:1
_	S	Radius	300 – 574 feet	300 – 1,100 feet
alid	nge	Length	500 – 820 feet	820 – 1,300 feet
$^{N}$	Ra	AADT	1,000 – 13,000 vpd	6,000 – 13,000 vpd

 Table 12. Benefit-Cost Ratios and Valid Ranges

The range of ratios is large and far outside of the limits of benefit-cost ratios in previous work. Two previous studies on horizontal curves found values between 6:1 and 146:1 (11, 14). These numbers are vastly different from the values obtained in this study. The study that concentrates on pavement markings and their economic effect found the larger of the ratios. However, the number they used for a fatal crash is approximately half of the cost used in this study (11). This large difference in costs can account for some of the discrepancy in ratio ranges. The second study focuses on application of signs on horizontal curves in Connecticut and Washington and is also much closer to the work done in this project though the method of determining the weighted mean crash cost was different. Their cost per crash was less than half of the value used in this study and was based on empirical data (14). Combined further, their estimate for the annual cost to install devices on a curve is larger than even the cost of advance warning signs and within curve signs from this study. The service life for both of these reports was approximately half of what was estimated from the survey in this report. The comparably large ratios from the study may be due in part to the long life span of the devices; many are useful for more than 10 years.

For RRPMs and delineators, the responding states' estimates on cost indicated that they are not the most expensive installations. In fact, the RRPMs are cheaper than any other installation

while delineators are second most expensive after chevrons. If these devices can be proved to reduce crashes, they could be economically sensible options.

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# **APPENDIX A: BENEFIT TABLES**

The following tables were used in the benefit portion of the benefit-cost analysis. The shaded portions represent statistically insignificant data due to limitations caused by the CMFunctions based on the radius. For advance warning signs, the CMFunctions are insignificant for radii greater than 574 feet.

						7	ADT:						
Radius:	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000
300	\$14,840	\$29,680	\$44,520	\$59,361	\$74,201	\$89,041	\$103,881	\$118,721	\$133,561	\$148,402	\$163,242	\$178,082	\$192,922
400	\$9,978	\$19,957	\$29,935	\$39,913	\$49,892	\$59,870	\$69,848	\$79,827	\$89,805	\$99,783	\$109,762	\$119,740	\$129,718
500	\$6,664	\$13,329	\$19,993	\$26,657	\$33,321	\$39,986	\$46,650	\$53,314	\$59,979	\$66,643	\$73,307	\$79,972	\$86,636
009	\$4,272	\$8,545	\$12,817	\$17,090	\$21,362	\$25,634	\$29,907	\$34,179	\$38,452	\$42,724	\$46,997	\$51,269	\$55,541
700	\$2,473	\$4,945	\$7,418	\$9,890	\$12,363	\$14,836	\$17,308	\$19,781	\$22,253	\$24,726	\$27,198	\$29,671	\$32,144
800	\$1,074	\$2,147	\$3,221	\$4,294	\$5,368	\$6,441	\$7,515	\$8,588	\$9,662	\$10,735	\$11,809	\$12,882	\$13,956
906	-\$43	-\$86	-\$128	-\$171	-\$214	-\$257	-\$299	-\$342	-\$385	-\$428	-\$470	-\$513	-\$556
1,000	-\$953	-\$1,906	-\$2,858	-\$3,811	-\$4,764	-\$5,717	-\$6,669	-\$7,622	-\$8,575	-\$9,528	-\$10,480	-\$11,433	-\$12,386
11,00	-\$1,708	-\$3,416	-\$5,124	-\$6,832	-\$8,540	-\$10,248	-\$11,956	-\$13,664	-\$15,371	-\$17,079	-\$18,787	-\$20,495	-\$22,203

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\$52,347

\$48,320

\$44,294 \$48,407

\$40,180

\$36,527

\$32,875

\$25,569

\$36,240 \$39,606 \$42,971

\$29,222 \$32,213

> \$28,187 \$30,804

\$24,160 \$26,404

\$20,133

\$14,611 \$16,107 \$22,003 \$23,873

\$17,603 \$19,098 \$20,594

\$13,202

\$8,801

\$4,401

\$14,324 \$15,446 \$16,568 \$17,689

\$9,549

\$4,775 \$5,149

\$10,297 \$11,045

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\$18,264

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\$7,305

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 Table 14: Yearly Benefit of Advance Warning Signs- Constant Radius (574 feet)

AADT:

\$71,793

\$66,270

\$60,748 \$64,861

\$46,337 \$49,703

\$38,658

\$33,135

\$27,613

\$22,090 \$23,586 \$25,082 \$26,577

\$41,275

\$35,379 \$37,622 \$39,866

\$29,482

\$31,352 \$33,222

\$18,811 \$19,933

\$12,541

\$5,523 \$5,896 \$6,270

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\$6,644

1,300

\$11,793

\$61,783

\$56,634

\$51,485 \$55,225

\$41,188 \$44,180

\$36,040

\$25,743

\$38,197

\$33,422

\$28,648 \$30,891 \$76,654

\$70,757

\$58,965

\$53,068

\$81,515

\$75,245 \$79,732

\$68,975

\$62,704 \$66,444

\$56,434 \$59,799

\$47,172 \$50,163

\$43,893

\$53,155

\$46,511

\$73,088

\$86,377

Page	116

				Rad	ius:				
Length:	300	400	500	600	700	800	900	1000	1100
500	\$72,577	\$47,123	\$30,621	\$19,202	\$10,913	\$4,667	-\$184	-\$4,043	-\$7,178
600	\$77,722	\$51,107	\$33,548	\$21,212	\$12,139	\$5,221	-\$206	-\$4,566	-\$8,137
700	\$82,867	\$55,090	\$36,474	\$23,222	\$13,365	\$5,776	-\$229	-\$5,089	-\$9,097
800	\$88,012	\$59,073	\$39,401	\$25,232	\$14,590	\$6,330	-\$252	-\$5,612	-\$10,056
900	\$93,157	\$63,057	\$42,327	\$27,242	\$15,816	\$6,885	-\$275	-\$6,135	-\$11,015
1,000	\$98,302	\$67,040	\$45,253	\$29,253	\$17,042	\$7,439	-\$298	-\$6,658	-\$11,974
1,100	\$103,447	\$71,023	\$48,180	\$31,263	\$18,268	\$7,994	-\$321	-\$7,181	-\$12,933
1,200	\$108,592	\$75,007	\$51,106	\$33,273	\$19,494	\$8,549	-\$343	-\$7,704	-\$13,893
1,300	\$113,737	\$78,990	\$54,032	\$35,283	\$20,719	\$9,103	-\$366	-\$8,227	-\$14,852

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The following tables represent yearly benefit for signs within the curve. The shaded portions represent insignificant data due to limitations caused by the CMFunctions based on AADT. For advance warning signs, the CMFunctions are insignificant for AADT less than 5,500 vpd.

						Α	ADT:						
Radius:	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000
300	-\$2,371	-\$994	\$3,652	\$11,142	\$21,101	\$33,196	\$47,134	\$62,656	\$79,533	\$97,564	\$116,573	\$136,404	\$156,922
400	-\$2,059	-\$863	\$3,171	\$9,676	\$18,325	\$28,829	\$40,934	\$54,414	\$69,071	\$84,730	\$101,238	\$118,460	\$136,280
500	-\$1,872	-\$785	\$2,883	\$8,797	\$16,660	\$26,209	\$37,214	\$49,469	\$62,793	\$77,029	\$92,037	\$107,694	\$123,894
009	-\$1,747	-\$733	\$2,691	\$8,210	\$15,549	\$24,463	\$34,734	\$46,172	\$58,608	\$71,895	\$85,903	\$100,517	\$115,637
700	-\$1,658	-\$695	\$2,554	\$7,792	\$14,756	\$23,215	\$32,962	\$43,817	\$55,619	\$68,228	\$81,521	\$95,390	\$109,739
800	-\$1,591	-\$667	\$2,451	\$7,478	\$14,161	\$22,279	\$31,633	\$42,050	\$53,377	\$65,478	\$78,235	\$91,545	\$105,315
006	-\$1,539	-\$645	\$2,371	\$7,233	\$13,699	\$21,551	\$30,600	\$40,677	\$51,633	\$63,339	\$75,680	\$88,554	\$101,875
1,000	-\$1,498	-\$628	\$2,307	\$7,038	\$13,329	\$20,969	\$29,773	\$39,578	\$50,238	\$61,628	\$73,635	\$86,162	\$99,123
1,100	-\$1,464	-\$614	\$2,254	\$6,878	\$13,026	\$20,493	\$29,097	\$38,679	\$49,097	\$60,228	\$71,962	\$84,204	\$96,871

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500	-\$1,338	-\$561	\$2,061	\$6,288	\$11,909	\$18,736	\$26,603	\$35,363	\$44,888	\$55,065	\$65,794	\$76,986	\$88,567
600	-\$1,475	-\$618	\$2,272	\$6,932	\$13,129	\$20,654	\$29,326	\$38,984	\$49,484	\$60,703	\$72,529	\$84,868	\$97,634
700	-\$1,612	-\$676	\$2,483	\$7,576	\$14,348	\$22,572	\$32,050	\$42,604	\$54,080	\$66,340	\$79,265	\$92,750	\$106,702
800	-\$1,749	-\$733	\$2,694	\$8,220	\$15,567	\$24,490	\$34,773	\$46,224	\$58,675	\$71,977	\$86,001	\$100,631	\$115,769
<b>006</b>	-\$1,886	-\$791	\$2,905	\$8,864	\$16,786	\$26,409	\$37,497	\$49,845	\$63,271	\$77,615	\$92,737	\$108,513	\$124,836
1,000	-\$2,023	-\$848	\$3,116	\$9,507	\$18,006	\$28,327	\$40,220	\$53,465	\$67,866	\$83,252	\$99,472	\$116,395	\$133,903
1,100	-\$2,160	-\$906	\$3,327	\$10,151	\$19,225	\$30,245	\$42,944	\$57,085	\$72,462	\$88,890	\$106,208	\$124,276	\$142,970
1,200	-\$2,297	-\$963	\$3,538	\$10,795	\$20,444	\$32,163	\$45,667	\$60,706	\$77,057	\$94,527	\$112,944	\$132,158	\$152,038
1,300	-\$2,434	-\$1,021	\$3,749	\$11,439	\$21,663	\$34,081	\$48,391	\$64,326	\$81,653	\$100,164	\$119,680	\$140,039	\$161,105

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				Rad	lius:				
Length:	300	400	500	600	700	800	900	1000	1100
500	\$7,724	\$6,833	\$6,238	\$5,813	\$5,495	\$5,247	\$5,049	\$4,887	\$4,751
600	\$8,377	\$7,486	\$6,891	\$6,466	\$6,148	\$5,900	\$5,702	\$5,539	\$5,404
700	\$9,030	\$8,138	\$7,544	\$7,119	\$6,801	\$6,553	\$6,355	\$6,192	\$6,057
800	\$9,683	\$8,791	\$8,197	\$7,772	\$7,454	\$7,206	\$7,008	\$6,845	\$6,710
900	\$10,336	\$9,444	\$8,850	\$8,425	\$8,106	\$7,859	\$7,661	\$7,498	\$7,363
1,000	\$10,989	\$10,097	\$9,503	\$9,078	\$8,759	\$8,512	\$8,313	\$8,151	\$8,016
1,100	\$11,642	\$10,750	\$10,156	\$9,731	\$9,412	\$9,165	\$8,966	\$8,804	\$8,669
1,200	\$12,295	\$11,403	\$10,809	\$10,384	\$10,065	\$9,818	\$9,619	\$9,457	\$9,322
1,300	\$12,948	\$12,056	\$11,462	\$11,037	\$10,718	\$10,471	\$10,272	\$10,110	\$9,975

Table 18:	Yearly Benefit of With	in the Curve Signs -	– Constant AADT (	6,000 vpd)

# **APPENDIX B: BENEFIT-COST RATIOS**

The following tables are the result of the benefit-cost analysis. The shaded portions represent insignificant data due to limitations caused by the CMFunctions based on the radius. For signs in advance to a curve, the results become statistically insignificant when the radius is greater than 574 feet.

	L	able 19:	Benefit-(	<b>Cost Rati</b>	o for Ad	vance W:	arning D	evices – (	Constant	Length (	820 feet)		
						AAD	.Т:						
<b>Radius:</b>	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000
300	194	387	581	774	968	1,162	1,355	1,549	1,742	1,936	2,130	2,323	2,517
400	130	260	391	521	651	781	911	1,041	1,172	1,302	1,432	1,562	1,692
500	87	174	261	348	435	522	609	695	782	869	956	1,043	1,130
009	56	111	167	223	279	334	390	446	502	557	613	699	725
700	32	65	97	129	161	194	226	258	290	323	355	387	419
800	14	28	42	56	70	84	98	112	126	140	154	168	182
006	-1	-1	-2	-2	ς	<u>د</u>	4-	4	-5	-9	-9	L-	-7
1,000	-12	-25	-37	-50	-62	-75	-87	-99	-112	-124	-137	-149	-162
1,100	-22	-45	-67	-89	-111	-134	-156	-178	-201	-223	-245	-267	-290
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500	48	95	143	191	238	286	334	381	429	477	524	572	619
009	53	105	158	210	263	315	368	420	473	525	578	630	683
700	57	115	172	230	287	344	402	459	517	574	631	689	746
800	62	125	187	249	311	374	436	498	561	623	685	747	810
906	67	134	201	269	336	403	470	537	604	672	739	806	873
1,000	72	144	216	288	360	432	504	576	648	720	792	865	937
1,100	77	154	231	308	385	462	538	615	692	769	846	923	1,000
1,200	82	164	245	327	409	491	573	654	736	818	900	982	1,063
1,300	87	173	260	347	433	520	607	693	780	867	953	1,040	1,127

				Radi	us:				
Length:	300	400	500	600	700	800	900	1,000	1,100
500	947	615	399	250	142	61	-2	-53	-94
600	1,014	667	438	277	158	68	-3	-60	-106
700	1,081	719	476	303	174	75	-3	-66	-119
800	1,148	771	514	329	190	83	-3	-73	-131
900	1,215	823	552	355	206	90	-4	-80	-144
1,000	1,282	875	590	382	222	97	-4	-87	-156
1,100	1,349	927	629	408	238	104	-4	-94	-169
1,200	1,417	978	667	434	254	112	-4	-100	-181
1,300	1,484	1,030	705	460	270	119	-5	-107	-194

 Table 21: Benefit-Cost Ratio for Advance Warning Devices – Constant AADT (6,000 vpd)

The following tables are the result of the benefit-cost analysis. The shaded portions represent an insignificant portion of the model due to limitations caused by the CMFunctions based on AADT. The model is insignificant for AADT less than 5,500 vpd.

Radius:       1,000       2,000       3,000       4,000       5,000         300       -14       -6       22       66       125         400       -12       -5       19       57       109         500       -11       -5       19       57       109         500       -11       -5       17       52       99         600       -10       -4       16       49       92	3,000         4,000           22         66									
Radius:         1,000         2,000         3,000         4,000         5,000           300         -14         -6         22         66         125           400         -12         -5         19         57         109           500         -11         -5         17         52         99           600         -10         -4         16         49         92	3,000         4,000           22         66		AAI	DT:						
300         -14         -6         22         66         125           400         -12         -5         19         57         109           500         -11         -5         17         52         99           600         -10         -4         16         49         92           700         -10         -4         15         46         88	22 66	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000
400     -12     -5     19     57     109       500     -11     -5     17     52     99       600     -10     -4     16     49     92       700     -10     -4     15     46     88		125	197	280	372	473	580	693	811	932
500         -11         -5         17         52         99           600         -10         -4         16         49         92           700         -10         -4         15         46         88	19 57	109	171	243	323	410	503	602	704	810
600         -10         -4         16         49         92           700         -10         -4         15         46         88	17 52	66	156	221	294	373	458	547	640	736
700 -10 -4 15 46 88	16 49	92	145	206	274	348	427	510	597	687
	15 46	88	138	196	260	331	405	484	567	652
800 -9 -4 15 44 84	15 44	84	132	188	250	317	389	465	544	626
<b>900</b> -9 -4 14 43 81	14 43	81	128	182	242	307	376	450	526	605
<b>1,000</b> -9 -4 14 42 79	14 42	79	125	177	235	299	366	438	512	589
<b>1,100</b> -9 -4 13 41 77	13 41	77	122	173	230	292	358	428	500	576

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		Table 2.	3: Benefi	it-Cost R	atio for V	Within C	urve Dev	ices – Co	nstant Ra	dius (574	feet)		
						AA	DT:						
Length:	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,00
500	-8	ч.	12	37	71	111	158	210	267	327	391	457	526
009	6-	4	13	41	78	123	174	231	294	360	431	504	580
700	-10	4	15	45	85	134	190	253	321	394	471	551	634
800	-10	4	16	49	92	145	206	274	348	427	511	598	687
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				Rad	ius:				
Length:	300	400	500	600	700	800	900	1000	1100
500	161	135	119	109	101	96	92	88	85
600	172	146	131	120	113	107	103	100	97
700	184	158	142	132	124	119	114	111	108
800	195	169	153	143	136	130	126	122	119
900	206	180	165	154	147	142	137	134	131
1,000	218	192	176	166	158	153	149	145	142
1,100	229	203	188	177	170	164	160	157	154
1,200	241	215	199	189	181	176	171	168	165
1,300	252	226	210	200	193	187	183	179	176

 Table 24: Benefit-Cost Ratio for Within Curve Devices – Constant AADT (6,000 vpd)

## APPENDIX C: VALUE OF A STATISTICAL LIFE

From the GES reports, the percentage for each of the KABCO level of crashes observed on curves was determined for the most recent data, 2012. The following rules were applied in identifying the crashes used to estimate the proportions of each severity level:

- Not intersection-related or interchange-related
- No work zones
- Not an interstate highway
- Crash occurred on the roadway (instead of the shoulder or off the roadway)
- Occurred at a curve on a 2-way, 2-lane road

The cost of a fatal crash is assumed to be \$9.2 million, and the cost of a PDO crash is assumed to be \$3,927. The Abbreviated Injury Scale (AIS) is used to identify the costs of various injury severity levels (1-5), assigning them a value proportional to the cost of a fatal crash (\$9.2 million). The proportions are reported in Table 16. While the percentages of each KABCO crash severity level are known (Table 15), the percentages need to be converted to the AIS scale in order to assign them a value. The conversion scale in Table 17 is used to convert the proportion of crashes from the KABCO severity levels to AIS severity levels.

Tuble Let Clu	ish i ei eentages
KABCO Rating	% of Crashes
PDO	69.2%
С	11.6%
В	11.8%
А	5.9%
К	1.5%

Table 25. Crash Percentage	Table 25.	<b>Crash Perc</b>	centages
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	Proportion of VSL	Assumed Value
Injury Level	(\$9.2 Million)	
1	0.003	\$28,000
2	0.047	\$430,000
3	0.105	\$970,000
4	0.266	\$2,400,000
5	0.593	\$5,500,000
6 (Fatal)	1.0	\$9.2 Million

The contribution of a fatal crash to the weighted average crash cost is calculated by multiplying the percentage of fatal crashes (1.5%) to the assumed value of a statistical life (\$9.2 million) (Equation 10).

(Equation 10)

Next, the contributions of crashes by degree of injury are calculated by using Table 17. In order to find the monetary values (Table 18) the following equation was followed:

Portion of Total Cost Attributed to a KABCO Level= (AIS Conversion Factor)×(Fatal Cost)×(KABCO to AIS Conversion Factor)× (Crash Percentages)

(Equation 11)

	PDO	С	В	А	К
0-No Injury (\$3,927)	0.925	0.234	0.0835	0.0344	0
1 (\$28,000)	0.0726	0.689	0.768	0.554	0
2 (\$430,000)	0.00198	0.0639	0.109	0.209	0
3 (\$970,000)	0.00008	0.0107	0.0319	0.144	0
4 (\$2.4 Million)	0	0.00142	0.0062	0.0399	0
5 (\$5.5 Million)	0.00003	0.00013	0.00101	0.0178	0
6-Fatal (\$9.2 Million)	0	0	0	0	1

### Table 27. KABCO to AIS Conversion Factors

The top row, the row corresponding to '0' is calculated slightly differently because there is no VSL to AIS conversion factor. Instead, the cost of a PDO crash is obtained from the Tiger BCA Reference Guide.

Portion of Total Cost Attributed to a KABCO Level =(Cost of PDO)×(KABCO to AIS Conversion Factor)×(Crash Percentages) (Equation1)

	PDO	С	В	A	K	
Costs:	69%	12%	12%	6%	1.5%	
0-No Injury (\$3,927)	\$2,513	\$107	\$227	\$8		
1 (\$28,000)	\$1,385	\$2,204	\$2,511	\$904		
2 (\$430,000)	\$592	\$3,200	\$5,579	\$5,343		
3 (\$970,000)	\$53	\$1,198	\$3,650	\$8,242		
4 (\$2.4 Million)	\$0	\$402	\$1,796	\$5,765		
5 (\$5.5 Million)	\$113	\$82	\$652	\$5,749		
6-Fatal (\$9.2 Million)	\$0	\$0	\$0	\$0	\$140,760	
Total:	\$2,144	\$7,086	\$14,189	\$26,003	\$140,760	\$190,182

#### Table 28. Cost to Crash-Weighted Average

The final weighted average of the cost of a crash is \$190,000.