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Participating Students: Felicia Desorcie, Ruoxin Jiang, Pete Kelly, Shawn Larson, Marcus Rasulo, Joshua Rivera, Hidi Wood. Supported by a grant from the U.S. Department of Transportation, University Transportation Centers Program.

16. Abstract

This report is a compilation of research papers written by students participating in the 2011 Undergraduate Transportation Scholars Program. The 10-week summer program, now in its 21st year, provides undergraduate students in Civil Engineering the opportunity to learn about transportation engineering through participating in sponsored transportation research projects. The program design allows students to interact directly with a Texas A&M University faculty member or Texas Transportation Institute researcher in developing a research proposal, conducting valid research, and documenting the research results through oral presentations and research papers.

The papers in this compendium report on the following topics, respectively: 1) evaluating the impact of nighttime work zone lighting characteristics on motorists; 2) late night roadway visibility; 3) investigation of the use and pricing of the I-15 express lanes in San Diego; 4) intercity passenger rail access to airports: a case study at the Milwaukee airport; 5) development of a background complexity assessment tool; 6) identifying pavement preservation treatments suitable for performance-related specifications; and 7) arsenic content and retroreflectivity of glass beads used in pavement markings.

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COMPENDIUM OF STUDENT PAPERS: 2011 UNDERGRADUATE TRANSPORTATION SCHOLARS PROGRAM

Participating Students (seated, left to right): Hidi Wood, Marcus Rasulo, and Shawn Larson
(standing, left to right): Pete Kelly, Felicia Desorcie, Ruoxin Jiang, and Joshua Rivera

Program Sponsored by

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Texas Transportation Institute
Texas A&M University System
College Station, TX 77843-3135

and the

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Texas A&M University
College Station, Texas 77843-3136

May 2012

PREFACE

The Southwest Region University Transportation Center (SWUTC), through the Transportation Scholars Program, the Texas 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 the summer of 2011, the following seven students and their faculty/staff mentors were:

STUDENTS	**MENTORS**
Felicia Desorcie Norwich University, Westford, VT	Ms. Melisa Finley
Ruoxin Jiang Texas A&M University, College Station, TX	Dr. Gene Hawkins
Pete Kelly Brigham Young University, Provo, UT	Dr. Mark Burris
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Sincere appreciation is extended to the following individuals:

- Mrs. Cathy Bryan, who assisted with program administrative matters and in the preparation of the final compendium.

The authors recognize that support was provided by a grant from the U. S. Department of Transportation, University Transportation Centers Program to the Southwest Region University Transportation Center.

CONTENTS

DISCLAIMER

Evaluating the Impact of Nighttime Work Zone Lighting Characteristics on Motorists

Prepared for
Undergraduate Transportation Scholars Program

by

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August 5, 2011

STUDENT BIOGRAPHY

Felicia Desorcie is a senior at Norwich University in Northfield, Vermont. She will graduate in May 2012 with a Bachelor of Science in Civil Engineering and a minor in Construction Engineering Management. Felicia is a Norwich Engineers' Society Clinton A. Renfrew Award and a Tau Beta Pi-Vermont Chapter Scholarship Recipient.

Outside of class, Felicia is the President of Tau Beta Pi and an active member in the American Society of Civil Engineers (ASCE), Society of Women Engineers (SWE), and Chi Epsilon. She also enjoys teaching as a peer tutor on campus. Felicia has played ice hockey for 14 years including two years at the collegiate level. She continues to stay actively involved in hockey through coaching and officiating.

Felicia plans to attend graduate school to earn a Master's degree in Civil Engineering and become a licensed Professional Engineer.

ACKNOWLEDGMENT

The research described in this paper was conducted as part of Project 0-6641, "Assessment of the Impact of Nighttime Work Zone Lighting on Motorists," sponsored by the Texas Department of Transportation (TxDOT). The research activities were conducted in support of the Undergraduate Transportation Scholars Program. The findings and recommendations included in this paper are based on the student's summer activities. They should be considered preliminary and not as representative of the findings and recommendations of the parent project. This paper has not been reviewed or approved by the sponsor. The contents of this paper reflect the views of the author, who is responsible for the facts and the accuracy of these data presented herein. The contents do not necessarily reflect the official view or policies of TxDOT.

The author would like to thank Melisa Finley for her guidance while working on this project, as well as Jeff Miles and Nada Trout for their assistance in data collection and reduction.

SUMMARY

Nighttime work zones are becoming a more popular alternative for maintenance and construction activities on high-volume roadways. One of the most important aspects of nighttime work zones is lighting as it not only affects the workers ability to produce a quality product in a timely fashion, but also affects worker and motorist safety. Before conducting closed-course human factors studies to evaluate the impact nighttime work zone lighting has on a motorist's ability to detect low contrast objects in and near the traveled way, researchers wanted to collect and analyze lighting characteristics and human subject data in actual work zones to better understand how work zone lighting affects the human eye.

Researchers went to the Dallas-Fort Worth area and collected vertical illuminance, pupil diameter, and position (latitude and longitude) data by using human subjects as drivers of an instrumented vehicle. Participants drove through series of six sections including a dark section with no existing fixed or work zone lighting, a section with only existing fixed lighting (mainly in the median), and four sections with work zone lighting. By comparing a work zone lighting section with the dark section, researchers found that an increase in illuminance yielded a decrease in pupil diameter. Through the work zone lighting section, the pupil diameter was on average smaller and fluctuated much more than in the dark section.

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INTRODUCTION

Nighttime work zones are becoming a more popular alternative for maintenance and construction activities on high-volume roadways. While working at night decreases traffic delays and public complaints, there are other safety concerns that need to be considered in this unique environment. One of the most important aspects of nighttime work zones is lighting as it not only affects the workers ability to produce a quality product in a timely fashion, but also affects worker and motorist safety.

Current guidelines for work zone lighting mostly consider the visual needs of the workers but do recognize that there are issues that may pertain to the needs of motorists (*1,2,3,4,5,6,7*). These guidelines address and provide potential remedies for glare from the lighting as it may be impacting motorists when they enter, drive through, and exit the nighttime work zone. However, the actual impact work zone lighting has on motorists is not known. This research effort investigated the relationship between vertical illuminance and pupil diameter in a dynamic nighttime work zone in the Dallas-Fort Worth (DFW) area.

BACKGROUND INFORMATION

This section describes information necessary to further understand the research that was conducted.

Parent Project

This research is a part of a larger parent project sponsored by the Texas Department of Transportation, "Assessment of the Impact of Nighttime Work Zone Lighting on Motorists (Project Number 0-6641)." The technical objectives of the parent project are to:

- assess the impact of work zone lighting on motorists and
- develop work zone lighting guidelines for nighttime operations, considering both worker and motorist's needs.

To date, Texas Transportation Institute (TTI) researchers have completed a review of published literature, department of transportation (DOT) policies and practices, and vendor technology issues and trends. Before conducting closed-course human factors studies to evaluate the impact nighttime work zone lighting has on a motorist's ability to detect low contrast objects in and near the traveled way, researchers wanted to collect and analyze lighting characteristics and human subject data in actual work zones to better understand how work zone lighting affects the human eye.

Illuminance

Illuminance is the measure of the amount of light (quantity) that is falling on a particular surface. Illuminance is often measured in terms of footcandles (fc) or lux (lx). Through the use of an illuminance meter, it is possible to know the quantity of light that is hitting perpendicular to the front of the meter. This allows researchers to know how much light is reaching the motorist.

Pupil Diameter

The average pupil diameter of the human eye ranges from 2 mm to 8 mm (*8*). As the human eye ages its ability to see clearly and precisely decreases. As the eye ages it also experiences a decrease in reaction time, is more susceptible to glare, and has a decreased dynamic range. Figure 1 illustrates the limited dynamic range of the pupil size as the eye ages.

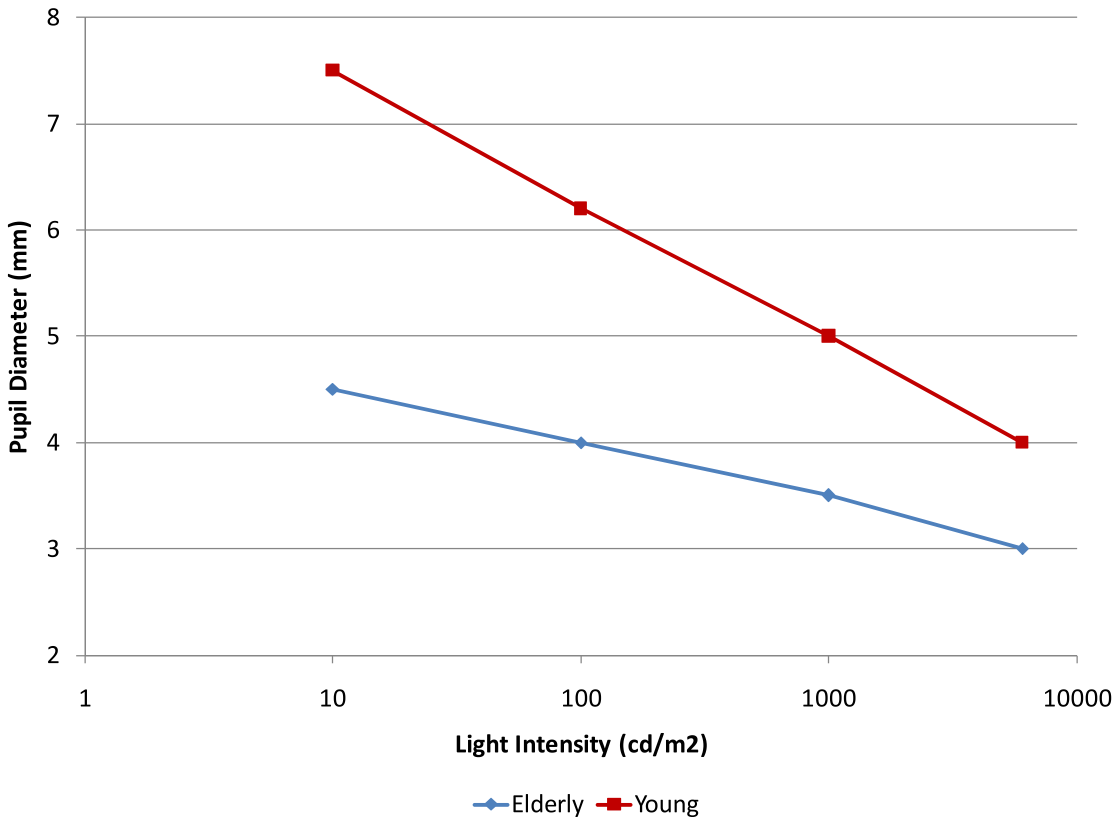

Figure 1. Pupil Size Variance due to Age.

GOALS AND OBJECTIVES

The goal of the research was to investigate the relationship between vertical illuminance and pupil diameter in a dynamic nighttime work zone environment. In order to achieve this goal, the following objectives were met:

- obtain measurements of vertical illuminance from a nighttime work zone,
- obtain measurements of driver pupil size,
- obtain subjective opinion data regarding the impact of nighttime work zone lighting on the driver, and
- correlate vertical illuminance data with pupil size data.

DATA COLLECTION

This section describes where the data were collected, what were collected, and how they were collected.

Location

Data were collected in the Dallas-Fort Worth area at the interchange of State Highway 114 and State Highway 121, known as the DFW Connector Project. At this location, major reconstruction is taking place on large multi-lane highways through the use of daytime and nighttime work zones. During data collection, the majority of the work zone lighting was not in the traveled way. Instead, the lighting was either immediately adjacent to the traveled way or offset from the traveled way. Near this location, there was another large multi-lane highway (Interstate 635) that did not have existing fixed or work zone lighting, but did have areas of commercial lighting since it was in a metropolitan area.

Equipment

All data collection was conducted at night. Through the use of the TTI instrumented vehicle (2006 Toyota Highlander), the researchers were able to collect the following data:

- vertical illuminance,
- left and right pupil diameter, and
- latitude and longitude.

The vertical illuminance data were collected using a Minolta T-10, which is shown in Figure 2. The illuminance meter was placed inside the vehicle in a vertical orientation facing out toward the front of the instrumented vehicle. Figure 3 depicts two cameras and infrared pods that were used to track the eye and measure the diameter of the pupil. A global position system (GPS) was used to collect latitude and longitude data. These data were needed to correlate the vertical illuminance and pupil diameter data. Subjective opinion data were also collected from the participants as they traveled through the nighttime work zone.

Participants

Research was conducted using six human subjects as the driver of the TTI instrumented vehicle. In order to have a representative sample, human subjects varied in gender and represented the following different age groups:

- 18 to 34,
- 35 to 54, and
- 55 or older.

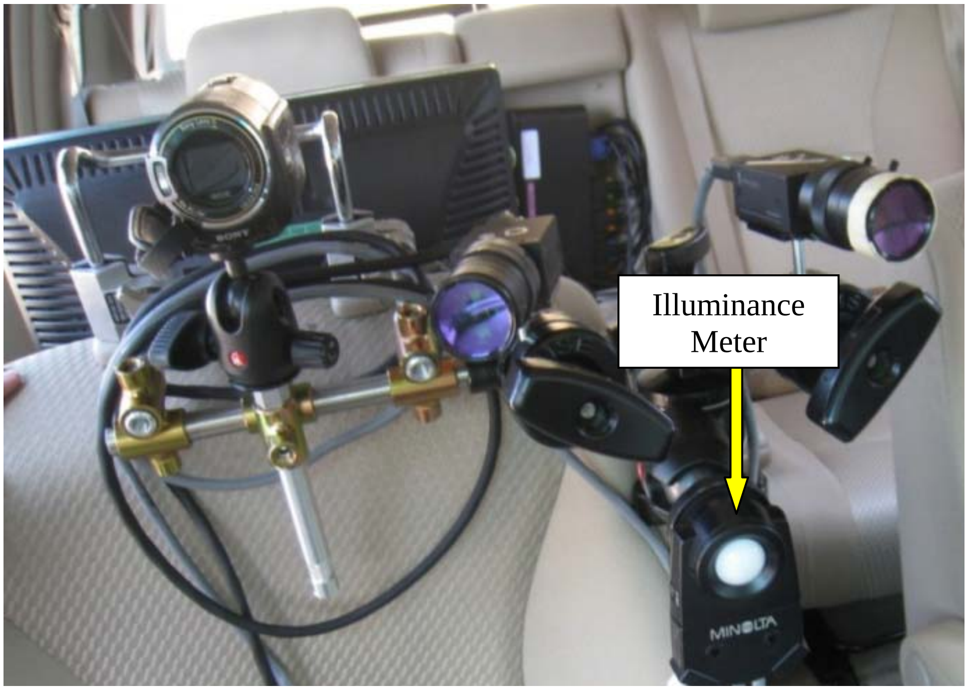

Figure 2. Minolta T-10 Illuminance Meter.

Figure 3. Eye Tracking Equipment.

Within the six participants, four were female and two were male. Three of the participants were in the 18 to 34 age category, two were in the 35 to 54 age category, and one was in the 55 or older age group. These age groups were selected due to the previously discussed affects that age has on the eye.

Study Procedure

Upon arrival, each participant checked in and a briefing took place. A researcher then provided the participants with an explanation of the study which included their driving tasks and asked them to read and sign an informed consent document. Participants then had their vision tested using a standard optometrist visual acuity chart, a visual contrast test, and a color blindness screening test. Participants were then informed that they would be driving a state-owned vehicle equipped with instrumentation that allows researchers to measure various driving data, but operates and drives like a normal vehicle.

Once in the vehicle, the eye-tracking equipment was calibrated for each participant. The participant was then instructed to comment on anything that helped or made it more difficult for them to travel through the work zone. Researchers did not specifically ask participants to comment on the work zone lighting, since this might have made the participants focus on the lighting (i.e., looked at more or longer than normal). The participant then drove through a series of six roadway sections including a dark section with no existing fixed or work zone lighting, a section with only existing fixed lighting (mainly in the median), and four sections with work zone lighting. After driving through each work zone section, the participant was asked several questions regarding the design of the work zone. Upon completion of the driving task, the participant was asked final questions about the work zone lighting.

DATA REDUCTION

Researchers attempted to collect vertical illuminance, pupil diameter, and GPS data for all six participants. However, the data for participants one and two were not complete due to equipment malfunctions and the data from participant six could not be used due to unexpected roadway congestion. Thus, only the data from participants three, four and five were reduced and analyzed. Due to the large amount of data and time constraints, only two roadway sections from the entire trip were analyzed: the dark section with no existing fixed and work zone lighting and a section with work zone lighting.

First, the raw output files were complied into a spreadsheet. Through the use of GPS data, the vertical illuminance and pupil diameter raw data were correlated. According to the eye tracking system used, in order to obtain an accurate reading of the pupil diameter the gaze quality parameter must be a three. So, all data that had a gaze quality less than three were removed from the data set. As discussed previously, the pupil diameter typically ranges from 2 mm to 8 mm; hence all data that had a diameter less than 2 mm or greater than 8 mm were eliminated from the data set. The eye tracking system measured the pupil diameter of each eye separately. A review of the pupil diameter for each eye revealed some large differences between the two measurements within one time period. Thus, researchers calculated the difference between the left and right pupil diameter. Researchers computed the minimum, maximum, mean, standard deviation, and 95 percent confidence interval of the difference between the two pupil diameters. The largest confidence interval for each section of interest was then identified, and all differences in pupil diameters that were outside that range were discarded.

Researchers then verified that all of the vertical illuminance data were greater than zero. Since the illuminance data were collected at a rate of one measurement per second and the eye tracking data were collected at a rate of 30 measurements per second, the right and left pupil diameter data were averaged for each illuminance reading yielding one average pupil diameter for each illuminance value. For each section of interest and each participant, descriptive statistics including minimum, maximum, mean, and standard deviation were computed for both the illuminance and average pupil diameter.

RESULTS

This section describes the results of two different roadway sections that were traveled.

Dark Segment: No Fixed or Work Zone Lighting

By driving through a roadway section that does not contain fixed or work zone lighting it was possible to obtain base line vertical illuminance and pupil diameter data for each participant. Table 1 shows the minimum, maximum, mean, and standard deviation for both measurements in the dark segment. In this section the overall mean vertical illuminance was 0.14 lux, and the minimum and maximum vertical illuminance values were 0.07 lux and 0.54 lux, respectively. As shown in Figure 4, the illuminance values were consistent with only minor increases, which most likely were the result of being in a metropolitan area where adjacent commercial lighting reached the roadway. While there are some fluctuations, the overall standard deviation was 0.06 lux, showing very little variation in the vertical illuminance data. The vertical illuminance values were also similar between each participant, although participant three's vertical illuminance values were slightly higher throughout. This slight increase can be attributed to participant three beginning just after dark while the other two participants started later that same evening.

Unlike the vertical illuminance, in this section the average pupil diameter between the three participants varied. As shown in Table 1 and Figure 5, the average pupil diameter for participant three was considerably lower than the average pupil diameter for participants four and five who have similar average pupil diameter data. This is consistent with the previously discussed decrease in the dynamic range of the pupil diameter as the eye ages. However, the standard deviation for each participant was less than 0.50 mm demonstrating that there was little change in the average pupil diameter throughout this section for each participant.

Table 1. Dark Section: Descriptive Statistics.

Participant	N	Illuminance				Average Pupil Diameter			
		Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
3	134	0.10	0.54	0.18	0.06	4.02	4.80	4.50	0.17
4	128	0.07	0.29	0.12	0.05	5.33	7.54	6.81	0.45
5	130	0.07	0.35	0.12	0.05	6.15	7.46	7.17	0.24
Overall	392	0.07	0.54	0.14	0.06	4.02	7.54	6.14	1.23

Figure 4. Dark Section: Distance vs Illuminance.

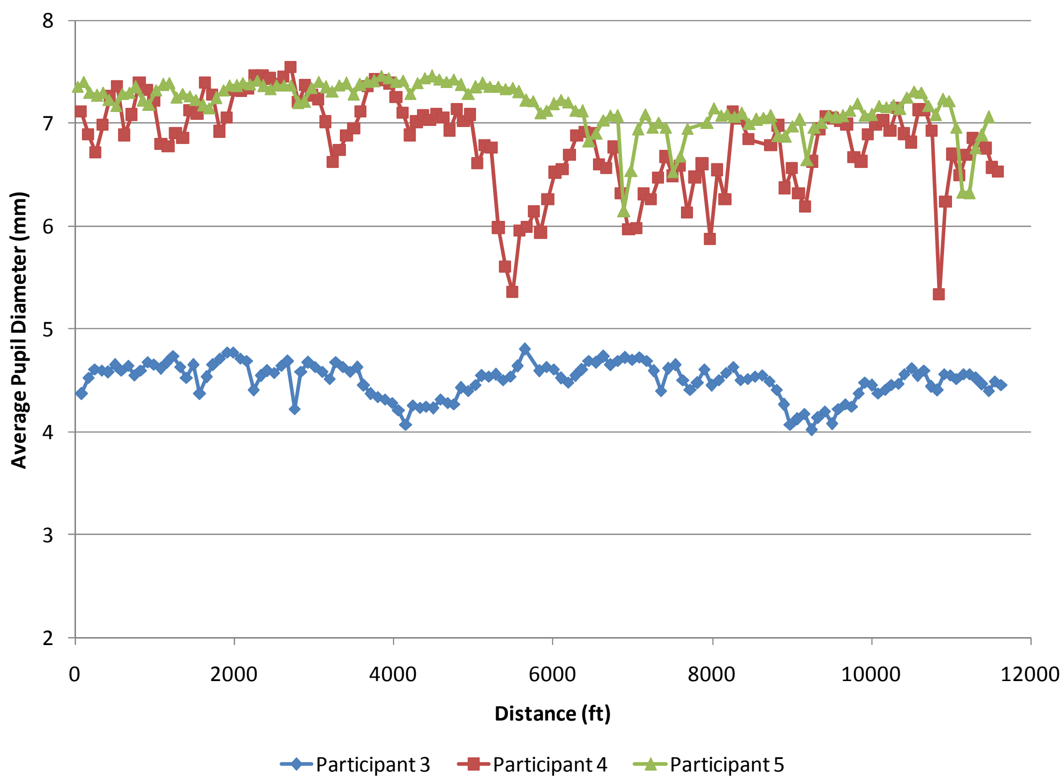

Figure 5. Dark Section: Distance vs Average Pupil Diameter.

Work Zone Segment: Work Zone Lighting

Table 2 shows the minimum, maximum, mean, and standard deviation for both the vertical illuminance and average pupil diameter data in the work zone segment. In this section, the overall mean vertical illuminance was 0.85 lux, and the minimum and maximum vertical illuminance values were 0.06 lux and 62.90 lux, respectively. While the minimum vertical illuminance value was similar to the dark section, the maximum value was 116 times greater than the maximum in the dark section (0.54 lux). The larger standard deviation in the work zone lighting section (2.74 lux) also demonstrates fluctuation in the illuminance levels, which was representative of going in and out of work zone lighting. As shown in Figure 6, while there are noticeable increases within the vertical illuminance data for this section, the increases were consistent across the three participants. The increase just before 5000 ft was an area of work zone lighting that consisted of equipment lighting and portable light towers on both sides of the road relatively close to the open travel lanes. The increase just before 10,000 ft also consisted of equipment lighting and portable light towers on both sides of the road but the lighting was not as close to the open travel lane. The increase at approximately 15,000 ft was a paving operation where there was approximately seven portable light towers and task lighting on all of the equipment. This lighting was on the right side of the road immediately adjacent to the open travel lane. The increase just before the 25,000 ft was created by task lighting located in a closed lane immediately adjacent to the travel lane.

Table 2. Work Zone Section: Descriptive Statistics.

Participant	N	Illuminance				Average Pupil Diameter			
		Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
3	381	0.07	62.90	0.99	3.81	2.83	4.59	4.09	0.29
4	322	0.06	15.91	0.78	1.95	4.77	7.79	6.46	0.62
5	324	0.06	13.32	0.76	1.72	4.76	7.36	6.58	0.44
Overall	1027	0.06	62.90	0.85	2.74	2.83	7.79	5.62	1.26

Similar to the dark section, the average pupil diameter for participants four and five was larger than the average pupil diameter for participant three. Figure 7 illustrates the average pupil diameter for each participant as they traveled through the work zone lighting. As expected, where there were increases in the vertical illuminance, there were decreases in the average pupil diameter. Specifically, there is a decrease (approximately 1mm to 1.5 mm) at approximately 15,000 ft, which was where the paving operation was that was adjacent to the travel lane. There were also decreases just before 5000 ft and 10,000 ft that were consistent with the increases seen in the vertical illuminance (approximately 1 mm to 2 mm). The minimum average pupil diameter in the work zone section was 2.83 mm, which was approximately 1.5 times lower than the minimum average pupil diameter in the dark section (4.02 mm), indicating both an increase of vertical illuminance but also a requirement of the eye to adjust more when returning back to a dark environment.

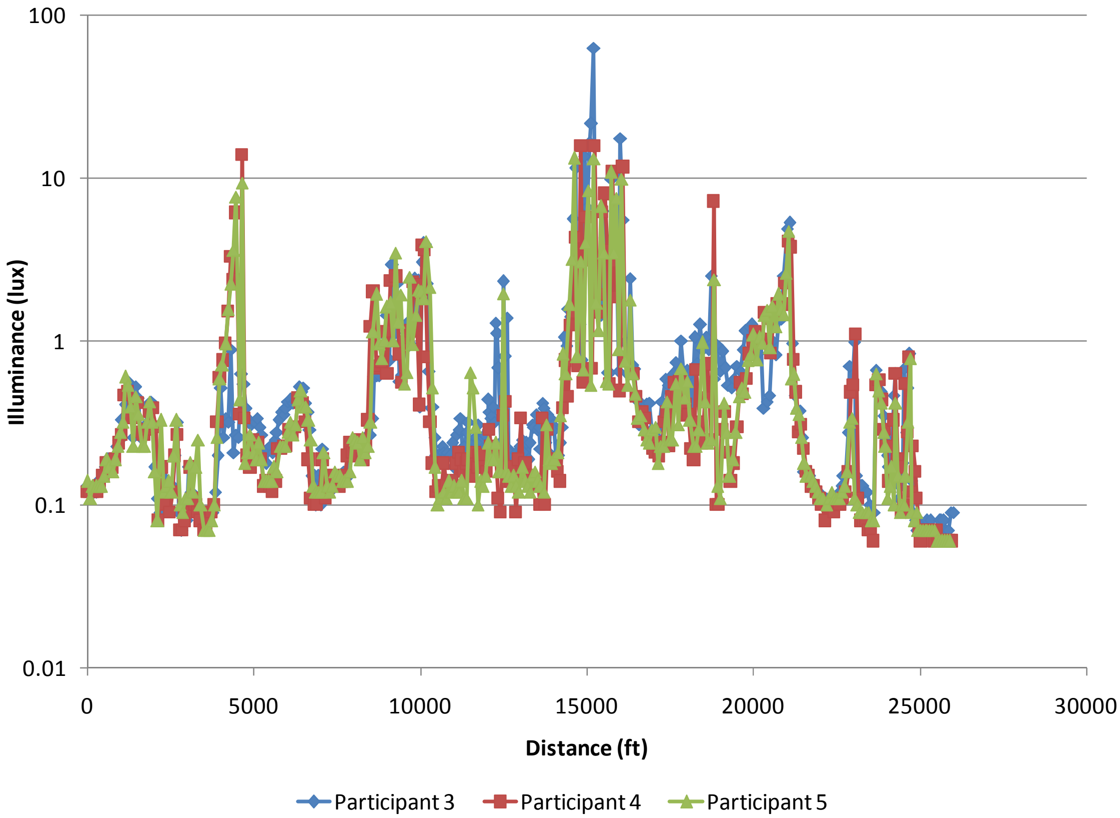

Figure 6. Work Zone Section: Distance vs Illuminance.

Just before the 25,000 ft point there was a decrease in the average pupil diameter (approximately 1 mm to 2 mm). However, this decrease correlated with only a small increase in the vertical illuminance. A review of other eye tracking data showed that all three participants looked directly at the task lighting. The reason why the vertical illuminance increase was not as great as the average pupil diameter decrease was most likely due to the limitations of the illuminance meter. By only being able to capture one vertical illuminance data point per second while traveling at highway speeds, it is probable that the illuminance meter did not capture an accurate reading of the vertical illuminance of the task lighting that the driver was seeing. Also, the illuminance meter was mounted onto the passenger seat capturing an overall scene vertical illuminance, which would be different than what the driver was directly looking at.

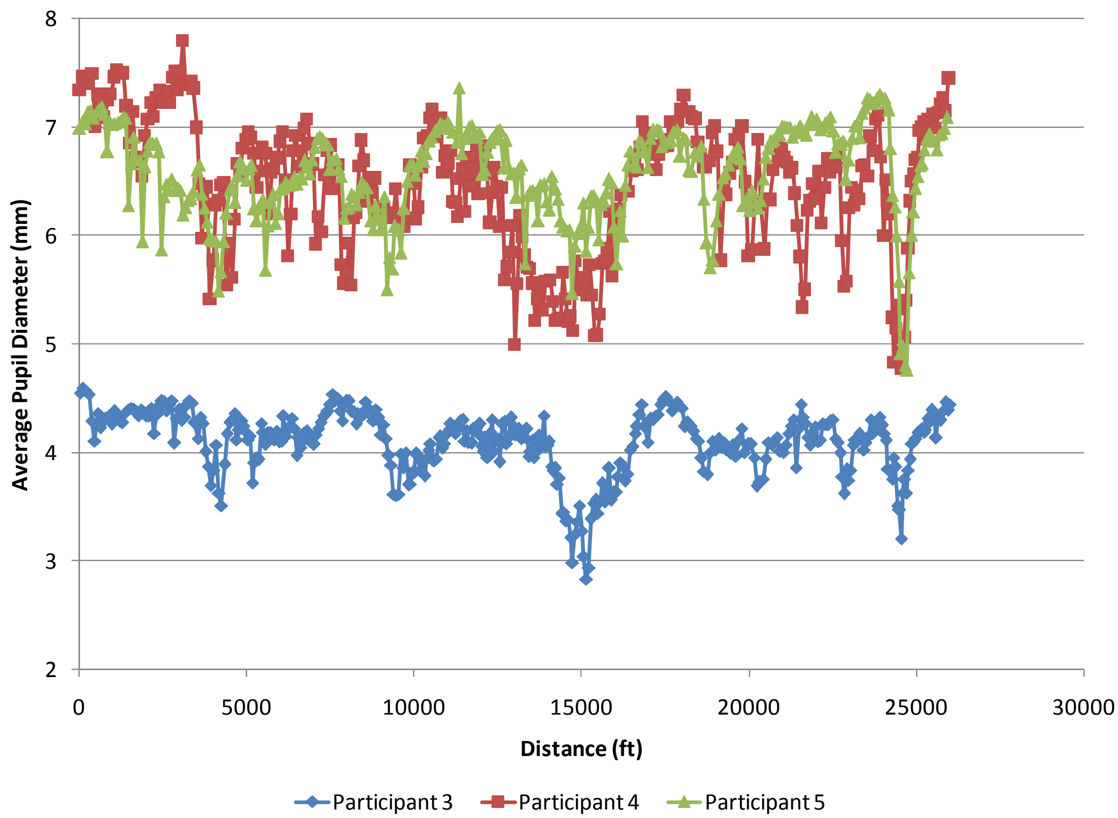

Figure 7. Work Zone Section: Distance vs Average Pupil Diameter.

SUMMARY AND CONCLUSIONS

Researchers went to the Dallas-Fort Worth area and collected vertical illuminance, pupil diameter, and position (latitude and longitude) data by using human subjects as drivers of an instrumented vehicle. Participants drove through series of six sections including a dark section with no existing fixed or work zone lighting, a section with only existing fixed lighting (mainly in the median), and four sections with work zone lighting. By comparing a work zone lighting section with the dark section, researchers found that an increase in illuminance yielded a decrease in pupil diameter. Through the work zone lighting section, the pupil diameter was on average smaller and fluctuated much more than in the dark section.

Throughout the work zone section, researchers saw that the vertical illuminance levels varied between 0 and 20 lux, but there were points when the vertical illuminance exceeded 60 lux. The average pupil diameter decreased by 1 mm to 2 mm throughout the work zone section. Therefore, before conducting closed-course human factors studies to evaluate the impact of nighttime work zone lighting on motorist's ability to detect low contracts objects in and near the traveled way, researchers need to design a simulated night time work zone that consist of lighting that produces vertical illuminance levels:

- from approximately 0 to 20 lux,
- that reach or exceed 60 lux, and
- that yield average pupil diameter decreases of 1 mm to 2 mm.

In addition, researchers should design the work zone lighting such that participants go into and out of several dark and lit sections.

Additional research should include expanding the data set to allow for more conclusive results and the ability to average the pupil diameter data between the three age groups. When more research is conducted, the researchers should maintain the three age groups due to the effects of aging on the eye. The illuminance meter in this research was only able to capture one vertical illuminance measurement per second, which did not fully capture the work zone lighting environment. Thus, having an illuminance meter that collects more than one measurement per second would be beneficial. However, it may be possible to understand the effects of the work zone lighting by using other lighting characteristics, such as luminance, which was also collected but not analyzed for this paper.

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Late Night Roadway Visibility

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Undergraduate Transportation Scholars Program

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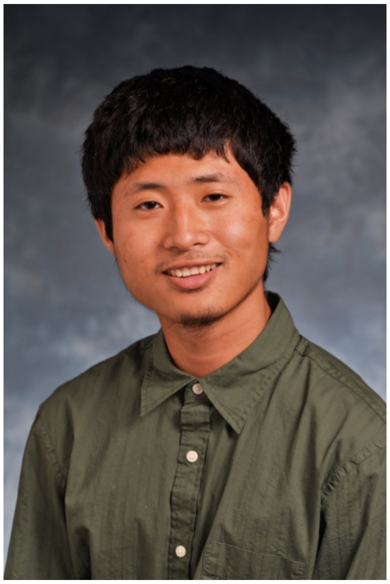
August 5, 2011



STUDENT BIOGRAPHY

Ruoxin Jiang is a senior at Texas A&M University in College Station Texas. He will be graduating in December 2011 with a Bachelor of Science in Civil Engineering. Jiang is a National Merit scholar and has been on the Dean's list at Texas A&M for multiple semesters.

Jiang was born in Beijing, China, but grew up in Norman, Oklahoma. Currently, he serves as the public relations officer for his multicultural fraternity Beta Xi Chi. Outside of school, Jiang enjoys playing music and writing songs. He runs his own business working as a part-time piano and guitar instructor for kids and adults. Following graduation from Texas A&M, Jiang plans to continue his studies at Texas A&M in graduate school with a focus in Transportation Engineering. His long-term goals include attaining a license as a Professional Engineer and working for a state DOT.

ACKNOWLEDGMENT

The research described in this paper was conducted as part of Project 0-6645, sponsored by the Texas Department of Transportation (TxDOT). The research activities were conducted in support of the Undergraduate Transportation Scholars Program. The findings and recommendations included in this paper are based on the student's summer activities. They should be considered preliminary and not as representative of the findings and recommendations of the parent project. This paper has not been reviewed or approved by the sponsor. The contents of this paper reflect the views of the author, who is responsible for the facts and the accuracy of these data presented herein. The contents do not necessarily reflect the official view or policies of TxDOT.

The author would like to express his appreciation to Dr. Gene Hawkins, Associate Professor, and Mr. Jeff Miles, Assistant Research Engineer, for their assistance and guidance throughout this project.

SUMMARY

Recently, TxDOT has been considering implementing a lighting curfew in which roadside lighting along freeways will be reduced or eliminated during select nighttime hours. One of the things to take into consideration when implementing a lighting curfew is visibility. Visibility is a key factor in driving safely on freeways at night. However, visibility can change throughout the night as a result of variable traffic patterns or the availability of commercial lighting. The purpose of this project was to gather nighttime visibility data along TxDOT freeways to assist in determining if and when a lighting curfew can be implemented.

The author collected visibility data in three urban areas across Texas. Data were collected using an instrumented vehicle. Dynamic measures were made using an illuminance meter while the

vehicle traversed study segments. For each location, forward and overhead illuminance data were gathered for inside and outside lanes in both directions of travel for various lighting conditions.

The author then took the data back to the office to reduce and analyze it. The author identified trends and relationships between illuminance, luminaire spacing, time, and lateral distance and plotted them in graphs and tables. The author assessed the different contributions of light to the overall lighting environment and how those contributions varied throughout the night and made several conclusions.

The author found that as the lateral distance from the luminaire increases, the overhead and forward illuminance decreases. The author saw that high mast lighting can produce greater overhead illuminance than conventional lighting even though high mast lighting is spaced further apart. Also, decreasing the spacing for high mast lighting increases the amount of overhead illuminance more so than the amount of forward illuminance percentage wise. Also, the author saw that commercial lighting has more impact on forward illuminance than overhead illuminance, but its impact is insignificant overall, at most a 1 lux increase. In addition, the author found that forward illuminance typically decreases throughout the night, more so for the inside lane, while overhead illuminance remains constant throughout the night. Also, forward illuminance is less when measured inside the vehicle than outside the vehicle. Finally, the author found that most of the segments did not meet AASHTO design criteria.

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INTRODUCTION

Roadway safety is a major concern on roadways at night. Darkness brings greater hazards to drivers as it reduces the distance they can see. The fatality rate on roadways at night is about three times the daytime rate. In order for a person to drive safely and confidently in the dark, the driver must visually determine the following:

- the location of objects or defects in the pavement in front of the vehicle at a reasonable distance,
- the location of lane and roadway edges,
- the location and meaning of the traffic control devices and signs ahead of the vehicle,
- the location of other vehicles and how they are moving, and
- the position of the driver's own vehicle relative to his destination, other objects, and intended turning locations.

To reduce nighttime fatality rates, a fixed lighting system can be installed to improve visibility at night. Overhead lighting typically improves nighttime roadway safety for motorists by revealing the environment beyond the range of vehicle headlights and reducing glare from oncoming vehicles by increasing the eye's adaptation level (*1*).

Besides improving safety, roadway lighting can also increase aesthetic appeal of the roadway and provide the driver with a sense of security. The IESNA Roadway Lighting Committee believes that roadway lighting is also economically practical. A community will have to pay less to install a lighting system than it would have to pay for accidents caused by inadequate visibility (*1*).

Recently, TxDOT has been considering implementing a lighting curfew in which roadway lighting along freeways will be reduced or eliminated during select nighttime hours. The idea is to dim or shut off the lights during periods in which lighting demand or traffic volume is so low that lighting may not provide the intended benefits. Currently, the luminaires installed along Texas freeways are unable to operate at less than full level. Thus, the only options are to either turn all of them off or some of them off along selected highway corridors at some point during the night. If adopted, a lighting curfew can benefit TxDOT by reducing energy consumption and electrical costs as well as reducing the amount of light spillover off the right-of-way and into the atmosphere.

One of the issues to consider when implementing a lighting curfew is that roadway lighting levels change throughout the night. This variability can be attributed to changes in nighttime traffic patterns or changes in nearby commercial lighting. By measuring lighting levels throughout the night, researchers can better decide for which hours there will be enough lighting to safely warrant shutting off the lights.

To address the issue, the student conducted data collection along selected highway corridors throughout the night. Using a Texas Transportation Institute vehicle and an illuminance meter, the student gathered illuminance data at various times throughout the night. The student then compiled and analyzed these data to assess the different contributions to the nighttime lighting environment and how those contributions change throughout the night. The measurements will also be checked against the requirements in the AASHTO *Roadway Lighting Design Guide*.

BACKGROUND INFORMATION

This research is part of a larger project sponsored by the Texas Department of Transportation called "Guidelines for Continuous and Safety Roadway Lighting" (Project No. 0-6645). The lighting data being collected will help the parent project establish guidelines for implementing a lighting curfew. As of yet, no state has developed specific guidelines for establishing a lighting curfew. This study will be dealing with continuous lighting, not safety lighting. "A continuous lighting system provides relatively uniform lighting on all main lanes and direct connections and complete interchange lighting of all interchanges" (*2*).

Generally, accidents on roadways increase as the lighting decreases. A study done in Syracuse, New York, in 1970 compared the night-day ratio of the number of accidents and accident costs for one year with the average maintained illumination of each study section. The study found higher night-day accident and accident cost ratios for sections with minimal illumination and sections with extremely high illumination levels (*3*). Another study was done in Austin, Texas, during the early 1970s to evaluate the effect of reduction in continuous roadway lighting on safety. Three freeway sections of southbound I-35 going through Austin, Texas, were used in this before and after study. With the lights turned off, the accident frequency increased significantly by 47.1 percent (*4*). In addition, more rear-end and pedestrian related accidents occurred.

Three criteria are typically used when designing a roadway lighting system. One proposed method is Small Target Visibility (STV) described in the ANSI-IESNA RP-8-00. STV measures the visibility of an array of targets on the roadway including the calculation of the target and background illuminance, adaptation level, and disability glare (*1*). Design is based on the ratio of the real difference in luminance between the target and its background to the luminance difference needed between the target and its background (*1*). The Texas Highway Illumination Method does not use STV and neither does this study (*2*).

The other two criteria used to design a roadway lighting system are illuminance and luminance. Illuminance is the amount of light falling on a surface, and it is measured in footcandles (fc) or lux (lx). Illuminance can be increased by increasing the intensity of the light source, increasing the number of light sources, or decreasing the distance between the light sources and the surface area (*5*).

Furthermore, illuminance can be divided into horizontal and vertical components. Horizontal, or overhead, illuminance shown in Figure 1 is light shining on a horizontal surface such as overhead luminaires shining on pavement markings. Vertical, or forward, illuminance shown in Figure 2 is light shining on a vertical surface such as vehicle headlights shining on a roadway sign.

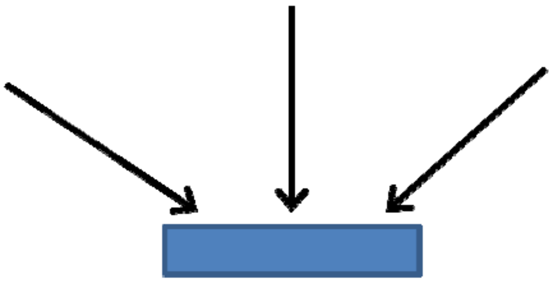

Figure 1. Horizontal or Overhead Illuminance.

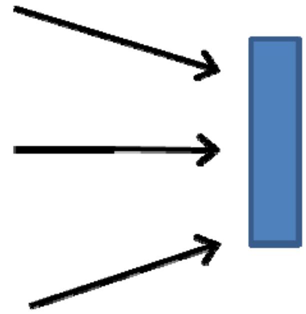

Figure 2. Vertical or Forward Illuminance.

Some segments of highways have luminaires that contribute greatly to the amount of overhead and forward illuminance on the roadway. Luminaires come in different types, sizes, and spacing. Conventional luminaires can be single arm or double arm. Double arm luminaires, also known as butterflies, are mounted along the median. Conventional luminaires are less than 50 ft tall and only have one or two light bulbs per pole (*2*). High mast lighting refers to luminaires that are over 100 ft tall with a group of lights at the top of the pole (*2*).

On a typical highway, the four main sources of illuminance come from roadway luminaires from above, commercial lighting on the sides, other vehicle headlights on the front and back, and environmental factors such as cloud cover or moonshine from above. The illuminance at any point will be the sum of illuminance from one or several sources. The research involves isolating the individual contributions of illuminance from different sources as well as determining how those contributions change with respect to time.

The illuminance from the moon will be insignificant compared to the illuminance from luminaires so the effects of the moon can be ignored. However, the lighting from the moon is more significant on empty stretches of rural roads that have no lighting installed. Moonlight will make a greater difference in visibility when it is the only source of illumination.

Illuminance depends on the distance the measurement is taken from the light source. If a surface is closer to a light source, it will take in more light and thus have a greater illuminance value. Uniformity is a design criterion specified in the AASHTO *Roadway Lighting Guide* that measures how evenly light is distributed to different areas. For example, a 1:1 uniformity ratio would mean that the roadway is equally bright in all areas; there would be no dark spots or bright spots. The uniformity ratio is defined as the ratio of the average or maximum illuminance to the minimum illuminance (*6*).

The amount of lighting on the highway at night is affected by established design guides. The TxDOT *Highway Illumination Manual* decides whether roadway lighting is required for certain parts of highways and governs how roadway lighting will be installed based on factors such as traffic volume, existing lighting, road type, etc. These guidelines establish details such as the types of luminaires installed, the spacing of the luminaires, and the mounting height of the luminaires all of which affect nighttime lighting. For example, TxDOT typically does not install lights for frontage roads so this will result in less illumination coming from the sides of the highway (*2*). Also affecting lighting are light distribution patterns that are specified by the

Illuminating Engineering Society of North America (IESNA). TxDOT uses luminaires that create type II and type III light distributions shown in Figure 3.

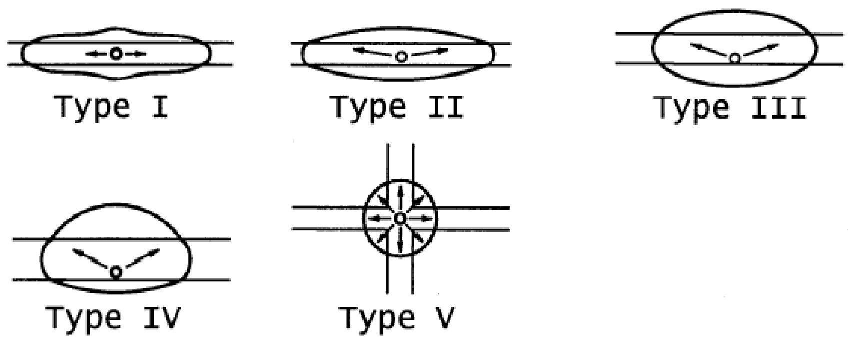

Figure 3. Lighting Distribution Patterns (*2*).

Some highways may not even have lighting installed because it is not warranted by the *Highway Illumination Manual*. Table 1 below summarizes warranting conditions for continuous lighting.

Table 1. Warranting Conditions for Continuous Lighting.

Case	**Warranting Conditions**
CL-1	Sections where the current average daily traffic (ADT) is 30,000 or greater.
CL-2	Sections where three or more successive interchanges are located with an average spacing of 1.5 miles or less and adjacent areas outside the right of way are substantially urban in character.
CL-3	Freeway sections of 2 miles or more passing through a substantially developed suburban or urban area in which two or more of the following conditions exist: • Local traffic operates on a complete street grid having some form of street lighting, parts of which are visible from the freeway. • The freeway passes through a series of developments such as residential, commercial, industrial and civic areas, colleges, parks, terminals, etc. that include lighted roads, streets, parking areas, yards, etc. • Separate cross streets, both with and without connecting ramps, occur with an average spacing of 0.5 miles or less, some of which are lighted as part of the local street system. • The freeway cross section elements, such as median and borders, are substantially reduced in width below desirable sections used in relatively open country.
CL-4	Sections where the ratio of night to day crash rates is at least 2.0 times the statewide average for all unlighted similar sections, and a study indicates that lighting may be expected to result in a significant reduction in the night crash rate.

Source: TxDOT Highway Illumination Manual (*2*)

After warranting conditions for continuous lighting are met, TxDOT uses the illumination method from the AASTHO *Roadway Lighting Design Guide* (*6*) as well as principles from the FHWA *Roadway Lighting Handbook* (*7*) to design the lighting system. The illumination method specifies design values for illuminance given the type of road, amount of pedestrians crossing the road, and pavement classification. The following is the illumination method used by TxDOT, which can be found in the AASHTO Roadway Lighting Design Guide. Table 2 shows a summary of AASHTO design requirements for overhead illuminance. The illuminance values are referring to overhead illuminance on the pavement. General land use is classified by the location of the road as well as the amount of pedestrian traffic there is. The uniformity ratio is taken as the average illuminance divided by the minimum illuminance. The cells highlighted in yellow represent the requirements the study segments need to be checked against.

Table 2. AASHTO Illuminance Method.

Roadway and Walkway Classification	Off-Roadway Light Sources: General Land Use	Illuminance Method: Average Maintained Illuminance R1 (Lux) (min)	R2 (Lux) (min)	R3 (Lux) (min)	R4 Lux (min)	Minimum Illuminance (Lux)	Illuminance Uniformity Ratio avg/min (max) *
Interstate and other freeways	Commercial	6-12	6-12	6-12	6-12	2	3:1 or 4:1
	Intermediate	6-10	6-10	6-10	6-10	2	3:1 or 4:1
	Residential	6-8	6-8	6-8	6-8	2	3:1 or 4:1
Other Principal Arterials (partial or no control of access)	Commercial	12	17	17	15	As uniformity ratio allows	3:1
	Intermediate	9	13	13	11		3:1
	Residential	6	9	9	8		3:1
Minor Arterials	Commercial	10	15	15	11		4:1
	Intermediate	8	11	11	10		4:1
	Residential	5	7	7	7		4:1
Notes: *Higher uniformity ratios are acceptable for elevated ramps near high-mast poles							

Source: AASHTO Roadway Lighting Design Guide (*6*)

GOALS AND OBJECTIVES

The goal of this research was to evaluate how lighting changes throughout the night. The author focused on continuous lighting as opposed to safety lighting. To assess the lighting throughout the night, the author collected lighting data in the form of illuminance along highway corridors during various hours of nighttime. Illuminance values were checked to see if they meet AASHTO design requirements. These measurements will be used to help the parent project, *Guidelines for Continuous and Safety Roadway Lighting*, determine if and at what hours a lighting curfew can be implemented.

DATA COLLECTION

The following sections describe the procedures for data collection as well as the equipment used for this project.

Test Locations

Three metropolitan areas across Texas were sampled for data collection. In three successive nights, the author collected data in Austin, San Antonio, and Houston. Measurements were taken on straight segments along highways without gores or overpasses. Specific locations along freeway corridors were chosen using Google Earth® and then finalized by driving out to the location at night to confirm the lighting conditions. In Figure 4, segments were done along I-35 in Austin. In Figure 5 and Figure 6, segments were done along I-10 in San Antonio and Houston, respectively.

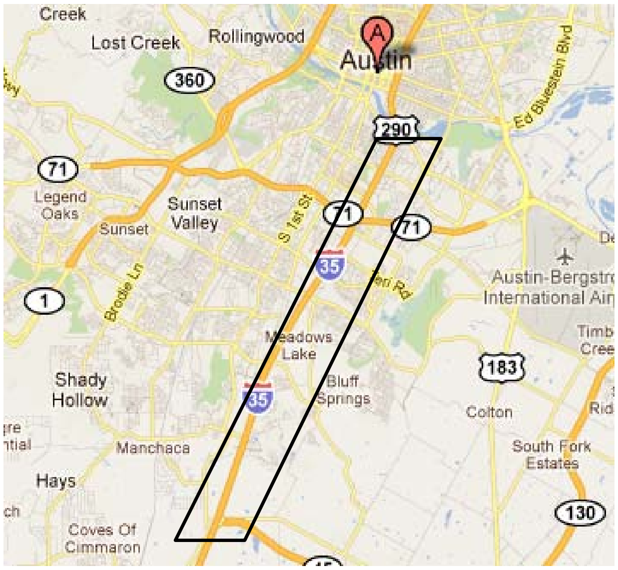

Figure 4. Austin Segment.

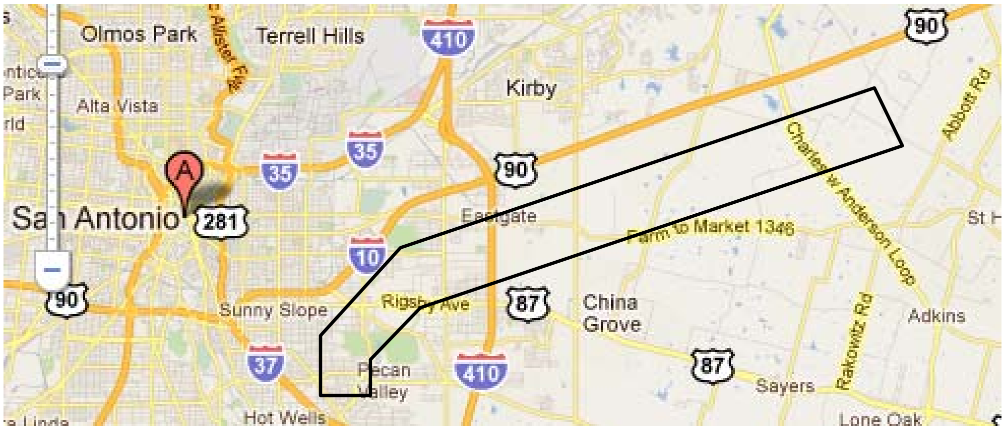

Figure 5. San Antonio Segment.

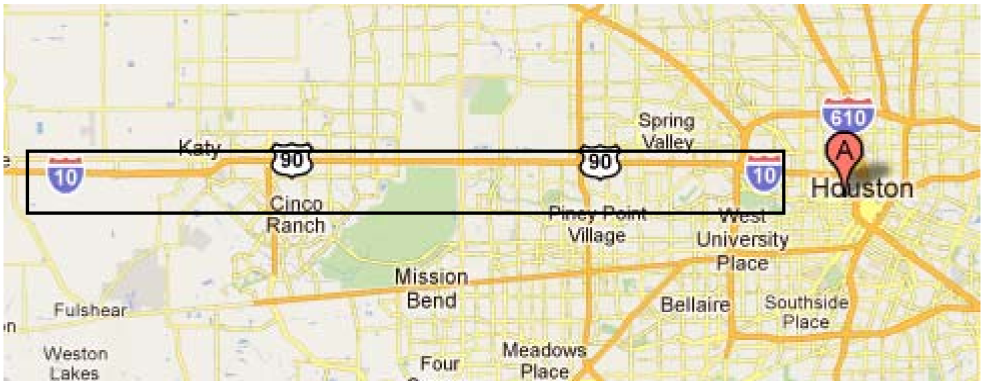

Figure 6. Houston Segment.

Segments were chosen based on the availability of overhead illumination and the availability of roadside commercial signs. Metropolitan areas typically have overhead illumination. Segments without overhead illumination were found in rural areas outside of the metropolitan area. Segments were chosen such that they did not have any gores or overpasses. For segments containing overhead luminaires, a segment had to have at least four luminaires in order to be chosen. Combinations of overhead illumination and commercial lighting give us four types of segments to study as shown in Figures 7 through 10.

Figure 7. Overhead Lighting Only.

Figure 8. No Overhead or Commercial Lighting.

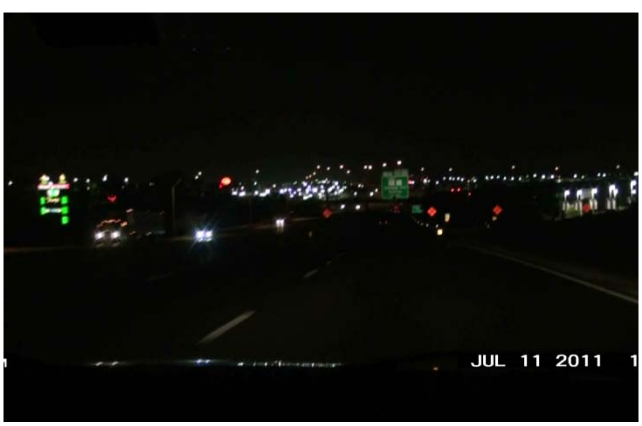

Figure 9. Commercial Lighting Only.

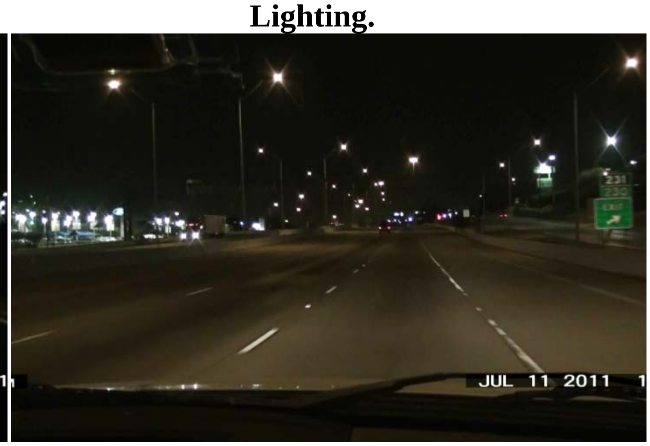

Figure 10. Overhead and Commercial Lighting.

Equipment

The T-10 Minolta illuminance meter shown in Figure 11 measured illuminance, both overhead and forward. The sensor was clamped on top of the vehicle to take measurements while the vehicle was moving. Another sensor was placed inside the vehicle on the passenger side front seat. The illuminance meter was hooked up to a computer so real time measurements could be displayed in tabular format. In the research, the illuminance meter was connected to three heads. These heads were daisy-chained together using CAT 5 cables.

As can be seen in Figure 12, flashing beacons were mounted on the bed rail of the vehicle to alert motorists of the slower moving vehicle during data collection. A bar with suction cups was attached to the top of the vehicle as shown in Figure 13. Installed on this bar were two sensor clamps. One clamp held a sensor facing upward and another held a sensor facing forward. The sensors were connected to illuminance meter heads inside the vehicle, which were then connected to the illuminance meter. The illuminance meter was then connected to a computer inside the vehicle. Figure 14 shows the computer monitor inside the vehicle used to display real-time illuminance data.

Figure 11. Illuminance Meter (*8*).

Figure 15 shows a headrest mount installed on the front passenger seat. Attached to this headrest mount is a sensor facing forward to gather forward illuminance inside the vehicle and a high definition video camera to document the data collection. The author also used a range finder to determine the height and spacing of the luminaires. The author went back after data collection to verify the spacing in Google Earth.

Figure 12. Flashing Beacons and Vehicle.

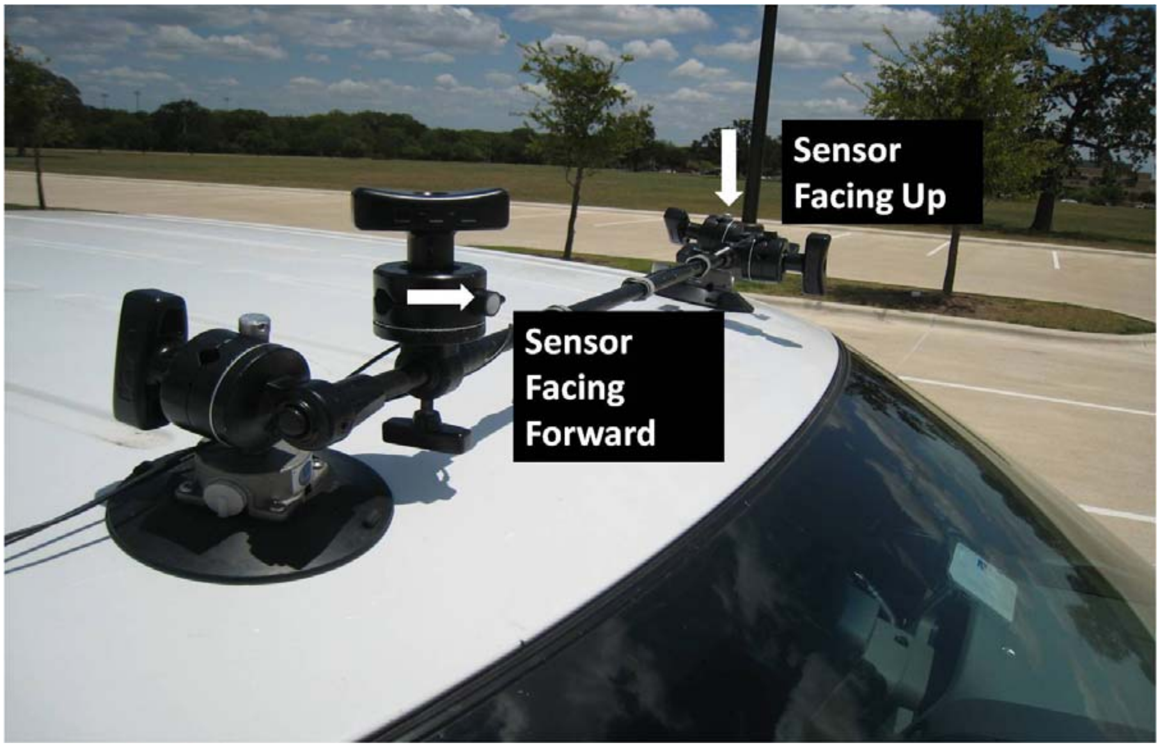

Figure 13. Mounting Bar and Sensors.

Figure 14. Monitor inside Vehicle.

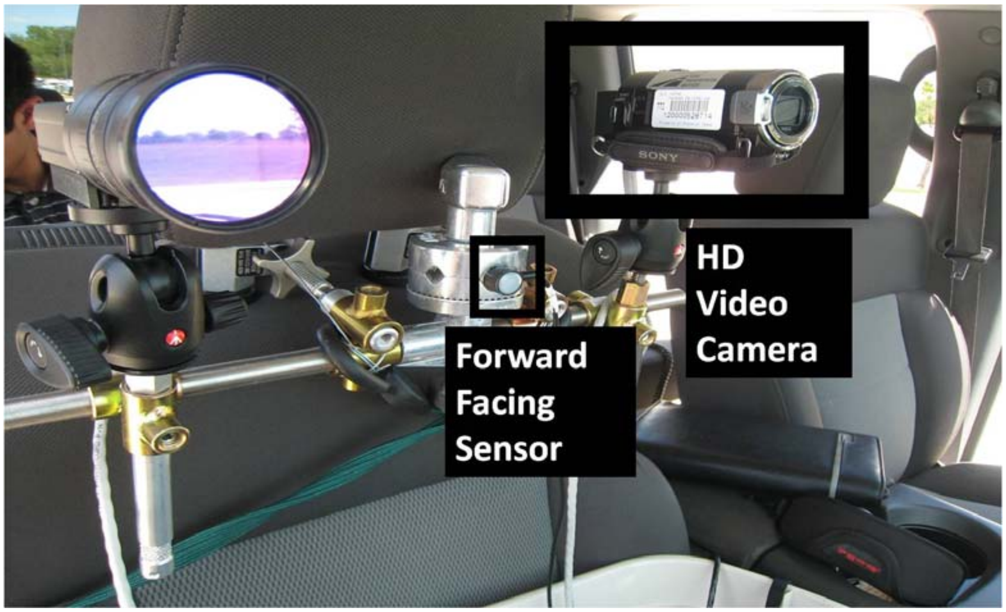

Figure 15. Headrest Mount.

Procedure

First, the author used Google Earth to tentatively select some study segments. These segments needed to be at least 1 mile long, free of gores or over passes, and be a combination of overhead lighting/commercial lighting.

Then, the author tested the data collection equipment in the lab. The author made sure that the software for the Minolta T-10 Illuminance meter was running properly and able to run simultaneously with the GPS software Microsoft® MapPoint North America 2006. The author used the GPS software to help us locate the segments the author found from Google Earth. The author also calibrated the sensors to make sure they were reading all the same and adjusted values for sensors that read low by a multiplier. After the vehicle had been set up and the equipment checked, the author embarked on his data collection adventure.

The author visited three metropolitan cities in three consecutive nights; going to Austin, San Antonio, and then Houston. While running through the study corridors, the author identified markers to indicate when a segment started and when a segment ended. These markers could be overhead guide signs, shoulder mounted guide signs, commercial establishment signs, etc. The author let the illuminance software collect data continuously as the author drove through the segments. The author drove the segments at 60 mph earlier in the night and did one run at 40 mph later at night when traffic volume was low enough.

The software recorded the time at which each data point was collected. When a segment started and ended, a person in the backseat would record the time the author entered the segment and subsequently the time the author exited the segment. The author would then go back to the office and extract the data between these start and stop times. Table 3 shows an example of how the author recorded the markers and times.

Table 3. Segment Markers and Times.

						Marker	
City	**Direction**	**Lane**	**Segment**	**Luminaire**	**Commercial**	**Start**	**End**
Austin	North	Outside	1	Yes	No	First high mast luminaire past bridge	Slaughter overpass one mile exit sign
		Outside	2	No	No	Harly flag	Bridge
		Outside	3	No	Yes	Slaughterlane exit 227	Holt cat sign
		Outside	4	Yes	Yes	First luminaire median mounted	Last luminaire median mounted
		Outside	5	Yes	Yes	Woodland sign	Bridge
						Times	
		Outside	1	Yes	No	4.25.12	4.27.10
		Outside	2	No	No	4.28.05	4.28.45
		Outside	3	No	Yes	4.29.09	4.29.52
		Outside	4	Yes	Yes	4.33.05	4.33.50
		Outside	5	Yes	Yes	4.35.43	4.36.22

DATA ANALYSIS

The following sections will describe trends and relationships found in the data.

Lateral Distance

From the data collected, the author found that the amount of overhead illuminance is affected by the lateral distance away from the luminaire. In other words, for a segment of roadway with luminaires mounted on the shoulder, driving on the outside lane resulted in higher values of overhead illuminance than driving on the inside lane. Figure 16 shows the overhead illuminance profiles for inside and outside lanes for northbound and southbound directions as the vehicle is driving at 40 mph. The data were taken on a segment in Austin with high mast overhead lighting and no commercial lighting. The luminaires are located closest to the NB outside lane. There are three lanes of travel in each direction.

It is seen that the overhead illuminance profiles have lower peaks as the author moved farther away from the high mast luminaires. This trend was found in San Antonio and Houston as well. Figure 16 shows there is a greater drop in peak illuminance as the author moves across the median and into the other direction of travel compared to moving from outside lane to inside lane. The median is 40 ft wide and the lanes are 12 ft wide. Moving from outside to inside lane involves increasing the lateral distance by 12 ft while changing from NB inside lane to SB inside lane involves increasing the lateral distance by 40 ft.

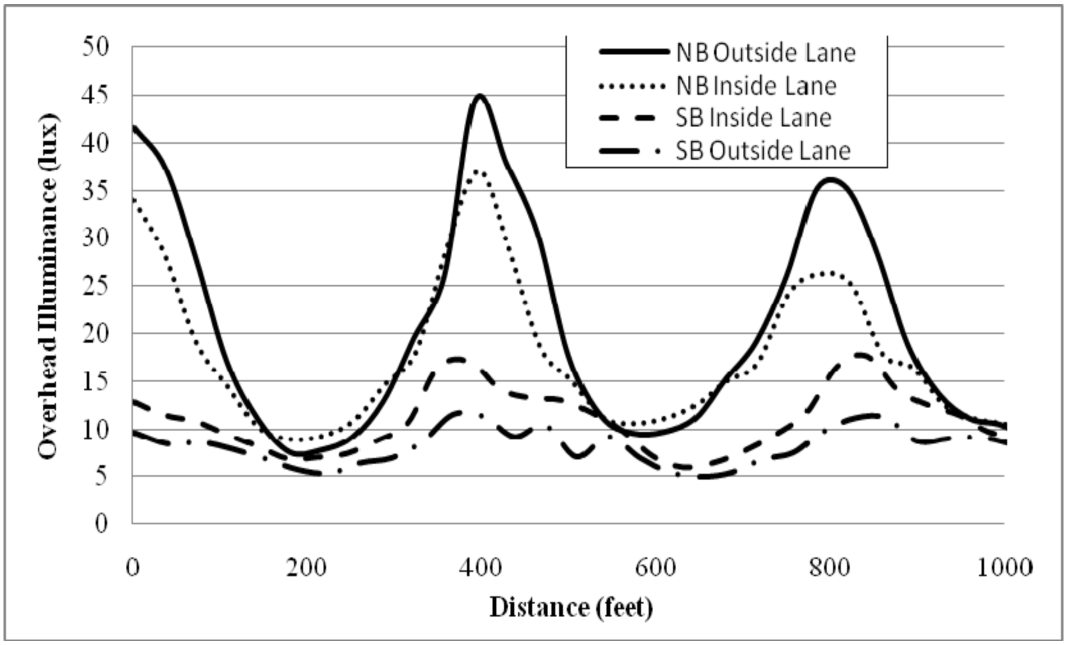

Figure 16. Austin Overhead Illuminance with Respect to Lane High Mast Lighting.

Forward illuminance also drops in a similar fashion as the lateral distance from the luminaire increases. Figures 17 and 18 show this trend for high mast lighting and conventional lighting respectively. The data were taken in Austin. Figure 17 shows the same segment as Figure 16.

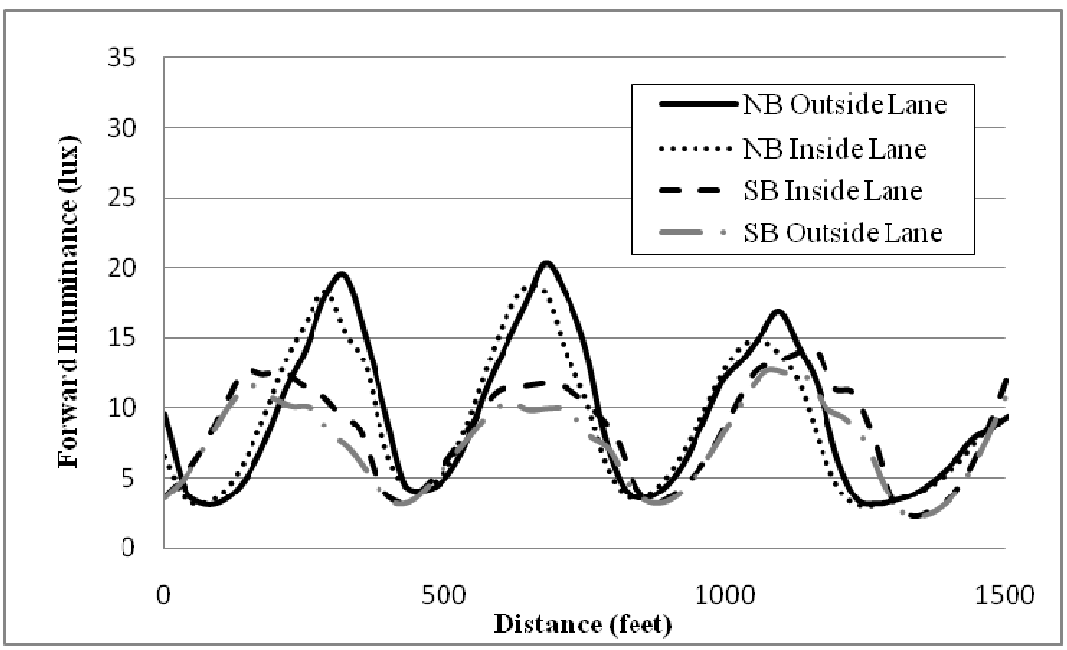

Figure 17. Forward Illuminance by Lane High Mast – Austin.

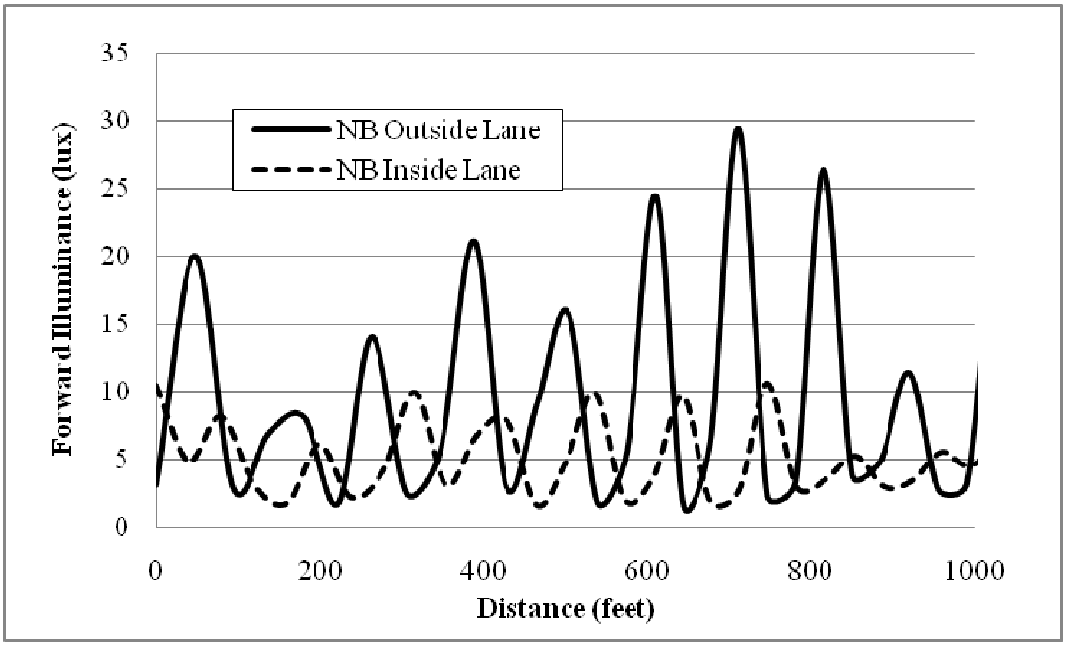

Figure 18. Forward Illuminance by Lane Side Mounted Single Arm Conventional – Austin.

Conventional Lighting vs High Mast Lighting

The author also found that high mast lighting 150 ft tall with 650 ft spacing has much greater peaks in its overhead illuminance profile than conventional median mounted single arm luminaires that are 50 ft tall with 280 ft spacing. Figure 19 shows data collected in Austin that illustrates this point.

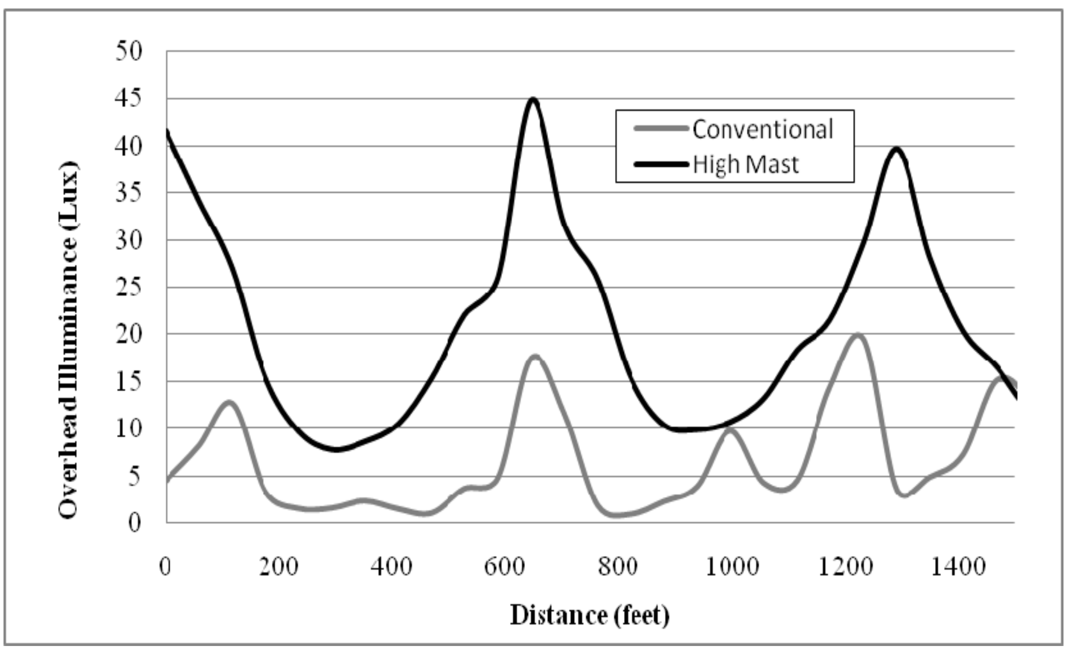

Figure 19. Conventional vs High Mast Lighting – Austin.

Effects of Spacing for High Mast Lighting

Table 4 shows that decreasing the spacing of high mast lighting had more of an effect on overhead illuminance as opposed to forward illuminance. The data were collected in Austin for the 650 ft spaced luminaires and Houston for the 2000 ft spaced luminaires.

Table 4. Effects of Spacing for High Mast Lighting.

Time	Type of Lighting	Spacing (ft)	Overhead Illuminance	Forward Illuminance
12:00 AM	High Mast Lighting	2000	6.5	5.2
		650	16.0	9.9
Percentage Increase			246	190
2:00 AM	High Mast Lighting	2000	6.5	5.1
		650	16.8	9.6
Percentage Increase			258	188

Contribution of Commercial Lighting

The author also looked at how much effect commercial lighting has on the nighttime lighting environment. By collecting overhead illuminance data for sections without luminaires, the author can directly compare the sections that have commercial lighting with the sections without commercial lighting. Figures 20 and 21 show the overhead and forward illuminance profiles for sections with commercial lighting versus sections without commercial lighting. The data were collected in Austin and San Antonio on different segments. From Figure 20, the author saw that commercial lighting increases forward illumination by at most 1 lux and overhead illumination by at most half a lux. Figure 21 shows similar trends in San Antonio. From the data, the author concludes that commercial lighting has more of an impact on forward illuminance than it does on overhead illuminance.

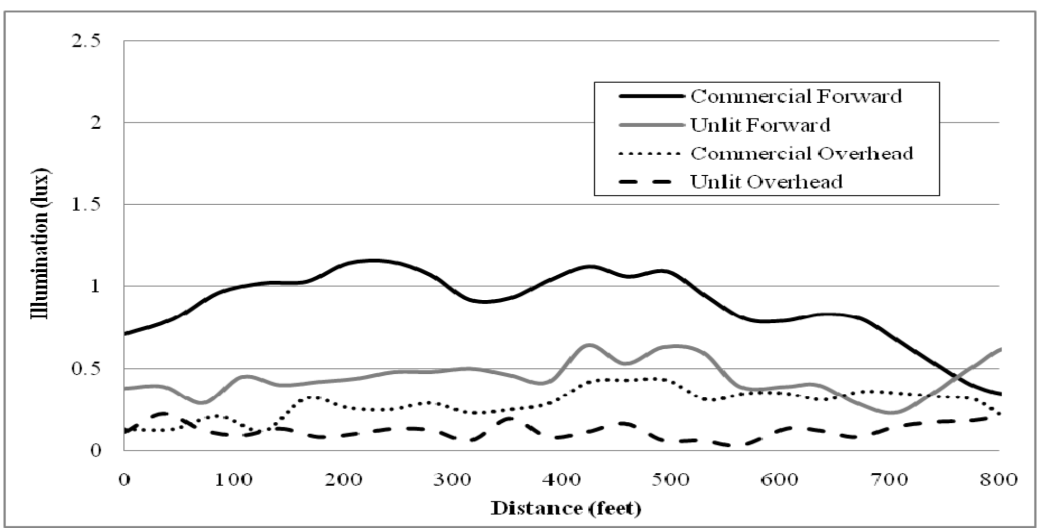

Figure 20. Effect of Commercial Lighting in Austin.

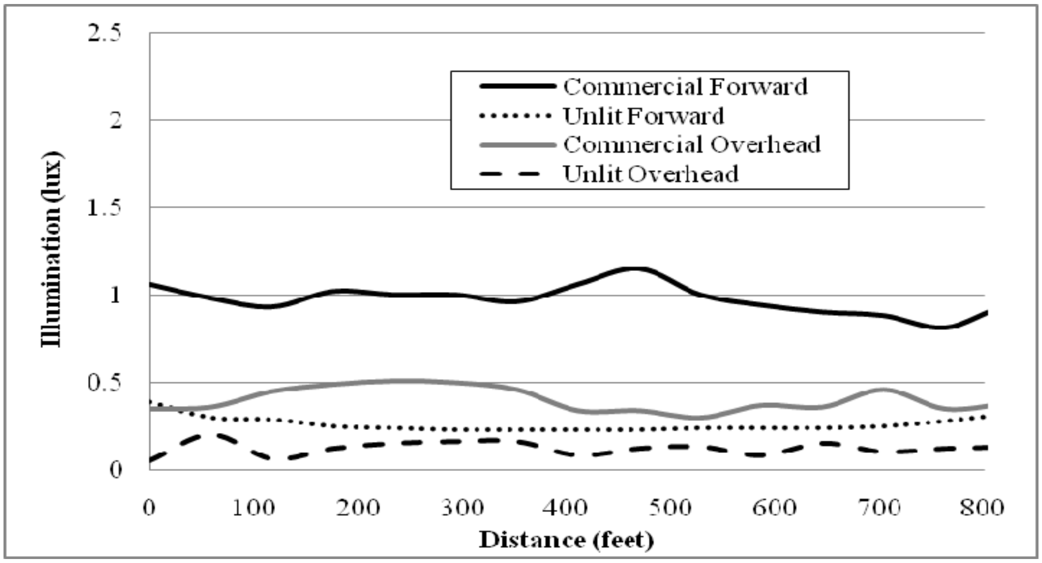

Figure 21. Effect of Commercial Lighting in San Antonio.

Forward Illuminance throughout the Night

Another trend the author noticed is that forward illumination drops throughout the night. Table 5 shows how the average forward illuminance differs based on the time the measurements were taken. The measurements were taken along several different segments in San Antonio. Typically, inside lane values for forward illuminance are greater than outside lane values because the inside lane is closer to oncoming traffic vehicle headlights. There is a greater percentage drop in forward illuminance on the inside lane than there is on the outside lane from 12:00 AM to 4:00 AM. The drop in forward illuminance suggests there is a decrease in traffic volume, especially on the inside lane.

Table 5. Change in Forward Illuminance – San Antonio.

Segment Lighting	Outside Lane			Inside Lane		
	12:00 AM	4:00 AM	% Drop	12:00 AM	4:00 AM	% Drop
Overhead and Commercial	6.2	5.6	10	8.4	7.5	11
Overhead and Commercial	7.2	6.9	4	9.4	8.4	11
Overhead Only	4.3	4.2	2	6.7	5.9	12
Overhead Only	4.6	4.2	9	7	5.6	20

In Austin, the author found forward illuminance to mostly drop from the hours of 11 PM to 1 AM. After 1 AM, forward illuminance dropped less dramatically, and even rose again on some segments. The forward illuminance rose again in segments closer to the city of Austin when the author was traveling northbound towards the city. This suggests a higher traffic volume coming out of the city around 1 AM to 2 AM. These trends are summarized in Figure 22.

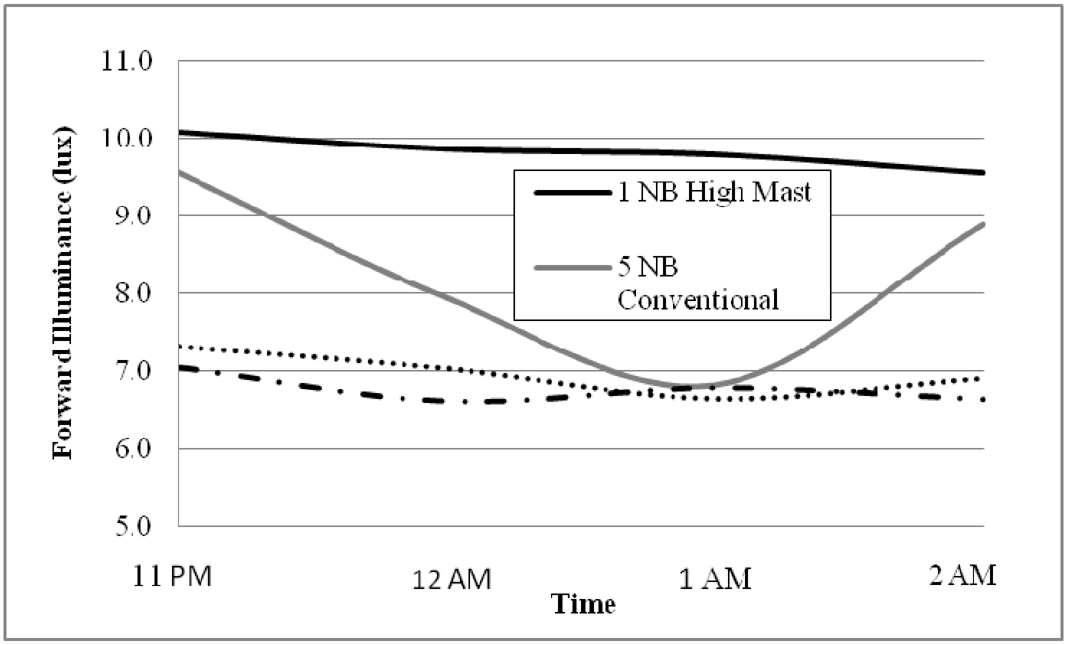

Figure 22. Forward Illuminance throughout Night – Austin.

Overhead Illuminance throughout the Night

The data the author collected also show that overhead illumination does not change throughout the night. This is to be expected as the main source of overhead illumination is from overhead luminaires and their lights do not change throughout the night. Figures 23 and 24 show that the overhead illuminance profiles do not change very much with respect to time in Austin and Houston, respectively.

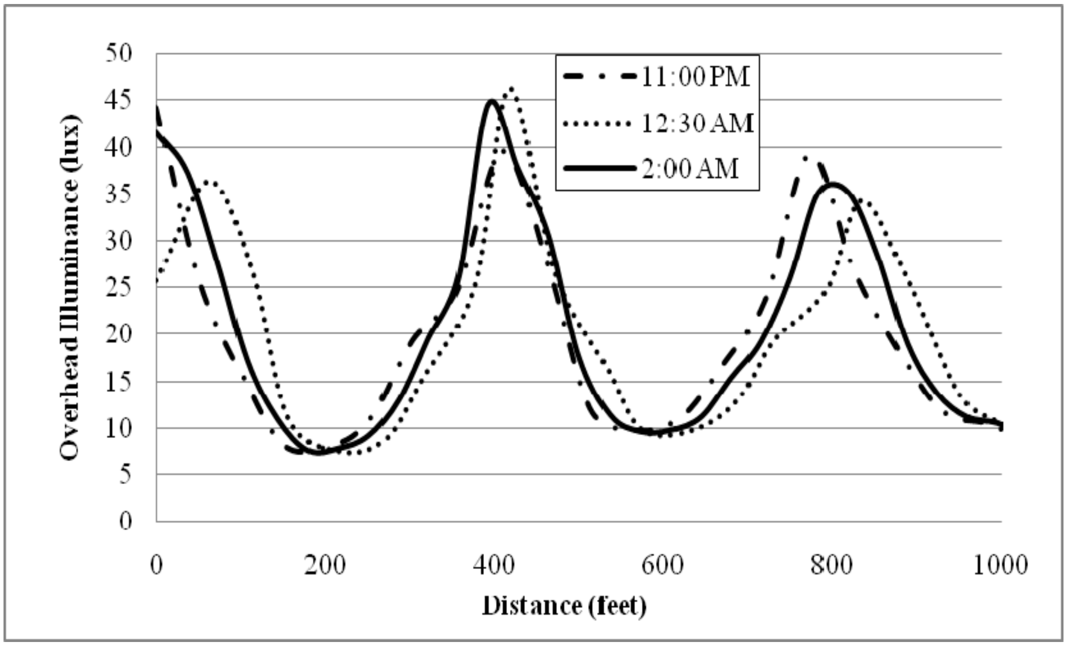

Figure 23. Overhead Illuminance with Respect to Time Austin High Mast Lighting.

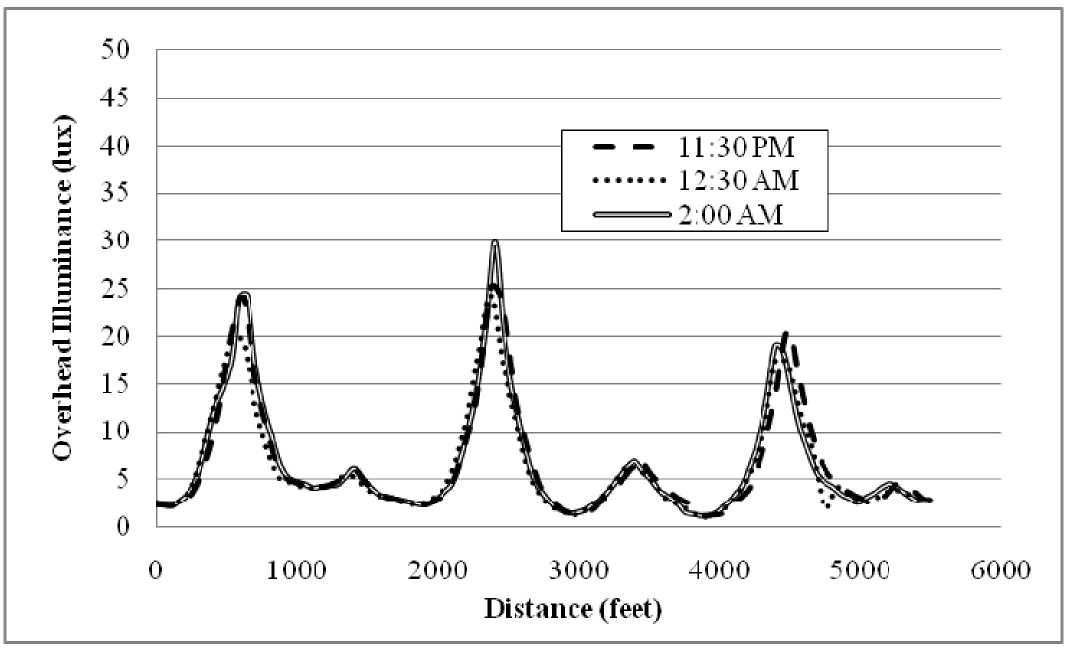

Figure 24. Overhead Illuminance with Respect to Time Houston High Mast Lighting.

Forward Illuminance inside Vehicle

A third sensor was placed inside of the vehicle facing forward on the passenger side seat. The author compared the forward illuminance values on this sensor to the sensor on top of the vehicle. The results are summarized in Table 6. The forward illuminance drops inside the vehicle compared to outside the vehicle. This is a result of the windshield blocking some light as well as the car ceiling or windows blocking out light. Similar trends were found in other cities.

Table 6. Forward Illuminance Inside Vehicle vs Outside Vehicle Houston.

Segment	Lane	Time Taken	Luminaire	Commercial	Outside	Inside	Ratio of Inside to Outside
4 East	Outside	11:55:32 PM	Yes	Yes	5.38	1.84	0.34
4 East	Outside	1:19:29 AM	Yes	Yes	5.10	1.73	0.34
4 East	Outside	2:28:03 AM	Yes	Yes	4.96	1.63	0.33
3 East	Outside	11:53:16 PM	Yes	No	4.17	1.12	0.27
3 East	Outside	1:17:11 AM	Yes	No	4.04	1.05	0.26
3 East	Outside	2:25:21 AM	Yes	No	4.61	1.12	0.24
2 East	Outside	11:48:27 PM	No	Yes	6.11	3.06	0.50
2 East	Outside	1:12:31 AM	No	Yes	1.36	0.69	0.51
2 East	Outside	2:20:32 AM	No	Yes	1.50	0.76	0.50
1East	Outside	11:47:15 PM	No	No	0.47	0.21	0.45
1East	Outside	1:11:19 AM	No	No	0.35	0.13	0.37
1East	Outside	2:18:46 AM	No	No	0.40	0.17	0.41

Checking Overhead Illuminance Values against Design Requirements

Three parameters needed to be checked according to the AASHTO *Roadway Lighting Design Guide*. The overhead illuminance must have a minimum value of 2 lux, an average value between 6–12 lux, and a maximum uniformity ratio of 4:1.

Before the overhead illuminance data could be checked, they had to first be adjusted. The raw data the author collected represent the amount of overhead illuminance on top of the vehicle. The author needed the amount of overhead illuminance hitting the pavement. To do this, the author applied the inverse square law, which states that illuminance is inversely proportional at a squared rate to the distance away from the light source. Figure 25 shows the parameters the author used to do the adjustment. The author used this formula to adjust the values:

$$E_{adjusted} = E_{original} \times (R_1/R_2)^2$$

where

$E_{adjusted}$ = the adjusted value of overhead illuminance.
$E_{original}$ = the original value of overhead illuminance, i.e., raw data.
R_1 = The distance from the top of the luminaire to the top of the vehicle.
R_2 = The distance from the top of the luminaire to the surface of the pavement.

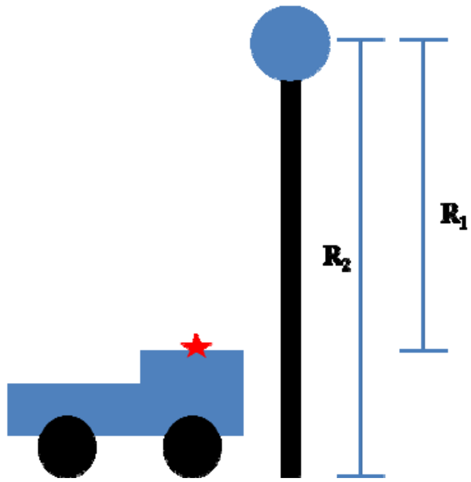

Figure 25. Illuminance Adjustment.

Adjusting the values caused them to decrease. Greater adjustments were needed for conventional lighting than high mast lighting. Values for high mast lighting were adjusted to about 90 percent of the original value, and conventional lighting values were adjusted to about 75 percent of the original values.

The AASHTO *Roadway Lighting Design Guide* is not very clear about how to check the requirements. The author checked the segments in two ways. First the author checked the segment by luminaire. To do this, the author took every set of two adjacent luminaires in a segment and found the minimum, average, and uniformity ratios for them all. The author then averaged them together to get a minimum, average, and uniformity ratio for the segment overall. The second way the author checked the segment was by finding the minimum, average, and uniformity ratio for the segment as a whole.

For both methods the author averaged the values for both inside and outside lanes. Tables 7, 8, and 9 show which segments met the requirements by the luminaire method for Austin, San Antonio, and Houston, respectively. North means northbound, south means southbound, O means outside lane, and I means inside lane. Cells highlighted in yellow mean that the requirement was met. The tables show that most of the segments did not meet the requirements.

Table 7. Austin Requirements Adjusted by Luminaire.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 North O	6.90	15.98	2.29	7.12	15.10	2.13
1 North I	7.33	14.21	1.98			
4 North O	1.98	6.71	3.94	1.82	8.28	5.22
4 North I	1.67	9.85	6.50			
5 North O	1.62	13.07	8.41	1.80	8.84	5.44
5 North I	1.99	4.62	2.48			
1 South O	2.12	7.27	3.45	2.01	9.01	4.54
1 South I	1.91	10.74	5.64			
4 South O	5.54	8.05	1.47	6.02	9.26	1.56
4 South I	6.51	10.47	1.64			

Table 8. San Antonio Requirements Adjusted by Luminaire.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
3 West O	1.79	9.37	5.47	1.69	11.67	7.27
3 West I	1.59	13.97	9.08			
4 West O	1.60	5.63	3.62	1.59	8.82	5.69
4 West I	1.58	12.00	7.76			
1 East O	1.74	6.34	4.08	1.82	9.88	5.92
1 East I	1.89	13.42	7.76			
2 East O	1.77	9.44	5.56	1.98	12.58	6.68
2 East I	2.18	15.71	7.80			

Table 9. Houston Requirements Adjusted by Luminaire.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 West O	1.59	5.99	3.90	1.59	6.07	4.20
1 West I	1.59	6.16	4.50			
2 West O	1.11	5.37	4.91	1.13	5.49	4.97
2 West I	1.16	5.61	5.03			
3 West O	1.47	7.32	4.98	1.54	7.23	4.72
3 West I	1.61	7.15	4.45			
3 East O	1.23	6.17	5.03	1.27	5.98	4.73
3 East I	1.30	5.79	4.44			
4 East O	1.20	5.23	4.47	1.20	5.45	4.69
4 East I	1.20	5.67	4.90			
5 East O	1.89	5.66	3.00	1.67	5.44	3.29
5 East I	1.46	5.22	3.58			

CONCLUSIONS

- As the lateral distance from the luminaire increases, the overhead and forward illuminance decreases.
- High mast lighting can produce greater overhead illuminance than conventional lighting even though high mast lighting is spaced farther apart.
- Decreasing the spacing for high mast lighting increases the amount of overhead illuminance more than the amount of forward illuminance.
- Commercial lighting has more impact on forward illuminance than overhead illuminance but it is impact is insignificant overall, at most a 1 lux increase.
- Forward illuminance typically decreases throughout the night, more so for the inside lane.
- Overhead illuminance remains constant throughout the night.
- Forward illuminance is less for inside the vehicle than it is for outside the vehicle.
- Most of the segments did not meet AASHTO design criteria.

Table 10 summarizes the percentage of segments that met AASHTO design criteria based on how the values were obtained and whether they were adjusted using the inverse square law. The values represent the averages of the inside and outside lane. From the table, more of the minimum values met the requirements when the author used the unadjusted values but fewer of the average values met the requirements.

Table 10. Percentage of Segments Meeting Requirements.

Method	Adjusted	Minimum	Average	Uniformity Ratio
Luminaire	Yes	20%	60%	20%
Segment	Yes	13%	67%	27%
Luminaire	No	60%	53%	20%
Segment	No	20%	67%	27%

REFERENCES

1. *American National Standard Practice for Roadway* Lighting. RP-8-00. American National standards Institute ANSI / IESNA, New York, New York June 2000, Reaffirmed 2005.
2. Texas Department of Transportation. *Highway Illumination Manual*. November 2003.
3. Box, P. C., *Comparison of Accidents and Illumination*, Highway Research Record 416 (1972), 10-20.
4. Richards, S., Effects of Turning Off Selected Roadway Lighting as an Energy Conservation Measure, Transportation Research Record 811 (1981), 23-25.
5. Ullman G, M. Finley. *Challenges to Implementation of Work Zone Lighting Guidelines*. Prepared for presentation at the 17^{th} TRB Visibility Symposium. April 17-19, 2007.
6. American Association of State and Highway Transportation Officials. *Roadway Lighting Design Guide*. October 2005.
7. US Department of Transportation Federal Highway Administration. *Roadway Lighting Handbook*. December 1978.
8. 0-6645 Overhead Highway Lighting Field Measurement Procedure.

APPENDIX A: SEGMENT INFORMATION

Table 11. Segment Lighting Information.

City	Direction	Segment	Luminaire	Commercial
Austin	North	1	Yes	No
		2	No	No
		3	No	Yes
		4	Yes	Yes
		5	Yes	Yes
	South	1	Yes	Yes
		2	No	No
		3	No	Yes
		4	Yes	No
San Antonio	West	1	No	Yes
		2	No	No
		3	Yes	Yes
		4	Yes	No
	East	1	Yes	No
		2	Yes	Yes
		3	No	No
		4	No	Yes
Houston	West	1	Yes	Yes
		2	Yes	No
		3	Yes	No
		4	No	No
		5	No	No
	East	1	No	No
		2	No	Yes
		3	Yes	No
		4	Yes	Yes
		5	Yes	Yes

Table 12. Segment GPS Coordinates.

			GPS Coordinates			
			Start		End	
City	**Direction**	**Segment**	**Lat**	**Long**	**Lat**	**Long**
Austin	North	**1**	30d 6m 51s N	97d 48m 22s W	30d 7m 23s N	97d 48m 9s W
		2	30d 8m 37s N	97d 47m 41s W	30d 8m 59s N	97d 47m 32s W
		3	30d 9m 14s N	97d 47m 28s W	30d 9m 41s N	97d 47m 20s W
		4	30d 12m 0s N	97d 45m 46s W	30d 12m 24s N	97d 45m 26s W
		5	30d 13m 41s N	97d 44m 39s W	30d 14m 3s N	97d 44m 27s W
	South	**1**	30d 12m 22s N	97d 45m 28s W	30d 11m 58s N	97d 45m 47s W
		2	30d 10m 54s N	97d 46m 34s W	30d 10m 33s N	97d 46m 48s W
		3	30d 9m 52s N	97d 47m 15s W	30d 9m 16s N	97d 47m 28s W
		4	30d 7m 56s N	97d 47m 56s W	30d 6m 49s N	97d 48m 23s N
San Antonio	West	**1**	29d 27m 42s N	98d 18m 21s W	29d 27m 26s N	98d 19m 19s W
		2	29d 27m 26s N	98d 19m 19s W	29d 27m 9s N	98d 20m 13s W
		3	29d 25m 59s N	98d 23m 55s W	29d 25m 43s N	98d 24m 56s W
		4	29d 24m 55s N	98d 25m 45s W	29d 24m 16s N	98d 26m 30s W
	East	**1**	29d 24m 19s N	98d 26m 25s W	29d 24m 48s	98d 25m 52s W
		2	29d 25m 43s N	98d 24m 55s W	29d 25m 59s N	98d 23m 55s W
		3	29d 27m 7s N	98d 20m 16s W	29d 27m 25s N	98d 19m 21s W
		4	29d 27m 25s N	98d 19m 21s W	29d 27m 40s N	98d 18m 28s W
Houston	West	1	29d 47m 6s N	95d 42m 30s W	29d 47m 7s N	95d 43m 29s W
		2	29d 47m 7s N	95d 44m 28s W	29d 47m 7s N	95d 45m 41s W
		3	29d 47m 7s N	95d 46m 46s W	29d 47m 7s N	95d 47m 41s W
		4	29d 46m 38s N	95d 51m 56s W	29d 46m 38s N	95d 52m 14s W
		5	29d 46m 38s N	95d 52m 59s W	29d 46m 38s N	95d 53m 42s W
	East	1	29d 46m 38s N	95d 53m 41s W	29d 46m 38s N	95d 52m 58s W
		2	29d 46m 38s N	95d 52m 15s W	29d 46m 38s N	95d 51m 54s W
		3	29d 47m 7s N	95d 48m 0s W	29d 47m 7s N	95d 47m 20s W
		4	29d 47m 7s N	95d 45m 59s W	29d 47m 6s N	95d 44m 41s W
		5	29d 47m 6s N	95d 43m 17s W	29d 47m 6s N	95d 42m 32s W

Table 13. Segment Luminaire Information.

City	Segment	Direction	Description	Spacing (ft)	Height (ft)
Austin	1	NB	One Side Mounted High Mast	650	150
	4	NB	Median Mounted Single Arm	280	50
	5	NB	Both Sides Mounted Single Arm	180	50
	1	SB	Median Mounted Single Arm	280	50
	4	SB	One Side Mounted High Mast	650	150
San Antonio	All Segments with Luminaires		Median Mounted Double Arm	50	270
Houston	All Segments with Luminaires		Both Sides Mounted High Mast Staggered	167	2028*

*Between two adjacent luminaires on one side

Table 14. Segment Start and End Markers.

City	Direction	Segment	Start	End
Austin	North	1	First high mast luminaire past bridge	Slaughter overpass one mile exit sign
		2	Harly flag	Bridge
		3	Slaughterlane exit 227	Holt cat sign
		4	First luminaire median mounted	Last luminaire median mounted
		5	Woodland sign	Bridge
	South	1	First luminaire	Last luminaire on left in center medium
		2	Gas blue logo sign	South congress ave net right loop 275
		3	Slaughterhouse overpass exit 226	Guide sign onion creek parkway 1/2 mile
		4	First luminaire on left	Buda next three exits sign
San Antonio	West	1	First Luminaire Pallet Place	Noahs arc Self Storage
		2	Noahs arc self storage	telephone pole before first luminaire on right frontage road
		3	Loop 13 WW white	Commerce street Houston Overhead guide sign exit 579
		4	Roland ave Victoria 1 mile guide sign	Roland Ave Victoria sign
	East	1	Pecan Valley Drive	AT&T center overhead guide sign
		2	410 Conally loop exit shoulder mounted sign	exit 410 exit only
		3	Converse 1 mile exit 585	Converse exit shoulder mounted sign
		4	Anderson loop guide sign	Last luminaire on right in Kenworth Truck center
Houston	West	1	Western green 3/4 mile sign	Blue sign (exit 745)
		2	Food sign exit 743	Begin work zone
		3	Katy mills exit 7041 us 90 west	Pin oak road 1 mile overhead guide sign
		4	First luminaire in holiday world	Last luminaire in holiday world
		5	Love's gas sign	Igloo road guide sign
	East	1	Pederson road guide sign exit 737 shoulder mounted	Love's gas sign
		2	First luminaire in holiday world	Last luminaire in holiday world
		3	State highway south exit sign	Mason road guide sign
		4	Hooter's sign	Houston community college katy campus
		5	Green house road exit 747b	Barker cyprus road exit

APPENDIX B: REQUIREMENTS FOR ADJUSTED AND UNADJUSTED OVERHEAD ILLUMINANCE VALUES BY LUMINAIRE AND SEGMENT

Table 15. Austin Requirements by Luminaire Adjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 North O	6.90	15.98	2.29	7.12	15.10	2.13
1 North I	7.33	14.21	1.98			
4 North O	1.98	6.71	3.94	1.82	8.28	5.22
4 North I	1.67	9.85	6.50			
5 North O	1.62	13.07	8.41	1.80	8.84	5.44
5 North I	1.99	4.62	2.48			
1 South O	2.12	7.27	3.45	2.01	9.01	4.54
1 South I	1.91	10.74	5.64			
4 South O	5.54	8.05	1.47	6.02	9.26	1.56
4 South I	6.51	10.47	1.64			

Table 16. Austin Requirements by Luminaire Unadjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 North O	7.55	17.48	2.29	7.79	16.52	2.13
1 North I	8.02	15.55	1.98			
4 North O	2.63	8.91	3.94	2.42	10.99	5.22
4 North I	2.21	13.08	6.50			
5 North O	2.15	17.35	8.41	2.39	11.75	5.44
5 North I	2.64	6.14	2.48			
1 South O	2.81	9.65	3.45	2.68	11.96	4.54
1 South I	2.54	14.27	5.64			
4 South O	6.06	8.81	1.47	6.59	10.13	1.56
4 South I	7.12	11.45	1.64			

Table 17. San Antonio Requirements by Luminaire Adjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
3 West O	1.79	9.37	5.47	1.69	11.67	7.27
3 West I	1.59	13.97	9.08			
4 West O	1.60	5.63	3.62	1.59	8.82	5.69
4 West I	1.58	12.00	7.76			
1 East O	1.74	6.34	4.08	1.82	9.88	5.92
1 East I	1.89	13.42	7.76			
2 East O	1.77	9.44	5.56	1.98	12.58	6.68
2 East I	2.18	15.71	7.80			

Table 18. San Antonio Requirements by Luminaire Unadjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
3 West O	2.37	12.44	5.47	2.24	15.50	7.27
3 West I	2.11	18.55	9.08			
4 West O	2.13	7.48	3.62	2.12	11.71	5.69
4 West I	2.10	15.93	7.76			
1 East O	2.31	8.41	4.08	2.41	13.12	5.92
1 East I	2.52	17.82	7.76			
2 East O	2.36	12.54	5.56	2.63	16.70	6.68
2 East I	2.90	20.87	7.80			

Table 19. Houston Requirements by Luminaires Adjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 West O	1.59	5.99	3.90	1.59	6.07	4.20
1 West I	1.59	6.16	4.50			
2 West O	1.11	5.37	4.91	1.13	5.49	4.97
2 West I	1.16	5.61	5.03			
3 West O	1.47	7.32	4.98	1.54	7.23	4.72
3 West I	1.61	7.15	4.45			
3 East O	1.23	6.17	5.03	1.27	5.98	4.73
3 East I	1.30	5.79	4.44			
4 East O	1.20	5.23	4.47	1.20	5.45	4.69
4 East I	1.20	5.67	4.90			
5 East O	1.89	5.66	3.00	1.67	5.44	3.29
5 East I	1.46	5.22	3.58			

Table 20. Houston Requirements by Luminaires Unadjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 West O	1.72	6.49	3.90	1.72	6.58	4.20
1 West I	1.72	6.67	4.50			
2 West O	1.20	5.82	4.91	1.23	5.95	4.97
2 West I	1.26	6.08	5.03			
3 West O	1.59	7.93	4.98	1.67	7.84	4.72
3 West I	1.74	7.75	4.45			
3 East O	1.33	6.69	5.03	1.37	6.48	4.73
3 East I	1.41	6.27	4.44			
4 East O	1.30	5.67	4.47	1.30	5.90	4.69
4 East I	1.30	6.14	4.90			
5 East O	2.05	6.13	3.00	1.81	5.90	3.29
5 East I	1.58	5.66	3.58			

Table 21. Austin Requirements by Segment Adjusted.

<table>
<tr><th>Segment</th><th>Minimum</th><th>Average Illuminance</th><th>Uniformity Ratio</th><th>Minimum Average of Lanes</th><th>Average Illuminance Average of Lanes</th><th>Uniformity Ratio Average of Lanes</th></tr>
<tr><td>1 North O</td><td>4.86</td><td>15.33</td><td>3.15</td><td rowspan="2">4.84</td><td rowspan="2">14.48</td><td rowspan="2">2.99</td></tr>
<tr><td>1 North I</td><td>4.81</td><td>13.62</td><td>2.83</td></tr>
<tr><td>4 North O</td><td>0.67</td><td>5.66</td><td>8.45</td><td rowspan="2">0.63</td><td rowspan="2">6.86</td><td rowspan="2">11.08</td></tr>
<tr><td>4 North I</td><td>0.59</td><td>8.06</td><td>13.72</td></tr>
<tr><td>5 North O</td><td>1.15</td><td>10.99</td><td>9.54</td><td rowspan="2">1.17</td><td rowspan="2">7.54</td><td rowspan="2">6.49</td></tr>
<tr><td>5 North I</td><td>1.19</td><td>4.08</td><td>3.43</td></tr>
<tr><td>1 South O</td><td>1.88</td><td>6.23</td><td>3.31</td><td rowspan="2">1.80</td><td rowspan="2">7.75</td><td rowspan="2">4.34</td></tr>
<tr><td>1 South I</td><td>1.72</td><td>9.27</td><td>5.38</td></tr>
<tr><td>4 South O</td><td>4.27</td><td>7.83</td><td>1.84</td><td rowspan="2">4.60</td><td rowspan="2">8.94</td><td rowspan="2">1.94</td></tr>
<tr><td>4 South I</td><td>4.94</td><td>10.05</td><td>2.04</td></tr>
</table>

Table 22. Austin Requirements by Segment Unadjusted.

<table>
<tr><th>Segment</th><th>Minimum</th><th>Average Illuminance</th><th>Uniformity Ratio</th><th>Minimum Average of Lanes</th><th>Average Illuminance Average of Lanes</th><th>Uniformity Ratio Average of Lanes</th></tr>
<tr><td>1 North O</td><td>5.32</td><td>16.77</td><td>3.15</td><td rowspan="2">5.29</td><td rowspan="2">15.84</td><td rowspan="2">2.99</td></tr>
<tr><td>1 North I</td><td>5.26</td><td>14.91</td><td>2.83</td></tr>
<tr><td>4 North O</td><td>0.89</td><td>7.52</td><td>8.45</td><td rowspan="2">0.84</td><td rowspan="2">9.11</td><td rowspan="2">11.08</td></tr>
<tr><td>4 North I</td><td>0.78</td><td>10.70</td><td>13.72</td></tr>
<tr><td>5 North O</td><td>1.53</td><td>14.60</td><td>9.54</td><td rowspan="2">1.56</td><td rowspan="2">10.01</td><td rowspan="2">6.49</td></tr>
<tr><td>5 North I</td><td>1.58</td><td>5.42</td><td>3.43</td></tr>
<tr><td>1 South O</td><td>2.50</td><td>8.27</td><td>3.31</td><td rowspan="2">2.40</td><td rowspan="2">10.29</td><td rowspan="2">4.34</td></tr>
<tr><td>1 South I</td><td>2.29</td><td>12.31</td><td>5.38</td></tr>
<tr><td>4 South O</td><td>4.67</td><td>8.57</td><td>1.84</td><td rowspan="2">5.04</td><td rowspan="2">9.79</td><td rowspan="2">1.94</td></tr>
<tr><td>4 South I</td><td>5.40</td><td>11.00</td><td>2.04</td></tr>
</table>

Table 23. San Antonio Requirements by Segment Adjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
3 West O	0.71	7.71	10.90	0.82	9.64	11.69
3 West I	0.93	11.57	12.49			
4 West O	0.78	4.75	6.07	0.80	7.18	8.94
4 West I	0.81	9.61	11.81			
1 East O	0.60	5.34	8.87	0.75	8.16	10.56
1 East I	0.90	10.98	12.25			
2 East O	1.07	8.15	7.62	1.20	10.53	8.63
2 East I	1.34	12.92	9.64			

Table 24. San Antonio Requirements by Segment Unadjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
3 West O	0.94	10.24	5.47	1.09	12.80	7.27
3 West I	1.23	15.36	9.08			
4 West O	1.04	6.31	3.62	1.06	9.53	5.69
4 West I	1.08	12.76	7.76			
1 East O	0.80	7.10	4.08	1.00	10.84	5.92
1 East I	1.19	14.58	7.76			
2 East O	1.42	10.82	5.56	1.60	13.99	6.68
2 East I	1.78	17.15	7.80			

Table 25. Houston Requirements by Segment Adjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 West O	1.04	4.46	4.27	0.92	4.53	5.01
1 West I	0.80	4.61	5.75			
2 West O	1.18	4.71	3.99	1.26	4.84	3.86
2 West I	1.33	4.96	3.73			
3 West O	1.47	7.32	4.98	1.54	7.23	4.72
3 West I	1.61	7.15	4.45			
3 East O	1.23	6.17	5.03	1.30	6.10	4.72
3 East I	1.37	6.03	4.41			
4 East O	1.02	5.38	5.25	1.00	5.55	5.55
4 East I	0.98	5.72	5.85			
5 East O	2.21	6.31	2.86	1.83	5.77	3.22
5 East I	1.46	5.22	3.58			

Table 26. Houston Requirements by Segment Unadjusted.

Segment	Minimum	Average Illuminance	Uniformity Ratio	Minimum Average of Lanes	Average Illuminance Average of Lanes	Uniformity Ratio Average of Lanes
1 West O	1.13	4.83	4.27	1.00	4.91	5.01
1 West I	0.87	5.00	5.75			
2 West O	1.28	5.11	3.99	1.36	5.24	3.86
2 West I	1.44	5.38	3.73			
3 West O	1.59	7.93	4.98	1.67	7.84	4.72
3 West I	1.74	7.75	4.45			
3 East O	1.33	6.69	5.03	1.41	6.61	4.72
3 East I	1.48	6.53	4.41			
4 East O	1.11	5.83	5.25	1.09	6.01	5.55
4 East I	1.06	6.20	5.85			
5 East O	2.39	6.84	2.86	1.99	6.25	3.22
5 East I	1.58	5.66	3.58			

Investigation of the Use and Pricing of the I-15 Express Lanes in San Diego

Prepared for
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by

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Pete Kelly is currently a senior attending Brigham Young University located in Provo, Utah. He will be graduating in April 2012 with a Bachelor of Science degree in Civil and Environmental Engineering.

Pete is a national member of the American Society of Civil Engineers as well as a member of the Brigham Young University student chapter where he has been involved in several service opportunities including home building with Habitat for Humanity and improvement of local parks. He has also been involved in the Tutor Outreach to Provo Schools program helping high school students learn mathematics. In addition to his school responsibilities, Pete is a husband and proud father to one daughter. After graduating, he plans to obtain a Master of Engineering degree in Civil Engineering with an emphasis in Urban Transportation Planning. In the future, he would like to work with cities and transit agencies to improve transit service and transportation infrastructure.

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The author would like to express his appreciation to Partha Gupta, Scott Nelson, and Young Jae Cho for their contributions in data collection and analysis.

SUMMARY

This research examined the use and pricing of the I-15 Express Lanes in San Diego County, California. It was found that many travelers were willing to pay a toll in order to obtain relatively small travel time savings (TTS). Most toll-paying travelers saved 1 to 2 minutes using the Express Lanes, while a few travelers saved up to 8 minutes. An average of approximately 14 percent of travelers was willing to pay a toll during the morning peak hour, and 11 percent were willing to pay a toll during the evening peak hour. Due to the fact that many travelers were willing to pay a toll for minimal TTS, it was observed that their value of time (VOT) was much higher than what was found in previous studies. These findings indicate that travelers may have reasons other than travel time savings for using the Express Lanes.

There was considerable variation in toll rates during the morning and afternoon peak hours with tolls ranging from $0.05 to $0.60 per mile. Conversely, off-peak times showed little to no variation. These trends were similar when looking at different days of the week and even from year to year. Therefore, although dynamic tolling can be more difficult to implement, it was useful in regulating traffic during peak periods.

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INTRODUCTION

In the past several decades, the United States has seen a tremendous increase in the number of miles traveled each year. According to the Federal Highway Administration, the number of vehicle miles traveled has more than doubled over the past 30 plus years, going from approximately 1.2 million in 1972 to 3 million in 2009. During this same time, lanes miles have grown very little (*1*). The issues associated with such a growing highway demand are very important to governments, corporations, travelers, and especially to transportation engineers. Among these issues are safety, air quality, economic well being, traffic congestion, and system sustainability. As the demand on our highway systems continues to increase, engineers must work together with their communities to provide innovative solutions that will ensure travelers a safe, convenient, and reliable travel experience.

One such innovative solution that has recently been implemented in several metropolitan areas in the U.S. is the conversion of high occupancy vehicle (HOV) lanes into high occupancy/toll (HOT) lanes. HOV lanes were first introduced as a way to encourage travelers to carpool by allowing them exclusive access to an express lane that would reduce travel time during peak traffic hours. HOV lanes were also designed to accommodate buses and other transit vehicles, as well as motorcycles and certain clean air vehicles in some areas. Since the introduction of these lanes in the United States, many have been underutilized in terms of capacity. In order to utilize these lanes to their full capacity, they may be converted into HOT lanes, which allow single occupancy vehicles (SOVs) to enter for a toll. Many of these HOT lanes have experienced success in terms of achieving higher traffic capacity, including the Interstate-15 (I-15) Express Lanes in San Diego, California. However, the questions remaining to be answered by research include the amount of time SOVs save by using the Express Lanes, the percentage of travelers willing to pay for their use, and the value drivers place on this alternative.

BACKGROUND

Traffic volumes on I-15 currently range between 190,000 and 270,000 on a given day, with commuter delays being an ever present concern. The latest project that the California Department of Transportation (CalTrans) and SANDAG, San Diego’s regional planning agency, have implemented to provide better, faster service is the I-15 Express Lanes project. This project consists of 4 HOT lanes that will eventually span 20 miles of the I-15 corridor from SR-63 to SR-78 in San Diego County. The project is being completed in three segments. The middle segment, which is 8 miles long and runs from SR-56/Ted Williams Parkway to Centre City Parkway, was completed in 2009 and is currently in service. The north segment that will reach SR-78 is scheduled for completion this year, while the south segment, which has already has two reversible HOT lanes in operation, will be expanded to four by 2012 (*2*) (Figure 1). Similar to other HOT lanes, they are being built in the median of the interstate and are physically separated from the general purpose lanes (GPLs) by concrete barriers. Having the Express Lanes physically separated from the GPLs reduces the likelihood of toll violations and provides an added measure of safety for travelers. Vehicles are permitted to enter using intermediate access points and direct access ramps (DARs) at certain locations along the corridor. One unique feature of these lanes is the movable center barrier, which is normally configured to allow two lanes of traffic in each direction, but can be moved by a specialized vehicle to allow up three to lanes in the same direction during peak hours. Upon completion, the Express Lanes will also provide service to a high frequency bus rapid transit (BRT) system via the DARs. This system is designed to provide travelers with the highest level of public transit service possible.

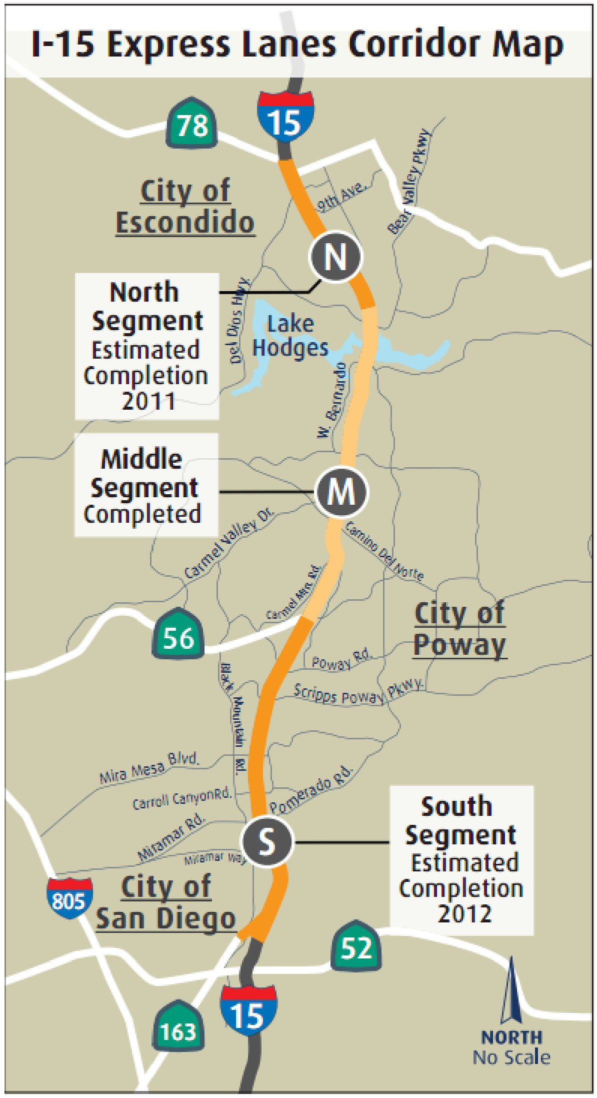

Figure 1. I-15 Express Lanes Corridor Map.

On the Express Lanes vehicles with two or more occupants (HOV2+), motorcycles, transit vehicles, and certain clean air vehicles are permitted to enter free of charge. Solo drivers who wish to obtain access have the option entering for a toll. Prior to using the Express Lanes, they must create an account with California's FasTrak program, which is used on toll roads throughout the entire state. The account is then linked to an electronic transponder that is installed in the windshield of the driver's vehicle. When driving onto the Express Lanes through an intermediate access point or DAR, the transponder will be detected by a FasTrak electronic toll collection machine, and the driver's account will be charged the appropriate toll amount (*2*) (Figure 2).

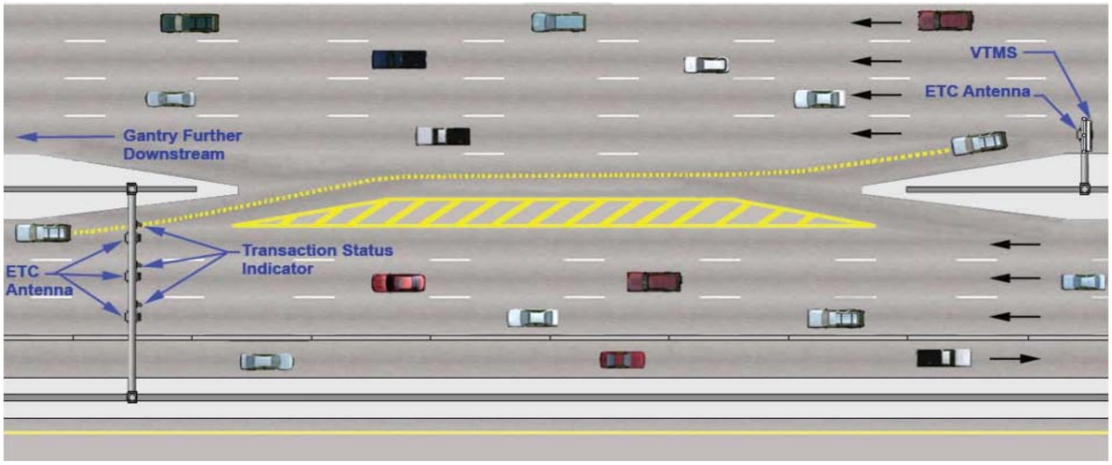

Figure 2. Intermediate Access Point Diagram.

When HOT lanes were first introduced in California, the tolling program was known as ExpressPass. ExpressPass customers paid a flat monthly fee for unlimited use that started out at $50 and eventually climbed to $70 before the program was renamed as FasTrak and began using a dynamic tolling system. With this system, tolls are charged on a per-mile basis for individual trips in the Express Lanes, and the toll price varies based on current traffic conditions to manage congestion. The toll price for an individual trip can range from $0.50 to $8.00, although for most travelers the maximum toll paid is $4.00. SOVs wishing to enter are able to see the current toll amount displayed on variable message signs (VMSs) just upstream of each intermediate access point. The purpose of dynamic tolling is to manage congestion in real-time so that free-flow speeds may be maintained at all times in the Express Lanes (*2*). This method has been met with some criticism in that travelers do not know what they can expect to pay until they arrive at the facility. Another method called variable tolling has been implemented in other HOT lane systems including the Katy Freeway managed lanes in Houston, TX. In a variable tolling system the tolls differ throughout the day, but are pre-determined on a set schedule based on long term travel patterns instead of real time traffic conditions. The most favorable element of variable tolling is the ability of travelers to know what toll they can expect to pay before traveling.

RESEARCH OBJECTIVES

The purpose of doing this research has been to measure how much time is saved by travelers using the Express Lanes, to understand how they value their time and to understand what portion of them are willing to pay for Express Lane service. Also important, is understanding whether the current tolling system is the most effective option. To answer these questions, several specific objectives were pursued during the course of research. They are as follows:

- Evaluate value of time (VOT).
    - Also referred to as cost of travel time savings, VOT is the toll amount the traveler pays for Express Lane use in terms of how much time is saved when compared to driving the same distance in the GPLs. For example, if a traveler pays $1.00 and he saves 1 minute, his VOT is $60/hr.

- Evaluate the percentage of travelers willing to pay (%WTP) for Express Lane use.
  - %WTP refers to the percentage of total travelers who use the Express Lanes and are charged a toll at a given time.
- Show how tolls vary based on time of day.
  - An important question to be answered is whether dynamic tolling has any considerable advantage over variable tolling in this scenario. Knowing the variance of tolls in different windows of the day can reveal whether tolls are generally the same, or vary greatly at certain times. If little variance is found in a particular time window, dynamic tolling has little to no advantage during that time. Conversely, if there is high variance for a given window it can be concluded that during that time there were highly concentrated surges of traffic, which are best managed with dynamic tolling.

METHODS

This section describes how the objectives listed previously were accomplished. The process involved data collection, data reduction, and data analysis.

Data Collection

The period of interest for collecting and analyzing data was April 2009 to June 2010. It is good to have at least one year of data when analyzing traffic patterns as it accounts for possible seasonal changes.

VDS Data

Vehicle Detector Stations (VDSs) were used to collect traffic speed and volume data. VDS is a logical grouping of detectors of a particular type at a location. Each VDS contains speed and flow information of all the lanes in a particular direction at that station. The VDS data are the property of CalTrans and are available to the public through the CalTrans website (*3*). All the VDS numbers of a particular Highway of California at a given time can be found at this website.

The speed and flow data used in this research have been obtained by selecting District 11, San Diego County, and I-15. Using this website, data from all mainline GPL and HOT lane VDSs located in the study section were obtained. The total number of VDSs on the GPLs is 15 northbound and 14 southbound. There is one VDS on the northbound HOT lanes and one VDS on the southbound HOT lanes.

Toll Payment Data

Toll payment data were provided by SANDAG. They provided data for each traveler who paid to use the FasTrak lanes from February 2009 to June 2010. The total amount of transactions is approximately 2.5 million for that time period. To make the results more uniform, February and March 2009 data were not analyzed due to a change in tolling scheme. Starting in mid-March 2009, tolls were charged on a per mile basis. The toll data include the start plaza, which refers to the point where the traveler was first detected, and the end plaza, which is the point where a traveler was last detected. In addition, the data also contain information on the cost of the toll for each traveler and the time the traveler was detected at the start plaza and at the end plaza.

Data Reduction

Data reduction involved calculating the average GPL speed, the average GPL volume, and the average HOT lane speed value for each section of the highway. Since 5 minute time intervals were used to extract VDS data for weekday morning, weekday afternoon and weekends, the average toll amount and the average number of paying travelers was also computed in 5 minute intervals. For convenience, southbound tolling plazas are referred to numerically as 1001–1008 and northbound tolling plazas are referred to as 2001–2009. Plaza locations can be seen in Figures 3 and 4.

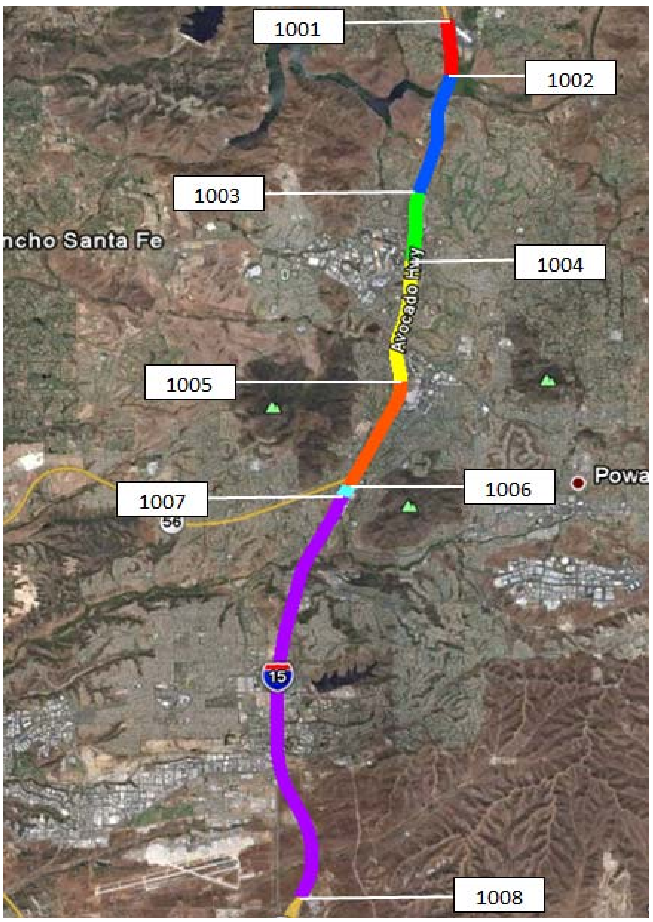

Figure 3. Southbound Tolling Plaza Locations.

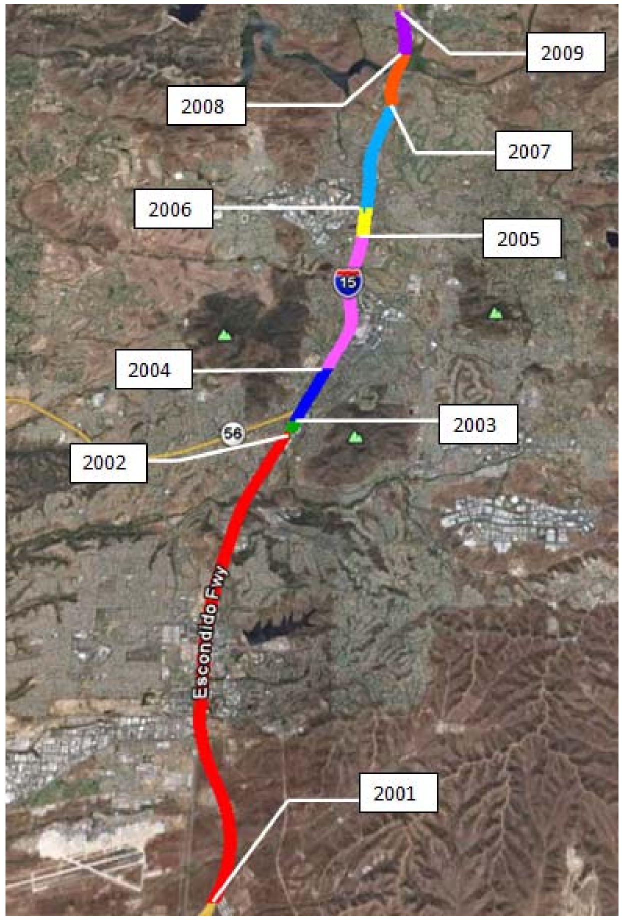

Figure 4. Northbound Tolling Plaza Locations.

For speeds, readings of zero mph or less, or 100 mph or greater were removed from the analysis. The assumption was that if an LDS (raw loop detector data) of a VDS recorded a speed of less than zero or speeds more than 100 mph, then the detector had a malfunction. A volume of less than zero was also treated as an error in VDS data. The detector data were then averaged (weighted by number of vehicles) for each section of the freeway (for example section 1001 to 1002). The matrix outputs included the average GPL speed and volume and the average HOT lane speed and volume. A similar procedure was performed to examine the toll data. Since there is only one VDS per HOT lane, VDS data were an insufficient means of obtaining HOT lane speeds and volumes. HOT lane speeds and volumes were alternatively obtained using the time stamp information included in the toll data and the distance between stations. In some cases, time stamp errors were observed resulting in travelers passing between stations in unreasonably small amounts of time. In order to compensate for time stamp errors, speeds over 100 mph were eliminated from Express Lane speed data. For a small number of 5-minute periods, no toll transactions were observed; but some speed readings on HOT lanes were associated with those periods (from HOVs). These speed values were removed from calculation of travel time savings as no toll paying travelers were saving time during those periods.

Data Analysis

The average GPL speeds and volumes and the average HOT lane speeds and toll paying vehicle volumes were used to compute travelers' value of time. The average speeds and volumes were calculated over the length of the section(s) of the highway being studied for a given 5-minute period of each day.

For toll data, the first and last toll stations for each vehicle were recorded. The volume of toll paying travelers for a particular section was determined by equation 1 for northbound trips. Similar equations were used for southbound trips but with data from stations 2001 to 2009.

$$V_{Toll\ (i \rightarrow j)} = \sum_{p=1001}^{i} \sum_{q=j}^{1008} V_{p \rightarrow q} \qquad \text{(Equation 1)}$$

where:

I	=	Start toll plaza for the section under consideration.
J	=	End toll plaza for the section under consideration.
$V_{Toll\ (i \rightarrow j)}$	=	Volume of toll paying vehicles traveling through section $i \rightarrow j$.
p, q	=	counter.

For example, the volume of toll paying vehicles within section 1003 to 1004 is the sum of the volumes of toll paying vehicles with start plaza 1001, 1002, or 1003, and end plaza 1004, 1005, 1006, 1007, or 1008.

The average volume of toll paying travelers over the entire length of the HOT lane in the southbound direction was found by using Equation 2.

$$V_{Toll\ avg} = \frac{V_{1001 \rightarrow 1002} + V_{1002 \rightarrow 1003} + \cdots + V_{1007 \rightarrow 1008}}{7} \qquad \text{(Equation 2)}$$

To compute the travelers' willingness to pay for travel time savings, the percentage of the travelers willing to pay (WTP) was determined by Equation 3.

$$\%WTP = \frac{V_{Toll\ avg}}{Average\ GPL\ Volume + V_{Toll\ avg}} \qquad \text{(Equation 3)}$$

Average travel time savings on a section for each 5 minute period was calculated by subtracting the weighted average travel time on GPL lanes from the weighted average travel time on HOT lanes (see Equation 4, 5, 6).

$$TTS\ (hrs) = \frac{(TT\ on\ GPL - TT\ on\ HOT)min}{60\ min/hr} \qquad \text{(Equation 4)}$$

Where: TTS is Travel Time Savings

Travel Time on GPL:

$$TT\ on\ GPL\ = \frac{Length\ traveled\ by\ the\ toll\ paying\ traveler}{Weighted\ Average\ GPL\ Speed} \qquad \text{(Equation 5)}$$

Travel Time on HOT:

$$TT\ on\ HOT = \frac{Length\ traveled\ by\ the\ toll\ paying\ traveler}{Weighted\ Average\ HOT\ Speed} \qquad \text{(Equation 6)}$$

TTS for each trip was determined based on what sections that traveler traveled at what time. To calculate the VOT for that trip, the toll amount the traveler paid was divided by this TTS (see Equation 7).

$$VOT\ (\$/hr) = \frac{Toll}{TTS} \qquad \text{(Equation 7)}$$

For any TT or TTS value, corresponding toll volume was considered as its frequency. For TT and TTS plots, travel time for the entire length of the HOT lane was used.

RESULTS

This section contains the results of data analysis. Seven different periods were analyzed:

- Monday-Thursday morning.
- Monday-Thursday morning peak.
- Monday-Thursday afternoon.
- Monday-Thursday afternoon peak.
- Friday morning.
- Friday afternoon.
- Weekends.

Monday-Thursday Morning (5:30 AM – 12:00 PM)

In this period it was found that about 80 percent of travelers using the GPLs spent 15 minutes or less to travel the entire length of the study area, while over 95 percent of travelers using the HOT lanes spent 15 minutes or less to travel the same length. The median toll paid by Express Lane users was $1.20, while the median toll-per-mile paid was $0.15. The median TTS for Express Lane users was 1.16 minutes. The median VOT was $49.22/hr, and 7.22 percent of travelers were willing to pay for Express Lane service (not including HOVs). Results are shown in Figures 5–9.

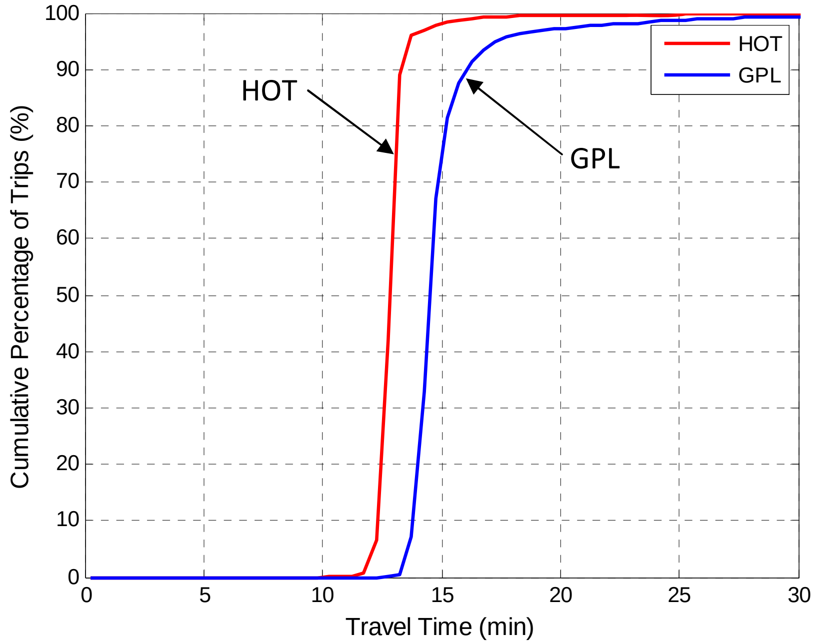

Figure 5. Mon-Thu Morning Cumulative Travel Time.

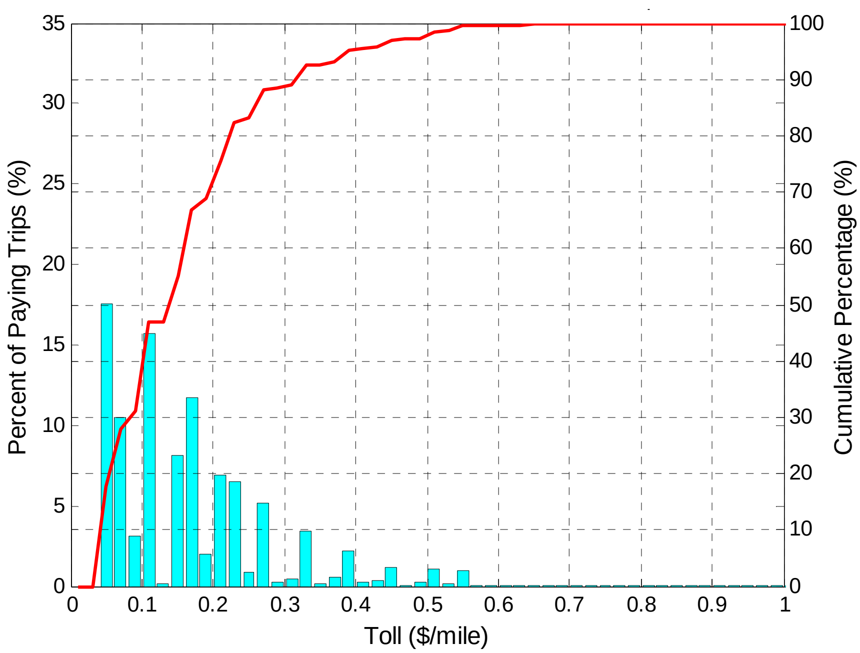

Figure 6. Mon-Thu Morning Toll-Per-Mile Distribution.

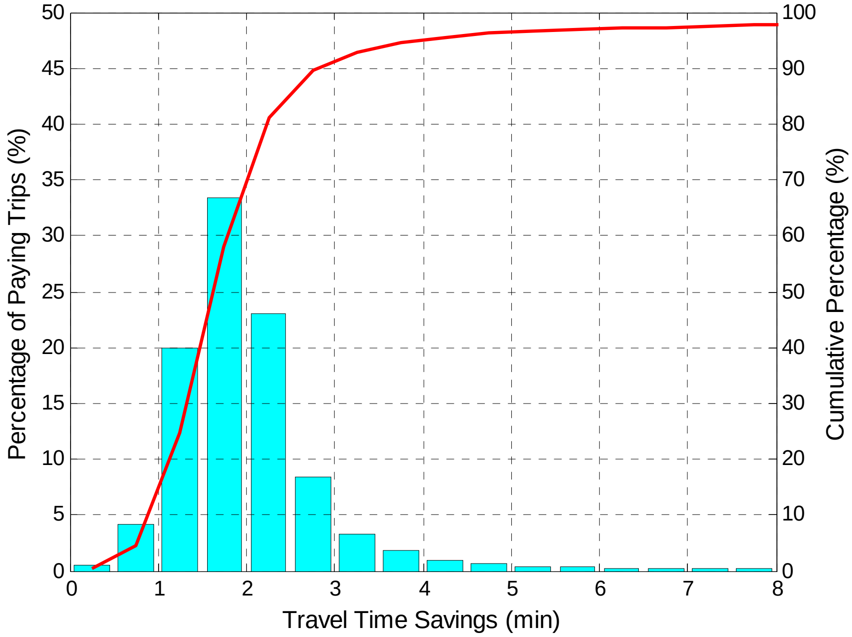

Figure 7. Mon-Thu Morning Travel Time Savings Distribution.

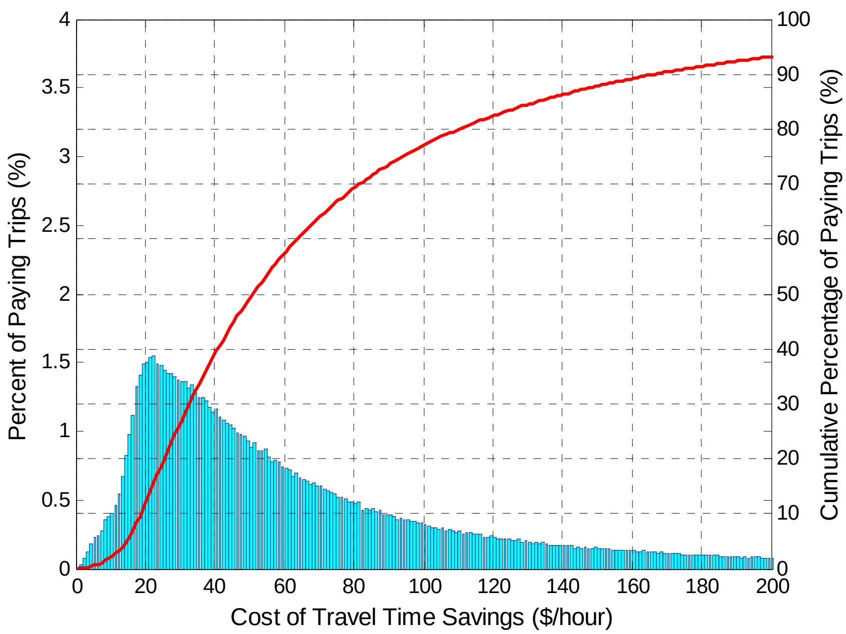

Figure 8. Mon-Thu Morning Value of Time Distribution.

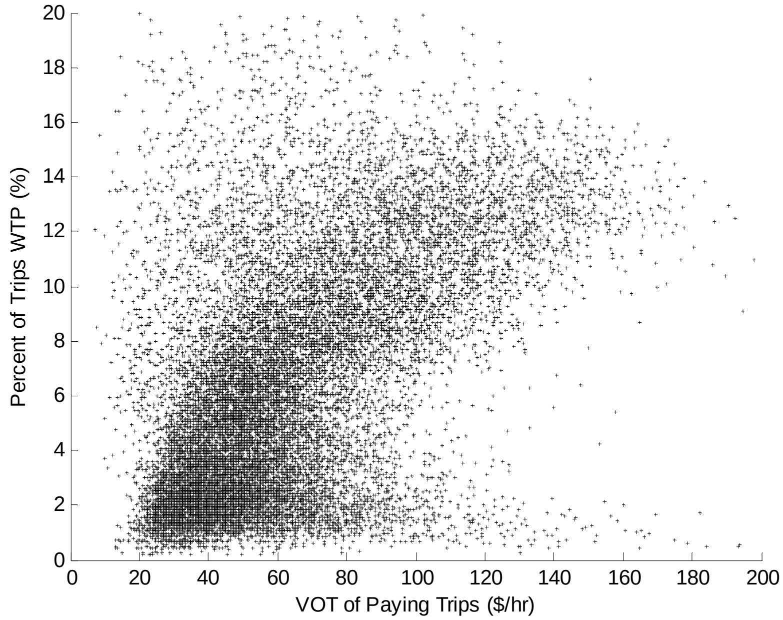

Figure 9. Mon-Thu Morning VOT vs.WTP.

Monday-Thursday Morning Peak (7:30 – 8:30 AM)

In this period it was found that about 60 percent of travelers using the GPLs spent 15 minutes or less to travel the entire length, while more than 95 percent of travelers using the HOT lanes spent 15 minutes or less to travel the same length. The median toll paid by Express Lane users was $2.00, and the median toll-per-mile paid was $0.21. The median TTS for Express Lane users was 1.05 minutes. The median VOT was $82.42/hr, and 14.29 percent of travelers were willing to pay for Express Lane service (not including HOVs). Results are shown in Figures 10–14.

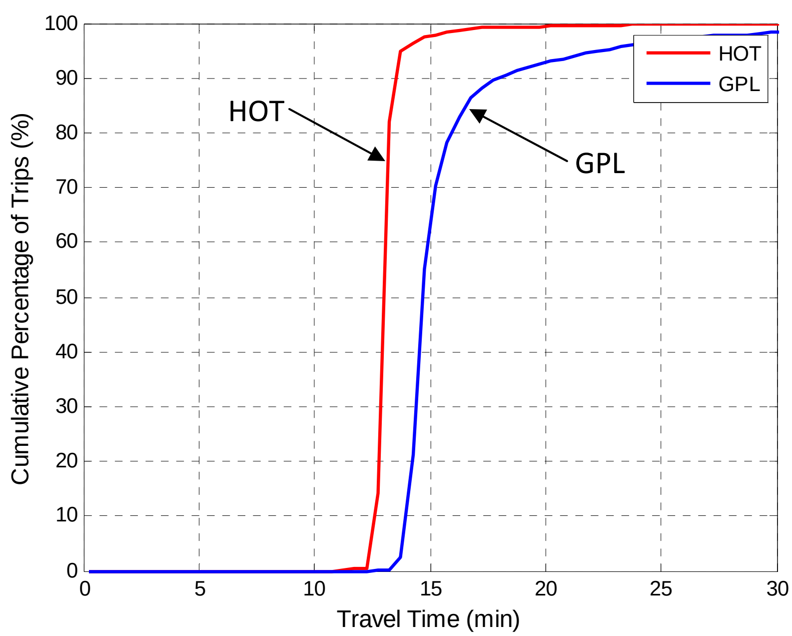

Figure 10. Mon-Thu Morning Peak Cumulative Travel Time.

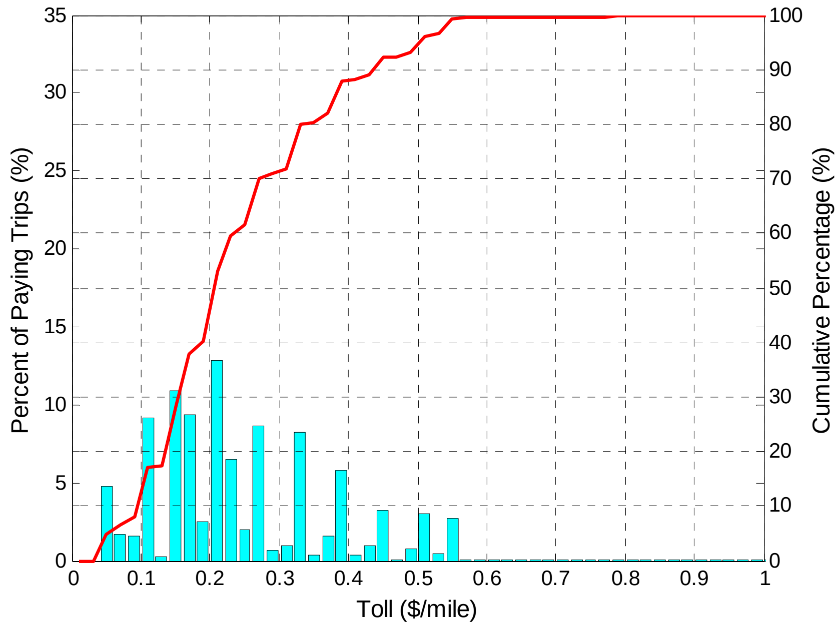

Figure 11. Mon-Thu Morning Peak Toll-Per-Mile Distribution.

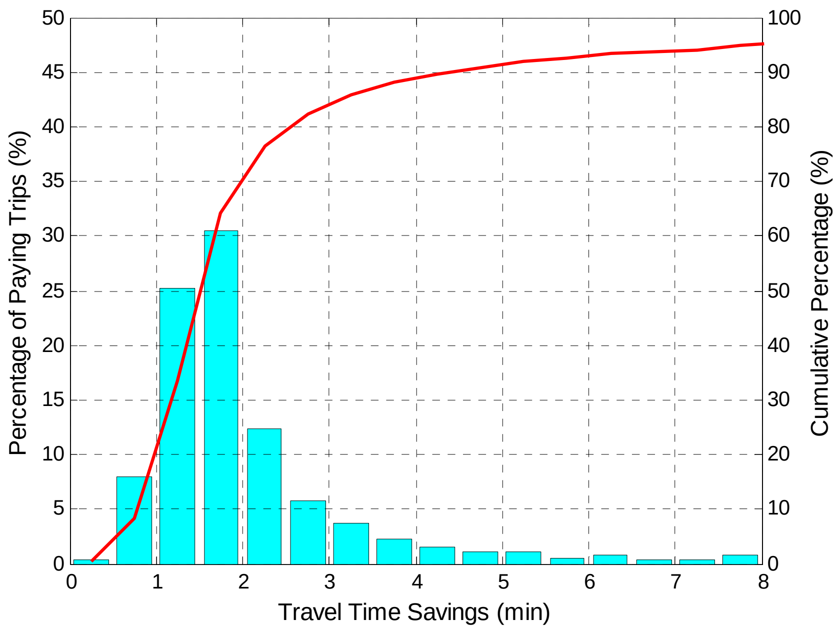

Figure 12. Mon-Thu Morning Peak Travel Time Savings Distribution.

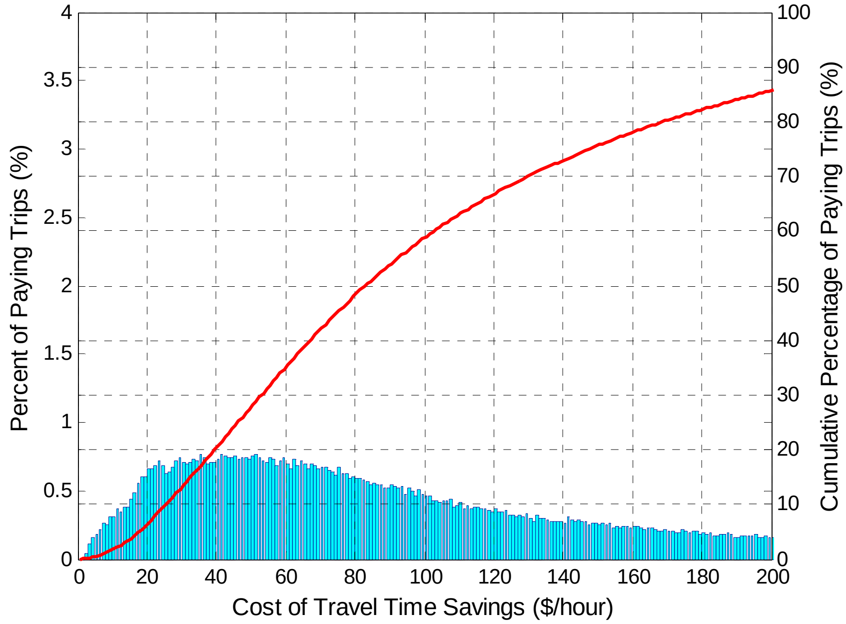

Figure 13. Mon-Thu Morning Peak Value of Time Distribution.

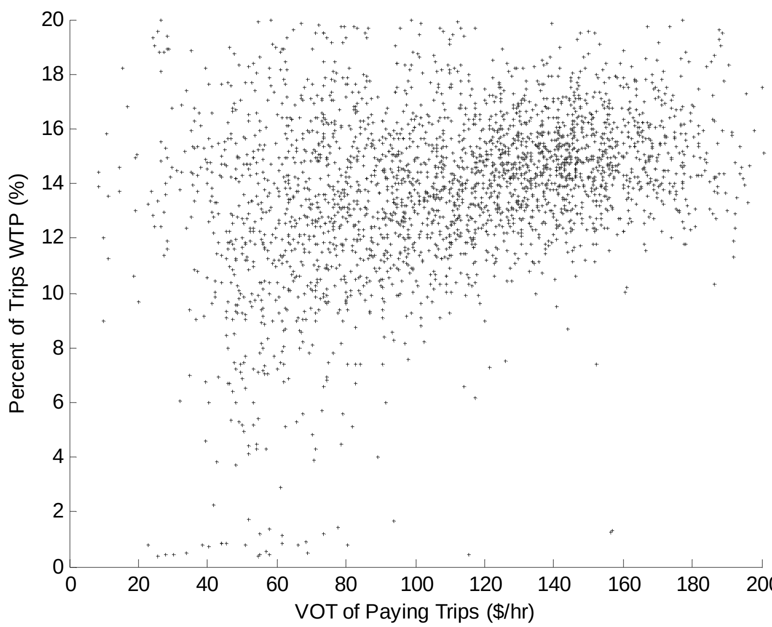

Figure 14. Mon-Thu Morning Peak VOT vs.WTP.

Monday-Thursday Evening (1:00 – 7:00 PM)

In this period it was found that about 70 percent of travelers using the GPLs spent 15 minutes or less to travel the entire length, while more than 95 percent of travelers using the HOT lanes spent 15 minutes or less to travel the same length. The median toll paid by Express Lane users was $1.40, and the median toll-per-mile paid was $0.18. The median TTS for Express Lane users was 1.11 minutes. The median VOT was $54.39/hr, and 6.9 percent of travelers were willing to pay for Express Lane service (not including HOVs). Results are shown in Figures 15–19.

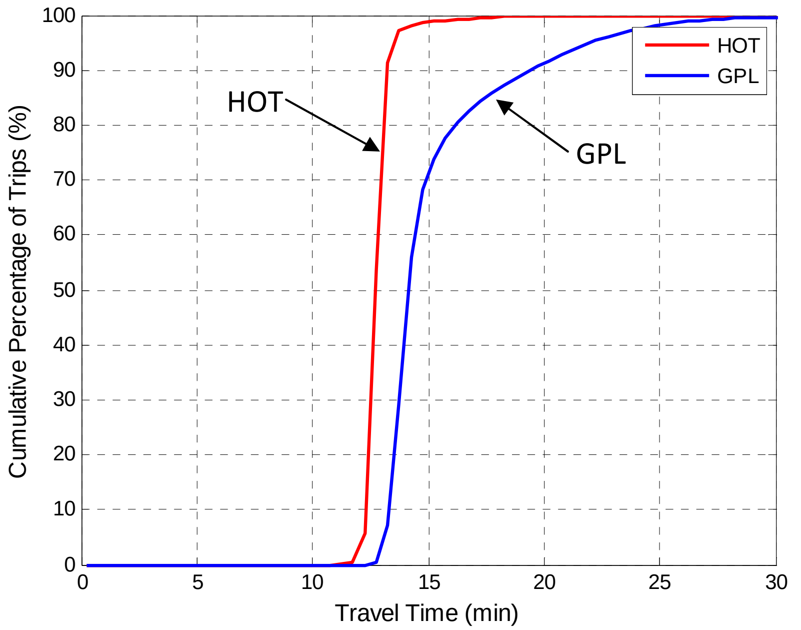

Figure 15. Mon-Thu Afternoon Cumulative Travel Time.

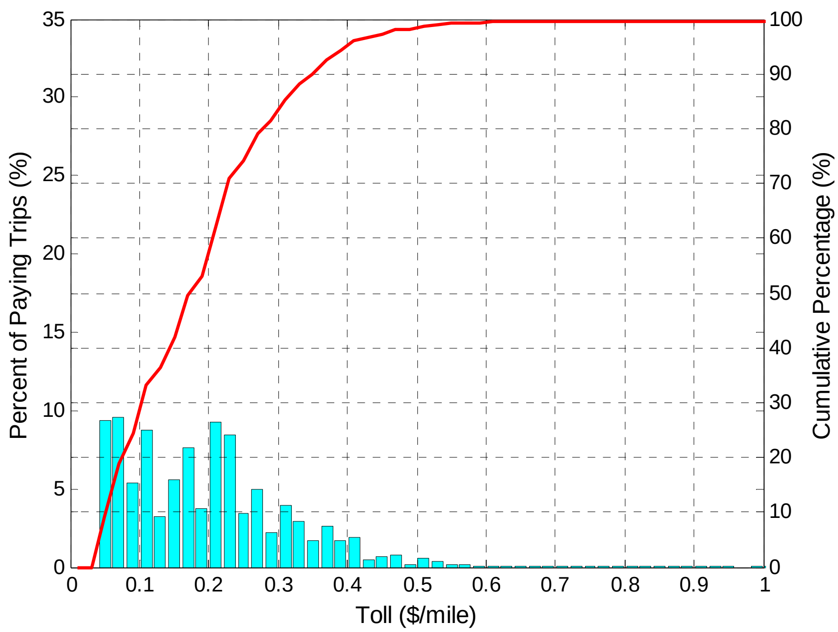

Figure 16. Mon-Thu Afternoon Toll-Per-Mile Distribution.

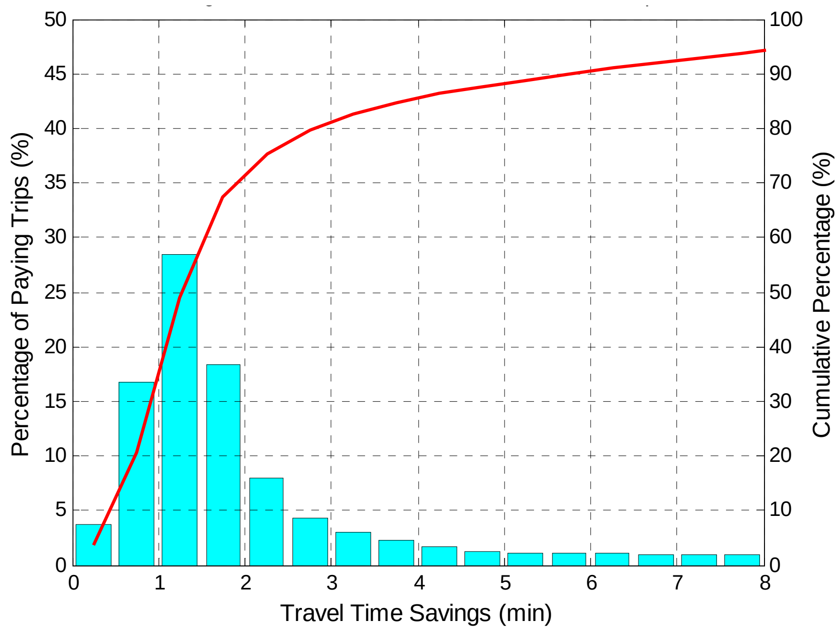

Figure 17. Mon-Thu Afternoon Travel Time Saving Distribution

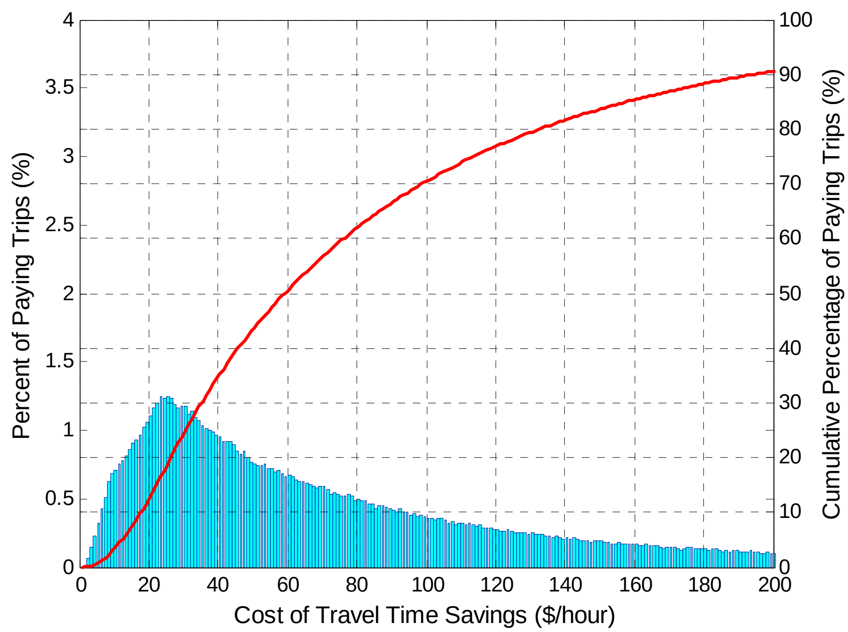

Figure 18. Mon-Thu Afternoon Value of Time Distribution

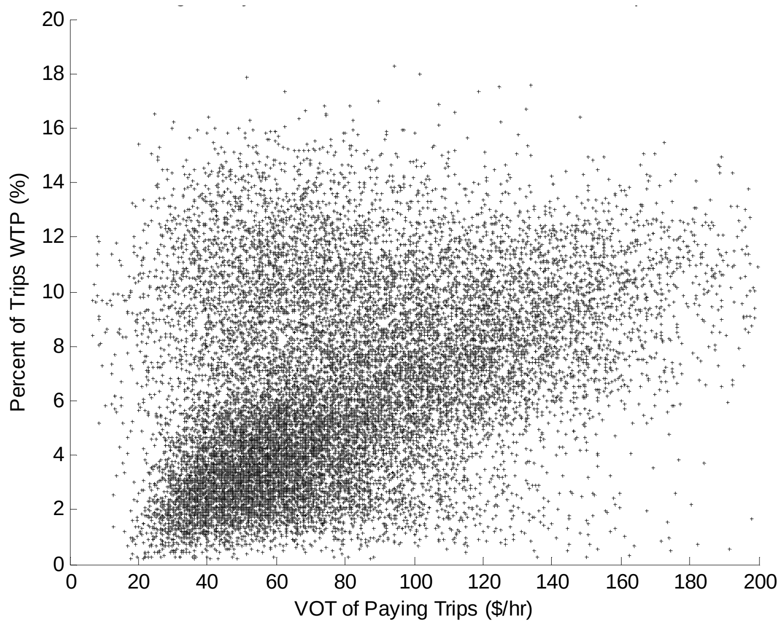

Figure 19. Mon-Thu Afternoon VOT vs.WTP.

Monday-Thursday Evening Peak (5:00 – 6:00 PM)

In this period it was found that only 30 percent of travelers using the GPLs spent 15 minutes or less to travel the entire length, while more than 95 percent of travelers using the HOT lanes spent 15 minutes or less to travel the same length. The median toll paid by Express Lane users was $2.40, and the median toll-per-mile paid was $0.28. The median TTS for Express Lane users was 1.55 minutes. The median VOT was $71.41/hr, and 11.06 percent of travelers were willing to pay for Express Lane service (not including HOVs). Results are shown in Figures 20-24.

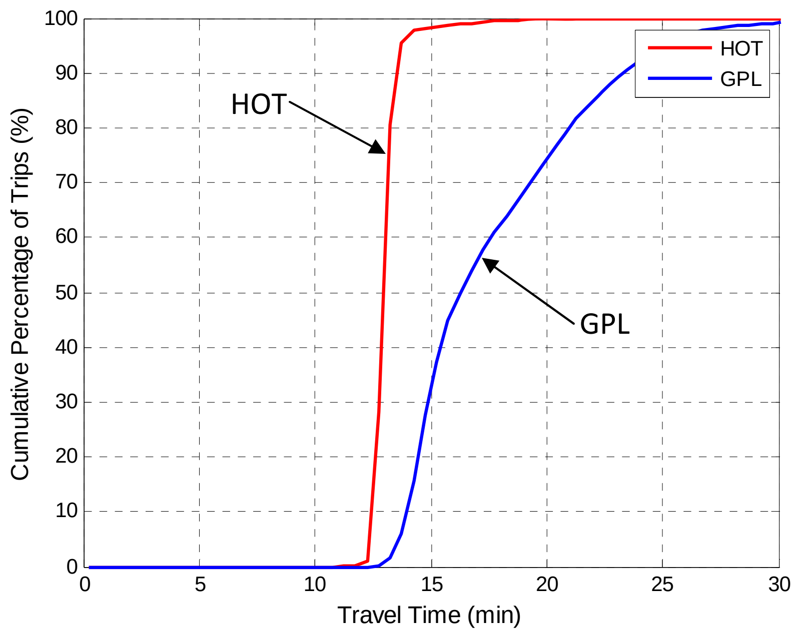

Figure 20. Mon-Thu Afternoon Peak Cumulative Travel Time.

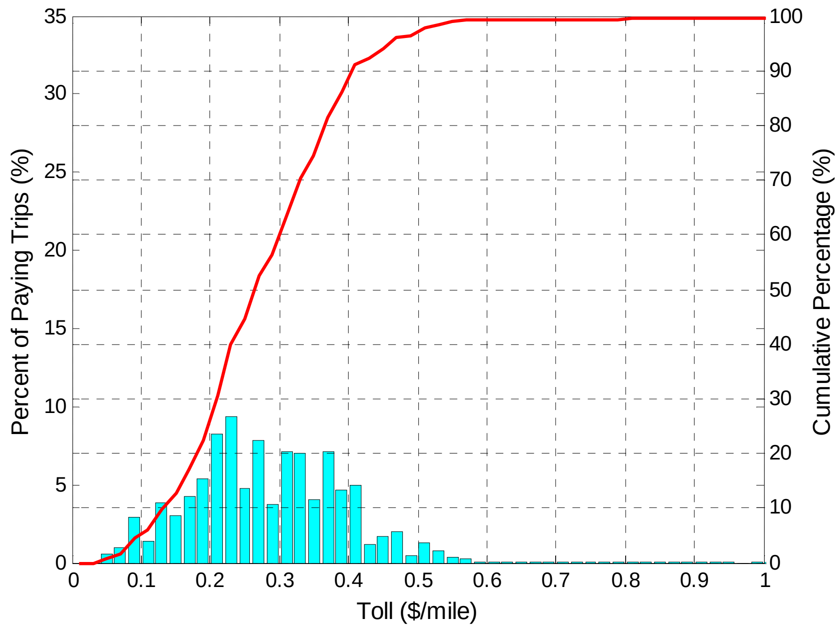

Figure 21. Mon-Thu Afternoon Peak Toll-Per-Mile Distribution.

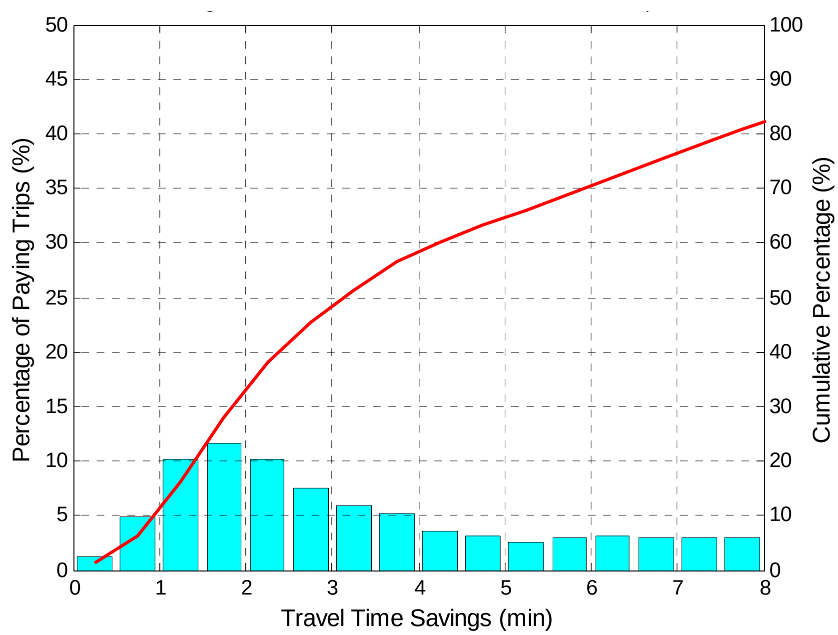

Figure 22. Mon-Thu Afternoon Peak Travel Time Savings Distribution.

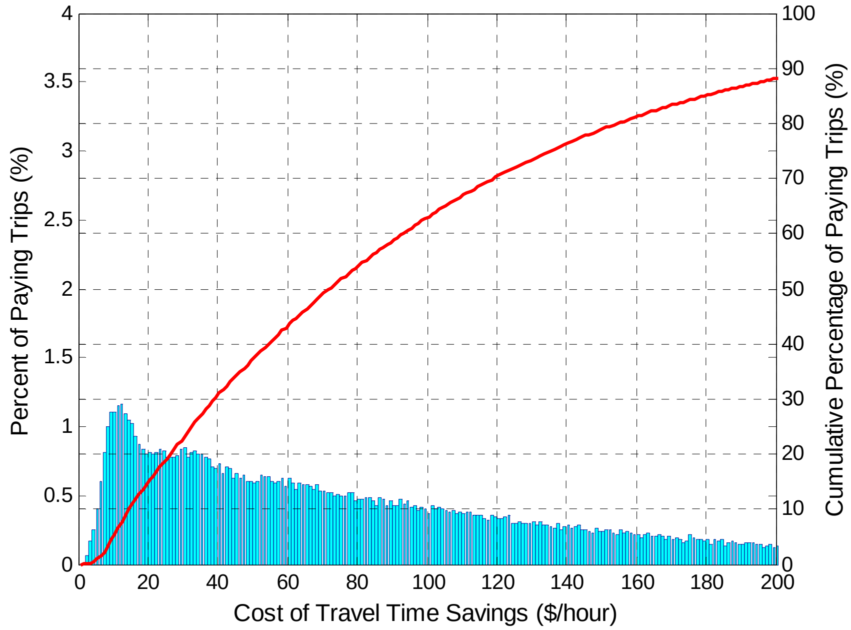

Figure 23. Mon-Thu Afternoon Peak Value of Time Distribution.

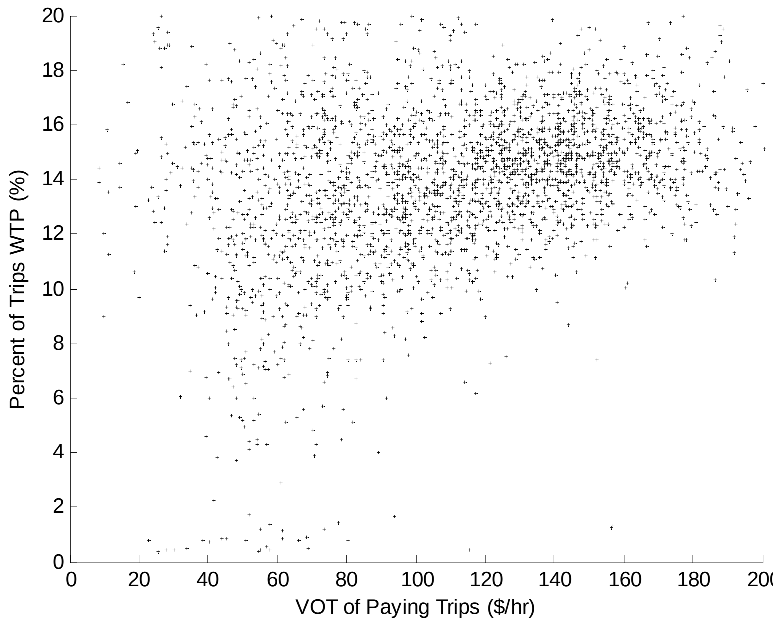

Figure 24. Mon-Thu Afternoon Peak VOT vs. WTP.

Friday Morning (5:45 – 11:00 AM)

In this period it was found that about 80 percent of travelers using the GPLs spent 15 minutes or less to travel the entire length, while all travelers using the HOT lanes spent 15 minutes or less to travel the same length. The median toll paid by Express Lane users was $0.80, and the median toll-per-mile paid was $0.11. The median TTS for Express Lane users was 1.13 minutes. The median VOT was $43.49/hr, and 6.82 percent of travelers were willing to pay for Express Lane service (not including HOVs). Results are shown in Figures 25–29.

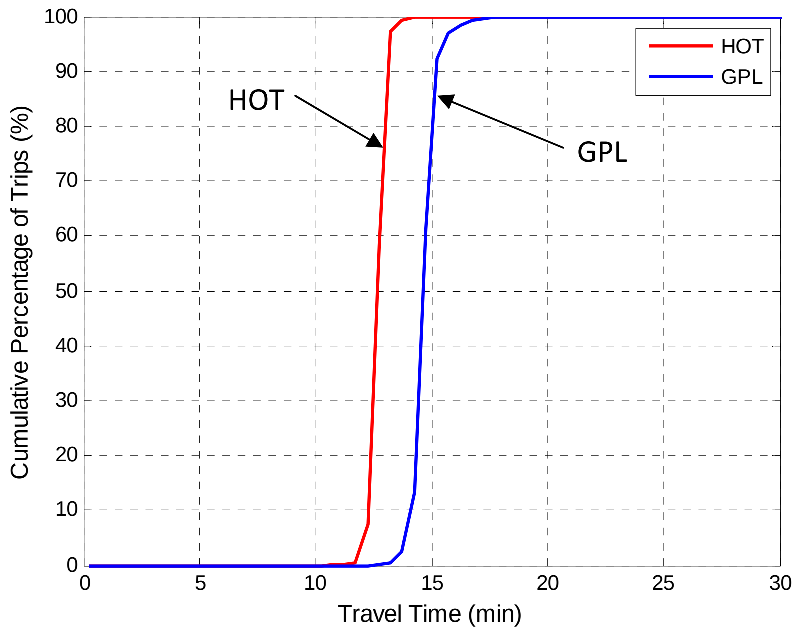

Figure 25. Friday Morning Cumulative Travel Time.

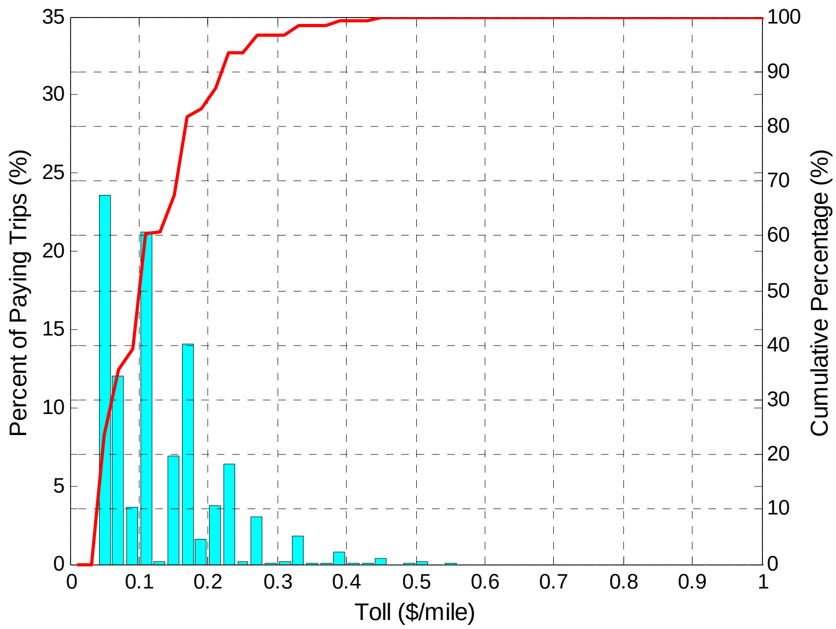

Figure 26. Friday Morning Toll-Per-Mile Distribution.

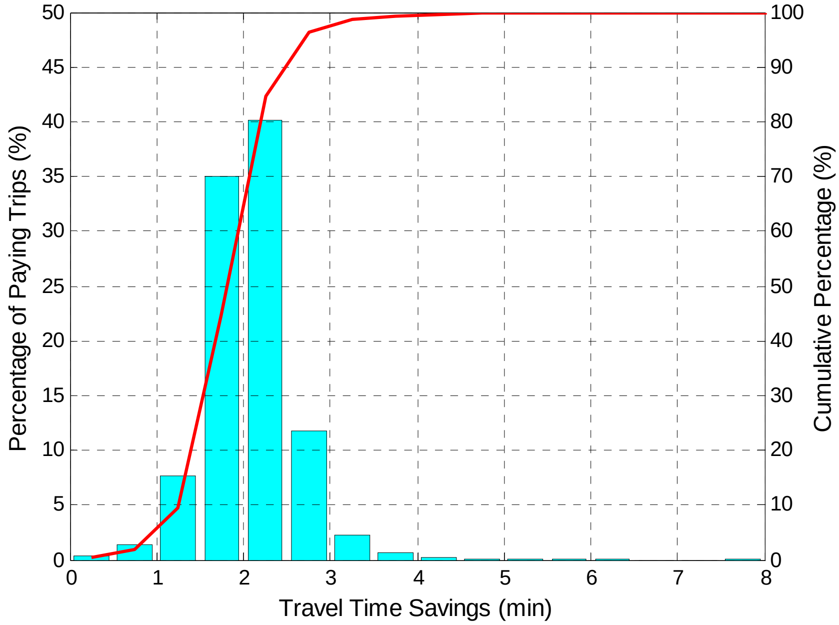

Figure 27. Friday Morning Travel Time Savings Distribution.

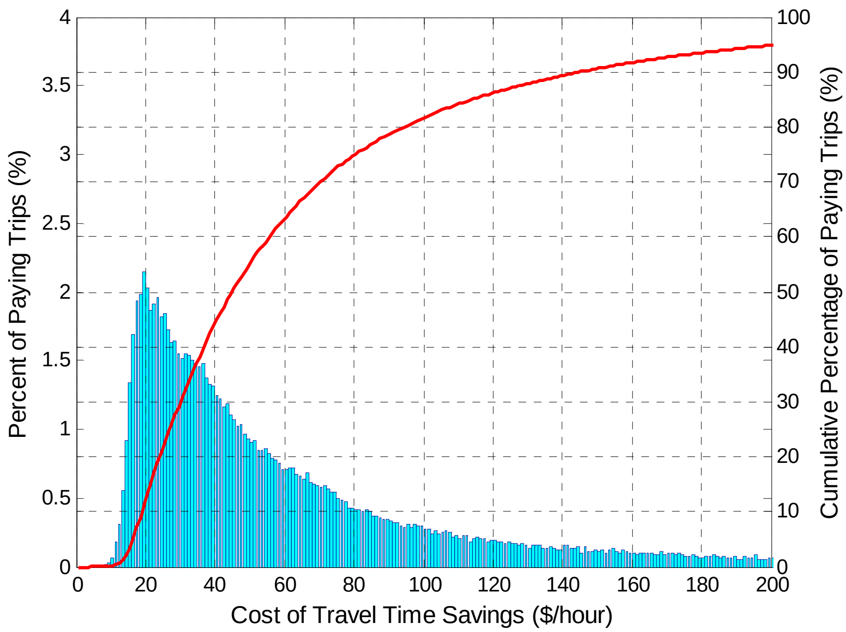

Figure 28. Friday Morning Value of Time Distribution.

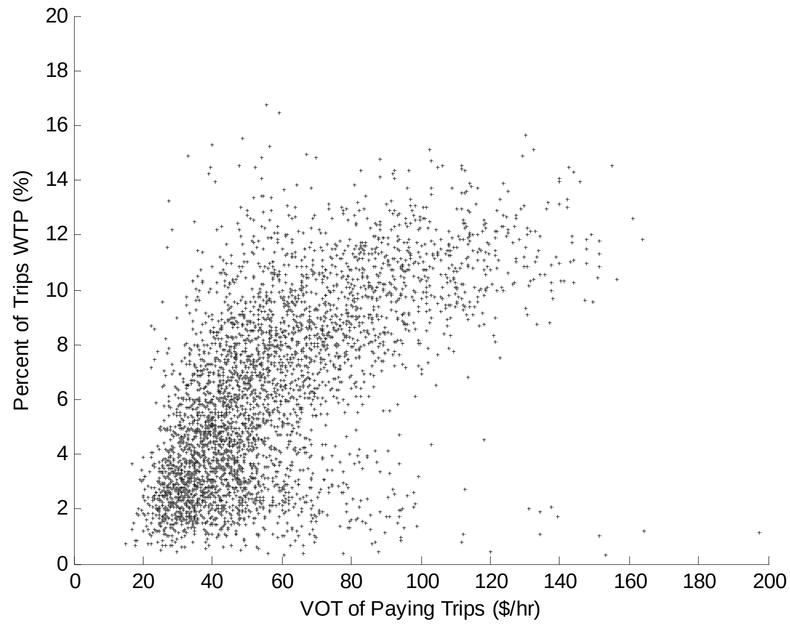

Figure 29. Friday Morning VOT vs.WTP.

Friday Evening (5:00 – 10:00 PM)

In this period it was found that about 65 percent of travelers using the GPLs spent 15 minutes or less to travel the entire length, while about 95 percent of travelers using the HOT lanes spent 15 minutes or less to travel the same length. The median toll paid by Express Lane users was $1.40, and the median toll-per-mile paid was $0.20. The median TTS for Express Lane users was 1.29 minutes. The median VOT was $32.14/hr, and 4.88 percent of travelers were willing to pay for Express Lane service (not including HOVs). Results are shown in Figures 30–34.

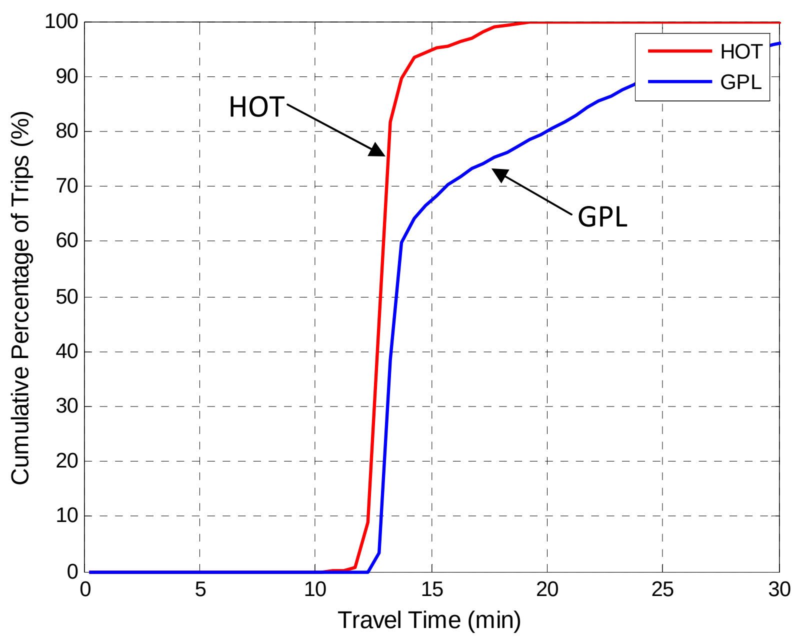

Figure 30. Friday Evening Cumulative Travel Time.

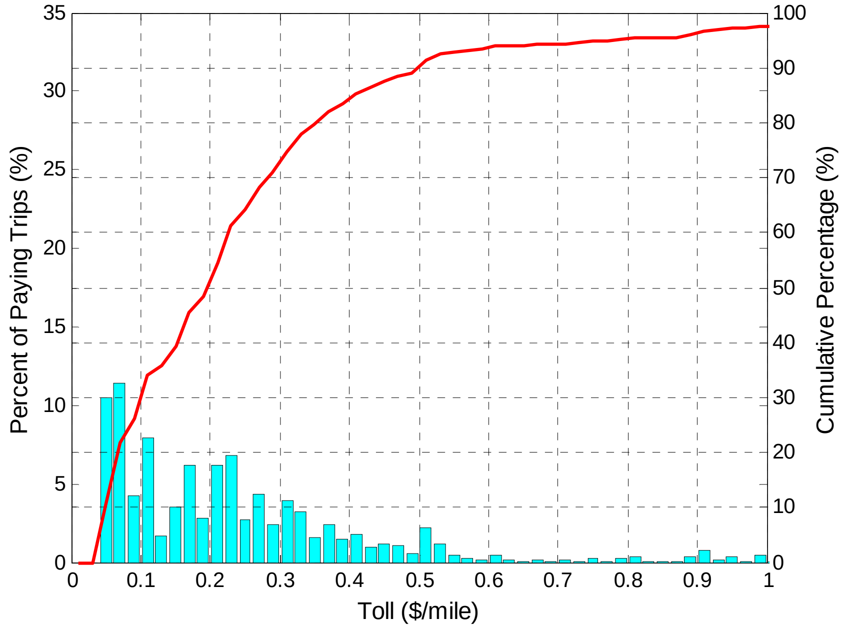

Figure 31. Friday Evening Toll-Per-Mile Distribution.

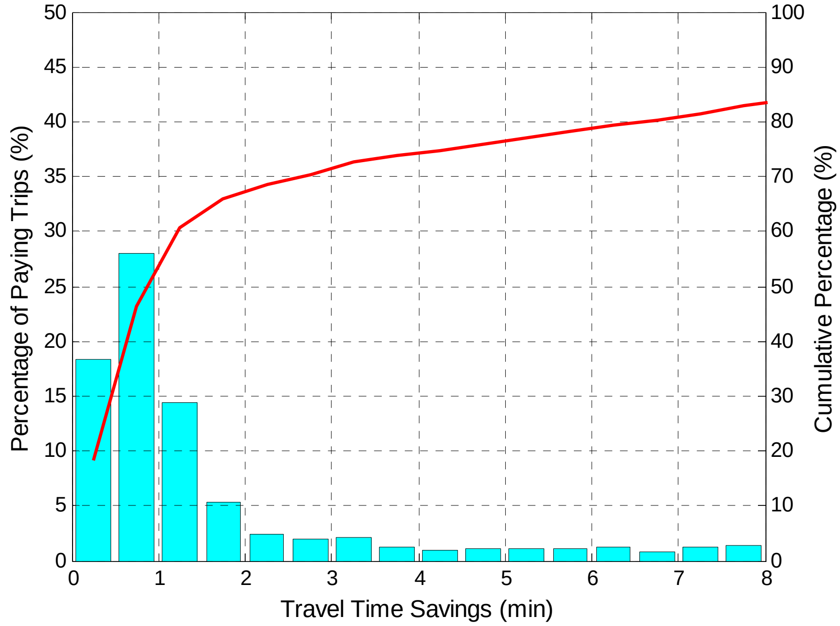

Figure 32. Friday Evening Travel Time Savings Distribution.

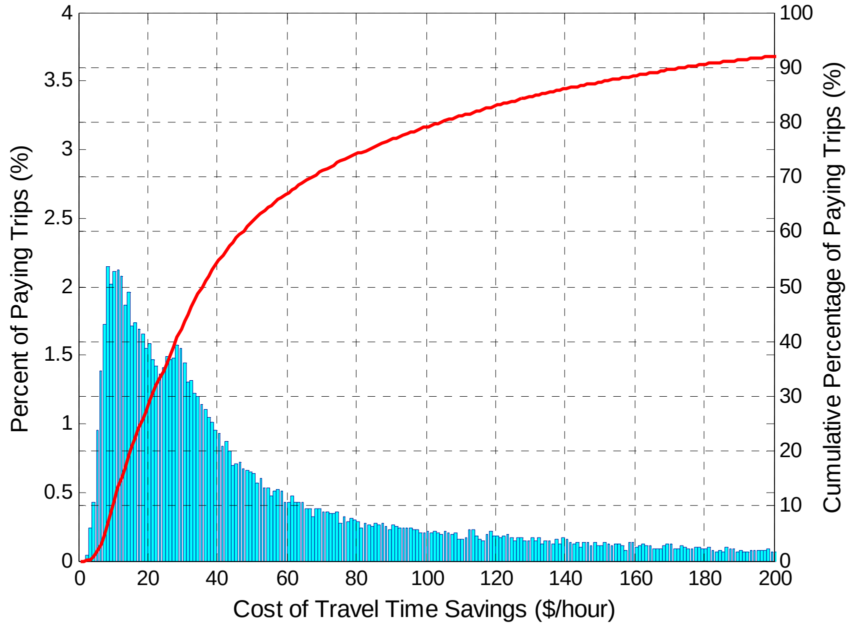

Figure 33. Friday Evening Value of Time Distribution.

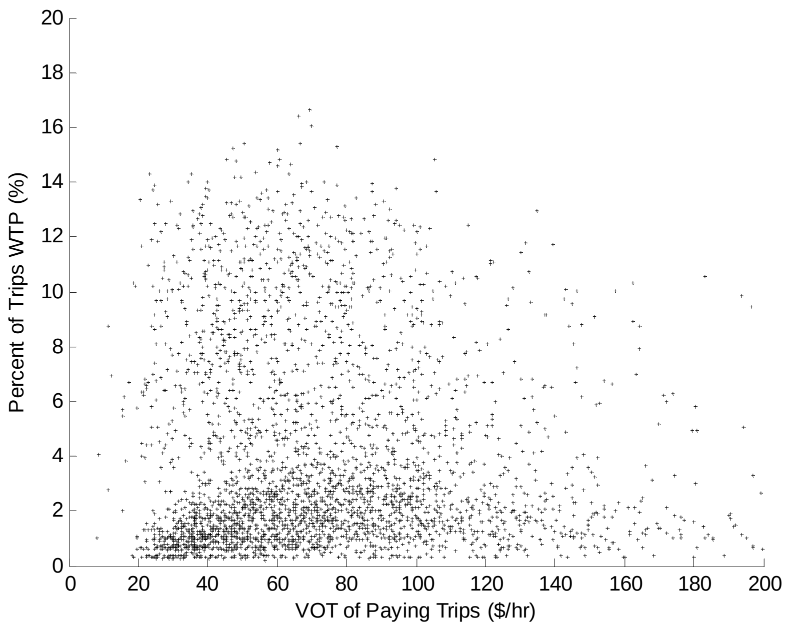

Figure 34. Friday Evening VOT vs.WTP.

Weekends (5:00 PM Friday – 5:00 AM Monday)

In this period it was found that about 95 percent of all travelers spent 15 minutes or less to travel the entire length. The median toll paid by Express Lane users was $0.50, and the median toll-per-mile paid was $0.10. In this case, TTS and VOT were insignificant compared to weekday periods, and only 1.49 percent of travelers were willing to pay for Express Lane service (not including HOVs). Results are shown in Figures 35–39.

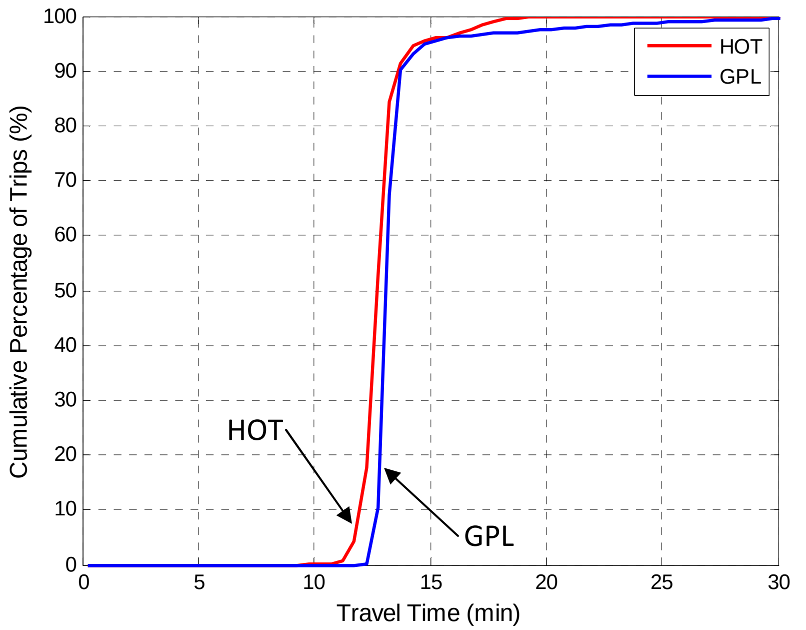

Figure 35. Weekend Cumulative Travel Time.

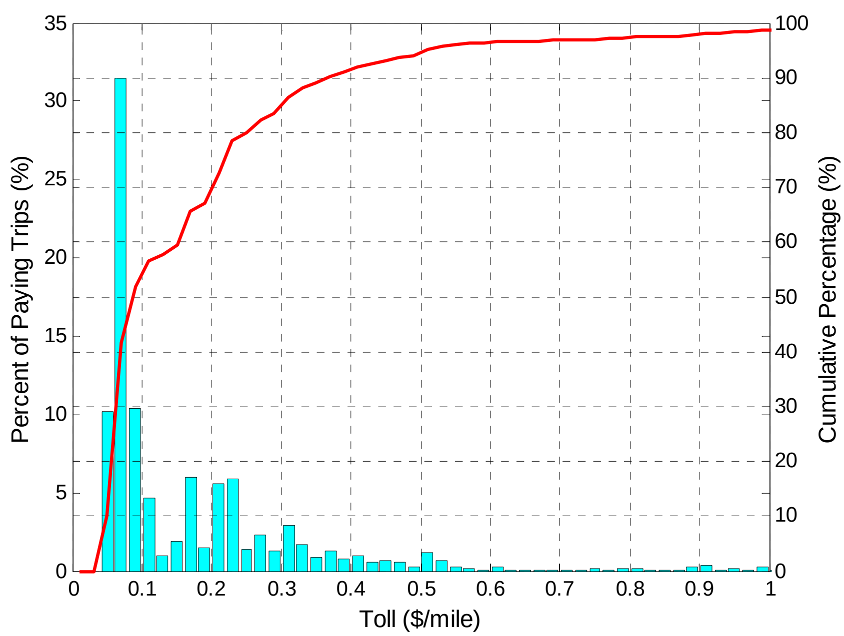

Figure 36. Weekend Toll-Per-Mile Distribution.

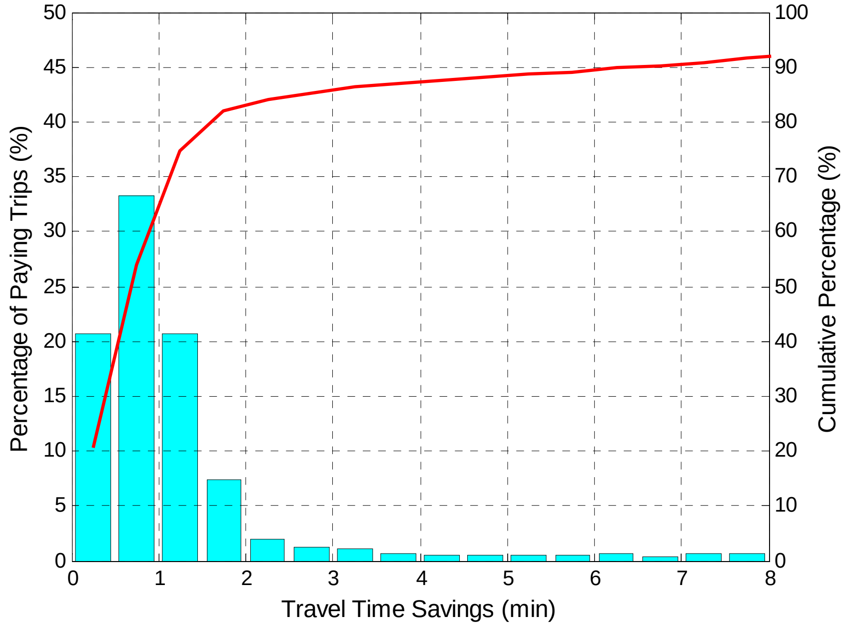

Figure 37. Weekend Travel Time Savings Distribution.

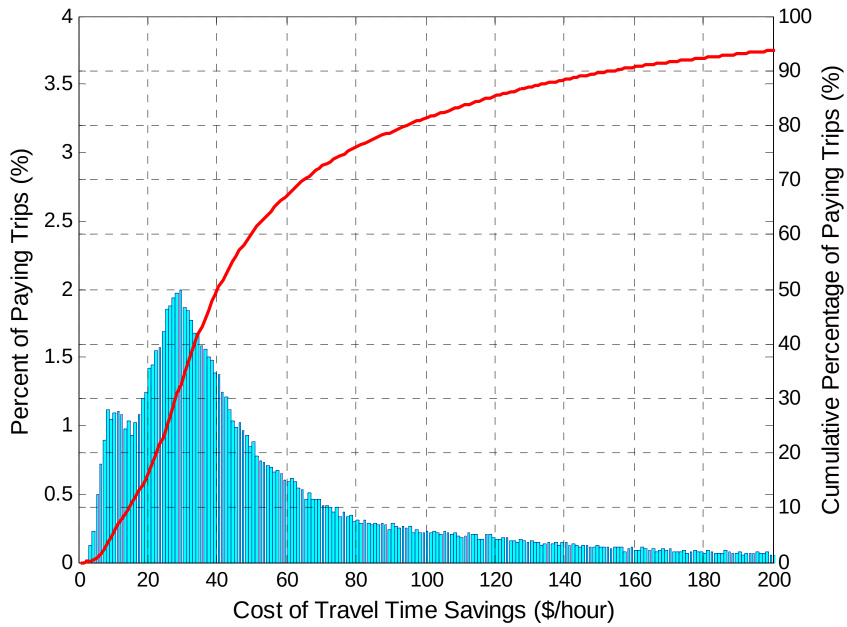

Figure 38. Weekend Value of Time Distribution.

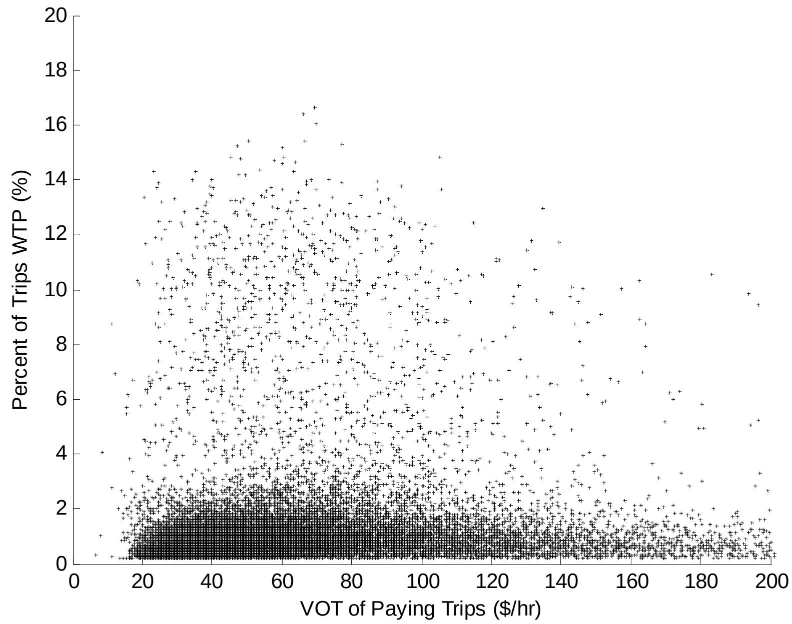

Figure 39. Weekend VOT vs.WTP.

Toll Variability

A toll variability analysis was performed on toll data from April 2009 to June 2010. It was found that the toll rate per mile was higher during peak periods than in off-peak periods. During off-peak times, much more concentrated and less variable toll distributions were encountered than during peak times (Figure 40).

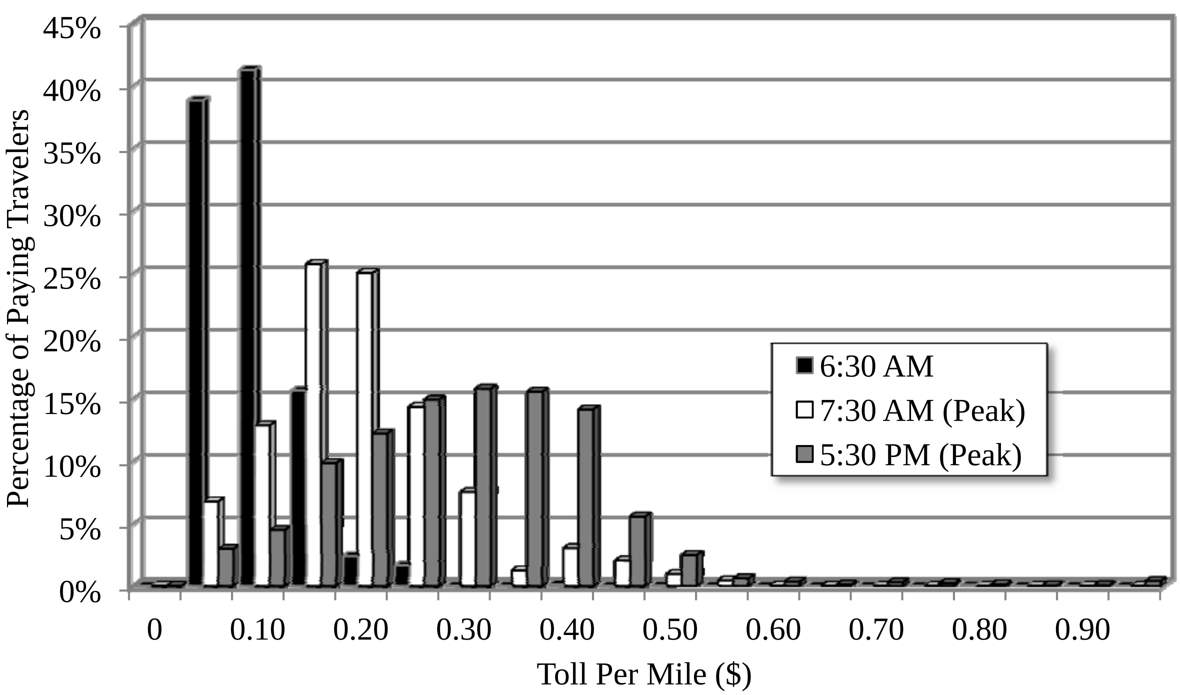

Figure 40. Peak vs. Off-Peak Toll Variability.

CONCLUSION

This research revealed that there was a surprisingly large percentage of travelers willing to pay for minimal TTS, resulting in a VOT that is $50 to $60 an hour more than what is suggested in previous studies as the average value of time based on hourly wage earnings (*4*). This indicates that there may be reasons other than TTS influencing travelers' decisions to use the Express Lanes during the morning peak. One possible reason could be that travelers place high value on travel time reliability, as it was observed in the results that 95 percent of Express Lane travelers could count on traveling the entire of the facility in 15 minutes or less regardless of the time of day or day of the week. Another reason could be the sense of urgency associated with trip purpose. For example, a traveler who is late to a morning appointment may place more value on his time than if he were going home in the evening. Other reasons including increased safety and the perception of getting a premium service are also possible alternatives. Further studies in this area may be of great benefit to future operational strategies of the facility.

It was observed that the dynamic tolling system on the Express Lanes had a significant amount of variance in the toll prices during peak periods, ranging from approximately $0.05 to $0.60 per mile. Conversely, off-peak periods showed less variation, ranging from approximately $0.05 to $0.25 per mile. These results show that although dynamic tolling may be more difficult to implement and less favored by some travelers, it was useful in regulating traffic during peak periods.

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INTERCITY PASSENGER RAIL ACCESS TO AIRPORTS: A CASE STUDY AT THE MILWAUKEE AIRPORT

Prepared for
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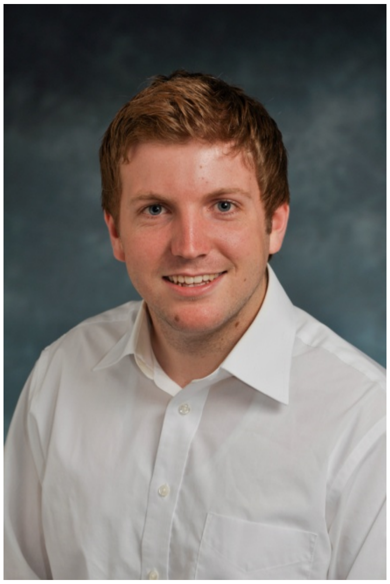

STUDENT BIOGRAPHY

Shawn Larson is a student at Brigham Young University (BYU) located in Provo, Utah. He will graduate in April 2012 with a Bachelor's degree in Civil and Environmental Engineering with an emphasis in transportation. He also plans on minoring in Mathematics. He has also received an Academic Scholarship for maintaining a grade point average of 3.7.

Shawn is an active member of the American Society of Civil Engineers (ASCE) and an officer in the BYU student chapter of the Institute of Transportation Engineers (ITE). He is also planning to attend graduate school to obtain a Master's degree in Transportation. His interests in transportation lie mainly in transportation planning and public transportation.

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SUMMARY

The link between airports and intercity passenger rail enhances regional and national mobility by improving the efficiency of intermodal connections. While intercity passenger rail stations at airports are common in Europe and Asia, there are only four of these connections in the U.S. One of these four is at the Milwaukee General Mitchell International Airport, Wisconsin, which is located along the Milwaukee-Chicago *Hiawatha Service* intercity passenger rail route. This paper describes a study that was developed to understand the broader impacts of this connection. A two-part data collection procedure was developed to understand who used the *Hiawatha Service* to connect to the airport and how travelers used this connection. Passengers who used the Milwaukee Airport Rail Station to connect to the airport were invited to participate in this study which included interviewing the passengers at the airport rail station as well as inviting them to participate in an online survey. The results of this study showed that this connection

expands the market area of the Milwaukee Airport into downtown Chicago. The passengers reported that convenience was an important factor to choosing to use the *Hiawatha Service*. This connection has impacts on a national level as the majority of passengers who used this connection are non-residents of the Milwaukee-Chicago region. The analysis also revealed that one-third of the passengers were using the connection to access other airport facilities such as car rental locations. Intercity passenger rail airport stations improve efficiency for passengers making intermodal connections, expand an airport's market area, and increase travel choices for non-resident travelers.

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INTRODUCTION

Mobility has been affected over history by the development of different modes of transportation. How these modes have interacted has also had a large and lasting effect on mobility. Intercity travel has especially been affected through the development of different modes of travel from the establishment of the rail system to the invention of air travel. How these modes interact, either as competitive or complimentary modes, has a great effect on regional and national travel. One of the major ways that modes can interact is through an intermodal center that allows passengers to change from one mode to another at one location.

Direct connection between intercity passenger rail and air travel is common in many parts of the world. This type of connection is accomplished most effectively by locating an intercity passenger rail station at the airport. With these connections passengers can connect to major airports from surrounding cities or to their final destination from an airport located in a different city by using intercity passenger rail in cooperation with air travel. In the United States, there are only four cases where this connection exists. Each of these airports has a rail station that is located adjacent to the airport and is served by Amtrak, the U.S. national rail system operator.

One of the four airport-intercity rail connections in the U.S. is located in Milwaukee, Wisconsin. The *Hiawatha Service* intercity passenger rail route runs from Chicago to downtown Milwaukee. One of the stations along this route is located three-fourths of a mile from the Milwaukee General Mitchell International Airport. This type of intermodal connection has potential to have high impacts on mobility on a national and regional level. In order to create a better understanding of these impacts, this project examines who uses this connection, how they use the connection, and how the connection affects mobility.

To develop a background understanding of the effect of this connection, a review of past studies and reports on the subjects of intercity passenger rail, airport ground access, and related topics has been preformed. The information that has been deemed pertinent to the study will be outlined in the background information section of this paper. Following that is an outline of the study with each of the steps taken to gather the necessary information to try and answer the question of how this type of interconnection affects mobility. The data that were received from these steps and the analysis of that data will be laid out and discussed. The conclusions and recommendations at the end of this paper will help to develop a better understanding of the effects of airport and intercity rail connections for the U.S. transportation system.

BACKGROUND

Numerous studies have been done on the subject of airport ground access. These studies have developed a foundation that will be necessary to be able to better understand the role of intercity passenger rail in airport ground access. A thorough review of airport connections by means by local passenger rail stations for airports in the United States was conducted. The frequency of this type of connection has been increasing and in some areas, rail services have claimed a significant portion of the ground access market share (*1*). A review of the existing air-intercity passenger rail connections in the U.S. was necessary and will also be provided in this section. Lastly, the connection between intercity passenger rail and airports in Europe and Asia was examined. While international experience might not translate directly to the U.S., it has implications for the U.S. and provides potential best practices for the development of connections of this type in the United States (*2*).

Airport Ground Access by Public Transportation

Air travel is an important part of national mobility. It has allowed longer distances to be covered in shorter travel times. A pivotal part of this is airports and airport access. There are many different modes for accessing airports. Over the recent years, there has been an increase in the number of airports that have established or are planning to establish a local public transportation connection; especially there has been an increase in the number of local rail connections. Most of these connections exist in larger urban areas and do not serve surrounding suburbs or cities. The main focus of these systems is the local market areas (*1*). Often, these areas consist of higher density populations. Knowledge gained from studies done on this type of mode connection is important because it helps to understand and show more of the needs and desire of the American people in their airport ground access mode choices. Past research has identified four unique market segments of airport ground access travelers (*2*). The four market segments are determined by trip purpose and residential status. Trip purpose is divided into business and non-business. Residential status is defined by the location of the passengers' home residence inside or outside of the market area for the airport being accessed. Figure 1 shows this four-cell matrix with the titles of each of the market segments.

		Resident Status	
		Resident	**Non-Resident**
Trip Purpose	**Business**	Resident Business	Non-Resident Business
	Non-Business	Resident Non-Business	Non-Resident Non-Business

Figure 1. Four Market Segments of Airport Ground Access Travelers (*2*).

Each of these market segments has different needs and desires in their airport ground access. For example, business travelers are typically more time-sensitive and less cost-sensitive than non-business travelers. Furthermore, residents of an airport's market area have a more in-depth knowledge of airport ground access trip options. The Resident Business market segment has the most knowledge of the different access options. This segment also tends to be "just-in-time" travelers who require reliability in their access mode. Resident Non-Business passengers normally travel in larger groups and with more baggage. This segment is the most likely to be dropped off or drive themselves. Non-Resident Business travelers frequently start their trips from central locations in the city center. The Non-Resident Non-Business segment is the least informed about the area. These passengers are commonly picked up from the airport by friends, relatives, or other local contacts (*2*).

Airport-Intercity Passenger Rail Connections in the U.S.

In the United States, there are a limited number of connections between the national rail system and air travel. The four U.S. airports with connections to adjacent intercity passenger rail stations are as follows:

- Baltimore Washington International Thurgood Marshall Airport;
- Bob Hope Airport;
- Milwaukee General Mitchell International Airport; and
- Newark Liberty International Airport.

These airports are linked to the Amtrak rail system through either shuttles or (in the case of Newark) a people mover. To go along with these four airports, there are a number of airports that can be connected to the national rail system through either rail transit or express bus. The major difference in the four airports listed and the other airports is the proximity and ease of access to the Amtrak station. In this section, information will be provided regarding these connections, with the exception of the Milwaukee Airport, which is discussed in a later section.

Baltimore/Washington International Thurgood Marshall Airport – Baltimore, Maryland

The Baltimore/Washington International Airport is another example of an airport that serves a larger region. There are also multiple airports in this region. The Baltimore/Washington Airport has an Amtrak station located close to the airport, which is served by a free shuttle. The shuttle operates on a fixed schedule and picks up passengers from the station every 12 minutes from 5:00 A.M. to 1:00 A.M. and every 25 minutes from 1:00 A.M. to 5:00 A.M. daily (*3*). The *Acela Express*, *Northeast Regional* and *Vermonter* lines all stop at the airport station. Not every *Acela Express* train stops at the station (*4*). The station is served by a train almost hourly. However, this station is also used by trains that are run by the Maryland Transit Administration, which is the Maryland Area Regional Commuter rail system. There were 191,000 originating air passengers that used this station in the year 2009 (*5*). This connection and the number of trains that service it allow the market area of the airport to expand. With intercity rail access to the Baltimore/Washington airport there is a primary market area in downtown Washington for the airport through the Amtrak system. Amtrak's mode share to the Baltimore airport from the Washington market is 14 percent (*2*). The Amtrak connection increases the number of access options for the Washington market, as well as making the Baltimore airport a more viable option when considering choice of airport. The Amtrak lines have a 2 percent share of the rail market. In 2009, the rail mode share among area residents was 2 percent, and the rail mode share among non-residents was 3 percent (*5*).

Bob Hope Airport – Burbank, California

The Bob Hope airport, which is located in Burbank, California, is a smaller airport but it does have a connection to the national passenger rail system. The airport serves 4.5 million passengers per year (*6*). The Amtrak station is one block away from the air terminal. While the walking distance from the station to the terminal is short there is also a free shuttle that is available upon request. The station is served by seven trains from each direction daily. Five of those trains are on the *Pacific Surfliner* route, while two are on the *Coast Starlight* route (*4*). The track that these trains run on is owned by Southern California Regional Rail Authority. Amtrak only serves about 0.8 percent of the ground access market for this airport. Rail access mode share among residents was 0.4 percent, and the share among visitors was 1.1 percent (*6*). The station is also used by Metrolink, which is a commuter rail system in the Los Angeles area. Along the corridor where the airport is located many of the stations are shared by Amtrak's *Pacific Surfliner* and the Metrolink Ventura County route. A program called "Rail 2 Rail" allows passengers who hold a Metrolink monthly pass to use Amtrak services along this corridor without additional charge, also holders of an Amtrak monthly or 10-trip ticket can use the Metrolink trains within the station pair with no additional cost (*7*).

Newark Liberty International Airport – Newark, New Jersey

In Newark, the airport is connected to Amtrak by a monorail named the AirTrain. The sole purpose of this Amtrak station is to serve the airport and is only accessible by an Amtrak train, the AirTrain or New Jersey Transit Lines. While it costs $5.50 to ride the AirTrain the price has been added into the ticket price for passengers using the Amtrak system. The situation in Newark is unique among airport located in the United States because at least 20 Amtrak trains serve the station on weekdays (*4*). There are trains that stop at this station almost hourly from the *Northeast Regional* route and a limited number from the *Keystone* route. This station is also used by New Jersey Transit trains. Another thing that makes this situation unique is the number of major cities in the area that have extensive public transportation systems. This makes access to the final destination of the passengers possible without high cost or inconvenience if they choose to use the Amtrak system for access to the airport. The other rail market section that includes Amtrak trains obtained a 2.9 percent share of the market for ground access to this airport (*8*). The rail mode share among international passengers was high, 6 percent compared to 2.6 percent for domestic passengers (*8*). Rail mode share was also higher among business travelers (3 percent) as compared to personal travelers (2 percent).

Other Airport Rail Connections

There are approximately 10 other airports in the U.S. with connections made possible by shuttle, and others that are possible through public transportation (*2*). Many of these connections are made possible by linking downtown stations with the airport. An example of this is the Los Angeles International Airport that has a shuttle called the Flyaway service, which links to Union Station in downtown Los Angeles (*4*). This service takes 40 minutes and costs $7.00. Other possible linkages include both of the Chicago O'Hare and Midway airports. Both of these airports are connected to downtown Chicago and end in a station that is only a few blocks from the Amtrak Union Station. Many connections such as this are possible through use of public transportation but because they are not advertised and of the inconveniencies of having to switched modes or walk it is unlikely that such links are well-used.

International Experience

Interaction between intercity passenger rail and air travel is a more common occurrence in Europe and Asia than it is in the United States. During the last 20 years, the number of high speed rail lines in Europe has dramatically increased (*9*). With that growth, there has also been an increase in the number of high speed rail stations at large international airports. This type of connection started in Europe in 1967, when the German Federal Government transport program decided to begin linking all major airports in Germany to the national railway network (*10*). The Frankfurt Airport was one of the first European airports to connect the terminals to the city center by a standard rail link, which allowed easy access to intercity rail lines from the airport. To make this connection work the Lufthansa Airport Service, a rail service, was created and linked Düsseldorf to the Frankfurt airport. Lufthansa Airlines had realized that to cover the costs of a Boeing 737 on the Cologne-Frankfurt route would require filling 130 percent of the available seats (*9*). This of course was impossible and so the airport decided to collaborate with the German railways and build a second station at the airport to serve intercity rail. The financial benefit of this action can be seen in the fact that the running cost of the Lufthansa train is $3,425 verse $6,000 to operate the smallest commercial aircraft. Other benefits that came from this connection between intercity rail and air travel was that the collaboration allowed the airports to redirect more short flight passengers unto the railways while opening space at the airport for more long distance flights. By replacing flights between Frankfurt, Düsseldorf, and Stuttgart with rail trips 20,000 airplane slots at airports could be opened for longer distance flights (*9*). Because of these experiences air travel and rail travel in Germany and throughout much of Europe has become complimentary to each other.

In Japan high speed rail and air travel are in direct competition with each other. But even with these services being competitive and not cooperative high speed rail still has managed to replace a large portion of flight for short distances. High speed rail had an 86 percent market share in the Tokyo-Osaka corridor in the year 1999. This corridor is 343 miles long and contains some of the highest populated areas in Japan. However, the longest distance routes lose their dominance over air travel with the route from Tokyo to Fukuoka, a distance of 733 miles, has only a 12 percent share of the combined Air-Rail market. From this example it can be determined that when rail and air travel are competitive shorter distances can be dominated by rail but they will lose more of the market with longer distances.

In the last two examples mobility is affected in different ways. In Europe with a reduction in short distances flights there are more long distance flights, which increase national and even international mobility. In contrast to this Japan with its competitive market encourages more frequent short distance flights in order to be competitive (*11*). This helps to increase local and regional mobility. In these examples there is one factor that must be taken into account when realizing the success of these systems. This one factor is scale of the already existing national rail network and supporting public transportation systems. Because of the funding and efforts that had previously been put into rail system in Europe and Japan and a lack of it in the United States similar strategies might not work at U.S. airports (*2*).

PROBLEM SOLVING APPROACH

This section discusses the approach used to solve the question of how an interconnection between the national rail system and airports affects mobility in the United States. First, more details of the problem and setting are given. Next, the method used to obtain information to allow for an analysis will be presented. In order to obtain enough information and be able to make the analysis more complete two different collection methods were used. The two methods used to collect the data are onsite interviews and an online survey. With the number of passengers using the station for a number of different reasons it was concluded that the data collection, including interviewing and passing out invitations to take the online survey, needed to take place onboard the shuttle. This allowed the staff member to only talk to those people who are using the *Hiawatha Service* to link to the airport. The data that were obtained through the interviews and survey were then reviewed to ensure the quality of the data.

Setting of the Study

The setting of this study was the Milwaukee General Mitchell International Airport, Wisconsin. This airport is linked to the Amtrak national intercity passenger rail system by the Milwaukee Airport Rail Station (MARS). The station opened in 2005 and is located three-fourths of a mile from the airport main terminal on the western edge of the airport property. Figure 2 shows an exterior view of the station facility.

Figure 2. Milwaukee Airport Rail Station (Source: Texas Transportation Institute).

The station facilities include a single train platform that is 400 ft in length and a 1,600 sq ft station building. The station is unstaffed but travelers can purchase tickets at two Quik-Trak automated ticket vending machines located inside the station building. Located next to the station is a park-and-ride facility, which has space for up to 282 vehicles. The station is a stop on the *Hiawatha Service* route which runs from Chicago, Illinois, to Milwaukee, Wisconsin. The *Hiawatha Service* is part of the Amtrak national intercity passenger rail system. The track for this route runs a distance of approximately 90 miles from Chicago to Milwaukee. It takes one hour and 30 minutes to travel from Union Station in Chicago to the Intermodal Station in Milwaukee, with stops at three intermediate stations. These three intermediate stations include a station at

Glenview, Illinois, Sturtevant, Wisconsin, and MARS. Seven trains run daily in each direction along the route with six on Sundays. Figure 3 shows the timetable for the *Hiawatha Service.*

HIAWATHA SERVICE

Chicago • Milwaukee

Train Number ▸				329	331	333	335	337	339	341
Normal Days of Operation ▸				Mo-Sa	Daily	Daily	Daily	Daily	Daily	Daily
On Board Service ▸										
	Mile	Symbol	▼							
Chicago, IL–Union Station (CT)	0	● ♿ QT	Dp	6 00A	8 25A	10 20A	1 05P	3 15P	5 08P	8 05P
Glenview, IL	18	● ♿ QT	↓	6 22A	8 47A	10 42A	1 27P	3 37P	5 32P	8 27P
Sturtevant, WI (Racine)	63	○ ♿ QT	↓	7 00A	9 25A	11 20A	2 05P	4 15P	6 14P	9 05P
Milwaukee Airport Rail Sta. ✈	78	○ ♿ QT 7	↓	7 14A	9 39A	11 34A	2 19P	4 29P	6 28P	9 19P
Milwaukee, WI (CT) Oshkosh, Wausau—see back	86	● ♿ QT	Ar	7 29A	9 54A	11 49A	2 34P	4 44P	6 45P	9 34P

Milwaukee • Chicago

Train Number ▸				330	332	334	336	338	340	342
Normal Days of Operation ▸				Mo-Sa	Daily	Daily	Daily	Daily	Daily	Daily
On Board Service ▸										
	Mile	Symbol	▼							
Milwaukee, WI (CT) Oshkosh, Wausau—see back	0	● ♿ QT	Dp	6 15A	8 00A	11 00A	1 00P	3 00P	5 45P	7 35P
Milwaukee Airport Rail Sta. ✈	8	○ ♿ QT 7	↓	6 26A	8 10A	11 10A	1 10P	3 10P	5 55P	7 45P
Sturtevant, WI (Racine)	23	○ ♿ QT	↓	6 43A	8 23A	11 23A	1 23P	3 23P	6 08P	7 58P
Glenview, IL	68	● ♿ QT	↓	7 25A	9 01A	12 01P	2 01P	4 01P	6 46P	8 36P
Chicago, IL–Union Station (CT)	86	● ♿ QT	Ar	7 57A	9 29A	12 29P	2 29P	4 29P	7 14P	9 04P

Figure 3. *Hiawatha Service* Timetable (*4*).

Passengers connect with the airport terminals from the intercity passenger rail station by a free shuttle. The free shuttle also transports passengers between the airport terminal and the long term parking areas. Figure 4 shows this shuttle.

Figure 4. Airport Shuttle (Source: Texas Transportation Institute).

This arrangement is similar to the Baltimore/Washington Airport and the Bob Hope Airport. All three of these airports are linked to an Amtrak Station by a free shuttle. The major difference in

Milwaukee is the frequency of the trains and shuttle service. At the Milwaukee Airport, the shuttles do not have a set schedule, but the drivers are aware of the train schedule and are instructed to arrive at MARS five minutes before the train arrives and if the train is late to wait five minutes before returning to their normal duty. For passengers to board the shuttle at MARS, they are required to present their Amtrak ticket to the driver. If there is no shuttle at the station when the train arrives, passengers can use a phone located at the station (shown in Figure 5) to call the shuttle. Each shuttle that serves the airport is marked by the sign shown in Figure 6.

Figure 5. Shuttle Telephone (Source: Texas Transportation Institute).

Figure 6. Shuttle Amtrak Station Sign (Source: Texas Transportation Institute).

On-Site Interviews

The first stage of the data collection consisted of on-site interviews of shuttle passengers at MARS. Appendix A gives an example of the form that the interviewer filled out. The interview lasted no longer than 20 to 30 seconds per passenger and gathered information such as direction of travel, gender of passengers, party size, business or personal reasons for travel, train number, and home residential zip code. In addition to the interview, each passenger was given a card with a code on it that invited them to take part in the Internet survey. Appendix B shows an example of this card. Each card has a unique access code for the survey that was recorded by the interviewer when the cards were handed out so that the survey can be linked with the interview data. The access codes varied according to the date of travel and which direction, to or from the airport, the traveler was going. A staff member was on-site for a total of 15 days to collect data and pass out the invitation cards for the online survey. These 15 days were May 25 and June 13 to June 26, 2011. Table 1 shows the results of the on-site data collection.

Table 1. Summary of Data Collection Activities.

Date	Riders Observed	Cards Distributed	Percent Contacted	Internet Completed	Percent Follow-Up
May 25, 2011	114	109	96%	16	14.5%
June 13, 2011	98	98	100%	13	13.3%
June 14, 2011	60	54	90%	13	24.1%
June 15, 2011	71	57	80%	14	24.6%
June 16, 2011	66	59	89%	13	22.0%
June 17, 2011	65	61	94%	13	21.3%
June 18, 2011	38	35	92%	4	11.4%
June 19, 2011	50	48	96%	11	22.9%
June 20, 2011	45	43	96%	12	27.9%
June 21, 2011	47	40	85%	8	20.0%
June 22, 2011	71	66	93%	8	12.1%
June 23, 2011	53	43	81%	3	7.0%
June 24, 2011	73	57	78%	12	21.1%
June 25, 2011	56	43	77%	9	20.9%
June 26, 2011	54	35	65%	6	17.1%
Total 15 Days	**961**	**848**	**88%**	**155**	**18.3%**

For the 15-day survey period, 961 riders were observed. Eighty-eight percent or 848 of those were given an invitation card for the online survey. Of the 848 passengers who were given a card took the survey, 155 responded, resulting in an overall response rate of 18.3 percent. However, not all passengers were recorded because no staff members were on site for the number 330 or the number 341 trains. The reason that these trains were not counted was due to the early arrive time of the 330 train and the late arrival time of the 341 train. These trains were thought to have a relatively low number of passengers and would not affect the overall findings significantly. It was not possible to have a staff member at the station for such an extended period of time.

Online Survey

The next stage of the data collection was an Internet survey that gathered more information about the *Hiawatha Service*, access to the airport, and the passengers themselves. An Internet survey was used because the passengers could be in a hurry to get to the shuttle or onto the train and did not have time to fill out a lengthy written survey. This method was selected to allow the passengers to fill out the survey at a later time. The passengers received cards containing a unique identification number, which was used on the website to access the survey. The Internet survey asked questions regarding reasons for choosing to use the *Hiawatha Service*, other modes used on this trip, passenger's car ownership, and information about connecting to flights at the airport. Appendix C shows the survey. The information provided by survey respondents was stored in an online database.

One of the possible disadvantages of this type of survey is that there might be a low participation percentage. For this reason, interviews were taken at the airport rail station at the same time the survey cards were distributed. To increase the likelihood of getting responses a random drawing was taken at the end of the survey and one of the participators received a reward of a $250 Visa gift card. After a passenger completed the survey, they were able to input contact information to enter into the drawing to win the gift card. This contact information was in no way linked to the survey questions answered.

Data Review

The purpose of the data review was to make sure that the information obtained from the interviews and online surveys was complete and correct. This was necessary so that the analysis would be able to draw accurate conclusions. The fact that there were two sets of data obtained from many of the passengers made it possible to correct incomplete answers in one or both of the sets. These two data sets were linked together with the unique access code that was distributed to the passengers during the initial interviews that allowed the passengers to take the online survey. Incomplete information from the interview was overwritten by the more complete data from the online survey in many cases. There were also a few cases where the survey data were incomplete and could be finished by information from the interviews. The other categories for the question were also reviewed by the author with assistance from an experienced Texas Transportation Institute researcher and where appropriate the more complete answer was assigned to one of the given answers. These two data sets allowed a more complete set of information for the analysis.

ANALYSIS AND FINDINGS

This section describes the information obtained from the analysis of the interviews and online surveys. The general characteristics of the passengers contacted will be shown first. Following this, the passengers will be broken down into each of the four market segment that is established from earlier airport ground access studies (*2*). These four market areas are Resident

Business (RB), Resident Non-Business (RNB), Non-Resident Business (NRB) and Non-Resident Non-Business (NRNB). For this study, the market area for the Milwaukee International Airport market area has been defined as the Milwaukee Metropolitan Statistical Area as well as the Racine and Chicago Metropolitan Statistical Areas. The reason for defining the residence this way is because the *Hiawatha Service* offers cost-competitive travel to the Milwaukee Airport from Chicago and passes through the Racine area. Those passengers who come from outside these statistical areas are defined as non-residents. This section will be followed by an analysis of alternate modes that passengers would have used if unable to use the *Hiawatha Service.* These alternatives also include the option of using a different airport. Next is a discussion of the analysis of the motivations that inspired passengers to use this service. This section will use information from the interviews as well as from the online survey.

General Characteristics

This section discusses the analysis that has been done to discover who is using the *Hiawatha Service.* Table 2 shows many of the characteristics of the passengers. The majority of passengers who rode the shuttle to the Milwaukee Airport during the survey period were male, 58 percent compared to 42 percent female. There were not many large groups who used the airport connection with the average party size being 1.4 adults and the average number of children as 0.1 per party. The majority of travelers either traveled alone or in small groups of two. The average age of the travelers was 39.7 year old with the NRNB having the highest average at age at 48.3. The majority, 66 percent, of the shuttle riders were employed full-time. Understandably this percentage increased with the business market segments. The average income for the passengers using the shuttle was $92,900. This correlates well with the high education level of most of the passengers. Thirty percent of have graduate degrees. Thirty-five percent have bachelor's degrees. One interesting characteristic of the passengers on the shuttle is the number of cars owned by their household. The largest group is passengers whose households have two cars; this group was 42 percent of the passengers. Only nine percent of the passengers did not own a car. This means that the majority of the passengers had alternative means of transportation or at least access to a car.

Table 2. General Characteristics of Air-Rail Transfer Passengers.

Characteristic	Shuttle Riders
Gender (% Female)	42.2
Average party size	1.4 adults
Average number of children	0.1 per party
Median Age	39.7
Median Income	$92,900
Employment (%)	
Full-time	66
Part-time	9
Unemployed	3
Retired	8
University/College Student	12
Homemaker	2
Education (%)	
Some High School	2
High School Graduate/GED	10
Some college	16
Associate Degree	7
Bachelor’s Degree	35
Graduate Degree	30
Household Vehicles (%)	
None	9
One	26
Two	42
Three	14
Four or more	8

Market Segments

Table 3 shows the residential status of the passengers who used the airport shuttle from MARS. The residential information obtained from the interview and online survey is compared to the information that was obtained from an on-board survey of all *Hiawatha Service* passengers. The on-board survey was taken over a weekday and weekend day in spring 2011. The on-board survey was a separate task of the parent project of this study. As shown there are some differences in the residential status of the passengers who use the train to connection to the airport and those who use it for other purposes. There are also some differences between the interviews and the online survey. In the online survey Chicago residents were overrepresented. This was probably because Chicago residents, who are more likely to use the service consistently, felt that the conclusions of the survey will affect them more.

Table 3. Residence and Market Segments of Air-Rail Transfer Passengers.

Market Segment	On-Site Interview	Internet Survey	On-Board Survey
Residential Status (%)			
Milwaukee MSA	8	8	58
Chicago MSA	33	43	23
Other (Non-Residents)	59	49	19
Market Segments (%)			
Resident Business (RB)	17	21	32
Non-Resident Business (NRB)	18	16	4
Resident Non-Business (RNB)	24	29	49
Non-Resident Non-Business (NRNB	41	34	15

For all riders of the *Hiawatha Service*, the largest residential segment came from the Milwaukee MSA, which covered 58 percent of the passengers. This is a strong contrast to those who use the airport shuttle at the Airport Rail Station. Only 8 percent of these passengers came from the Milwaukee MSA. This indicates that Milwaukee resident have more preferable travel options for reaching the airport. There is also an increase in the number of non-residents on the shuttle when compared with the train. For the shuttle 59 percent of the passengers were non-residents. The online survey showed a smaller percentage of non-residents with a higher percentage of Chicago residents.

The on-board survey showed that for the train only 19 percent of the passengers were not residents of either Chicago or Milwaukee. This is explained by the other section of Table 3, which shows that for the shuttle NRNB travelers were the largest market segment by percentage. This segment had 41 percent of the passengers. Of the other three market segments, the RNB had 24 percent, NRB 18 percent, and RB 17 percent of passengers. Approximately 65 percent of the passengers were non-business travelers and 35 percent business. This is similar to the 64 percent non-business passengers on the *Hiawatha Service*.

Alternative Modes

To better understand the effect that the *Hiawatha Service* has on the mobility of the region and how it affects trips created or changed, the passengers were asked how they would make the trip if this service was not available. Travelers were given a variety of modes to choose from as an option for travel to the Milwaukee Airport. Also they were given the option of choosing another airport. Table 4 shows the distribution of answers to this question.

Table 4. Passenger Alternatives to Rail Access.

Mode	RB	RNB	NRB	NRNB	All Riders
I Would Use a Different Airport	13%	60%	35%	24%	34%
Chicago - O'Hare	3%	51%	22%	22%	27%
Chicago - Midway	9%	9%	13%	2%	7%
Drove Myself and Parked	56%	20%	13%	16%	25%
Motorcoach Bus/Shuttle Service	16%	11%	17%	4%	11%
Taxi/Car Service	6%	2%	9%	22%	11%
Driven by Relative, Friend, or Colleague	3%	4%	13%	16%	9%
Local Transit Service	0%	2%	0%	6%	3%
Rental Car	0%	0%	4%	8%	3%
Other	6%	0%	9%	6%	5%

Over one-third of the passengers, 34 percent, would have chosen a different airport if the *Hiawatha Service* was not available. The majority of this 34 percent, 27 percent of the total said that they would have used the Chicago O'Hare International Airport. A smaller portion, 7 percent of the total, would have used the Chicago Midway Airport. The RNB market segment had the largest percentage of passengers who would have used a different airport with 60 percent. The market area with the lowest percentage was the RB with only 13 percent of the passengers in this segment choosing to use a different airport. This segment is also the one with the highest percentage of people choosing to drive and park at the Milwaukee airport had the *Hiawatha Service* not been available, with 56 percent choosing this option. The total for the option to drive and park at the airport was 25 percent of all the passengers. This percentage was the second highest after the percentage for using a different airport. This shows how the *Hiawatha Service* not only replaces many car trips but it also diverts some passengers from other airports around the region. This is not surprising because of ease of access that this service allows to the Milwaukee Airport from downtown Chicago. Also this train is affordable and the distance short enough to make it competitive with other airports.

Passenger Motivations

This section of the analysis focuses on the motivations for using intercity rail to connect with the Milwaukee Airport. This information was obtained from the passengers on the online survey. Those who took the survey were given these 16 factors in random order and asked to rate the importance of each one. The possible answers the passengers were given to choose from ranged from extremely important, which is represented by the value of five, to extremely unimportant which is valued as one. The average value of the 16 factors is given in Table 5 below, as well as the standard deviation. The average for each of the four market segments is also given. The two factors with the highest values were "more convenient than other options" and "convenient to my final destination." With average values of 4.10 and 4.22 these two factors were important to make that decision. These factors also had the lowest standard deviation meaning that a majority of passengers agreed on the importance of this factor in their decision to use the train. The high value placed on these factors was not unexpected as the *Hiawatha Service* is a convenient option for those traveling to or from the airport from downtown Chicago, and these are the travelers who are most likely to use the *Hiawatha Service* because of the convenience.

Table 5. Motivations for Using *Hiawatha Service* for Airport Access.

Motivation	RB	RNB	NRB	NRNB	All Riders	Standard Deviation
Less Expensive than Other Options	3.85	3.98	4.25	3.72	3.91	1.11
More Convenient than Other Options	4.24	4.11	3.71	4.28	4.10	0.97
More Reliable than Other Options	3.61	3.76	3.42	3.56	3.61	1.06
Faster than Other Options	3.97	3.78	3.54	3.66	3.77	1.08
Safer than Other Options	3.24	3.44	2.88	3.22	3.24	1.17
Convenient to My Residence	3.73	3.78	2.46	2.90	3.38	1.25
Convenient to My Final Destination	4.00	4.09	4.42	4.46	4.22	0.99
Schedule Matched My Schedule Needs	4.00	3.89	3.71	4.24	3.97	1.11
No Other Transportation Available	3.03	3.02	2.79	2.72	2.91	1.27
Avoid Highway Congestion	4.00	3.93	3.88	4.00	3.96	1.21
Usual Option Not Available	2.58	2.40	2.42	2.58	2.55	1.09
Opportunity to Sleep/Relax	4.00	3.76	3.25	3.32	3.56	1.14
Opportunity to Work While Traveling	3.64	3.42	3.50	2.88	3.28	1.13
Avoid Airport Parking	3.12	3.27	2.54	3.06	3.05	1.28
Recommended by Family/Friend/Colleague	2.48	3.13	2.96	2.88	2.90	1.09
More Comfortable than Other Options	3.76	3.89	3.50	3.64	3.69	1.15

The lowest average factor among all riders was the "Usual Option Not Available" factor. This factor had a value of 2.55 with a standard deviation of 1.09. This indicated that most of the passengers agree that this was not important in their transportation mode decision. The low average response for this factor demonstrates that the passengers were aware of and had access to other options for their airport access. The motivation "No Other Form of Transportation Available" also had the third lowest average. Together these factors show that that the train ride that these travelers took to get to the airport was a replacement of a car trip or alternative means of transportation.

Most of the averages for the individual market sections are relatively close to the overall average. A couple of exceptions to this include the NRB average for "Less Expensive than Other Options." This is important because business travelers are thought to be less cost sensitive than non-business (*2*). The recent recession and economic problems of many companies might have impacted this motivation. Another instance of one average being different from the other averages is "Avoid Airport Parking" this time the average for NRB travelers is lower than the other three. There are also differences in some of these motivations for resident versus non-resident. For the motivation "Convenient to My Residence" the residents had a much higher average, which was to be expected because non-residents did not live in the Chicago or Milwaukee Metropolitan Statistical Areas. Another difference can be found in "Opportunity to Sleep and Relax," which was higher for residents than non-residents. This shows some of the difference in needs and desire for airport ground access by the various market segments.

Connections Made

One of the surprises that came from this study was the way that many of the passengers were using the airport connection. A surprising number of passengers, 29 percent, were using the airport rail station shuttle to connect with other forms of transportation instead of air travel. A large portion of the RB market segment was using the airport for purposes other than air travel, 42 percent were connecting to other options. One of the main other options available at the airport was rental cars. Airports typically have a number of car rental facilities that have a higher number of cars and are open longer hours than other locations. The airport rail station has become more than just an intermodal connection for rail and air travel but for other modes of transportation as well.

Table 6. Connections Made by Passengers at the Milwaukee Airport.

Connecting To:	RB	RNB	NRB	NRNB	All Riders
Low-Cost Airline	33	58	38	48	46
Connection to Other Transportation	42	20	8	27	29
Legacy Carriers	24	22	54	25	25

CONCLUSIONS AND RECOMMENDATIONS

The connection between the *Hiawatha Service*, an intercity passenger rail route, and the Milwaukee Airport has many effects on mobility. These effects can be seen on a regional and a national level. This study helps to develop an understanding of what these effects are. With this information, some recommendations can be made for future expansion of such connections elsewhere in the U.S.

On a regional level, this multimodal connection impacts the market area of the Milwaukee Airport by expanding it. A large portion of passengers on the *Hiawatha Service* who used the airport rail station were residents of the Chicago MSA. It would be expected that these passengers would use the Chicago airports, which are closer, but with the ease of access that the *Hiawatha Service* creates for the Milwaukee Airport the downtown Chicago market area is now shared by these three airports. Residents of downtown Chicago now have more airport options to choose from and another mode to choose from for their airport access trip. The ability to access the Milwaukee Airport through the *Hiawatha Service* also allows the residents of the Chicago MSA to access the other services that are located at the airport, such as the car rental facilities. This leads to increased mobility through creating more transportation options and creating a new intermodal interchange for more than just rail and air.

National mobility is affected by the interaction between intercity rail and air travel. In Europe this type of connection made it possible that intercity rail and air travel could be complimentary, with the rail served as a feeder system for the airport. In the United States this type of connection means that air and rail can become complimentary if employed to a greater extent. The air-rail connection at the Milwaukee Airport makes it possible for rail and air transportation to work together in this area and it will effect nationally how passengers travel to and from this region. The majority of passengers interviewed in this study were non-residents of the Chicago or Milwaukee areas. This shows that this connection type can have an effect on travel patterns not just on a regional scale but also on a wider national level.

In order to better understand this type of connection, the author would recommend additional studies at the other three existing airport-intercity passenger rail connections in the United States. This type of connection should also be considered with any future plans for high-speed rail. This type of connection could be a great benefit to both the airlines and the rail companies if it can find its place in the U.S. transportation system.

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APPENDIX A: ON-SITE SURVEY INTERVIEW FORM

Milwaukee Airport Amtrak Shuttle Passenger Interview Form
Texas Transportation Institute / Wisconsin DOT

Date: ________________ Staff Name: ________________________

	Going To	Train #	Adults	Child	Gender	Purpose	Residence/Zip Code	Token Code
1.	Air Rail				M / F	Business Personal		
2.	Air Rail				M / F	Business Personal		
3.	Air Rail				M / F	Business Personal		
4.	Air Rail				M / F	Business Personal		
5.	Air Rail				M / F	Business Personal		
6.	Air Rail				M / F	Business Personal		
7.	Air Rail				M / F	Business Personal		
8.	Air Rail				M / F	Business Personal		
9.	Air Rail				M / F	Business Personal		
10.	Air Rail				M / F	Business Personal		
11.	Air Rail				M / F	Business Personal		
12.	Air Rail				M / F	Business Personal		
13.	Air Rail				M / F	Business Personal		
14.	Air Rail				M / F	Business Personal		
15.	Air Rail				M / F	Business Personal		
16.	Air Rail				M / F	Business Personal		
17.	Air Rail				M / F	Business Personal		
18.	Air Rail				M / F	Business Personal		
19.	Air Rail				M / F	Business Personal		
20.	Air Rail				M / F	Business Personal		

Form Instructions: One interview row per adult traveler. Fill in travel direction, train number, and personal information from observation. Fill in purpose and zip code from verbal interview prompts. If person does not want to give zip code then community name is acceptable. Record token code if card distributed or "N/A" if card was refused.

APPENDIX B: ONLINE SURVEY RECRUITMENT CARD

Milwaukee Airport Shuttle Passenger Study

Texas Transportation Institute

The Texas Transportation Institute and WisDOT invite you to participate in a research study on how travelers utilize the Amtrak *Hiawatha Service* to connect with the Milwaukee Airport. Your participation in this research study is voluntary, and your responses are confidential.

Please visit the following website to take our survey:

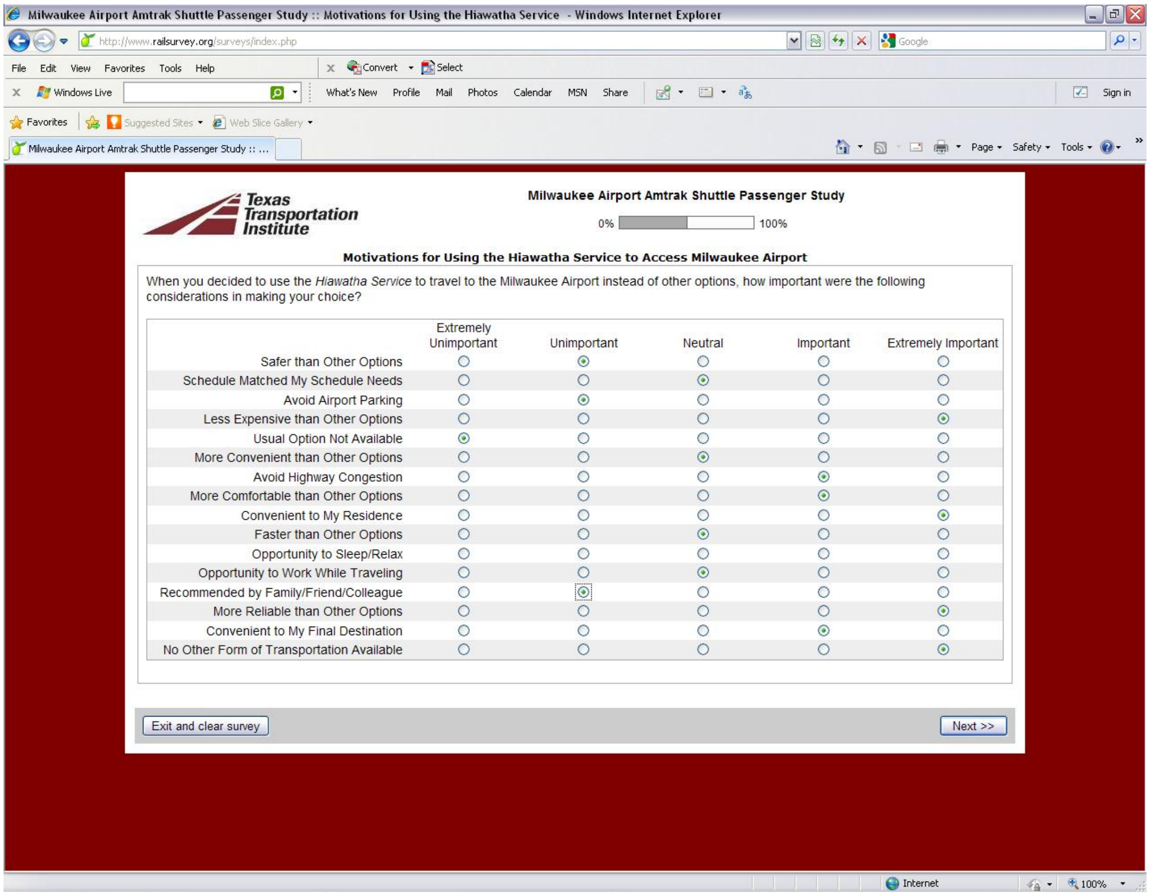
http://www.railsurvey.org/mke

When Prompted, Please Enter the Following Code: **626201**

One Randomly-Selected Respondent will Receive a **$250 Visa Gift Card**

Your Participation by July 17, 2011 is Appreciated.

APPENDIX C: ONLINE SURVEY EXAMPLE



Development of a Background Complexity Assessment Tool

Prepared for
Undergraduate Transportation Scholars Program

by

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Southwest Region University Transportation Center

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STUDENT BIOGRAPHY

Marcus Rasulo is a senior at Boise State University, in Boise, Idaho. He will be graduating in May of 2012 with his Bachelor of Science in Civil Engineering, as well as from the University's Honors College.

Marcus has been involved on campus in the University's Honors College and Engineering Residential College. Off campus he serves as a volunteer Young Life leader, a non-denomination Christian youth outreach. After graduating from Boise State, Marcus plans to continue his education into graduate school and eventually earn his P.E.

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The author would like to express his appreciation to Jeff Miles for his guidance during this project and especially for his late night assistance during data collection.

SUMMARY

The purpose of the project was to develop a method to collect human factors data rating the background complexity around overhead guide signs. The data will be used for the parent project to develop a method for rating background complexity.

To portray a range of background complexities from real world situations the researchers collected images of overhead guide signs along interstate highways around Dallas, Austin, and San Antonio, Texas. The images portrayed a range of complexities from single rural signs to clusters of urban signs. A limited selection of those images was then used to develop a survey to collect the human factors data. The survey was piloted through a test group of 22 participants. Nineteen of those participants were considered average drivers while the remaining three, who were familiar with sign visibility, were used as an expert panel to establish a baseline.

The results showed consistency between the expert panel and the average drivers, and between the average drivers' rankings and ratings. During the survey the researchers noted some

participants ignored the sign identification, rated the sign, and were confused by differences in the clarity of the images.

The survey preliminarily identified that the number of lights, the close proximity of light to the sign, and the presence of multiple signs increased the complexity, while having a clear border region around the sign decreased the complexity.

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INTRODUCTION

Overhead guide signs provide information that is important for the benefit and direction of drivers. The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) requires that signs are legible and understandable in time for drivers to respond appropriately both day and night (*1*). While visibility is not usually an issue during the day, it can become an issue during the night due to the reduced illumination. To improve the nighttime visibility signs are augmented through the use of headlight illumination, retroreflective sign materials, and occasionally fixed sign lighting.

The MUTCD permits the use of retroreflective materials without illumination if an engineering study shows that the sign alone will perform effectively (*1*). While the MUTCD sets minimum retroreflectivity levels, the MUTCD does not set any standards for what is effective performance. However, the minimum levels do not guarantee visibility because retroreflectivity is only one of the factors affecting visibility. Retroreflectivity is a physical property of the material, and it does not take into account the on-site conditions that affect performance. When given a dark rural environment versus a complex urban setting, such as Las Vegas, identical signs with the same retroreflectivity are not likely to have the same performance.

One on-site factor that affects performance is background complexity. Background complexity is often recognized as an important factor in visibility but is usually simplified down into vague qualitative descriptions, or ignored altogether in design. Even with its accepted impact on visibility, there is no current method established to measure background complexity.

The purpose of the project was to develop a method to collect the human factors data to assess background complexity. The project involved collecting images around Austin, San Antonio, and Dallas, Texas. Those images were then used to develop and test a pilot survey to collect human factors data.

BACKGROUND

This section outlines the current topics relating to the relationship between background complexity and sign visibility.

Retroreflectivity

Retroreflection is a property of a material where light is reflected back to its source with minimal scattering. Retroreflective materials are used in signs to increase their brightness and visibility by redirecting the light from vehicle headlights back to the driver. The retroreflectivity of a sign is referred to at the coefficient of retroreflection, R_A, and can be thought of ratio of luminance (reflected light), to illuminance (light falling on the sign) or the efficiency of a sign at returning light back to its source. The MUTCD established minimum maintained retroreflectivity standards, which it states are acceptable without illumination if they prove effective (*1*), but does not address what is effective. In addition, those standards are further called into question because they were based off of human factors data in dark rural environments (*2*), where on-site conditions usually have minimal effect. The shortcoming of using only retroreflectivity is it is only one of multiple factors affecting visibility and does not address the on-site conditions.

Parent Project

The project is a subset of the larger National Cooperative Highway Research Project *Guidelines for Nighttime Visibility of Overhead Guide Signs* (NCHRP 5-20). The parent project is investigating how different on-site factors affect visibility. The goal is to develop a model to objectively evaluate the background complexity of overhead guide signs and to recommend guidelines for when supplemental lighting should be used to improve nighttime visibility.

Background Complexity

Background complexity can be described as the level of visual clutter around the sign that competes for a driver's attention. Assessing visibility without accounting for background complexity implies that we are ignoring the background around the sign, which is simulated below in Figure 1. In reality the environment around the sign competes for your attention as show in Figure 2. Background complexity has a major effect on the visibility and conspicuity of a sign, because highly complex backgrounds have been shown to decrease visibility (*3*). In addition attempts to improve the visibility through the use of fixed illumination have been shown to be dependent on background complexity. Illumination provides little to no improvement in detection distance in low background complexities, and increasingly improves detection distance as complexity increases (*4*).

Figure 1.: Ignoring Background.

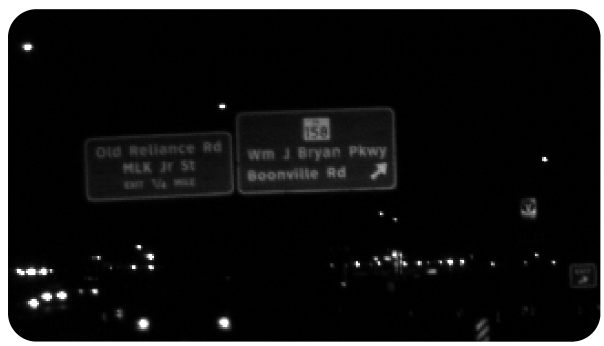

Figure 2. Including Background.

AASHTO

The American Association of State Highway and Transportation Officials (AASHTO) addresses background complexity through ambient luminance. Ambient luminance can be described as the background luminance or general level of light surrounding the sign (*5*). As ambient luminance increases AASHTO recommends increased sign illumination to achieve effective visibility. However AASHTO stops short of developing a method to classify ambient luminance but instead uses a qualitative description shown in Table 1.

Table 1. AASHTO Ambient Luminance Descriptions.

Low	Low levels of ambient luminance exist in rural areas without roadway and/or intersection lighting. Objects at night are visible only in bright moonlight. There is very little or no other lighting in the area.
Medium	Medium levels of ambient luminance exist in intermediate areas with some roadway and/or intersection lighting. May contain small areas of commercial lighting.
High	High levels of ambient luminance exist in urban areas with high levels of roadway lighting. May contain brightly lighted commercial advertising signs, building facades, and/or highly illuminated parking facilities (*5*).

These descriptions leave some uncertainty in classification. Phrases such as “some roadway and/or intersection lighting” have no definite meaning, and some specific situations such as residential, or safety lighting are not addressed. The uncertainty between classifications leaves the decision in the hands of the design engineer’s judgment, and can lead to inconsistency.

GOALS AND OBJECTIVES

The purpose of this research was to develop a method to collect human factors data for background complexity. Those data will be used in the development of a model to objectively rate background complexity. In order to achieve this goal the researchers completed the following objectives:

- Gathered images of various background complexities that can be used for a human factors survey as well as for analysis.
- Created a pilot survey to collect human factors data.
- Evaluated the effectiveness of the survey.
- Revised the survey for use in the parent project.

PROBLEM APPROACH

The initial approach to the overall project was to attempt to develop a method with which background complexity can be objectively calculated using an algorithm based on factors surrounding the sign. A still image would be used to capture the background behind the sign. The initial belief was that a region of evaluation could be established around the sign based off of some factor multiplied by the dimensions of the sign in each direction. The established region would then be evaluated using the algorithm based off of factors such as ambient luminance, the number of lights, their brightness, and the numbers of signs.

However, the automated system must be calibrated with human factors data. While the parent project will ultimately gather human factors field data, the belief was a pilot survey could be used for the initial model calibration, and the validation of perceived components that impact background complexity.

METHODOLOGY

The following sections detail the process used to create the background complexity pilot survey.

Field Data Collection

To portray a range of background complexity from real world situations the researchers collected images of guide signs along interstate highways in three urban areas in Texas. Over 1700 images were gathered from areas around Dallas, Austin, and San Antonio. The size of these cities allowed for a full range of background complexities from the heavily urban downtowns to the rural outskirts of the cities.

The images were taken while in motion from the perspective of the driver under constant settings with a high bit depth. This allowed for the same image to be used for future analysis using the high bit depth and to be converted to a lower bit depth to be used for human factors. The higher bit depth allows more precise analysis while the lower bit depth enables the image to be seen on a standard monitor. The researchers attempted to select camera settings to insure clear photos. This meant balancing the need to increase exposure time to take brighter images in the dark environment, and the need to limit exposure time to avoid blurring the images from the motion and vibration of the vehicle.

Image Selection

The researchers selected a 16 image subset from the over 1700 initial images to be used in the survey. These images can be seen in Appendix A. The images were selected based off of clarity, position, distance, and range of complexity. The selection criteria can be seen in more detail below:

- **Clarity** - Due to the images being taken from a vehicle moving at freeway speeds some images varied in quality because the motion and the vibration of the vehicle. The images were first narrowed down by removing any images that were blurry or fuzzy.
- **Position** - Next to select images that can be analyzed every sign had needed to have a region of analysis around it. The images were selected based off of the target sign's position. Any images without a region around the extending at least one times the signs dimensions in each direction were removed.
- **Distance** - In order to achieve comparable human factors data those images were further narrowed down to images of similar distance from the sign.
- **Complexity** - From the images that met all of these requirements 16 were then selected to portray a range of background complexities. These images ranged from a low complexity single overhead guide sign against a dark background, Figure 3, to a high complexity cluster of overhead guide signs surrounded by lights, Figure 4. During the selection the researchers specifically attempted to include images that had varying numbers of signs.

Figure 3. Low Complexity.

Figure 4. High Complexity.

Pilot Survey

The researchers used the 16 selected images to create a pilot survey. The survey lasted between 15–20 minutes and surveyed 22 participants. Out of the 22 participants, 19 were average drivers while the remaining 3 were familiar with sign visibility and constituted an expert panel. The survey, shown in Appendix B, was designed to give a brief general description of the project and consisted of two parts, a ranking and a rating.

Part 1: Ranking

The ranking used 10 of the 16 selected images. Each image was printed on a 6 in. × 8 in. laminated card. The ranking gave the participants a chance to rank the images from first to tenth place in relation to each other. The cards where shuffled randomly, to ensure an unbiased presentation, then handed to the participants. They were instructed to sort the cards in order from least complex (#1) to most complex (#10). Most complex was described as being the hardest to locate the sign and the most distracting, while least complex was described as the easiest to locate the sign and the least distracting. The hope was not only to gain the ranking data but also to familiarize the participants with a range of what complexity can be to limit the learning curve for the rating.

Part 2: Rating

The rating used all 16 of the selected images and repeated two of the images. The two images were repeated to see if there was any noticeable effect between different signs in the same image. The images were presented in a slideshow format, a sample of which can be seen in Appendix C. The researchers instructed the participants that they would be shown a slide with the information needed to identify the sign around which they were to rate the background, then they would be shown an image with the sign. The participants were asked to rate the background complexity from 1 to 5, with 1 being the least complex (i.e., easy to find and no or few distractions) and 5 being most complex (i.e., hard to find the sign and many distractions). They were also instructed to comment on any factors that seemed to increase or decrease the complexity of the background. Each participant was then shown the shown a survey slideshow. To prevent bias the researchers developed three surveys that each had different random sign order. After each ranking any comments about factors that reduced or increased the background complexity were recorded.

RESULTS

The results of the ranking can be seen in Table 2. The ranking had a standard deviation of 1.5. Assuming a linear trend between the rankings, each ranking was then averaged and then re-ranked in from least to most complex, as seen in Table 3. When re-ranked the images had an average difference between the expert panel and the other participants of 0.8.

Table 2. Ranking Data.

Image	Expert Panel			Participant																			
	A	**B**	**C**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**
A	1	1	2	1	1	1	1	1	1	1	1	1	1	5	3	1	1	2	1	1	1	9
B	10	9	9	10	9	10	10	9	9	8	10	10	10	10	5	7	10	9	9	8	9	10
C	8	8	8	8	8	5	8	7	6	7	9	8	8	8	8	9	8	8	8	7	8	7
D	5	4	6	4	6	7	3	6	8	10	4	5	5	7	9	8	2	7	6	9	5	8
E	3	2	1	2	4	6	4	2	3	3	2	3	3	1	4	3	3	1	5	6	2	3
F	4	6	4	5	3	4	5	5	4	4	5	4	4	2	1	4	4	4	3	3	4	6
G	6	5	7	6	7	3	7	8	7	6	7	7	6	3	6	5	7	6	4	5	7	1
H	3	2	3	3	4	6	4	2	3	3	2	3	3	1	4	2	2	3	2	2	3	5
I	9	10	10	9	10	8	9	10	10	9	8	9	9	9	10	10	9	10	10	10	10	2
J	7	7	5	7	5	2	6	4	5	5	6	6	7	6	7	6	6	5	7	4	6	4

Table 3. Re-ranking.

Image	Participant Average	Std Dev.	Participant Re-ranking	Expert Panel Re-ranking	Difference
A	1.8	2.0	1	1	0
B	9.1	1.3	10	9	1
C	7.6	1.0	8	8	0
D	6.3	2.2	7	5	2
E	3.2	1.4	3	2	1
F	3.9	1.1	4	4	0
G	5.7	1.8	6	6	0
H	2.9	1.2	2	3	1
I	9.0	1.8	9	10	1
J	5.5	1.3	5	7	2

The results of the rating can be seen in Table 4, and Table 5. The rating had a standard deviation of 0.83 and an average difference between the expert panel and participants of 0.36.

Table 4. Rating Data.

Image	Expert Panel			Participant																		
	A	**B**	**C**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**
A	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
B	5	5	3	5	5	4	4	4	3	5	5	5	5	5	1	3	5	5	3	3	4	3
C	4	3	3	4	5	4	4	3	2	3	4	3	4	3	2	3	5	4	2	4	3	4
D	4	4	2	4	4	2	4	5	1	3	3	5	3	2	3	3	3	4	3	3	4	2
E	4	3	3	2	3	5	3	1	1	2	2	3	3	4	1	3	3	4	2	2	2	5
F	3	2	2	2	2	2	2	1	1	1	2	2	3	1	1	1	2	3	1	1	2	3
G1	1	2	2	2	2	4	3	1	5	2	1	2	2	1	2	2	2	2	2	2	2	3
G2	2	2	2	2	2	3	3	1	2	1	2	2	3	*	1	2	2	2	2	1	2	3
H	4	2	3	3	2	2	4	4	1	4	3	3	4	2	3	4	2	4	2	4	3	3
I	2	2	2	1	2	2	2	1	1	1	1	2	2	2	1	1	2	2	2	1	1	2
J	1	2	1	1	1	2	1	1	2	1	2	1	1	1	1	1	1	1	1	1	1	1
K	3	3	1	2	3	3	2	1	1	1	3	3	2	1	1	1	3	3	1	2	1	2
L	3	3	3	2	4	1	4	3	2	3	4	4	4	3	1	3	3	3	2	2	4	1
M	2	2	1	2	1	3	1	1	1	1	2	1	2	1	1	2	2	1	1	1	2	1
N1	5	5	5	5	5	3	5	4	3	5	5	5	5	5	5	5	3	5	4	4	5	3
N2	5	5	4	5	4	2	5	4	2	5	4	5	5	5	5	5	4	5	4	4	5	4
O	2	2	2	3	3	2	3	1	1	1	2	2	3	3	1	2	2	3	2	1	2	1
P	4	4	3	4	3	1	3	1	1	1	2	3	3	4	1	3	3	1	3	2	3	1
Series[1]	c	a	b	c	c	b	b	a	a	c	b	a	c	b	b	a	a	b	a	b	c	c

*Participant stated he or she was rating the sign
[1]Refers to the different image order survey that were developed

When the same 10 images used in both the Ranking and the Rating were both re-ranked based upon their averages the images had almost the same rating with only image B and I alternating between 9th and 10th as shown in Table 6.

Participants commented repeatedly that having a dark/clear border in the area immediately around the sign helped to decrease background complexity, while multiple signs, lots of lights, lights close to the sign and traffic increased complexity.

During the survey the researchers also observed that some of the participants appeared to rate the signs, focused on the clarity, or were uncertain of how large of an area they should be evaluating.

Table 5. Rating Analysis.

Image	Participant Average	Std Dev.	Expert Average	Difference
A	1.1	0.23	1.3	0.28
B	4.1	1.13	4.3	0.28
C	3.5	0.90	3.3	0.14
D	3.2	1.03	3.3	0.12
E	2.7	1.20	3.3	0.65
F	1.7	0.73	2.3	0.60
G1	2.2	0.98	1.7	0.54
G2	2.0	0.69	2.0	0.00
H	3.0	0.94	3.0	0.00
I	1.5	0.51	2.0	0.47
J	1.2	0.37	1.3	0.18
K	1.9	0.88	2.3	0.44
L	2.8	1.08	3.0	0.21
M	1.4	0.61	1.7	0.25
N1	4.4	0.84	5.0	0.58
N2	4.3	0.95	4.7	0.35
O	2.0	0.82	2.0	0.00
P	2.3	1.10	3.7	1.40

Table 6. Ranking and Rating Comparison.

Image	Ranking	Rating
A	1	1
B	10	9
C	8	8
D	7	7
E	3	3
F	4	4
G	6	6
H	2	2
I	9	10
J	5	5

FINDINGS

The results from the survey showed that the participants rated the guide signs very similarly to the expert panel. The participants also identified many of the same factors the researchers believed affect visibility. These results preliminarily support that the number of lights, the close proximity of light to the sign and having multiple signs increased the background complexity, while having a clear dark border immediately around the sign decreased it.

During the survey some of the participants quickly passed over the identification slides. While some were able to quickly read it, a few were clearly ignoring it. This was evident by participants asking how they were supposed to know which sign to look at, or stating they had already rated the sign when shown images that were repeated with a different target sign. This is an issue because without knowing which sign they were rating some participants were not necessarily rating the correct sign when multiple signs were present.

Some of the participants appeared to focus on the message of the sign. They commented that the message was confusing, or they did not know which lane they would need to be in had they been driving there. Even asked repeatedly to not rate the sign, some people seemed unable to separate the two, which raises the concern that they may have been rating the message as well as the background.

While various efforts were made to take images of similar quality and format, some of the participants noted that there were some variations between the images. The participants commented that some signs were slightly clearer that others, which again suggests some participants may have been also rating the sign’s message. Variation in quality can potentially distract the participants from focusing on the background complexity.

The sign eccentricity is how far off from the viewer’s center of vision a sign is located. While in most images the signs were focused in the center of vision, in one image the signs varied substantially from the center of the image. This image seemed to have a higher rating than an image with the sign centered in a similar background complexity.

RECOMMENDATIONS

During the research, factors were found that had some adverse effects on the survey. Some participants ignored the identification slide in the rating, some rated the message on the sign, and some images varied in clarity and sign eccentricity. Following the pilot survey, the researchers recommend the following steps be taken to improve the accuracy of the human factors data:

- Collect additional images focusing on:
    - Centering the sign in the image.
    - Taking the images at the same distance.
    - Improving the clarity.
- Crop the images to the same area of evaluation for the human factors data as the evaluation model. The region of analysis should be based off of a realistic field of vision, potentially focusing on the foveal vision region. The foveal region is the central part of

your vision which is used for important activities and is where your vision is the sharpest. Using a region based off of your vision also ensures the same angular region of analysis for every sign. This would prevent larger signs from having larger evaluation regions, which could lead to higher complexity ratings for larger signs even though they are less affected by background complexity.

- Remove the target signs messages. To deal with both issues of participants ignoring the identification slides and focusing on the message from the sign the researchers suggest editing the survey images to remove the message from the sign. The message would then be replaced with a consistent identification mark, such as a dot or standard identification message. Removing the message will limit the participants' ability to judge the sign and give them a consistent object to identify.
- Increase the survey's length. To gain more complete human factors data, the researchers also suggest increasing the number of images used in the survey. Using more images will allow the researchers to further investigate the influence of different factors such as varying numbers of signs and evaluating different signs in the same image.

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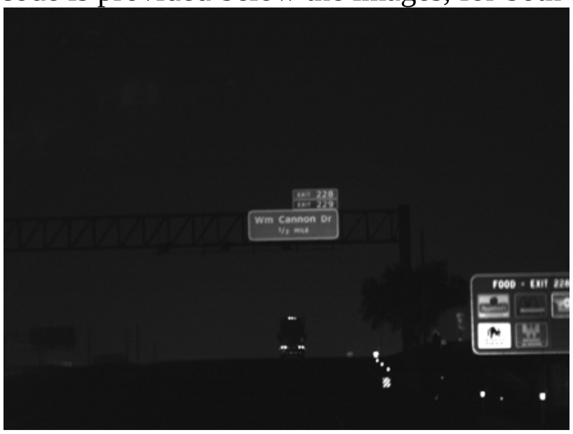
3. Paulmier, G., C. Brusque, V. Carta, and V. Nguyen. "The Influence of Visual Complexity on the Detection of Targets Investigated by Computer Generated Images." *Lighting Research and Technology*, Volume 33, 2001, pg. 197–205.
4. Schieber, F., and C.H. Goodspeed III. "Nighttime Conspicuity of Highway Signs as a Function of Sign Brightness, Background Complexity and Age of Observers." *Human Factors and Ergonomic Society*, Albuquerque, NM, 1997, pg. 1362–1366.
5. *AASHTO Roadway Lighting Design Guide*. American Association of State Highway and Transportation Officials, Washington, D.C., 2005 Edition.

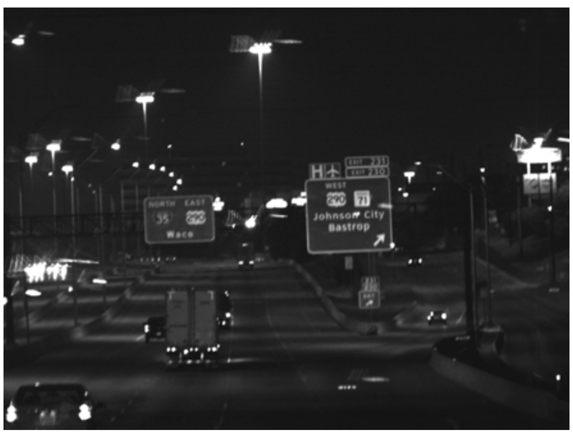
APPENDIX A: 8 BIT IMAGES

Note: The coding used for images may vary between the ranking and rating. Image reference code is provided below the images, for both the rating and the ranking.

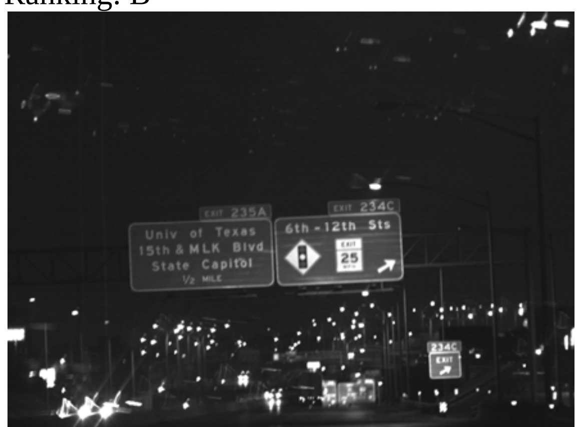


Rating: A (Wm Cannon Dr ½ Mile)
Ranking: A

Rating: B (Woodward St Edwards Univ Exit 231)
Ranking: B

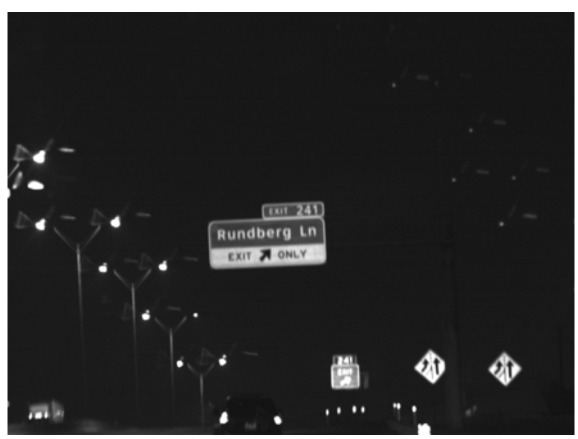


Rating: C (North 35 East 290 Waco)
Ranking: C



Rating: D (6th-12th Sts)
Ranking: NA

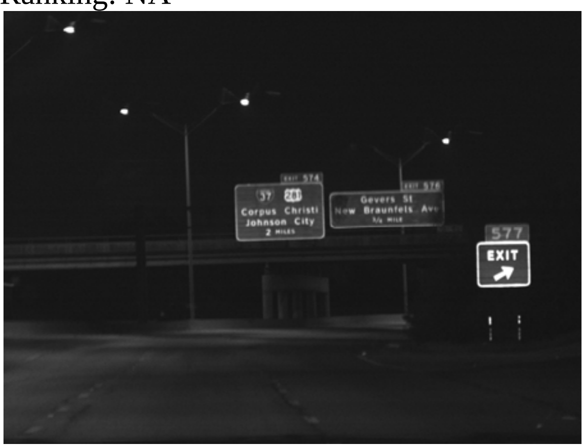
Rating: E (Rundberg Ln)
Ranking: NA



Rating: F (Rundberg Ln exit only)
Ranking: NA

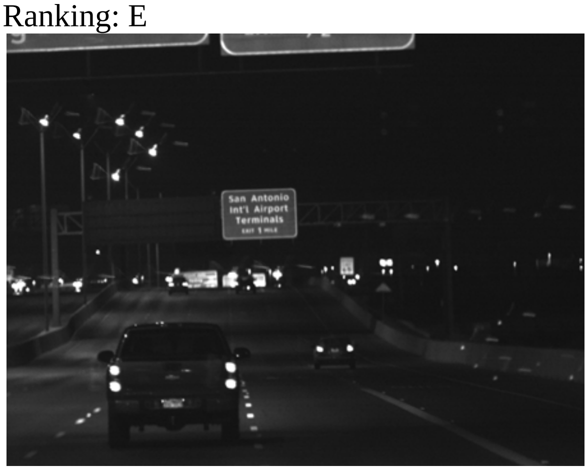
Rating: G1(South 35 West 290 32nd Dean Keeton)
G2 (South 35 West 290 15th-11th St)
Ranking: NA

Rating: H (West 10 North 87 El Paso)
Ranking: D



Rating: I (Corpus Christi Johnson City 2 Miles)
Ranking: E

Rating: J (St. Mary's St Stadium Dr Exit Only)
Ranking: NA



Rating: K (San Antonio Int'l Airport Terminals)
Ranking: F

Rating: L (Nacogdoches Rd)
Ranking: G

Rating: M (To 75 Mc Kinnney ¼ Mile)
Ranking: H

Rating: N1 (Interchange Pkwy Perrin Creek Dr)
Rating: N2 (South 35 410 San Antonio Exit Only)
Ranking I

Rating: O (Southcross Blvd)
Ranking: NA

Rating: P (Interstate 635 (Shield))
Ranking: J

APPENDIX B: PILOT SURVEY

Date: _______________ **Image Series: A**

ANSWER FORM
Background Complexity

This study is part of the National Highway Cooperative Research Project 5-20, which is investigating how different factors affect overhead guide sign's visibility, your ability to see the sign. Guide signs are the large green directional signs located along roadways.

This part of the study is focus on how background complexity affects visibility. Background complexity is the level of clutter around the sign from objects, lights, and their brightness. The belief is that a sign will become less visible more complex the background. In more a complex background it would be difficult to locate the sign and it can be distracting, while in a less complex background it would easy to locate the sign and less distracting. As drivers we would like your input on what constitutes background complexity in the form of ranking and rating images.

Part 1-Ranking

You will be handed 10 cards each with an image of an overhead guide signs. Look at each card and sort the cards into order from least complex, to most complex backgrounds. Least complex means the easiest to locate guide signs and the least distracting from focusing on the sign and most complex means the hardest to locate guide signs, and has the most factors distracting you from the sign.

Rank	*Card #*	*Comments:*
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Part 2-Rating

Now you will be shown a series of 18 images. Before each image you will be shown the information you would need to reach a destination to identify the single sign you should focus on. Then we will show you an image with the guide sign, and you will then rate the complexity of the area surrounding the sign from 1 to 5. A "1" means you can easily locate the sign and there are few distractions, and a "5" means it is hard to locate the sign and there are a lot of distractions. We could also like any comments about what increases or minimizes the complexity. Each image will be ranked on its own and any rating may be repeated, i.e., multiple images may be rated 3 or any number. We would like to have your first reaction and remember there is no right or wrong answer.

Sign 1- Rating_____ -Target Description *St. Mary's St Stadium Dr Exit Only*
Comments:____
____
____

Sign 2- Rating_____ -Target Description *Exit 234C 6th-12th Sts Exit 25 mph*
Comments:____
____
____

Sign 3- Rating_____ -Target Description *North 35 East 290 Waco*
Comments:____
____
____

Sign 4- Rating_____ -Target Description *Wm Cannon Dr ½ MILE*
Comments:____
____
____

Sign 5- Rating_____ -Target Description *Woodward St St Edwards Univ Exit 231*
Comments:____
____
____

Sign 6- Rating_____ -Target Description *Exit 37 Southcross Blvd*
Comments:____
____
____

Sign 7- Rating_____ -Target Description *South 35 West 290 15th-11th Sts*
Comments:____
____
____

Sign 8- Rating_____ -Target Description *West 10 North 87 El Paso*
Comments:____
____
____

Sign 9- Rating_____ -Target Description *Exit 241 Rundberg Ln*
Comments:____
____
____

Sign 10- Rating_____ -Target Description *Exit 26b Interchange Pkwy Perrin Creek Dr*
Comments:____
____
____

Sign 11- Rating_____ -Target Description *South 35 West 290 32nd St Dean Keeton*
Comments:____
____
____

Sign 12- Rating_____ -Target Description *Corpus Christi Johnson City 2 Miles*
Comments:____
____
____

Sign 13- Rating_____ -Target Description *Interstate 635 (Shield)*
Comments:____
____
____

Sign 14- Rating_____ -Target Description *South 35 410 San Antonio Exit Only*
Comments:____
____
____

Sign 15- Rating_____ -Target Description *To 75 Mc Kinney 1/4 Mile*
Comments:____
____
____

Sign 16- Rating_____ -Target Description *Exit 241 Rundberg Ln Exit Only*
Comments:____
____
____

Sign 17- Rating_____ -Target Description *San Antonio Int'l Airport Terminals Exit 1 mile*
Comments:____
____
____

Sign 18- Rating_____ -Target Description *Exit 23 Nacogdoches Rd*
Comments:____
____

APPENDIX C: SAMPLE OF POWERPOINT SURVEY

Instructions Series A

- First you will be given the information to identify the sign
- Second you will be shown an image with the sign
- Rate the background around the sign from 1 to 5
  - 1 means easy to find the sign and few distractions in the background
  - 5 means hard to find the sign and many distractions in the background

Remember

- The intent is to rate the background not the sign remember to focus on the background around the sign
- Please provide comments on anything in the background that makes it particularly difficult to find the sign.

St. Mary's St
Stadium Dr
Exit Only

6th-12th Sts

Identifying Pavement Preservation Treatments Suitable for Performance-Related Specifications

Prepared for
Undergraduate Transportation Scholars Program

by

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Joshua is a member of the American Society of Civil Engineers, an officer of the Society of Future Engineers at Palo Alto College and an officer of the arts organization, Screeners. He is a National Science Foundation STEM scholar and mentors other engineering students in the program. He is involved with his community by regularly volunteering time to South Texas schools and local festivals. Outside of engineering, he enjoys camping, riding motorcycles, and being with his family. Joshua plans on attending graduate school following graduation and attaining a Professional Engineering license.

ACKNOWLEDGMENT

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The author would like to express his appreciation to Nasir Gharaibeh for guidance during the course of this research effort. The author would also like to thank Litao Liu for his help with R programming and analysis.

SUMMARY

With increasing economic strife, cost effectiveness and quality are two very important factors many highway agencies try to control through the use of pavement preservation treatments. These preservation methods help to stretch the lifetime of pavements. According to the Federal Highway Association, pavement preservation treatments are defined as treatments applied to slow the deterioration of an existing pavement and its functional condition without substantially increasing its structural capacity (*1*). Performance-related specifications (PRS) provide highway agencies with guidelines to reward the contractor for exceptional work and ensure quality. While PRS exists for new pavements, there are no such guidelines for preservation treatments.

The purpose of the study presented here was to identify initial construction and material properties that correlate with future performance of these preservation treatments. The preservation treatments that show this correlation will be considered suitable for the PRS. The future performance distresses chosen were the amount of cracking, rutting, and roughness. The Long Term Pavement Performance database provided the initial quality and in-service performance data used in this project.

Two statistical methods were performed in order to identify any correlations found between initial quality and in-service performance. Canonical correlation and multiple linear regression analysis were chosen for their ability to find the statistically significant properties. Multiple regression analysis allows for measuring the degree of correlation between a dependent variable and a set of independent variables (i.e., one-to-many). Canonical correlation analysis allows for measuring the degree of correlation between the observed values of two sets of variables (i.e., many-to-many)

The results of the statistical analysis provided significant correlations for the initial properties to the future cracking of each treatment studied. However, some treatments had no correlations to rutting or roughness due to lack of data or very low values of the correlation coefficients. These results will be used to select three treatment types for inclusion into PRS guidelines.

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INTRODUCTION

The need for safe and reliable roads grows along with the nation's population and economy. Therefore, increasing portions of state and federal budgets are being allotted to the maintenance of existing highways. For example, the SAFETEA-LU federal highway bill authorized $25.2 billion to preserve the interstate highway system for the period of 2005 to 2009. In order to maximize the benefits of this appropriation, states may opt for preventative maintenance rather than rehabilitation of existing highways. According to the Federal Highway Administration, each dollar spent on preventative maintenance saves up to $6 in the future (*2*). While preventative maintenance is a cost effective method to curb costs rather than rehabilitation, there is little research to correlate quality assurance methods and in-service performance of the preservation treatments.

Understandably, the lack of some performance-based quality assurance programs for preservation treatments is limiting to both highway agencies and contractors. Highway agencies lack a method for measuring performance lost or gained due to differences in quality between as-designed and as-constructed treatments. Contractors are not given opportunity to innovate and focus on quality that affects the treatment's short- and long-term performance. Performance-related specifications (PRS) provide a way to correlate initial quality and in-service performance. According to the Transportation Research Board, PRS is defined as quality assurance specifications that are based on acceptance quality characteristics (AQCs) that are found to correlate with future performance (*3*). PRS has become a popular quality assurance system for new pavements but applicable PRS guidelines for pavement preservations treatments do not exist.

BACKGROUND INFORMATION

This research is a part of a much larger project sponsored by the National Cooperative Highway Research Program (NCHRP), "Performance-Related Specifications for Pavement Preservation Treatments." The objective of this project is to develop guidelines for use in preparing PRS for pavement preservation treatments. The project deals with preservation treatments for all pavement types, but this paper will only include treatments for Hot-Mix Asphalt (HMA) surfaces pavements.

Performance-Related Specifications

As referenced in the introduction, PRS gives the ability to link initial quality characteristics with the long-term performance of the finished product. A complete and scientifically sound PRS should include the following elements (*4*):

- Characteristics that correlate with the performance of the pavement, that are measurable, and that can be controlled by the material supplier or contractor.
- Pavement performance indicators that are affected by the defined AQCs.
- Statistical acceptance sampling and testing plan (including definition of lots, subplots, and sample size).
- Pay adjustment plan.

Performance prediction indicators are necessary to quantify the performance of these treatments and for PRS. One model in current use for HMA preservation treatments is the Kaplan-Meier method shown below. The model variables are defined as: $F(t_r)$ as the probability of treatment failure at a given time, n as the total number of treatments, and r as the rank of the section in question (*5*).

$$F(t_r) = 1 - \left\{ \frac{n-1}{n} \times \cdots \times \frac{n-(r-1)}{n-(r-1)+1} \times \frac{n-r}{n-r+1} \right\}$$

One can quickly see from this model that initial material and construction (M/C) characteristics are not included into the prediction of pavement performance for preservation treatments. The research performed seeks to correlate these initial M/C parameters to the future distresses in HMA preservation treatments.

Pavement Preservation Treatments

For the purpose of this research project, pavement preservation treatments are defined as treatments applied to slow the deterioration of an existing pavement and its functional condition without substantially increasing its structural capacity (*6*). Preservation treatments are a cost-effective approach that provides an alternative approach to major rehabilitation. The table below details the types of preservation treatments for HMA-surfaced pavements that will be considered in this research effort.

Table 1. Preservation Treatments for HMA-Surfaced Pavements.

Treatment	Description	Purpose
Chip Seals	Application of asphalt to the pavement surface, followed by application of rolled aggregate chips.	• Seal cracking • Inhibit raveling • Improve friction • Inhibit bleeding
Crack Seals	Application of sealant to cracks that undergo little movement.	• Prevent intrusion of moisture through existing cracks
Slurry Seals	A mixture of well-graded aggregate and asphalt emulsion spread in a thin layer (less than 10 mm) over the entire pavement surface.	• Inhibit raveling • Retard asphalt aging • Inhibit bleeding • Improve friction
Thin HMA Overlay	Application of a thin layer of hot-mix asphalt.	• Remove surface distresses • Lower IRI • Seal pavement from water
Hot In-Place Recycling	Removing the existing pavement surface, mixing with a recycling agent, possibly adding virgin asphalt, and replacing it on the pavement.	• Remove low-severity cracking • Remove raveling • Improve friction • Inhibit bleeding

The effect of pavement preservation treatments will be to postpone costly reconstruction and increase the service life of the highways. Figure 1 shows the effect of preservation treatments on pavement performance and service life. The solid line shows the traditional approach of major rehabilitation of the pavement condition as time passes. The shaded region shows the effect preservation treatments and the extension of the service life of the pavements.

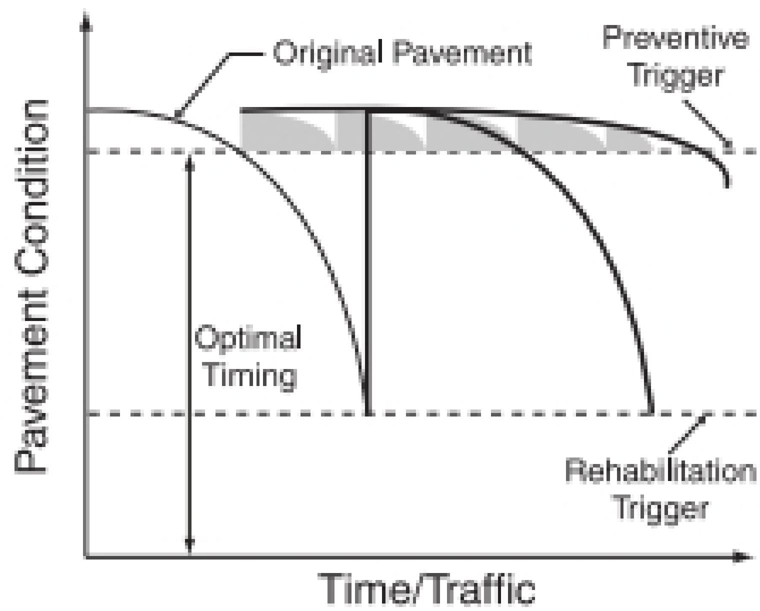

Figure 1. Effect of Preservation Treatments on Pavement Performance.

RESEARCH TASKS

The goal of this research is to identify strong correlations between M/C characteristics and treatment performance. In order to accomplish this, appropriate pavement treatment performance data were collected and prepared for analysis. Statistical analysis was then used to evaluate the suitability of treatments for consideration in PRS.

Data Preparation

The Long Term Pavement Performance (LTPP) database was identified as the primary source of data due to its many advantages. The LTPP is publicly available and has been used in previous research studies. The database is not limited to any particular locality and has detailed data on both initial quality and in-service performance of these treatments. Figure 2 shows the different locations in North America where LTPP test sections are located. Also, the LTPP database is subject to a quality control process, which will protect against any anomalies. The data extracted from the LTPP website were inserted into a readable format that served as the basis for the correlation analyses conducted for each preservation treatment selected. Since the LTPP database includes data unnecessary to this research, Microsoft Access® was used to compile the data into a spreadsheet that will organize each pavement preservation treatment with its performance data.

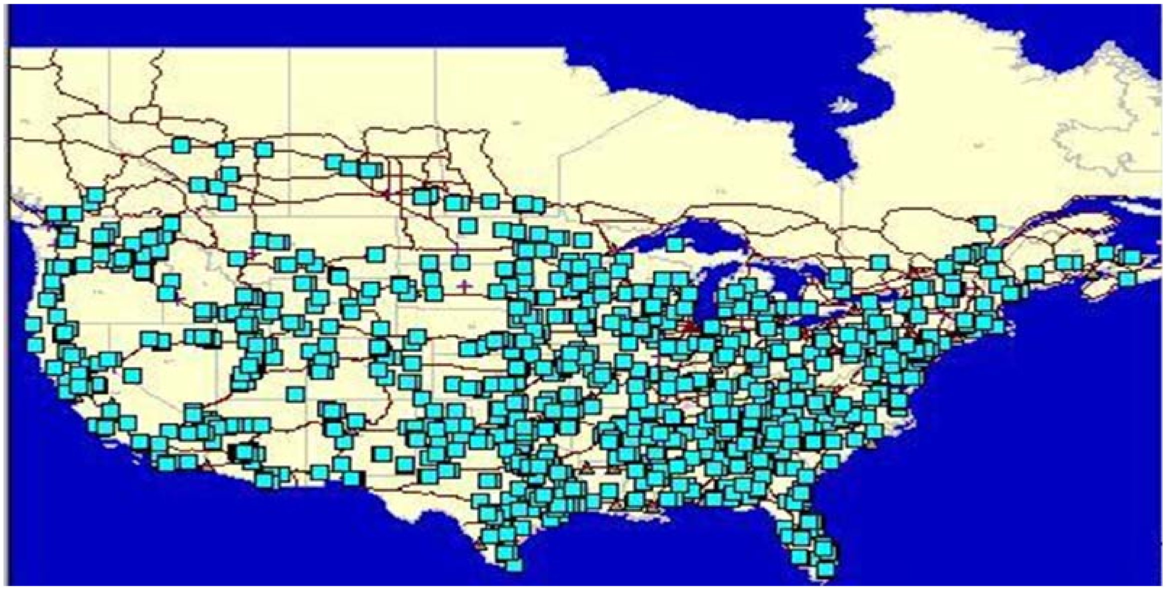

Figure 2. LTPP Test Site Locations.

Statistical Analysis

Canonical correlation analysis (CCA) and linear regression were performed to find any correlations between initial M/C characteristics and treatment performance. CCA can find linear combinations of two sets of variables that have maximum correlation with each other. The linear combinations in CCA are called canonical variables, which are a type of latent variable obtained by multiplying a vector of canonical coefficients to each set of variables. Comparatively, multiple regression allows us to assess the relationship between a dependent variable and a set of independent variables. In this study, the statistical software R is used to conduct CCA and StatTools, an excel add-on, is used to conduct multiple linear regression analysis.

The average distress values for a three-year period are used as the dependent variables for the CCA, while the age of the treatment is used for the dependent variable for regression. The LTPP database may have data of one distress type for up to a time span of 15 years, but in most cases ages one through nine years cover the majority of the distress points. So only the first nine years are used in CCA, meaning there are three independent variables (i.e., Age 1-3, Age 4-6, and Age 7-9). The independent variables included three distress types chosen for analysis. The distress types are rutting, roughness (measured in International Roughness Index, IRI) and a combination of longitudinal and transverse cracking (Total Cracking). The M/C parameters chosen are reasoned to be controllable by the contractor. The table below shows the different M/C characteristics for each individual preservation treatment. The table includes the standard deviation, mean, and minimum and maximum values to show the scope of the LTPP data.

Table 2. M/C Parameters.

Thin HMA Overlay M/C Parameters	**Mean**	**Std. Dev**	**Min**	**Max**
Overlay Thickness, in.	1.11	0.30	0.50	1.90
Asphalt Specific Gravity	1.02	0.012	0.99	1.05
% Passing #4 Sieve	64.22	10.90	35.00	97.00
% Passing # 200 Sieve	3.94	1.71	1.00	7.30
% Asphalt Content	5.65	0.79	4.30	8.10
% Air Voids	4.90	1.77	1.30	8.70
Chip Seal M/C Parameters	**Mean**	**Std. Dev**	**Min**	**Max**
Seal Thickness, in.	0.29	0.12	0.10	0.80
Asphalt Dist. Rate Ratio	1.00	0.073	0.82	1.15
Aggregate Dist. Rate Ratio	1.07	0.19	0	1.46
Temperature, °F	160.18	14.43	132.0	185.00
Flakiness Index	12.47	2.95	7.00	21.00
% Passing #4 Sieve	5.25	9.24	1.00	54.00
% Passing #200 Sieve	0.78	0.44	0	1.90
% Cracking Sealed	38.54	43.00	0	100.00
Penetration, .1mm	119.78	48.45	32.00	216.00
Viscosity at 50°C, s	127.96	65.25	23.00	321.00
Crack Seal M/C Parameters	**Mean**	**Std. Dev**	**Min**	**Max**
Avg. Width of Prepared Crack, in.	1.16	0.50	0.12	1.55
Avg. Depth of Prepared Crack, in.	0.76	1.47	0.10	9.99
Avg. Sealant Temperature, °F	377.46	12.89	349.00	405.00
Avg. Width of Completed Crack, in.	1.95	0.87	0.80	3.40
Avg. Sealant Thickness, in	0.26	0.13	0.03	0.50
Slurry Seal M/C Parameters	**Mean**	**Std. Dev**	**Min**	**Max**
Seal Thickness, in	0.24	0.16	0.10	1.00
Penetration	64.45	21.77	31.00	157.00
Viscosity at 25°C, s	19.15	3.54	7.00	29.00
% Passing #4 Sieve	86.04	4.12	77.00	94.00
% Passing #200 Sieve	10.65	1.33	7.00	15.00
Slurry Dist. Rate Ratio	1.01	0.13	0.79	1.41
% Cracking Sealed	36.22	42.07	0	100. 00
Air Temperature, °F	85.90	9.02	62.0	108.00
Hot-In-Place Recycling M/C Parameters	**Mean**	**Std. Dev**	**Min**	**Max**
Pavement Processed	0.91	0.29	0	1.00
% Passing #4 Sieve	63.80	9.95	47.00	93.10
% Passing #200 Sieve	6.97	3.13	1.00	14.00
Asphalt Amount New	4.03	1.11	0.80	6.30
Bulk Specific Gravity	2.35	0.10	2.14	2.61
Asphalt Content	5.13	1.10	3.30	7.80
% Air Voids	4.35	1.61	3.10	16.50

RESULTS

The following tables include the results of the CCA and regression analysis performed for each preservation treatment. The CCA outputs include canonical correlations and test of significance, canonical coefficients, and loading coefficients (i.e., correlations between individual M/C variables and canonical variables). The linear regression outputs include R-square, regression coefficients, and p-values. For each treatment, the first table will list the canonical correlations for a linear set of the M/C parameters and pavement distresses; the second table presents the loadings of M/C variables on their canonical variables of each distress type. More than one loading coefficients are tabulated if multiple significant canonical correlations are found. A 0.30 guideline has been used as a rule of thumb by authorities, which recommends that only loading coefficients with an absolute magnitude of 0.30 or higher be treated as meaningful (*7*).

Thin HMA Overlay

Table 3 indicates that significant canonical correlations between M/C variables and distress variables exist for total cracking and rutting, but not for roughness (IRI). Three canonical correlations are found for total cracking, while one is found for rutting. No significant correlation could be found for IRI so this was not included in the table.

Table 3. Canonical Correlations and Tests of Significance.

Performance Indicator	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Total cracking	0.80	0.165	3.720	27	117	4.10E-07
	0.60	0.462	2.412	16	82	0.0051
	0.53	0.715	2.389	7	42	0.0376
Rutting	0.77	0.290	1.911	18	63	0.0311

Table 4 below presents the loadings of the M/C parameters for thin HMA overlay distresses. Based on the 0.30 guideline, the multivariate vector of total cracking is associated with all the M/C variables listed. Asphalt specific gravity and aggregate gradation (percent passing #4 and #200 sieve sizes) have a meaningful association with rutting.

Table 4. Loading Coefficients of M/C Variables on Canonical Variables.

M/C Variable	Total Cracking			Rutting
	1	2	3	
Overlay thickness	-0.03	0.36	-0.31	0.06
Asphalt specific gravity	-0.39	0.21	0.13	0.41
% Passing #4 Sieve	0.71	-0.21	0.21	0.67
% Passing #200 Sieve	-0.28	-0.38	0.09	0.61
%AC	-0.05	-0.57	-0.24	0.06
%AV	-0.01	-0.18	0.32	0.20

Table 5 summarizes the output of linear regression for thin overlay treatments. The fit for total cracking is acceptably large and low for rutting and IRI. The number of M/C variables that are found to be significant factors in these fitted linear models is very minimal.

Table 5. Regression Output for Thin HMA Overlay Treatments.

Distress	No. of Obs.	R-square	Significant Variables	p-value
Total cracking	77	0.4987	Overlay Thickness	0.0304
			Age	<0.0001
Rutting	59	0.2799	% Air Voids	0.0467
			Age	0.0062

Chip Seal

The following set of tables show the output results for chip sealing treatments. It can be seen from Table 6 that significant canonical correlations are found for total cracking, roughness, while rutting did not have correlations so this was not included in this table.

Table 6. Canonical Correlations and Tests of Significance.

Performance Indicator	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Total cracking	0.93	0.066	5.298	39	137	1.62E-13
	0.58	0.461	1.853	24	94	0.0191
IRI	0.61	0.495	2.474	16	94	0.0035

Table 7 presents the canonical loadings of the M/C variables in chip seal on their canonical variables. Based on the 0.30 guideline seal thickness, aggregate distribution rate ratio, flakiness index, percent passing #4 sieve, percent cracking sealed, and viscosity of asphalt are associated with the multivariate vector of total cracking. Temperature, percent passing #4 sieve, penetration, and viscosity of asphalt are associated with the multivariate vector of roughness (IRI).

Table 7. Loading Coefficients of M/C Variables on Canonical Variables.

M/C Variable	Total Cracking		IRI
	1	2	
Seal thickness	-0.79	-0.03	0.30
Asphalt distr. rate ratio	0.25	-0.17	0.23
Aggregate distr. rate ratio	0.30	0.01	-0.11
Temperature	0.08	-0.15	0.30
Flakiness index	0.48	-0.31	0.27
% Passing #4 sieve	0.38	-0.08	0.62
% Passing #200 sieve	0.28	-0.06	-0.03
% Cracking sealed	-0.12	-0.50	-
Penetration	-0.01	-0.06	-0.49
Viscosity at 50°C	0.33	0.17	0.66

Table 8 presents the summarized linear regression output for chip seal treatments. Adequate R-square values can be seen for most of the considered distress types. Remarkably increased numbers of significant independent variables are found in the fitted models, compared to those of thin overlay treatments.

Table 8. Regression Output for Chip Seal Treatments.

Distress	No. of Obs.	R-square	Significant Variables	p-value
Total cracking	58	0.4877	Asphalt Distribution-Rate Ratio	0.0309
			Percent Cracks Sealed	<0.0001
			Penetration	0.0106
			Viscosity at 50C	0.0036
			Age	0.0002
IRI	57	0.4544	Seal Thickness	<0.0001
			Aggregate Application-Rate Ratio	<0.0001
			Temperature	0.0358
			Flakiness Index	<0.0001
			%Passing #4 Sieve	<0.0001
			%Passing #200 Sieve	0.0297
			Viscosity at 50C	0.0151

Crack Seal

There was a lack of data beyond six years for crack sealing treatments so a two-year increment was used for the average distress values used for canonical correlation. From Table 9 it can be seen there is a significant relationship between the M/C variables and total cracking. Only total cracking is considered for crack sealing treatments.

Table 9. Canonical Correlations and Test of Significance.

Performance Indicator	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Total cracking	0.95	0.084	9.962	15	103	3.84E-14

The table below shows only average width of completed crack as the only variable associated with total cracking.

Table 10. Loading Coefficients of M/C Variables on Canonical Variables.

M/C Variable	Total Cracking
Avg. width of prepared crack	-0.06
Avg. depth of prepared crack	0.06
Avg. sealant temperature	-0.20
Avg. width of completed crack	0.92
Avg. sealant thickness above or below pavement surface	0.12

The linear regression results in Table 11 show age as the only significant variable to total cracking.

Table 11. Regression Output for Crack Seal Treatments.

Distress	No. of Obs.	R-square	Significant Variables	p-value
Total cracking	63	0.0467	Age	0.0331

Slurry Seal

Table 12 shows total cracking and IRI have significant correlations with M/C variables in the slurry seal treatments. Two canonical correlations are found for total cracking, and one for roughness. No significant correlation can be found in the rutting data so this information was not included in the table.

Table 12. Canonical Correlations and Tests of Significance.

Performance Indicator	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Total cracking	0.96	0.037	9.63	42	199	1.03E-29
	0.68	0.439	2.665	26	136	0.0001
Roughness (IRI)	0.89	0.132	3.655	36	134	2.80E-08

Based on the 0.30 guideline, Table 13 indicates that penetration and viscosity of asphalt, percent passing #4 sieve, crack severity, percent cracking sealed prior to sealing, and temperature are associated with the multivariate vector of total cracking; while penetration of asphalt, aggregate gradation, aggregate moisture, slurry distribution rate ratio, and temperature are correlated to roughness.

Table 13. Loading Coefficients of M/C Variables on Canonical Variables.

M/C Variable	Total Cracking		IRI
	1	2	
Seal Thickness	0.09	0.25	0.13
Penetration	0.09	0.41	-0.61
Viscosity at 25C	-0.39	-0.11	0.00
%Passing #4 Sieve	-0.03	-0.62	0.44
%Passing #200 Sieve	-0.08	-0.06	-0.34
Slurry Distribution Rate Ratio	-0.21	-0.42	0.38
Crack Severity	0.01	-0.36	-
%Cracking Sealed	0.37	-0.12	-
Air Temperature	-0.59	-0.21	0.42

Table 14 shows the linear regression results for slurry seal treatments. The R-square values are considerably low, comparing to those in thin overlay and chip seal. Moreover, the R-square for IRI model is very low although significant canonical correlation is found from CCA.

Table 14. Regression Output for Slurry Seal Treatments.

Distress	No. of Obs.	R-square	Significant Variables	p-value
Total cracking	84	0.4030	%Passing #4 Sieve	0.0002
			Crack Severity	0.0046
			Age	<0.0001
IRI	85	0.1357	Seal Thickness	0.0094
			%Passing #200 Sieve	0.0374

Hot-In-Place Recycling

In the table below cracking and roughness are found to have significant correlations with M/C variables, and that three canonical correlations exist for roughness. The LTPP database did not include enough data points to perform CCA or regression for rutting.

Table 15. Canonical Correlations and Tests of Significance.

Performance Indicator	Canonical Correlation	Wilks' L	F	df1	df2	p-value
Total cracking	0.96	0.052	17.739	12	103	4.59E-20
IRI	0.77	0.167	8.900	21	216	1.25E-19
	0.69	0.414	7.021	12	152	4.63E-10
	0.47	0.781	4.312	5	77	0.0016

Table 16 shows that percent passing #200 sieve and asphalt content are associated with total cracking, while all M/C variables are associated with roughness.

Table 16. Loading Coefficients of M/C Variables on Canonical Variables.

M/C Variable	Total Cracking	IRI		
		1	2	3
Pavement Processed	-	-0.80	-0.36	0.01
%Passing #4 Sieve	0.29	0.37	-0.51	-0.37
%Passing #200 Sieve	0.50	0.38	-0.42	-0.13
Asphalt Amount New	-	-0.03	0.02	-0.95
Bulk Specific Gravity	-	0.01	0.192	0.33
Asphalt Content	0.94	0.26	-0.69	-0.41
Percent Air Voids	-0.06	-0.15	-0.43	0.08

Table 17 is a summary of linear regression output for hot in-place recycling treatments. The R-square values are very low, indicating a poor fit of the linear models. As with CCA, rutting was not included due to lack of LTPP data.

Table 17. Regression Output for Hot-In-Place Recycling.

Distress	No. of Obs.	R-square	Significant Variables	p-value
Total cracking	115	0.3212	%Passing #200 Sieve	<0.0001
			Asphalt Content	<0.0001
			%Air Voids	<0.0001
			Age	<0.0001
IRI	112	0.2856	%New Asphalt Cement	<0.0001

CONCLUSIONS

CCA and linear regression were performed on LTPP data for HMA pavement preservation treatments to study the association between material and construction and in-service performance. When the performance data of a certain treatment type is treated appropriately, CCA can be applied to study the existence of correlation between M/C variables and performance variables. This study showed the existence of significant correlations between M/C properties and one or more performance indicators (cracking, rutting, and roughness) for each preservation treatment. The results from linear regression verify some of the results of the CCA. However, the results do not link up for crack seal treatment. Thin HMA overlays were the only treatment type to produce any correlation for rutting distresses. The parent research project will use these results to select appropriate preservation treatment types to be used in developing guidelines for PRS.

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APPENDIX A: THIN HMA OVERLAY REGRESSION OUTPUT TABLES

Table 18. Total Cracking Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.7062	0.4987	0.4475	75.65
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	10	557805.63	55780.56	9.7476
Unexplained	98	560806.90	5722.52	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	-68.75	826.21	-0.0832	0.9339
OL_THICKNESS	-70.76	32.22	-2.1962	0.0304
ASP_SG	48.87	828.09	0.0590	0.9531
NO_4_PASSING	-0. 30	0.99	-0.3006	0.7643
NO_200_PASSING	2.89	4.99	0.5790	0.5639
%AC	6.08	14.15	0.4297	0.6684
%AV	4.75	5.44	0.8732	0.3847
AGE	18.98	2.07	9.1504	< 0.0001

Table 19. Rutting Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.5291	0.2799	0.1866	1.51
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	7	48.11	6.87	2.9992
Unexplained	54	123.76	2.29	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	-22.63	20.03	-1.1299	0.2635
OL_THICKNESS	-0.88	1.17	-0.7527	0.4549
ASP_SG	19.38	19.52	0.9929	0.3252
NO_4_PASSING	0.09	0.06	1.4895	0.1422
NO_200_PASSING	-0.07	0.21	-0.3475	0.7296
%AC	-0.49	0.37	-1.3342	0.1877
%AV	0.46	0.23	2.0361	0.0467
AGE	0.16	0.05	2.8474	0.0062

APPENDIX B: CHIP SEAL REGRESSION OUTPUT TABLES

Table 20. Total Cracking Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.6984	0.4877	0.4453	67.50
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	13	681012.11	52385.55	11.4988
Unexplained	157	715253.20	4555.75	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	193.54	131.79	1.4686	0.1440
THICKNESS	32.72	67.48	0.4849	0.6285
ASP_DIST_RATE_RATIO (ACTUAL/TARGET)	-171.84	78.90	-2.1779	0.0309
AGG_APPL_RATE_RATIO (ACTUAL/TARGET)	36.81	44.51	0.8270	0.4095
TEMPERATURE	0.11	0.56	0.1887	0.8506
FLAKINESS_INDEX	2.40	2.15	1.1161	0.2661
NO_4_PASSING	0.31	0.54	0.5763	0.5652
NO_200_PASSING	-26.03	13.78	-1.8887	0.0608
PERCENT_SEALED	0.69	0.15	4.6613	< 0.0001
PENETRATION	-0.44	0.17	-2.5878	0.0106
VISCOSITY_AT_50	-0.34	0.11	-2.9555	0.0036
AGE	6.25	1.65	3.7870	0.0002

Table 21. IRI Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.6741	0.4544	0.4304	0.51
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	10	48.35	4.83	18.9090
Unexplained	227	58.04	0.25	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	1.58	0. 70	2.2687	0.0242
THICKNESS	2.19	0.41	5.3777	< 0.0001
ASP_DIST_RATE_RATIO (ACTUAL/TARGET)	-0.81	0.49	-1.6396	0.1025
AGG_APPL_RATE_RATIO (ACTUAL/TARGET)	-1.86	0.26	-7.0498	< 0.0001
TEMPERATURE	0.01	0.00	2.1114	0.0358
FLAKINESS_INDEX	0.07	0.01	5.1676	< 0.0001
NO_4_PASSING	0.02	0.00	6.0637	< 0.0001
NO_200_PASSING	-0.19	0.09	-2.1879	0.0297
PENETRATION	0.00	0.00	2.0252	0.0440
VISCOSITY_AT_50	0.00	0.00	2.4485	0.0151
AGE	0.02	0.01	2.1851	0.0299

APPENDIX C: CRACK SEAL REGRESSION OUTPUT TABLE

Table 22. Total Cracking Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.2160	0.0467	0.0120	136.78
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	6	151121.89	25186.98	1.3463
Unexplained	165	3086804.55	18707.91	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	-100.06	390.40	-0.2563	0.7980
WIDTH_MEAN	34.97	28.62	1.2219	0.2235
DEPTH_MEAN	45.07	58.16	0.7750	0.4395
AVG_SEAL_TEMP	0.37	1.08	0.3388	0.7352
AVG_WIDTH_CRACK	28.86	16.31	1.7702	0.0785
SEAL_THICKNESS	-88.30	114.40	-0.7718	0.4413
AGE	9.19	4.28	2.1491	0.0331

APPENDIX D: SLURRY SEAL REGRESSION OUTPUT TABLES

Table 23. Total Cracking Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.6348	0.4030	0.3630	110.29
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	13	1592842.522	122526.35	10.0721
Unexplained	194	2359994.426	12164.92	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	524.67	238.27	2.2020	0.0288
SL_THICKNESS	-113.33	134.37	-0.8434	0.4000
DUCTILITY	4.66	1.21	3.8621	0.0002
PENETRATION	0.17	0.46	0.3695	0.7122
VISCOSITY_AT_25	4.54	2.40	1.8901	0.0602
NO_4_PASSING	-7.36	1.94	-3.7917	0.0002
NO_200_PASSING	-11.04	5.65	-1.9543	0.0521
SLURRY_RATE_RATIO	-77.89	73.06	-1.0661	0.2877
PERCENT_SEALED	0.24	0.20	1.1897	0.2356
PAVE_TEMP	0.09	1.10	0.0848	0.9325
AIR_TEMP	-2.36	1.48	-1.5977	0.1117
AGE	20.12	2.50	8.0609	< 0.0001

Table 24. IRI Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.3683	0.1357	0.0962	0.56
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	11	12.02	1.09	3.4386
Unexplained	241	76.58	0.32	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	2.26	1.80	1.2597	0.2090
SL_THICKNESS	1.69	0.65	2.6177	0.0094
PENETRATION	0.00	0.00	-1.7165	0.0874
VISCOSITY_AT_25	0.001	0.01	0.7614	0.4471
NO_4_PASSING	-0.02	0.01	-1.6121	0.1082
NO_200_PASSING	0.06	0.03	2.0934	0.0374
SLURRY_RATE_RATIO	-0.17	0.40	-0.4359	0.6633
AIR_TEMP	0.00	0.01	0.2040	0.8385
AGE	0.02	0.01	1.6371	0.1029

APPENDIX E: HOT-IN-PLACE RECYCLING REGRESSION OUTPUT TABLES

Table 25. Total Cracking Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.5667	0.3212	0.3135	100.49
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	5	2116739.177	423347.84	41.9190
Unexplained	443	4473943.792	10099.20	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	280.28	33.22	8.4367	< 0.0001
NO_4_PASSING	-0.54	0.61	-0.8826	0.3779
NO_200_PASSING	-7.87	1.55	-5.0755	< 0.0001
ASPHALT_CONTENT	-27.03	4.60	-5.8710	< 0.0001
PERCENT_AIR_VOIDS	-15.00	3.66	-4.0997	< 0.0001
AGE	10.62	1.12	9.4868	< 0.0001

Table 26. IRI Regression.

Summary	**Multiple R**	**R-Square**	**Adjusted R-Square**	**StErr of Estimate**
	0.5345	0.2856	0.2727	0.267
ANOVA Table	**Degrees of Freedom**	**Sum of Squares**	**Mean of Squares**	**F-Ratio**
Explained	7	10.99	1.57	22.0498
Unexplained	386	27.49	0.07	
Regression Table	**Coefficient**	**Standard Error**	**t-Value**	**p-Value**
Constant	2.15	0.53	4.0483	< 0.0001
NO_4_PASSING	0.00	0.00	-1.6145	0.1072
NO_200_PASSING	0.00	0.01	-0.1548	0.8771
AC_AMOUNT_NEW	-0.10	0.02	-5.1327	< 0.0001
BULK_SPEC_GRAVITY	-0. 10	0.19	-0.5114	0.6094
ASPHALT_CONTENT	-0.04	0.02	-1.9388	0.0533
PERCENT_AIR_VOIDS	-0.02	0.01	-1.5568	0.1203
AGE	0.00	0.00	0.8301	0.4070

Arsenic Content and Retroreflectivity of Glass Beads Used in Pavement Markings

Prepared for
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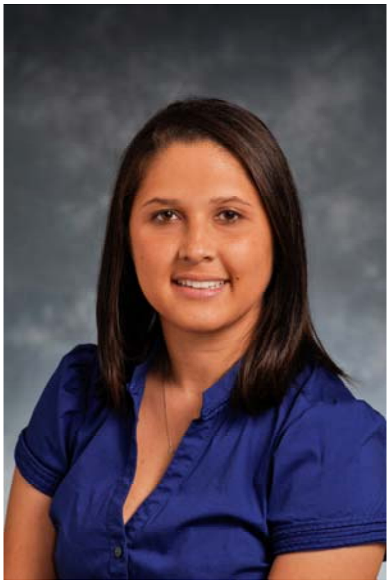

STUDENT BIOGRAPHY

Hidi Marie Wood is from Austin, Texas, and is a senior at Texas A&M University in College Station, Texas. She will be graduating in December 2011 with a Bachelor of Science degree in Civil Engineering with a focus in Transportation Engineering and a minor in business. She is a Zachry Family Scholarship Recipient and an Associated General Contractors Scholarship Recipient. Hidi is a member of the American Society of Civil Engineers, Society of Women Engineers, and Sigma Alpha Lambda National Honor Society. She enjoys spending time with her family and friends. Some of Hidi's interests involve playing the violin, going to the movies, shopping, and playing golf. After Hidi completes her undergraduate degree she plans to obtain a master's degree in civil engineering and become a licensed Professional Engineer.

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SUMMARY

The objective of the research was to evaluate the relationship between arsenic content and retroreflective performance of 10 glass bead samples used in pavement markings that were provided by various state Department of Transportation agencies. The total arsenic content of the beads was determined by digesting the beads according the Pacific Northwest National Laboratory's KOH Fusion (KOH Fusion) method followed by analysis with EPA Method 6020A (inductively coupled plasma mass spectroscopy, ICP-MS). Retroreflective performance of the bead samples was determined by creating pavement marking samples on metal slabs and measuring the resulting marking retroreflectivity using a retroreflectometer. Pearson's product moment correlation coefficient was determined and used to assess the direction and the strength of the correlation between the arsenic content of the beads and their retroreflective performance.

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INTRODUCTION

Pavement markings are vital for ensuring road safety. Due to their retroreflective properties, glass beads allow pavement markings to be visible during poor driving conditions including wet weather and at night. However, glass beads are known to contain part-per-million (ppm) concentrations of arsenic and other heavy metals. Exposure to beads during their manufacturing, application, product use in markings, and marking removal may pose a level of risk to people and the environment that is currently undefined. Research occurring at TTI seeks to characterize the risk of arsenic within glass beads used in pavement markings. The research also seeks to determine if a relationship exists between the retroreflective properties of the beads and the arsenic content of the beads in order to inform decision making.

BACKGROUND

Pavement Markings

Pavement markings are a communication tool assisting road users to travel the road in a safe and efficient manner (*1*). Based on the Manual on Uniform Traffic Control Devices requirements, markings across the nation are standardized so that road users can easily recognize what is expected from the user to drive safely (*1*). The American Association of State Highway and Transportation Officials reported that on average a highway death occurs due to lane departure every 21 minutes, which makes driver safety one of the biggest concerns in transportation (*2*). Improving the visibility of pavement markings can significantly contribute to reducing highway mortality. While there are several ways of improving visibility of pavement markings under poor conditions, the most common approach is to use retroreflective glass beads.

Retroreflective Glass Beads

Retroreflective glass beads used in pavement markings are predominantly manufactured using discarded glass. The discarded glass stream originates from residential glassware such as cathode-ray tubes from televisions, windowpanes, stained glass, incandescent bulbs, and other industrial and commercial sources. The discarded glass contains variable amounts of metals, including arsenic, depending on the source of the discarded glass, which ends up in the recycled glass bead product. Glass beads are an integral portion of pavement marking visibility on roadways due to their low cost and effective properties. The beads allow for the vehicles headlamps to return, or retroreflect, light back to the driver making the pavement markings more visible (*3*). Figure 1 shows how glass beads retroreflect light (*3*). Retroreflectivity is important for safe and efficient traveling when visibility is low, such as at night or when it is raining. The retroreflective properties of the glass beads are dependent upon the shape and optical properties of the glass. Figure 2 shows predominantly spherical beads with minor visible imperfections, while Figure 3 shows spherical and non-spherical beads with visible imperfections within the glass matrix (*Dr. Paul Carlson unpublished data*). Because beads that contain imperfections result in lower performance in retroreflectivity, beads of higher purity are preferred for use in pavement markings (*Dr. Paul Carlson unpublished data*).

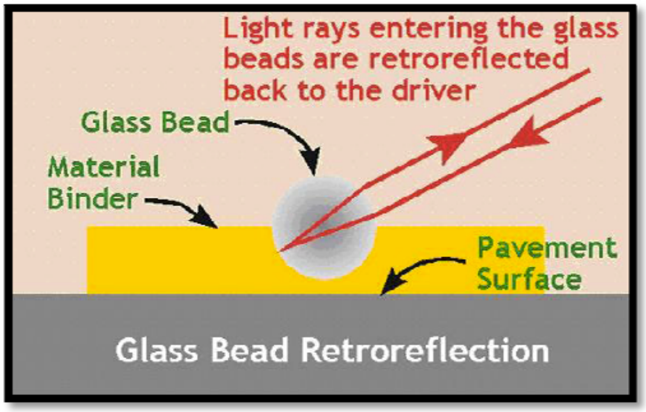

Figure 1. Pavement Marking Retroreflectivity Using Glass Beads (*3*).

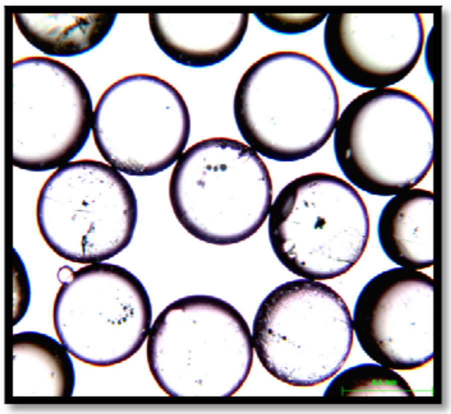

Figure 2. Beads Having Lower Visible Impurities (*Dr. Paul Carlson unpublished data*).

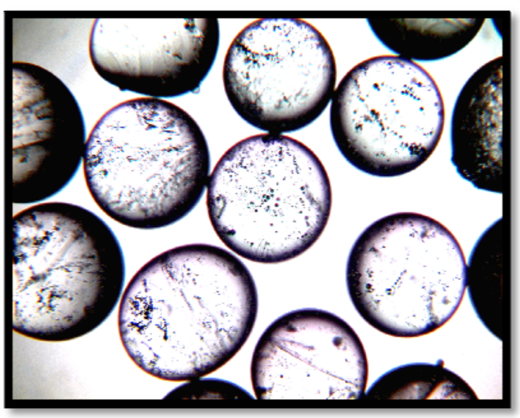

Figure 3. Beads with Visible Impurities (*Dr. Paul Carlson unpublished data*).

Previous Projects

Several heavy metals, including arsenic, are found in glass beads used in pavement markings. Texas Transportation Institute (TTI) and Texas A&M University investigated the metal content in glass beads with support from American Glass Beads Manufacturing Association (AGBMA) in 2010. The study involved testing three separate batches of Type 1 AASHTO M247 beads using the Pacific Northwest Laboratory's KOH fusion method to determine the total arsenic content of the glass (*4*). Findings from the TTI/TAMU study, shown in Table 1 (*4*), confirmed the presence of arsenic in the samples that were tested. The study also determined that arsenic leached from the bead when the bead was placed in water.

Table 1. Mean ± Standard Deviation Arsenic Contents of AGBMA Provided Samples (adapted from reference *4*).

Bead	(µg arsenic)/(g bead)
Batch 1	83.3±1.42
Batch 2	308±23.6
Batch 3	393±6.53

GOALS AND OBJECTIVES

The goal of this study was to evaluate the relationship between arsenic content and retroreflective performance of glass beads used in pavement markings. The following three objectives were used to pursue the goal of this research.

Objective 1: Determine the arsenic content of 10 samples of glass beads provided by DOTs from several states

Objective 2: Create pavement markings from the provided glass beads and measure their retroreflective performance

Objective 3: Determine if a correlation exists between arsenic content and retroreflective performance of the beads.

METHODS TO COLLECT DATA

Ten samples of glass beads and one blank were analyzed for their arsenic content by digesting the samples according to the KOH Fusion method followed by ICP-MS analysis according to EPA Method 6020A.

KOH Fusion Glass Beads Digestion

One hundred grams subsamples of each bead evaluated in the study were place into marked Ziploc bags for storage. Five grams of each subsampled bead was crushed using a ceramic pestle and mortar and sieved using a US sieve No. 130. The crushed bead was stored in labeled tubes. Researchers placed 0.25 g crushed beads, 0.2 g potassium nitrate, and 1.8 g potassium hydroxide into a carbon crucible. The components in the crucible were heated over a Bunsen burner to melt the contents. Seven mL of deionized water (DI water) was placed into the crucible to dissolve the melt, and the dissolved melt was transferred to a 1000 mL volumetric flask. Additional 7 mL DI water aliquots was repeatedly used to dissolve the melt to make sure that all melt contents were transferred to the flask.

Five hundred mL of DI water was then added to the flask and 25 mL of nitric acid was added to dissolve any precipitate that is in the flask. The flask was swirled to aid the dissolution process. For the precipitates that did not dissolve using nitric acid, 0.3 g of oxalic acid was added to the flask. The swirling continued until all the precipitates were dissolved. The flask was filled to the 1000 mL mark with DI water, and a 15 mL sample was stored at 4°C until ICP-MS analysis was conducted. The blank was processed following the same steps outlined above; however, the 0.25 g of crushed bead was not added to the crucible prior to processing.

Evaluation of Metal Content in Glass Beads

Arsenic content of the digested bead solution was measured using an ELAN® DRC II ICP-MS housed within TAMU’s Center for Chemical Characterization. Prior to analysis, samples were preserved with 1% HNO_3 by volume and placed in storage at 4°C. Analysis was carried out as described in EPA Method 6020A using a four point calibration curve ranging from 1 to 100 µg/L. The method detection limit for arsenic in solution was 0.74 µg/L and the practical quantification limit was set at 1 µg/L (the lowest calibration standard).

Retroreflective Performance Measurements

The retroreflective performance measurements were conducted for the 10 samples previously digested and analyzed for arsenic following the KOH fusion method. A metal sheet was used to create the pavement markings. The metal sheet was placed onto a wooden apparatus that holds the sheet in place during applications of paint and glass beads. The glass beads were placed in the bead dispenser holder for even application on the paint. The shoe, a metal square containing paint, was placed on the far end of the metal sheet. The shoe was dragged along the metal to spread the paint marking evenly over the pavement marking. It is important that spreading of the paint is done at the same speed consistently to obtain a uniform thickness of paint.

After the paint was applied, the glass beads were dispersed using the bead dispenser. The bead dispenser is a wooden box that has grids in the inside of the box that allows the glass beads to be applied to the sample pavement marking in a random and dispersed manner. This process must occur quickly after the paint has been applied to the metal sheet for optimal binding of the glass beads to the paint. After the glass beads were applied to the pavement marking, the markings were cured for a 24-hour period. A subset of the created markings is shown in Figure 4. The following day, a retroreflectometer was used to measure the retroreflectivity of the pavement marking samples. The retroreflectivity was measured in two directions; in the direction of the application of paint and the opposite direction. In each direction the retroreflectometer was used to take five independent measurements in each direction, which were summed together to determine the final retroreflectivity value for each sample.

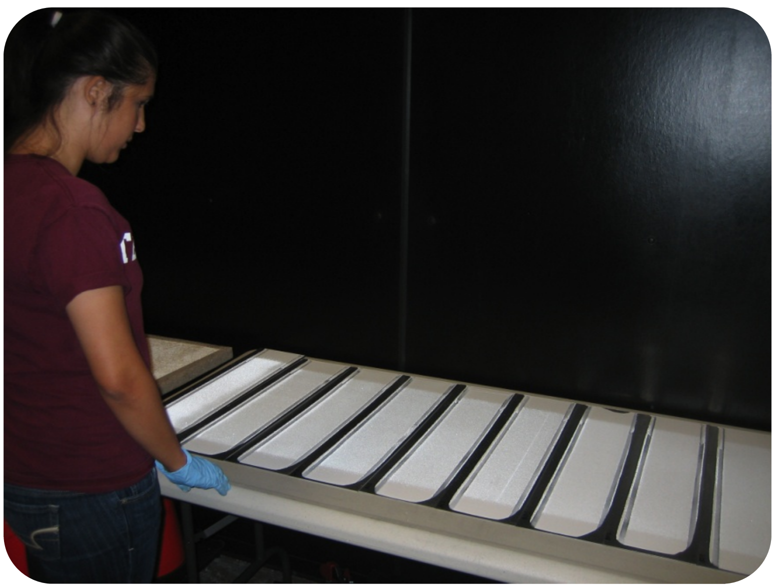

Figure 4. Pavement Markings Created for Retroreflectivity Evaluation.

Data Analysis

The arsenic content from the KOH Fusion Method and the retroreflective performance measurements were first analyzed by averaging the values for the triplicate bead subsamples. Standard deviations were calculated for each sample. Pearson's product moment correlation coefficient (r) was used to determine the direction and strength of the correlation between arsenic content and retroreflectivity. Excel was used for all data processing and plotting.

RESULTS

The mean and standard deviation arsenic content of each bead sample are shown in Figure 5. Total arsenic content of the beads ranged from 30 to 78 µg arsenic per gram bead (µg/g = ppm). The blank did not have detectable levels of arsenic present.

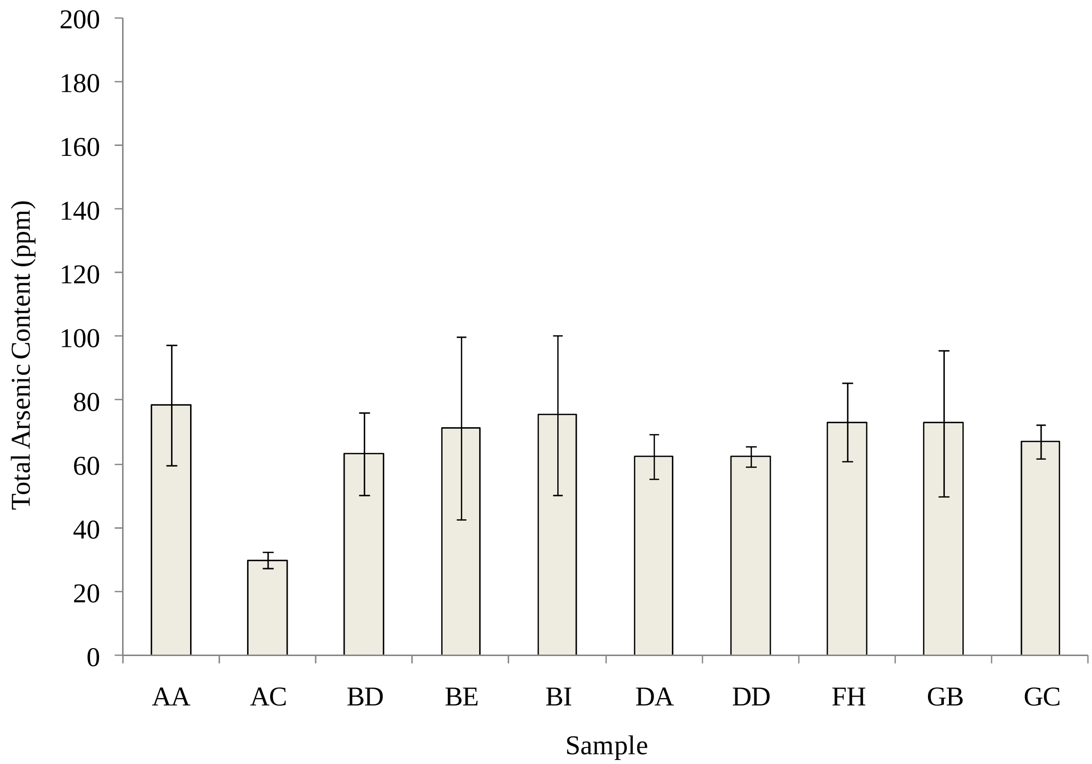

Figure 5. Mean ± Standard Deviation of Total Arsenic Content in Bead Samples.

The results for the retroreflectivity performance are presented in Figure 6. For each bead sample, the values for the retroreflectivity were between 170 and 430 mcd/(m^2·lux). The five replicate readings in both directions were similar, and the independent measurements were averaged for each bead subsample to obtain the representative retroreflectivity value.

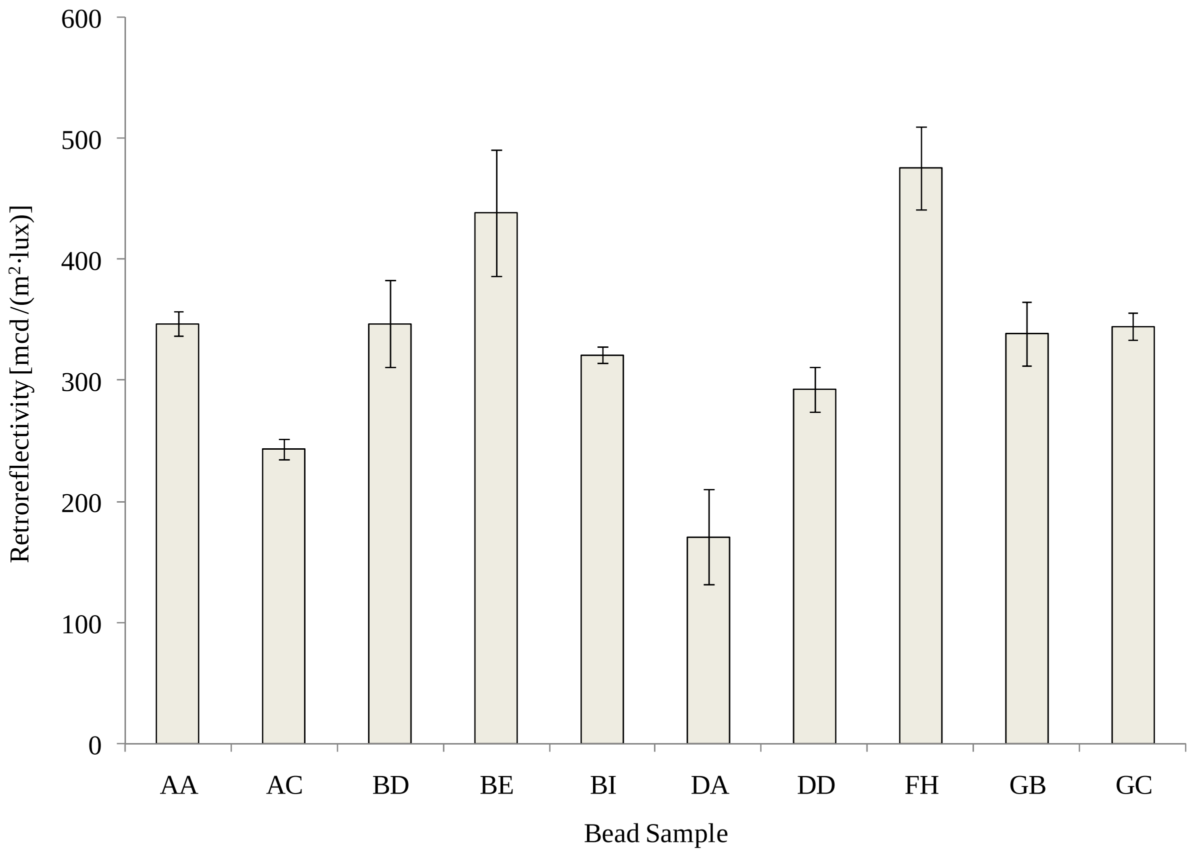

Figure 6. Mean ± Standard Deviation of Retroreflectivity in Bead Samples.

Figure 7 presents the scatter plot of total arsenic content versus retroreflectivity. The calculated Pearson's product moment correlation coefficient for the samples is 0.522. The coefficient indicates a positive moderate correlation between the two factors, suggesting that a correlation may exist between the arsenic content and retroreflective performance. However, additional samples should be analyzed to determine if a correlation actually exists. In this study, the range of arsenic contents was limited to between 30 and 78 ppm. Arsenic contents of previously analyzed beads were an order of magnitude greater than the beads analyzed from state DOTs, and these high arsenic beads and beads with lower arsenic content (below 30 ppm) should be included in additional studies that explore this correlation. Additionally, a greater number of beads should be evaluated to determine if a correlation does exist.

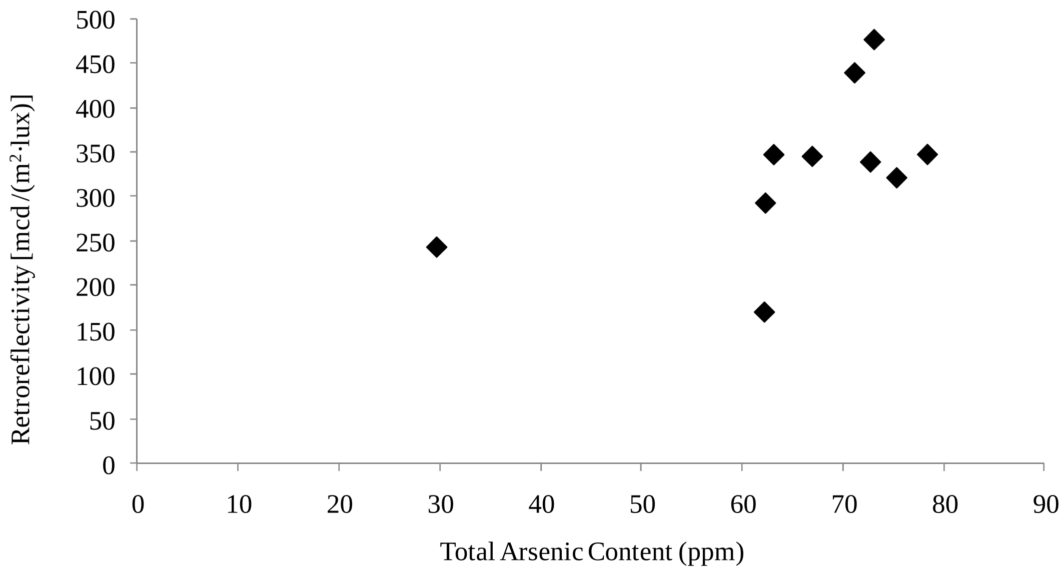

Figure 7. Retroreflectivity vs. Total Arsenic Content.

CONCLUSION

Glass beads used in pavement markings offer important benefits to society by improving visibility of pavement markings under all driving conditions. However, glass beads are also known to contain arsenic. Because arsenic was used historically to remove impurities from glass, the relationship between arsenic content and retroreflective performance was evaluated. In the 10 samples examined within this study, a moderate positive correlation between arsenic content and the retroreflective performance of the glass beads was observed. Additional samples are required to further assess the correlation observed within this preliminary evaluation.

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