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16. Abstract

This report is a compilation of research papers written by students participating in the 2008 Undergraduate Transportation Scholars Program. The ten-week summer program, now in its eighteenth 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) selecting warning signs using decision theory and systems engineering concepts; 2) estimating corridor travel time from arterial traffic volume; 3) evaluating the effectiveness of life cycle variables in travel demand modeling; 4) estimating cross median crashes on horizontal curves; and 5) driver workload and visual studies.

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# COMPENDIUM OF STUDENT PAPERS:

# 2008 UNDERGRADUATE

# TRANSPORTATION SCHOLARS PROGRAM

Participating Students (left to right):
Taileah J. Hunter, Lisa K. Larsen, Matthew P. Mulkern,
Rolando A. Ayala, II and James A. Robertson

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## 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 2008, the following five students and their faculty/staff mentors were:

| STUDENTS | MENTORS |
| --- | --- |
| Mr. Rolando A. Ayala, II<br>Texas A&M University, College Station, TX | Dr. H. Gene Hawkins |
| Ms. Taileah J. Hunter<br>The University of Texas, Arlington, TX | Dr. Yunlong Zhang<br>Dr. William L. Eisele |
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Sincere appreciation is extended to the following individuals:

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The contents of this report reflect the view of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

# SELECTING WARNING SIGNS USING DECISION THEORY AND SYSTEMS ENGINEERING CONCEPTS

Prepared for
Undergraduate Transportation Scholars Program

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Rolando is a member of the Society of Hispanic Professional Engineers, the Society of Mexican American Engineers and Scientists, the American Society of Civil Engineers, and the Institute of Transportation Engineers student chapters at Texas A&M University. He is also an active member of St. Mary's Catholic Center. He is involved in Campus RENEW, Aggie Awakening, and the Knights of Columbus. Rolando has gained internship experience while working in the design division at the Texas Department of Transportation Pharr District.

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## SUMMARY

Traffic control devices are a vital component of the transportation system as they communicate important information to road users. Warning signs are one type of traffic control devices that serve an important role as they provide road users with advance notice of potentially hazardous conditions which are not self-evident and are located on, or adjacent to, a roadway.

There are a large number of warning signs in the *Manual on Uniform Traffic Control Devices*. The MUTCD offers guidelines on the intended use of warning signs and the different situations they should be used to address; however, it lacks a systematic procedure for selecting them. As a result of the large number of warning signs and the lack of specific installation requirements, it can be difficult when trying to determine whether to install a warning sign.

The primary purpose of this project was to address the lack of a systematic process for the selection of warning signs, and to develop a conceptual framework for a selection process for warning signs. In trying to develop a system for the selection of warning signs, three concepts were investigated: systems engineering, decision theory, and multi-criteria decision methods.

Although these concepts may be different, they share many similarities. They address a problem and develop a method for coming up with a solution to the problem. The project determined that there is a basis for using decision theory for warning sign selection, but identified the need for additional development of the concept before it is a viable process for practitioners.

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## INTRODUCTION

Traffic control devices are very important for the safe and efficient transport of people and goods (*1*). They provide road users with a variety of information which include: traffic laws, traffic regulations, traffic control features, potential hazards in or near the road, distances, and directions to various destinations. Some examples of the most commonly known traffic control devices include regulatory signs, guide signs, pavement markings, traffic signals, and warning signs.

Warning signs are used to call attention to potentially hazardous conditions which are not self-evident and are located on, or adjacent to, a roadway (*1). *The purpose of a warning sign is to prevent users from doing something they would otherwise do or to induce users to do something they would not normally do *(2).* Aside from this, warning signs provide a convenient and useful means of informing users of the potential hazards associated with the environment they are traveling in. The *Manual on Uniform Traffic Control Devices* (MUTCD) contains an abundance of information on warning signs which include standards (requirements) on the design, and application of not only warning signs but other traffic control devices *(1).* The MUTCD also offers guidance (recommendations), options, and support (background) provisions *(1).*

The *MUTCD* is one of the key documents in the field of transportation engineering because it contains standards and warrants for the design and application of traffic control devices *(2).* The purpose of the MUTCD is to provide uniformity amongst signs in order to promote safety and efficiency on streets and highways. Uniformity is achieved by traffic engineers adhering to the principles of the MUTCD and being consistent with the common practices of traffic control devices. Uniformity has been created through many years of revision, research, collaborative engineering efforts, and implementation of standards. This uniformity has aided in increasing driving comprehension of warning signs by providing information in a consistent matter, therefore reducing crashes and improving the efficiency of transportation systems *(2).*

Although the MUTCD promotes uniformity amongst warning signs, it has yet to develop a functional process that links many considerations to the various factors associated with the selection of traffic control devices. The current process for selecting traffic control devices consists primarily of the use of either individual engineering judgment or previous traffic studies (Section 1A.09) *(1)*. Current decisions regarding traffic control devices are often made on a device by device basis and not as part of a uniform system. The purpose of this project is to address the missing process for the selection of traffic control devices, more specifically warning signs.

This research developed a framework for a conceptual process which ties several different concepts together, including systems engineering, decision theory, and multi-criteria decision methods. Systems engineering is the integration of many engineering disciplines, which focuses on the development and organization of complex systems such as transportation management systems *(3)*. The use of Decision Theory further supplements the implementation of a System Engineering approach. Decision Theory is also an interdisciplinary area of study which concerns mathematicians, statisticians, managers and anyone else interested in analytical techniques used in decision making *(4)*. There are two types of decision theory, normative and descriptive *(4)*.

This research project used the application of normative decision theory since it is aimed at finding tools and methodologies to help promote the selection of better decisions. Multi-criteria decision methods was also incorporated into the development of the conceptual framework since it offers support for decision makers who are faced with making numerous and conflicting evaluations such as those associated with warning signs.

## GOAL AND OBJECTIVES

The goal of this research effort was to develop a conceptual framework for the selection of warning signs using systems engineering and decision theory concepts. As this framework is developed through future research efforts it will evolve into one that links many considerations to the various factors associated with traffic control device decision.

In order to begin developing the conceptual framework for all traffic control devices, the author created a preliminary one for the selection of warning signs. This framework ties together many factors such as the intended purpose, targeted audience, costs, individual and system performance, risk management, and other factors that are applied in the selection, design, installation, operation, maintenance, and related activities of warning signs. Quintessentially the research combines normative decision theory principles with traffic engineering and creates a conceptual method, such as the Analytic Hierarchy Process, which considers:

- Installation and life-cycle costs of the device,
- Effectiveness of the device,
- Promotion of traffic safety by the device,
- Operational benefit of device,
- Method of communication by the device,
- Alternatives for communication by the device,
- Risks associated with the device,
- Tort concerns associated with the device,
- Political considerations associated with the use or non-use of the device.

In order to complete the goal of developing a quantifiable model that defines relationships between the various factors, a series of measurable objectives were defined to achieve the overall goal. The first measurable objective was to receive input from traffic engineers as to what they take into consideration when dealing with traffic control devices. Based upon the input from participants, the development of a list of survey questions was the next measurable objective. This survey was constructed as a result of expert input and quantifiable relationships. Based upon the results received, the next task was to determine how the concepts of systems engineering, decision theory, and multi-criteria decision analysis could be applied in developing the conceptual framework. This stage of the project involved an extensive amount of literature review because of the level of complexity of these subjects. However, once the literature review was completed the next step of the project was to incorporate these concepts in creating the conceptual framework. The development of the framework involved a collaborative effort among the researcher and those providing factors that should be incorporated into the process. Once the framework was developed all results and conclusions were prepared for this paper.

## PROCEDURE

In developing the conceptual framework, there were a number of tasks that needed to be completed. The first task was to define the relationship between various factors involved in the decisions made on warning signs. For this task to be complete, input from traffic engineers was needed so that a list of common factors could be determined. A series of interviews were conducted with a variety of traffic engineers. The traffic engineers selected for the interviews included those who have or are currently serving on the Regulatory and Warning Sign Technical Committee of the National Committee on Uniform Traffic Control Devices. These engineers were selected because of their high level of expertise and extensive knowledge of factors that are commonly associated with the selection of warning signs. They were able to provide expert input and establish some of the main factors involved in the decisions made on warning signs.

After some of the main factors were identified, the next objective was to determine how important these factors were in relation to each other. The survey results would be used to determine how important the factors previously established are in relation to each other. In order to determine this, a series of surveys were conducted. A wide variety of transportation engineers participated in the survey and was instructed to rank and assign a percentage to each of the factors to indicate the relative importance of the factor relative to the other factors. For a sample of the survey given refer to Appendix A.

Once the survey was conducted the next object was to determine how the concepts of systems engineering and decision theory could be applied to developing a system for the selection of warning signs. This stage of the project involved an extensive amount of literature review.

After the literature review was completed, the conceptual framework was developed. In order to create the conceptual framework there were many things that needed to be integrated. This involved the incorporation of the results received from the interviews and surveys so that the criteria of the analytic hierarchy process could be determined. Following the establishment of the criteria needed for the development of the framework, the process was carried out by asking several engineers to participate in the conceptual process that was created. A step by step process will be explained later in this paper.

## RESULTS

The following sections will describe the results received throughout the research process. These results help contribute to the development of the conceptual framework that was applied for the selection of warning signs.

### Interview Results

The interviews conducted during the course of this research were conducted over the phone. Interviews consisted of informal discussions about the factors related to the selection of warning signs. Although the number of participants was limited to five, those who participated dealt with warning signs on a daily basis. Participants were asked to state the factors they considered when making decisions on the installation of signs and why they considered them to be important.

Based upon the responses received from the interviews, the most important factors traffic engineers consider when making decisions on warning signs were identified. The following sections describe what each factor means in relation to warning signs.

- **Benefits.** Like all traffic control devices, warning signs are installed because of the benefits they provide to road users. Some of the benefits that warning signs have to offer are the ability to improve traffic operations and most importantly the safety of not only motorist but pedestrians as well. The reason warning signs are able to improve traffic is that they provide the road user with adequate time to assess the potential hazard and respond properly. If a warning sign were not in place to warn of the oncoming hazard, motorists would be unaware of the situation and as a result traffic would be affected. Not only do warning signs provide an operational benefit they also provide safety benefits for motorists. By installing warning signs drivers are aware of hazards on the road and can safely commute on the roads.
- **Potential Effectiveness** represents how effective a particular warning could be if it is installed. Potential effectiveness is composed of many things, such as how well does the device warn motorists of the hazard. Is the warning sign difficult for motorist to understand, which leads to a decrease in motorist comprehension? Does the sign command respect from road users or has its integrity gone down due to the misuse of this sign? These are all factors that are related to potential effectiveness and should be thought about when deciding when, where, and how a warning sign should be used.
- **Cost** is often an important factor when dealing with the installation of traffic control devices. More often than not, cost issues affect the selection of warning signs. However, the Analytic Hierarchy Process enables decision makers to include this criterion in the decision making process so that appropriate priority is assigned to this factor. Although decision makers may decide not to place great priority on cost issues, it will still offer input to the global priority of the alternatives available.
- **Constraints** are always a part of any engineering process or decision. Constraints often have a great influence on decisions because of how much they affect the intended outcome. Although there may not seem like there are many constraints associated with warning signs there are a few that will be addressed later on in this report.
- **Need** may be the criteria that requires the most analysis. The MUTCD states that all traffic control devices must meet five basic requirements so that they are effective, and one of those requirements is that the device must fulfill a need. There are several types of needs that warning signs are meant to address, so for that reason this criterion will be the most complex and will require the most comparison.
- **Correct Practice** is a criterion that decision makers often overlook when making decisions on warning signs. Engineers and practitioners have worked many years on creating the uniformity that the MUTCD has established today. Due to this great effort, it is important that traffic engineers take in to consideration the consistency with the local practices. This will ensure that road users are familiar with warning signs and it will help increase driver comprehension of these signs.

After these factors were identified, there was a need to state a few key factors that fell under these general categories. The reason for this is that there needs to be a set of sub criteria so that the analysis of the hierarchy can take place.

- **Traffic Operations** is a sub criterion of benefits. Traffic engineers are always concerned with how specific traffic control devices impact traffic operations, more importantly their ability to improve traffic operations. Although warning signs may not have a great influence on improving traffic operations they are still important.
- **Safety** is another sub criterion of the possible benefits that warning signs can provide. This sub criterion refers to the amount of safety a warning sign contributes to road users. For example, if there is a potential hazard ahead and it is not apparent or expected by a driver, there are safety concerns associated with it. In order to promote safer travel for road users and to prevent injury, the potential safety benefit of warning signs should be considered in the analytic hierarchy process.
- **Initial** costs are an important factor on decisions made concerning hazard signs. Although costs should not be an issue when trying to improve safety and traffic operations, it often influences the decision of traffic engineers.
- **Life Cycle** costs are the costs required to maintain the traffic control device. For signs, life cycle cost would entail replacing the poles that they are mounted on if they are damaged and replacing the signs once they no longer meet retroreflectivity standards.
- **Installation** constraints involve installing warning signs so that they meet the standards stated in the MUTCD. There may be other installation constraints such as whether appropriate response distances are given for the driver to respond.
- **Maintenance** constraints entail how often a warning sign will need maintenance. This includes that the warning signs meet retroreflectivity standards. It would also entail how often signs need to be replaced. Although there may not be many maintenance issues pertaining to warning signs, there may be many more with other traffic control devices.
- **Operational** constraints are those that are involved with keeping the traffic control device operating correctly. Not only are there operational constraints but others as well. These may be whether or not the device does what it is intended to do and in what ways is it limited.
- **Warning Presence** criteria deal with how often the warning is present. The warning presence may either be fixed, present all the time, or transient, present only part of the time. For those warnings that are present only part of the time, the decision maker would need to determine how often the hazard is present and if it is severe enough to warrant the installation of the sign.
- The **Impacts** associated with a warning sign installation are those such as the risk of an accident or a legal claim being filed. Since warning signs often deal with hazardous situations, there is a possibility of these two things happening.
- **Consequences** fall into three categories that are based upon their severity. The first consequence is a minor consequence. A minor consequence involves minor damage caused to the vehicle as a result of an accident. The second consequence would be any major ones. This may involve great damage to a vehicle and some physical injury caused to the motorist. Finally the last major category of a consequence is a severe consequence. A severe consequence would involve a fatally as a result of an accident.
- **Political** needs are often the ones that are the least stated. Signs are sometimes installed for other reason than what they are intended for, such as political influences. A local politician may want a sign installed because of complaints received from the public or to reduce the risk of potential lawsuits.

- **MUTCD** correct practice is the most important practice that should be followed. The reason of the MUTCD is to great uniformity among all traffic control devices and therefore all warning signs should be consistent with the correct practice stated in the MUTCD. This would include following all design, installation, placement and all other standards stated in the current issue of the MUTCD.
- **Local Practices** entails state MUTCD's as well as common practices in the area. It is important that signs follow the correct practice.

**Survey Results**

The survey conducted listed several factors that are involved in decisions made on the installation of warning signs. The fifteen engineers who participated in the survey were asked to assign a percentage to the factors provided to indicate their relative importance in relation to each other. The figure below represents the total percentage each factor received.

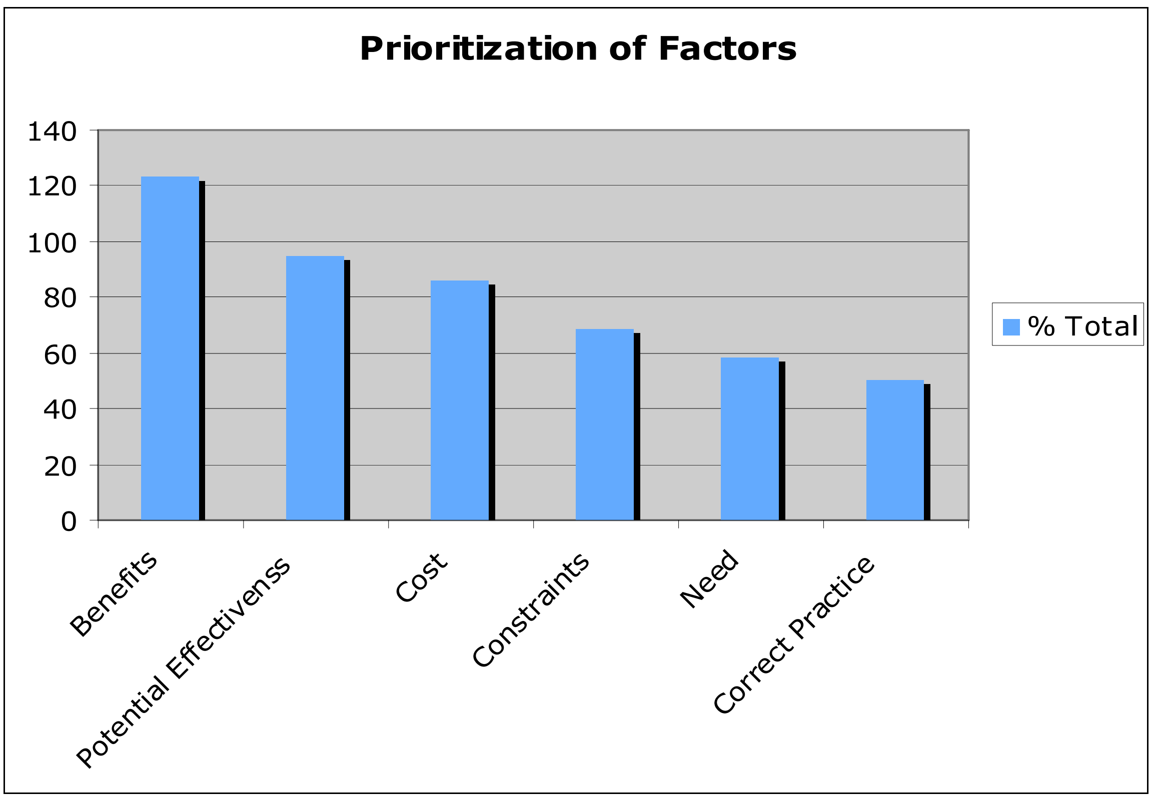


**Figure 1. Survey Results**

**Literature Review**

Once the survey was conducted, the next objective was to determine how the concepts of systems engineering and decision theory could be applied to developing a system for the selection of warning signs. This stage of the project involved an extensive amount of literature review because of the level of complexity of these subjects. The following sections will describe the concepts used in this research project in detail.

*Manual on Uniform Traffic Control Devices*

The MUTCD is one of the key documents in the field of transportation engineering because of the standards and warrants it contains for the design and application of traffic control devices. Although it may offer guidance on the use and application of devices, it offers limited guidelines for selecting warning signs. The MUTCD states that the decision to use a particular device at a particular location should be made on the basis of either an engineering study or the application of engineering judgment (Section 1A.09) *(1)*. By allowing this and not having a systematic selection process, it opens the door to inconsistency and misuse of warning signs.

Although the MUTCD may lack a defined process for selecting traffic control devices it has accomplished great uniformity. In the early years of highway signs, there was no consistency in their appearance or use. Signs were typically hand painted and took whatever appearance the creator thought would be most effective *(5)*. However as automobile users began to increase, traffic engineers began to realize the need for a consistent and uniform signing system. This eventually led to the development of the first national manual that addressed the appearance and application of traffic control devices *(5)*. Through many years of revision, research, collaborative engineering efforts, and implementation, the MUTCD has created a uniform standard on TCDs that provides excellent transportation conditions for motorist. By creating such great uniformity it has aided in the safe and efficient transportation of people and goods. The uniformity of traffic control devices is especially important for warning signs. It helps establish a level of familiarity and establishes a prior knowledge of warning signs, so that motorists are able to recognize and perform the desired operation.

*Systems Engineering*

Systems engineering is an interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed *(6)*. It deals with work-processes and tools to handle this and overlap with both technical fields like control engineering and with project management *(7)*. Systems engineering's main responsibility is creating and executing an interdisciplinary process to ensure that the needs of the problems are met *(6)*. The process usually involves seven steps.

1. **State the problem**: This part of the process involves the description of the problem being addressed. The problem statement should express the needs that are being addressed and this information should be input by all those involved in the process.
2. **Investigate alternatives**: The alternatives are determined and evaluated based on overall performance on solving the problem. No alternative is likely to be the best so multicriteria decision-aiding techniques should be used to reveal the preferred alternatives. By incorporating this, it eliminates the possibility of decision makers choosing their predetermined solution.
3. **Model the system**: In this part of the process, a model is developed for the alternative designs. Then the model for the preferred alternative is expanded and used to help manage the system throughout its entire life cycle. For the application of this project, the model will be a preliminary flow chart, which should include the major criteria and sub criteria concerning the factors that are associated with warning signs.

4. **Integrate**: This part of the process is where everything that has been done for the project is brought together so that they work as a whole. This allows decision makers to see how everything ties together and allows for minor changes to be made so that the system works well together.
5. **Launch the system**: This step is meant for systems that require operation. In this step the system is running and producing outputs. In a manufacturing environment this means actually making things. However for the application of this project it would entail using the proposed flowchart for selecting a warning sign. This would be done by completing all the steps that are involved in the analytic hierarchy process.
6. **Assess performance**: For this set the decision maker would have to evaluate how well the analytic hierarchy process worked in selecting a warning sign. Did the process lead to a reasonable conclusion or is it one that was unexpected? The decision maker would have to decide what changes should be made so that a reasonable conclusion is reached through the process.
7. **Re-evaluate**: This is arguably the most important of the seven steps. For a century, engineers have used feedback to help control systems and improve their performance and effectiveness. Re-evaluate means observing the output and using the information received to modify the system and the inputs so that the process is a logical one *(6)*.

Like all processes, the systems engineering process is not one that is applicable to all processes. The above description of the Systems Engineering process is just one of the many that have been proposed and should be modified according to its application.

Since Systems Engineering is such a large and complex field, there are many techniques and tools that can be used. Perhaps the most fundamental technique is the flowchart, a graphical display composed of boxes representing individual components or subsystems of the complete systems, plus arrows from box to box to show how they interact *(7)*. This representation is very useful in the initial parts of a study and is essentially qualitative. A more effective approach to the flow chart would be the incorporation of a mathematical model, which consists of a set of some type of equations that would help describe the interactions quantitatively *(7)*. When it comes to systems engineering tools there is a great deal of diversity. The incorporation of different mathematical, statistical, logical, and decision methods are endless, which makes the discipline useful and unique.

*Decision Theory*

Decision theory is an interdisciplinary area of study that concerns mathematicians, statisticians, economists, philosophers, managers, politicians, psychologists and anyone else interested in analyses of decisions and their consequences *(8)*. It has developed since the middle of the 20$^{th}$ century through the contribution of several academic disciplines. There are two types of decision theories: normative and descriptive *(8)*. A normative decision theory is a theory about how decisions should be made, and descriptive theory is a theory about how decisions are actually made *(8)*. Decision theory can apply to conditions of certainty, risk, or uncertainty. It also recognizes that the ranking produced by using a criterion has to be consistent with the decision maker's objectives and preferences. Decision theory offers a vast realm of techniques and procedures that introduce decision makers into models of decision. The theory is not meant to define objectives, design alternatives or assess consequences but define a simple procedure for selecting a choice.

There have been many stages of the evolution of decision theory. The first general stage was started by the great enlightenment philosopher Condorcet in 1793 *(8)*. He divided the decision process into three stages: discuss the principles that will serve as the basis for the decision, the decision is reduced to a choice between a manageable set of alternatives, and the third part is the actual choice between these alternatives *(8)*. After this stage of evolution decision it was further evolved by the efforts of John Dewey, Herbert Simon, and Brim et al. Their proposals were all sequential in the sense that they divided the decision process into parts that were always in the same order. Their decision process consisted of these steps:

1. Identification of the problem,
2. Obtaining necessary information,
3. Production of possible solutions,
4. Evaluation of such solutions, and
5. Selection of a strategy for performance *(8)*.

Another influential evolution of decision theory was contributed by Mintzberg, Raisinghani, and Theoret (1976). They viewed the decision process of consisting of distinct phases, but these phases did not have a sequential relationship. Their decision process consisted of three major phases which were: identification, development and selection *(8)*. Although they felt that their process was not sequential, it had many similarities to the previous processes.

Most people often make choices out of habit or tradition, without going through the decision-making process steps systematically *(8)*. Decisions may be made under social pressure or time constraints which interfer with a careful consideration of the options and consequences. Decisions may also be influenced by decision maker's emotions, which often lead to unwanted results. For this reason decision theory is used by decision makers when faced with difficult and conflicting decisions such as decisions made on traffic control devices. One example to be looked at is the practical application of the normative decision theory, which is called decision analysis. Decision analysis is aimed at finding tools, methodologies and software to help people make better decisions. One discipline of this is the Multi-Criteria Decision Analysis (MCDA), or Multi Criteria Decision Making (MCDM).

*Multi-Criteria Decision Methods*

Multi-Criteria Decision Methods (MCDM) is a discipline that helps decision makers make a decision when faced with a problem that has numerous and conflicting criteria *(9)*. MCDM finds a way to evaluate each conflict and derives a way to come to a compromise where each conflicting criteria is taken into consideration *(9)*. The Analytic Hierarchy Process (AHP) is a MCDM method that was applied in developing the conceptual framework for the selection of warning signs. The Analytic Hierarchy Process is a basic approach to decision making, that it is designed to cope with both the rational and intuitive to select the best from a number of alternatives evaluated with respect to several criteria *(10)*. It was developed by Dr. Thomas L.

Saaty in 1970s, and this process has been used to assist in numerous corporate and government decisions *(10)*.

Part of the reason the analytic hierarchy process is an effective way to determine the best alternative for any decision lies in the structure. When constructing hierarchies the decision maker must be sure to include enough relevant detail so that the problem is represented as thoroughly as possible *(10)*. However it should not be so thorough that it loses sensitivity to change in certain elements. When constructing the hierarchy the decision maker should first ask the question: “Can I compare the elements on a lower level in terms of some or all of the elements on the next higher level?” *(11)*. This will help make comparisons reasonable and possible. It will also help in selecting the set of the major criteria that needs to be addressed as well as the set of sub criteria that needs to be taken into consideration in the decision making process. By arranging the goals, attributes, and issues in a hierarchy, it provides the decision maker with an overall view of the complex relationships present in the situation and judgment process. Aside from this, it allows the decision maker to assess whether he or she is comparing issues of the same order of magnitude and if it is consistent with the overall goal *(11)*.

By developing the hierarchy for the problem being addressed, it allows for the elements to be compared two by two *(11)*. The decision makers compare the set of criteria against each other and then the same pairwise comparison process is applied to the sub criteria. The comparison is performed by determining how important an element is when compared to one another and how important it is with respect to the goal. Things change a bit when we get to the alternatives row. Here, the alternatives are compared pair-by-pair with respect to the covering criterion of the group, which is the node directly above them in the hierarchy *(12)*. What we are doing here is evaluating the models under consideration with respect to the set of sub criteria. In order for the comparison to be quantified each comparison will need to be assigned an intensity value. These values will help assign priorities values to each set of criteria and help in calculating the significance of each element to the overall goal of the decision.

Assigning intensity values to each set of pairwise comparison allows for the priority vector, also known as the normalized Eigen vector, to be computed *(12)*. The Eigen value is very important for many applications in science and engineering because of its numerous applications. The normalized principal Eigen vector is applied in the Analytic Hierarchy Process so that all the relative weights among the things that are compared are shown. Aside from illustrating the relative weights of each set of criteria in relation to the overall goal, Eigen values help check the consistency of the alternative selected *(12)*.

Although the Analytic Hierarchy Process may seem like it is very complex, it is rather simple. One of the most important parts of the process is that the following three steps are accomplished:

- State the objective,
- Define the criteria, and
- Pick the alternatives.

## ANALYTIC HIERARCHY PROCESS EXAMPLE

In order to better understand the AHP process, the following section is dedicated to the explanation of the process that was developed as a result of this research. As mentioned earlier, there are three main steps that need to be determined to complete the AHP process.

- State the objective (should a warning sign be installed?),
- Define the criteria (benefits, potential effectiveness, cost, constraints, need, correct practice), and
- Pick the alternatives (install or do not install).

The following example provides a step by step process for the use of the analytic hierarchy process. The following created scenario is one that could be faced by a practitioner. The basic scenario is whether a series of Slippery When Wet signs should be installed on a six-mile stretch of roadway where the pavement friction value on the road has dropped below the agency threshold value. The agency has programmed the road for resurfacing, but it will be eighteen months before this is completed. The following process can be used by a practitioner in helping them decide whether to install the sign. The figure below was developed for the selection of warning signs using the research results obtained through this project.

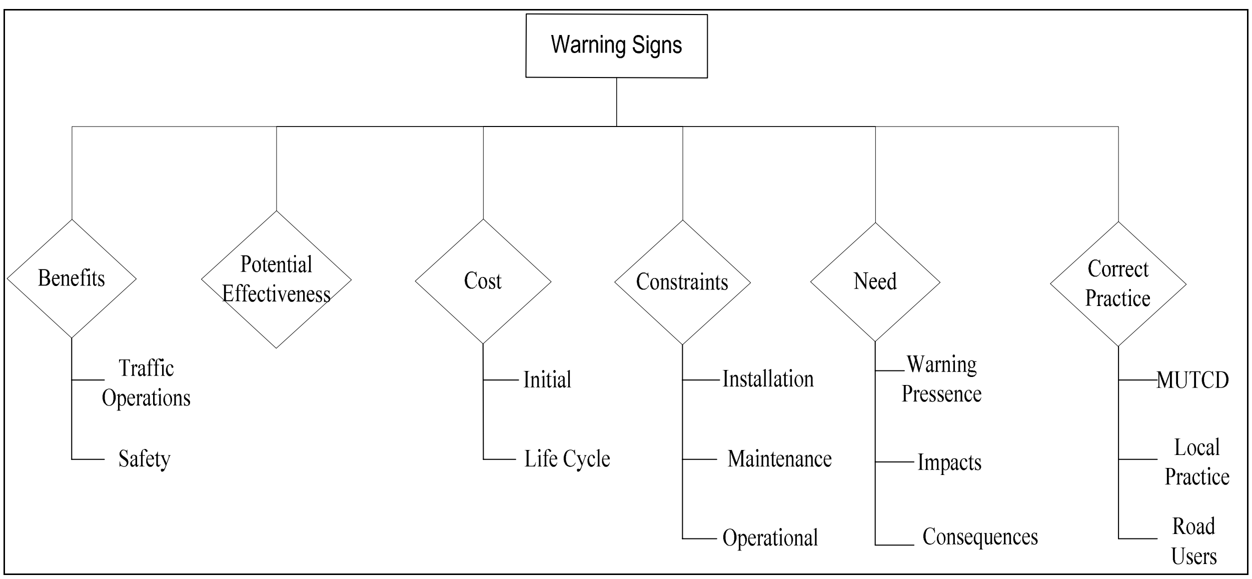


**Figure 2. AHP Hierarchy for Slippery When Wet Sign**

The next step of the Analytic Hierarchy Process is to synthesize all of the criteria established in the previous step *(12)*. This is done to determine the relative ranking of alternatives. To determine the relative importance of the criteria, a series of pairwise comparisons were performed. In performing pairwise comparisons, the decision maker who participated in the research was asked to evaluate each criterion in pairs and assign an intensity value to the comparison. The intensity values found in Table 1 are those developed by Dr. Thomas L. Saaty.

**Table 1. Fundamental Scale for Pairwise Comparisons** *(12)*

| Intensity of Importance | Definition of Importance | Explanation |
|---|---|---|
| 1 | Equal Importance | Two elements contribute equally to the objective |
| 3 | Moderate Importance | Experience and judgment slightly favor one element over the other |
| 5 | Strong Importance | Experience and judgment strongly favor one element over the other |
| 7 | Very Strong Importance | One element is favored very strongly over another, its dominance is demonstrated in practice |
| 9 | Extreme Importance | The evidence favoring one element over another is of the highest possible order of affirmation |
| Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance. | | |

Table 2 contains the values assigned by the engineer making the decision on the installation of the Slippery When Wet sign. An "A" in the "More Important" column indicates that the benefit under Criteria A is more important in a pairwise comparison than the benefit under Criteria B. The intensity indicates the importance of the relationship.

**Table 2. Level One Pairwise Comparison**

| Criteria | | More Important | Intensity |
|---|---|---|---|
| A | B | | |
| Benefits | Potential Effectiveness | A | 6 |
| Benefits | Cost | A | 3 |
| Benefits | Constraints | A | 2 |
| Benefits | Need | A | 5 |
| Benefits | Correct Practice | A | 6 |
| Potential Effectiveness | Cost | A | 4 |
| Potential Effectiveness | Constraints | A | 3 |
| Potential Effectiveness | Need | A | 7 |
| Potential Effectiveness | Correct Practice | A | 4 |
| Cost | Constraints | A | 5 |
| Cost | Need | A | 7 |
| Cost | Correct Practice | A | 4 |
| Constraints | Need | A | 8 |
| Constraints | Correct Practice | A | 6 |
| Need | Correct Practice | A | 7 |

The intensity values from Table 2 are inserted in a matrix that establishes a numerical relationship between any two criteria. Table 3 is a representation of the decision maker's pairwise comparison values in matrix form. A value greater than 1 in a cell indicates that the criteria in the first column is more important than the criteria in the first row. All values in the upper right portion of the matrix diagonal (the diagonal is defined by a cell value of 1) have values greater than 1. The cell values in the lower left portion of Table 3 were established by using the reciprocal values of the upper diagonal *(12)*. If $A_{ij}$ is the element of row $i$ column $j$ of the matrix, then the lower diagonal is filled using the formula below. The sum of each of the columns is included in this table because it will be used later in the process to compute the Priority vector.

$$\mathbf{A_{ij}} = \frac{\mathbf{1}}{\mathbf{A_{ij}}}$$

**Table 3. Complete Comparison Matrix**

| Criteria | Benefits | Potential Effectiveness | Cost | Constraints | Need | Correct Practice |
|---|---|---|---|---|---|---|
| **Benefits** | 1 | 6 | 3 | 2 | 5 | 6 |
| **Potential Eff.** | 1/6 | 1 | 4 | 3 | 7 | 4 |
| **Cost** | 1/3 | 1/4 | 1 | 5 | 7 | 4 |
| **Constraints** | 1/2 | 1/3 | 1/4 | 1 | 8 | 6 |
| **Need** | 1/5 | 1/7 | 1/7 | 1/8 | 1 | 7 |
| **Correct Practice** | 1/6 | 1/4 | 1/4 | 1/6 | 1/7 | 1 |
| **Sum** | 2.367 | 7.976 | 8.643 | 11.292 | 28.143 | 28.000 |

The next step is to compute the priority vector. To do this first one divides each cell of the matrix by the sum of its column. (i.e., 1.00/2.367 = 0.423) *(12)*. By doing this, we have the normalized relative weight, and the result is that the sum of each column should be 1. Once this done the priority vector can be computed by averaging the values across the rows *(12)*.

**Table 4. Normalized Relative Weight with Priority Vector Values**

| Criteria | Benefits | Potential Effectiveness | Cost | Constraints | Need | Correct Practice | Priority Vector |
|---|---|---|---|---|---|---|---|
| **Benefits** | 0.423 | 0.752 | 0.347 | 0.177 | 0.178 | 0.214 | 34.85% |
| **Potential Eff.** | 0.070 | 0.125 | 0.463 | 0.266 | 0.249 | 0.143 | 21.93% |
| **Cost** | 0.141 | 0.031 | 0.116 | 0.443 | 0.249 | 0.143 | 18.70% |
| **Constraints** | 0.211 | 0.042 | 0.029 | 0.089 | 0.284 | 0.214 | 14.48% |
| **Need** | 0.085 | 0.018 | 0.017 | 0.011 | 0.036 | 0.250 | 6.93% |
| **Correct Practice** | 0.070 | 0.031 | 0.029 | 0.015 | 0.005 | 0.036 | 3.10% |
| **Sum** | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 100.00% |

At this point, all the comparisons for the level one criterion have been made, and the priority vectors have been derived. The next step is to compute the local priority vectors of the subcriteria found in level two *(12)*. The items in each group of subcriteria should be pairwise compared and then the manipulation of these results will provide the local priorities. Table 6 provides the pairwise comparison values assigned by the engineer for each of the subcriteria.

**Table 5. Level Two Pairwise Comparisons**

| Criteria | | More Important | Intensity |
|---|---|---|---|
| **A** | **B** | | |
| Traffic Operations | Safety | B | 8 |
| | | | |
| Initial | Life Cycle | A | 4 |
| | | | |
| Installation | Maintenance | B | 4 |
| Installation | Operational | B | 5 |
| Maintenance | Operational | A | 3 |
| | | | |
| Warning Presence | Impacts | A | 5 |
| Warning Presence | Consequences | B | 7 |
| Impacts | Consequences | A | 2 |
| | | | |
| MUTCD | Local Practice | A | 7 |
| MUTCD | Road Users | A | 3 |
| Local Practice | Road Users | A | 1 |

Once the decision maker has determined the intensity values, the calculation of the local priorities is now possible. Local priorities are the overall priorities of each factor with respect to its specific level *(12)*. The priorities in each group should always total 100 percent. The calculation is the same as the previous example (Table 5) except that the comparisons are made for a smaller number of subcriteria. Table 7 illustrates the calculation of the priority vectors for traffic operations and safety. Table 8 contains all the values for each set of subcriteria.

**Table 6. Subcriteria Comparison Maxtrix for Traffic Operations and Safety**

| Subcriteria | Traffic Operations | Safety | | Subcriteria | Traffic Operations | Safety | Priority Vector |
|---|---|---|---|---|---|---|---|
| Traffic Operations | 1 | 1/8 | | Traffic Operations | 1/9=0.1111 | 0.125/1.125=0.1111 | 11.11% |
| Safety | 8 | 1 | | Safety | 8/9=0.8888 | 1/1.125=0.8888 | 88.89% |
| Sum | 9 | 1.125 | | Sum | 1 | 1 | 100% |

The next step in determining whether the sign should be installed is to calculate the global priority of each subcriteria *(12)*. This will show us the priority of each subcriteria with respect to the goal. The way to calculate the global priority is to multiply the priority vector from level one by the local priority vector from level two (i.e., $0.3485 \times 0.111 = 0.0387$) *(12)*. Table 9 indicates the global priorities.

Based on the judgments entered by the engineer, the AHP has derived the priorities for the factors against which each of the two alternatives will be compared *(12)*. They are shown, from highest to lowest, in Table 10. Notice that Benefits, Cost, Constraints, Need, and Correct Practice will not be evaluated directly, but that each of their Subcriteria will be evaluated on its own.

**Table 7. Subcriteria Local Priorities**

| Subcriteria | Local Priority | | Subcriteria | Local Priority |
|---|---|---|---|---|
| Traffic Operations | 11.11% | | Warning Presence | 31.22% |
| Safety | 88.89% | | Impacts | 27.15% |
| Sum | 100.00% | | Consequences | 41.63% |
| | | | Sum | 100.00% |
| Initial | 80.00% | | | |
| Life Cycle | 20.00% | | MUTCD | 68.51% |
| Sum | 100.00% | | Local Practice | 13.60% |
| | | | Road Users | 17.90% |
| Installation | 10.18% | | Sum | 100.00% |
| Maintenance | 58.20% | | | |
| Operational | 31.62% | | | |
| Sum | 100.00% | | | |

**Table 8. Subcriteria Global Priorities**

| Subcriteria | Global Priority | | Subcriteria | Global Priority |
|---|---|---|---|---|
| Traffic Operations | 3.87% | | Operational | 4.58% |
| Safety | 30.98% | | Warning Presence | 2.16% |
| Potential Effectiveness | 21.93% | | Impacts | 1.88% |
| Initial | 14.96% | | Consequences | 2.89% |
| Life Cycle | 3.74% | | MUTCD | 2.12% |
| Installation | 1.47% | | Local Practices | 0.42% |
| Maintenance | 8.43% | | Road Users | 0.55% |

**Table 9. AHP Global Priorities**

| Criteria | Subcriteria | Priority |
|---|---|---|
| Benefits | Safety | 30.98% |
| Potential Effectiveness | none | 21.93% |
| Cost | Initial | 14.96% |
| Constraints | Maintenance | 8.43% |
| Constraints | Operational | 4.58% |
| Benefits | Traffic Operations | 3.87% |
| Cost | Life Cycle | 3.74% |
| Need | Consequences | 2.89% |
| Need | Warning Presence | 2.16% |
| Correct Practice | MUTCD | 2.12% |
| Need | Impacts | 1.88% |
| Constraints | Installation | 1.47% |
| Correct Practice | Road Users | 0.55% |
| Correct Practice | Local Practices | 0.42% |

The next step is to evaluate each of the alternatives with respect to these factors. In the technical language of AHP, we will pairwise compare the alternatives with respect to their covering criteria and use this information to calculate local and global priorities for each of the alternatives *(12)*. Table 11 indicates these intensities.

**Table 10. Pairwise Comparison of Alternatives with Respect to the Factors**

| Factors | Alternative | | Intensity |
|---|---|---|---|
| | A (Install) | B (Do Not Install) | |
| Safety | X | | 6 |
| Initial | | X | 3 |
| Potential Effectiveness | X | | 3 |
| Maintenance | | X | 4 |
| Operational | | X | 8 |
| Traffic Operations | X | | 3 |
| Life Cycle | | X | 7 |
| Consequences | | X | 2 |
| Warning Presence | X | | 4 |
| MUTCD | X | | 2 |
| Impacts | X | | 6 |
| Installation | | X | 1 |
| Road Users | X | | 1 |
| Local Practices | | X | 2 |

The calculations of the local priorities are computed in the same fashion as before. The global priorities are calculated using the local priorities for this table and the global priorities from Table 9. The result is the global priorities shown in Table 12. For any one factor, the sum of the “install” and “do not install” priority percentages is equal to global priority percentage from Table 9.

At the end of all these calculations, all the global priorities are arranged for each of the alternatives. Their grand total is 100 percent, which is identical to the priority of the goal. Each alternative has a global priority corresponding to its fit to the engineer’s judgments about all the aspects involved. Table 13 provides a summary of the global priorities of all the alternatives.

**Table 11. Local and Global Priority of Alternatives with Respect to the Factors**

| Factors | Alternative | Local Priority | Global Priority |
|---|---|---|---|
| Traffic Operations | Install | 75.00% | 2.90% |
| | Do Not Install | 25.00% | 0.97% |
| Safety | Install | 85.72% | 26.56% |
| | Do Not Install | 14.29% | 4.43% |
| | | | |
| Potential Effectiveness | Install | 75.00% | 16.45% |
| | Do Not Install | 25.00% | 5.48% |
| | | | |
| Initial | Install | 25.00% | 3.74% |
| | Do Not Install | 75.00% | 11.22% |
| Life Cycle | Install | 12.50% | 0.47% |
| | Do Not Install | 87.50% | 3.27% |
| | | | |
| Installation | Install | 50.00% | 0.74% |
| | Do Not Install | 50.00% | 0.74% |
| Maintenance | Install | 20.00% | 1.69% |
| | Do Not Install | 80.00% | 6.74% |
| Operational | Install | 11.11% | 0.51% |
| | Do Not Install | 88.89% | 4.07% |
| | | | |
| Warning Presence | Install | 80.00% | 1.73% |
| | Do Not Install | 20.00% | 0.43% |
| Impacts | Install | 85.71% | 1.61% |
| | Do Not Install | 14.29% | 0.27% |
| Consequences | Install | 33.33% | 0.96% |
| | Do Not Install | 66.67% | 1.93% |
| | | | |
| MUTCD | Install | 66.67% | 1.41% |
| | Do Not Install | 33.33% | 0.71% |
| Local Practices | Install | 33.33% | 0.14% |
| | Do Not Install | 66.67% | 0.28% |
| Road Users | Install | 50.00% | 0.28% |
| | Do Not Install | 50.00% | 0.28% |

**Table 12. Decision to Install a Slippery When Wet Sign**

| Alternatives | Benefits | | Potential Effectiveness | Cost | | Constraints | | | Need | | | Correct Practice | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Traffic Operations | Safety | | Initial | Life Cycle | Instl. | Maint. | Oper. | Warn. Pres. | Impacts | Conseq. | MUTCD | Local Pract. | Road Users | |
| **Install** | 2.90% | 26.56% | 16.45% | 3.74% | 0.47% | 0.74% | 1.69% | 0.51% | 1.73% | 1.61% | 0.96% | 1.41% | 0.14% | 0.28% | 59.19% |
| **Do Not Install** | 0.97% | 4.43% | 5.48% | 11.22% | 3.27% | 0.74% | 6.74% | 4.07% | 0.43% | 0.27% | 1.93% | 0.71% | 0.28% | 0.28% | 40.82% |
| **TOTALS** | 3.87% | 30.99% | 21.93% | 14.96% | 3.74% | 1.48% | 8.43% | 4.58% | 2.16% | 1.88% | 2.89% | 2.12% | 0.42% | 0.56% | 100.00% |
| | 34.86% | | | 18.70% | | 14.49% | | | 6.93% | | | 3.10% | | | 100.00% |
| | 100.00% | | | | | | | | | | | | | | 100.00% |

The decision that was reached based on the engineer's judgments was to install the Slippery When Wet sign. This alternative had a global priority of 59.19 percent which contributed most to the goal of the hierarchy.

After the decision is reached to install the Slippery When Wet signs, it is now time to compute the consistency of the engineer's judgment. To calculate the consistency of the judgment, we will need to go back to the level one comparison matrices. In order to compute the consistency of the decision maker's answers we will need to obtain the Principal Eigen value *(12)*. This value is calculated using the summation of the products from the sum of the columns from the complete comparison matrix in Table 4 and its corresponding priority vector in Table 5 *(12)*. The calculation is shown below.

$$\lambda_{\max} = 2.360 \times 0.3485 + 7.976 \times 0.2196 + 8.643 \times 0.1870 + 11.292 \times 0.1448 + 28.143 \times 0.0693 + 28.00 \times 0.0310 = 8.6437$$

Once we have calculated the Principal Eigen value, we can now calculate the Consistency Index, which is one step closer to measuring the overall consistency of the decision makers answers for the level one pairwise comparisons *(12)*. To compute the Consistency Index we use the formula below where n is the number of critieria. In this case, there are six criteria (benefits, potential effectiveness, cost, constraints, need, correct practice).

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{8.6437-6}{6-1} = 0.5287$$

Knowing the Consistency Index, the new question is how do we use this index? Dr. Saaty proposed that we use this index by comparing it with an appropriate one. The appropriate

Consistency Index is called Random Consistency Index (RI) *(12)*. Dr. Saaty developed the values in this index by performing many calculations using various sample size.

**Table 13. Random Consistency Index (RI)** ***(12)***

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | .58 | .9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

After Dr. Saaty developed this table, he proposed what is called the Consistency Ratio, which is a comparison between Consistency Index and Random Consistency Index *(12)*. The formula for this is:

$$CR = \frac{CI}{RI} = \frac{0.5287}{1.24} = 42.64\%.$$

If the value of the Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable *(12)*. If the Consistency Ratio is greater than 10%, we need to revise the subjective judgment *(12)*. Therefore with this knowledge, we can conclude that the decision maker involved in this example was not consistent in his/her judgment to install the Slippery When Wet sign.

## CONCLUSIONS

After the development of the conceptual framework for the selection of warning signs, there are several conclusions that were reached. There is a need to further develop this concept and continue to investigate the incorporation of a system for the selection of warning signs. In investigating the application of these concepts, decision theory concepts seemed to have the most application for creating the framework. Decision theory offers a variety of analytical tools, such as statistical analysis, which can be applied in creating optimal decision making methods for practitioners to use in the selection of warning signs.

Although the application of systems engineering was useful in developing the framework for the conceptual model, it lacked the tools necessary for evaluating the selection of warning signs. It provided a great set of steps to follow for the development of a system but offered limited analytical tools. The incorporation of systems engineering seems to have more of an application for the development of a system that produces tangible objects. Systems engineering concepts still should be used in creating logical steps to develop a process for the selection of warning signs.

## RECOMMENDATIONS

As the project is developed, the future researcher should continue to investigate the concepts of systems engineering and decision theory. Future research should investigate the application of other normative decision theory methods such as the one used in this project. In doing so the investigator should look at incorporating methods which involve statistical tools for the analysis of a decision. By incorporating statistical tools, it will better define interrelationships between factors affecting the decisions made on warning signs.

Future researchers should look at finding ways to improve the analytic hierarchy process used in this effort. The process provided a great way to evaluate each criterion in relation to each other but there were many problems associated with the calculation of the consistency index. Many times the consistency ratio would state that the judgmental process was inconsistent when it may have not been. Due to this, future investigators should look at other ways of calculating the consistency of judgments made or look at another method to replace the analytic hierarchy process.

**REFERENCES**

1. *Manual on Uniform Traffic Control Devices*. U.S. Department of Transportation, Federal Highway Administration, Washington D.C., November 2003. http://mutcd.fhwa.dot.gov.
2. Hawkins, H.G., Jr. *An Analytical Model for Interpreting Driver Comprehension of Warning Signs*, Doctor of Philosophy in Civil Engineering Dissertation, Texas A&M University, College Station, Texas, 1993.
3. International Council of Systems Engineering. *What is Systems Engineering?* June 14, 2004. http://www.incose.org/practice/whatissystemseng.aspx. Accessed June 5,2008.
4. Department of Philosophy and the History of Technology. *Decision Theory A Brief Introduction*. Aug. 23, 2005. http://www.infra.kth.se/~soh/decisiontheory.pdf. Accessed June 6, 2008.
5. Hawkins, H.G., Jr. Evolution of the MUTCD: Early Standards for Traffic Control Devices. *ITE Journal*, Institute of Transportation Engineers, Washington, D.C., July 1992, pp. 23-26.
6. *What is Systems Engineering? A Consensus of the INCOSE Fellows*. International Council on Systems Engineering. http://www.incose.org/practice/fellowsconsensus.aspx. Accessed July 3, 2008.
7. Sage, Andrew P., and James E. Armstrong Jr. *Introduction to Systems Engineering*, Wiley, New York, 2000, pp. 1-19.
8. Hansson, Sven Ove. *Decision Theory: A Brief Introduction*, Department of Philosophy and the History of Technology, Royal Institute of Technology, Stockholm, Sweden, 1994, pp. 1-12.
9. Baska, Sener. *Landfill Site Selection by using Geographic Information Systems*. M.S. thesis. Middle East Technical University, Ankara, Turkey, 2004, pp.30-54.
10. Saaty, Thomas L. *The Analytic Hierarchy Process*. McGraw-Hill, Inc., 1980, pp. 3-10.
11. Saaty, Thomas L. and Luis G. Vargas, *Models Methods, Concepts & Application of the Analytic Hierarchy Process*, Kluwer Academic Publishers, Norwell, Massachusetts, 2000, pp. 1-43.
12. Teknomo, Kardi. (2006) Analytic Hierarchy Process (AHP) Tutorial, http://people.revoledu.com/kardi/tutorial/ahp/.

**APPENDIX A**

**SURVEY OF PROFESSIONALS**
**SYSTEMS ENGINEERING APPROACH FOR**
**SELECTING TRAFFIC CONTROL DEVICES**

**Note to Participants:** This survey is being conducted as part of an exploratory research project investigating the potential to develop a systems engineering approach for the selection of traffic control devices. Your responses will help the researcher identify critical factors that should be considered in selecting devices and the relative importance of those factors. Participation in the survey is voluntary. Individual survey responses will not be included in any reports and respondents will not be identified by name in any reporting of the results. Please return the survey to Gene Hawkins at 979-845-9294, fax 979-845-6481, or gene-h@tamu.edu. You can contact Gene Hawkins if you have any questions.

Name: Phone:
Organization: Email:

1. What type of organization do you work for?
   - ❑ Government – federal ❑ Government – state
   - ❑ Government – city ❑ Government – county
   - ❑ Government – other (please identify) ______________________________
   - ❑ Consultant ❑ Industry
   - ❑ Research
   - ❑ Other (please identify) _____________________________________

2. How familiar are you with issues related to the selection and use of traffic control devices?
   - ❑ Very
   - ❑ Somewhat
   - ❑ Vaguely
   - ❑ Not much
   - ❑ Not at all

3. Do you believe that the *Manual on Uniform Traffic Control Devices* provides adequate guidance for practitioners to make informed and appropriate decisions regarding whether a particular device should be used in a specific situation?

4. To what extent does the decision making process change as a function of the type of devices you are considering for installation?

5. Do you believe that there would be a benefit to developing a systematic procedure to guide practitioners through the decision making process relative to the need for a traffic control device?

6. Please assign a percentage to each of the following factors to indicate the relative importance of the factor relative to the other factors. The total should add up to 100 percent. You can assign 0 percent to a factor if you think it is not pertinent.

| Selection Factor | Relative Importance (Percent) | Comments |
|---|---|---|
| Initial cost of the device | | |
| Life cycle cost of the device | | |
| Installation demands of the device | | |
| Operational demands of the device | | |
| Maintenance demands of the device | | |
| Potential of the device to improve safety | | |
| Potential of the device to improve operations/mobility | | |
| Significance of situation the device is addressing | | |
| Lack of other alternatives to address the need | | |
| Similarity in use of the device with related devices | | |
| Ability of road users to understand the device | | |
| Likelihood of device attaining the desired intent | | |
| Compliance with state/national standards/MUTCD | | |
| Potential of device to reduce tort claims/lawsuits | | |
| Desires of elected officials to install the device | | |
| Other factors (list below and assign percentage) | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| Total | 100% | |

# Estimating Corridor Travel Time from Arterial Traffic Volume

Prepared for
Undergraduate Transportation Scholars Program

by

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Currently, Ms. Hunter is the vice president of Chi Epsilon National Civil Engineering Honor Society UT-Arlington student chapter, an American Society of Civil Engineers member, a member of the Institute of Transportation Engineers, National Scholars Honor Society Member, National Dean's List, and Honor Roll Recipient for the last several semesters. She has worked at the Texas Department of Transportation Paris District for the Sulphur Springs office as an Engineering Technician and is certified by the State of Texas to run several tests on concrete samples. Taileah has been involved in structural research at the University of Texas at Arlington. She was the guest speaker at the Gainesville State School and spoke to a group of 50 young men at their commencement ceremony. She will continue to help in the community and be a positive image to others as her career progresses.

**ACKNOWLEDGMENT**

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**SUMMARY**

Dealing with congestion has become routine for the average person. With growing urban areas and population, congestion not only increases in size but in density thus increasing travel time. Travel time is of high importance to travelers. Travelers tend to base their travel plans on the time it takes to get to their destination and attempt to avoid obstructions, such as traffic congestion, to make it in a timely manner. Many cities and state agencies provide travelers with travel time estimates and information displayed on message boards regarding traffic conditions to assist with commute.

The scope of this project was to estimate corridor travel time from arterial traffic volumes. In doing this, researchers are able to predict travel time at various traffic volumes and can make changes to signals timings and roadways to meet different levels of demand. From this analysis, researchers were able to understand the flow on University Drive and are now able to predict travel times for various events and traffic volumes. The results and models obtained from this study can be used to predict flow conditions for signalized corridors in mid-sized urban communities. With additional research and more recent data collection, the models generated can be used to identify threshold demand level when congestion level increases drastically and mitigation becomes necessary.

**TABLE OF CONTENTS**

## INTRODUCTION

Traveling is the change in location from point A to point B and to make that change in location takes time. Many state departments of transportation (DOTs) have message signs located on major highways to inform travelers of traffic conditions, attempting to ease congestion and persuading motorists to take alternate routes to their destinations, if necessary. However, there are many causes of congestion and delay that can impede free-flow travel—too many vehicles, construction, population growth, crashes, traffic control, vehicle breakdown, etc. All of these factors can cause congestion, and that costs the motoring public time, fuel, and money. The *2007 Urban Mobility Report (145)* states in 2005, the most current data available, that congestion wasted 2.9 billion gallons of fuel, 4.2 billion hours of time, and $78 billion of delay and fuel cost. The transportation system of an urban area includes both uninterrupted (freeways) and interrupted (arterial) facilities. Typically, as major freeways in an urban area began to build traffic volume and become congested, arterial roads become congested also. With increases in traffic volume and incidents, recurring and non-recurring congestion will increase—increasing costs to the motoring public. As transportation agencies struggle with limited financial resources, the efficient management of existing facilities is imperative. There is a need for planning tools to better understand traffic congestion impacts. Planning tools and models that estimate arterial travel time are especially valuable because of the multitude of factors that can contribute to congestion in the arterial environment (e.g., traffic signals, access density).

## BACKGROUND

The motivation of this project is monitoring mobility as well as transportation system performance measurement. Transportation professionals need to understand how their system is operating. A common concern is identifying the level of congestion on a roadway. Travel time data are often used to answer this question. Transportation professionals can use travel time to identify locations that may be congested, and to prioritize where to allocate resources for roadway improvements. Some estimation models use historic traffic data while others rely on real-time traffic information *(2)*. Traffic volume is one variable representing demand that can be used to estimate travel time, and practitioners can obtain volume data from permanent roadway instrumentation (e.g., loops), which collect real-time data, or from temporary tube counters. As an indicator of mobility, travel time is often presented relative to the free-flow travel time and realizing it increases with demand.

Travel time is easily understood by a large range of stakeholders—both technical and non-technical audiences. Communicating congestion levels to the general public in terms of travel time is effective. There are numerous research projects and references accessible to assist with a more in depth understanding of travel time such as the Federal Highway Administration's (FHWA's*) Travel Time Data Collection Handbook (2)*, the Texas Transportation Institute's (TTI's) *Urban Mobility Report (1)*, and National Cooperative Highway Research Program Report 398, *Quantifying Congestion (3).*

The Bureau of Public Roads (BPR) is the former name of FHWA and was developed in 1918 *(4)*. The Bureau produced a travel time function; however, it is for freeway segment and does not consider signal density, vehicle progression, or cross-street effects (e.g., side-street volume). The

Bureau's model is commonly used for planning purposes. The proposed work establishes relationships between travel time and traffic volume that can be used in models researchers are developing for the mobility study of signalized corridors.

**Limitations of Existing Models**

There are several limitations of existing models. The following common limitations are discussed below:

- Limited field data;
- Need for extensive inputs;
- Link-based analysis units;
- Estimating congested conditions; and
- Transferability.

The first limitation is limited field data. Some models use micro-simulation to calibrate their model, with limited *(5)*, or no *(6,8)*, actual field data. There is a need for models that are calibrated with extensive field data. The proposed work develops a model using extensive field data.

Some models require practitioners to collect extensive inputs. This can be difficult if practitioners do not have the data readily available. The *Highway Capacity Manual* lists, among others, signal control, speed, delay, saturation flow rate and lost time, and queuing as parameters for interrupted traffic flow *(7)*. Related models in the literature require extensive inputs that may not be readily available to practitioners *(8,9).*To simplify the process, there is a need to investigate relationships that rely on fewer, and less complicated, inputs.

Another limitation is that many models use link-based analysis procedures. A link may be defined as a section of roadway from signal to signal. Such models estimate traffic operations for each link, and then corridor travel time is estimated by "adding up" each link. While this does make some models more transferable, there is still a question of whether this "addition" really equates to actual travel time through the corridor. Study of the correlations between arterial through link travel times and flow values reveal that detector data have limited significance to the process of forecasting arterial link travel times *(5)*. In addition, researchers have developed link-based methods for dynamic assignment on signalized networks, which include extensive inputs *(9)*. This suggests a corridor approach may be more effective.

Another limitation is estimating congestion conditions. Many models are acceptable for estimating travel time for non-congested (free-flow) conditions, but have increased error during congested conditions. A previous distribution-free model was applied to free- flow conditions, but has the ability to be converted to a time-dependent form to account for congestion *(6)*. Congested conditions are of primary interest for practitioners who want to report congested conditions. There is a need to investigate and incorporate travel time estimates in the arterial environment for both congested and non-congested conditions.

A final limitation is transferability. All models are calibrated and developed for specific operating conditions. This means that the models cannot be applied to conditions beyond those for which the model was calibrated, without introducing some error. While this proposed work investigates only one signal density for the corridor discussed below, future work will investigate other signal densities, therefore increasing transferability.

## GOAL AND OBJECTIVES

The goal reached for this research was to estimate corridor travel time from arterial traffic volumes. The goal was reached by completing the following two objectives:

1. Developing a relationship between corridor travel time and average traffic volume.
2. Investigating variability of travel time estimates for varying traffic volume.

The work plan below highlights the key tasks performed that satisfied these objectives.

## RESEARCH TASKS

This portion of the research is composed of five parts. Each part needed an extensive amount of time dedicated to it so that the information and results were accurate and presentable.

### Literature Review

Previous work includes many existing models for estimating arterial travel time. During this task, researchers performed a literature review to identify previous relevant research on estimating travel time in an arterial environment. Researchers gained a better understanding of the limitations of existing models mentioned in the "BACKGROUND" of this report. Researchers also reviewed literature on the related topic of travel time data collection. A review of more literature will be an advantage to get a better understanding of limitations and existing models previously discussed as well as travel time data.

### Data Collection

The test corridor for this study is University Drive (FM 60), located in College Station, Texas. The roadway is 2.55 miles from SH 6 East Frontage Road to Ireland Street. There are 12 signalized intersections, and the signal density is 4.7 signals per mile. The signalized intersections do not have uniform spacing, and they are closer on the west end of the corridor. There are three through lanes both in the eastbound and westbound direction along the corridor and left-and right-hand turn lanes at the major signalized intersections. The median treatment varies along the corridor with raised medians near SH 6 and no medians near campus. The land use along the corridor includes several shopping centers, restaurants, and hotels. The west end of the corridor is along the north side of the Texas A&M University campus. With the population growth of the community and the university, recurring congestion is growing.

Travel time runs were previously collected on a Wednesday and Thursday morning during the hours of 6:00 a.m. to 10:00 a.m., and on a Saturday before a football game during the hours of 10:00 a.m. and 1:00 p.m. This equates to 11 hours of travel time data. The travel time runs were collected using global positioning system (GPS). Researchers collected 283 runs eastbound and 280 runs westbound

GPS-instrumented test vehicles used the "floating car" driving method. The "floating car" test vehicle driving style is when the driver "floats" with the traffic by attempting to safely pass as many vehicles as pass the test vehicle *(2)*. There were 40 locations of tube counts to collect average daily traffic (ADT) between major signalized intersections and at major cross streets. Video was recorded at major intersections to obtain queue data at signals. This will be used for the CORSIM model calibration.

During this task, the primary researcher became familiar with the previous data collection to facilitate understanding for data reduction performed in the next task.

**Data Reduction**

The travel time data used in this study are based on both field observations (GPS runs) and traffic simulation. Travel time estimation was performed using a calibrated CORridor SIMulation (CORSIM) model. CORSIM is a well-known, widely used micro-simulation tool. Researchers calibrated the CORSIM model with field data, including travel time runs, signalized intersection queue data, traffic volumes, and signal timing plans. This was done by matching queue lengths, at intersections, travel time values from simulation with field observations through adjusting simulation parameters. A calibrated CORSIM model was developed to allow analysis of corridor travel time given varying traffic volume inputs.

Selected travel time runs that were collected for the entire corridor for both directions were used to calibrate this model. The travel time run data were inserted into PC-travel, a travel time and delay data analysis software, created by JAMAR. The travel time data were summarized in Excel. The ADTs, average daily traffic counts, were also entered into Excel. With 11 hours of data, there are twenty-two 30-minute periods. A peak period from 8:00 a.m. to 8:30 a.m. was selected from Wednesday, November 8, 2006, to initially calibrate the model. From that 30-minute period, 21 other cases were created by using average daily traffic volumes, as well as signal timings.

Using these 22 cases, researchers ran each case eleven times to produce 242 cases. Each run will include both the eastbound and westbound directions to obtain 484 observations of traffic volume and travel time. Four extreme cases were created to fill gaps, if necessary, using the data from the 8:00-8:30 a.m. peak period as the baseline condition. These four extreme cases were run eleven times in both directions to produce 88 extreme cases. Researchers then went into CORSIM's output screen and pulled out corridor travel time data, and used the data to plot the relationship between travel time and volume for all 572 total cases.

The four extreme cases, as stated above, were created using the data from the 8:00-8:30a.m. peak period. Extreme case one was formed by making a 20% volume increase for major inputs and a 0% for minor inputs. Extreme case two kept the volume increase for major inputs at 20% and increased the minor inputs to 10%. Extreme case three increased the volume for major inputs to 30% with the minor inputs remaining at 10%. Lastly, extreme case four had a 40% volume increase for major inputs and remained 10% for minor inputs. Major and minor inputs for the extreme cases are as follows:

- Major inputs- include Texas northbound and southbound entrance to University Drive and east and west end entrances to University Drive
- Minor inputs- include all other streets on the twelve signalized corridor.

Researchers defined the corridor travel time along University Drive as the amount of time spent in the entire corridor from entrance to exit which is the sum of the eleven segments. The corridor volume was defined as the average through volume on links. An example of what links were used to get the average corridor volumes and corridor travel times are shown in Table 1.

**Table 1. Example of the Links Used to Calculate Average Corridor Volume and Corridor Travel Time for Both Directions**

| Wed 6:00-6:30am | | | | | | | |
|---|---|---|---|---|---|---|---|
| Original | | | Link Volume (vehicles) | | Free Flow Time (distance/free flow speed) | Travel Time (vehicle-minutes) | Link Travel Time (seconds) |
| | All | Left turn | Through | Right Turn | Through | Through | Through |
| East to Ireland | 1498 | 76 | 1353 | 69 | 14.29 | 895.70 | 39.7 |
| East to Spence | 1399 | 36 | 1333 | 30 | 19.51 | 384.72 | 17.3 |
| East to College | 1445 | 132 | 1040 | 273 | 12.94 | 592.80 | 34.2 |
| East to Polo | 1269 | 0 | 1243 | 26 | 37.30 | 670.98 | 32.4 |
| East to Texas | 1250 | 169 | 683 | 398 | 28.50 | 471.00 | 41.4 |
| East to Tarrow W | 1314 | 0 | 1262 | 52 | 58.62 | 1701.25 | 80.9 |
| East to Tarrow E | 1523 | 313 | 1195 | 15 | 16.46 | 1376.47 | 69.1 |
| East to Spring Loop | 1212 | 27 | 1175 | 10 | 50.74 | 1484.73 | 75.8 |
| East to Forest | 1502 | 178 | 1324 | 0 | 17.70 | 478.33 | 21.7 |
| East to Glenhaven | 1347 | 134 | 1105 | 108 | 23.70 | 730.88 | 39.7 |
| East to WFR | 1181 | 0 | 669 | 512 | 13.32 | 467.05 | 41.9 |
| East to EFR | 999 | 554 | 445 | 0 | 21.86 | 313.40 | 42.3 |
| East to Out | 690 | 0 | 690 | 0 | 10.00 | 115.48 | 10.0 |
| **Total Eastbound** | **16629** | **1619** | **13517** | **1493** | **324.9** | **9682.79** | **546.4** |
| | | | | | | | |
| | | | Link Volume (vehicles) | | Free Flow Time (distance/free flow speed) | Travel Time (vehicle-minutes) | Link Travel Time (seconds) |
| | All | Left turn | Through | Right Turn | Through | Through | Through |
| West to EFR | 574 | 0 | 501 | 73 | 10.00 | 334.02 | 40.0 |
| West to WFR | 1627 | 252 | 1375 | 0 | 21.86 | 508.45 | 22.2 |
| West to Glenhaven | 2158 | 186 | 1873 | 99 | 13.32 | 1556.12 | 49.8 |
| West to Forest | 2027 | 45 | 1926 | 56 | 23.70 | 1460.88 | 45.5 |
| West to Spring Loop | 2081 | 198 | 1679 | 204 | 17.70 | 1269.42 | 45.4 |
| West to Tarrow E | 1697 | 17 | 1557 | 123 | 50.74 | 2236.10 | 86.2 |
| West to Tarrow W | 1534 | 45 | 1489 | 0 | 16.46 | 436.73 | 17.6 |
| West to Texas | 1880 | 408 | 1205 | 267 | 58.62 | 1876.83 | 93.5 |
| West to Polo | 1928 | 127 | 1801 | 0 | 28.50 | 1052.33 | 35.1 |
| West to College | 1826 | 45 | 1626 | 155 | 37.30 | 1728.80 | 63.8 |
| West to Spence | 1965 | 33 | 1910 | 22 | 12.94 | 491.55 | 15.4 |
| West to Ireland | 1977 | 281 | 1604 | 92 | 19.51 | 794.43 | 29.7 |
| West to Out | 1659 | 0 | 1659 | 0 | 14.29 | 328.18 | 11.9 |
| **Total Westbound** | **22933** | **1637** | **20205** | **1091** | **324.9** | **14073.84** | **556.0** |

When traveling east, there are nine segments used to get the average volume which extends from Ireland Street to Glenhaven Drive. When traveling west, there are eleven segments used to get the average volume which extends from SH 6 West Frontage Road to Ireland Street. The difference in the length of these two corridor volumes is because when traveling east, a significant portion of the total traffic does not continue to flow through the corridor but rather turns right to get onto the West Frontage Road traveling south.

The 572 cases that were entered into Excel were summarized into tables of each time period with its eleven runs with the average corridor volume and corridor travel time. The average of the eleven runs average corridor volumes were calculated and documented as well as the corridor travel time mean and standard deviation for the eleven runs. These tables are located in Appendix A.

**Data Analysis/Statistical Modeling**

The first objective was to develop a relationship between average corridor travel time and traffic volume (see #1 in Figure 1). Using Excel, researchers investigated the shape of the relationship—linear, non-linear, and slope changes. The second objective was to investigate the variability of travel time over the range of traffic volumes (see #2 in Figure 1).

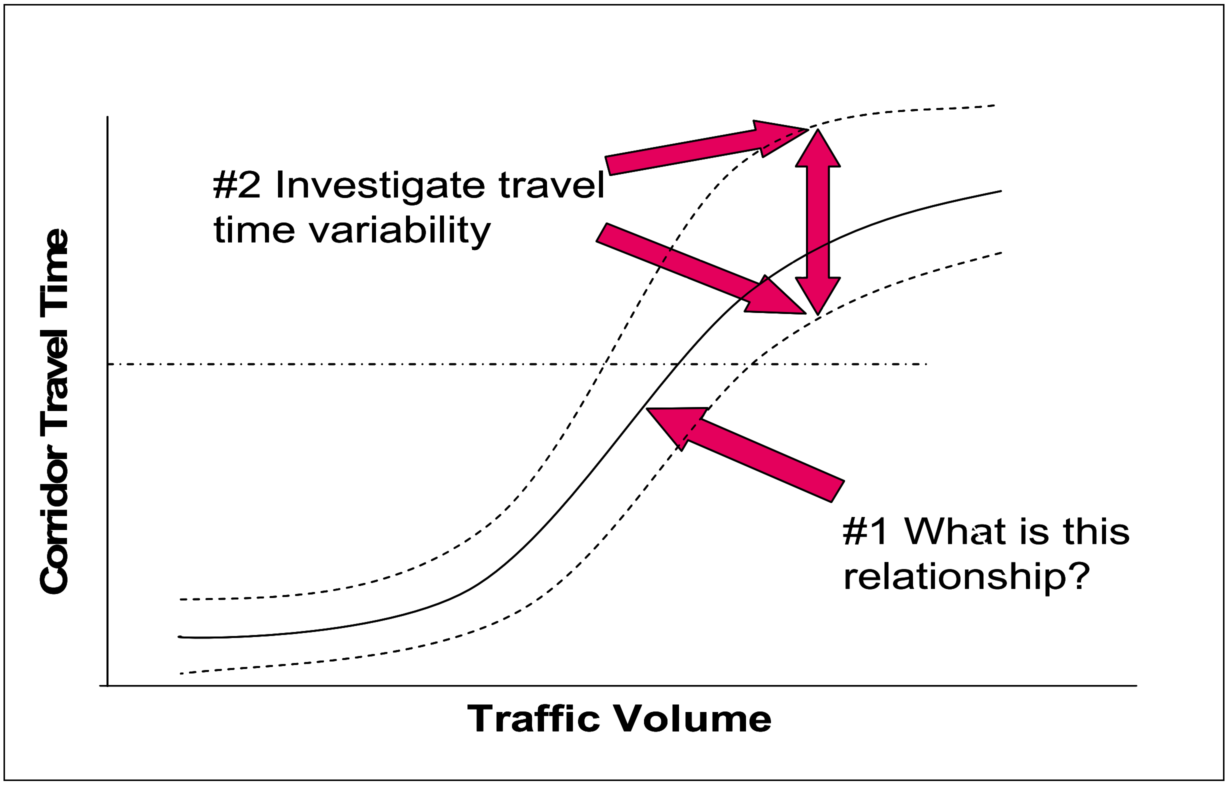


**Figure 1. Traffic Volume vs. Corridor Travel Time**

After calibrating the model and plotting the corridor travel time versus the traffic volume, the relationship was investigated (see Figures 2, 3, and 4). Figure 2 is a graph of the 286 cases collected for the eastbound direction showing a relationship between the average corridor volumes versus the corridor travel time. The graph illustrates a slight curve as both travel time and volume increases. A small cluster of data points appears as outliers because of a gap. Micro-simulation was used to fill gaps in volume range shown by the model but since there are no observations or simulation cases for low to moderate conditions or p.m. conditions, a gap is present.

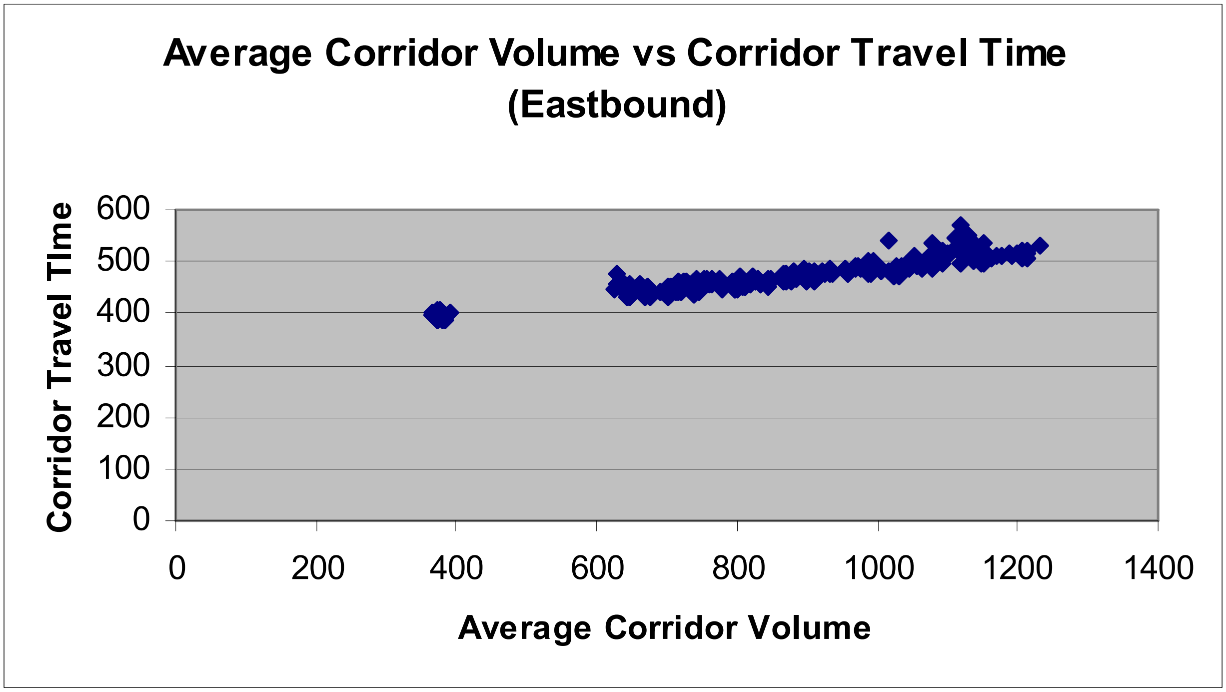


**Figure 2. Average Corridor Volume vs. Corridor Travel Time for Eastbound Direction**

The graph of the 286 cases collected for the peak flow direction is shown in Figure 3. This illustration has a gap for the same reasons as the non-peak direction graph. There is also a curve viewable in this graph but it has a more rapid increase than the eastbound direction.

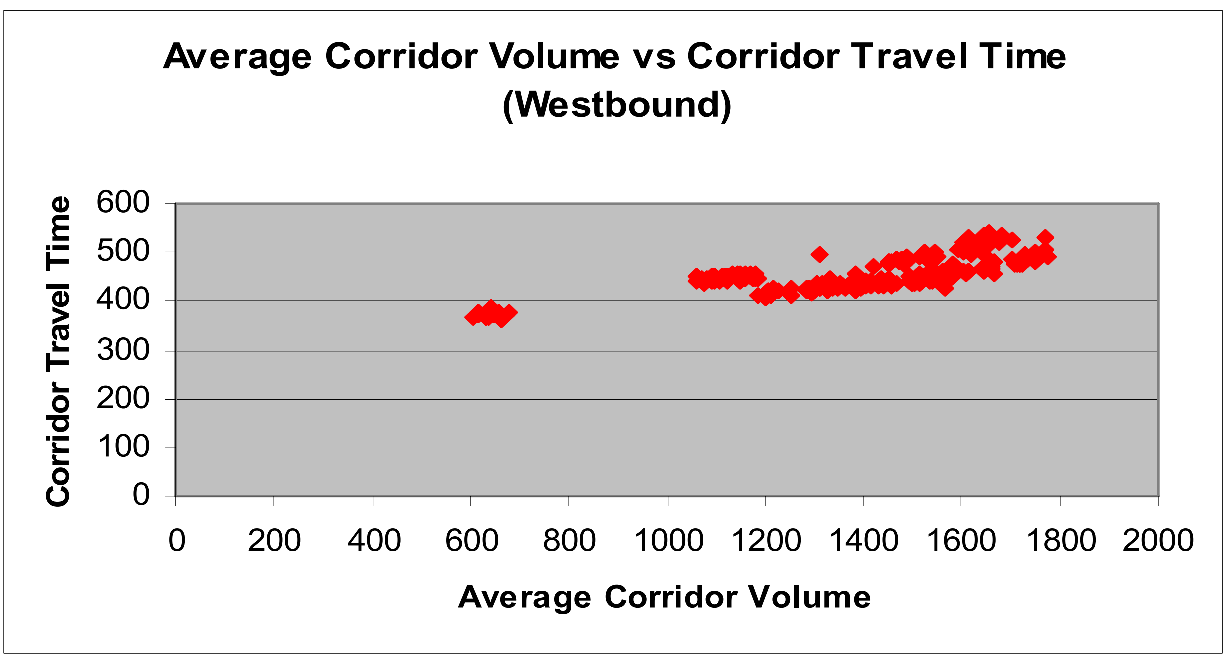


**Figure 3. Average Corridor Volume vs. Corridor Travel Time for Westbound Direction**

Both the peak and non-peak conditions were plotted, in Figure 4, for comparison. The eastbound direction has smaller volumes and higher travel times than the westbound direction. This is because signal timing favors peak direction by giving more green time and better offset considerations.

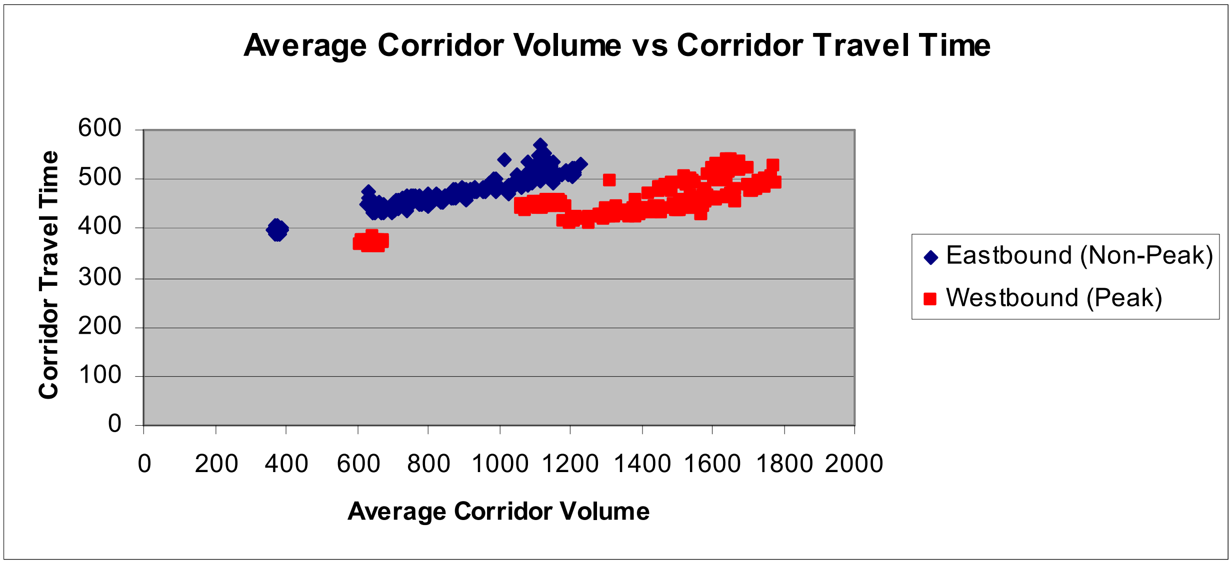


**Figure 4. Average Corridor Volume vs. Corridor Travel Time for Comparison of Both Eastbound and Westbound Directions**

Researchers used regression analysis to estimate the relationship between traffic volume and travel time and to investigate travel time variability. Using Excel and running an analysis of variance (ANOVA), a linear model for the eastbound and westbound directions were developed. The analysis is shown in Table 2, and the linear regression model is shown below in Figure 5 for the non-peak direction.

**Table 2. Statistical Analysis Summary Output of the Linear Model for the Eastbound Direction**

SUMMARY OUTPUT

**Eastbound (Non-Peak)**

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.946352349 |
| R Square | 0.895582768 |
| Adjusted R Square | 0.895215102 |
| Standard Error | 11.54956229 |
| Observations | 286 |

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 324924.8629 | 324924.8629 | 2435.857585 | 2.3138E-141 |
| Residual | 284 | 37883.43851 | 133.3923891 | | |
| Total | 285 | 362808.3014 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
|---|---|---|---|---|---|---|---|---|
| Intercept | 337.0463649 | 2.778485439 | 121.3057878 | 1.1194E-246 | 331.5773273 | 342.5154026 | 331.5773273 | 342.5154026 |
| X Variable 1 | 0.155680214 | 0.003154333 | 49.35440796 | 2.3138E-141 | 0.149471377 | 0.161889051 | 0.149471377 | 0.161889051 |

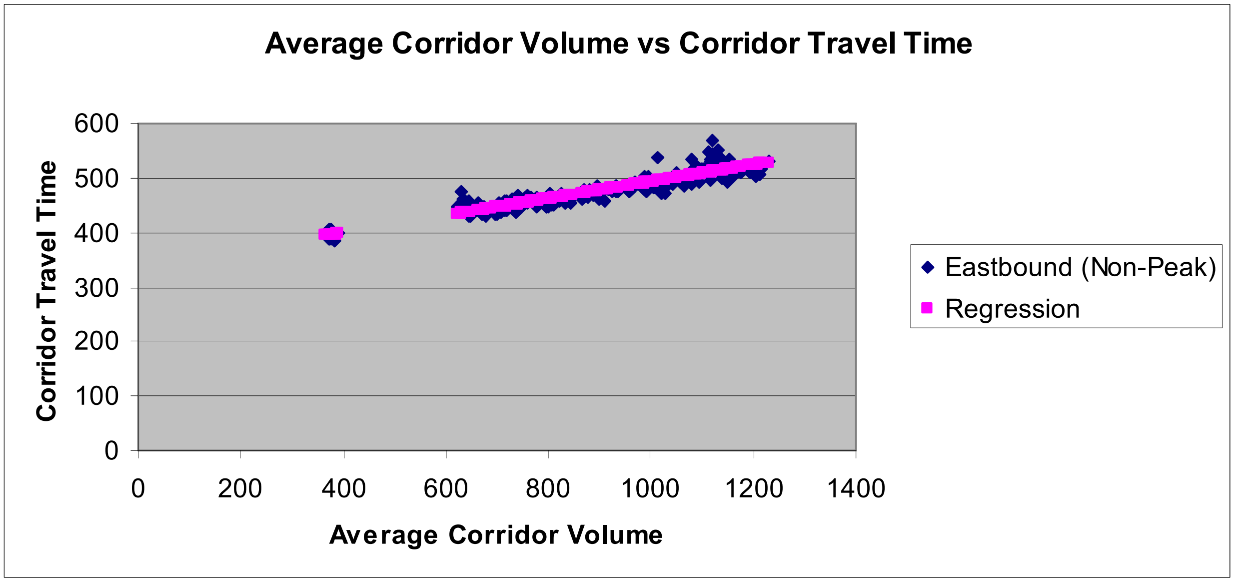


**Figure 5. Linear Regression Model of the Average Corridor Volume vs. Corridor Travel Time for the Eastbound Direction**

The model for the eastbound regression is as follows: TT= 337.05+0.15568*CV. The model resulted in a $R^2$ value of 0.895 which is a strong correlation. Below in Table 3 and Figure 6 are the analysis and linear regression model for the westbound direction.

**Table 3. Statistical Analysis Summary Output of the Linear Model for the Westbound Direction**

SUMMARY OUTPUT

**Westbound (Peak)**

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.779453872 |
| R Square | 0.607548338 |
| Adjusted R Square | 0.606166466 |
| Standard Error | 21.53649932 |
| Observations | 286 |

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 203921.5995 | 203921.5995 | 439.6560011 | 1.25826E-59 |
| Residual | 284 | 131725.1081 | 463.8208031 | | |
| Total | 285 | 335646.7076 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
|---|---|---|---|---|---|---|---|---|
| Intercept | 315.9292428 | 6.460382709 | 48.90255841 | 2.3972E-140 | 303.2129349 | 328.6455506 | 303.2129349 | 328.6455506 |
| X Variable 1 | 0.097091073 | 0.004630446 | 20.96797561 | 1.25826E-59 | 0.087976726 | 0.106205421 | 0.087976726 | 0.106205421 |

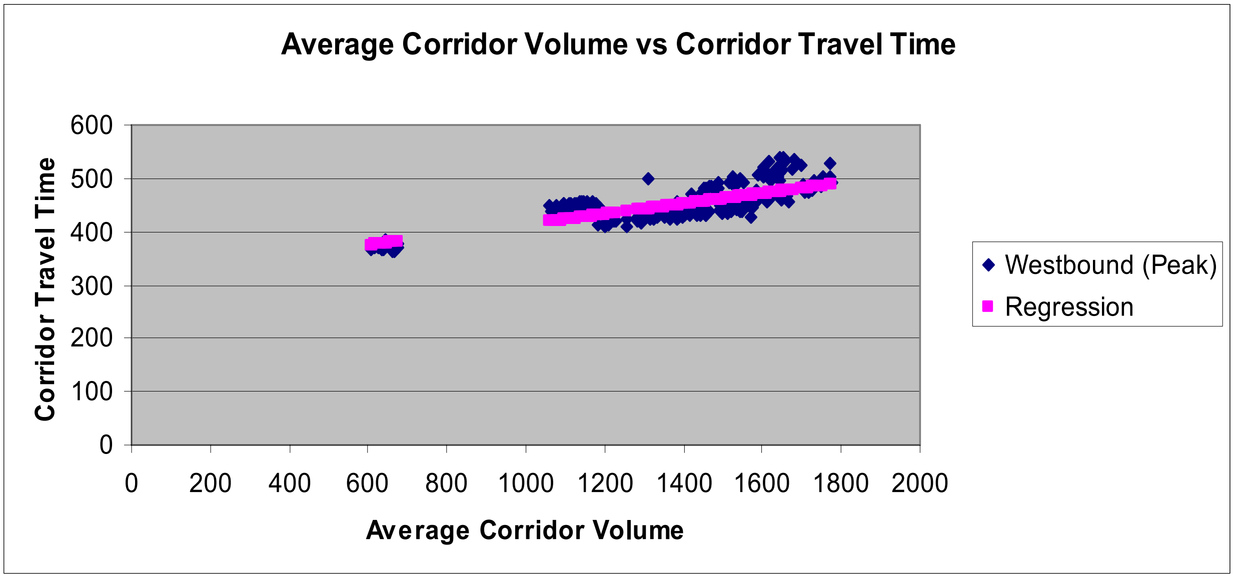


**Figure 6. Linear Regression Model of the Average Corridor Volume vs. Corridor Travel Time for the Westbound Direction**

A moderate $R^2$ value of 0.608 was the output from the model of TT=315.93+0.09709*CV. The same analysis was performed again but with another model to see how results varied. The results are presented in Table 4 and Figure 7 for the non-peak condition.

**Table 4. Statistical Analysis Summary Output of the Non-Linear Model for the Eastbound Direction**

SUMMARY OUTPUT

**Eastbound (Non-Peak)**

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.946820739 |
| R Square | 0.896469513 |
| Adjusted R Square | 0.896104969 |
| Standard Error | 11.50041645 |
| Observations | 286 |

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 325246.5811 | 325246.5811 | 2459.153317 | 6.8889E-142 |
| Residual | 284 | 37561.72029 | 132.2595785 | | |
| Total | 285 | 362808.3014 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
|---|---|---|---|---|---|---|---|---|
| Intercept | 356.5760433 | 2.385612188 | 149.4694088 | 4.9769E-272 | 351.8803186 | 361.2717681 | 351.8803186 | 361.2717681 |
| X Variable 1 | 0.034153362 | 0.000688717 | 49.58985095 | 6.8889E-142 | 0.032797725 | 0.035508999 | 0.032797725 | 0.035508999 |

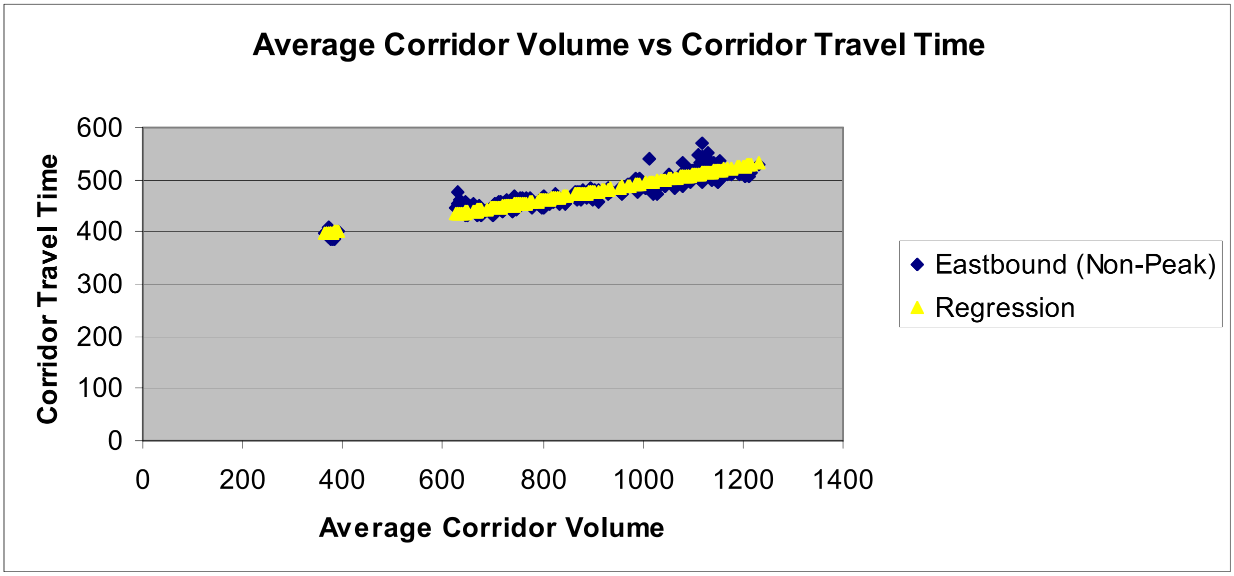


**Figure 7. Non-Linear Regression Model of the Average Corridor Volume vs. Corridor Travel Time for the Eastbound Direction**

Even though the regression appears to be linear, the model $TT=356.58+0.03415*(CV)^{1.2}$ has an $R^2$ value of 0.896, which is comparable to the linear model. Table 5 and Figure 8 display the analysis and regression for the peak condition.

**Table 5. Statistical Analysis Summary Output of the Non-Linear Model for the Westbound Direction**

SUMMARY OUTPUT

**Westbound (Peak)**

| *Regression Statistics* | |
|---|---|
| Multiple R | 0.779729803 |
| R Square | 0.607978566 |
| Adjusted R Square | 0.606598209 |
| Standard Error | 21.52469132 |
| Observations | 286 |

ANOVA

| | *df* | *SS* | *MS* | *F* | *Significance F* |
|---|---|---|---|---|---|
| Regression | 1 | 204066.004 | 204066.004 | 440.4501842 | 1.0764E-59 |
| Residual | 284 | 131580.7036 | 463.3123366 | | |
| Total | 285 | 335646.7076 | | | |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* |
|---|---|---|---|---|---|---|---|---|
| Intercept | 333.9687642 | 5.61451963 | 59.48305219 | 2.3643E-162 | 322.9174127 | 345.0201156 | 322.9174127 | 345.0201156 |
| X Variable 1 | 0.019691062 | 0.000938255 | 20.98690506 | 1.0764E-59 | 0.017844247 | 0.021537878 | 0.017844247 | 0.021537878 |

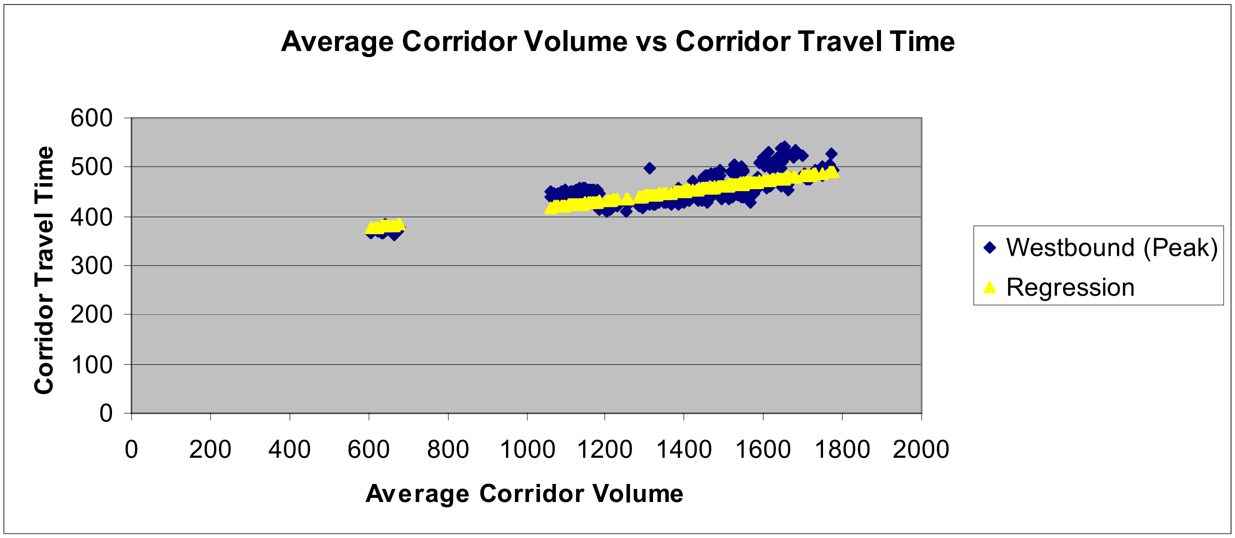


**Figure 8. Non-Linear Regression Model of the Average Corridor Volume vs. Corridor Travel Time for the Westbound Direction**

When this analysis was applied to the westbound direction, the westbound model of $TT= 333.97+0.01969 *(CV)^{1.2}$ produced a $R^2$ value of 0.608. This value was also comparable to the linear model for the peak condition.

After reviewing the relationship between travel time and traffic volume, which was the first objective, the travel time variability can be evaluated from the models and data. Summary tables showing variance for the peak and non-peak conditions can be seen in Table 6 and Table 7. Note that the volume range intervals for the directions are of the same size. As the travel time range increases so does the variance.

**Table 6. Travel Time Variability for Eastbound Direction**

| Average Corridor Volume Range | Travel Time Range (sec.) | Variance (sec.) |
|---|---|---|
| 365-582 | 386.5-407.3 | 32.29 |
| 583-800 | 430.6-475.7 | 100.24 |
| 801-1027 | 447.4-539.0 | 180.88 |
| 1028-1245 | 484.8-570.3 | 303.11 |

**Table 7. Travel Time Variability for Westbound Direction**

| Average Corridor Volume Range | Travel Time Range (sec.) | Variance (sec.) |
|---|---|---|
| 606-899 | 361.7-384.9 | 31.80 |
| 900-1193 | 412.3-456.4 | 50.70 |
| 1194-1487 | 408.5-498.1 | 350.67 |
| 1488-1781 | 428.7-539.7 | 763.96 |

After completing and analyzing the data from graphs and summary outputs produced in Excel, results can be concluded.

**Results**

All of the 572 cases that were plotted are located in Appendix B in summary tables. The average of the averaged corridor volumes were calculated for the 572 cases, as well as the mean and standard deviation of the corridor travel time are summarized in Table 8 and Table 9 below.

**Table 8. Summary of Eastbound Corridor Volumes and Travel Time Mean and Standard Deviation for Various Time Periods**

| Time Period | Average of Averaged Corridor Volumes | Average Travel Time (sec) mean | Average Travel Time (sec) standard deviation |
|---|---|---|---|
| **Wed 6:00-6:30am** | 1150 | 504.8 | 7.113 |
| **Wed 6:30-7:00am** | 1022 | 482.3 | 6.585 |
| **Wed 7:00-7:30am** | 377 | 397.9 | 5.599 |
| **Wed 7:30-8:00am** | 814 | 458.8 | 6.195 |
| **Wed 8:00-8:30am** | 697 | 439.7 | 7.600 |
| **Wed 8:30-9:00am** | 663 | 440.0 | 8.198 |
| **Wed 9:00-9:30am** | 755 | 458.4 | 3.365 |
| **Wed 9:30-10:00am** | 643 | 451.9 | 2.698 |
| **Thur 6:00-6:30am** | 1204 | 515.9 | 7.264 |
| **Thur 6:30-7:00am** | 1069 | 494.2 | 5.427 |
| **Thur 7:00-7:30am** | 375 | 394.0 | 5.318 |
| **Thur 7:30-8:00am** | 865 | 468.0 | 6.515 |
| **Thur 8:00-8:30am** | 741 | 447.3 | 7.727 |
| **Thur 8:30-9:00am** | 661 | 440.6 | 12.636 |
| **Thur 9:00-9:30am** | 735 | 458.6 | 4.717 |
| **Thur 9:30-10:00am** | 732 | 456.8 | 4.496 |
| **Sat 10:00-10:30am** | 888 | 473.3 | 6.710 |
| **Sat 10:30-11:00am** | 974 | 487.7 | 9.451 |
| **Sat 11:00-11:30am** | 1076 | 511.7 | 10.440 |
| **Sat 11:30-12:00pm** | 1116 | 522.8 | 14.461 |
| **Sat 12:00-12:30pm** | 1113 | 533.0 | 16.500 |
| **Sat 12:30-1:00pm** | 1110 | 524.5 | 14.405 |
| **Extreme Case 1** | 808 | 455.1 | 6.420 |
| **Extreme Case 2** | 821 | 457.7 | 6.832 |
| **Extreme Case 3** | 869 | 468.2 | 7.028 |
| **Extreme Case 4** | 920 | 476.0 | 6.355 |

From the time periods on Saturday, November 11, 2006, and the first hour for the weekdays, the data illustrate that there were more volume during these periods and less volume during the extreme cases and the other three hours of the weekdays.

**Table 9. Summary of Westbound Corridor Volumes and Travel Time Mean and Standard Deviation for Different Time Periods**

| Time Period | Average of Averaged Corridor Volumes | Average Travel Time (sec) | Average Travel Time (sec) |
|---|---|---|---|
| | | mean | standard deviation |
| **Wed 6:00-6:30am** | 1626 | 510.5 | 10.723 |
| **Wed 6:30-7:00am** | 1463 | 480.1 | 4.764 |
| **Wed 7:00-7:30am** | 657 | 371.8 | 5.615 |
| **Wed 7:30-8:00am** | 1318 | 433.1 | 5.685 |
| **Wed 8:00-8:30am** | 1330 | 427.8 | 2.232 |
| **Wed 8:30-9:00am** | 1464 | 437.3 | 6.291 |
| **Wed 9:00-9:30am** | 1156 | 449.4 | 4.707 |
| **Wed 9:30-10:00am** | 1094 | 447.7 | 4.279 |
| **Thur 6:00-6:30am** | 1651 | 522.5 | 12.242 |
| **Thur 6:30-7:00am** | 1512 | 488.8 | 12.322 |
| **Thur 7:00-7:30am** | 625 | 372.4 | 5.916 |
| **Thur 7:30-8:00am** | 1296 | 425.9 | 7.482 |
| **Thur 8:00-8:30am** | 1378 | 440.8 | 19.416 |
| **Thur 8:30-9:00am** | 1406 | 434.9 | 5.085 |
| **Thur 9:00-9:30am** | 1149 | 450.8 | 4.557 |
| **Thur 9:30-10:00am** | 1110 | 446.7 | 3.056 |
| **Sat 10:00-10:30am** | 1202 | 419.8 | 7.128 |
| **Sat 10:30-11:00am** | 1412 | 431.3 | 5.804 |
| **Sat 11:00-11:30am** | 1517 | 444.9 | 6.926 |
| **Sat 11:30-12:00pm** | 1539 | 456.0 | 9.103 |
| **Sat 12:00-12:30pm** | 1582 | 455.4 | 6.641 |
| **Sat 12:30-1:00pm** | 1547 | 446.9 | 6.976 |
| **Extreme Case 1** | 1547 | 453.4 | 6.501 |
| **Extreme Case 2** | 1570 | 455.5 | 5.046 |
| **Extreme Case 3** | 1671 | 471.2 | 8.751 |
| **Extreme Case 4** | 1742 | 492.0 | 15.200 |

From the extreme cases and the time periods on Saturday, November 11, 2006, the data illustrate that there were more volume during these periods and less volume during the weekdays.

When comparing and relating travel time to traffic volume, they are proportional. When volume increases, travel time generally increases and vice versa. When comparing and relating the peak and non-peak conditions, the peak condition generally had the upper hand because of the favoritism that the timing plan shows.

## CONCLUSION

Based on the results of the study, several conclusions were made by the researchers.

The following is a summary of conclusions made from the study:

- Westbound traveling has more volume but shorter travel time because of the timing plan favoring peak direction.
- Westbound has a larger range in travel time.
- Relationship appears to be linear mostly, then goes up non-linearly as demand increases.
- Eastbound data have a stronger linear correlation than westbound data.

From the results and conclusions presented in the paper and with additional research and more recent data collection, future model generation will be better at estimating traffic volumes. The results and models obtained from this study can be used to predict flow conditions for signalized corridors in mid-sized urban communities.

## FUTURE RESEARCH

In the future, the following procedures can be carried out to produce better results and accuracy of the data:

- PM + low to moderate volume data to fill the gap;
- Investigate relationship models considering multiple factors as the same time (i.e., intersection density, major cross street, etc.); and
- Identify a threshold demand level.

With the continuation of research for this project and with data relative to the city's population gradual increase, researchers and transportation engineers will have the opportunity to limit, if not remove, the build-up of congestion.

## REFERENCES

1. Schrank, D. L. and Lomax, T. J. (2007). "The 2007 Urban Mobility Report." Texas Transportation Institute.
2. Turner, S.M., Eisele, W. L., Benz, R., and Holdener, D. (1998). *Travel Time Data Collection Handbook*. FHWA-PL-98-0351, Texas Transportation Institute, Federal Highway Administration, Washington, D.C., 3-2.
3. Lomax, T. J., Turner, S. M., Shunk, G. A., Levinson R. H., Bay, P. N., and Douglas, G. B. (1997). "Quantifying Congestion, Volume 1, Final Report." *National Cooperative Highway Research Program (NCHRP) Report 398*, Transportation Research Board, Washington, D.C., 2.
4. Federal Highway Administration, U.S. Department of Transportation. www.fhwa.dot.gov. Accessed June 11, 2008.
5. Sisiopiku, V., Rouphail, N. M., and Santiago, A. (1994). "Analysis of the Correlation Between Arterial Travel Times and Detector Data from Simulation and Field Studies." *Transportation Research Board*. 1457, Transportation Research Board, National Research Council, Washington, D.C., 166-173.
6. Tarko, A. and Rouphail, N. M. (1994). "A Distribution-Free Model for Estimating Random Queues in Signalized Networks." *Transportation Research Record. 1457*, Transportation Research Board, National Research Council, Washington, D.C., 192-197.
7. Transportation Research Board (TRB). (2000). *Highway Capacity Manual 2000*, Highway Capacity Committee, TRB, Washington, D.C.
8. Li, J., Rouphail, N. M., and Tarko, A. (1996). "An Overflow Delay Model for Signalized Arterials." *Transportation Research Record, 1555*. Transportation Research Board, National Research Council, Washington, D.C., 1-8.
9. Ran, B., Rouphail, N. M., Tarko, A., and Boyce, D. (1997). "Toward a Class of Link Travel Time Functions for Dynamic Assignment Models on Signalized Networks." *Transportation Research*, part B: Methodological, 31(4), 227-290.

## APPENDIX A

### Table A1. Summary of Time Period Wed. 6:00-6:30am Eleven Cases for Eastbound

| Wed 6:00-6:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1151 | 496.6 | |
| Case 1 | 1149 | 494.1 | |
| Case 2 | 1158 | 512.5 | |
| Case 3 | 1144 | 507.9 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1168 | 508.5 | 1150 |
| Case 5 | 1162 | 504.5 | |
| Case 6 | 1177 | 510.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 1138 | 499.5 | mean=504.8 |
| Case 8 | 1150 | 508.4 | standard deviation=7.113 |
| Case 9 | 1140 | 514.0 | |
| Case 10 | 1117 | 495.8 | |

### Table A2. Summary of Time Period Wed. 6:00-6:30am Eleven Cases for Westbound

| Wed 6:00-6:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1640 | 504.1 | |
| Case 1 | 1649 | 513.2 | |
| Case 2 | 1601 | 521.1 | |
| Case 3 | 1626 | 508.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1614 | 531.8 | 1626 |
| Case 5 | 1634 | 518.4 | |
| Case 6 | 1620 | 494.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 1591 | 507.7 | mean=510.5 |
| Case 8 | 1645 | 496.0 | standard deviation=10.723 |
| Case 9 | 1625 | 509.9 | |
| Case 10 | 1643 | 510.3 | |

### Table A3. Summary of Time Period Wed. 6:30-7:00am Eleven Cases for Eastbound

| Wed 6:30-7:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1030 | 471.8 | |
| Case 1 | 1022 | 472.9 | |
| Case 2 | 1028 | 489.3 | |
| Case 3 | 1019 | 482.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1044 | 487.9 | 1022 |
| Case 5 | 1035 | 489.6 | |
| Case 6 | 1042 | 488.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 1004 | 483.3 | mean=482.3 |
| Case 8 | 1018 | 481.2 | standard deviation=6.585 |
| Case 9 | 1006 | 483.7 | |
| Case 10 | 991 | 474.8 | |

### Table A4. Summary of Time Period Wed. 6:30-7:00am Eleven Cases for Westbound

| Wed 6:30-7:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1485 | 478.0 | |
| Case 1 | 1485 | 476.8 | |
| Case 2 | 1421 | 471.5 | |
| Case 3 | 1470 | 484.2 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1450 | 479.7 | 1463 |
| Case 5 | 1475 | 480.3 | |
| Case 6 | 1450 | 474.0 | **Corridor Travel Time(seconds)** |
| Case 7 | 1453 | 482.8 | mean=480.1 |
| Case 8 | 1457 | 481.7 | standard deviation=4.764 |
| Case 9 | 1468 | 486.6 | |
| Case 10 | 1478 | 485.7 | |

**Table A5. Summary of Time Period Wed. 7:00-7:30am Eleven Cases for Eastbound**

| Wed 7:00-7:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 375 | 394.6 |
| Case 1 | 375 | 393.8 |
| Case 2 | 390 | 399.8 |
| Case 3 | 384 | 396.7 |
| Case 4 | 386 | 395.1 |
| Case 5 | 371 | 407.3 |
| Case 6 | 367 | 401.9 |
| Case 7 | 378 | 397.0 |
| Case 8 | 367 | 397.8 |
| Case 9 | 375 | 405.2 |
| Case 10 | 380 | 387.2 |

**Average of Averaged Corridor Volumes**
377

**Corridor Travel Time(seconds)**
mean=397.9
standard deviation=5.599

**Table A6. Summary of Time Period Wed. 7:00-7:30am Eleven Cases for Westbound**

| Wed 7:00-7:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 664 | 363.1 |
| Case 1 | 664 | 361.7 |
| Case 2 | 647 | 376.9 |
| Case 3 | 675 | 370.4 |
| Case 4 | 638 | 366.3 |
| Case 5 | 661 | 375.9 |
| Case 6 | 652 | 373.6 |
| Case 7 | 648 | 373.2 |
| Case 8 | 659 | 376.5 |
| Case 9 | 648 | 375.0 |
| Case 10 | 677 | 376.8 |

**Average of Averaged Corridor Volumes**
657

**Corridor Travel Time(seconds)**
mean=371.8
standard deviation=5.615

**Table A7. Summary of Time Period Wed. 7:30-8:00am Eleven Cases for Eastbound**

| Wed 7:30-8:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 796 | 451.5 |
| Case 1 | 794 | 449.5 |
| Case 2 | 818 | 457.3 |
| Case 3 | 816 | 461.9 |
| Case 4 | 819 | 460.9 |
| Case 5 | 826 | 463.3 |
| Case 6 | 824 | 471.0 |
| Case 7 | 820 | 456.2 |
| Case 8 | 820 | 462.6 |
| Case 9 | 826 | 460.0 |
| Case 10 | 797 | 452.8 |

**Average of Averaged Corridor Volumes**
814

**Corridor Travel Time(seconds)**
mean=458.8
standard deviation=6.195

**Table A8. Summary of Time Period Wed. 7:30-8:00am Eleven Cases for Westbound**

| Wed 7:30-8:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1307 | 437.1 |
| Case 1 | 1311 | 432.5 |
| Case 2 | 1290 | 426.6 |
| Case 3 | 1340 | 430.3 |
| Case 4 | 1300 | 422.4 |
| Case 5 | 1333 | 444.2 |
| Case 6 | 1309 | 432.3 |
| Case 7 | 1318 | 437.2 |
| Case 8 | 1319 | 434.1 |
| Case 9 | 1329 | 433.8 |
| Case 10 | 1338 | 433.5 |

**Average of Averaged Corridor Volumes**
1318

**Corridor Travel Time(seconds)**
mean=433.1
standard deviation=5.685

## Table A9. Summary of Time Period Wed. 8:00-8:30am Eleven Cases for Eastbound

| Wed 8:00-8:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 677 | 430.9 |
| Case 1 | 677 | 434.6 |
| Case 2 | 699 | 444.0 |
| Case 3 | 701 | 431.8 |
| Case 4 | 706 | 435.8 |
| Case 5 | 699 | 436.8 |
| Case 6 | 702 | 452.8 |
| Case 7 | 690 | 442.1 |
| Case 8 | 704 | 452.3 |
| Case 9 | 714 | 441.5 |
| Case 10 | 698 | 434.1 |

| Average of Averaged Corridor Volumes |
|---|
| 697 |

| Corridor Travel Time(seconds) |
|---|
| mean=439.7<br>standard deviation=7.6 |

## Table A10. Summary of Time Period Wed. 8:00-8:30am Eleven Cases for Westbound

| Wed 8:00-8:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1323 | 426.0 |
| Case 1 | 1325 | 423.8 |
| Case 2 | 1313 | 425.0 |
| Case 3 | 1355 | 430.4 |
| Case 4 | 1328 | 429.7 |
| Case 5 | 1350 | 426.6 |
| Case 6 | 1303 | 430.5 |
| Case 7 | 1334 | 428.5 |
| Case 8 | 1324 | 428.2 |
| Case 9 | 1326 | 427.5 |
| Case 10 | 1355 | 429.5 |

| Average of Averaged Corridor Volumes |
|---|
| 1330 |

| Corridor Travel Time(seconds) |
|---|
| mean=427.8<br>standard deviation=2.232 |

## Table A11. Summary of Time Period Wed. 8:30-9:00am Eleven Cases for Eastbound

| Wed 8:30-9:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 644 | 433.2 |
| Case 1 | 645 | 430.6 |
| Case 2 | 673 | 435.6 |
| Case 3 | 674 | 435.8 |
| Case 4 | 669 | 435.9 |
| Case 5 | 669 | 444.4 |
| Case 6 | 672 | 443.1 |
| Case 7 | 673 | 439.2 |
| Case 8 | 672 | 438.8 |
| Case 9 | 635 | 461.2 |
| Case 10 | 671 | 441.8 |

| Average of Averaged Corridor Volumes |
|---|
| 663 |

| Corridor Travel Time(seconds) |
|---|
| mean=440.0<br>standard deviation=8.198 |

## Table A12. Summary of Time Period Wed. 8:30-9:00am Eleven Cases for Westbound

| Wed 8:30-9:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1457 | 429.8 |
| Case 1 | 1457 | 430.6 |
| Case 2 | 1444 | 434.1 |
| Case 3 | 1493 | 450.7 |
| Case 4 | 1452 | 436.1 |
| Case 5 | 1493 | 439.7 |
| Case 6 | 1444 | 431.5 |
| Case 7 | 1467 | 438.8 |
| Case 8 | 1449 | 437.8 |
| Case 9 | 1450 | 445.1 |
| Case 10 | 1496 | 436.5 |

| Average of Averaged Corridor Volumes |
|---|
| 1464 |

| Corridor Travel Time(seconds) |
|---|
| mean=437.3<br>standard deviation=6.291 |

**Table A13. Summary of Time Period Wed. 9:00-9:30am Eleven Cases for Eastbound**

| Wed 9:00-9:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 755 | 457.8 | |
| Case 1 | 757 | 455.7 | |
| Case 2 | 757 | 461.8 | |
| Case 3 | 750 | 456.0 | **Average of Averaged Corridor Volumes** |
| Case 4 | 789 | 457.2 | 755 |
| Case 5 | 764 | 461.5 | |
| Case 6 | 776 | 464.3 | **Corridor Travel Time(seconds)** |
| Case 7 | 737 | 456.1 | mean=458.4 |
| Case 8 | 742 | 457.6 | standard deviation=3.365 |
| Case 9 | 749 | 461.1 | |
| Case 10 | 728 | 453.0 | |

**Table A14. Summary of Time Period Wed. 9:00-9:30am Eleven Cases for Westbound**

| Wed 9:00-9:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1186 | 445.0 | |
| Case 1 | 1186 | 445.6 | |
| Case 2 | 1123 | 442.2 | |
| Case 3 | 1148 | 455.8 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1158 | 447.5 | 1156 |
| Case 5 | 1167 | 452.6 | |
| Case 6 | 1127 | 451.3 | **Corridor Travel Time(seconds)** |
| Case 7 | 1138 | 452.9 | mean=449.4 |
| Case 8 | 1149 | 443.9 | standard deviation=4.707 |
| Case 9 | 1157 | 453.0 | |
| Case 10 | 1179 | 454.1 | |

**Table A15. Summary of Time Period Wed. 9:30-10:00am Eleven Cases for Eastbound**

| Wed 9:30-10:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 645 | 451.6 | |
| Case 1 | 645 | 450.5 | |
| Case 2 | 647 | 457.1 | |
| Case 3 | 637 | 449.5 | **Average of Averaged Corridor Volumes** |
| Case 4 | 673 | 449.1 | 643 |
| Case 5 | 642 | 451.9 | |
| Case 6 | 662 | 454.4 | **Corridor Travel Time(seconds)** |
| Case 7 | 630 | 454.8 | mean=451.9 |
| Case 8 | 637 | 452.4 | standard deviation=2.698 |
| Case 9 | 632 | 451.9 | |
| Case 10 | 624 | 448.0 | |

**Table A16. Summary of Time Period Wed. 9:30-10:00am Eleven Cases for Westbound**

| Wed 9:30-10:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1125 | 452.2 | |
| Case 1 | 1125 | 449.4 | |
| Case 2 | 1062 | 439.6 | |
| Case 3 | 1093 | 445.4 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1087 | 445.9 | 1094 |
| Case 5 | 1097 | 453.1 | |
| Case 6 | 1060 | 449.9 | **Corridor Travel Time(seconds)** |
| Case 7 | 1079 | 447.8 | mean=447.7 |
| Case 8 | 1093 | 443.4 | standard deviation=4.279 |
| Case 9 | 1096 | 452.8 | |
| Case 10 | 1116 | 445.0 | |

**Table A17. Summary of Time Period Thur. 6:00-6:30am Eleven Cases for Eastbound**

| Thur 6:00-6:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1212 | 507.4 |
| Case 1 | 1206 | 504.4 |
| Case 2 | 1213 | 520.3 |
| Case 3 | 1206 | 521.3 |
| Case 4 | 1207 | 521.6 |
| Case 5 | 1214 | 515.1 |
| Case 6 | 1231 | 529.6 |
| Case 7 | 1193 | 511.5 |
| Case 8 | 1199 | 516.7 |
| Case 9 | 1189 | 516.4 |
| Case 10 | 1175 | 510.1 |

**Average of Averaged Corridor Volumes**
1204

**Corridor Travel Time(seconds)**
mean=515.9
standard deviation=7.264

**Table A18. Summary of Time Period Thur. 6:00-6:30am Eleven Cases for Westbound**

| Thur 6:00-6:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1679 | 534.1 |
| Case 1 | 1701 | 523.3 |
| Case 2 | 1617 | 507.9 |
| Case 3 | 1659 | 532.2 |
| Case 4 | 1644 | 537.5 |
| Case 5 | 1640 | 519.9 |
| Case 6 | 1644 | 515.1 |
| Case 7 | 1604 | 501.8 |
| Case 8 | 1675 | 518.6 |
| Case 9 | 1653 | 539.7 |
| Case 10 | 1650 | 517.0 |

**Average of Averaged Corridor Volumes**
1651

**Corridor Travel Time(seconds)**
mean=522.5
standard deviation=12.242

**Table A19. Summary of Time Period Thur. 6:30-7:00am Eleven Cases for Eastbound**

| Thur 6:30-7:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1079 | 487.6 |
| Case 1 | 1078 | 490.3 |
| Case 2 | 1068 | 491.8 |
| Case 3 | 1065 | 484.8 |
| Case 4 | 1085 | 500.9 |
| Case 5 | 1077 | 494.3 |
| Case 6 | 1089 | 501.6 |
| Case 7 | 1058 | 493.3 |
| Case 8 | 1067 | 499.7 |
| Case 9 | 1057 | 497.5 |
| Case 10 | 1041 | 494.2 |

**Average of Averaged Corridor Volumes**
1069

**Corridor Travel Time(seconds)**
mean=494.2
standard deviation=5.427

**Table A20. Summary of Time Period Thur. 6:30-7:00am Eleven Cases for Westbound**

| Thur 6:30-7:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1551 | 492.0 |
| Case 1 | 1543 | 499.6 |
| Case 2 | 1489 | 481.5 |
| Case 3 | 1534 | 491.5 |
| Case 4 | 1515 | 490.5 |
| Case 5 | 1524 | 503.3 |
| Case 6 | 1488 | 492.6 |
| Case 7 | 1384 | 456.2 |
| Case 8 | 1527 | 486.6 |
| Case 9 | 1531 | 487.8 |
| Case 10 | 1547 | 494.7 |

**Average of Averaged Corridor Volumes**
1512

**Corridor Travel Time(seconds)**
mean=488.8
standard deviation=12.322

**Table A21. Summary of Time Period Thur. 7:00-7:30am Eleven Cases for Eastbound**

| Thur 7:00-7:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 374 | 387.4 |
| Case 1 | 373 | 388.4 |
| Case 2 | 386 | 395.1 |
| Case 3 | 377 | 390.1 |
| Case 4 | 385 | 398.8 |
| Case 5 | 370 | 392.7 |
| Case 6 | 366 | 397.8 |
| Case 7 | 376 | 396.9 |
| Case 8 | 365 | 397.7 |
| Case 9 | 371 | 402.6 |
| Case 10 | 382 | 386.5 |

**Average of Averaged Corridor Volumes**
375

**Corridor Travel Time(seconds)**
mean=394.0
standard deviation=5.318

**Table A22. Summary of Time Period Thur. 7:00-7:30am Eleven Cases for Westbound**

| Thur 7:00-7:30am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 633 | 365.9 |
| Case 1 | 634 | 364.7 |
| Case 2 | 617 | 374.4 |
| Case 3 | 642 | 374.2 |
| Case 4 | 606 | 365.1 |
| Case 5 | 625 | 370.2 |
| Case 6 | 615 | 371.7 |
| Case 7 | 613 | 374.3 |
| Case 8 | 633 | 375.0 |
| Case 9 | 618 | 376.4 |
| Case 10 | 644 | 384.9 |

**Average of Averaged Corridor Volumes**
625

**Corridor Travel Time(seconds)**
mean=372.4
standard deviation=5.916

**Table A23. Summary of Time Period Thur. 7:30-8:00am Eleven Cases for Eastbound**

| Thur 7:30-8:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 843 | 453.7 |
| Case 1 | 842 | 461.5 |
| Case 2 | 870 | 477.4 |
| Case 3 | 871 | 466.4 |
| Case 4 | 872 | 471.2 |
| Case 5 | 876 | 470.3 |
| Case 6 | 881 | 470.1 |
| Case 7 | 871 | 475.9 |
| Case 8 | 871 | 467.8 |
| Case 9 | 868 | 468.0 |
| Case 10 | 848 | 465.9 |

**Average of Averaged Corridor Volumes**
865

**Corridor Travel Time(seconds)**
mean=468.0
standard deviation=6.515

**Table A24. Summary of Time Period Thur. 7:30-8:00am Eleven Cases for Westbound**

| Thur 7:30-8:00am | Average Corridor Volume | Corridor Travel Time(seconds) |
|---|---|---|
| Original | 1294 | 418.0 |
| Case 1 | 1291 | 424.7 |
| Case 2 | 1255 | 411.1 |
| Case 3 | 1312 | 428.2 |
| Case 4 | 1283 | 422.1 |
| Case 5 | 1303 | 434.3 |
| Case 6 | 1290 | 424.6 |
| Case 7 | 1285 | 426.2 |
| Case 8 | 1301 | 427.2 |
| Case 9 | 1303 | 438.7 |
| Case 10 | 1335 | 430.3 |

**Average of Averaged Corridor Volumes**
1296

**Corridor Travel Time(seconds)**
mean=425.9
standard deviation=7.482

## Table A25. Summary of Time Period Thur. 8:00-8:30am Eleven Cases for Eastbound

| Thur 8:00-8:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 718 | 443.4 | |
| Case 1 | 719 | 439.5 | |
| Case 2 | 745 | 444.3 | |
| Case 3 | 746 | 448.3 | **Average of Averaged Corridor Volumes** |
| Case 4 | 745 | 448.2 | 741 |
| Case 5 | 746 | 454.0 | |
| Case 6 | 742 | 450.8 | **Corridor Travel Time(seconds)** |
| Case 7 | 740 | 445.1 | mean=447.3 |
| Case 8 | 744 | 443.6 | standard deviation=7.727 |
| Case 9 | 765 | 465.7 | |
| Case 10 | 739 | 437.5 | |

## Table A26. Summary of Time Period Thur. 8:00-8:30am Eleven Cases for Westbound

| Thur 8:00-8:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1384 | 427.7 | |
| Case 1 | 1380 | 430.3 | |
| Case 2 | 1367 | 433.7 | |
| Case 3 | 1414 | 442.4 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1376 | 434.1 | 1378 |
| Case 5 | 1400 | 436.8 | |
| Case 6 | 1352 | 436.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 1311 | 498.1 | mean=440.8 |
| Case 8 | 1378 | 433.7 | standard deviation=19.416 |
| Case 9 | 1380 | 438.7 | |
| Case 10 | 1412 | 436.4 | |

## Table A27. Summary of Time Period Thur. 8:30-9:00am Eleven Cases for Eastbound

| Thur 8:30-9:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 648 | 431.8 | |
| Case 1 | 648 | 430.8 | |
| Case 2 | 665 | 439.5 | |
| Case 3 | 671 | 433.3 | **Average of Averaged Corridor Volumes** |
| Case 4 | 671 | 440.4 | 661 |
| Case 5 | 670 | 432.0 | |
| Case 6 | 664 | 439.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 662 | 446.9 | mean=440.6 |
| Case 8 | 674 | 440.1 | standard deviation=12.636 |
| Case 9 | 630 | 475.7 | |
| Case 10 | 672 | 435.9 | |

## Table A28. Summary of Time Period Thur. 8:30-9:00am Eleven Cases for Westbound

| Thur 8:30-9:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1401 | 432.2 | |
| Case 1 | 1401 | 434.1 | |
| Case 2 | 1379 | 437.4 | |
| Case 3 | 1433 | 430.9 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1397 | 427.2 | 1406 |
| Case 5 | 1431 | 437.8 | |
| Case 6 | 1389 | 437.3 | **Corridor Travel Time(seconds)** |
| Case 7 | 1405 | 438.4 | mean=434.9 |
| Case 8 | 1396 | 430.7 | standard deviation=5.085 |
| Case 9 | 1401 | 432.4 | |
| Case 10 | 1436 | 445.8 | |

## Table A29. Summary of Time Period Thur. 9:00-9:30am Eleven Cases for Eastbound

| Thur 9:00-9:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 732 | 455.3 | |
| Case 1 | 734 | 454.7 | |
| Case 2 | 742 | 467.9 | |
| Case 3 | 737 | 455.2 | **Average of Averaged Corridor Volumes** |
| Case 4 | 759 | 455.8 | 735 |
| Case 5 | 742 | 456.7 | |
| Case 6 | 758 | 466.8 | **Corridor Travel Time(seconds)** |
| Case 7 | 717 | 458.9 | mean=458.6 |
| Case 8 | 726 | 455.6 | standard deviation=4.717 |
| Case 9 | 728 | 460.9 | |
| Case 10 | 713 | 456.3 | |

## Table A30. Summary of Time Period Thur. 9:00-9:30am Eleven Cases for Westbound

| Thur 9:00-9:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1178 | 445.1 | |
| Case 1 | 1176 | 446.4 | |
| Case 2 | 1117 | 448.5 | |
| Case 3 | 1142 | 455.5 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1147 | 443.6 | 1149 |
| Case 5 | 1157 | 454.9 | |
| Case 6 | 1114 | 451.8 | **Corridor Travel Time(seconds)** |
| Case 7 | 1135 | 456.4 | mean=450.8 |
| Case 8 | 1142 | 448.8 | standard deviation=4.557 |
| Case 9 | 1169 | 455.4 | |
| Case 10 | 1160 | 452.3 | |

## Table A31. Summary of Time Period Thur. 9:30-10:00am Eleven Cases for Eastbound

| Thur 9:30-10:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 733 | 452.3 | |
| Case 1 | 733 | 452.5 | |
| Case 2 | 738 | 461.5 | |
| Case 3 | 733 | 453.0 | **Average of Averaged Corridor Volumes** |
| Case 4 | 765 | 458.6 | 732 |
| Case 5 | 741 | 461.7 | |
| Case 6 | 755 | 464.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 713 | 455.0 | mean=456.8 |
| Case 8 | 717 | 455.7 | standard deviation=4.496 |
| Case 9 | 724 | 458.7 | |
| Case 10 | 707 | 451.4 | |

## Table A32. Summary of Time Period Thur. 9:30-10:00am Eleven Cases for Westbound

| Thur 9:30-10:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1143 | 448.1 | |
| Case 1 | 1144 | 446.4 | |
| Case 2 | 1078 | 443.1 | |
| Case 3 | 1097 | 442.7 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1108 | 442.4 | 1110 |
| Case 5 | 1119 | 450.4 | |
| Case 6 | 1072 | 446.2 | **Corridor Travel Time(seconds)** |
| Case 7 | 1091 | 450.1 | mean=446.7 |
| Case 8 | 1112 | 447.4 | standard deviation=3.056 |
| Case 9 | 1110 | 450.9 | |
| Case 10 | 1130 | 446.2 | |

## Table A33. Summary of Time Period Sat. 10:00-10:30am Eleven Cases for Eastbound

| Sat 10:00-10:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 865 | 463.8 | |
| Case 1 | 871 | 463.5 | |
| Case 2 | 895 | 484.2 | |
| Case 3 | 895 | 479.6 | **Average of Averaged Corridor Volumes** |
| Case 4 | 897 | 471.4 | 888 |
| Case 5 | 904 | 479.0 | |
| Case 6 | 898 | 470.9 | **Corridor Travel Time(seconds)** |
| Case 7 | 890 | 471.8 | mean=473.3 |
| Case 8 | 897 | 480.2 | standard deviation=6.710 |
| Case 9 | 883 | 472.1 | |
| Case 10 | 873 | 469.8 | |

## Table A34. Summary of Time Period Sat. 10:00-10:30am Eleven Cases for Westbound

| Sat 10:00-10:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1210 | 413.7 | |
| Case 1 | 1211 | 415.9 | |
| Case 2 | 1183 | 412.3 | |
| Case 3 | 1230 | 420.5 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1201 | 408.5 | 1202 |
| Case 5 | 1223 | 420.3 | |
| Case 6 | 1075 | 434.5 | **Corridor Travel Time(seconds)** |
| Case 7 | 1208 | 421.8 | mean=419.8 |
| Case 8 | 1207 | 421.4 | standard deviation=7.128 |
| Case 9 | 1215 | 424.3 | |
| Case 10 | 1255 | 425.1 | |

## Table A35. Summary of Time Period Sat. 10:30-11:00am Eleven Cases for Eastbound

| Sat 10:30-11:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 959 | 473.6 | |
| Case 1 | 956 | 475.2 | |
| Case 2 | 986 | 501.3 | |
| Case 3 | 973 | 490.3 | **Average of Averaged Corridor Volumes** |
| Case 4 | 975 | 487.3 | 974 |
| Case 5 | 993 | 501.4 | |
| Case 6 | 987 | 493.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 970 | 486.1 | mean=487.7 |
| Case 8 | 988 | 478.2 | standard deviation=9.451 |
| Case 9 | 970 | 492.6 | |
| Case 10 | 954 | 485.3 | |

## Table A36. Summary of Time Period Sat. 10:30-11:00am Eleven Cases for Westbound

| Sat 10:30-11:00am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1388 | 428.5 | |
| Case 1 | 1385 | 428.6 | |
| Case 2 | 1365 | 424.6 | |
| Case 3 | 1429 | 439.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1385 | 430.3 | 1412 |
| Case 5 | 1413 | 429.9 | |
| Case 6 | 1403 | 430.6 | **Corridor Travel Time(seconds)** |
| Case 7 | 1384 | 423.9 | mean=431.3 |
| Case 8 | 1399 | 440.8 | standard deviation=5.804 |
| Case 9 | 1406 | 439.1 | |
| Case 10 | 1569 | 428.7 | |

### Table A37. Summary of Time Period Sat. 11:00-11:30am Eleven Cases for Eastbound

| Sat 11:00-11:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1055 | 496.3 | |
| Case 1 | 1051 | 499.4 | |
| Case 2 | 1080 | 533.5 | |
| Case 3 | 1089 | 505.4 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1076 | 509.1 | 1076 |
| Case 5 | 1089 | 518.6 | |
| Case 6 | 1098 | 518.1 | **Corridor Travel Time(seconds)** |
| Case 7 | 1074 | 507.9 | mean=511.7 |
| Case 8 | 1092 | 520.1 | standard deviation=10.440 |
| Case 9 | 1081 | 511.6 | |
| Case 10 | 1051 | 509.2 | |

### Table A38. Summary of Time Period Sat. 11:00-11:30am Eleven Cases for Westbound

| Sat 11:00-11:30am | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1512 | 435.9 | |
| Case 1 | 1506 | 437.3 | |
| Case 2 | 1492 | 442.7 | |
| Case 3 | 1562 | 450.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1509 | 452.0 | 1517 |
| Case 5 | 1513 | 440.0 | |
| Case 6 | 1519 | 442.7 | **Corridor Travel Time(seconds)** |
| Case 7 | 1497 | 438.4 | mean=444.9 |
| Case 8 | 1523 | 451.6 | standard deviation=6.926 |
| Case 9 | 1513 | 445.9 | |
| Case 10 | 1541 | 456.8 | |

### Table A39. Summary of Time Period Sat. 11:30-12:00pm Eleven Cases for Eastbound

| Sat 11:30-12:00pm | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1094 | 493.9 | |
| Case 1 | 1091 | 508.9 | |
| Case 2 | 1119 | 544.8 | |
| Case 3 | 1131 | 530.9 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1126 | 520.4 | 1116 |
| Case 5 | 1128 | 521.8 | |
| Case 6 | 1141 | 531.9 | **Corridor Travel Time(seconds)** |
| Case 7 | 1114 | 523.3 | mean=522.8 |
| Case 8 | 1129 | 530.4 | standard deviation=14.461 |
| Case 9 | 1118 | 535.6 | |
| Case 10 | 1087 | 508.6 | |

### Table A40. Summary of Time Period Sat. 11:30-12:00pm Eleven Cases for Westbound

| Sat 11:30-12:00pm | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1529 | 453.0 | |
| Case 1 | 1525 | 446.9 | |
| Case 2 | 1528 | 448.8 | |
| Case 3 | 1564 | 461.4 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1524 | 448.6 | 1539 |
| Case 5 | 1546 | 450.9 | |
| Case 6 | 1541 | 465.1 | **Corridor Travel Time(seconds)** |
| Case 7 | 1514 | 455.7 | mean=456.0 |
| Case 8 | 1535 | 455.6 | standard deviation=9.103 |
| Case 9 | 1543 | 451.9 | |
| Case 10 | 1583 | 477.8 | |

### Table A41. Summary of Time Period Sat. 12:00-12:30pm Eleven Cases for Eastbound

| Sat 12:00-12:30pm | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1105 | 517.3 | |
| Case 1 | 1102 | 517.1 | |
| Case 2 | 1119 | 570.3 | |
| Case 3 | 1139 | 533.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1125 | 523.0 | 1113 |
| Case 5 | 1145 | 525.7 | |
| Case 6 | 1153 | 535.0 | **Corridor Travel Time(seconds)** |
| Case 7 | 1123 | 531.7 | mean=533 |
| Case 8 | 1015 | 539.0 | standard deviation=16.5 |
| Case 9 | 1130 | 552.5 | |
| Case 10 | 1092 | 517.2 | |

### Table A42. Summary of Time Period Sat. 12:00-12:30pm Eleven Cases for Westbound

| Sat 12:00-12:30pm | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1563 | 448.8 | |
| Case 1 | 1557 | 453.6 | |
| Case 2 | 1572 | 451.1 | |
| Case 3 | 1616 | 459.9 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1571 | 457.7 | 1582 |
| Case 5 | 1581 | 452.0 | |
| Case 6 | 1574 | 445.0 | **Corridor Travel Time(seconds)** |
| Case 7 | 1571 | 451.3 | mean=455.4 |
| Case 8 | 1591 | 466.9 | standard deviation=6.641 |
| Case 9 | 1590 | 460.1 | |
| Case 10 | 1616 | 463.1 | |

### Table A43. Summary of Time Period Sat. 12:30-1:00pm Eleven Cases for Eastbound

| Sat 12:30-1:00pm | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1087 | 501.4 | |
| Case 1 | 1090 | 512.4 | |
| Case 2 | 1111 | 547.8 | |
| Case 3 | 1122 | 526.0 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1115 | 521.7 | 1110 |
| Case 5 | 1123 | 532.6 | |
| Case 6 | 1135 | 530.8 | **Corridor Travel Time(seconds)** |
| Case 7 | 1109 | 519.2 | mean=524.5 |
| Case 8 | 1119 | 541.3 | standard deviation=14.405 |
| Case 9 | 1115 | 531.0 | |
| Case 10 | 1086 | 504.9 | |

### Table A44. Summary of Time Period Sat. 12:30-1:00pm Eleven Cases for Westbound

| Sat 12:30-1:00pm | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1549 | 440.8 | |
| Case 1 | 1522 | 439.1 | |
| Case 2 | 1543 | 438.9 | |
| Case 3 | 1575 | 455.0 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1544 | 455.8 | 1547 |
| Case 5 | 1549 | 438.9 | |
| Case 6 | 1542 | 448.5 | **Corridor Travel Time(seconds)** |
| Case 7 | 1549 | 444.7 | mean=446.9 |
| Case 8 | 1545 | 449.5 | standard deviation=6.976 |
| Case 9 | 1548 | 448.2 | |
| Case 10 | 1552 | 456.9 | |

## Table A45. Summary of Extreme Case 1 Eleven Cases for Eastbound

| Extreme Case 1 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 779 | 450.9 | |
| Case 1 | 778 | 447.0 | |
| Case 2 | 795 | 459.6 | |
| Case 3 | 807 | 451.6 | **Average of Averaged Corridor Volumes** |
| Case 4 | 812 | 452.2 | 808 |
| Case 5 | 810 | 456.3 | |
| Case 6 | 803 | 470.0 | **Corridor Travel Time(seconds)** |
| Case 7 | 795 | 454.0 | mean=455.1 |
| Case 8 | 807 | 457.4 | standard deviation=6.420 |
| Case 9 | 910 | 458.9 | |
| Case 10 | 795 | 448.5 | |

## Table A46. Summary of Extreme Case 1 Eleven Cases for Westbound

| Extreme Case 1 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1536 | 443.4 | |
| Case 1 | 1534 | 451.5 | |
| Case 2 | 1525 | 450.9 | |
| Case 3 | 1576 | 466.9 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1529 | 448.6 | 1547 |
| Case 5 | 1569 | 458.9 | |
| Case 6 | 1528 | 452.6 | **Corridor Travel Time(seconds)** |
| Case 7 | 1544 | 459.6 | mean=453.4 |
| Case 8 | 1543 | 447.5 | standard deviation=6.501 |
| Case 9 | 1556 | 455.1 | |
| Case 10 | 1579 | 452.7 | |

## Table A47. Summary of Extreme Case 2 Eleven Cases for Eastbound

| Extreme Case 2 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 797 | 446.2 | |
| Case 1 | 801 | 447.4 | |
| Case 2 | 813 | 453.4 | |
| Case 3 | 833 | 455.5 | **Average of Averaged Corridor Volumes** |
| Case 4 | 834 | 455.0 | 821 |
| Case 5 | 831 | 462.0 | |
| Case 6 | 829 | 464.9 | **Corridor Travel Time(seconds)** |
| Case 7 | 821 | 460.9 | mean=457.7 |
| Case 8 | 829 | 467.2 | standard deviation=6.832 |
| Case 9 | 823 | 462.7 | |
| Case 10 | 819 | 459.1 | |

## Table A48. Summary of Extreme Case 2 Eleven Cases for Westbound

| Extreme Case 2 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1564 | 450.0 | |
| Case 1 | 1564 | 453.8 | |
| Case 2 | 1549 | 452.1 | |
| Case 3 | 1610 | 458.0 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1549 | 449.9 | 1570 |
| Case 5 | 1592 | 462.9 | |
| Case 6 | 1547 | 455.2 | **Corridor Travel Time(seconds)** |
| Case 7 | 1563 | 449.2 | mean=455.5 |
| Case 8 | 1555 | 457.3 | standard deviation=5.046 |
| Case 9 | 1576 | 459.2 | |
| Case 10 | 1601 | 463.3 | |

## Table A49. Summary of Extreme Case 3 Eleven Cases for Eastbound

| Extreme Case 3 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 846 | 464.7 | |
| Case 1 | 843 | 455.0 | |
| Case 2 | 865 | 471.7 | |
| Case 3 | 877 | 463.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 886 | 466.5 | 869 |
| Case 5 | 882 | 474.2 | |
| Case 6 | 880 | 478.6 | **Corridor Travel Time(seconds)** |
| Case 7 | 867 | 461.4 | mean=468.2 |
| Case 8 | 880 | 472.8 | standard deviation=7.028 |
| Case 9 | 865 | 475.5 | |
| Case 10 | 870 | 467.0 | |

## Table A50. Summary of Extreme Case 3 Eleven Cases for Westbound

| Extreme Case 3 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1662 | 475.7 | |
| Case 1 | 1665 | 455.0 | |
| Case 2 | 1640 | 467.7 | |
| Case 3 | 1716 | 474.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1647 | 461.6 | 1671 |
| Case 5 | 1704 | 487.3 | |
| Case 6 | 1653 | 471.6 | **Corridor Travel Time(seconds)** |
| Case 7 | 1661 | 466.3 | mean=471.2 |
| Case 8 | 1659 | 469.3 | standard deviation=8.751 |
| Case 9 | 1666 | 479.2 | |
| Case 10 | 1709 | 475.6 | |

## Table A51. Summary of Extreme Case 4 Eleven Cases for Eastbound

| Extreme Case 4 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 901 | 468.9 | |
| Case 1 | 900 | 463.0 | |
| Case 2 | 925 | 474.8 | |
| Case 3 | 923 | 479.1 | **Average of Averaged Corridor Volumes** |
| Case 4 | 930 | 485.1 | 920 |
| Case 5 | 935 | 474.7 | |
| Case 6 | 931 | 484.3 | **Corridor Travel Time(seconds)** |
| Case 7 | 917 | 477.6 | mean=476.0 |
| Case 8 | 932 | 474.3 | standard deviation=6.355 |
| Case 9 | 917 | 477.8 | |
| Case 10 | 910 | 479.5 | |

## Table A52. Summary of Extreme Case 4 Eleven Cases for Westbound

| Extreme Case 4 | Average Corridor Volume | Corridor Travel Time(seconds) | |
|---|---|---|---|
| Original | 1731 | 486.7 | |
| Case 1 | 1717 | 477.7 | |
| Case 2 | 1730 | 494.3 | |
| Case 3 | 1777 | 492.9 | **Average of Averaged Corridor Volumes** |
| Case 4 | 1724 | 478.0 | 1742 |
| Case 5 | 1770 | 503.6 | |
| Case 6 | 1725 | 487.5 | **Corridor Travel Time(seconds)** |
| Case 7 | 1715 | 477.4 | mean=492.0 |
| Case 8 | 1748 | 483.3 | standard deviation=15.200 |
| Case 9 | 1751 | 502.7 | |
| Case 10 | 1773 | 528.3 | |

# EVALUATING THE EFFECTIVENESS OF LIFE CYCLE VARIABLES IN TRAVEL DEMAND MODELING

Prepared for
Undergraduate Transportation Scholars Program

by

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**SUMMARY**

In order to prioritize and plan for future transportation projects, survey data are analyzed and used to estimate trip rate. Currently, in Texas, socioeconomic variables such as income and household size are used in estimation. These variables may not be the best trip rate estimators because many trips are necessary and not a luxury that can be foregone with economic difficulty. Travel has continued to increase over the past few decades while income level remains relatively constant, adding to the idea that socioeconomic variables may be becoming more obsolete in their trip estimation capabilities. It is hypothesized that life cycle variables, which consider the stage of life of a household, may be better variables to use in future travel demand modeling. As part of an Interagency Agreement funded by the Texas Department of Transportation, household travel survey data from the Texas urban areas of Tyler, Longview, Austin, and San Antonio were analyzed. The effectiveness of the socioeconomic variable of income level was compared

against that of four life cycle variables, which include households with no children, households with children under 16-years old, number employed in the household, and the head of household's age.

Based on statistical analysis, the head of household's age estimates trips significantly better than income level, yielding less than 1% error for the overall trips made in the four tested Texas urban areas. The number employed per household is also a better trip estimator than income level, but by less than 1% error. Though the variable of households with no children does not yield the most accurate trip estimations, a one-to-one comparison against income level shows comparable effectiveness. The number of kids under 16 yields a poorer estimation than income level.

Further research of life cycle variables is recommended. Though the results show some of the tested life cycle variables are more effective estimators than income level, all of the variables give somewhat comparable results. Thus, desired accuracy level, time constraints, and data availability should all be considered when deciding upon which variable to use in travel demand modeling. When the highest level of effectiveness is desired, the head of household's age variable is recommended.

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## INTRODUCTION

Trip generation is the first step in the travel demand modeling process. In order to ensure accurate information is available for use in the steps that follow, great care should be taken in the gathering and analysis of data used in trip generation. For organized analysis, trip rate estimation is carried out in areas of similar geographic location, often called Traffic Analysis Zones (*1*). For analysis purposes, a trip is produced at the home and attracted to the business, regardless of whether the home is the trip's starting or ending point (*2*).

Information about the travel of an area is often obtained through travel surveys, containing questions not only about the number of trips made but also when, for what purpose, and by whom. Planners are then able to analyze the data. Socioeconomic variables such as income and household size are currently used in Texas for travel demand forecasting. However, socioeconomic variables may not be the most accurate means of obtaining estimates of future trip rate because many trips are necessary and not a luxury that can be foregone due to economic difficulty. Also, over the past few decades, travel has continued to increase while income level remains relatively constant. Thus, the effectiveness of socioeconomic variables in trip rate estimation may be decreasing with time. Life cycle variables, which consider the stage of life, may be more effective in travel demand modeling.

Research of specific life cycle variables has been done in the past. One existing model relates age of an individual and the average age of their household, claiming that distinct, repetitive trends occur that may be useful in predicting trip rate (*3*). Other research considers the effect historic events (period effects) and generation differences (cohort effects) play in travel demand modeling (*4*). Though there are a number of life cycle variables with the potential to accurately predict future travel, in order to be useful in real-world application the variable must be able to be accurately projected 20 or more years into the future.

It is hypothesized that some, if not all, life cycle variables may be more effective in travel demand modeling than the socioeconomic variable of income level. In order to test this hypothesis, statistical analysis was performed on household survey data obtained through the Texas Department of Transportation Travel Survey Program. The research was funded by the Texas Department of Transportation as part of Interagency Contract F, Travel Demand Model Data and Training.

## BACKGROUND

### Travel Survey Program

In an effort to more accurately and reliably estimate travel throughout Texas, the Travel Survey Program was established in 1990. The information obtained through these surveys is used to prioritize future road projects and improvements. The four main facets of the survey program include external surveys, household surveys, work place surveys, and commercial vehicle surveys. Each region in Texas is surveyed in a rotational manner, allowing for widespread and continual travel demand modeling improvements (*5*). Because Texas is one of the few states with an organized travel survey program in place, the results are sometimes borrowed by other states and adapted for use in transportation project planning.

**Texas Urban Areas**

Four of the Texas urban areas recently surveyed as part of the Travel Survey Program include Tyler, Longview, Austin and San Antonio. Individual organization of each area was performed, and then the data were combined for analysis. Though individual area comparisons may be indicative of unique transportation environments, often a low number of households are included in survey substratum when only considering one area, leading to somewhat skewed and random trip rate estimates. Thus, in many respects, the combination of urban area results is more accurate and meaningful for future model use. For this reason, as well as time constraints, the percent error in estimating total trips made was only calculated for the combined survey data from all four urban areas.

It is important to note that although the household travel surveys were not performed in the same year for all four areas, the 2.5-year time span of fall 2003 to spring 2006 is considered insignificant for the purposes of the research. Background information on each area, obtained from technical reports compiled by the Texas Department of Transportation, follows. Figure 1 shows the general geographic location within Texas of each analyzed urban area.


**Figure 1. General Location of Urban Areas**

*Tyler/Smith County*

- Household travel survey conducted on a school year weekday in fall 2003
- Households: 69,600 (estimated)
- Average Number of Vehicles Per Household: 1.9 vehicles
- Population: 178,000 (estimated)
- Average Number of Trips per Person: 3.6 trips
- Average Trip Distance: 6.1 miles
- Average Trip Duration: 9 minutes
- Percent of Vehicles that are Pick-up Trucks: 28% (higher than national statistic of 18%) (*6*)

*Longview/Gregg County*

- Household travel survey data collected during a school year weekday in fall 2003
- Households: 42,782 (estimated)
- Average Number of Vehicles per Household: 1.9 vehicles
- Population: 113,624 (estimated)
- Average Number of Trips per Person: 4.0 trips
- Average Trip Distance: 4.6 miles
- Average Trip Duration: 7.3 minutes
- Percent of Vehicles that are Pick-Up Trucks: 29% (*7*)

*Austin/Capitol Area*

- Household travel survey data conducted during a school year weekday in fall 2005 and spring 2006
- Included Areas: Bastrop, Caldwell, Hays, Travis, and Williamson counties
- Home of University of Texas (contributing to 24% of population being students)
- Households: 574,225 (estimated)
- Average Number of Vehicles per Household: 1.88 vehicles
- Population: 1,484,934 (taken from expanded survey – Tyler and Longview technical reports make no mention of expanded version use)
- Average Trip Distance: 7.8 miles
- Average Trip Duration: 12.8 minutes
- Home of University of Texas (contributing to 24% of population being students) (*8*)

*San Antonio*

- Household travel survey data conducted during a school year weekday in fall 2005 and spring 2006
- Included Areas: Kendall, Comal, Guadalupe, Wilson, and Bexar counties
- Number of Households Surveyed: 2,000
- Households: 641,487 (expanded and estimated)
- Population: 1,791,418
- Average Number of Person Trips: 3.31 trips
- Similar to Austin, 25% of population is students (*9*)

## RESEARCH PROCESS

### Literature Review

In order to become more familiar with trip generation and life cycle variables, a literature review was performed. Information on travel demand modeling, household travel surveys, previous research involving life cycle variables, as well as the Texas urban areas of interest was reviewed. As the research developed, there was a continual need to glean more information related to the project. Literature review was particularly concentrated near the beginning and end of the project.

**Proposal and Variable Selection**

Although not followed in its entirety, an original proposal of the research project was created, outlining how to organize and analyze the data. This served to guide the sequence of steps involved in the research project. Also, prior to the start of the project, life cycle variables of particular interest were selected for study. Small adjustments to the substratum breakdown and variable classifications were made throughout the project. Selected life cycle variables, along with income level, were analyzed on a household basis and include the following:

- Income Level
  - Level 1 (0-$19,999)
  - Level 2 ($20,000-$34,999)
  - Level 3 ($35,000-$49,999)
  - Level 4 ($50,000-$74,999)
  - Level 5 ($75,000 + )
- Number of Kids Under 16
  - 0
  - 1
  - 2
  - 3+
- No Children (Under 18)
- Head of Household's Age (in years)
  - 18-24
  - 25-34
  - 35-49
  - 50-64
  - 65+
- Number Employed
  - 0
  - 1
  - 2+

Note that the substratums are set-up such that each household can only fit into one substratum per variable. This is a critical component in the analysis, ensuring that no double counting of households occurs and that results are not confusing and misleading. Also notice that there may be differences in the number of households with 0 kids under 16 and households with no children, as "no children" is defined as households with no members under 18, not 16. The variable of the number of kids under 16 was of particular interest because prior to 16, kids are unable to legally drive without an adult. Thus, it was hypothesized that households with kids under 16 make more person trips because every time a kid makes a trip in a vehicle so does an adult.

For consistency throughout the analysis, the head of household is defined as the oldest member of the household. The head of household's age substratum breakdown was chosen in an attempt to roughly capture distinct stages of life. For example, 18-24 is college age, 25-34 is young adult life, 35-49 is child-rearing years, 50-64 is middle-age, and 65+ is retired. While not everyone's situation fits succinctly into these categories, it yields a general picture of travel during different stages of life.

**Data Organization**

The survey data files for each urban area had to be properly formatted and organized prior to any analysis. The data were imported into Excel and given column labels. Tabulation columns were added for more efficient analysis. Because much of the data was in code, it took time to become familiar with the set-up and meaning. Filters and the sort option within Excel were utilized to more quickly and accurately tabulate trip rates for each variable's substratum. Initially the filtering option posed difficulties, allowing for the summing of only information lining up perfectly with the filtered row. The fact that blank cells indicate that no trip was made by that household member was clarified mid-tabulation, and proper corrections applied. Due to the steep learning curve associated with such difficulties, data organization and manipulation were done one urban area at a time so that the same mistakes and difficulties were not repeatedly encountered.

**Statistical Analysis**

Multiple statistical methods were utilized in analysis. Linear regression was performed, yielding graphs, correlation coefficients, and equations for each variable. In addition, cross classification matrices were created showing the average person trips per household, number of households, and 90% Confidence Interval associated with the person trips per households made in each substratum. While these two methods give a rough idea of the effectiveness of each tested variable, a quantitative method was needed for solid statistical results. Thus, the percent error was calculated using subsets consistent with a one-to-one comparison between the life cycle variables and income level.

**RESULTS**

Multiple urban areas, life cycle variables, and statistical methods pertain to this research project, generating a large volume of figures and tables. For the purposes of the paper, only the combined overall data from all four urban areas are included and discussed within the body of the text. Refer to the Appendix for partial results obtained for each individual area. Note that some tables in the Appendix contain cells where either not enough information was available (nei) or the available data were limited in scope and not applicable to the cell (NA). For Tyler and Longview in particular, the equations and correlation coefficient values obtained from the line forced through the origin are not applicable to for those households with 3 or more kids under 16.

**Linear Regression**

The linear regression graphs created allow trends between household size and the average person trips per household to be seen; a positive trend existing for each tested variable. Figures 2-6 show the graphs and their associated trends. Notice that the graphs include only those lines that were forced through the origin. This was done to ensure that practical results were represented. A household with 0 persons would be expected to make 0 trips.

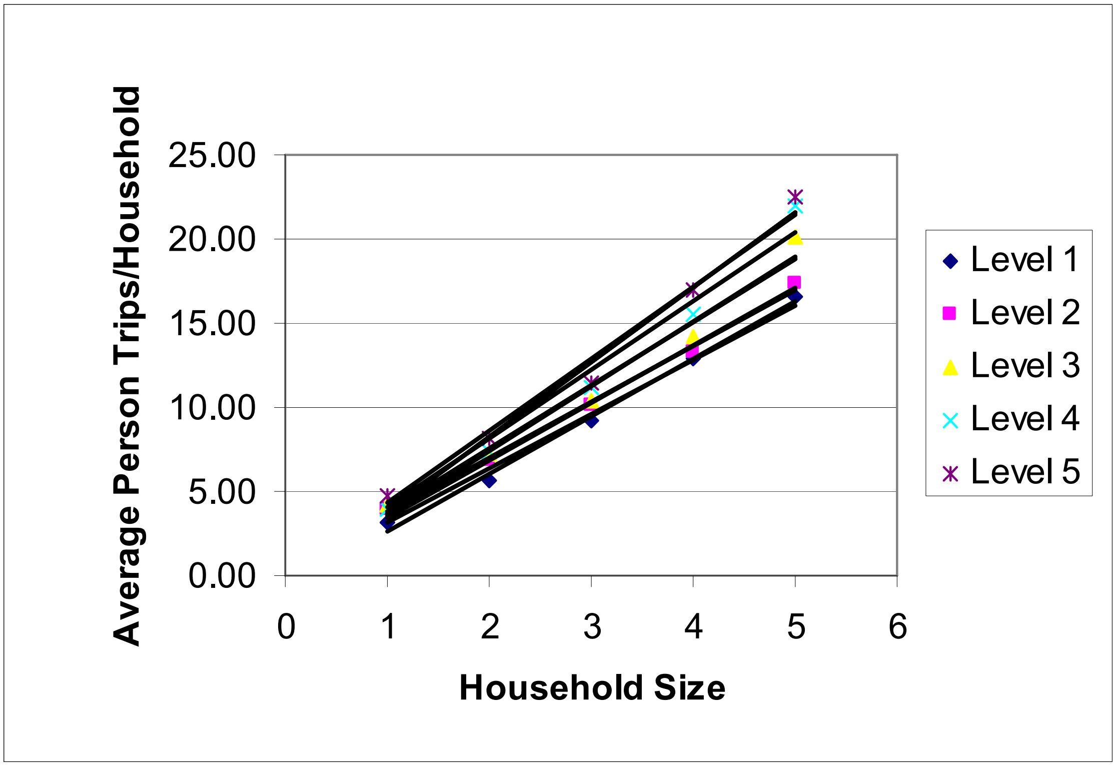


**Figure 2. Linear Regression Forced through Origin for Income Level**

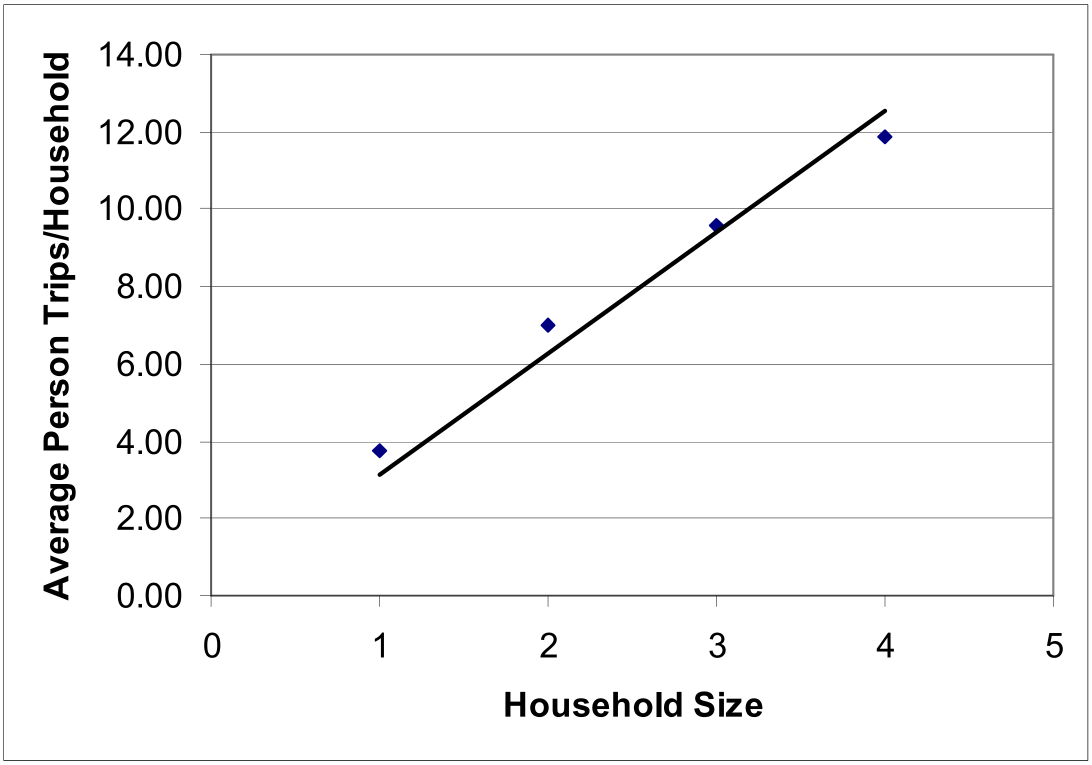


**Figure 3. Linear Regression Forced through Origin for No Children**

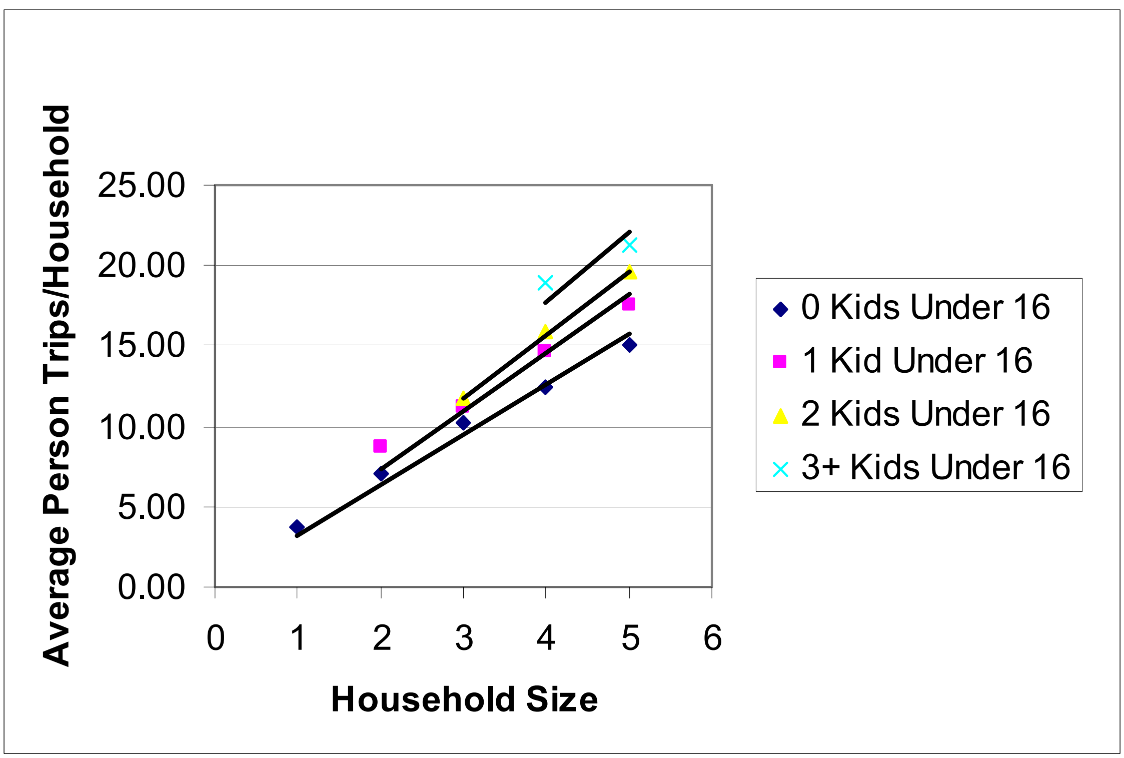


**Figure 4. Linear Regression Forced through Origin for Number of Kids Under 16**

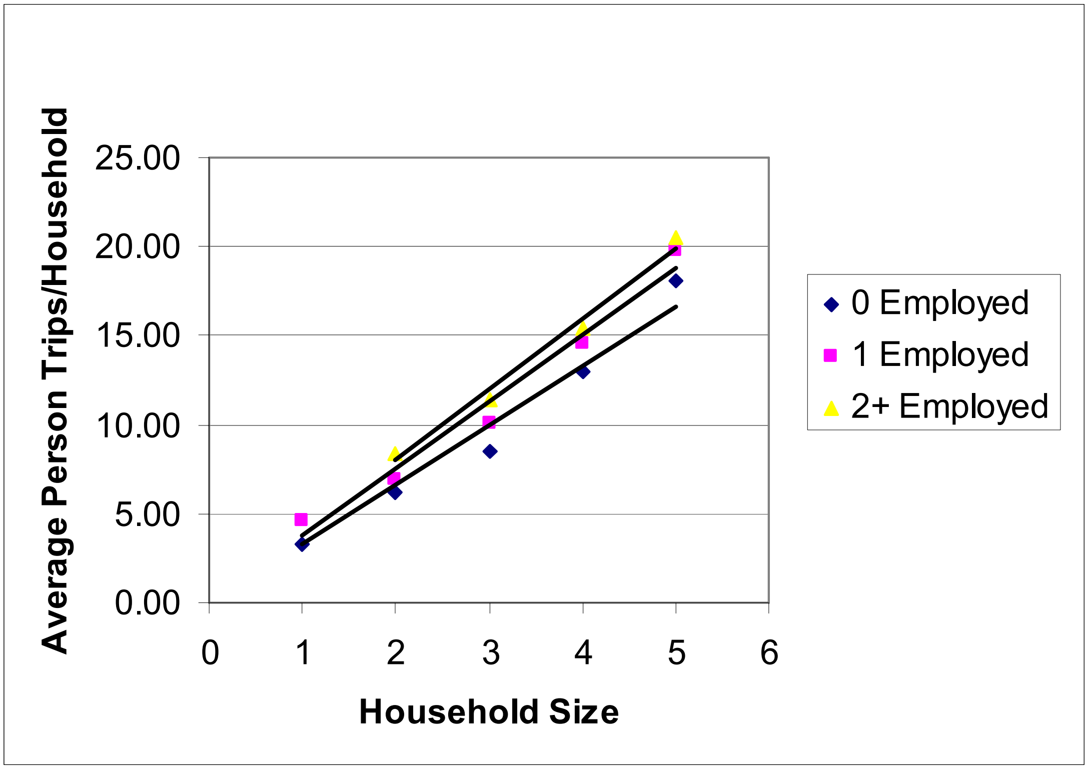


**Figure 5. Linear Regression Forced through Origin for Number Employed**

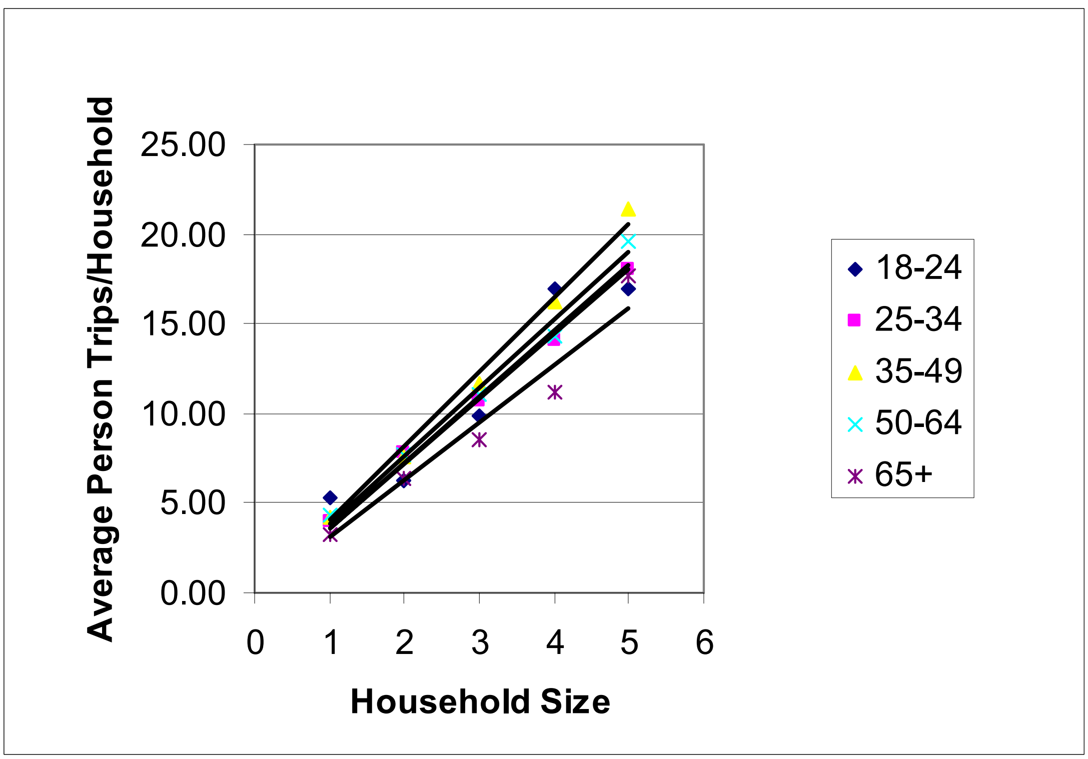


**Figure 6. Linear Regression Forced through Origin for Head of Household's Age**

Although more closely modeling real-life, the lines forced through the origin do not cross through the plotted points as accurately as the line of best fit. This difference can be seen in how the correlation coefficients move farther away from magnitude 1 when the line is forced through the origin. Table 1 shows the correlation coefficients and equations associated with both type of lines. Because the values are rounded to the nearest two decimal places, small adjustments to the correlation coefficients are not seen, though still present. Note that when significant changes in the slope of the line occur, changes also occur in the correlation coefficient. The fact that little, if any, noticeable change occurs in correlation coefficient values for income level indicates that little adjustment is needed to ensure real-life modeling.

**Table 1. Linear Regression Equations and Correlation Coefficients**

| | Income Level | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 3.43x - 0.81 | y = 3.32x + 0.36 | y = 3.86x - 0.36 | y = 4.40x - 1.23 | y = 4.44x - 0.57 |
| **$r^2$ Value** | 0.99 | 1.00 | 0.98 | 0.98 | 0.98 |
| **Forced through Origin** | | | | | |
| **Equation** | y = 3.21x | y = 3.42x | y = 3.77x | y = 4.07x | y = 4.28x |
| **$r^2$ Value** | 0.99 | 1.00 | 0.98 | 0.97 | 0.98 |

The correlation coefficient for the variable of no children varies more than the coefficients for income level do when forced to meet practical limitations. However, the difference is still considered minor, with the coefficient staying in the 0.90-1.00 range. Notice that the slope difference between the two lines is more drastic than any differences existing for the income level variable, explaining the greater change in correlation coefficient value as seen in Table 2.

**Table 2. Linear Regression Equations and Correlation Coefficients**

| | No Children |
|---|---|
| **Line of Best Fit** | |
| **Equation** | y = 2.71x + 1.29 |
| **$r^2$ Value** | 0.99 |
| **Forced through Origin** | |
| **Equation** | y = 3.14x |
| **$r^2$ Value** | 0.96 |

As seen in Table 3, for the number of kids under 16 variable, the correlation coefficients obtained from the line of best fit yield correlation coefficients equal, or nearly equal to 1.00. However, this apparent high level of correlation disappears for the substratum of 3 or more kids under 16 when the line is forced through the origin. One of the reasons for this drastic decrease is the fact that only households in the 4 and 5 or more household size substratums ever have 3 or more kids under 16. Thus, for the line of best fit equation, the line goes right through these two points, yielding a correlation coefficient of 1.00. Because there are not more household sizes represented on the graph, when forced through the origin the slope of the line greatly increases, causing the correlation to steeply decrease.

**Table 3. Linear Regression Equations and Correlation Coefficients**

| Number of Kids Under 16 | | | | |
|---|---|---|---|---|
| | **0** | **1** | **2** | **3+** |
| **Line-of-Best-Fit** | | | | |
| **Equation** | y = 2.81x + 1.25 | y = 3.02x + 2.45 | y = 3.89x + 0.17 | y = 2.35x + 9.46 |
| **$r^2$ Value** | 0.99 | 1.00 | 1.00 | 1.00 |
| **Forced through Origin** | | | | |
| **Equation** | y = 3.15x | y = 3.65x | y = 3.93x | y = 4.43x |
| **$r^2$ Value** | 0.98 | 0.95 | 1.00 | 0.21 |

For the number employed variable, there is no noticeable change in any of the correlation coefficients (when rounded to two decimal places), as seen in Table 4. This indicates that the lines of best fit represent real-life limitations fairly accurately, even prior to ensuring the lines pass through the origin.

**Table 4. Linear Regression Equations and Correlation Coefficients**

| Number Employed | | | |
|---|---|---|---|
| | **0** | **1** | **2+** |
| **Line of Best Fit** | | | |
| **Equation** | y = 3.64x - 1.12 | y = 3.82x - 0.22 | y = 4.04x - 0.18 |
| **$r^2$ Value** | 0.97 | 0.98 | 0.99 |
| **Forced through Origin** | | | |
| **Equation** | y = 3.33x | y = 3.75x | y = 3.99x |
| **$r^2$ Value** | 0.97 | 0.98 | 0.99 |

For the head of household's age, very little change in the correlation coefficients is seen between the two types of generated lines. However, the 18-24-year-old substratum correlation coefficient values obtained from both line type cases is lower than the coefficients of the other age category substratum. This lower coefficient, though still indicating high correlation, may be partially explained by the fact that so few 18-24 year-old households participated in the survey. The surveys are completed on a voluntary basis, with no one being forced to fill-out and return the survey. The younger generation is not as likely to return the survey, causing under-representation and making it difficult to accurately model their travel. Another component that may contribute to the low number of younger generation surveys is that the head is defined to be the oldest person within the household. If an older spouse, parent, or grandparent is living in the same household, their age trumps the 18-24-year-old. The head of household's age results can be seen in Table 5.

**Table 5. Linear Regression Equations and Correlation Coefficients**

| | Head of Household's Age | | | | |
|---|---|---|---|---|---|
| | **18-24** | **25-34** | **35-49** | **50-64** | **65+** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 3.41x + 0.85 | y = 3.45x + 0.58 | y = 4.31x - 0.72 | y = 3.72x + 0.24 | y = 3.35x - 0.63 |
| **$r^2$ Value** | 0.91 | 1.00 | 0.99 | 0.99 | 0.95 |
| **Forced through Origin** | | | | | |
| **Equation** | y = 3.65x | y = 3.61x | y = 4.11x | y = 3.79x | y = 3.18x |
| **$r^2$ Value** | 0.91 | 0.99 | 0.99 | 0.99 | 0.95 |

**Cross Classification Matrices**

In addition to linear regression analysis, cross classification matrices were created as a quick means to see and explain trends. Matrices showing the average person trips per household, the number of households, and the 90% confidence intervals associated with the average person trips per household for each substratum were created. While it is desirable to have at least 30 households in each substratum to better ensure data are representative of the population, even after combining the results from all four urban areas there are still substratum with low household counts. This shortcoming contributes to some of the estimation error.

The matrices containing the 90% confidence intervals for the average person trips per household give a general idea of how reliable the tabulated average person trips per household value is. Generally, the smaller the interval, the more accurately the average person trips per household represents the average of the population and not just the sample. In essence, the interval is saying that we would expect the average person trips per household to fall within the given interval 90% of the time when sampling. A built-in Excel function was used to calculate the desired confidence interval, following the calculation of the standard deviation using another built-in Excel function.

The income level matrices are shown in Table 6. True to intuition, as household size increases, the average person trips per household also increase. Vertically moving down the chart for a given household size, as income level increases so does the average person trips made per household. A minor exception to this overall trend occurs between income levels 3 and 4 for households of 1 person.

**Table 6. Cross Classification Matrices for Income Level**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Income Level** | **1** | **2** | **3** | **4** | **5+** |
| **1** | 3.11 | 5.60 | 9.23 | 12.88 | 16.64 |
| **2** | 3.94 | 6.89 | 10.12 | 13.31 | 17.33 |
| **3** | 4.21 | 7.28 | 10.40 | 14.16 | 20.10 |
| **4** | 4.01 | 7.31 | 11.17 | 15.47 | 21.94 |
| **5** | 4.68 | 8.15 | 11.46 | 16.94 | 22.48 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **Income Level** | **1** | **2** | **3** | **4** | **5+** |
| **1** | 372 | 371 | 124 | 74 | 77 |
| **2** | 228 | 401 | 177 | 144 | 124 |
| **3** | 218 | 391 | 215 | 197 | 114 |
| **4** | 103 | 399 | 216 | 192 | 109 |
| **5** | 95 | 410 | 294 | 246 | 158 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **Income Level** | **1** | **2** | **3** | **4** | **5+** |
| **1** | (2.88,3.34) | (5.25,5.95) | (8.34,10.13) | (11.31,14.45) | (15.05,18.22) |
| **2** | (3.66,4.22) | (6.51,7.27) | (9.40,10.84) | (12.23,14.38) | (16.01,18.64) |
| **3** | (3.87,4.55) | (6.90,7.67) | (9.75,11.05) | (13.35,14.96) | (18.55,21.65) |
| **4** | (3.65,4.36) | (6.89,7.72) | (10.46,11.87) | (14.57,16.37) | (20.33,23.54) |
| **5** | (4.20,5.17) | (7.79,8.51) | (10.87,12.06) | (16.10,17.77) | (20.80,24.16) |

Looking at the matrices found in Tables 6-10, it is interesting to note that the most common surveyed household size is 2 persons, with households of 5 or more persons being the least common household size. This is consistent with the trends discussed in each area's technical summary (*6-9*).

Table 7 shows the matrices for households with no children. While it is interesting to note the increase in person trips per household with increase in household size, the sudden drop in surveyed households as you increase to households with 4 or more persons is stark. It is for this reason that the no children variable was grouped into household size substratum differently than the other variables. The estimations deviated from their linear nature when the household size substratum went up to 5 or more persons.

**Table 7. Cross Classification Matrices for No Children**

| | | | | |
|---|---|---|---|---|
| **Average Person Trips/ Household** | | | | |
| **Household Size** | | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | 3.74 | 7.00 | 9.59 | 11.90 |
| **Number of Households in Each Substratum** | | | | |
| **Household Size** | | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | 1056 | 1993 | 449 | 106 |
| **90% Confidence Interval** | | | | |
| **Household Size** | | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | (3.60,3.88) | (6.83,7.16) | (9.12,10.07) | (10.81,12.98) |

The life cycle variable of number of kids under 16 has increasingly fewer and fewer household sizes represented as the number of kids in the household increases because it is not possible for there to be more kids under 16 than there are persons in the household. Although theoretically possible, no households exist where the number of kids under 16 equals the household size. Kids under 16 are not yet independent and need the support and care of an adult. This dependency appears to transfer over into trips. Although able to use other forms of transportation independently, kids under 16 cannot make a trip in a vehicle without a licensed driver accompanying them. As can be seen in Tables 8, as the number of kids under 16 increases so does the average person trips per household for a given household size. There are very few households with 4 persons and 3 or more kids under 16, as this may indicate a single parent of multiple children. Likewise, there are also only a small number of households with no kids under 16 and 5 or more household members.

Table 9 shows that roughly half of the households with no one employed have 2 persons, a possible indication of retired couples. Also, there are very few large households with no one employed. It makes sense that as the number of mouths to feed increases, an income must be earned through employment.

**Table 8. Cross Classification Matrices for Number of Kids Under 16**

| Average Person Trips/ Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| # Kids Under 16 | 1 | 2 | 3 | 4 | 5+ |
| 0 | 3.74 | 7.01 | 10.19 | 12.42 | 15.09 |
| 1 | none | 8.66 | 11.17 | 14.65 | 17.56 |
| 2 | NA | none | 11.76 | 15.91 | 19.55 |
| 3+ | NA | NA | none | 18.87 | 21.22 |
| **Number of Households in Each Substratum** | | | | | |
| | Household Size | | | | |
| # Kids Under 16 | 1 | 2 | 3 | 4 | 5+ |
| 0 | 1056 | 2012 | 546 | 148 | 22 |
| 1 | none | 53 | 461 | 202 | 72 |
| 2 | NA | none | 38 | 494 | 150 |
| 3+ | NA | NA | none | 15 | 343 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| # Kids Under 16 | 1 | 2 | 3 | 4 | 5+ |
| 0 | (3.60,3.88) | (6.84,7.17) | (9.75,10.63) | (11.47,13.37) | (12.39,17.79) |
| 1 | none | (7.34,9.98) | (10.72,11.62) | (13.81,15.49) | (15.73,19.38) |
| 2 | NA | none | (10.22,13.31) | (15.32,16.50) | (18.14,20.95) |
| 3+ | NA | NA | none | (15.95,21.79) | (20.23,22.20) |

**Table 9. Cross Classification Matrices for Number Employed**

| Average Person Trips/ Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| # Employed | 1 | 2 | 3 | 4 | 5+ |
| 0 | 3.24 | 6.25 | 8.48 | 12.93 | 18.09 |
| 1 | 4.58 | 6.97 | 10.12 | 14.62 | 19.83 |
| 2+ | NA | 8.38 | 11.46 | 15.43 | 20.52 |
| **Number of Households in Each Substratum** | | | | | |
| | Household Size | | | | |
| # Employed | 1 | 2 | 3 | 4 | 5+ |
| 0 | 667 | 873 | 113 | 27 | 34 |
| 1 | 393 | 640 | 357 | 330 | 224 |
| 2+ | NA | 554 | 575 | 504 | 329 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| # Employed | 1 | 2 | 3 | 4 | 5+ |
| 0 | (3.07,3.41) | (6.00,6.50) | (7.56,9.39) | (10.10,15.76) | (15.66,20.52) |
| 1 | (4.34,4.81) | (6.67,7.27) | (9.64,10.60) | (13.89,15.35) | (18.57,21.08) |
| 2+ | NA | (8.06,8.71) | (11.02,11.89) | (14.88,15.98) | (19.79,21.25) |

While Table 10 shows an increase in average person trips per household with increase in household size, there is not an obvious trend among the different head of household age categories. Once again, there are a very small number of households in the 18-24-year-old range, possibly skewing the results.

**Table 10. Cross Classification Matrices for Head of Household's Age**

| Average Person Trips/ Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Head's Age** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 5.27 | 6.31 | 9.87 | 17.00 | 17.00 |
| **25-34** | 4.00 | 7.78 | 10.65 | 14.12 | 18.07 |
| **35-49** | 4.19 | 7.53 | 11.71 | 16.19 | 21.41 |
| **50-64** | 4.29 | 7.74 | 11.11 | 14.34 | 19.61 |
| **65+** | 3.28 | 6.42 | 8.55 | 11.24 | 17.62 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **Head's Age** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 11 | 13 | 15 | 5 | 3 |
| **25-34** | 31 | 81 | 115 | 137 | 88 |
| **35-49** | 140 | 193 | 354 | 459 | 312 |
| **50-64** | 308 | 726 | 330 | 189 | 122 |
| **65+** | 570 | 1053 | 231 | 68 | 61 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | (3.87,6.68) | (4.76,7.86) | (7.56,12.17) | (8l76,25.24) | (14.49,19.51) |
| **25-34** | (3.43,4.57) | (6.85,8.70) | (9.77,11.53) | (13.06,15.17) | (16.40,19.74) |
| **35-49** | (3.86,4.52) | (7.03,8.03) | (11.16,12.26) | (15.59,16.78) | (20.40,22.43) |
| **50-64** | (3.00,4.58) | (7.45,8.04) | (10.57,11.65) | (13.45,15.22) | (18.04,21.17) |
| **65+** | (3.10,3.46) | (6.20,6.65) | (7.94,9.16) | (9.74,12.73) | (15.27,10.98) |

## Percent Error

Although linear regression analysis and cross classification matrices serve as quick tools to observe general statistical results, it became necessary to quantitatively determine which variable type (life cycle or socioeconomic) serves as a more effective forecaster in travel demand modeling. The percent error in trip estimation was found based on the linear regression equation of the line forced through the origin. The percent error equation is as follows:

$$\%Error = \frac{100 \cdot (\varepsilon - \alpha)}{\alpha} \quad \text{(Equation 1)}$$

where

$\varepsilon =$ Estimated Number of Trips

$\alpha =$ Actual Number of Trips

Thus, the closer the estimated number of trips is to the actual number of trips made, the smaller the percent error. The value may be positive or negative depending on whether the number of trips was over or under estimated; magnitude is what is generally important. However, if all estimates are significantly off in the same direction, the cause should be further investigated. In order for a one-to-one comparison to be made between income level and the tested life cycle variables, appropriate subsets of households were formed and used in finding the percent error. Life cycle variables were sorted such that only those households counted in a previous income level analysis were counted for the percent error calculation. The same substratum was used for all variables, except households with no children, as all households with children are excluded in the total trip tabulation for households without children. It is important to distinguish between trip rate and total trips made, as both terms are used in analysis. Trip rate, for the purposes of the research project, is person trips per household. By multiplying trip rate by the number of surveyed households, the total trips made are calculated. Though the created matrices show trip rates, the percent error calculation deals with total trips made, which is ultimately what engineers and planners consider when planning for future projects. Tables 11 and 12 show the percent error calculated using the equation for the line forced through the origin.

**Table 11. Percent Error Based on Linear Equation Forced through Origin**

| Variable | Actual Trips | Estimated Trips | % Error |
|---|---|---|---|
| **Income Level** | 53191 | 54638.54 | 2.72 |
| **# Kids Under 16** | 53193 | 51091.25 | -3.95 |
| **# Employed** | 53193 | 54147.33 | 1.79 |
| **Head's Age** | 53193 | 53400.64 | 0.39 |

**Table 12. Percent Error Based on Linear Equation Forced through Origin**

| Variable | Actual Trips | Estimated Trips | % Error |
|---|---|---|---|
| **Income Level** | 22572 | 24630.33 | 9.12 |
| **No Children** | 22572 | 20573.28 | -8.85 |

In looking at the overall percent error results, it is clear that all tested variables exhibit an ability to estimate trips, with all variables estimating the actual number of trips with less than 10% error. However, the head of household's age is the most accurate estimator, with less than 1% error in estimating the actual number of trips made by the selected subset of households. The number employed is also more effective than income level, though not by as large a percentage. Surprisingly, the number of kids under 16 is less effective than income level in trip estimation. Using the equations of the lines forced through the origin, households by the number of kids under 16 and households with no children underestimate trips made, while all other variables overestimate. Figure 7 gives a visual representation of the overall percent error magnitude for each variable.

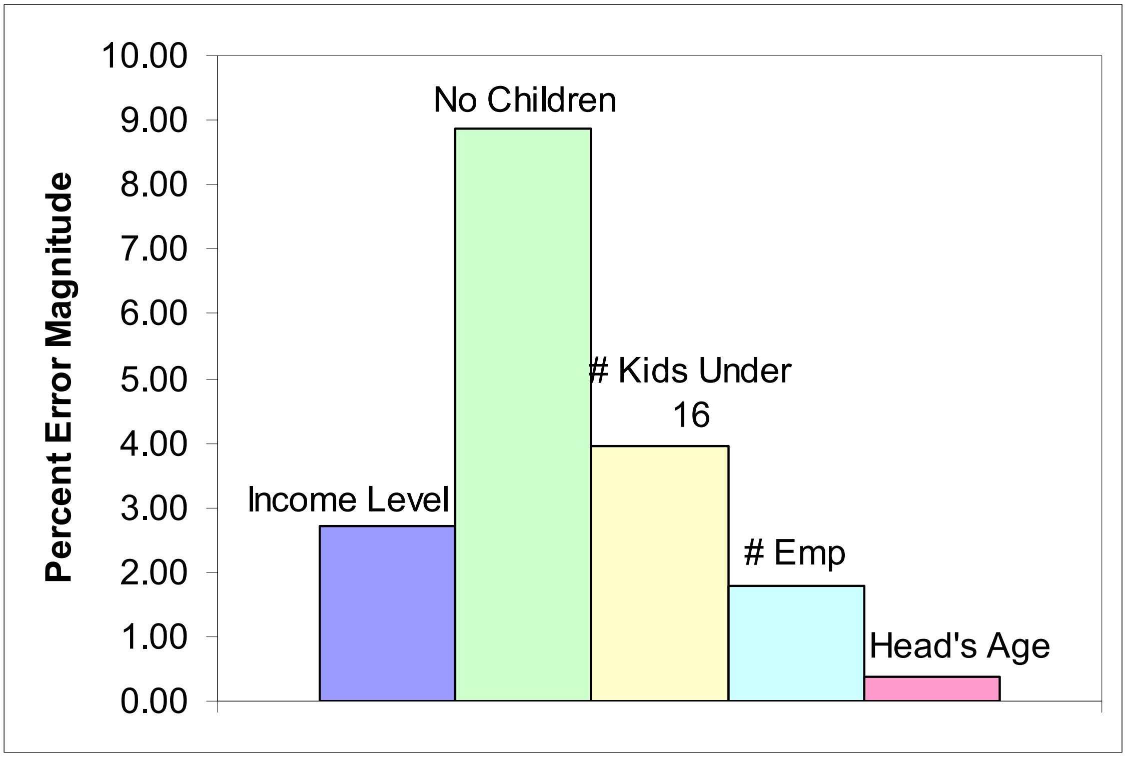


**Figure 7. Overall Percent Error Magnitude**

Note that income level was able to predict the actual number of trips made with only 2.72% error when calculated for all substratum for which the equation was created. However, when the same equation was applied only up until the 4 or more persons per household substratum, the estimation accuracy greatly decreased to 9.12% error. This adjustment was nonetheless needed to allow for a one-to-one comparison with households with no children, but undoubtedly contributed to the larger percent error for income level than previously calculated. Looking at the data valid for a one-to-one comparison, the magnitude of percent error is nearly identical for income level and households with no children. Thus, while the no children variable appears to be the least effective trip estimator overall, it is a slightly better estimator than income level.

However, when looking at the range that exists between the two percent errors, there is nearly an 18% difference, with income level overestimating and the households with no children variable underestimating the actual number of trips made. Figure 8 shows the difference in percent error between each life cycle variable and the appropriate one-to-one comparison results for income level. Those life cycle variables plotted above the x-axis indicate a more effective trip estimate than income level, while the number of kids under 16 variable is less effective.

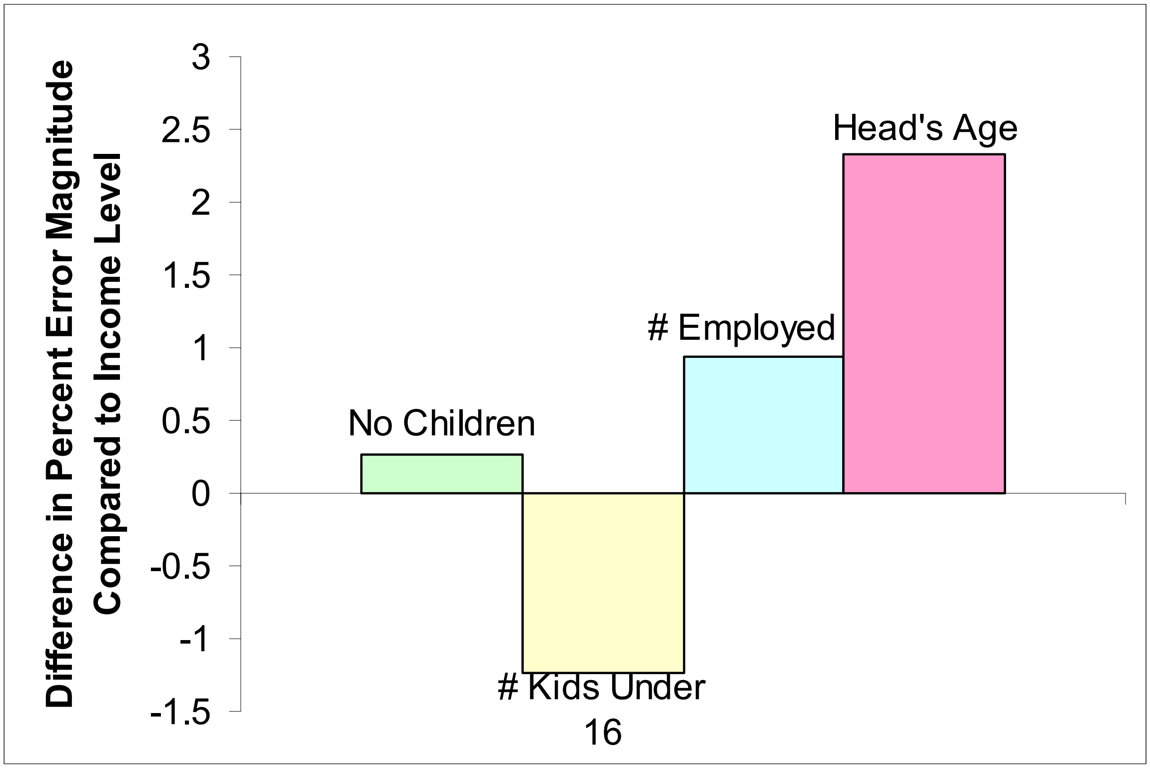


**Figure 8. Percent Error Magnitude Compared to Income Level**

## CONCLUSION

Based upon the results, the hypothesis that at least one of the tested life cycle variables is a better estimator of trip rate than income level is correct. The head of household's age is significantly more effective, estimating the actual person trips made with only 0.39% error. The number employed is also more effective than income level, though differing by less than 1% error.

The life cycle variable of no children, although more effective than income level in a one-to-one comparison, is the worst tested variable, underestimating the actual number of trips made by well over 8%. Surprisingly, the number of kids under 16 is not more effective than income level, as was anticipated during the variable selection process. Overall, no tested variable should be considered a terrible trip estimator. All tested variables correlate to trip indication, predicting the actual number of trips made with relative accuracy.

## BENEFITS

The research results are exciting in the future of survey data analysis. While the commonly used socioeconomic variable of income level performed relatively well, three of the four tested life cycle variables performed more effectively in trip estimation. With more effective variable options available, engineers and planners will be able to more efficiently plan for and implement future transportation projects. Effective and efficient trip generation analysis will lead to success in the steps that follow in the travel demand modeling process, benefiting all who travel.

## RECOMMENDATIONS

Use of these life cycle variables is recommended in future travel survey data analysis. However, consideration as to the data and time available, as well as the desired level of accuracy in trip estimation should be taken in selecting variables for use in transportation planning. Time is money, and thus whatever data are most readily accessible may be the best variable to use in modeling. When data and time permit, it is recommended that the head of household's age be selected for trip estimation.

Further research of life cycle variables is recommended. The results obtained in this research project could be expounded upon. For instance, the head of household age groupings could be altered or considered dually with other variable subsets such as gender. Graphs, equations, and correlation coefficients could be made using exponential or quadratic settings to better explain deviance in linear regression analysis. Regression analysis of multiple life cycle variables at a time could be performed, combining the factors associated with such variables as head of household's age and the number employed. It would also be interesting to complete the analysis started on each individual urban area, allowing for comparison. For this process, it is recommended that a larger number of households be surveyed in those substratums that are under-represented. It is possible that individual urban areas would yield different results that may be explained by the demographics of an area.

## REFERENCES

1. *An Introduction to Urban Travel Demand Forecasting – A Self Instructional Text*, http://ntl.bts.gov/DOCS/UT.html. Accessed June 2, 2008.
2. *Trip Generation Analysis.* U.S. Department of transportation, Federal Highway Administration, Urban Planning Division, Washington D.C. 1975.
3. Richardson, *Alternative Measure of Household Structure and Stage in Life Cycle for Transport Modeling.* Transportation Research Record 1995.
4. Marker, *Period Effects and Cohort Effects in Life Cycles, Preliminary Analysis.* Transportation Research Record. Paper No. 00.0557.
5. Hall, C., *Texas Department of Transportation Travel Survey Program Brochure*. Texas Department of Transportation, Transportation Planning & Programming Division.
6. *2003 Tyler and Smith County Texas Household Travel Survey Technical Summary*. Texas Transportation Institute, August 2005.
7. *2003 Longview and Gregg County, Texas Household Travel Survey Technical Summary*. Texas Transportation Institute, March 2006.
8. Dresser, G.B., and D. Pearson, *2006 Capital Area Metropolitan Planning Organization Household Travel Survey Technical Summary.* Texas Transportation Institute, April 2008.
9. Spillane, D., and D. Pearson*, 2006 San Antonio Area Metropolitan Planning Organization Household Travel Survey Technical Summary.* Texas Transportation Institute, February 2008.

**APPENDIX**

**Tyler**

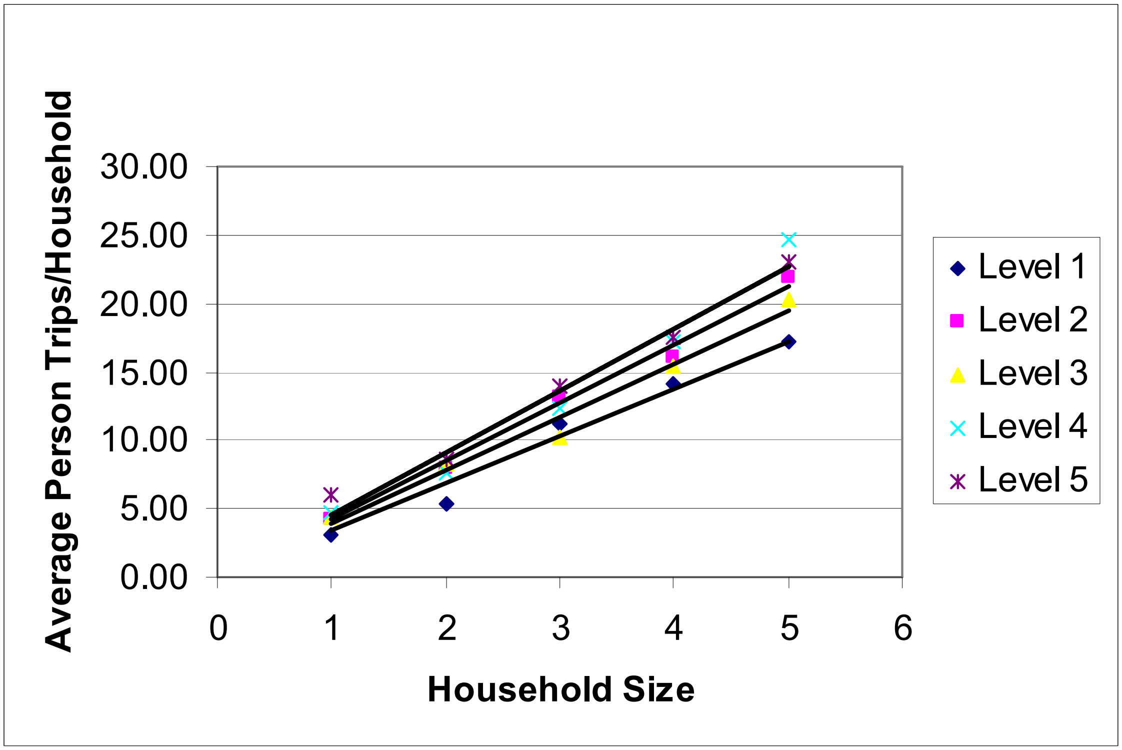


**Figure A1. Tyler Linear Regression Forced through Origin for Income Level**

**Table A1. Tyler Linear Regression Equations and Correlation Coefficients**

| | **Income Level** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 3.72x - 0.97 | y = 4.34x - 0.37 | y = 3.90x + 0.01 | y = 4.97x - 1.61 | y = 4.31x + 0.91 |
| **$r^2$ value** | 0.98 | 0.99 | 0.98 | 0.97 | 0.99 |
| **Forced through Origin** | | | | | |
| **Equation** | y = 3.45x | y = 4.24x | y = 3.90x | y = 4.53x | y = 4.55x |
| **$r^2$ value** | 0.97 | 0.99 | 0.98 | 0.97 | 0.98 |

**Table A2. Tyler Cross Classification Matrices**

| Average Person Trips/HH | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | 3.04 | 5.30 | 11.24 | 14.06 | 17.25 |
| 2 | 4.27 | 7.89 | 13.19 | 16.04 | 21.92 |
| 3 | 4.39 | 8.29 | 10.16 | 15.39 | 20.33 |
| 4 | 4.67 | 7.60 | 12.26 | 17.26 | 24.67 |
| 5 | 6.00 | 8.57 | 13.97 | 17.53 | 23.05 |
| **Number of Households in Each Substratum** | | | | | |
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | 96 | 82 | 25 | 18 | 8 |
| 2 | 48 | 81 | 26 | 26 | 25 |
| 3 | 62 | 105 | 38 | 31 | 12 |
| 4 | 21 | 91 | 39 | 31 | 9 |
| 5 | 23 | 94 | 38 | 30 | 20 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | (2.59,3.50) | (4.55,6.06) | (9.20,13.28) | (10.35,17.76) | (13.01,21.49) |
| 2 | (3.62,4.93) | (6.94,8.84) | (11.46,14.93) | (13.07,19.01) | (19.04,24.80) |
| 3 | (3.82,4.95) | (7.44,9.13) | (8.82,11.49) | (12.88,17.90) | (13.44,27.22) |
| 4 | (3.66,5.67) | (6.61,8.60) | (10.69,13.82) | (14.74,19.77) | (20.54,28.80) |
| 5 | (4.80,7.20) | (7.78,9.37) | (12.25,15.69) | (14.50,20.56) | (18.23,27.87) |

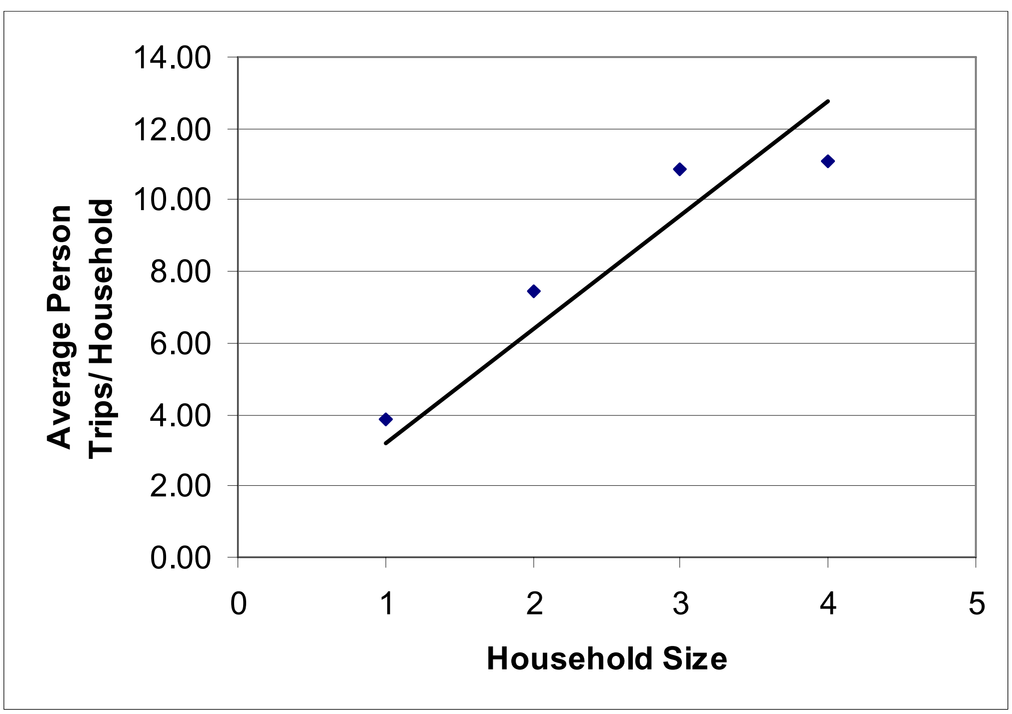


**Figure A2. Tyler Linear Regression Forced through Origin for No Children**

**Table A3. Tyler Linear Regression Equations and Correlation Coefficients**

| No Children | |
|---|---|
| **Line of Best Fit** | |
| **Equation** | y = 2.51x + 2.02 |
| **$r^2$ Value** | 0.91 |
| **Forced through Origin** | |
| **Equation** | y = 3.19x |
| **$r^2$ Value** | 0.83 |

**Table A4. Tyler Cross Classification Matrices**

| Average Person Trips/HH | | | | |
|---|---|---|---|---|
| **Household Size** | | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | 3.84 | 7.44 | 10.84 | 11.09 |
| **Number of Households in Each Substratum** | | | | |
| **Household Size** | | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | 282 | 482 | 61 | 11 |
| **90% Confidence Interval** | | | | |
| **Household Size** | | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | (3.56,4.13) | (7.07,7.81) | (9.67,12.00) | (6.96,15.22) |

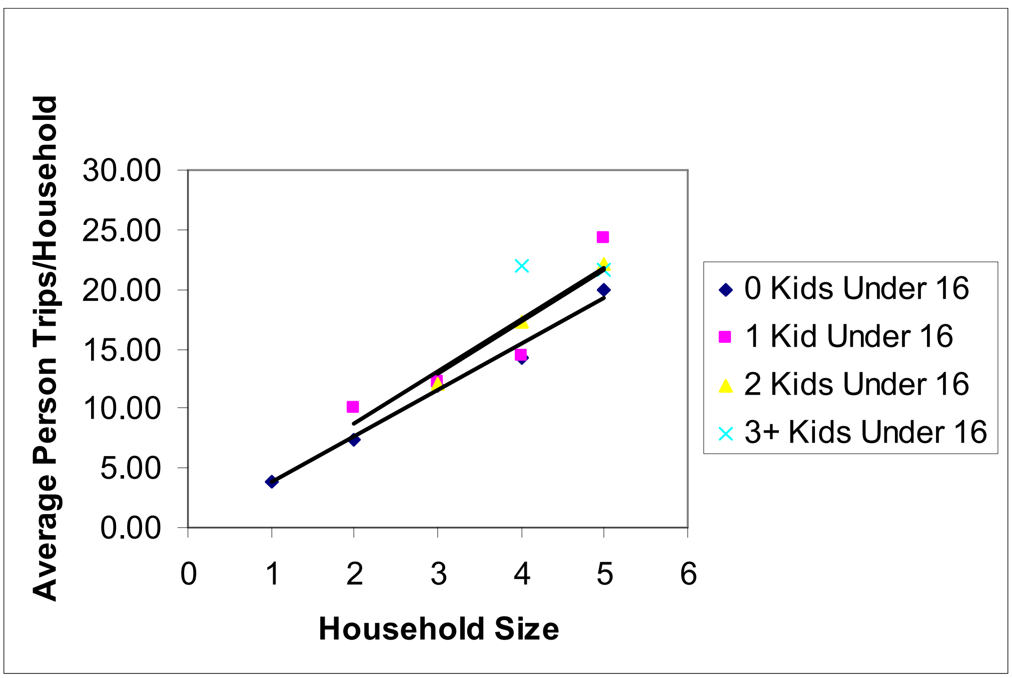


**Figure A3. Tyler Linear Regression Forced through Origin for # of Kids Under 16**

**Table A5. Tyler Linear Regression Equations and Correlation Coefficients**

| | Number of Kids Under 16 | | | |
|---|---|---|---|---|
| | **0** | **1** | **2** | **3+** |
| **Line of Best Fit** | | | | |
| **Equation** | y = 3.91x - 0.25 | y = 4.45x - 0.33 | y = 5.10x - 3.25 | y = -0.31x + 23.24 |
| **$r^2$ Value** | 0.99 | 0.85 | 1.00 | 1.00 |
| **Forced through Origin** | | | | |
| **Equation** | y = 3.85x | y = 4.36x | y = 4.32x | NA |
| **$r^2$ Value** | 0.99 | 0.85 | 0.98 | NA |

**Table A6. Tyler Cross Classification Matrices**

| Average Person Trips/HH | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 3.84 | 7.44 | 11.92 | 14.27 | 20.00 |
| **1** | none | 10.13 | 12.19 | 14.38 | 24.22 |
| **2** | NA | None | 12.00 | 17.25 | 22.20 |
| **3+** | NA | NA | none | 22.00 | 21.69 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 282 | 489 | 79 | 26 | 1 |
| **1** | none | 15 | 88 | 21 | 9 |
| **2** | NA | None | 9 | 89 | 25 |
| **3+** | NA | NA | none | 2 | 42 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | (3.56,4.13) | (7.07,7.81) | (10.79,13.05) | (11.42,17.12) | nei |
| **1** | none | (7.06,13.20) | (11.14,13.25) | (11.61,17.15) | (18.37,30.07) |
| **2** | NA | None | (8.73,15.27) | (15.65,18.85) | (18.95,25.45) |
| **3+** | NA | NA | none | (10.49,33.51) | (18.75,24.63) |

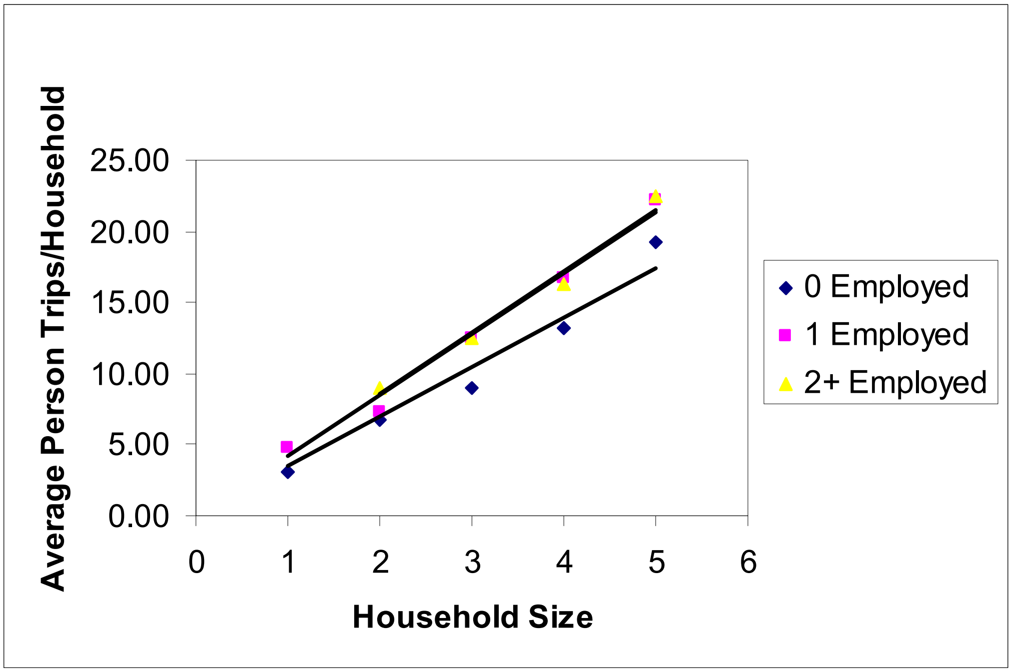


**Figure A4. Tyler Linear Regression Forced through Origin for # Employed**

**Table A7. Tyler Linear Regression Equations and Correlation Coefficients**

| | Number Employed | | |
|---|---|---|---|
| | **0** | **1** | **2+** |
| **Line of Best Fit** | | | |
| **Equation** | y = 3.86x - 1.36 | y = 4.41x - 0.57 | y = 4.44x - 0.48 |
| **$r^2$ Value** | 0.97 | 0.99 | 0.98 |
| **Forced through Origin** | | | |
| **Equation** | y = 3.49x | y = 4.26x | y = 4.31x |
| **$r^2$ Value** | 0.96 | 0.99 | 0.98 |

**Table A8. Tyler Cross Classification Matrices**

| Average Person Trips/HH | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 3.13 | 6.69 | 8.95 | 13.17 | 19.20 |
| **1** | 4.79 | 7.28 | 12.46 | 16.70 | 22.15 |
| **2+** | NA | 8.99 | 12.43 | 16.24 | 22.50 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 160 | 210 | 19 | 6 | 5 |
| **1** | 122 | 149 | 57 | 50 | 34 |
| **2+** | NA | 145 | 100 | 82 | 38 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | (2.74,3.51) | (6.11,7.26) | (6.87,11.02) | (9.08,17.25) | (12.33,26.07) |
| **1** | (4.41,5.16) | (6.59,7.97) | (11.03,13.88) | (14.54,18.86) | (18.86,25.43) |
| **2+** | NA | (8.34,9.63) | (11.49,13.37) | (14.61,17.88) | (19.75,25.25) |

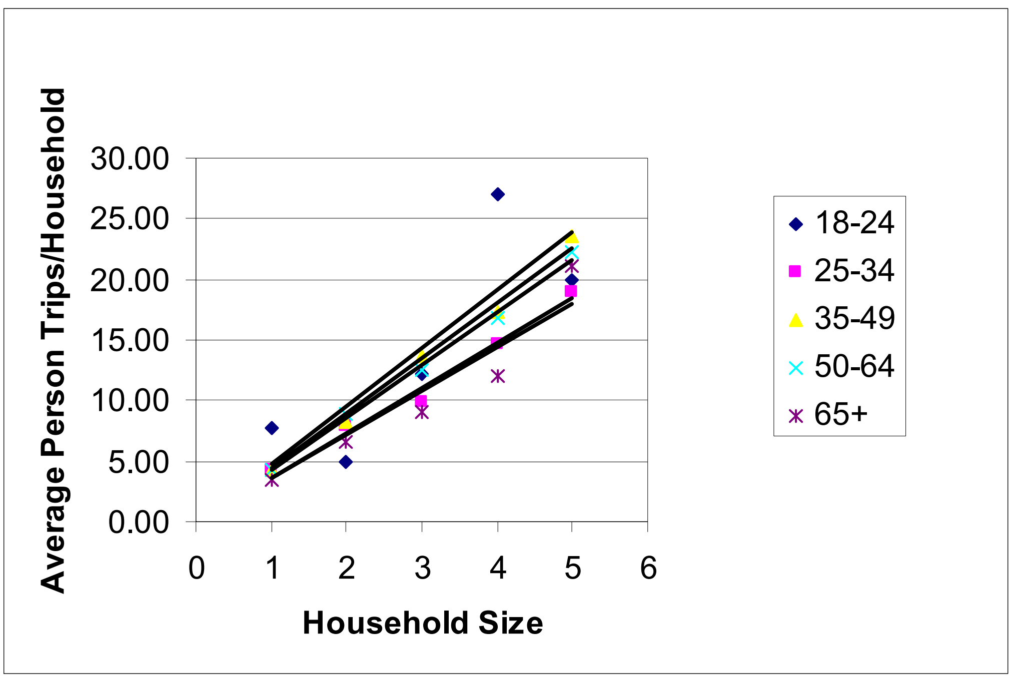


**Figure A5. Tyler Linear Regression Forced through Origin for Head's Age**

**Table A9. Tyler Linear Regression Correlation Coefficients and Equations**

| | Age of Household's Head | | | | |
|---|---|---|---|---|---|
| | **18-24** | **25-34** | **35-49** | **50-64** | **65+** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 4.65x + 0.44 | y = 3.62x + 0.27 | y = 4.78x - 0.96 | y = 4.39x - 0.23 | y = 4.10x - 1.85 |
| **$r^2$ Value** | 0.66 | 0.98 | 0.99 | 0.99 | 0.92 |
| **Forced through Origin** | | | | | |
| **Equation** | y = 4.77x | y = 3.70x | y = 4.52x | y = 4.33x | y = 3.59x |
| **$r^2$ Value** | 0.66 | 0.98 | 0.99 | 0.99 | 0.90 |

**Table A10. Tyler Cross Classification Matrices**

| Average Person Trips/HH | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 7.75 | 5.00 | 12.20 | 27.00 | 20.00 |
| **25-34** | 4.25 | 7.90 | 9.94 | 14.64 | 19.00 |
| **35-49** | 4.24 | 8.16 | 13.60 | 17.33 | 23.54 |
| **50-64** | 4.28 | 8.91 | 12.52 | 16.74 | 22.33 |
| **65+** | 3.39 | 6.52 | 9.09 | 12.08 | 21.10 |

| Number of Households in Each Substratum | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 4 | 6 | 5 | 2 | 1 |
| **25-34** | 8 | 20 | 16 | 33 | 13 |
| **35-49** | 42 | 50 | 70 | 69 | 35 |
| **50-64** | 72 | 169 | 52 | 23 | 18 |
| **65+** | 157 | 258 | 33 | 12 | 10 |

| 90% Confidence Interval | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Head's Age** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | (5.93,9.57) | (3.30,6.70) | (6.38,18.02) | (13.84,40.16) | nei |
| **25-34** | (2.83,5.67) | (5.92,9.88) | (7.48,12.40) | (12.00,17.27) | (13.17,24.83) |
| **35-49** | (3.75,4.73) | (7.02,9.30) | (12.43,14.77) | (15.53,19.14) | (20.48,26.61) |
| **50-64** | (3.74,4.82) | (8.25,9.56) | (11.26,13.78) | (14.15,19.33) | (18.36,26.31) |
| **65+** | (2.99,3.80) | (6.03,7.02) | (7.48,10.70) | (8.01,16.16) | (16.45,25.75) |

**Longview**

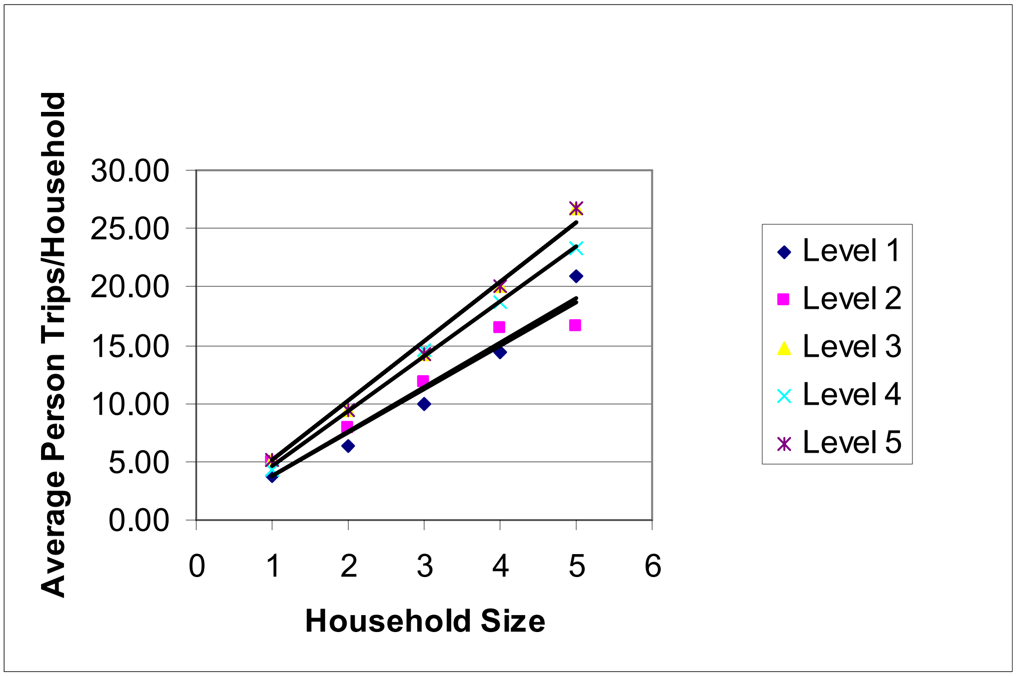


**Figure A6. Longview Linear Regression Forced through Origin for Income Level**

**Table A11. Longview Linear Regression Equations and Correlation Coefficients**

| | Income Level | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 4.26x - 1.72 | y = 3.19x + 1.99 | y = 5.41x - 1.09 | y = 4.74x - 0.15 | y = 5.41x - 1.09 |
| **$r^2$ Value** | 0.97 | 0.95 | 0.99 | 1.00 | 0.99 |
| **Forced Through Origin** | | | | | |
| **Equation** | y = 3.79x | y = 3.73x | y = 5.11x | y = 4.70x | y = 5.11x |
| **$r^2$ Value** | 0.96 | 0.92 | 0.99 | 1.00 | 0.99 |

**Table A12. Longview Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Income Level** | **1** | **2** | **3** | **4** | **5+** |
| **1** | 3.70 | 6.35 | 9.92 | 14.38 | 21.00 |
| **2** | 4.97 | 7.83 | 11.88 | 16.48 | 16.58 |
| **3** | 4.04 | 7.96 | 14.31 | 15.00 | 23.06 |
| **4** | 4.27 | 9.50 | 14.50 | 18.76 | 23.37 |
| **5** | 5.08 | 9.42 | 14.29 | 20.00 | 26.82 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **Income Level** | **1** | **2** | **3** | **4** | **5+** |
| **1** | 53 | 84 | 26 | 16 | 11 |
| **2** | 37 | 52 | 25 | 25 | 19 |
| **3** | 25 | 54 | 51 | 45 | 31 |
| **4** | 11 | 52 | 36 | 37 | 19 |
| **5** | 12 | 43 | 51 | 41 | 17 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **Income Level** | **1** | **2** | **3** | **4** | **5+** |
| **1** | (2.92,4.48) | (5.47,7.22) | (7.89,11.95) | (10.48,18.27) | (14.62,27.38) |
| **2** | (4.17,5.78) | (6.57,9.09) | (9.60,14.16) | (13.55,19.41) | (13.17,19.99) |
| **3** | (3.04,5.04) | (6.74,9.18) | (12.81,15.82) | (13.27,16.73) | 20.57,25.56) |
| **4** | (3.00,5.55) | (8.05,10.95) | (12.14,16.86) | (16.38,21.13) | (18.45,28.28) |
| **5** | (3.84,6.32) | (8.19,10.65) | (12.53,16.06) | (18.18,21.82) | (22.24,31.41) |

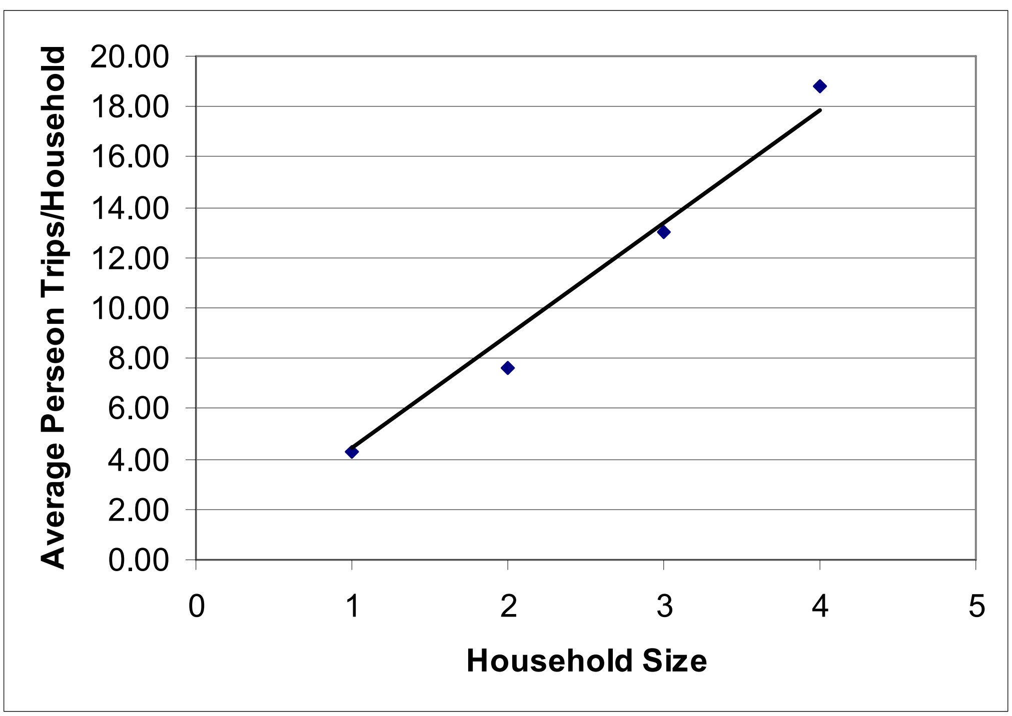


**Figure A7. Longview Linear Regression Forced through Origin for No Children**

**Table A13. Longview Linear Regression Equations and Correlation Coefficients**

| No Children | |
|---|---|
| **Line of Best Fit** | |
| **Equation** | y = 4.90x - 1.33 |
| **$r^2$ Value** | 0.99 |
| **Forced Through Origin** | |
| **Equation** | y = 4.46x |
| **$r^2$ Value** | 0.98 |

**Table A14. Longview Cross Classification Matrices**

| Average Person Trips/Household | | | | |
|---|---|---|---|---|
| | **Household Size** | | | |
| | 1 | 2 | 3 | 4+ |
| **No Children** | 4.27 | 7.59 | 13.05 | 18.80 |
| **Number of Households in Each Substratum** | | | | |
| | **Household Size** | | | |
| | 1 | 2 | 3 | 4+ |
| **No Children** | 147 | 304 | 58 | 10 |
| **90% Confidence Interval** | | | | |
| | **Household Size** | | | |
| | 1 | 2 | 3 | 4+ |
| **No Children** | (3.85,4.70) | (7.09,8.09) | (11.31,14.79) | (14.63,22.97) |

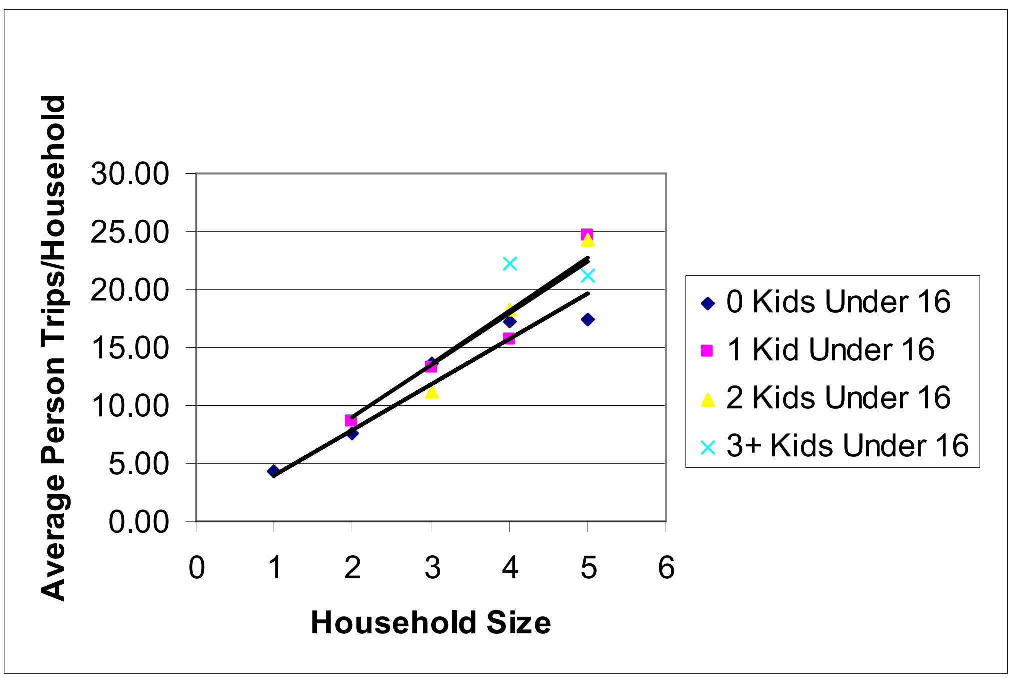


**Figure A8. Longview Linear Regression Forced through Origin for # of Kids Under 16**

**Table A15. Longview Linear Regression Equations and Correlation Coefficients**

| | Number of Kids Under 16 | | | |
|---|---|---|---|---|
| | **0** | **1** | **2** | **3+** |
| **Line of Best Fit** | | | | |
| **Equation** | y = 3.61x + 1.22 | y = 5.02x - 2.03 | y = 6.56x - 8.33 | y = -0.92x + 25.87 |
| **$r^2$ Value** | 0.94 | 0.94 | 1.00 | 1.00 |
| **Forced through Origin** | | | | |
| **Equation** | y = 3.94x | y = 4.49x | y = 4.56x | NA |
| **$r^2$ Value** | 0.93 | 0.93 | 0.90 | NA |

**Table A16. Longview Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 4.27 | 7.63 | 13.57 | 17.29 | 17.50 |
| **1** | none | 8.65 | 13.25 | 15.69 | 24.57 |
| **2** | NA | none | 11.14 | 18.34 | 24.27 |
| **3+** | NA | NA | none | 22.20 | 21.28 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 147 | 309 | 84 | 14 | 2 |
| **1** | none | 20 | 107 | 58 | 7 |
| **2** | NA | none | 7 | 91 | 30 |
| **3+** | NA | NA | none | 5 | 60 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | (3.85,4.70) | (7.13,8.13) | (12.16,14.98) | (13.21,21.36) | (5.16,29.84) |
| **1** | none | (6.36,10.94) | (12.13,14.37) | (14.09,17.29) | (19.68,29.46) |
| **2** | NA | none | (8.26,14.02) | (16.89,19.79) | (20.68,27.85) |
| **3+** | NA | NA | none | (15.49,27.91) | (19.03,23.54) |

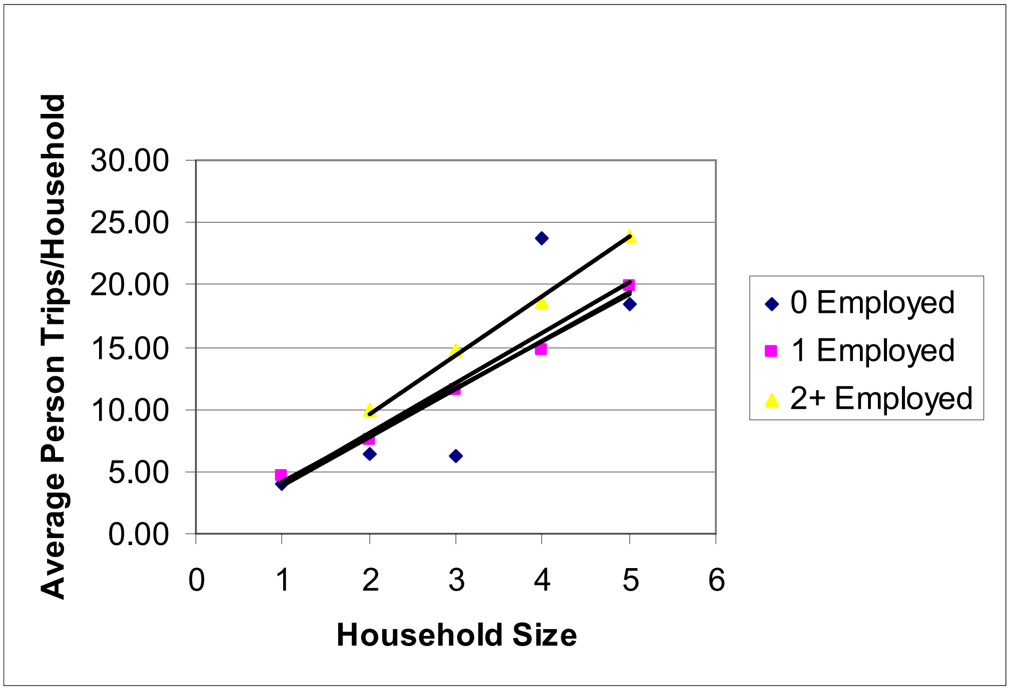


**Figure A9. Longview Linear Regression Forced through Origin for # Employed**

**Table A17. Longview Linear Regression Equations and Correlation Coefficients**

| | # Employed | | |
|---|---|---|---|
| | **0** | **1** | **2+** |
| **Line of Best Fit** | | | |
| **Equation** | y = 4.64x - 2.14 | y = 3.79x + 0.33 | y = 4.58x + 0.76 |
| **$r^2$ Value** | 0.70 | 0.99 | 1.00 |
| **Forced through Origin** | | | |
| **Equation** | y = 4.06x | y = 3.88x | y = 4.78x |
| **$r^2$ Value** | 0.68 | 0.99 | 0.99 |

**Table A18. Longview Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 3.94 | 6.46 | 6.25 | 23.75 | 18.50 |
| **1** | 4.66 | 7.53 | 11.54 | 14.83 | 19.97 |
| **2+** | NA | 9.93 | 14.75 | 18.62 | 23.92 |
| **Number of Households in Each Substratum** | | | | | |
| | Household Size | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 88 | 140 | 12 | 4 | 4 |
| **1** | 62 | 104 | 57 | 60 | 34 |
| **2+** | NA | 85 | 129 | 105 | 61 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | (3.36,4.53) | (5.70,7.21) | (3.38,9.12) | (20.72,26.78) | (8.13,28.87) |
| **1** | (4.09,5.23) | (6.75,8.31) | (10.26,12.83) | (13.03,16.64) | (16.79,23.15) |
| **2+** | NA | (8.98,10.87) | (13.67,15.83) | (17.38,19.86) | (21.74,26.10) |

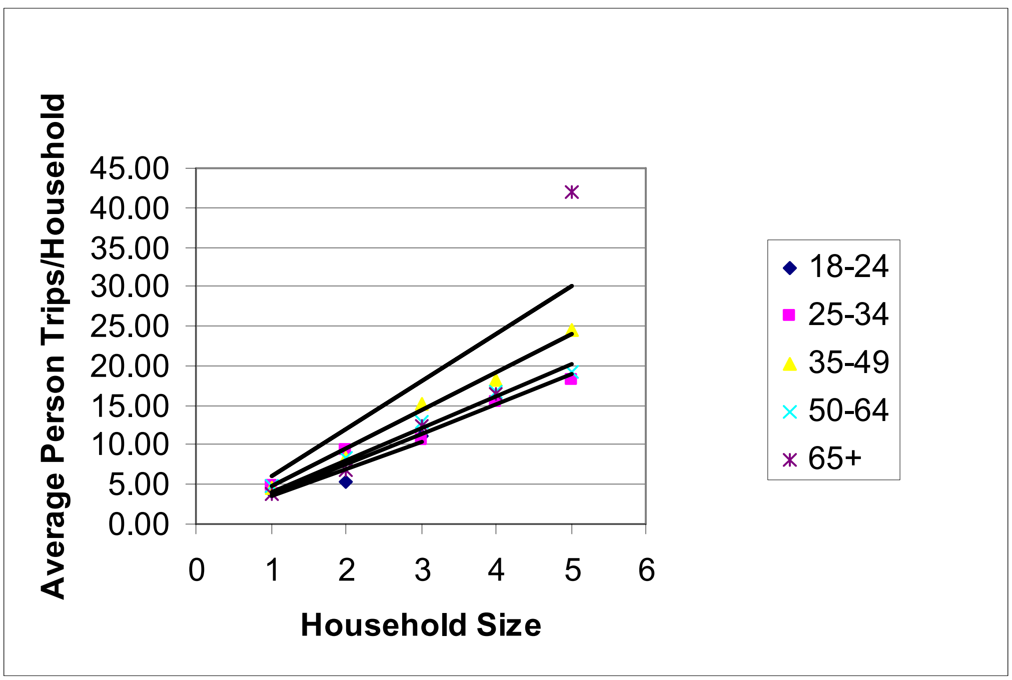


**Figure A10. Longview Linear Regression Forced through Origin for Head's Age**

**Table A19. Longview Linear Regression Equations and Correlation Coefficients**

| | Age of Household's Head | | | | |
|---|---|---|---|---|---|
| | **18-24** | **25-34** | **35-49** | **50-64** | **65+** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 3.63x - 0.39 | y = 3.26x + 1.89 | y = 5.00x - 0.79 | y = 3.74x + 1.18 | y = 8.61x - 9.53 |
| **$r^2$ Value** | 0.88 | 0.98 | 0.99 | 0.99 | 0.80 |
| **Forced through Origin** | | | | | |
| **Equation** | y = 3.46x | y = 3.78x | y = 4.78x | y = 4.06x | y = 6.01x |
| **$r^2$ Value** | 0.88 | 0.95 | 0.99 | 0.98 | 0.71 |

**Table A20. Longview Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 4.00 | 5.33 | 11.25 | none | none |
| **25-34** | 4.83 | 9.35 | 10.69 | 15.41 | 18.12 |
| **35-49** | 4.62 | 8.29 | 15.22 | 18.27 | 24.62 |
| **50-64** | 4.75 | 8.34 | 12.92 | 16.65 | 19.27 |
| **65+** | 3.75 | 6.89 | 12.34 | 16.44 | 42.00 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 4 | 3 | 4 | none | none |
| **25-34** | 6 | 20 | 35 | 27 | 25 |
| **35-49** | 21 | 34 | 78 | 105 | 58 |
| **50-64** | 48 | 119 | 52 | 26 | 15 |
| **65+** | 71 | 153 | 29 | 9 | 1 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **Head's Age** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | (1.77,6.23) | (2.43,8.23) | (8.29,14.21) | none | none |
| **25-34** | (3.84,5.82) | (7.17,11.53) | (8.95,12.42) | (13.26,17.55) | (14.92,21.32) |
| **35-49** | (3.69,5.55) | (6.93,9.65) | (13.77,16.67) | (16.97,19.56) | (22.22,27.02) |
| **50-64** | (3.93,5.57) | (7.51,9.16) | (11.63,14.21) | (13.77,19.54) | (15.76,22.77) |
| **65+** | (3.14,4.36) | (6.18,7.59) | (9.57,15.12) | (10.31,22.58) | nei |

**Austin**

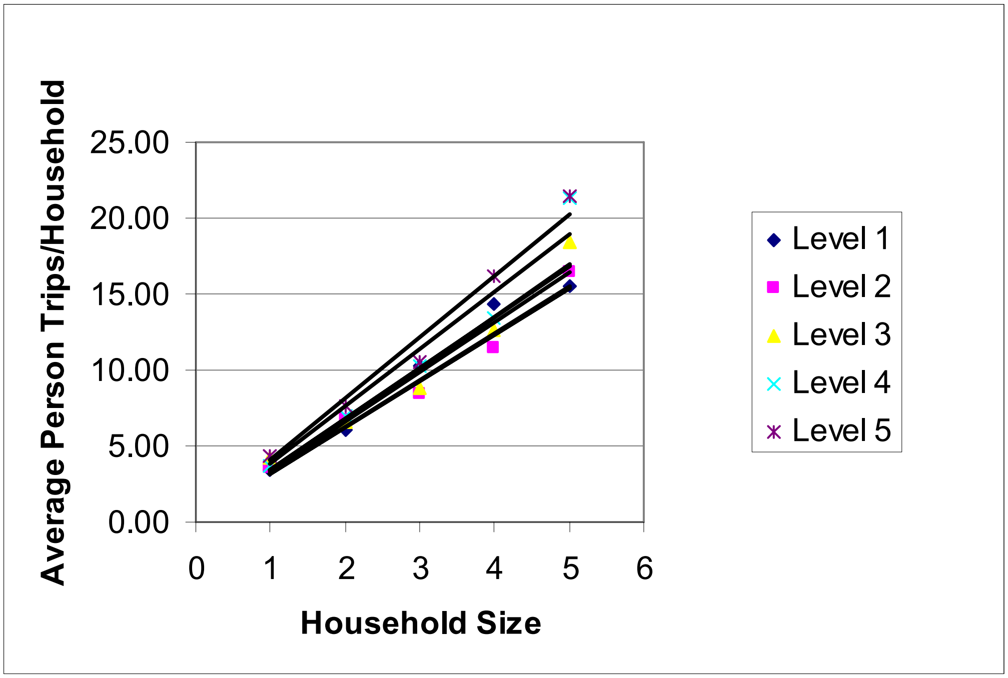


**Figure A11. Austin Linear Regression Forced through Origin for Income Level**

**Table A21. Austin Linear Regression Equations and Correlation Coefficients**

| | Income Level | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 3.26x + 0.12 | y = 3.05x + 0.17 | y = 3.44x - 0.24 | y = 4.16x - 1.35 | y = 4.28x - 0.81 |
| **$r^2$ Value** | 0.98 | 0.97 | 0.96 | 0.95 | 0.98 |
| **Forced Through Origin** | | | | | |
| **Equation** | y = 3.29x | y = 3.10x | y = 3.38x | y = 3.79x | y = 4.06x |
| **$r^2$ Value** | 0.98 | 0.97 | 0.96 | 0.95 | 0.98 |

**Table A22. Austin Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | 3.36 | 6.03 | 10.26 | 14.29 | 15.53 |
| 2 | 3.56 | 6.75 | 8.39 | 11.43 | 16.47 |
| 3 | 4.16 | 6.57 | 8.81 | 12.58 | 18.37 |
| 4 | 3.73 | 6.91 | 10.28 | 13.44 | 21.26 |
| 5 | 4.37 | 7.63 | 10.51 | 16.19 | 21.51 |
| **Number of Households in Each Substratum** | | | | | |
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | 111 | 91 | 31 | 14 | 34 |
| 2 | 64 | 115 | 56 | 42 | 34 |
| 3 | 58 | 107 | 52 | 55 | 35 |
| 4 | 26 | 99 | 46 | 41 | 39 |
| 5 | 19 | 104 | 89 | 86 | 49 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | (2.96,3.77) | (5.39,6.68) | (8.30,12.21) | (10.55,18.03) | (13.46,17.60) |
| 2 | (3.09,4.04) | (6.08,7.42) | (7.37,9.42) | (9.75,13.10) | (13.78,19.16) |
| 3 | (3.71,4.60) | (5.95,7.19) | (7.71,9.90) | (11.33,13.83) | (15.72,21.03) |
| 4 | (3.00,4.46) | (6.20,7.62) | (9.03,11.54) | (12.04,14.84) | (18.71,23.80) |
| 5 | (3.55,5.19) | (7.04,8.23) | (9.69,11.32) | (14.83,17.54) | (18.65,24.37) |

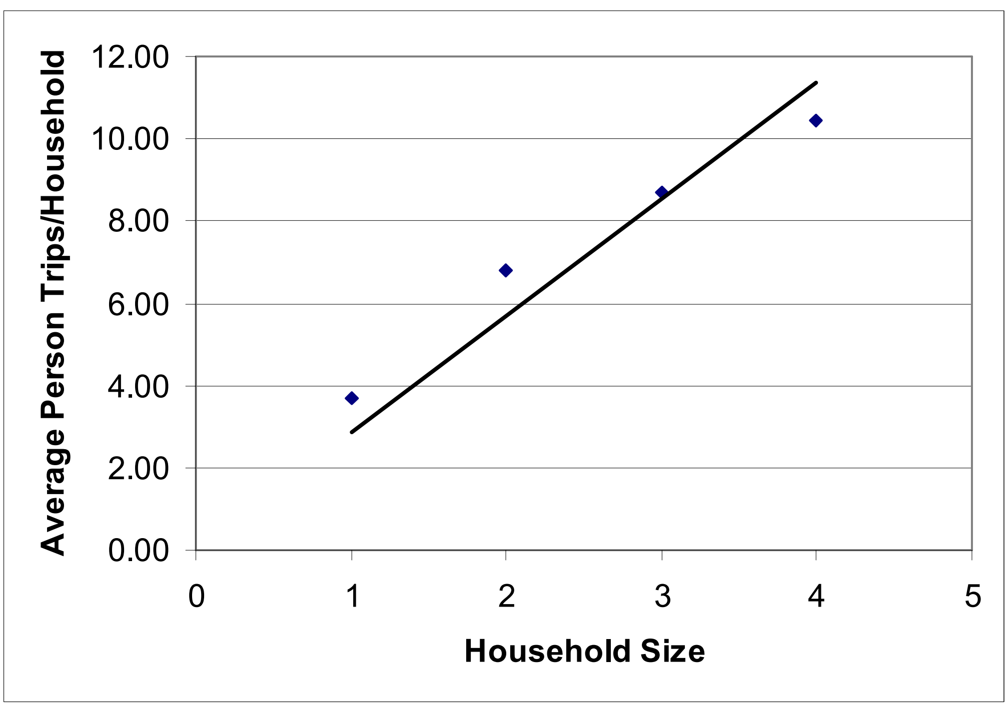


**Figure A12. Austin Linear Regression Forced through Origin for No Children**

**Table A23. Austin Linear Regression Equations Correlation Coefficients**

| No Children | |
|---|---|
| **Line of Best Fit** | |
| **Equation** | y = 2.22x + 1.86 |
| **$r^2$ Value** | 0.98 |
| **Forced Through Origin** | |
| **Equation** | y = 2.84x |
| **$r^2$ Value** | 0.89 |

**Table A24. Austin Cross Classification Matrices**

| Average Person Trips/ Household | | | | |
|---|---|---|---|---|
| | **Household Size** | | | |
| | 1 | 2 | 3 | 4+ |
| **No Children** | 3.68 | 6.82 | 8.71 | 10.46 |
| **Number of Households in Each Substratum** | | | | |
| | **Household Size** | | | |
| | 1 | 2 | 3 | 4+ |
| **No Children** | 277 | 458 | 109 | 28 |
| **90% Confidence Interval** | | | | |
| | **Household Size** | | | |
| | 1 | 2 | 3 | 4+ |
| **No Children** | (3.45,3.92) | (6.52,7.12) | (7.92,9.50) | (8.97,11.96) |

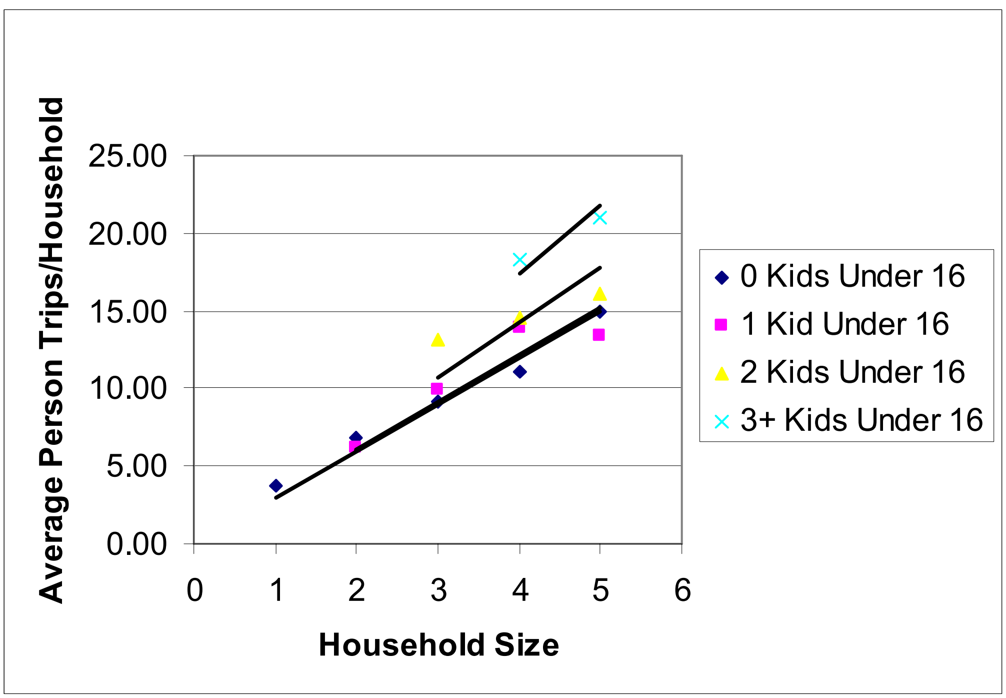


**Figure A13. Austin Linear Regression Forced through Origin for # of Kids Under 16**

**Table A25. Austin Linear Regression Equations and Correlation Coefficients**

| | Number of Kids Under 16 | | | |
|---|---|---|---|---|
| | 0 | 1 | 2 | 3+ |
| **Line-of-Best-Fit** | | | | |
| **Equation** | y = 2.69x + 1.08 | y = 2.59x + 1.78 | y = 1.50x + 8.59 | y = 2.69x + 7.57 |
| **$r^2$ Value** | 0.99 | 0.86 | 1.00 | 1.00 |
| **Forced through Origin** | | | | |
| **Equation** | y = 2.98x | y = 3.05x | y = 3.57x | y = 4.35x |
| **$r^2$ Value** | 0.97 | 0.83 | -0.95 | 0.61 |

**Table A26. Austin Cross Classification Matrices**

| Average Person Trips/ Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| # Kids Under 16 | 1 | 2 | 3 | 4 | 5+ |
| 0 | 3.68 | 6.81 | 9.17 | 11.08 | 15.00 |
| 1 | none | 6.13 | 9.92 | 13.86 | 13.43 |
| 2 | NA | none | 13.09 | 14.62 | 16.10 |
| 3+ | NA | NA | none | 18.33 | 21.02 |
| **Number of Household in Each Substratum** | | | | | |
| | Household Size | | | | |
| # Kids Under 16 | 1 | 2 | 3 | 4 | 5+ |
| 0 | 277 | 461 | 132 | 39 | 5 |
| 1 | none | 8 | 131 | 50 | 23 |
| 2 | NA | none | 11 | 146 | 40 |
| 3+ | NA | NA | none | 3 | 123 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| # Kids Under 16 | 1 | 2 | 3 | 4 | 5+ |
| 0 | (3.45,3.92) | (6.52,7.11) | (8.47,9.86) | (9.81,12.34) | (10.53,19.47) |
| 1 | none | (3.81,8.44) | (9.20,10.64) | (12.14,15.58) | (11.38,15.49) |
| 2 | NA | none | (9.47,16.71) | (13.65,15.59) | (13.42,18.48) |
| 3+ | NA | NA | none | (14.05,22.62) | (19.49,22.56) |

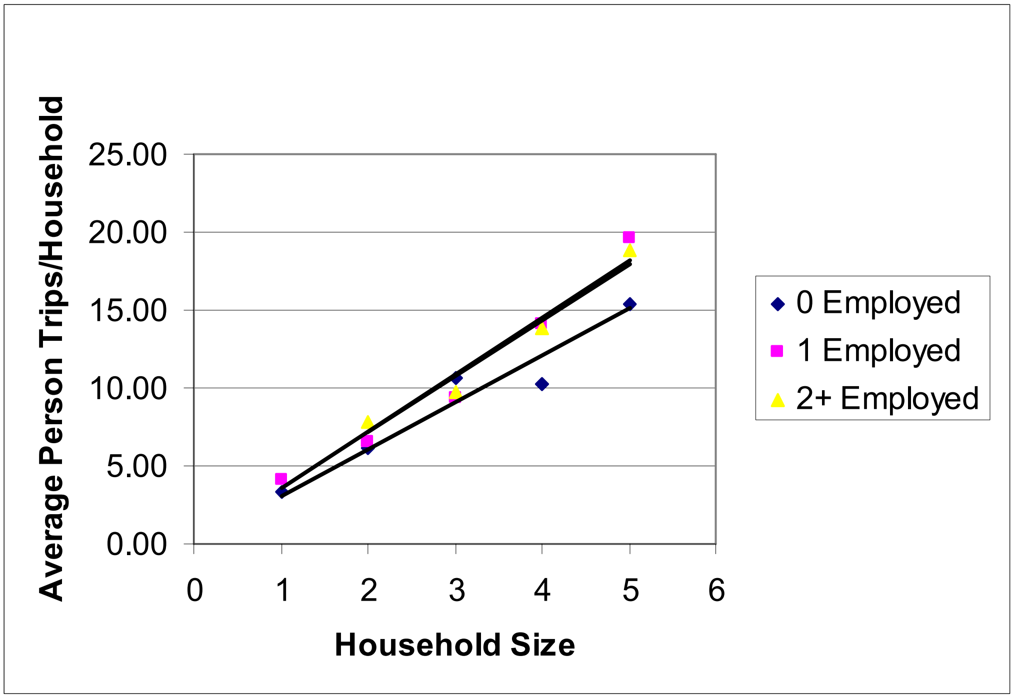


**Figure A14. Austin Linear Regression Forced through Origin for # Employed**

**Table A27. Austin Linear Regression Equations and Correlation Coefficients**

| | Number Employed | | |
|---|---|---|---|
| | 0 | 1 | 2+ |
| **Line of Best Fit** | | | |
| **Equation** | y = 2.83x + 0.69 | y = 3.85x - 0.80 | y = 3.73x - 0.49 |
| **$r^2$ Value** | 0.93 | 0.97 | 0.97 |
| **Forced Through Origin** | | | |
| **Equation** | y = 3.02x | y = 3.63x | y = 3.60x |
| **$r^2$ Value** | 0.93 | 0.97 | 0.97 |

**Table A28. Austin Cross Classification Matrices**

| Average Person Trips/ Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 3.33 | 6.21 | 10.65 | 10.25 | 15.44 |
| **1** | 4.13 | 6.50 | 9.42 | 14.16 | 19.56 |
| **2+** | NA | 7.79 | 9.72 | 13.89 | 18.82 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 158 | 203 | 23 | 4 | 9 |
| **1** | 120 | 149 | 102 | 90 | 68 |
| **2+** | NA | 164 | 149 | 144 | 114 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | (3.00,3.65) | (5.76,6.65) | (8.54,12.77) | (5.30,15.20) | (10.37,20.52) |
| **1** | (3.81,4.45) | (5.97,7.03) | (8.58,10.26) | (12.72,15.59) | (17.19,21.93) |
| **2+** | NA | (7.24,8.33) | (9.06,10.37) | (13.06,14.71) | (17.41,20.22) |

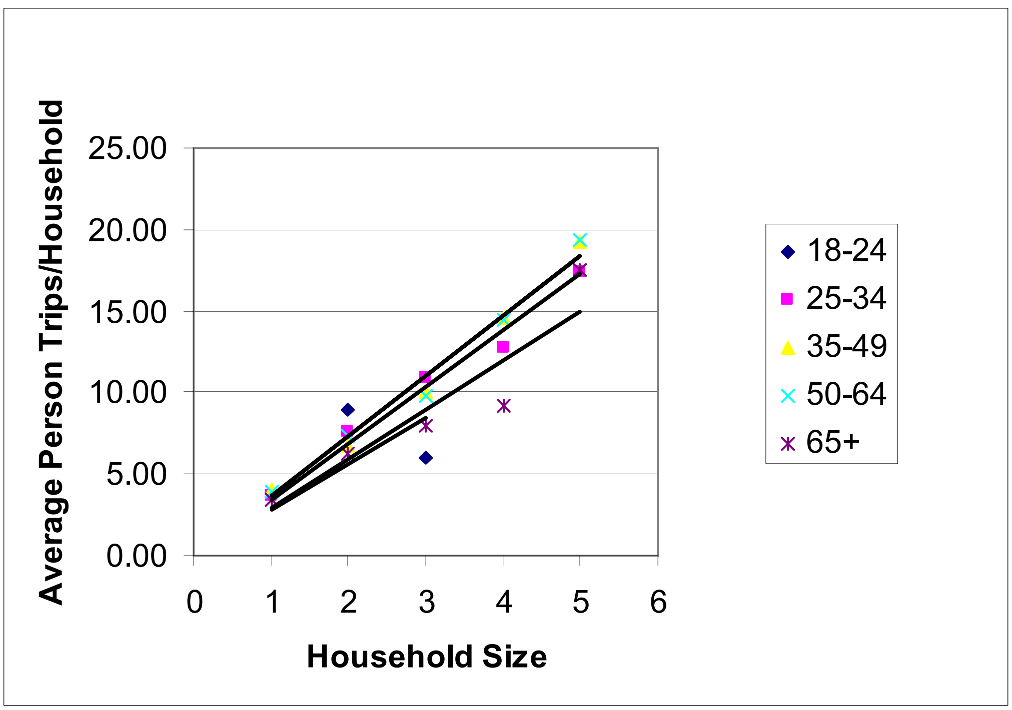


**Figure A15. Austin Linear Regression Forced through Origin for Head's Age**

**Table A29. Austin Linear Regression Equations and Correlation Coefficients**

| | Age of Household's Head | | | | |
|---|---|---|---|---|---|
| | **18-24** | **25-34** | **35-49** | **50-64** | **65+** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 1.17x + 3.89 | y = 3.26x + 0.71 | y = 3.82x - 0.54 | y = 3.80x - 0.41 | y = 3.12x - 0.52 |
| **$r^2$ Value** | 0.19 | 0.99 | 0.99 | 0.98 | 0.87 |
| **Forced through Origin** | | | | | |
| **Equation** | y = 2.83x | y = 3.45x | y = 3.67x | y = 3.69x | y = 2.98x |
| **$r^2$ Value** | -0.26 | 0.98 | 0.98 | 0.98 | 0.86 |

**Table A30. Austin Cross Classification Matrices**

| **Average Person Trips/ Household** | | | | | |
|---|---|---|---|---|---|
| | **Household Size** | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 3.67 | 9.00 | 6.00 | none | none |
| **25-34** | 3.69 | 7.62 | 10.92 | 12.79 | 17.38 |
| **35-49** | 4.06 | 6.69 | 10.01 | 14.57 | 19.20 |
| **50-64** | 3.89 | 7.41 | 9.82 | 14.44 | 19.36 |
| **65+** | 3.37 | 6.21 | 7.98 | 9.19 | 17.50 |
| **Number of Household in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | 3 | 4 | 3 | none | none |
| **25-34** | 16 | 34 | 36 | 33 | 21 |
| **35-49** | 50 | 59 | 106 | 132 | 114 |
| **50-64** | 85 | 180 | 83 | 57 | 39 |
| **65+** | 124 | 239 | 46 | 16 | 16 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | (2.22,5.12) | (5.78,12.22) | nei | nei | nei |
| **25-34** | (2.94,4.43) | (6.36,8.87) | (9.40,12.43) | (11.10,14.47) | (14.80,19.97) |
| **35-49** | (3.52,4.60) | (5.89,7.50) | (9.19,10.83) | (13.55,15.59) | (17.80,20.61) |
| **50-64** | (3.44,4.34) | (6.89,7.92) | (8.88,10.76) | (12.88,16.00) | (16.18,22.53) |
| **65+** | (3.02,3.72) | (5.80,6.61) | (6.97,8.99) | (7.36,11.02) | (11.10,23.90) |

**San Antonio**

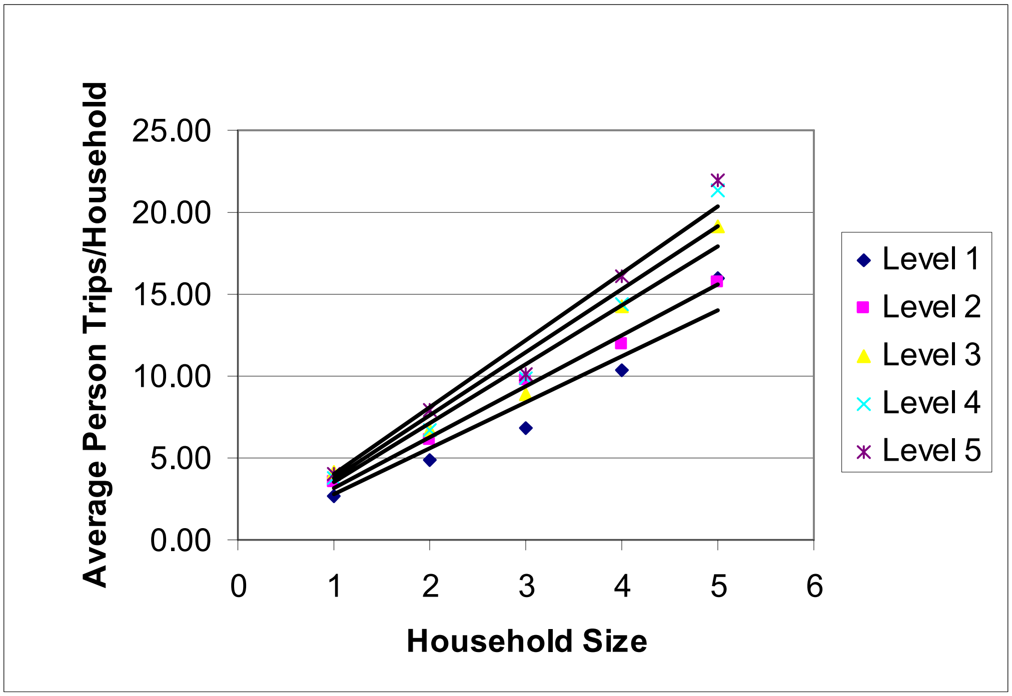


**Figure A16. San Antonio Linear Regression Forced through Origin for Income Level**

**Table A31. San Antonio Linear Regression Equations and Correlation Coefficients**

| | Income Level | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 3.22x - 1.52 | y = 3.02x + 0.36 | y = 3.75x - 0.59 | y = 4.27x - 1.62 | y = 4.41x - 1.22 |
| **$r^2$ Value** | 0.95 | 0.99 | 0.97 | 0.96 | 0.97 |
| **Forced Through Origin** | | | | | |
| **Equation** | y = 2.81x | y = 3.12x | y = 3.59x | y = 3.83x | y = 4.08x |
| **$r^2$ Value** | 0.93 | 0.99 | 0.96 | 0.95 | 0.96 |

**Table A32. San Antonio Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | 2.65 | 4.86 | 6.86 | 10.38 | 16.00 |
| 2 | 3.56 | 6.15 | 9.73 | 11.90 | 15.78 |
| 3 | 4.16 | 6.76 | 8.95 | 14.32 | 19.14 |
| 4 | 3.80 | 6.66 | 9.88 | 14.34 | 21.33 |
| 5 | 3.98 | 7.92 | 10.13 | 16.06 | 21.96 |
| **Number of Households in Each Substratum** | | | | | |
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | 112 | 114 | 42 | 26 | 24 |
| 2 | 79 | 153 | 70 | 51 | 46 |
| 3 | 73 | 125 | 74 | 66 | 36 |
| 4 | 45 | 157 | 95 | 83 | 42 |
| 5 | 41 | 169 | 116 | 89 | 72 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| Income Level | 1 | 2 | 3 | 4 | 5+ |
| 1 | (2.28,3.02) | (4.30,5.42) | (5.65,8.06) | (8.53,12.24) | (13.41,18.59) |
| 2 | (3.11,4.00) | (5.60,6.70) | (8.56,10.89) | (10.33,13.47) | (13.89,17.68) |
| 3 | (3.42,4.91) | (6.15,7.37) | (7.99,9.90) | (12.94,15.69) | (16.41,21.87) |
| 4 | (3.39,4.21) | (6.11,7.20) | (8.97,10.80) | (7.26,21.42) | (18.82,23.85) |
| 5 | (3.30,4.65) | (7.34,8.49) | (9.24,11.02) | (14.73,17.38) | (19.34,24.58) |

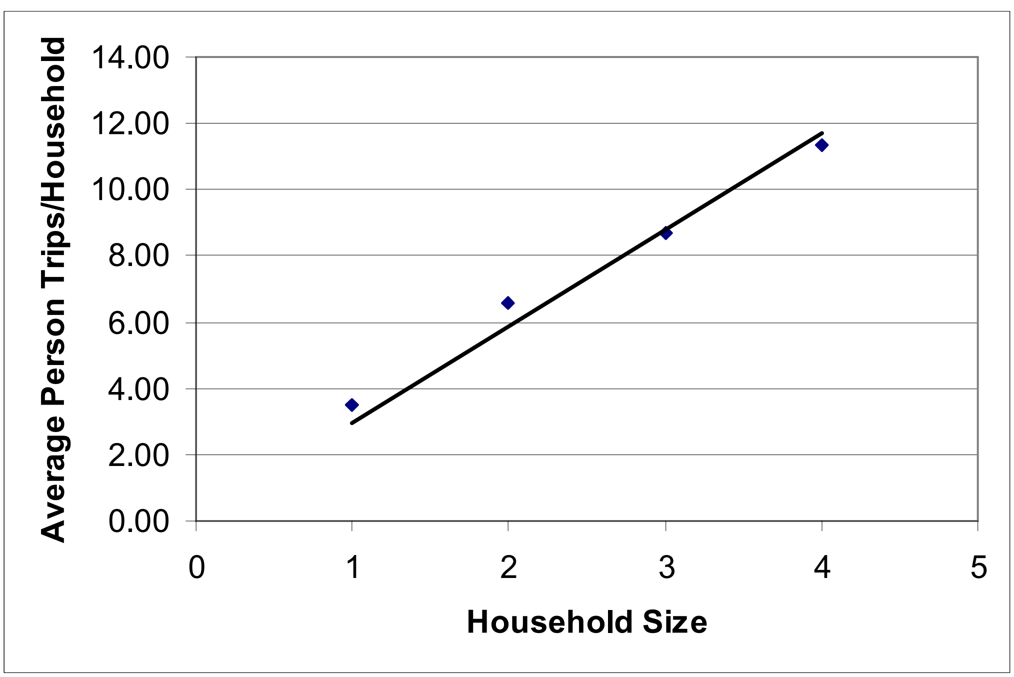


**Figure A17. San Antonio Linear Regression Forced through Origin for No Children**

**Table A33. San Antonio Linear Regression Equations and Correlation Coefficients**

| No Children | |
|---|---|
| **Line of Best Fit** | |
| **Equation** | y = 2.57x + 1.09 |
| **$r^2$ Value** | 1.00 |
| **Forced through Origin** | |
| **Equation** | y = 2.93x |
| **$r^2$ Value** | 0.97 |

**Table A34. San Antonio Cross Classification Matrices**

| Average Person Trips/Household | | | | |
|---|---|---|---|---|
| | Household Size | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | 3.47 | 6.55 | 8.71 | 11.32 |
| **Number of Households in Each Substratum** | | | | |
| | Household Size | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | 350 | 704 | 221 | 57 |
| **90% Confidence Interval** | | | | |
| | Household Size | | | |
| | **1** | **2** | **3** | **4+** |
| **No Children** | (3.23,3.72) | (6.29,6.82) | (8.05,9.36) | (9.89.12.74) |

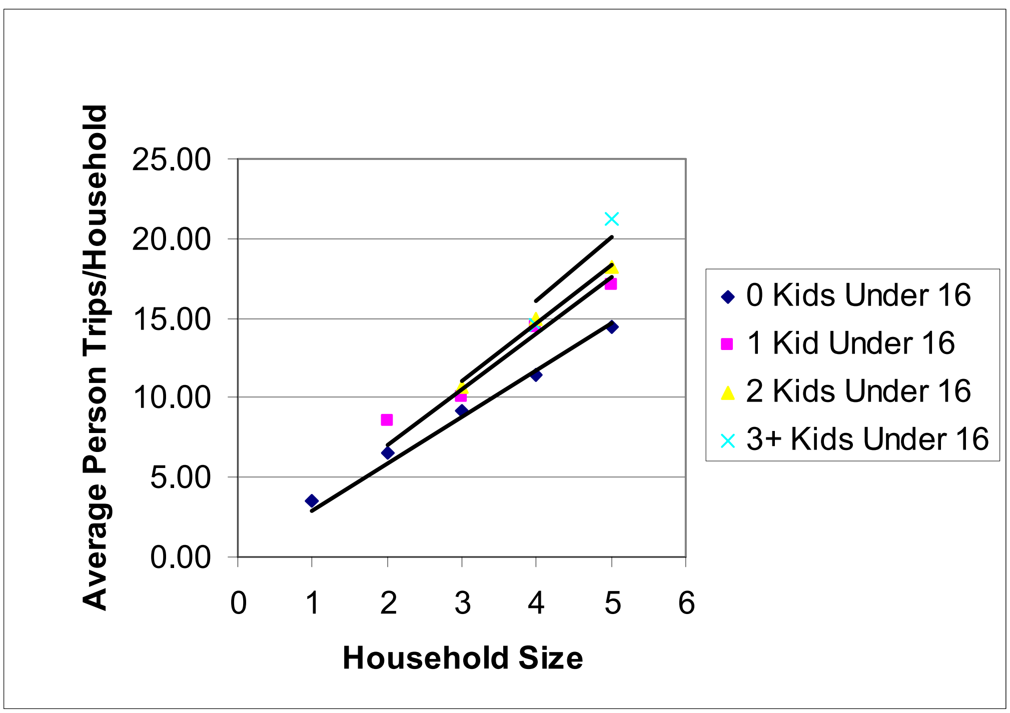


**Figure A18. San Antonio Linear Regression Forced through Origin for # of Kids Under 16**

**Table A35. San Antonio Linear Regression Equations and Correlation Coefficients**

| | Number of Kids Under 16 | | | |
|---|---|---|---|---|
| | **0** | **1** | **2** | **3+** |
| **Line of Best Fit** | | | | |
| **Equation** | y = 2.68x + 0.96 | y = 3.03x + 1.94 | y = 3.82x - 0.64 | y = 6.62x - 11.88 |
| **$r^2$ Value** | 1.00 | 0.97 | 0.99 | 1.00 |
| **Forced through Origin** | | | | |
| **Equation** | y = 2.95x | y = 3.53x | y = 3.67x | y = 4.01x |
| **$r^2$ Value** | 0.99 | 0.94 | 0.99 | 0.84 |

**Table A36. San Antonio Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 3.47 | 6.56 | 9.11 | 11.49 | 14.43 |
| **1** | none | 8.50 | 10.06 | 14.45 | 17.12 |
| **2** | NA | none | 10.64 | 15.00 | 18.27 |
| **3+** | NA | NA | none | 14.60 | 21.22 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 350 | 708 | 252 | 69 | 14 |
| **1** | none | 10 | 135 | 73 | 33 |
| **2** | NA | none | 11 | 168 | 55 |
| **3+** | NA | NA | none | 5 | 118 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **# Kids Under 16** | **1** | **2** | **3** | **4** | **5+** |
| **0** | (3.23,3.72) | (6.30,6.82) | (8.51,9.72) | (10.22,12.77) | (10.68,18.17) |
| **1** | none | (6.68,10.32) | (9.35,10.77) | (13.11,15.79) | (14.32,19.92) |
| **2** | NA | none | (8.12,13.15) | (14.05,15.95) | (16.30,20.25) |
| **3+** | NA | NA | none | (10.65,18.55) | (19.40,23.04) |

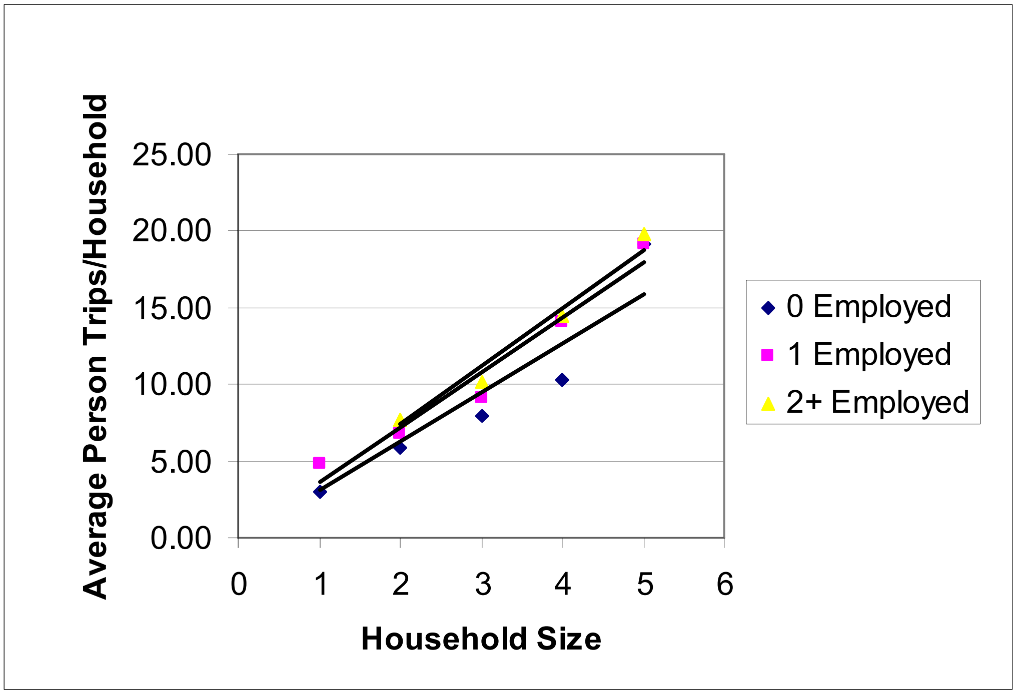


**Figure A19. San Antonio Linear Regression Forced through Origin for # Employed**

**Table A37. San Antonio Linear Regression Equations and Correlation Coefficients**

| | Number Employed | | |
|---|---|---|---|
| | **0** | **1** | **2+** |
| **Line of Best Fit** | | | |
| **Equation** | y = 3.66x - 1.74 | y = 3.57x + 0.05 | y = 4.07x - 1.25 |
| **$r^2$ Value** | 0.89 | 0.96 | 0.98 |
| **Forced through Origin** | | | |
| **Equation** | y = 3.19x | y = 3.59x | y = 3.74x |
| **$r^2$ Value** | 0.87 | 0.96 | 0.97 |

**Table A38. San Antonio Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 3.02 | 5.89 | 7.93 | 10.31 | 19.13 |
| **1** | 4.82 | 6.82 | 9.11 | 14.05 | 19.08 |
| **2+** | NA | 7.63 | 10.12 | 14.42 | 19.75 |
| **Number of Households in Each Substratum** | | | | | |
| | **Household Size** | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | 261 | 320 | 59 | 13 | 16 |
| **1** | 89 | 238 | 141 | 130 | 88 |
| **2+** | NA | 160 | 197 | 172 | 116 |
| **90% Confidence Interval** | | | | | |
| | **Household Size** | | | | |
| **# Employed** | **1** | **2** | **3** | **4** | **5+** |
| **0** | (2.80,3.23) | (5.52,6.26) | (6.69,9.17) | (5.83,14.79) | (16.03,22.22) |
| **1** | (4.16,5.48) | (6.34,7.30) | (8.46,9.76) | (13.03,15.06) | (17.13,21.03) |
| **2+** | NA | (7.08,8.18) | (9.42,10.81) | (13.54,15.31) | (18.04,21.46) |

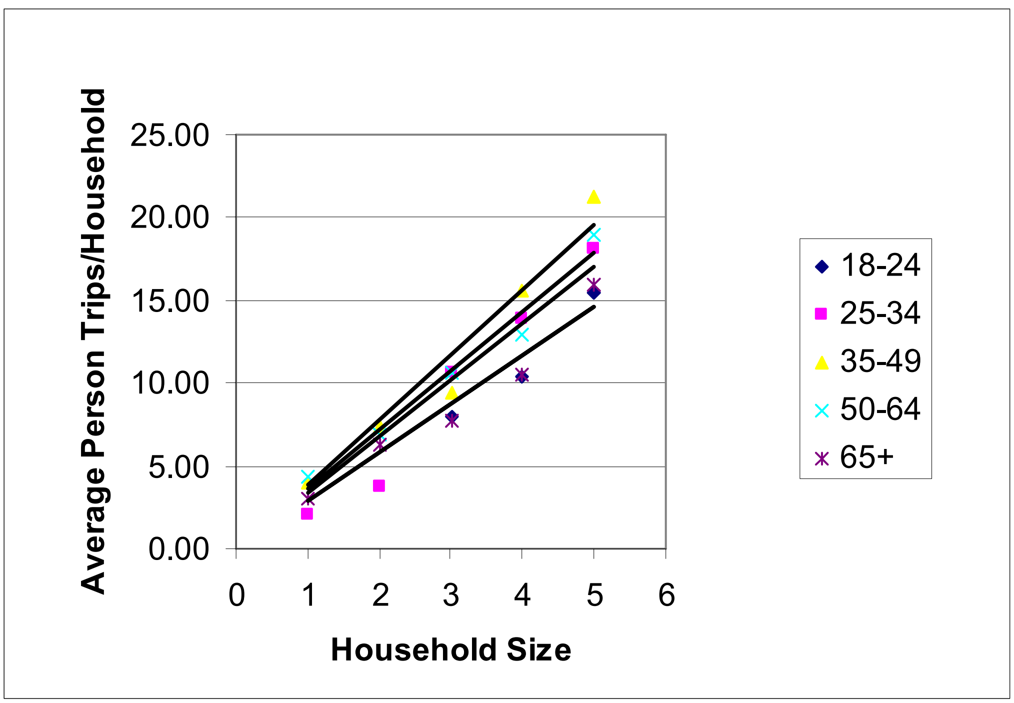


**Figure A20. San Antonio Linear Regression Forced through Origin for Head's Age**

**Table A39. San Antonio Linear Regression Equations and Correlation Coefficients**

| | Age of Household's Head | | | | |
|---|---|---|---|---|---|
| | **18-24** | **25-34** | **35-49** | **50-64** | **65+** |
| **Line of Best Fit** | | | | | |
| **Equation** | y = 3.01x - 0.34 | y = 4.24x - 3.04 | y = 4.27x - 1.27 | y = 3.50x + 0.27 | y = 3.01x - 0.34 |
| **$r^2$ Value** | 0.95 | 0.97 | 0.96 | 0.97 | 0.95 |
| **Forced Through Origin** | | | | | |
| **Equation** | y = 2.91x | y = 3.41x | y = 3.92x | y = 3.57x | y = 2.91x |
| **$r^2$ Value** | 0.95 | 0.93 | 0.96 | 0.97 | 0.95 |

**Table A40. San Antonio Cross Classification Matrices**

| Average Person Trips/Household | | | | | |
|---|---|---|---|---|---|
| | Household Size | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | none | none | 8.00 | 10.33 | 15.50 |
| **25-34** | 2.00 | 3.71 | 10.68 | 13.93 | 18.10 |
| **35-49** | 4.04 | 7.36 | 9.44 | 15.61 | 21.26 |
| **50-64** | 4.40 | 6.94 | 10.69 | 12.88 | 18.92 |
| **65+** | 2.98 | 6.32 | 7.72 | 10.45 | 15.94 |
| **Number of Households in Each Substratum** | | | | | |
| | Household Size | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | none | none | 3 | 3 | 2 |
| **25-34** | 1 | 7 | 28 | 44 | 29 |
| **35-49** | 27 | 50 | 100 | 154 | 105 |
| **50-64** | 103 | 258 | 143 | 83 | 50 |
| **65+** | 219 | 403 | 123 | 31 | 34 |
| **90% Confidence Interval** | | | | | |
| | Household Size | | | | |
| **Age of Head** | **1** | **2** | **3** | **4** | **5+** |
| **18-24** | none | none | (4.20,11.80) | (6.05,14.62) | (14.68,16.32) |
| **25-34** | nei | (2.93,4.49) | (8.96,12.40) | (12.04,15.82) | (15.16,21.05) |
| **35-49** | (3.13,4.94) | (6.56,8.16) | (8.68,10.20) | (14.66,16.56) | (19.31,23.21) |
| **50-64** | (3.82,4.98) | (6.47,7.40) | (9.81,11.56) | (11.67,14.09) | (16.58,21.26) |
| **65+** | (2.74,3.22) | (5.97,6.66) | (7.01,8.43) | (8.49,12.41) | (13.57,18.31) |

# Examining Cross Median Crashes on Horizontal Curves

Prepared for
Undergraduate Transportation Scholars Program

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0-4703

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Mr. Mulkern is a member of the American Society of Civil Engineers (ASCE), the Institute of Transportation Engineers (ITE), Pi Mu Epsilon honour society, and Chi Epsilon honour society. He is also a University of Maine Presidential Scholar and a Member of the National Honour Society. He is Vice-President of the Canadian Club at the University of Maine. He previously has worked as a Disc Jockey for radio stations WMEB 91.9FM, Orono, Maine, and CJMQ 88.9FM, Sherbrooke, Québec, and for University of Maine home athletic events. In addition, he has worked in the field of Sports Management for University of Maine sports marketing auxiliary services.

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## SUMMARY

The purpose of this project was to analyze crash characteristics involving medians on horizontal curve and tangent freeway segments, and establish relationships between crashes and geometric design characteristics. A secondary objective was to develop Accident Modification Factors (AMF) for medians (if time permitted).

In this project, the author analyzed left (inside) shoulder width and median width and their impact on the number and severity of cross-median collisions on curved and tangent freeway sections. In addition, the researchers collected data for horizontal curves and an adjacent tangent freeway sections, confirmed the TRM data with Google Earth, analyzed data using descriptive statistics, ANOVA and regression analysis by means of a negative binomial model (if time permitted).

This study is a part of a larger project associated with project TxDOT 0-4703 by TXDOT [Incorporating Safety into the Highway Design Process] lead by Dr. James Bonneson (TTI) and sponsored by the Texas Department of Transportation (TxDOT). Some of the findings of this report will complement the larger project, including a few of the recommendations and future areas of study.

Ultimately, not all of the objectives of this project were achieved due to the time constraints of the summer work session and errors inherent in the precision of crash location identification.

**TABLE OF CONTENTS**

## INTRODUCTION

Medians are part of all freeways, expressways and principle arterials separating two flows of opposing traffic. According to the American Association of State Highway and Transportation Officials (AASHTO) *Roadside Design Guide (1)***,** a median is the portion of the divided roadway, including inside shoulders, that separates the traveled way for through traffic in opposing directions of travel. Some freeways have medians with concrete positive barriers while others just have a grassy center in the middle. In addition to dividing traffic, a median also provides a recovery area for wayward vehicles, a stopping location for emergencies, glare reduction for oncoming headlights and space for future lane expansion.

Cross-median crashes are usually violent collisions between two vehicles traveling in opposite directions. These crashes often involve high traveling speeds. Furthermore, although cross-median crashes do not happen frequently, they are more likely to be scrutinized by the media since they often lead to serious injuries. For instance, a North Carolina study *(2)* found that 40 % of the injuries sustained in cross-median collisions resulted in incapacitating and fatal injuries. In addition, horizontal curves are associated with a disproportionate number of severe crashes *(3).* Furthermore, a Pennsylvania Study *(4)* found that nearly 15% of cross median collisions involve fatalities and 72% involve non-fatal injuries. There is a need for a comprehensive study on median width and safety to help prevent these types of collisions.

Agencies are seeking a better understanding of roadway or roadside features that affect safety. The objectives of this study were to analyze cross median crash characteristics for urban and rural, four or more lanes divided limited access highways and to determine the effect median type and width of horizontal curves have on crashes as compared to adjacent tangent sections. Data available for use in the evaluation included 169.889 centerline miles of highways. A secondary objective was to use negative binomial regression models to determine the effects of independent variables on crashes, if time permitted. Variables considered in developing the base models included lane width, outside shoulder width, insider shoulder width, median width (which excluded inside shoulder width), median type, segment length, and annual average daily traffic. Five years (1997-2001) of highway segment crashes were examined.

The product of this research could be useful in the course of developing the Highway Safety Manual (HSM). The HSM is envisioned to become a nationwide predictive tool available to evaluate the safety performance of streets and highways. Additional information is available on the HSM website (http://www.highwaysafetymanual.org/). The HSM is being developed under the direction of the Transportation Research Board Highway Safety Manual Task Force. The manual's goal is to provide the best available safety knowledge in a condensed and widely usable form for designers and practitioners *(5)*. With such a tool, agencies can identify potential areas of concern on streets and highways that can lead to safety performance improvement associated with those facilities. The first edition of the HSM is expected for public release in the summer of 2009.

## BACKGROUND

This section describes background information on the project with additional information about previous research involving median width and median barriers.

### Previous Research

For the past decades, limited research has been conducted on crashes occurring within medians of high-speed highways. Within the past few years, however, greater attention has been focused on median-related crashes and, in particular, cross-median crashes. The latter category of crashes tends to involve high speeds and results in multiple injuries and fatalities. The research into cross-median crashes typically provides advice on when to install a median barrier for a given AADT and median width. For example, a Texas study *(6)* developed improved guidelines for the use of median barriers on new and existing high-speed, multilane, divided highways. As part of their research, they reviewed existing guidelines for the installation need of median barriers. States developing policy on installing median barriers include North Carolina, California, Washington, Florida, and Pennsylvania.

Miaou, et al. as summarized by Fitzpatrick et al. *(7)* notes that median barriers could reduce cross-median crashes by keeping errant vehicles from reaching the other side of the traffic lanes. However, median barriers do not prevent crashes and may, in fact, increase the number of crashes. Barriers are also obstacles on the roadside and it is possible they will be struck because of their close proximity to the moving vehicles. Miaou et al. summarized the median-related crash rates from several studies as shown in Table 1 *(8)*. They also provided the distribution of severity of the crashes used in their analysis (see Table 2).

The Missouri DOT (MDOT) started installing cable barriers on their Interstate Highways in 1999 on small high-volume segments located in the metropolitan districts of Kansas City and St. Louis (i.e., Interstates 44, 70 and 435) *(9)*. Following the successful outcome these installations, MDOT decided that cable barriers would be installed on all Missouri Interstates with medians less than 60 feet wide due to their over-representation in cross-median crash numbers. A great reduction in cross-median fatalities was noticed as the number of miles with barrier increased. A graph of the decline of cross-median fatalities on I-70 as more miles of cable median were installed is shown in Figure 1.

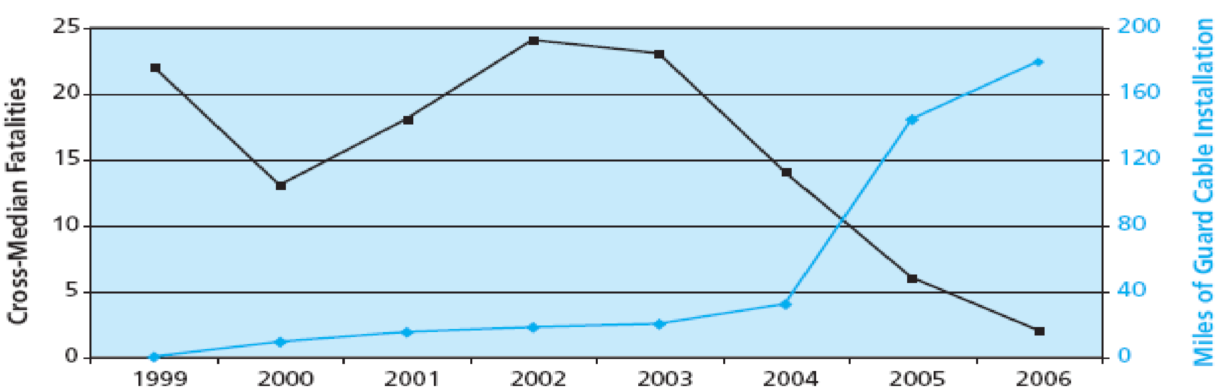



**Figure 1. Cross-Median Fatalities on I-70 in Missouri as Miles of Cable Barriers Were Installed *(9)***

Table 1. Median Related Crash Rates of Previous Studies as Summarized by Miaou et al. *(6) (8)*
Table 2. Number and Distribution of Crashes by Severity of Injury for 2006 Miaou et al. *(6) (8)*

**Table 1. Median-Related Crash Rates.**

| Study | Crash rates (crashes/MVM) | | | |
|---|---|---|---|---|
| | With Barrier | Without Barrier | Subsets of Without Barrier crashes | |
| | | | Cross Median | Other Median Related |
| **Previous Studies (as summarized by Miaou et al. 2006)** | | | | |
| Miaou, 1998-1999 data | 0.108 | 0.087 | 0.009 | 0.078 |
| PA, 1994-1998 data, Interstate | --- | --- | 0.004 | --- |
| PA, 1994-1998 data, Freeways | --- | --- | 0.007 | --- |
| CA, 1984-188 data, Freeways | --- | --- | 0.007 | --- |
| Washington, Sites where barriers were added due to crash history | --- | --- | 0.021 | --- |
| **Current Study (TX, 1997-2001 data)** | | | | |
| With barriers, all crashes<br>With barriers, KABC* crashes | 0.105<br>0.059 | --- | --- | --- |
| Without barrier, rural, all crashes<br>Without barrier, rural, KABC crashes | --- | 0.068<br>0.024 | --- | --- |
| Without barrier, urban, all crashes<br>Without barrier, urban, KABC crashes | --- | 0.065<br>0.036 | --- | --- |

--- = crash rate not identified in the study
* KABC crashes includes fatal (K), incapacitating injury (A), non incapacitating injury (B), and possible injury (C)

**Table 2. Number and Distribution of Crashes by Severity of Injury for 2006 Miaou Study.**

| Barrier and Crash Type | Total Number of Crashes | Severity Type | | | | |
|---|---|---|---|---|---|---|
| | | Fatal (K) | Incapacitating Injury (A) | Non Incapacitating Injury (B) | Possible Injury (C) | Property Damage Only (PDO) |
| **No barrier** | | | | | | |
| Cross-median crashes | 346<br>100% | 73<br>21.1% | 73<br>21.1% | 82<br>23.7% | 58<br>16.8% | 60<br>17.3% |
| Other median-related crashes | 3064<br>100% | 71<br>2.3% | 272<br>8.9% | 639<br>20.9% | 734<br>23.9% | 1348<br>44.0% |
| **With Longitudinal Barrier** | | | | | | |
| All median-related crashes (including hit-median-barrier crashes) | 3672<br>100% | 36<br>1.0% | 190<br>5.2% | 681<br>18.5% | 1098<br>29.9% | 1667<br>45.5% |
| Hit-median-barrier crashes | 2714<br>100% | 13<br>0.5% | 128<br>4.7% | 490<br>18.0% | 835<br>30.8% | 1248<br>46.0% |

### Median Width

Previous research on this topic has produced many conflicting results on the impact of median width and safety along with the uncertainty about the role of the median barrier. Although the standards state the median should “be as wide as possible,” economic conditions dictate otherwise. It is unknown what the optimal width should be for the median. Hauer *(10)* summarized previous studies in his report on median width and safety**.** He concluded that previous studies showed that total accident rates by median width are not associated with each other. However, he notes that the results of these studies are questionable because of the omission of the influence of some important variables (rural vs. urban, speed limit, highway type, right shoulder width, etc.). He also mentions that the previous research has visibly shown that medians wider than 50 feet show a clear reduction in cross-median collisions than with medians less than 50 feet wide. Finally, he remarks that there is a probability the accident rates of median-related crashes for medians without-barriers increase with median width up to 30 feet then decline as the median gets wider *(11)*.

### Median Barriers

A study conducted by the Texas Transportation Institute on median barriers reported that the presence of a median barrier “does not eliminate crashes occurring in medians but alters the character of those crashes” *(12)***.** In other words, the overall amount of median-related crashes would probably increase but the overall severity of cross-median collisions would be reduced. As the report notes however, the median width is already established or constrained by right-of-way restrictions.

## DATA COLLECTION

This section describes the data collection processes to obtain the appropriate sample size for developing the statistics in this paper.

### Data Collection Process

Many variables were considered as input data. The researchers’ (the ones associated with TxDOT Project 0-4703) approach was to determine if a difference in roadway elements influence the number and severity of median-related and cross-median crashes. To do this, they collected sections of roadways in pairs. The sections were a horizontal curved segment with an adjacent tangent segment separated by a tenth of a mile buffer. The attributes within each pair needed to be identical except for the difference in the attribute(s) of interest. By selecting pairs of matched sections, the effect of the selected attribute(s) on safety is isolated and other factors are better controlled.

### Selection Procedure

For this study, controlled access divided highways were selected to be adjacent to each other on the same roadway to ensure that the pairs are as nearly matched as possible. Sites were eliminated if the horizontal curve was longer than 1.5 miles or less than one-tenth of a mile or degree of curvature information was not available for the curve. In addition, the curves were eliminated if the aerial photos showed the road under construction or were not clear enough. The tangent prior to or following the horizontal curve was required to be equal to the curve length plus 0.1 of a mile. The 0.1 mile represents the "buffer zone" that was eliminated from the evaluation to ensure that curve-related crashes are not inadvertently placed on the tangent segment and vice versa. The length of the buffer reflects recognition of the precision of crash location in the Texas Department of Public Safety (DPS) crash database. The database locates crashes to the nearest 0.1 mi.

Because data for only a sample of the curves could be collected, the researchers selected districts in different regions of Texas. Geometric and crash data were collected on the curves within ten districts that match the project criteria. Freeways and divided highways located in the following Texas Department of Transportation (TxDOT) districts were considered for inclusion for the sample size (number of curves from each district in parenthesis):

- Amarillo (35)
- Austin (50)
- Beaumont (26)
- Bryan (34)
- El Paso (42)
- Ft. Worth (71)
- Houston (84)
- Laredo (10)
- Odessa (87)
- San Antonio (151)

The dataset for the study included 590 curves in total. Table 3 shows the location and number of curves collected for this study.

*Types of Roadway Used*

The TxDOT Reference Marker Database (TRM) was used to identify potential highway segments. The roadway geometric characteristics for segments were used when the following conditions were met:

- Main-lanes
- Highway design type = freeway or expressway with no high-occupancy vehicle (HOV) lanes, no railroad crossings, no at grade intersections and no tolls
- Median Type = no median, grass, or flush
- Barrier Type = none, concrete, or W-beam
- Total number of lanes is four or greater

Researchers then located each horizontal curve segment within an aerial photograph using previously found GIS coordinates. See Figure 2 for an example of an aerial photograph of a horizontal curve. Preference was to use Google's Google Earth® program for the aerial photographs of the roadways. The degree of curvature geometric information was obtained from the TxDOT TRM database. If a curve could not be found or the photo was unreliable (i.e., showing the road under construction or the resolution too small) the data entry was deleted. If the quality of the view available on the photograph was sufficient for data collection, the following segment characteristics were identified for the horizontal curve and for the associated tangent section:

- Lane width (ft) [for increasing and decreasing milepoints],
- Outside {Right} shoulder width (ft) [for increasing and decreasing milepoints],
- Inside {Left} shoulder width (ft) [for increasing and decreasing milepoints],
- Median type (e.g., none, grass, flush),
- Barrier type (rigid [includes both concrete barrier or W-beam] or no barrier),
- Median width (ft) (without inside shoulders),
- Distance to Barrier (ft) {if applicable}[for increasing and decreasing milepoints],
- Number of Lanes (both directions),

In addition, the following values were collected from the TRM database:

- Speed Limit (Miles per Hour)
- AADT
- Curve Length
- Right of Way (ROW) Width (ft)

**Table 3. Location and Number of Curves Collected for This Study**

| District Number | District Name | All Curves | Collected |
|---|---|---|---|
| 2 | Ft. Worth | 192 | 71 |
| 4 | Amarillo | 79 | 35 |
| 20 | Beaumont | 55 | 26 |
| 17 | Bryan | 80 | 34 |
| 22 | Laredo | 41 | 10 |
| 15 | San Antonio | 254 | 151 |
| 12 | Houston | 281 | 84 |
| 24 | El Paso | 76 | 42 |
| 14 | Austin | 135 | 50 |
| 6 | Odessa | 119 | 87 |
| Total | | | 590 |

Tables and Figures in the Appendix show the distribution of the section attributes that were the same for both the tangent and horizontal curve sections.


**Figure 2. Sample Aerial Photo/Google Maps® Image**
The horizontal curve segment of the highway is outlined in this sample image.

## Crash Data

Crash data for each section were extracted from the DPS electronic database. A total of five years of crash data (1997 to 2001) was used. Crashes for all severity levels were extracted. Analyses were performed using only fatal (K), incapacitating-injury (A), non-incapacitating injury (B), and minor injury (C) [KABC Crashes]. Due to their unreliability (i.e., under-reporting), property damage only (PDO) crashes were not used in the analysis.

The values listed in the tables in the Appendix are based on crashes that occurred during the five-year period of 1997 to 2001 for the 590 segments.
Crashes were grouped into three categories: Median-Related Crashes (MRC), Median Crossover Crashes Type 1 (MCC1) and Median Crossover Crashes Type 2 (MCC2). MRC are described as when a vehicle is traveling in the main-lanes, crashes and ends up in the median area (excluding shoulders). See Figure 3 for more details by lane number. MRC can be single or multi-vehicle

accidents. MCC1 are depicted as when a vehicle is traveling in the main-lanes and crosses over the median and collides with another vehicle traveling in the opposite flow of traffic thus ending up on the opposite side on the median but still on the main-lanes of the freeway. MCC1 are multi-vehicle collisions only. See Figure 3 for more details by lane number. MCC2 are described as when a vehicle is traveling in the main-lanes, crosses the median and crashes as a single vehicle accident in the opposing main-lanes of travel or continues over all the way to the opposing frontage road and beyond. This type of collision could involve a single vehicle or multiple vehicles (i.e., on the frontage opposite frontage road). Consequently, MCC2 can be single or multi-vehicle crashes. See Figure 3 for more details by lane number.

Due to data inconsistencies, the researchers limited the data for with-barrier MCC1 and with-barrier MCC2 to two (2) or less crashes per section for each the horizontal curve segment and tangent segment. The breakdown of curves for Crash Data analysis is presented in Table 4.

*Roadway Statistics*

The researchers computed various figures from the roadway dataset. The charts of the roadway statistics are displayed in Appendix A. Additionally, graphical summaries of the distribution of variables per number of miles for with and without barrier segments in the freeway dataset are displayed in Appendix D and Appendix E. Table A-1 shows the summary of statistics of the roadway characteristics for all 590 segments. The researchers divided the 590 segments into the 225 with-barrier and the 365 without barrier segments. For each of the roadway characteristics listed above, the researchers recorded the average (arithmetic mean), minimum, maximum and standard deviation for the with-barrier segments, without-barrier segments and the whole dataset.

To compute the standard deviations of the data, the following equation was used:

$$\sigma = \frac{\sqrt{\sum (x-\bar{x})^2}}{(n-1)}$$

Where,

$x$ = Individual Value
$\bar{x}$ = Sample Mean
$n$ = Sample Size

*Accident Statistics*

The author plotted the relative frequency of the data compared to crash rate and crashes per mile for the six sets of data. As shown in Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, and Figure 9 only the data for Median Related Crashes with-barrier follows a normal pattern. As these figures illustrate, nearly all of the crash rates are below 0.02 Crashes/mvm and the majority of the segments are under one crash per mile. This is because for about 80% of the Median Crossover Crash segments, Types 1 and 2, and Median-Related Crashes without-barrier there were no crashes at all thus their values are zero. For Median Related Crashes with-barrier the data are more spread out among the variables, and only about 30-35% of the segments have no crashes on them.

**Table 4. Breakdown of Segments for Crash Statistics**

| **Breakdown of Segments for Crash Statistics** | |
|---|---|
| **Total Curves** | **590** |
| With Barrier | 225 |
| Without Barrier | 365 |
| | |
| **Median Related Crashes** | |
| **With Barrier** | |
| Horizontal Curve | 225 |
| Tangent | 225 |
| **Total** | **450** |
| **Without Barrier** | |
| Horizontal Curve | 365 |
| Tangent | 365 |
| **Total** | **730** |
| **Median Crossover Crashes 1** | |
| **With Barrier** | |
| Horizontal Curve [2 or Less Crashes] | 223 |
| Tangent [2 or Less Crashes] | 222 |
| **Total** | **445** |
| **Without Barrier** | |
| Horizontal Curve [All] | 365 |
| Tangent [All] | 365 |
| **Total** | **730** |
| **Median Crossover Crashes 2** | |
| **With Barrier** | |
| Horizontal Curve [2 or Less Crashes] | 210 |
| Tangent [2 or Less Crashes] | 210 |
| **Total** | **420** |
| **Without Barrier** | |
| Horizontal Curve [All] | 365 |
| Tangent [All] | 365 |
| **Total** | **730** |

In Appendix A, the tables summarizing the crash characteristics for horizontal curve and tangent segments are shown in Table A-2 and Table A-3, respectively. Again, the segments were divided into with-barrier and without-barrier sections. The data were separated into horizontal curve sections and tangential sections for crash comparisons. After each crash was separated into HC and TAN segments, they were further divided into the three types of crashes, as described above: Median Related Crashes (MRC), Median Crossover Crashes Type 1 (MCC1) and Median Crossover Crashes Type 2 (MCC2). Once more, for Median Crossover Crashes types 1 and 2 with-barrier, the data were limited to two crashes per segment for each of the horizontal curve and tangent segments. For each subset, average crashes per segment, maximum number crashes on an individual segment, minimum number of crashes on an individual segment, the total number of crashes, the standard deviation, the crash count and the crash rate were calculated.

To compute the crash rate, the following equation was used *(13)*:

Crash Rate/MEV = $\frac{N}{DEV} \times \frac{1{,}000{,}000}{5yr \times 365 days / year}$

Where,

MEV = Million Vehicle Miles
DEV= Length of Segment*AADT
AADT = Annual Average Traffic per Day in vehicle per day

To compute the crash count per mile, the following equation was used:

Crash Count 5-yr= $\frac{N}{L \times 5yr}$

Where,

*N* = Total Number of Crashes for five year period
*L* = Length of Segment
*5yr* = Five year period of crash data

## DATA ANALYSIS

This section of the paper describes the data analysis and the various techniques the author used to evaluate the data.

### Analysis of Variance

The author calculated the Analysis of Variance (ANOVA) for Median-Related Crashes with and without-barrier, Median Crossover Crashes Type 1 without-barrier and Median Crossover Crashes Type 2 without-barrier comparing the crash rate and crashes per mile of the tangent and horizontal curve segments. A summary of the results is shown in Table 5, and the full calculations are shown in Tables B-1 – B-4 in Appendix B. First, the Fisher F-Test was calculated on an Excel spreadsheet, and then the p-value was calculated using an internet math program *(14)*. The F-test is a statistical test in which the test statistic has an F-distribution if the null hypothesis is true. The hypothesis shows that the averages of multiple normally distributed populations with the same standard deviation are equal and thus that they are of comparable origin. The p-value is the probability of obtaining a value of the test statistic at least as extreme as the one that was actually observed, given that the null hypothesis is true. The null hypothesis can be rejected if the p-value is smaller than or equal to the significance level, (in this case $\alpha$= 0.05) [i.e., degree of confidence equals 95%] *(15)*. A null hypothesis is a scenario set up to be nullified or disproved statistically in order to support an alternative hypothesis. The null hypothesis is assumed true until statistically proved otherwise.

As shown, the F-value varies significantly from the critical value of 3.84. Additionally, the p-values are smaller than α when the F-test is less than the critical value, thus those values the null hypothesis is true. For median related crashes and cross median crashes type 1, there is a statistical difference between tangent and horizontal curves, but not for cross median crashes type 2.

**Table 5. Analysis of Variance Calculations Summary for Comparison Tangents – Horizontal Curves**

| **ANOVA Results for Comparison Tangents – Horizontal Curves** | | |
|---|---|---|
| **Crash Rate** | | |
| Variables | Barrier | No Barrier |
| Median-Related | F=0.12 (p<0.73) | F=6.43 (p<0.01) |
| Cross-Median Type 1 | --- | F=3.74 (p<0.05) |
| Cross-Median Type 2 | ---- | F=1.92 (p<0.17) |
| | c.v. = 3.84 | α = .05 |
| **Crashes per Mile** | | |
| Variables | Barrier | No Barrier |
| Median-Related | F=0.39 (p<0.53) | F=5.22 (p<0.02) |
| Cross-Median Type 1 | --- | F=8.19 (p<0.004) |
| Cross-Median Type 2 | ---- | F=0.45 (p<0.50) |
| | c.v. = 3.84 | α = .05 |

To compute variance, the following equation was used:

$$s^2 = \frac{\sum (x - \bar{x})^2}{(n-1)}$$

Where,

$x =$ Individual Value
$\bar{x} =$ Sample Mean
$n =$ Sample Size

Unfortunately, the data were not without errors. Due to time restraints, the data could only be rechecked and verified a limited number of times before the dataset was finalized for analysis. During the analysis of the data, inconsistencies were found. There were a large number of cross-median collisions on roadways with positive barriers, which is counterintuitive. The roadway segments with barriers that have experienced an unusually large number of crashes will have to be checked individually to verify the validity of the statistics and to confirm whether a barrier was installed since the period of the crash data [1997-2001]. Measures will be taken to correct the data for the larger TxDOT study [Incorporating Safety into the Highway Design Process 0-4703]. However, due to time constraints the author for this summer project did not have the time or resources to complete that task. Consequently, for each of the two types of roadway with barrier [Horizontal Curve and Tangential] and for each Median Crossover division [Median Crossover Type 1 and Median Crossover Type 2] the data were limited to a maximum of two crashes per segment. This split the data into four sets as shown in Table 4.

**Statistical Modeling**

The author planned to use the Statistical Analysis Software (SAS) program to model the data. Subsequently, the author intended to derive AMFs from the developed models. However, due to time limitations and data error, neither goal was accomplished.

## RESULTS

This section of the paper displays the results of the research compiled by the author.

**Figures**

The following are the Figures referenced earlier in the text.

Refer to Figure 1 for the following explanations of crash categories:

*Median Related Crashes (MRC)***:** the vehicle is traveling in lanes 10, 11, 12, 80 or 81 for decreasing Milepoint or 16, 17, 18, 82 or 83 for increasing Milepoint and ends up in 63 [the median].

*Median Crossover Crashes (MCC1***):** the first vehicle is traveling in lanes 10, 11, 12, 80 or 81, crosses the median and collides with a vehicle traveling in lanes 16, 17, 18, 82, or 83 [for decreasing Milepoint], or the first vehicle is traveling in lanes 16, 17, 18, 82 or 83 crosses the median and collides with a vehicle traveling in lanes 10, 11, 12, 80 or 81.

*Median Crossover Crashes Type 2 (MCC2):*
**Case 1** [Single Vehicle Accident Scenario]: The vehicle originates in lanes 10, 11, 12, 80 or 81 crosses the median and comes to stop in lanes 6, 7, 8, 16, 17, 18, 26, 27, 28, 29, 58, 64, 82 or 83, [for decreasing Milepoint] or the vehicle originated in lanes 16, 17, 18, 82, 83 crosses the median and comes to stop in lanes 1, 2, 3, 10, 11, 12, 20, 21, 22, 23 52, 62, 80 or 81 [for increasing Milepoint] without striking another vehicle.

**Case 2** [Multi-Vehicle Accident Scenario]: The first vehicle originates in lanes 10, 11, 12, 80 or 81 crosses the median and collides with a vehicle in lanes 26, 27, 28 or 29 [for decreasing Milepoint] or the first vehicle originates in lanes 16, 17, 18, 82, 83 crosses the median and collides with a vehicle in lanes 20, 21, 22, 23 [for Increasing Milepoint].

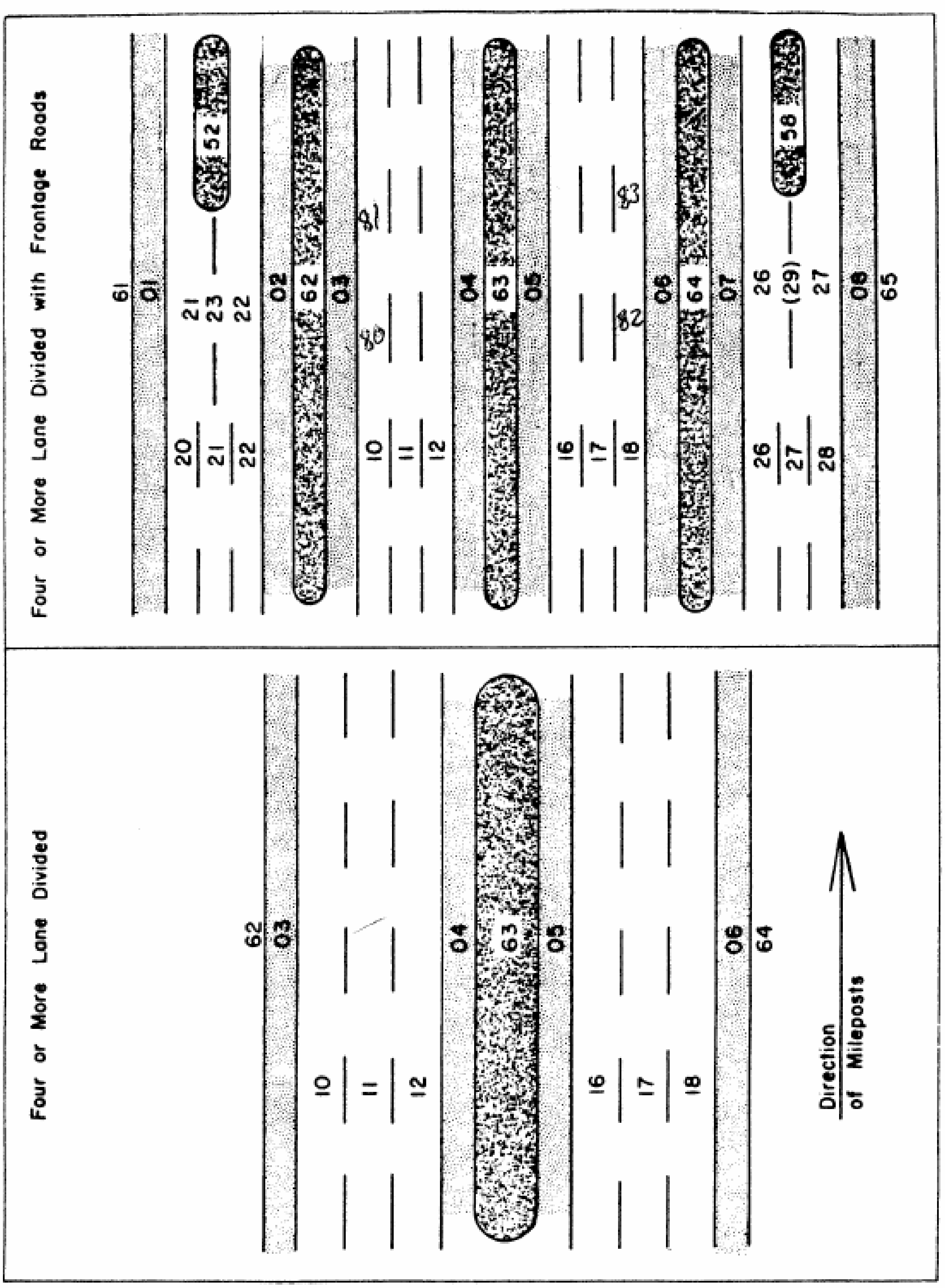
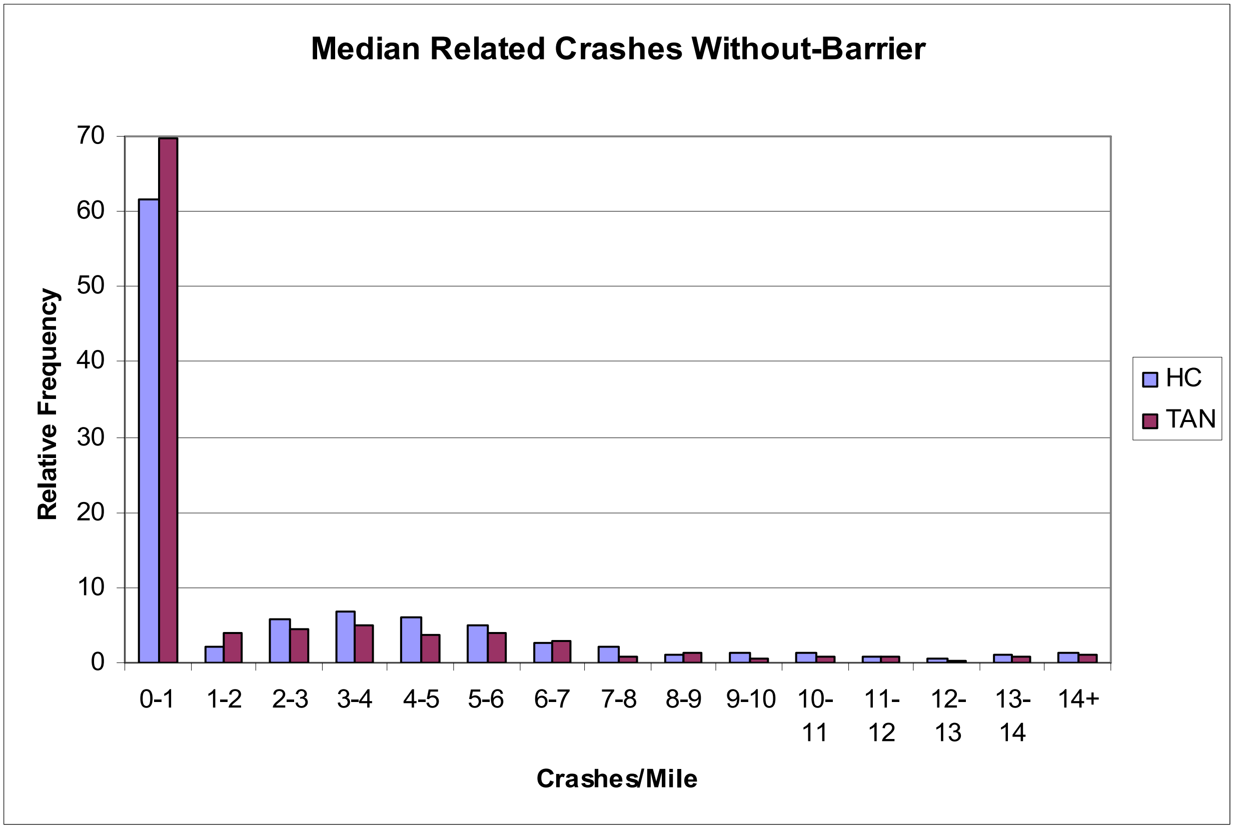



**Figure 3. Lane Descriptions [Lanes 80, 81 or 82, 83 are the Fourth and Fifth Main-Lanes in Each Direction if Applicable]** *Adapted from Accident and Roadway Inventors (16)*



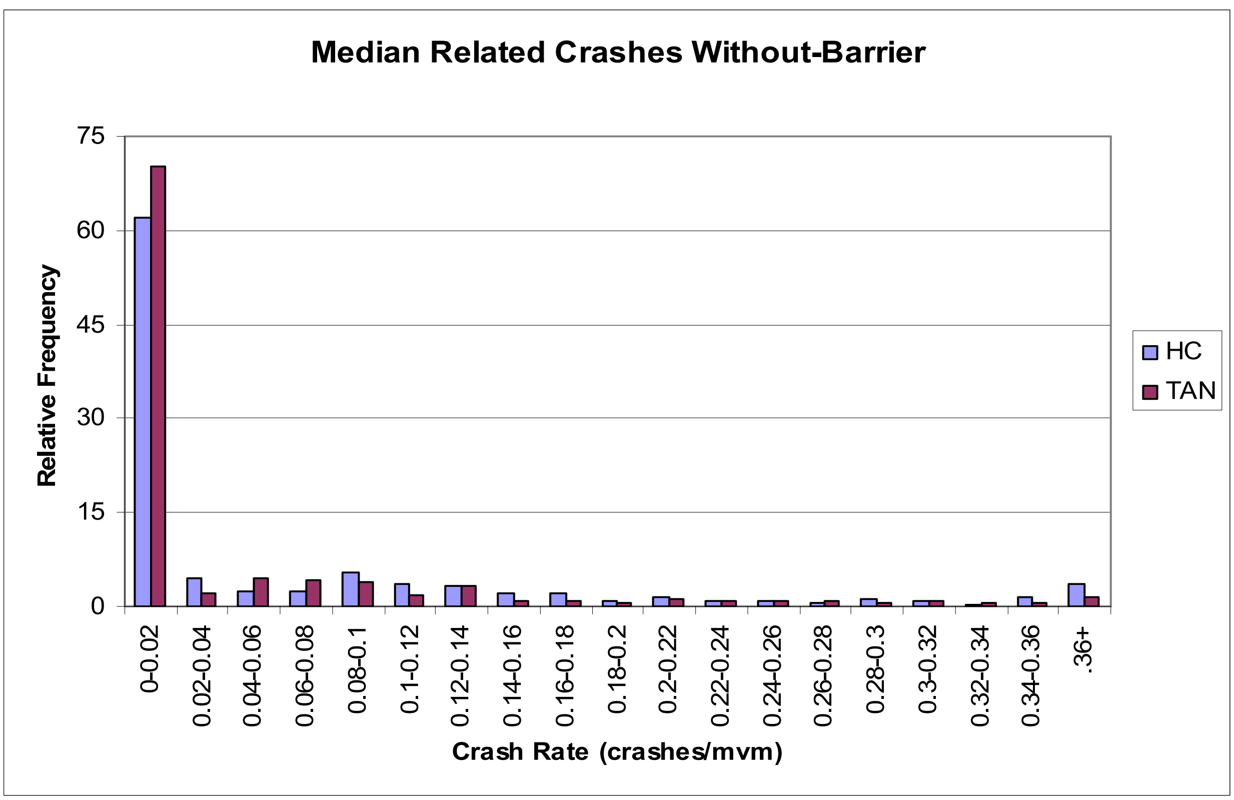
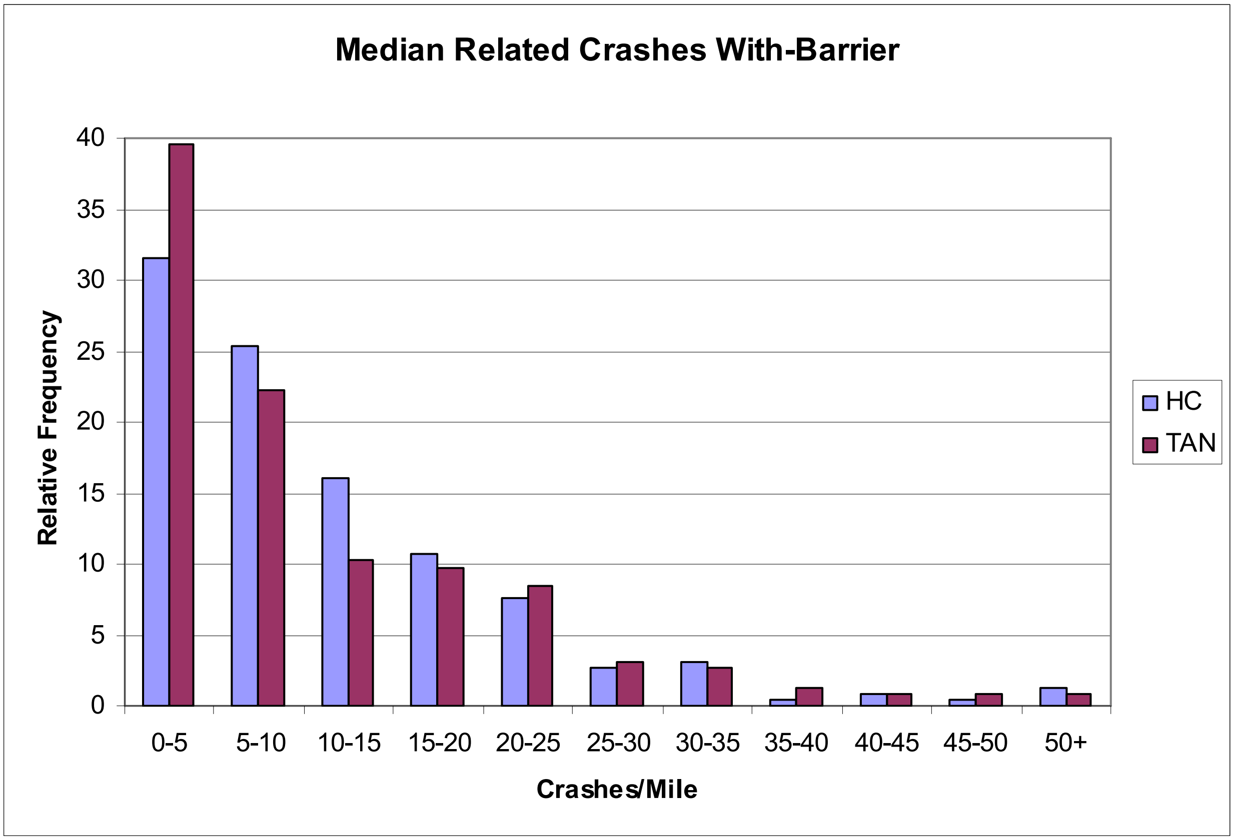




**Figure 4. MRC Without-Barrier Crash Statistics**



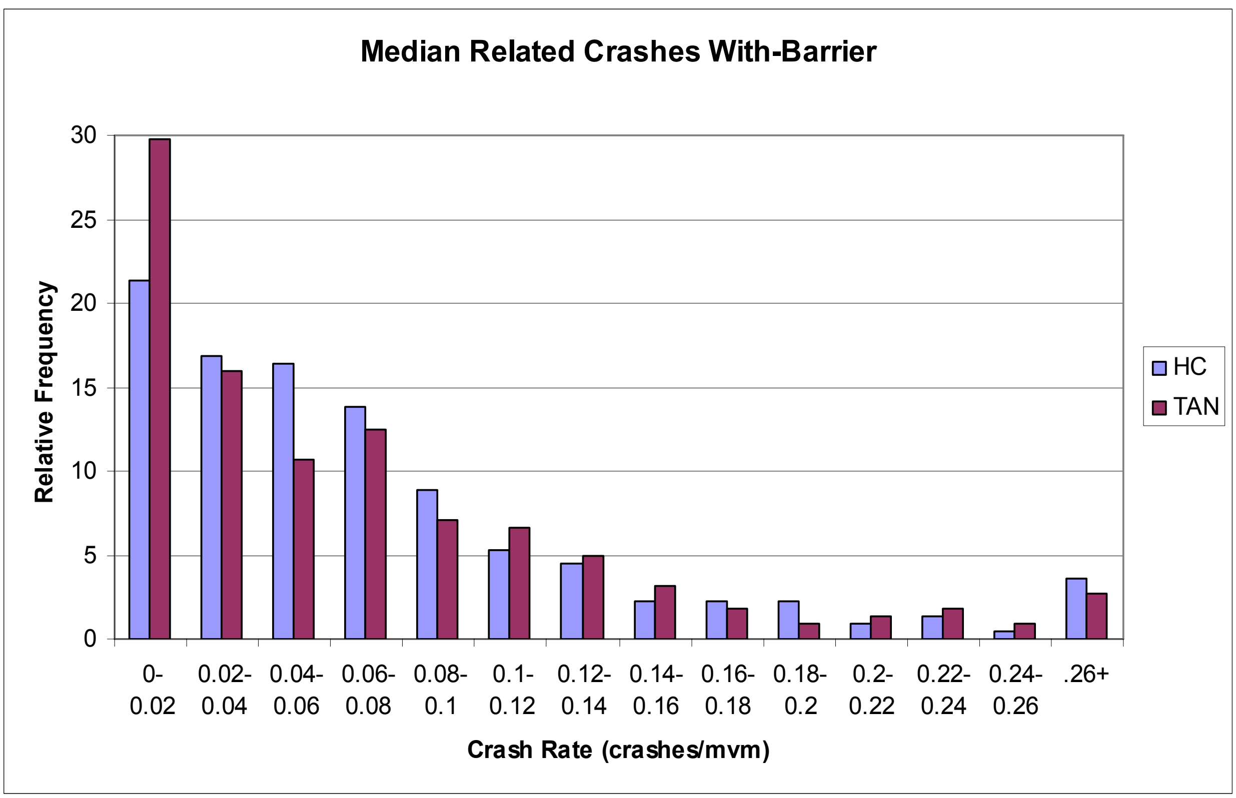
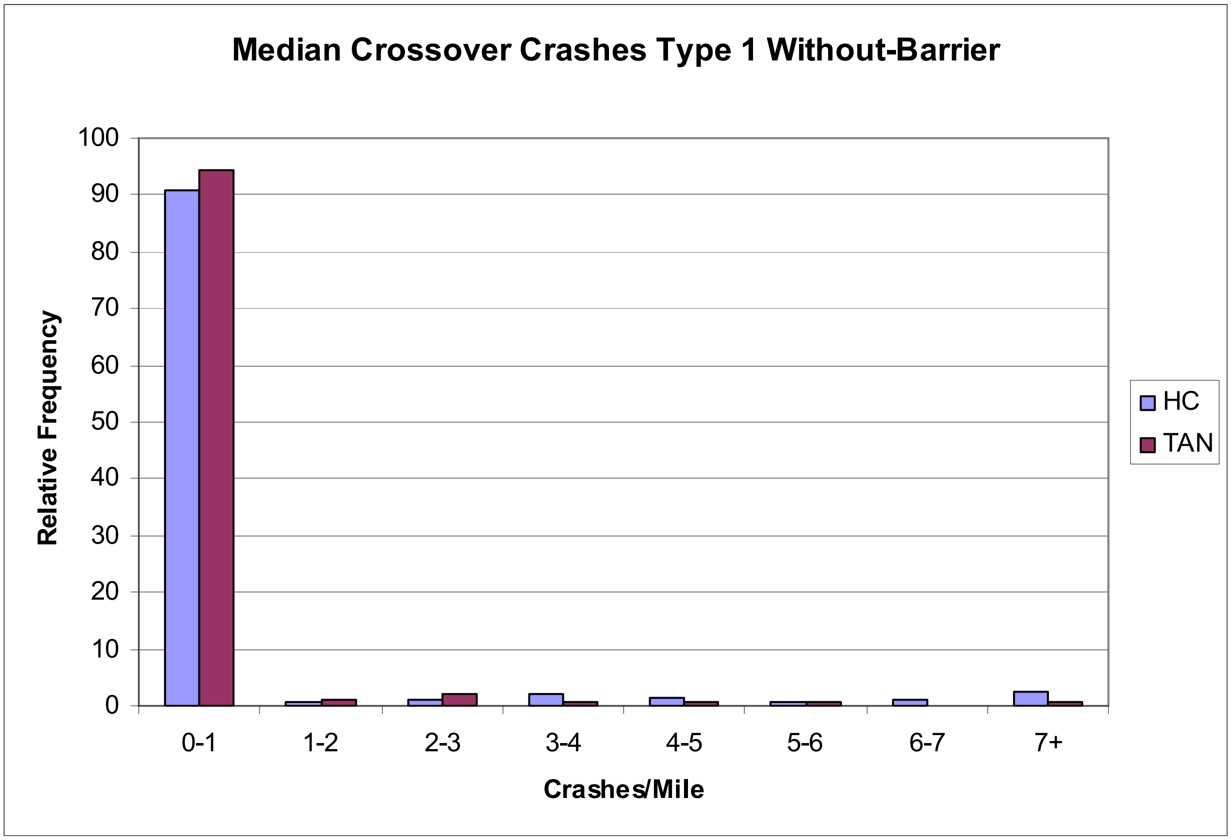




**Figure 5. MRC With-Barrier Crash Statistics**



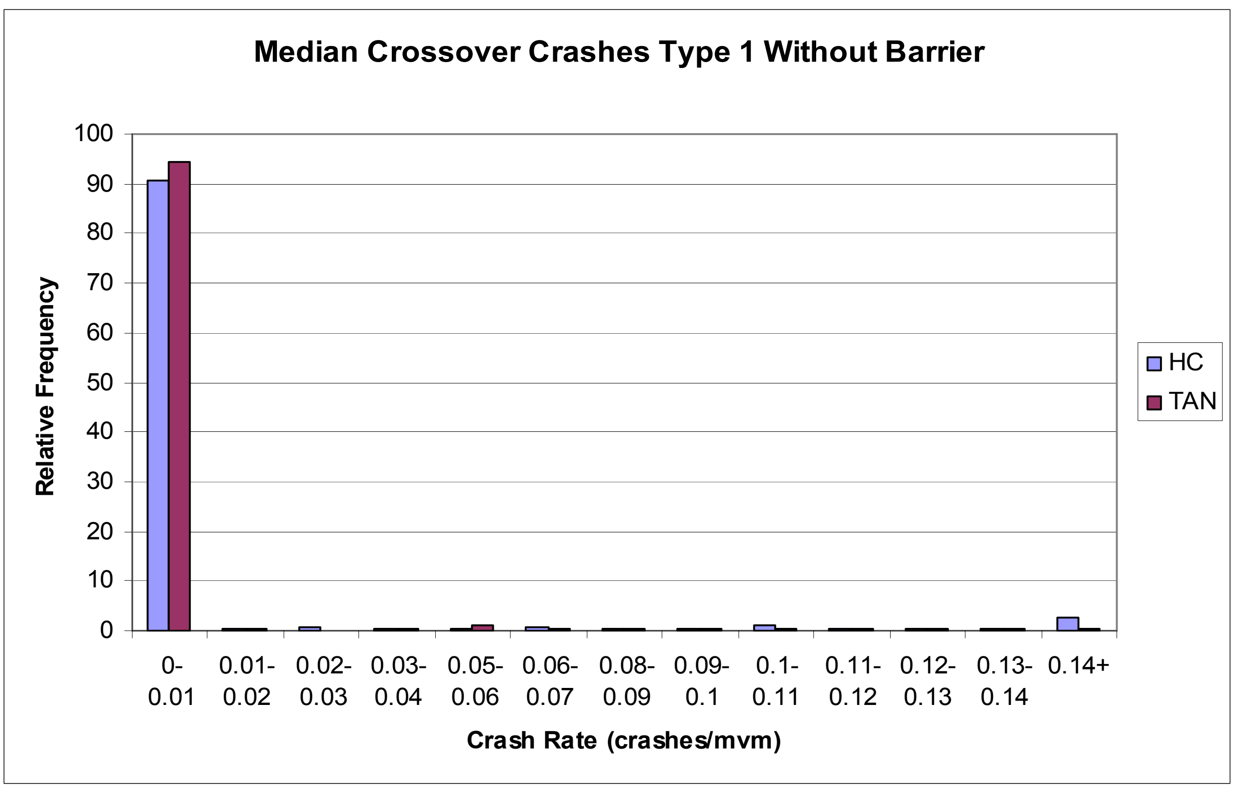
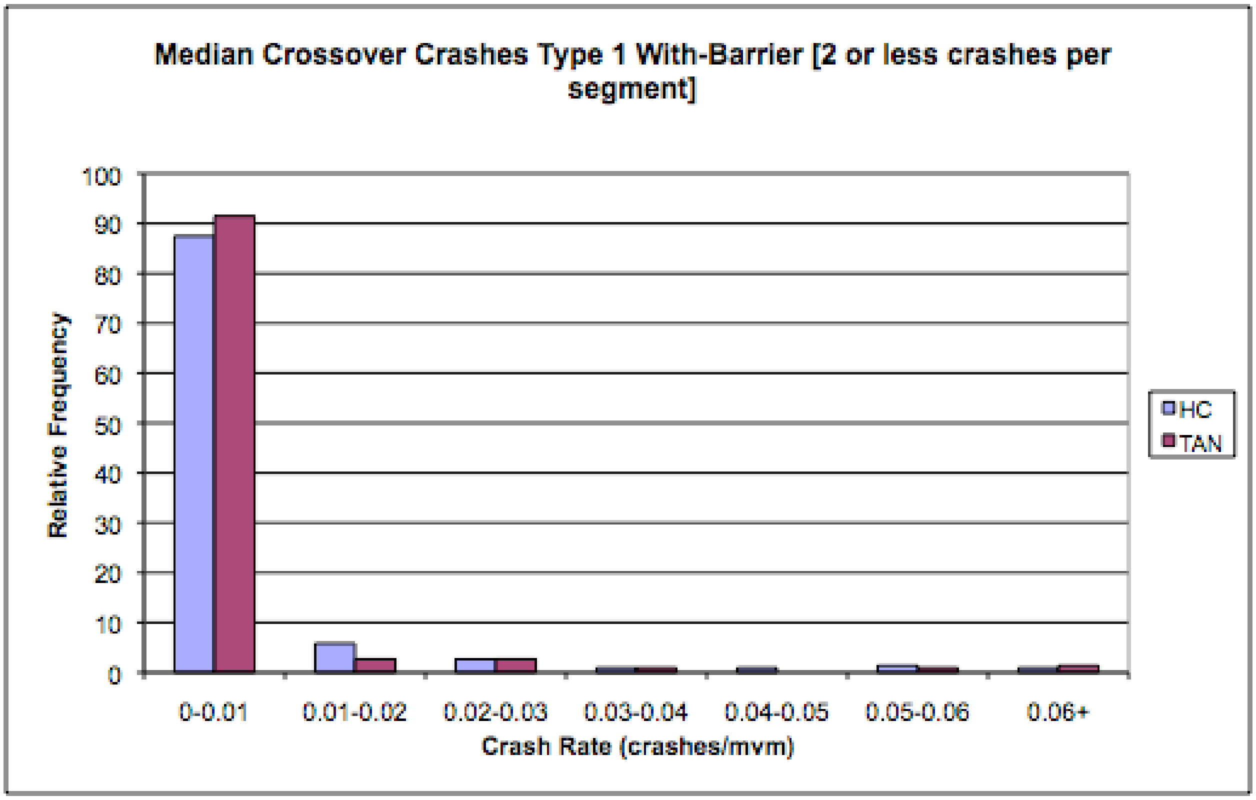




**Figure 6. MCC Type 1 Without-Barrier Crash Statistics**



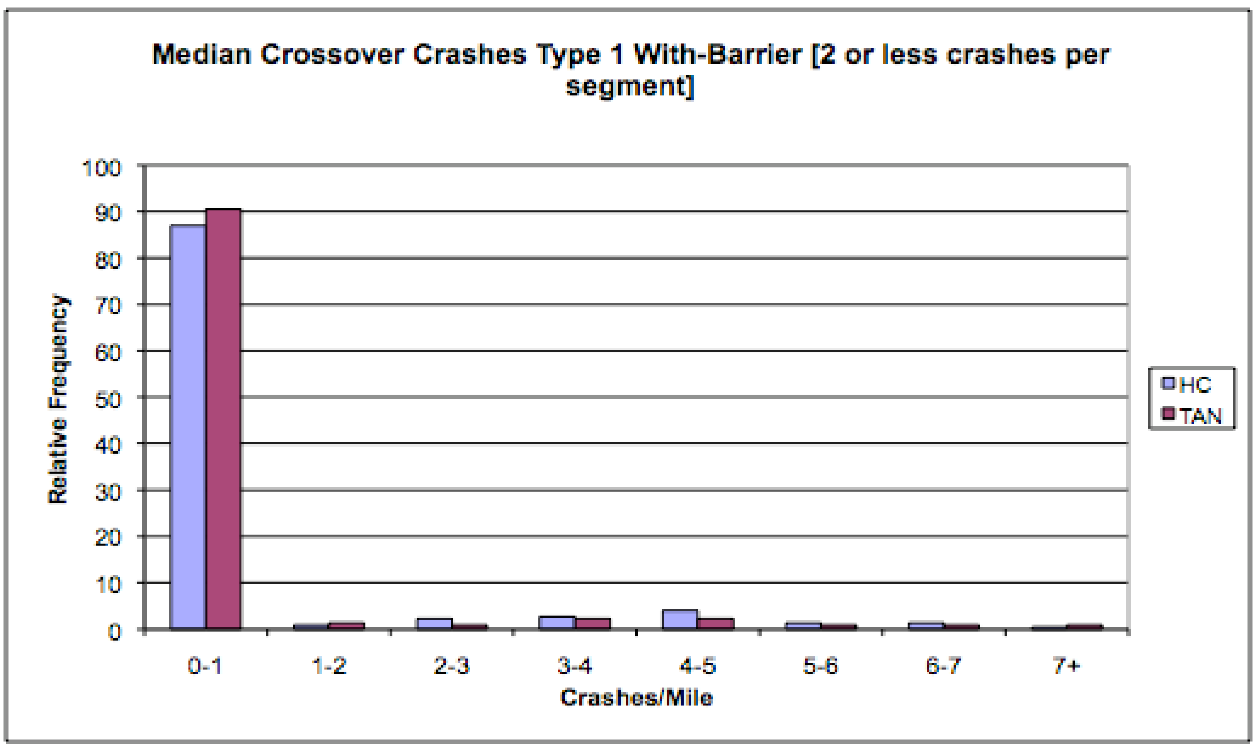
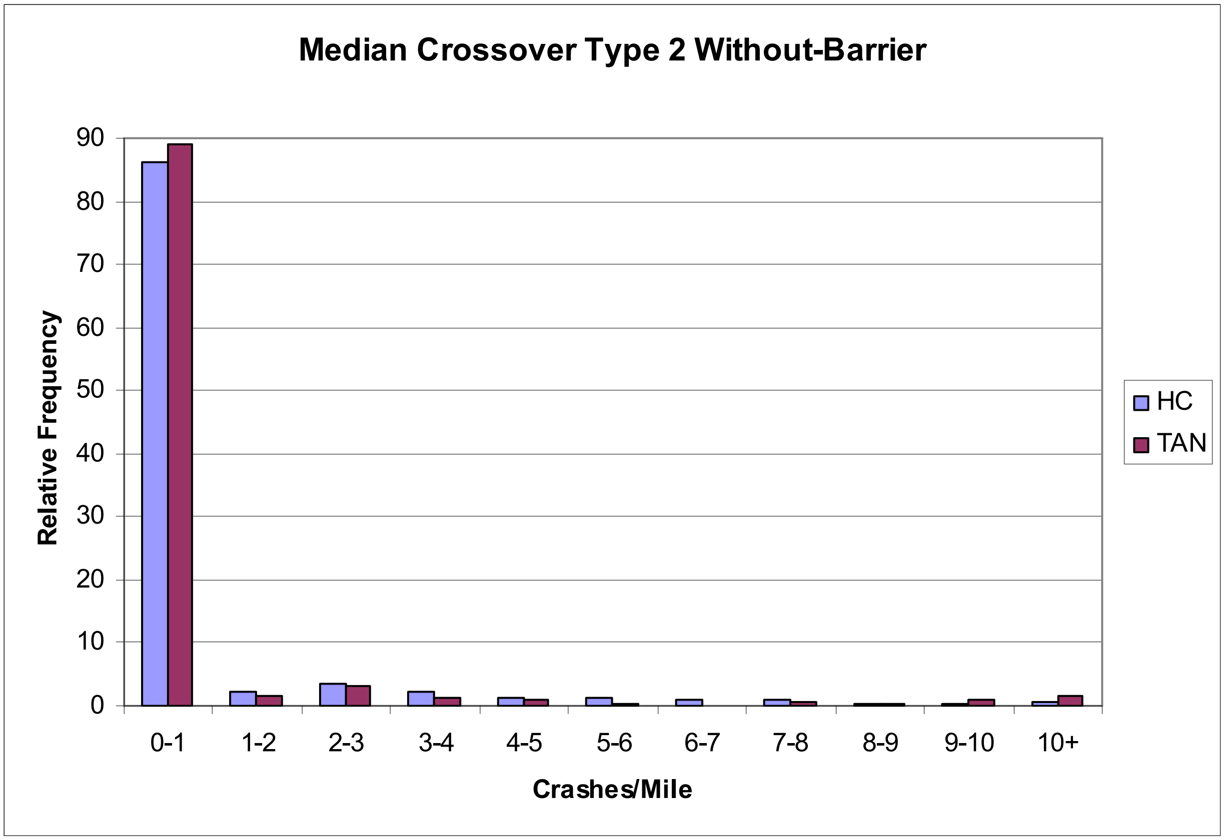




**Figure 7. MCC Type 1 With-Barrier Crash Statistics**



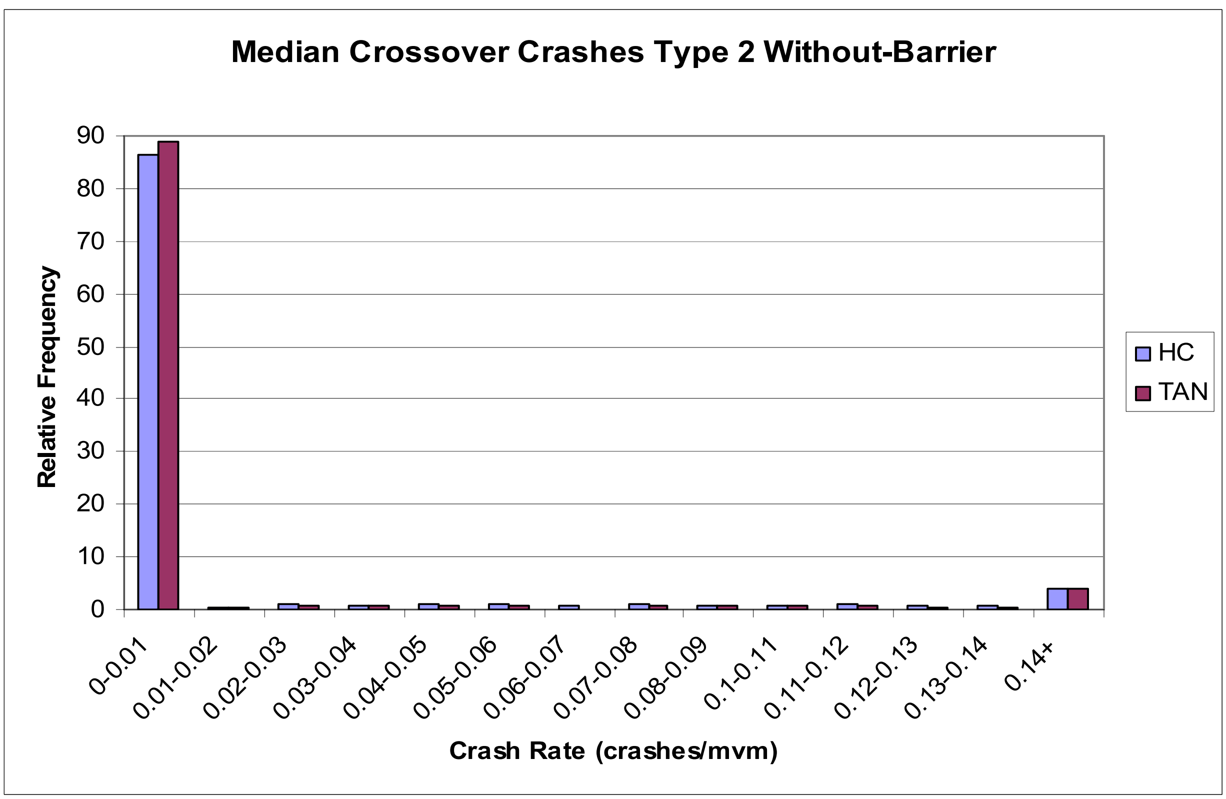
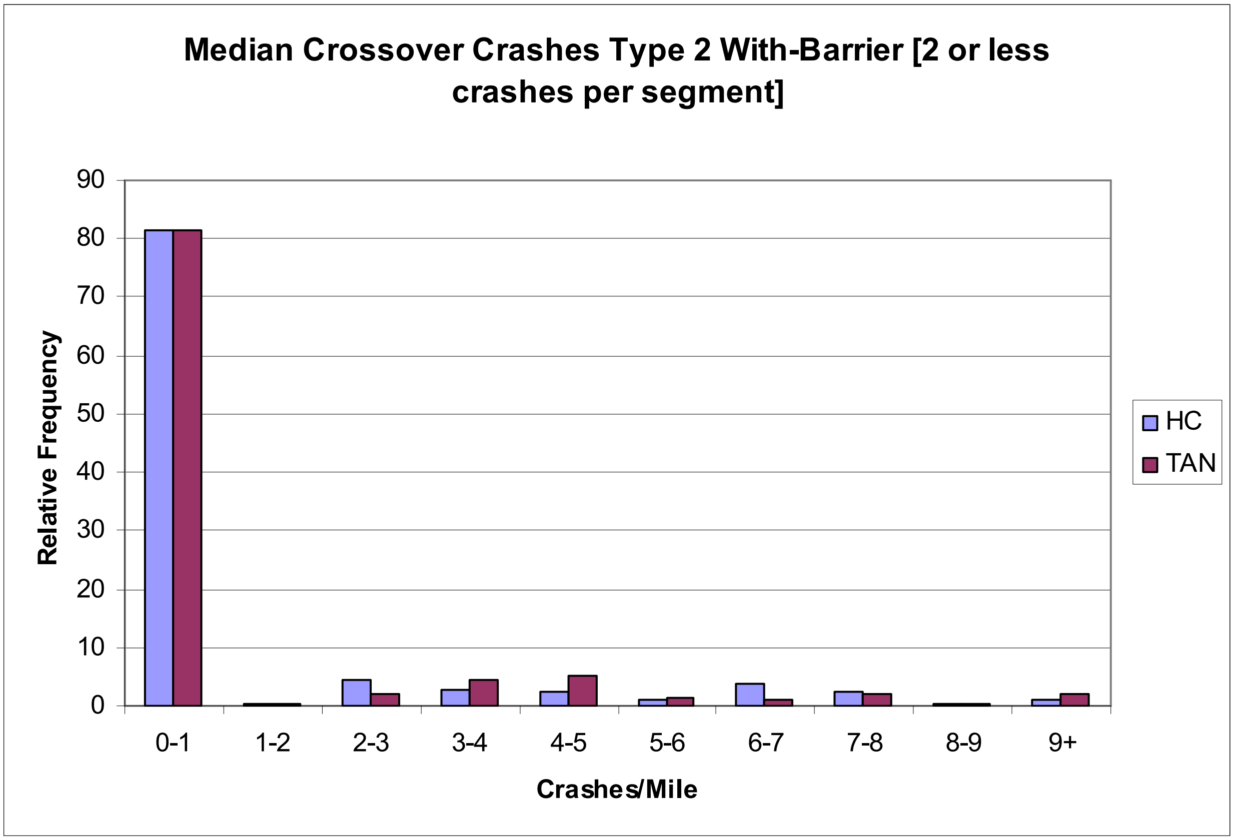




**Figure 8. MCC Type 2 Without-Barrier Crash Statistics**



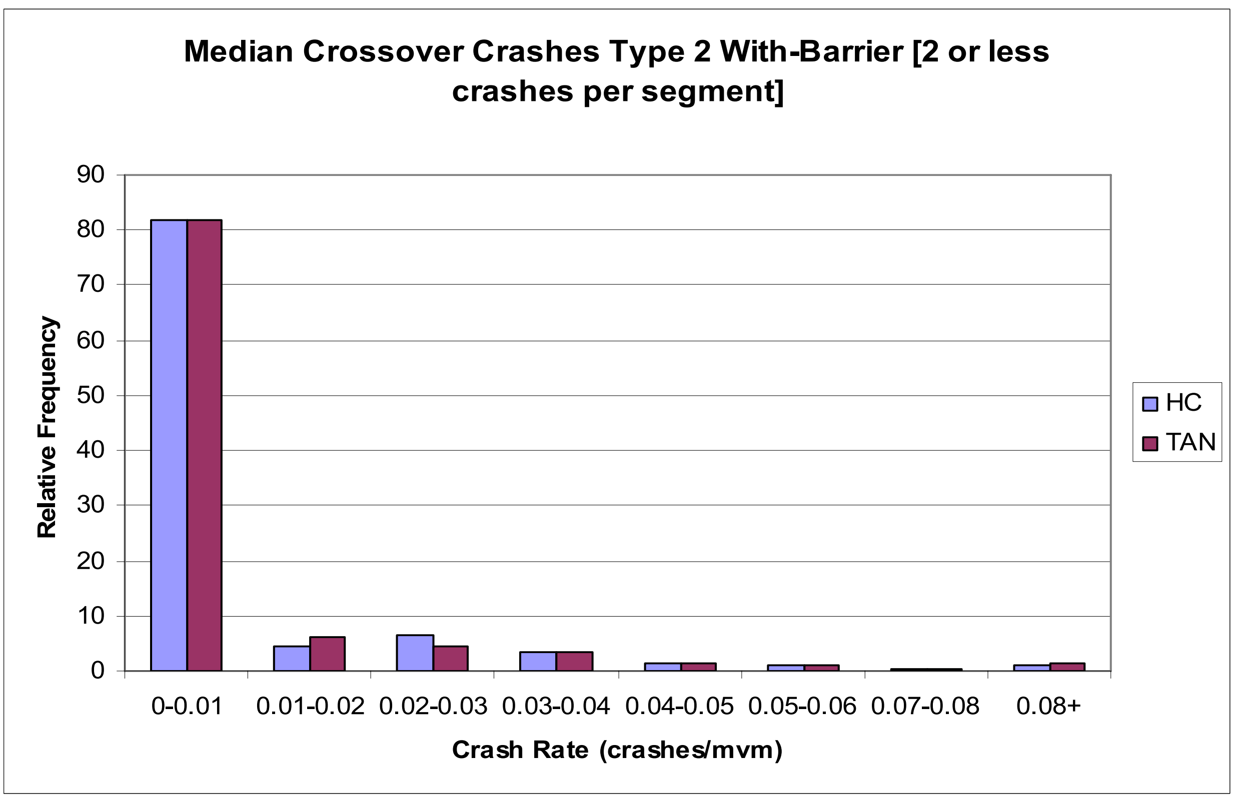




**Figure 9. MCC Type 2 With-Barrier Crash Statistics**

## RECOMMENDATIONS

Due to time constraints, the author was not able to finish the requirements by the paper deadline. However, the next step would involve the estimation of predictive models using statistical software programs, such as SAS or Gentstat to predict and derive Accident Modification Factors. Additionally, information is needed for the development of predictive models using Negative Binomial regression models. This would necessitate a better estimate about the actual influence of median width on cross-median collisions. These tasks are scheduled to be completed later. The author was unable to include these analyses in this work. The final goal will be to incorporate the results into the larger TxDOT Project [0-4703] and the Highway Safety Manual.

## CONCLUSIONS

This report examined the relationships and results of cross-median crashes on horizontal curves. The researchers found that segments with barriers have higher crash rates than segments without barriers. Furthermore, it was discovered that larger median widths have fewer cross-median collision crashes although their rate of reduction is not very sizeable in comparison to median width. Finally, it was learned that horizontal curve segments experience more median-related and cross-median type 1 crashes per mile than tangential segments for the same exposure (length and traffic flow).

## REFERENCES

1. Roadside Design Guide. American Association of State Highway and Transportation Officials, Washington, D.C., 1996.
2. Lynch, J.M., N.C. Crowe, and J.F. Rosendahl. *Across Media Accident Study: A Comprehensive Study of Traffic Accidents Involving Errant Vehicles which Cross the median Divider Strips on North Carolina Highways*, North Carolina Department of Transportation, July 1993
3. Bonneson, J., M. Pratt, J. Miles, and P. Carlson. Horizontal Curve Signing Handbook. Texas Transportation Institute. Texas A&M University System, College Station, Texas: Texas Department of Transportation, October 2007
4. Donnell, E., D. Harwood, K. Bauer, J. Mason, Jr., and M. Pietrucha (2003) Cross-Median Collisions on Pennsylvania Interstates and Expressways. *Transportation Research Record* 1784, pp. 91-99.
5. Fitzpatrick, K., D. Lord, and B.-J. Park (2008) Horizontal Curve Accident Modification Factors with Consideration of Driveway Density on Rural, Four-Lane Highways in Texas. Paper submitted to the 88th Annual Meeting to the Transportation Research Board, Washington, D.C.
6. Miaou, S.P., R.P. Bligh, and D. Lord (2005) Developing Median Barrier Installation Guidelines: A Benefit/Cost Analysis using Texas Data. *Transportation Research Record* 1904, pp. 3-19.
7. Fitzpatrick, K., D. Lord, and B.-J. Park. Accident Modification Factors for Medians on Freeways and Multilane Highways in Texas. Texas Transportation Institute. November 2007

8. Fitzpatrick, K., D. Lord, and B.-J. Park. Development of Accident Modification Factors for Medians on Freeways and Multilane Highways in Texas. Technical Memorandum Number 12, Texas Transportation Institute. July 2007
9. Chandler, B. (2007) Eliminating Cross-Median Fatalities: Statewide Installation of Median Cable Barrier in Missouri. *Transportation Research News* (*TR News*) 248, pp. 29-31
10. Hauer, E. The Median and Safety. University of Toronto. 2000.
11. Hauer, E. Shoulder Width, Shoulder Paving and Safety. University of Toronto. 2000.
12. Roger B, S.-P. Miaou, D. Lord, and S. Cooner. Median Barrier Guidelines for Texas. Texas Transportation Institute. Austin, Texas: Texas Department of Transportation, 2006.
13. Handbook of Simplified Practice for Traffic Studies: Crash Analysis. Center for Transportation Research and Education, Iowa State University, November 2002
14. Free p-Value Calculator for the Fisher F-Test: http://www.danielsoper.com/statcalc/calc07.aspx Accessed August, 2008
15. Glover, T., K. Mitchell. An Introduction to Biostatistics. Waveland Press, Inc. Long Grove, Illinois, 2002
16. Accident and Roadway Inventors SAS Data Files User Manual. Accident Analysis Division, Texas Transportation Institute, Texas A&M University System, August 1984

**APPENDICES**

## APPENDIX A [ROADWAY STATISTICS CHARTS]

**Table A-1:** Roadway Characteristics- Summary of Statistics for the 590 Segments

| Roadway Characteristics | | | | |
|---|---|---|---|---|
| **Summary of Statistics** | | | | |
| **Variable** | | | **Condition** | |
| | | Total | With Barrier | Without Barrier |
| Total Sites | | 590 | 225 | 365 |
| Sum of Segment Lengths (miles) | | 169.889 | 56.713 | 113.176 |
| Average Curve Length (miles) | Average | 0.288 | 0.252 | 0.310 |
| | Minimum | 0.101 | 0.101 | 0.102 |
| | Maximum | 0.982 | 0.944 | 0.982 |
| | SD** | 0.162 | 0.162 | 0.162 |
| AADT for All Sites (2003^) | Average | 55,714 | 102,861 | 26,650 |
| | Minimum | 4,020 | 16,530 | 4,020 |
| | Maximum | 265,280 | 265,280 | 151,220 |
| | SD** | 54866.35 | 54082.76 | 55055.07 |
| Average AADT for All Sites ('97-'01) | | 50,282 | 93,643 | 23,554 |
| Speed Limit (Miles Per Hour) | Average | 65.90 | 60.53 | 69.21 |
| | Minimum | 40 | 40 | 55 |
| | Maximum | 75 | 70 | 75 |
| | SD** | 6.538 | 6.538 | 6.539 |
| Number of Lanes {TRM Data}* | Average | 4.95 | 6.07 | 4.24 |
| | Minimum | 4 | 4 | 4 |
| | Maximum | 11 | 11 | 9 |
| | SD** | 1.524 | 1.524 | 1.523 |
| Right of Way [ROW] Width (ft) | Average | 340.41 | 314.66 | 353.58 |
| | Minimum | 120 | 120 | 200 |
| | Maximum | 785 | 520 | 785 |
| | SD** | 61.31 | 67.02 | 61.50 |
| Right Shoulder Width [Increasing Milepoint] (ft) | Average | 10.17 | 10.50 | 10.05 |
| | Minimum | 3.5 | 3.5 | 4 |
| | Maximum | 20 | 20 | 15 |
| | SD** | 1.498 | 1.909 | 1.502 |
| Left Shoulder Width [Increasing Milepoint] (ft) | Average | 6.85 | 9.61 | 5.14 |
| | Minimum | 0 | 0 | 0 |
| | Maximum | 24 | 20 | 24 |
| | SD** | 3.863 | 4.113 | 3.870 |
| Lane Width [Increasing Milepoint] (ft) | Average | 11.65 | 11.66 | 11.64 |
| | Minimum | 10 | 10 | 10 |
| | Maximum | 13 | 13 | 13 |
| | SD** | 0.647 | 0.533 | 0.648 |

| | | | | | |
|---|---|---|---|---|---|
| | **Roadway Characteristics** | | | | |
| | **Summary of Statistics** | | | | |
| | **Variable** | | | **Condition** | |
| | | | Total | With Barrier | Without Barrier |
| | Distance to Barrier [Increasing Milepoint] (ft) *{If Applicable}* | Average | 12.03 | 12.03 | |
| | | Minimum | 0.5 | 0.5 | |
| | | Maximum | 66 | 66 | |
| | | SD** | 8.659 | 8.659 | |
| | Median Width without Shoulder (ft) | Average | 34.82 | 8.43 | 51.08 |
| | | Minimum | 2 | 2 | 7 |
| | | Maximum | 142 | 70 | 142 |
| | | SD** | 27.254 | 13.858 | 27.233 |
| | Distance to Barrier [Decreasing Milepoint] (ft) *{If Applicable}* | Average | 10.78 | 10.78 | |
| | | Minimum | 0.5 | 0.5 | |
| | | Maximum | 40 | 40 | |
| | | SD** | 5.375 | 5.375 | |
| | Left Shoulder Width [Decreasing Milepoint] (ft) | Average | 6.77 | 9.41 | 5.14 |
| | | Minimum | 0 | 0 | 0 |
| | | Maximum | 25 | 25 | 24 |
| | | SD** | 3.677 | 3.676 | 3.682 |
| | Lane Width [Decreasing Milepoint] (ft) | Average | 11.65 | 11.66 | 11.64 |
| | | Minimum | 10 | 10 | 10 |
| | | Maximum | 13 | 13 | 13 |
| | | SD** | 0.633 | 0.503 | 0.634 |
| | Right Shoulder Width [Decreasing Milepoint] (ft) | Average | 10.17 | 10.37 | 10.05 |
| | | Minimum | 3 | 3 | 3 |
| | | Maximum | 22 | 17 | 22 |
| | | SD** | 1.544 | 1.800 | 1.548 |
| | | | | | |
| | ^ Latest Year Data is Available * Total Number of Lanes in Both Directions ** Standard Deviation | | | | |

**Table A-2:** Crash Characteristics for Horizontal Curve Portion of Roadway

| **Crash Characteristics** | | | | | |
|---|---|---|---|---|---|
| **Horizontal Curve Portion of Roadway (Two or less Crashes per segment with barrier)** | | | | | |
| **Variable** | | | | Crash Characteristics KABC* Crashes | |
| | | | | **Condition** | |
| | | | Total | With Barrier | Without Barrier |
| Total Sites | | | 590 | 225 | 365 |
| Sum of Segment Lengths (miles) | | | 169.889 | 56.713 | 113.176 |
| Median Related Crashes (MRC) in Five Years (1997 to 2001) | Per Segment | Average | 1.454 | 2.73 | 0.67 |
| | | Minimum | 0 | 0 | 0 |
| | | Maximum | 17 | 17 | 6 |
| | | SD** | 2.188 | 2.191 | 2.189 |
| | All Segments | Sum | 858 | 614 | 244 |
| | | Crash Count (crashes/mile-yr) | 1.010 | 2.165 | 0.431 |
| | | Crash Rate (crashes/mvm)^ | 0.055 | 0.063 | 0.051 |
| | | | | | |
| Total Sites | | | 588 | 223 | 365 |
| Sum of Segment Lengths (miles) | | | 168.461 | 55.285 | 113.176 |
| Median Crossover Crashes 1 (MCC1) in Five Years (1997 to 2001) | Per Segment | Average | 0.16 | 0.15 | 89.75 |
| | | Minimum | 0 | 0 | 0 |
| | | Maximum | 7 | 2 | 7 |
| | | SD** | 0.384 | 0.418 | 0.611 |
| | All Segments | Sum | 94 | 34 | 60 |
| | | Crash Count (crashes/mile-yr) | 0.112 | 0.123 | 0.106 |
| | | Crash Rate (crashes/mvm) | 0.006 | 0.004 | 0.012 |
| | | | | | |
| Total Sites | | | 575 | 210 | 365 |
| Sum of Segment Lengths (miles) | | | 165.589 | 52.413 | 113.176 |
| Median Crossover Crashes 2 (MCC2) in Five Years (1997 to 2001) | Per Segment | Average | 0.21 | 0.23 | 0.20 |
| | | Minimum | 0 | 0 | 0 |
| | | Maximum | 5 | 2 | 5 |
| | | SD** | 0.432 | 0.513 | 1.182 |
| | All Segments | Sum | 120 | 48 | 72 |
| | | Crash Count (crashes/mile-yr) | 0.145 | 0.183 | 0.127 |
| | | Crash Rate (crashes/mvm) | 0.008 | 0.006 | 0.015 |

* Fatal (K), incapacitating injury (A), non-incapacitating- injury (B), and minor injury (C) crashes

** Standard Deviation ^ Crash rate has units of yearly crashes per million vehicle miles

**Table A-3:** Crash Characteristics for Tangent Portion of Roadway

| Tangent Portion of Roadway (two or less Crashes per segment with barrier) | | | | | |
|---|---|---|---|---|---|
| **Variable** | | | Crash Characteristics KABC* Crashes | | |
| | | | **Condition** | | |
| | | | Total | With Barrier | Without Barrier |
| Total Sites | | | 590 | 225 | 365 |
| Sum of Segment Lengths (miles) | | | 169.889 | 56.713 | 113.176 |
| Median Related Crashes (MRC) in Five Years (1997 to 2001) | Per Segment | Average | 1.27 | 2.50 | 0.52 |
| | | Minimum | 0 | 0 | 0 |
| | | Maximum | 16 | 16 | 14 |
| | | SD** | 2.128 | 2.132 | 2.134 |
| | All Segments | Sum | 751 | 563 | 188 |
| | | Crash Count (crashes/mile-yr) | 0.884 | 1.985 | 0.332 |
| | | Crash Rate (crashes/mvm)^ | 0.048 | 0.057 | 0.039 |
| | | | | | |
| Total Sites | | | 587 | 222 | 365 |
| Sum of Segment Lengths (miles) | | | 168.391 | 55.215 | 113.176 |
| Median Crossover Crashes 1 (MCC1) in Five Years (1997 to 2001) | Per Segment | Average | 0.09 | 0.11 | 48.54 |
| | | Minimum | 0 | 0 | 0 |
| | | Maximum | 2 | 2 | 2 |
| | | SD** | 0.319 | 0.313 | 0.719 |
| | All Segments | Sum | 50 | 25 | 25 |
| | | Crash Count (crashes/mile-yr) | 0.059 | 0.091 | 0.044 |
| | | Crash Rate (crashes/mvm) | 0.003 | 0.003 | 0.005 |
| | | | | | |
| Total Sites | | | 575 | 210 | 365 |
| Sum of Segment Lengths (miles) | | | 165.522 | 52.346 | 113.176 |
| Median Crossover Crashes 2 (MCC2) in Five Years (1997 to 2001) | Per Segment | Average | 0.24 | 0.24 | 6.36 |
| | | Minimum | 0 | 0 | 0 |
| | | Maximum | 11 | 2 | 11 |
| | | SD** | 0.426 | 0.537 | 1.192 |
| | All Segments | Sum | 139 | 50 | 89 |
| | | Crash Count (crashes/mile-yr) | 0.168 | 0.191 | 0.157 |
| | | Crash Rate (crashes/mvm) | 0.010 | 0.006 | 0.018 |

* Fatal (K), incapacitating injury (A), non-incapacitating- injury (B), and minor injury (C) crashes

** Standard Deviation ^ Crash rate has units of yearly crashes per million vehicle miles

## APPENDIX B [ANOVA ANALYSIS]

**Table B-1:** Analysis of Variance (ANOVA) for Median Related Crashes (MRC) With-Barrier

### Median Related Crashes With-Barrier Analysis

**CRASH RATE**

**Summary Statistics**

| | HC | TAN | Total |
|---|---|---|---|
| T | 15.88882 | 15.12637 | 31.01519 |
| N | 225 | 225 | 450 |
| X Bar | 0.07062 | 0.06723 | 0.06892 |
| s^2 | 0.00473 | 0.00601 | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 31.01519 | 961.94207 | 2.13765 |
| Sigma I Sigma J **X i j** Squared | 4.545829 | | |

(SS Treat)

| | |
|---|---|
| SS Total | 2.40818 |
| SS Sites | 0.001292 |
| SS Error | 2.406888 |
| MS Sites | 0.001292 |
| MS Error | 0.010793 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 0.001292 | 1 | 0.001292 | 0.11969 | 0.729631 |
| Error | 2.406888 | 448 | 0.005373 | | |
| Total | 2.408180 | 449 | | | α = .05 |
| | | | | c.v. = 3.84 | |

**Crashes per Mile**

**Summary Statistics**

| | HC | TAN | Total |
|---|---|---|---|
| T | 2560.391335 | 2402.482034 | 4962.87337 |
| N | 225 | 225 | 450 |
| X Bar | 11.37951704 | 10.67769793 | 11.02860749 |
| s^2 | 143.6909957 | 140.7005831 | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 4962.873 | 24630112 | 54733.58 |
| Sigma I Sigma J **X i j** Squared | 118492.7 | | |

(SS Treat)

| | |
|---|---|
| SS Total | 63759.13 |
| SS Sites | 55.41 |
| SS Error | 63703.71 |
| MS Sites | 55.41188 |
| MS Error | 142.1958 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 55.4 | 1 | 55.41188 | 0.389687 | 0.532827 |
| Error | 63703.7 | 448 | 142.1958 | | |
| Total | 63759.1 | 449 | | | α = .05 |
| | | | | c.v. = 3.84 | |

**Table B-2:** Analysis of Variance (ANOVA) for Median Related Crashes (MRC) Without-Barrier

**Median Related Crashes Without-Barrier Analysis**

**Summary Statistics**

| | HC | TAN | Total | |
|---|---|---|---|---|
| T | 23.78600732 | 16.04699916 | 39.83300647 | **CRASH RATE** |
| N | 365 | 365 | 730 | |
| X Bar | 0.065167143 | 0.043964381 | 0.054565762 | |
| s^2 | 0.016474147 | 0.009042104 | | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 39.83301 | 1586.668 | 2.173518 |
| Sigma I Sigma J **X i j** Squared | 11.54348 | | |

| | |
|---|---|
| SS Total | 9.36996 |
| SS Sites | 0.082044 |
| SS Error | 9.287916 |
| MS Sites | 0.082044 |
| MS Error | 0.012758 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 0.001292 | 1 | 0.001292 | 6.430739 | 0.011424 |
| Error | 2.406888 | 728 | 0.003306 | | |
| Total | 2.408180 | 729 | | | α = .05 |
| | | | | c.v.=3.84 | |

**Summary Statistics**

| | HC | TAN | Total | |
|---|---|---|---|---|
| | | | | **Crashes per Mile** |
| T | 821.8185888 | 603.7858326 | 1425.604421 | |
| N | 365 | 365 | 730 | |
| X Bar | 2.251557777 | 1.654207761 | 1.952882769 | |
| s^2 | 14.24440257 | 10.69142609 | | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 1425.604 | 2032348 | 2784.038 |
| Sigma I Sigma J **X i j** Squared | 11925.8 | | |

| | | |
|---|---|---|
| | SS Total | 9141.763 |
| (SS Treat) | SS Sites | 65.12 |
| | SS Error | 9076.642 |
| | MS Sites | 65.12094 |
| | MS Error | 12.46791 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 65.1 | 1 | 65.12094 | 5.223082 | 0.022577 |
| Error | 9076.6 | 728 | 12.46791 | | |
| Total | 9141.8 | 729 | | | α = .05 |
| | | | c.v. = | 3.84 | |

**Table B-3:** Analysis of Variance (ANOVA) for Median Crossover Crashes Type 1 (MCC1) Without-Barrier

**Median Crossover Crashes Type 1 Without-Barrier Analysis**

**Summary Statistics**

| | HC | TAN | SUMMARY | |
|---|---|---|---|---|
| T | 4.507294 | 2.181582 | 6.688875 | **CRASH RATE** |
| N | 365 | 365 | 730 | |
| X Bar | 0.01234875 | 0.005976936 | 0.009162843 | |
| s^2 | 0.002674097 | 0.001284613 | | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 6.688875 | 44.74105 | 0.061289 |
| Sigma I Sigma J **X i j** Squared | 1.509669 | | |

| | |
|---|---|
| SS Total | 1.44838 |
| SS Sites | 0.00741 |
| SS Error | 1.44097 |
| MS Sites | 0.00741 |
| MS Error | 0.001979 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 0.007410 | 1 | 0.00741 | 3.743393 | 0.053407 |
| Error | 1.440970 | 728 | 0.001979 | | |
| Total | 1.448380 | 729 | | | α = .05 |
| | | | c.v. = | 3.84 | |

**Summary Statistics**

| | HC | TAN | | |
|---|---|---|---|---|
| | | | | **Crashes per Mile** |
| T | 201.822891 | 76.65553681 | 278.4784278 | |
| N | 365 | 365 | 730 | |
| X Bar | 0.552939427 | 0.210015169 | 0.381477298 | |
| s^2 | 4.236219107 | 1.003697757 | | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 278.4784 | 77550.23 | 106.2332 |
| Sigma I Sigma J **X i j** Squared | 2035.024 | | |

| | | |
|---|---|---|
| | SS Total | 1928.791 |
| (SS Treat) | SS Sites | 21.46 |
| | SS Error | 1907.33 |
| | MS Sites | 21.46146 |
| | MS Error | 2.619958 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 21.46 | 1 | 21.46146 | 8.191527 | 0.00433 |
| Error | 1907.33 | 728 | 2.619958 | | |
| Total | 1928.79 | 729 | | | α = .05 |
| | | | c.v. = | 3.84 | |

**Table B-4:** Analysis of Variance (ANOVA) for Median Crossover Crashes Type 2 (MCC2) Without-Barrier

**Median Crossover Crashes Type 2 Without-Barrier Analysis**

**Summary Statistics** — **CRASH RATE**

| | HC | TAN | SUMMARY |
|---|---|---|---|
| T | 6.6490171 | 4.6384890 | 11.2875060 |
| N | 365 | 365 | 730 |
| X Bar | 0.018216485 | 0.012708189 | 0.015462337 |
| s^2 | 0.003935894 | 0.001812514 | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 11.28751 | 127.4078 | 0.174531 |
| Sigma I Sigma J **X i j** Squared | 2.272489 | | |

| | |
|---|---|
| SS Total | 2.097958 |
| SS Sites | 0.005537 |
| SS Error | 2.09242 |
| MS Sites | 0.005537 |
| MS Error | 0.002874 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 0.005537 | 1 | 0.005537 | 1.926548 | 0.165566 |
| Error | 2.092420 | 728 | 0.002874 | | |
| Total | 2.097958 | 729 | | | α = .05 |

c.v. = 3.84

**Summary Statistics** — **Crashes per Mile**

| | HC | TAN | |
|---|---|---|---|
| T | 211.259026 | 255.176304 | 466.435330 |
| N | 365 | 365 | 730 |
| X Bar | 0.578791853 | 0.69911316 | 0.638952507 |
| s^2 | 2.924479621 | 8.879708764 | |

| | | | |
|---|---|---|---|
| Sigma I Sigma J **X i j** | 466.4353 | 217561.9 | 298.03 |
| Sigma I Sigma J **X i j** Squared | 4597.397 | | |

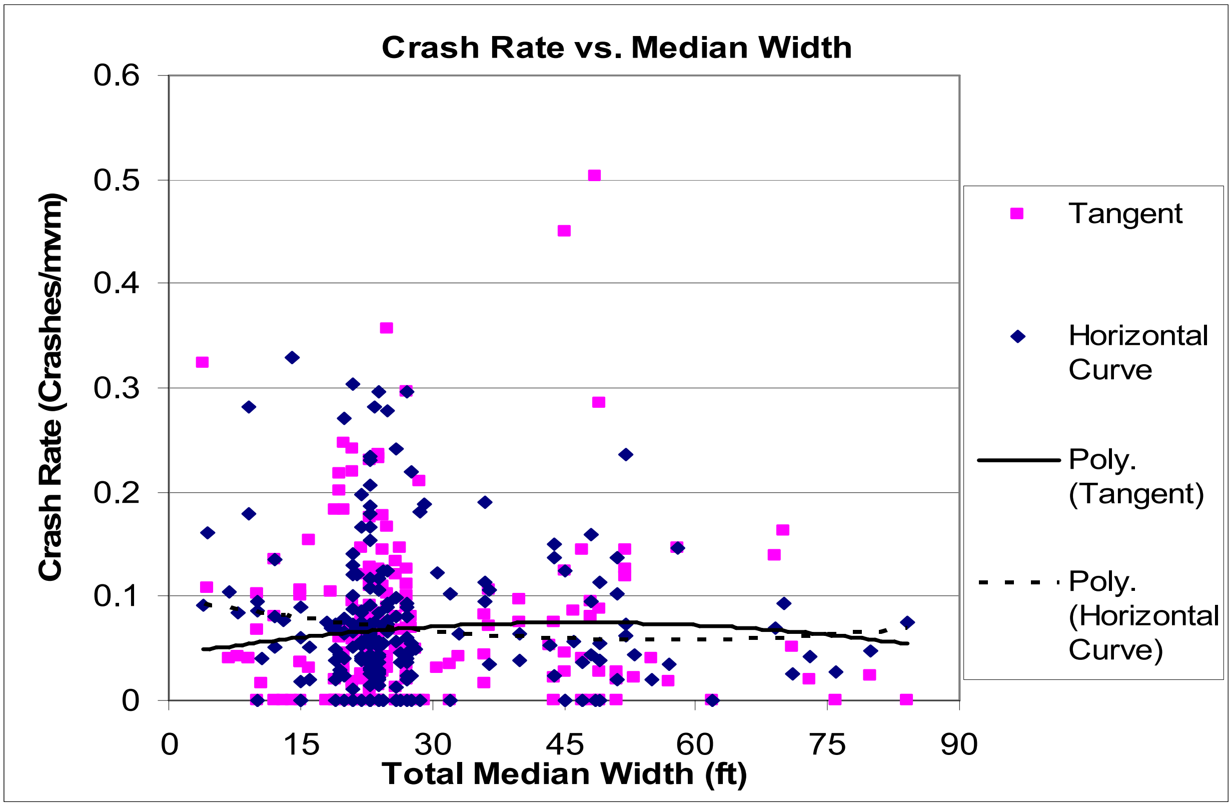
(SS Treat)

| | |
|---|---|
| SS Total | 4299.367 |
| SS Sites | 2.64 |
| SS Error | 4296.725 |
| MS Sites | 2.642092 |
| MS Error | 5.902094 |

| Source of Variation | Sum of Squares | df | MS | F | p Value |
|---|---|---|---|---|---|
| Segments | 2.64 | 1 | 2.642092 | 0.447653 | 0.503689 |
| Error | 4296.72 | 728 | 5.902094 | | |
| Total | 4299.37 | 729 | | | α = .05 |

c.v. = 3.84

## APPENDIX C [GRAPHS]



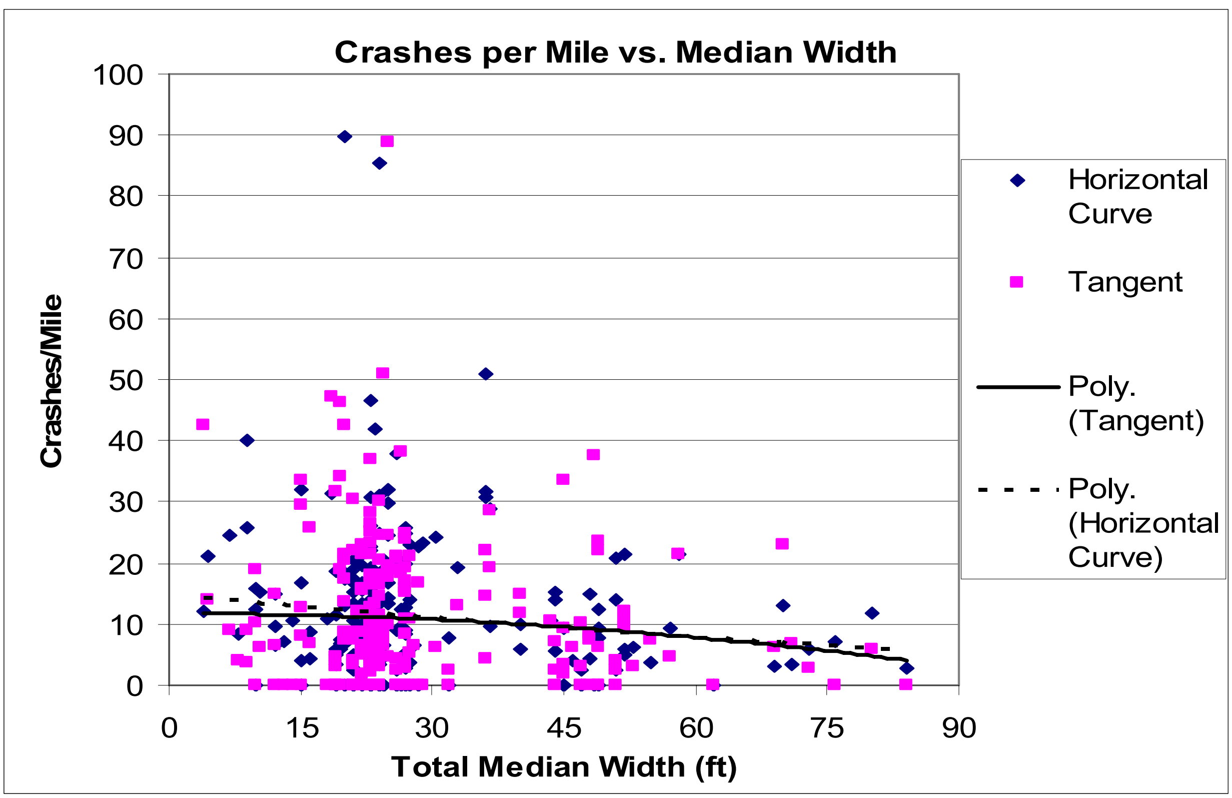
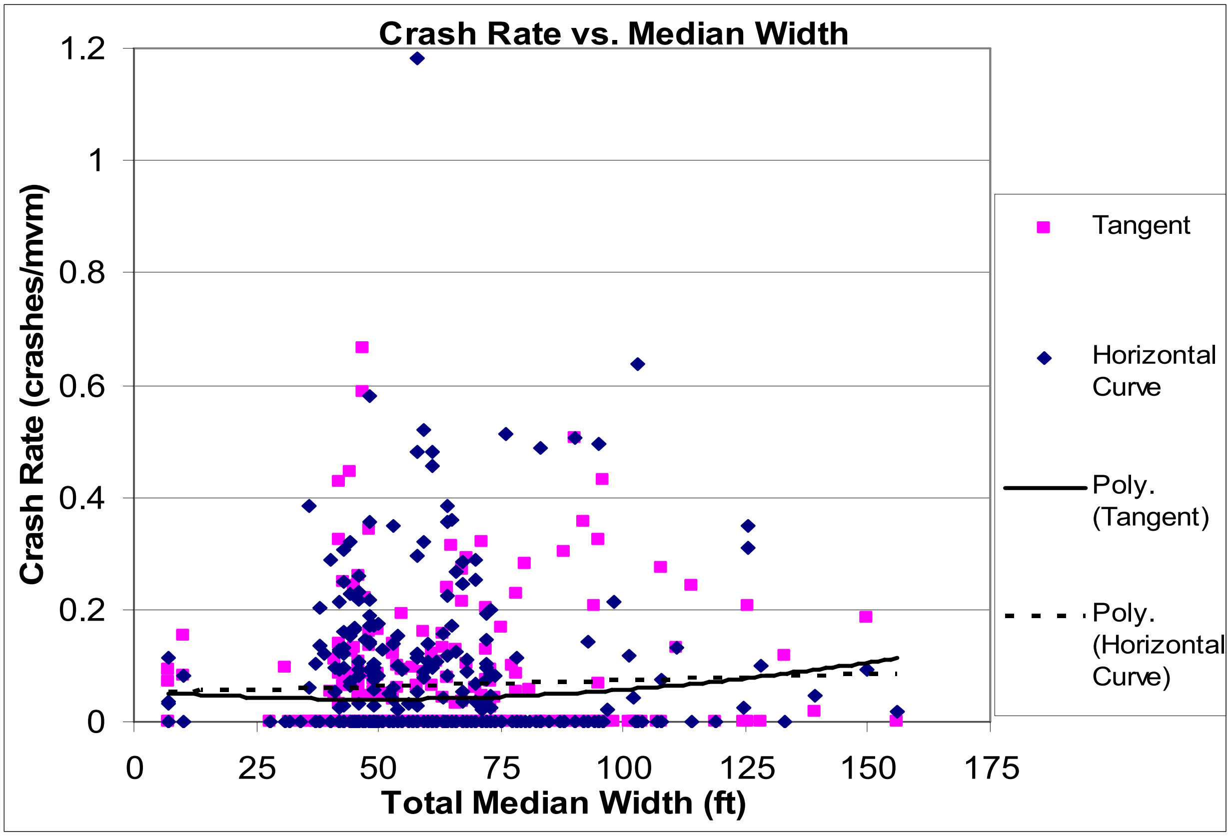




**Figure C-1:** Median Related Crashes With-Barrier Graphs



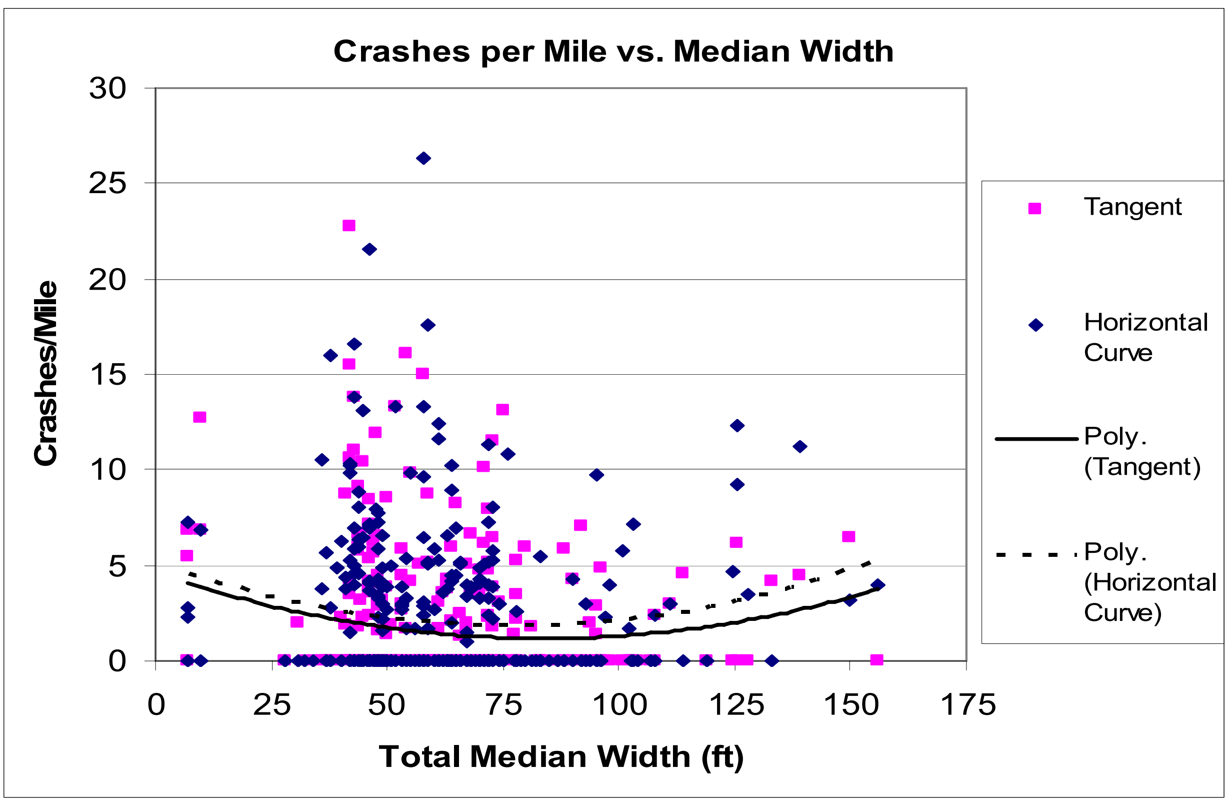




**Figure C-2:** Median Related Crashes Without-Barrier Graphs

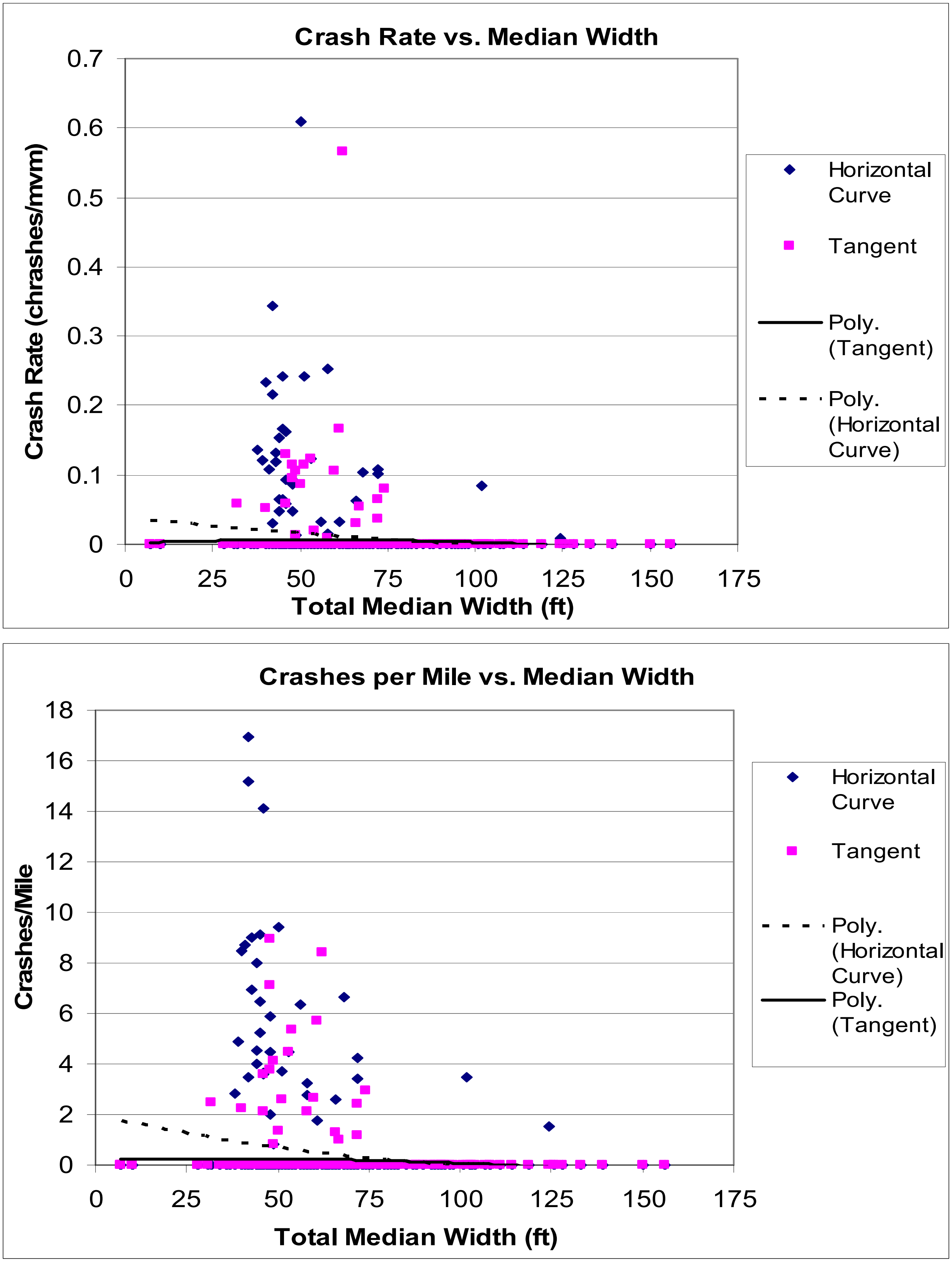
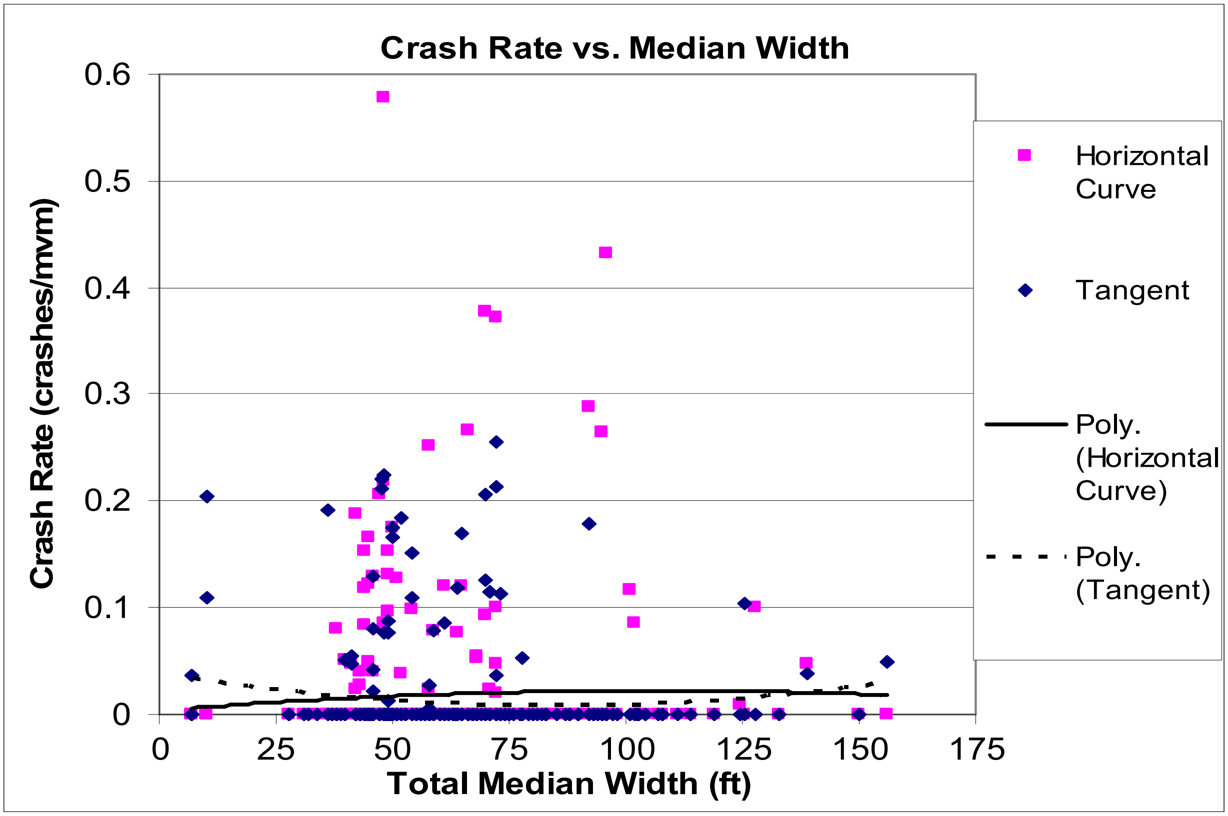



**Figure C-3:** Median Crossover Crashes Type 1 Without-Barrier Graphs



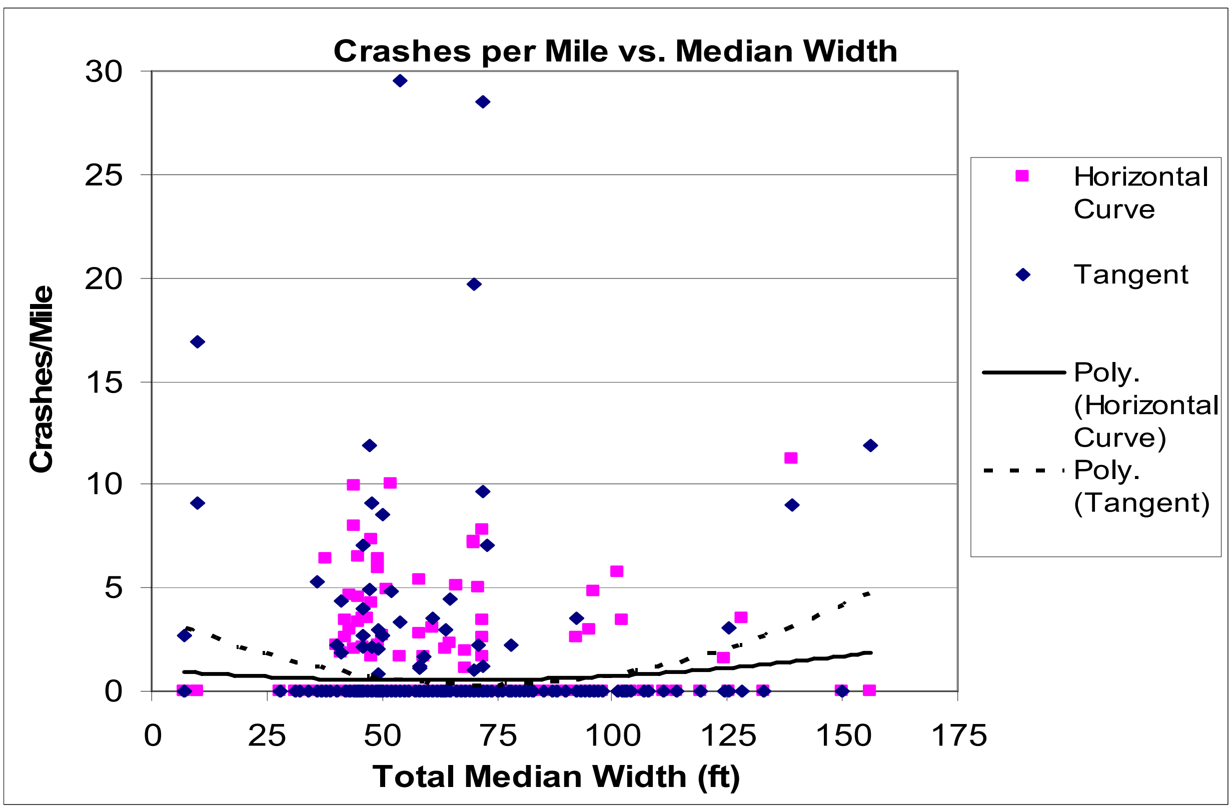




**Figure C-4:** Median Crossover Crashes Type 2 Without-Barrier Graphs

**APPENDIX D [ROADWAY STATISTICS GRAPHS WITH-BARRIER]**
Distribution of variables per number of miles (y-axis is in mile) for with-barrier segments in the freeway dataset graphical summary
[Range of variables are listed as x-y with x being inclusive and y being exclusive]

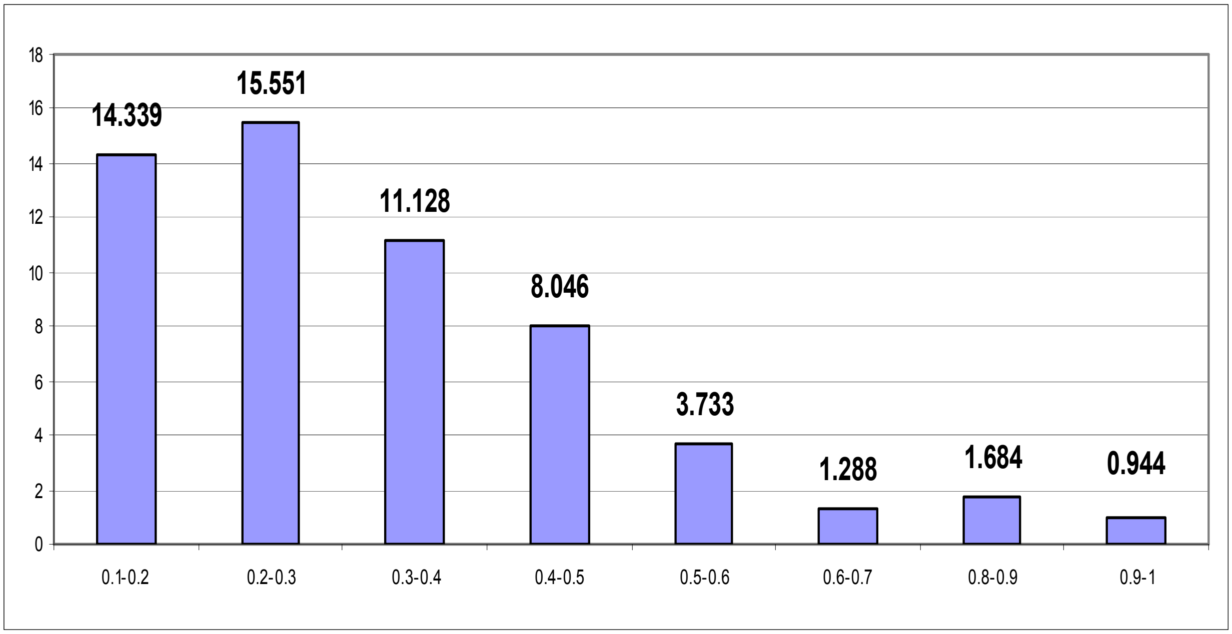



**Figure D-1**: Section Length (in Miles)

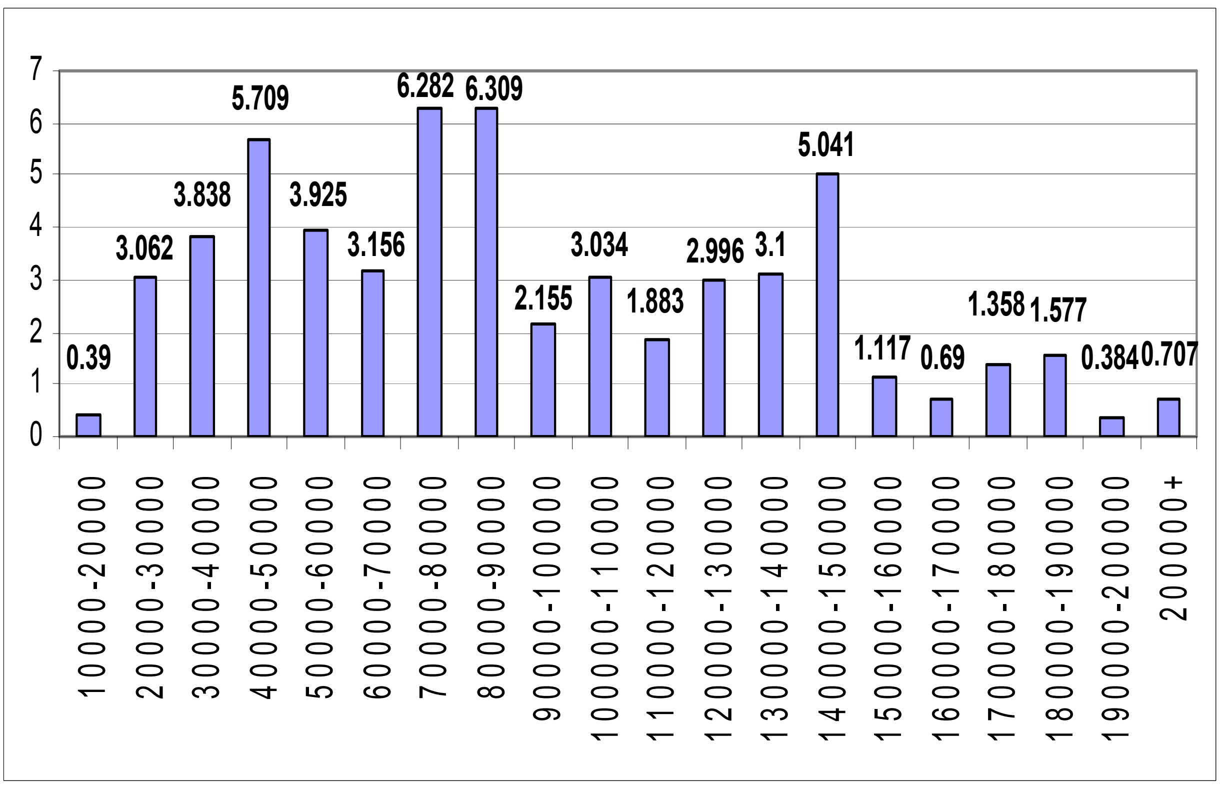



**Figure D-2**: Annual Average Daily Traffic (AADT)

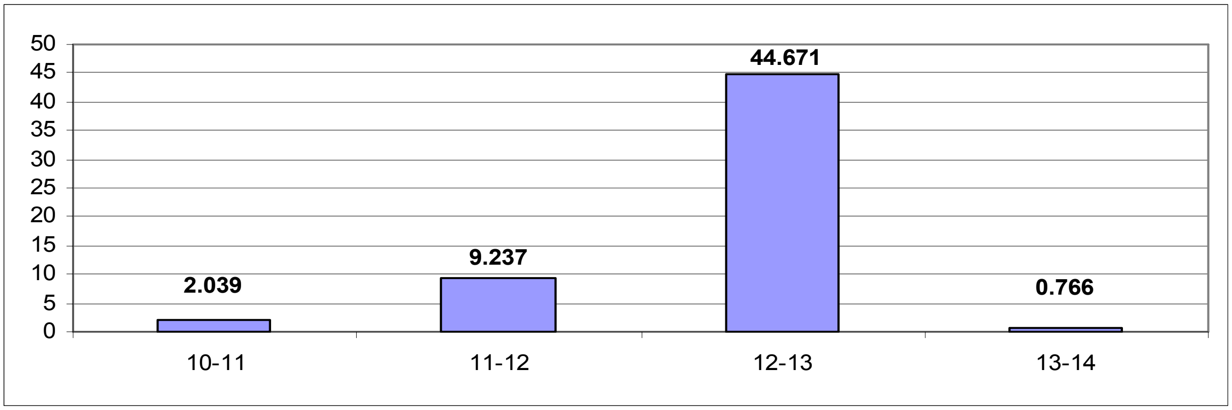



**Figure D-3:** Lane Width (ft) [Decreasing Milepoint]

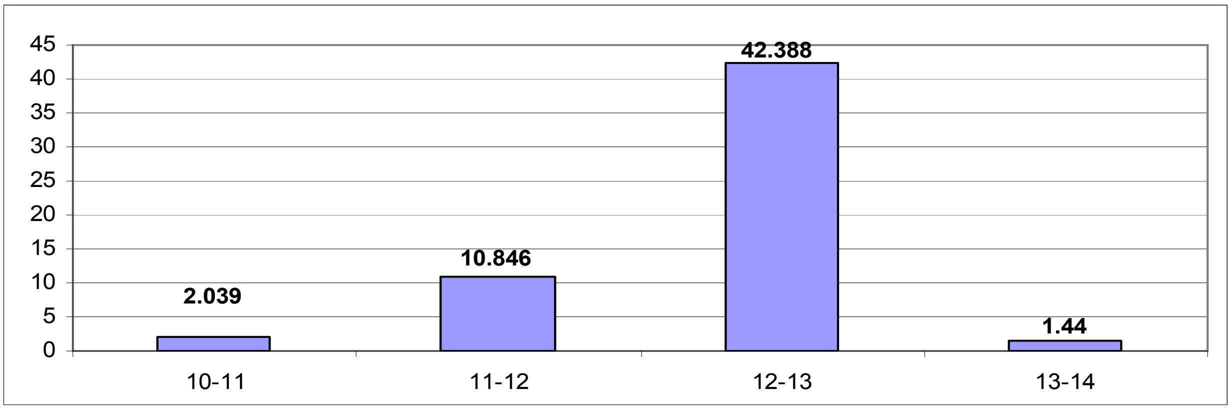



**Figure D-4:** Lane Width (ft) [Increasing Milepoint]

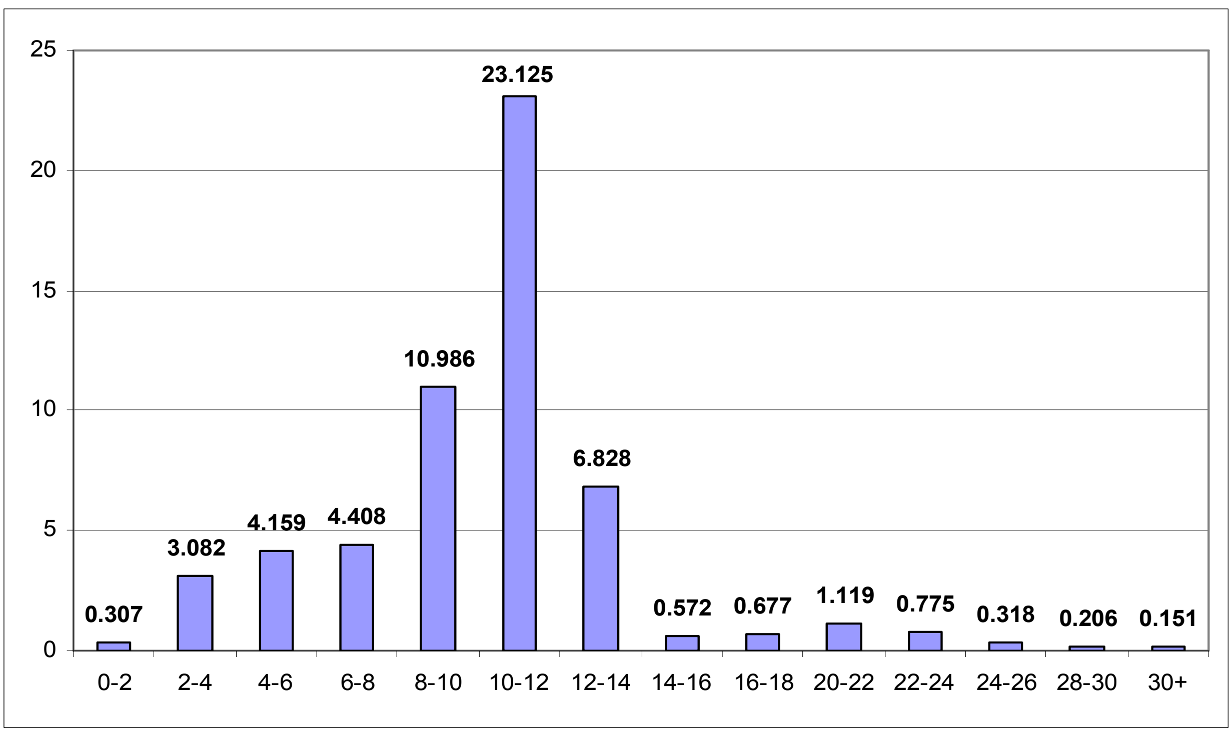



**Figure D-5:** Inside Shoulder Width (ft) [Increasing Milepoint]

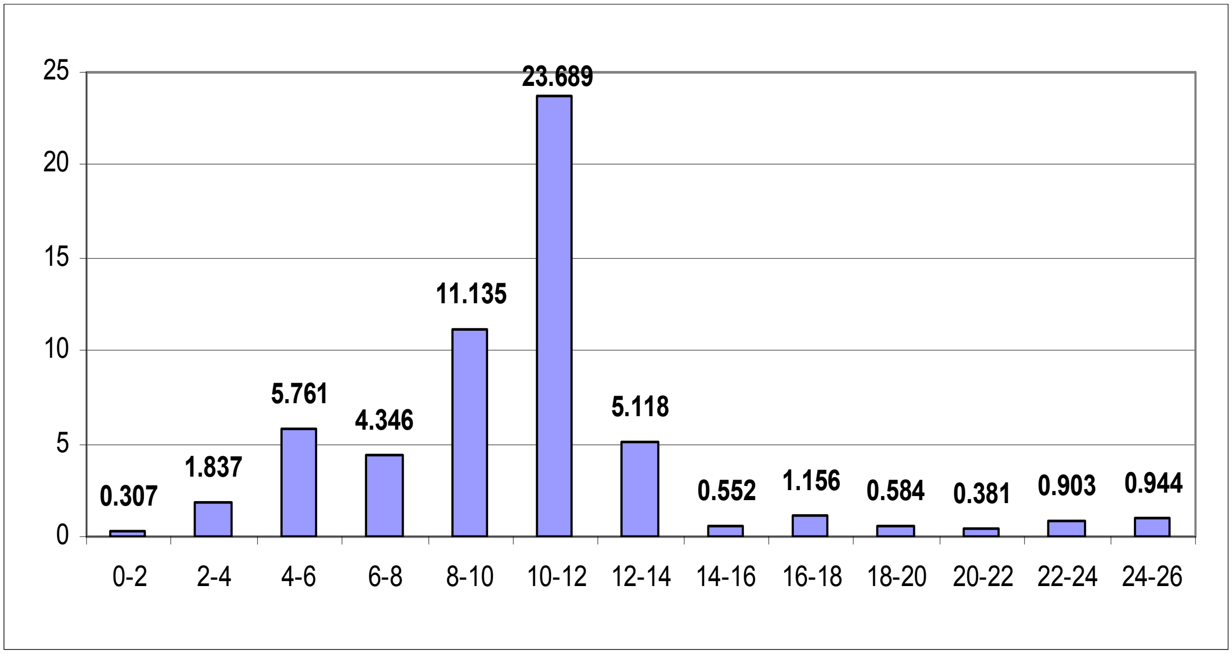



**Figure D-6:** Inside Shoulder Width (ft) [Decreasing Milepoint]

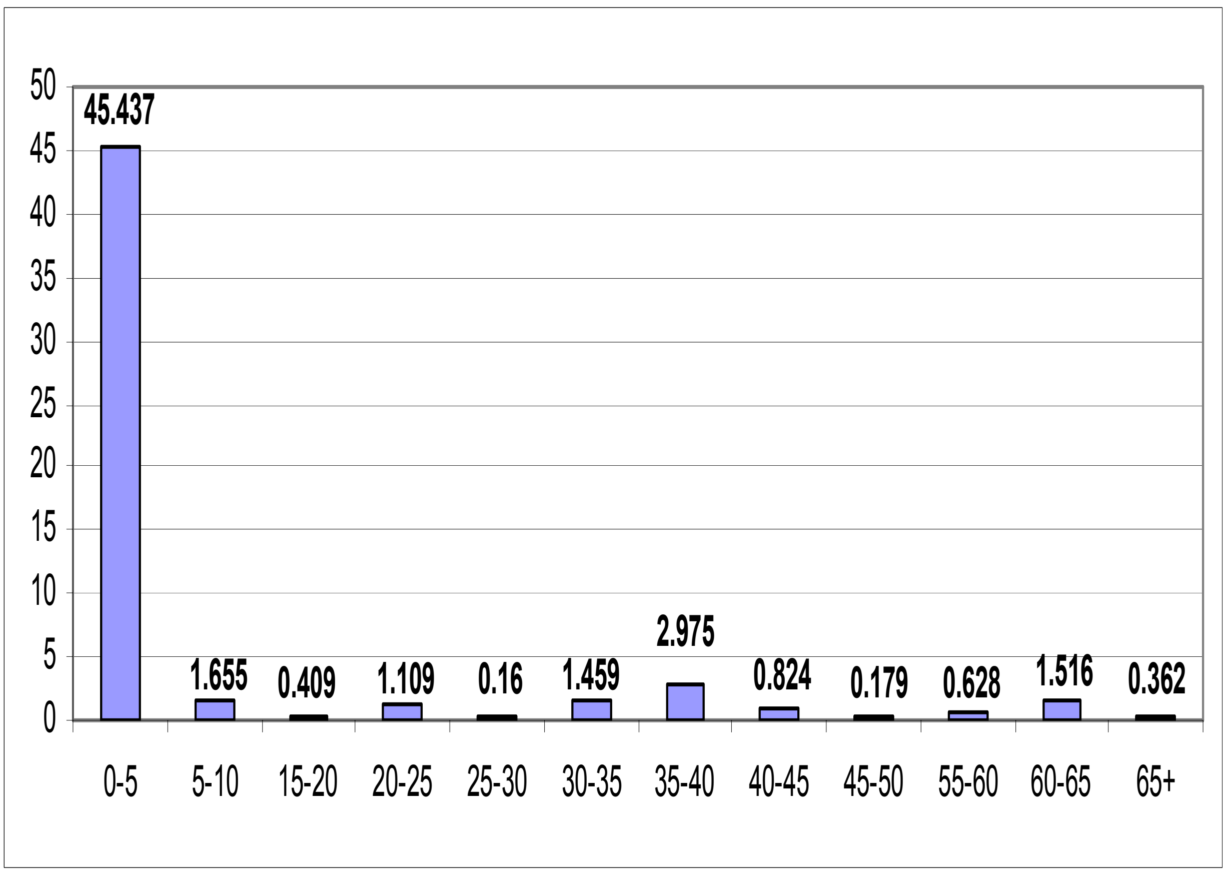



**Figure D-7:** Median Width (ft) [Not Including Inside Shoulders]

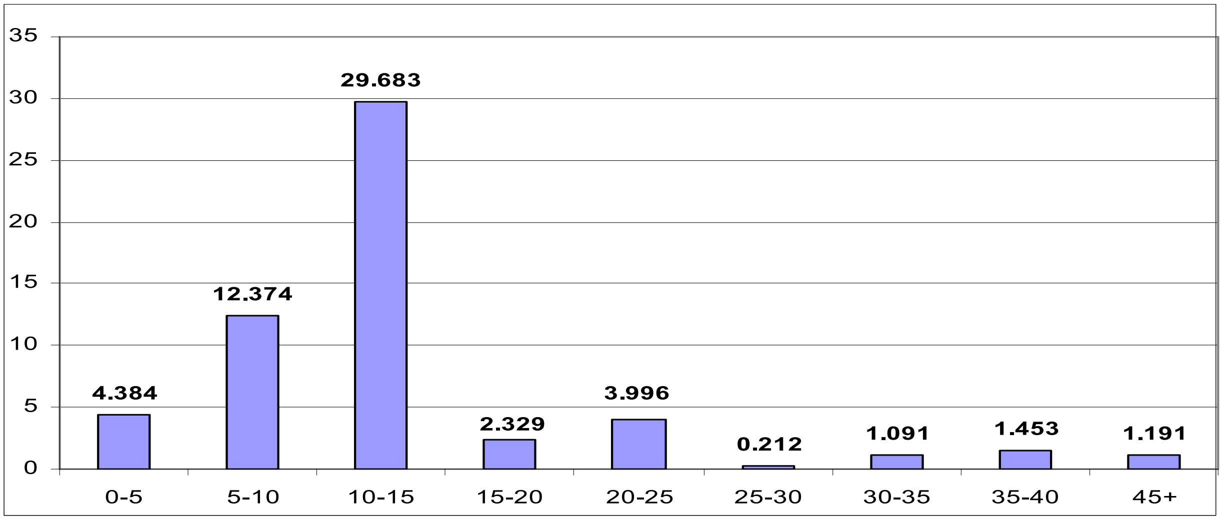



**Figure D-8:** Total Barrier Offset (ft) [Increasing Milepoint]

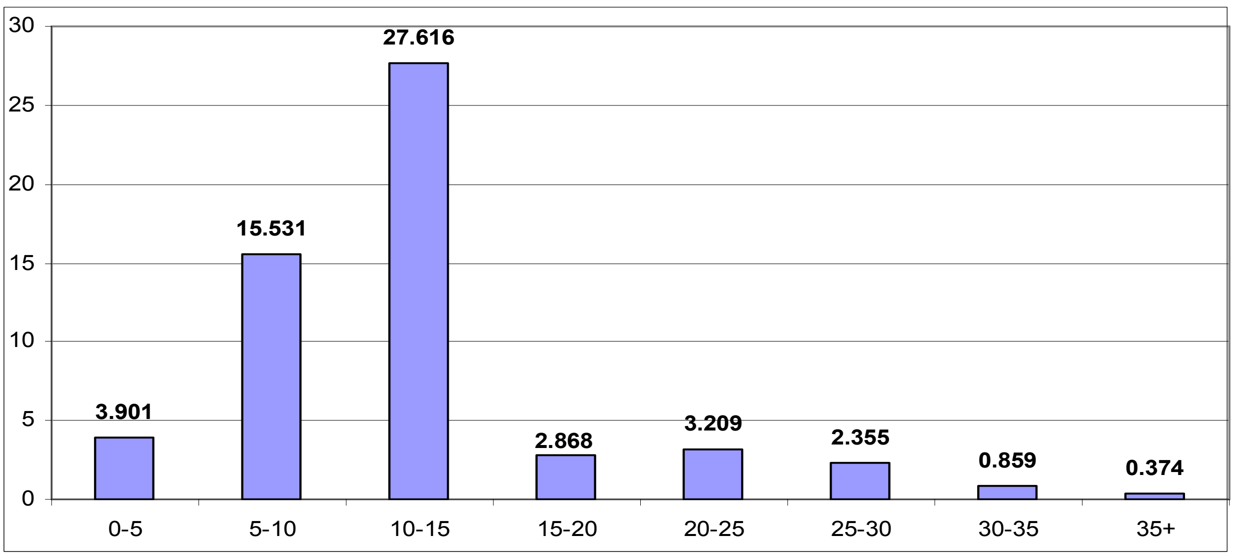



**Figure D-9:** Total Barrier Offset (ft) [Decreasing Milepoint]

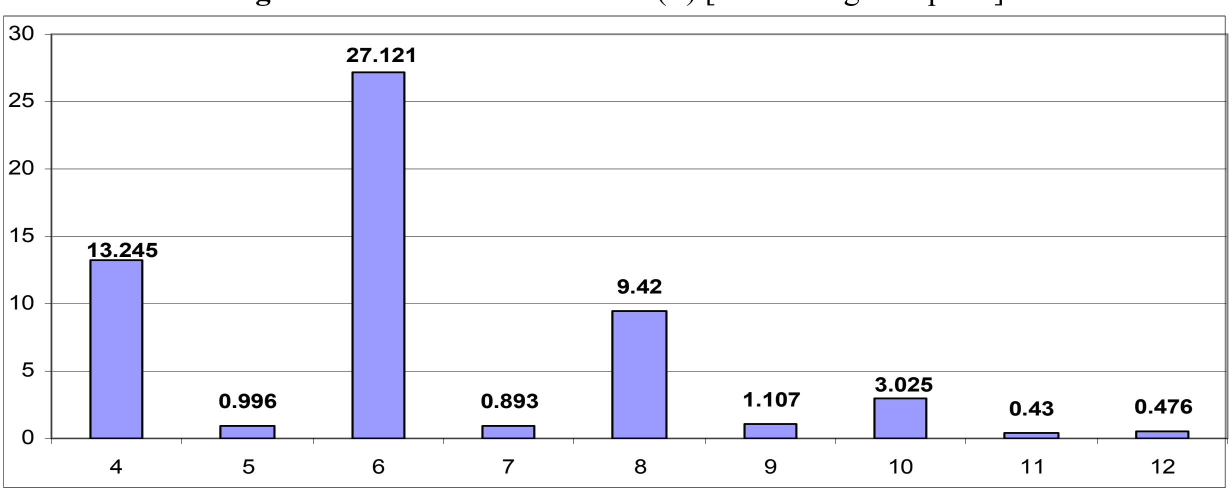



**Figure D-10:** Total Number of Lanes (Both Directions)

**APPENDIX E [ROADWAY STATISTICS GRAPHS WITHOUT-BARRIER]**
Distribution of variables per number of miles (y-axis is in mile) for without-barrier segments in the freeway dataset graphical summary
Range of variables are listed as x-y with x being inclusive and y being exclusive

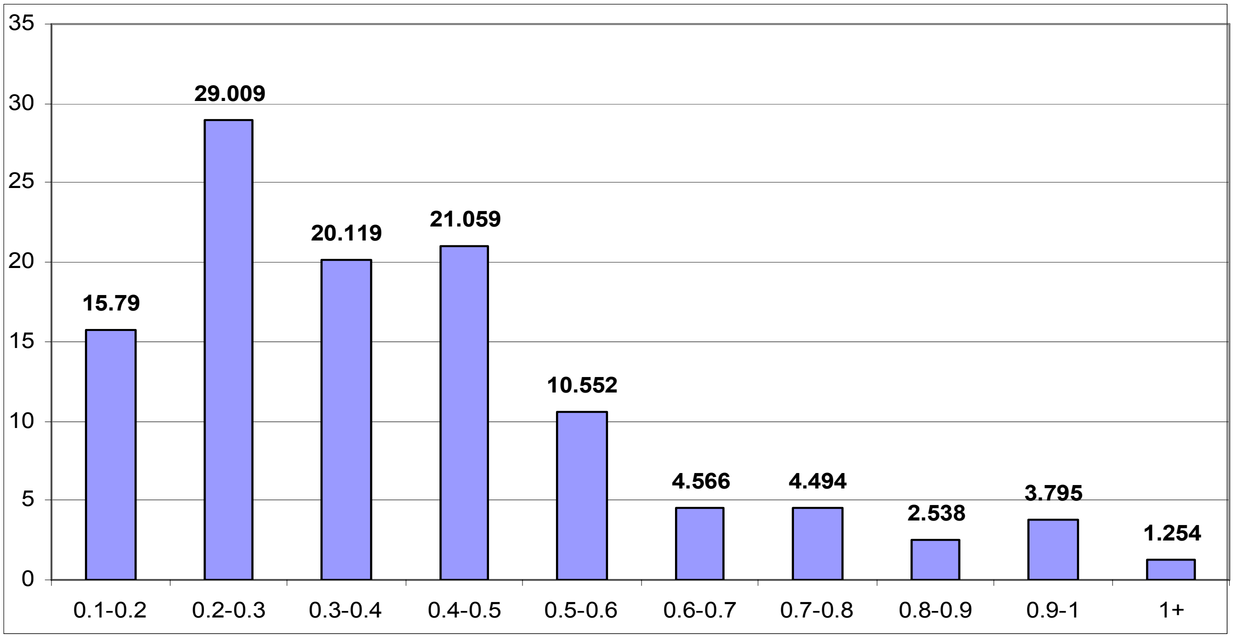



**Figure E-1:** Section Length (in Miles)

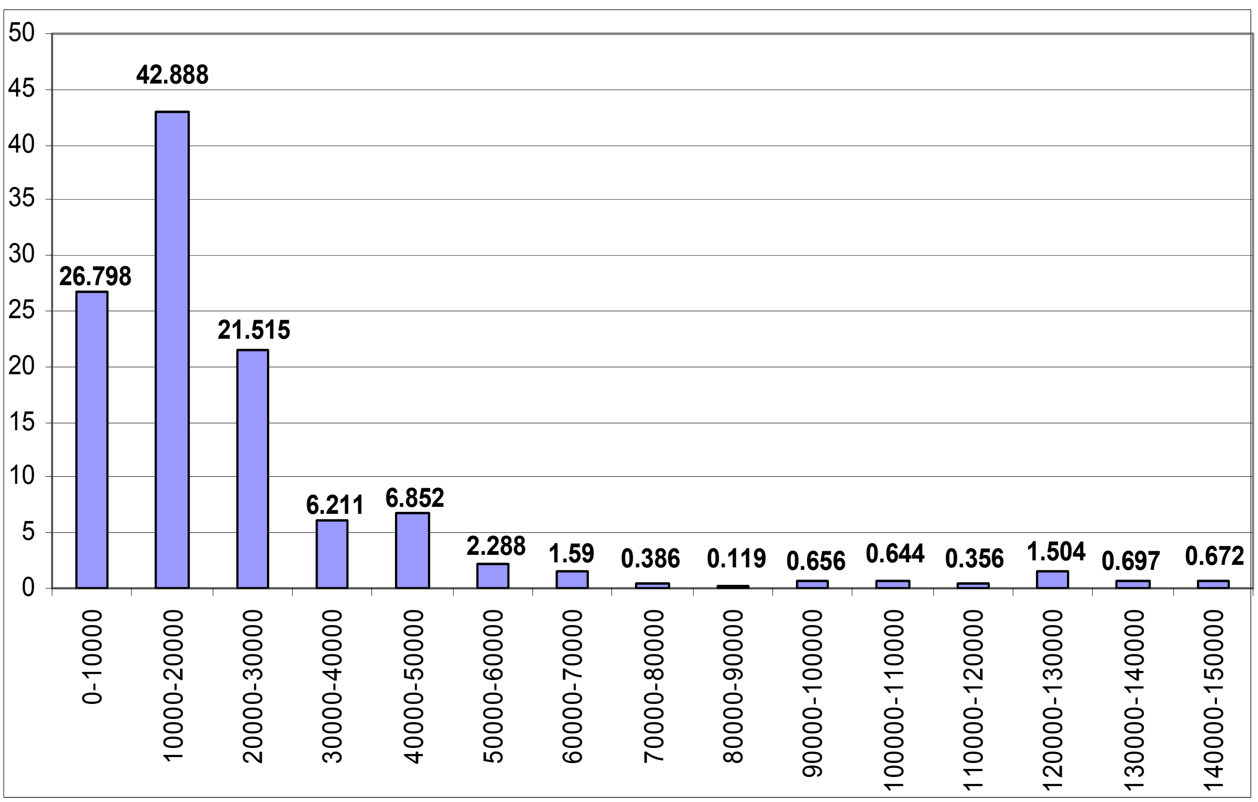



**Figure E-2:** Annual Average Daily Traffic (AADT)

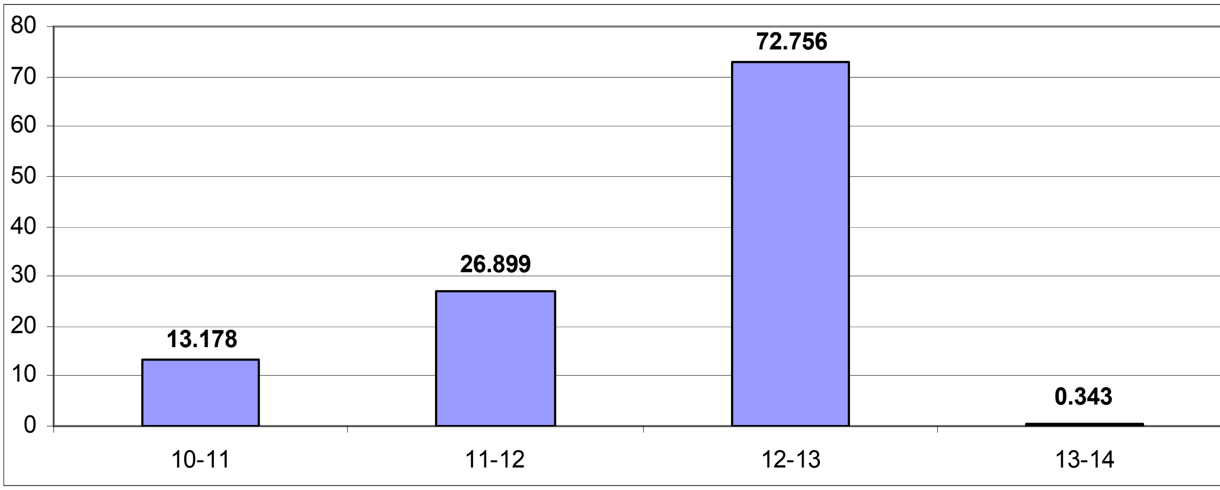



**Figure E-3:** Lane Width (ft) [Decreasing Milepoint]

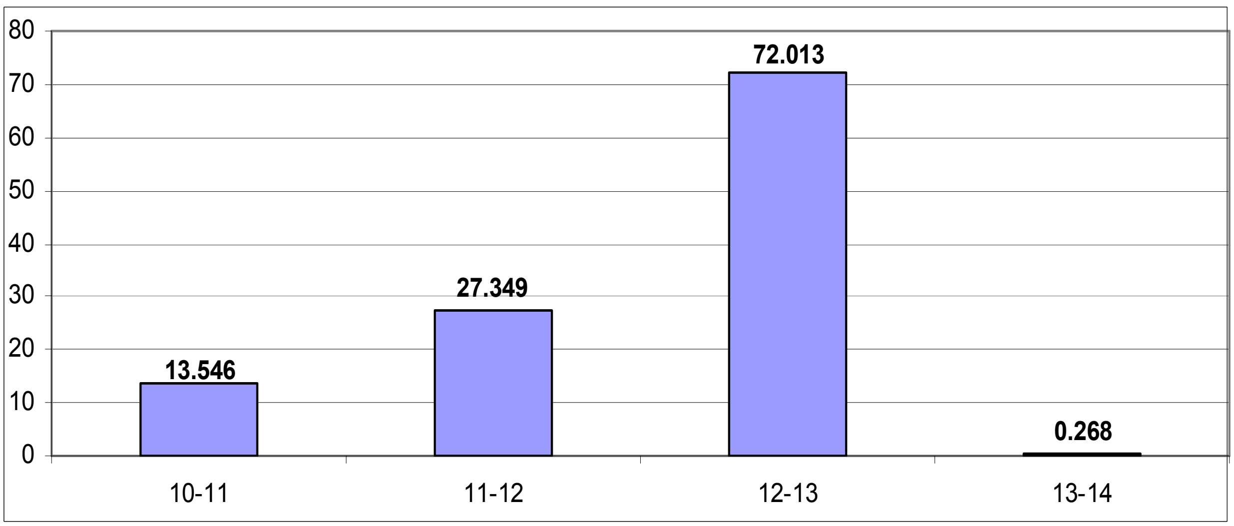



**Figure E-4:** Lane Width (ft) [Increasing Milepoint]

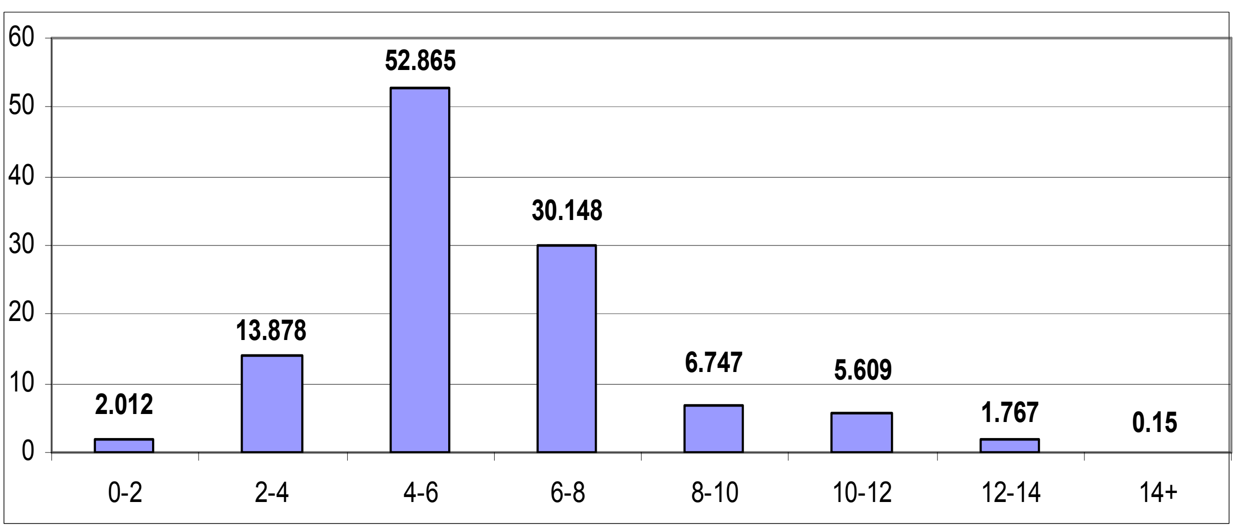



**Figure E-5:** Inside Shoulder Width (ft) [Increasing Milepoint]

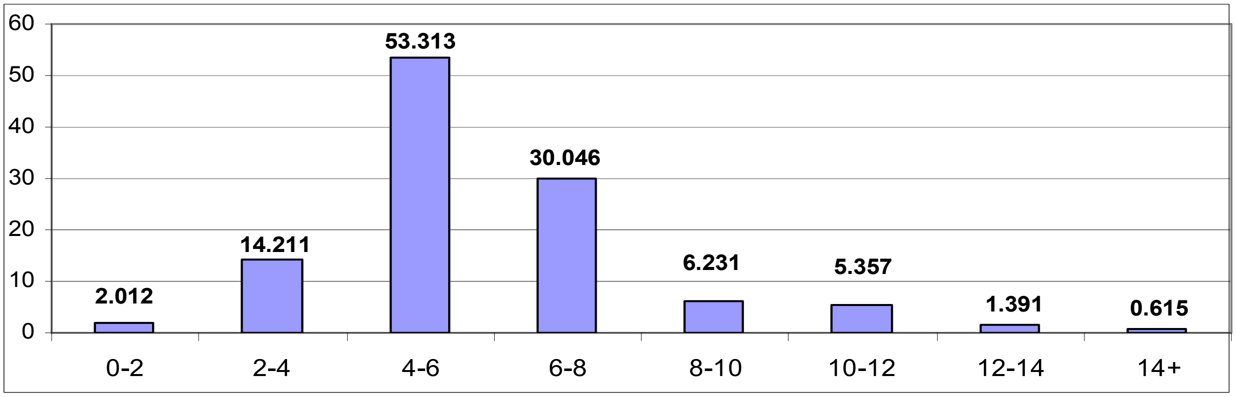



**Figure E-6:** Inside Shoulder Width (ft) [Decreasing Milepoint]

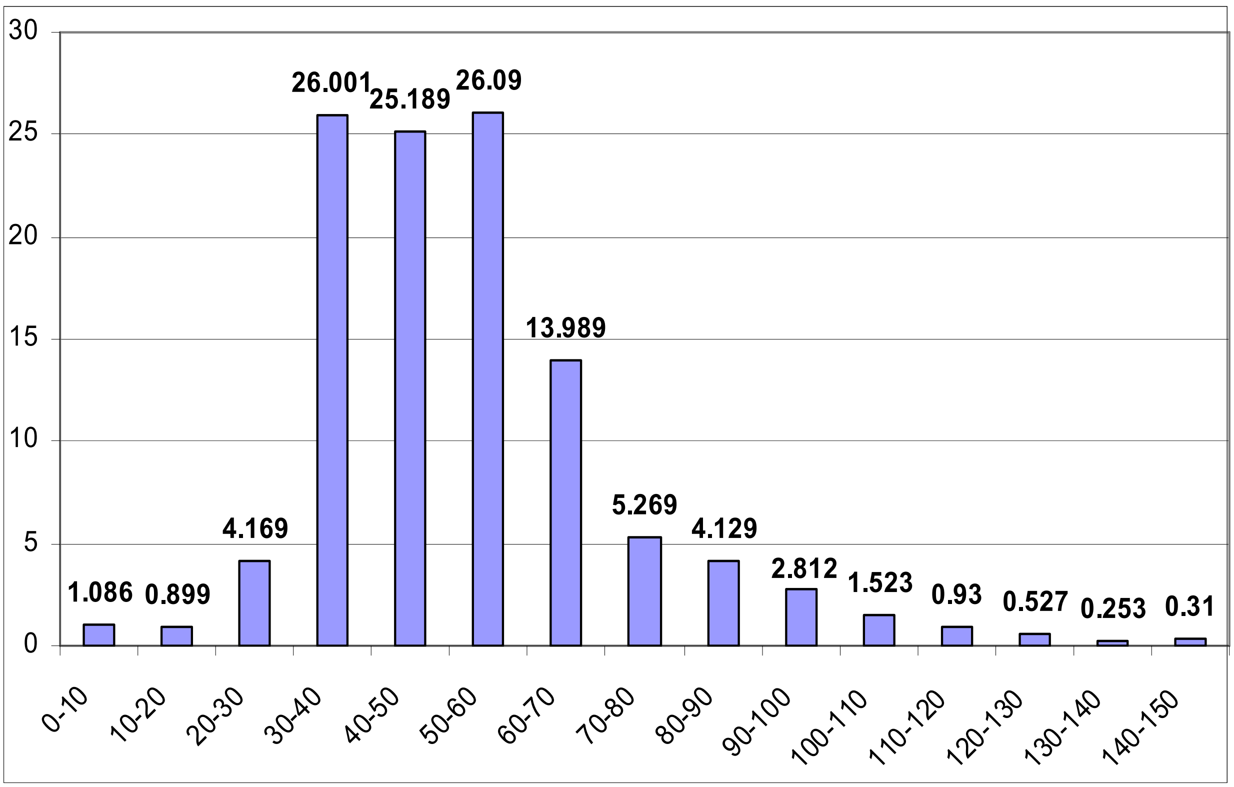



**Figure E-7:** Median Width (ft) [Not Including Inside Shoulders]

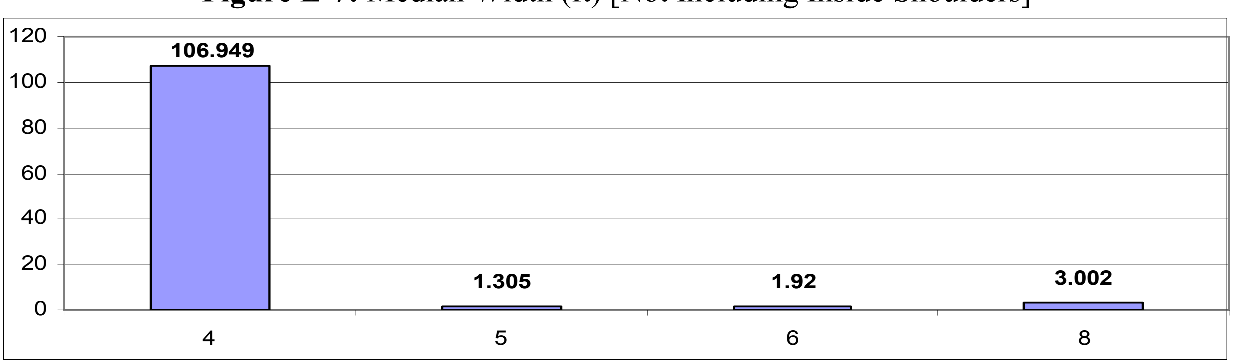



**Figure E-8:** Total Number of Lanes (Both Directions)

# Driver Workload and Performance on an Interstate with Posted Speed Limits of 70 and 80 mph

Prepared for
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Southwest Region University Transportation Center

August 7, 2008

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During his undergraduate career James devoted his free time to helping others through organizations such a Circle K International and the Knights of Columbus. Some of his fondest memories involve tutoring underserved students in the South Bend community and his participation in research on motivation in middle school math classrooms. During his last semester at Michigan State University James will serve as the lead tutor for the college of Engineering ROSES program, a community living option for first and second year undergraduate engineering students that provides support in all aspects of the college experience.

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**SUMMARY**

In this preliminary investigation of driver workload and visual capabilities at high speeds, fourteen subjects drove the Texas Transportation Institute instrumented vehicle along a section of interstate in west Texas where the speed limit changed from 70 to 80 mph. Four of the subjects were female, and the average age for the total was 48 years with the minimum of 20 and maximum of 71. A Dewetron 5000 computer synchronized three video cameras, sub meter GPS, lane tracking, and forward radar unit every tenth of a second. The forward viewing camera, driver viewing camera, and other synchronized devices were used to code the presence of vehicles around the instrumented vehicle along with driver non-forward glance rates and hand placement. These data were further reduced using computer macros to investigate the differences in lane geometry, vehicle velocity, lateral offset, driver non-forward glance rates, and driver

hand positions in the two speed conditions. Vehicles traveling in the left lane were found to offset further to the left than vehicle traveling in the right lane in the 70 mph condition. This same difference was not found in the 80 mph condition presenting the possibility in difference between the two speed conditions and driver's lane maintenance. No measured practical differences in roadway geometry, vehicle velocity, driver non-forward glance rates and driver hand placement between the two available speed conditions were found. Recommendations were developed for the next step in this two year study.

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## INTRODUCTION

In Project 0-5544 Texas Department of Transportation (TxDOT) sought to develop design criteria for high speed facilities. High speed facilities were defined as 70 to 100 mile per hour. One of Project 0-5544's conclusions was the need for research to be conducted related to driver performance, workload, and visual capabilities at these speeds. TxDOT Project 0-5911 was created to investigate those question posed by Project 0-5544.

TxDOT Project 0-5911 is a two year study interested in driver workload and visual capabilities at high speeds. Due to a lack of collective knowledge of driver behavior at these speeds an expansive study is being conducted which includes a preliminary research stage. This preliminary research stage includes a test track following distance study, open road driving study, and driving simulator study. These three preliminary studies are being conducted to evaluate the most effective way for the second half of Project 0-5911 to be conducted.

This paper encompasses the reduction and analysis of the preliminary open road data collection study using the Texas Transportation Institute (TTI) instrumented vehicle. These data were collected as the instrumented vehicle drove from the test track study to study headquarters and back along a 70 mile stretch of interstate, which had a posted speed limit changing from 70 to 80 mph along its route. This section of interstate was selected due to its proximity to the test track and change in posted speed limit along the route. Specific questions to be answered by this portion of Project 0-5911 were:

1. Is vehicle lateral offset different for horizontal curves than tangent sections of the road at high speeds? Does lane of travel affect these values?
2. Is the lateral offset different between speed conditions? Does lane of travel affect these values?
3. What is the relationship between speed limits and actual velocity of vehicles at these speeds?
4. Is there a change in driver glance rates between speed conditions? Does lane of travel affect these values?
5. Does driver hand placement and number of hands on top of the steering wheel vary between speed conditions? Does lane of travel affect driver hand placement?
6. How can data collection methods be changed in the final study to provide relevant data more efficiently?

These questions were answered through the performance of a literature review and the development of data reduction methods to be used with the TTI instrumented vehicle.

## LITERATURE REVIEW

In TxDOT Project 0-5544, design criteria were identified for design speeds of 85 to 100 mph (*1*). Engineering judgment and extrapolation were used in the absence of previous research on driver performance at these speeds (*1*). A specific area of interest was driver workload and visual acuity. Previous comprehensive research was conducted at speeds below 60 mph (*2*).

**Driver Characteristics**

According to the Virginia Tech Transportation Institute 100 car study, 93% of vehicle collisions and 68% of near collisions with lead a vehicle were found to have driver inattention as a contributing factor (*3*). Driver inattention encompassed secondary task engagement, fatigue, non-specific eye glances, and driving-related inattention to the forward roadway. Classical understanding only looked at secondary task engagement and fatigue. Task engagement and fatigue are part of a single construct referred to as driver arousal level (*4*). According to the Yerkes-Dodson law driver's quality of performance is based upon their arousal level. Driver performance level has been found to be poor at both low and high levels of arousal. Figure 1 shows the effect that arousal level has on quality of performance when conducting simple and complex tasks. This theory suggests simple tasks such as lane keeping are less affected by arousal than a complex task such as avoiding an unexpected object in the roadway.

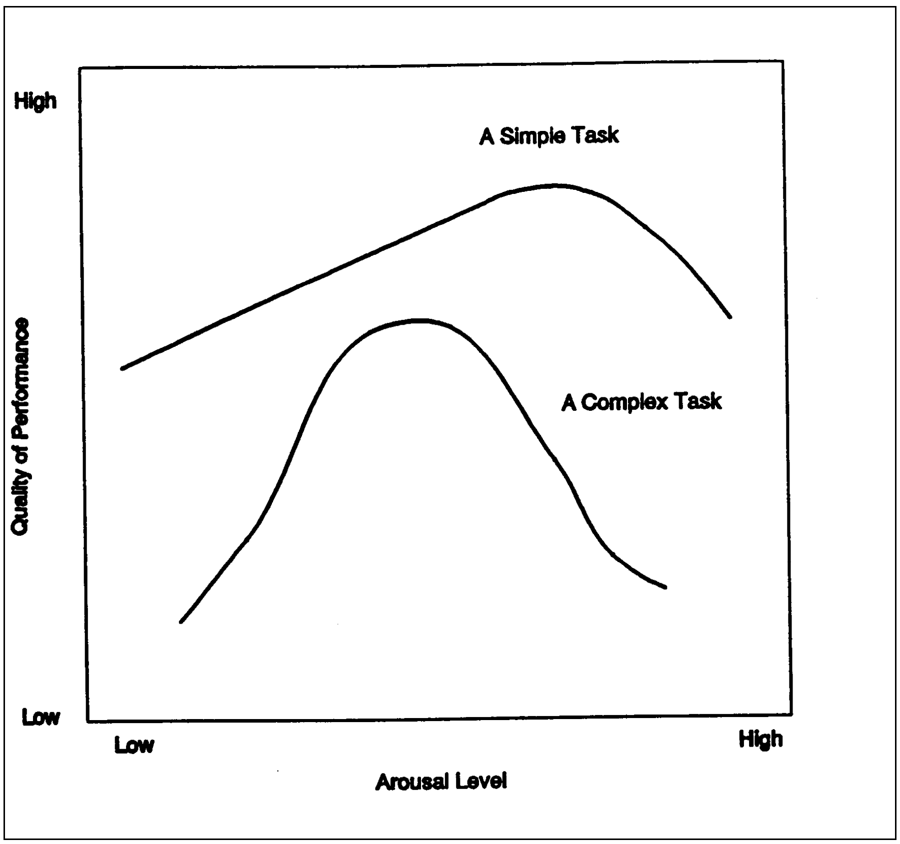


**Figure 1. Effect on Task Performance as Arousal Level Increases**

Simonov's (*5*) "Information Theory of Emotions" work describes a similar pattern when looking at workload. When experiencing extremely high or low levels of workload, performance declines. At intermediate levels performance is generally at an improved level. Hancock's illustration of this phenomenon could be considered more realistic, when considering driving, view of performance (*6*). Figure 2 shows Hancock's theory which includes a wide "comfort zone" that covers a workload range which is found during more normative driving. As the driver becomes more or less stressed their ability to adapt, perform, becomes compromised. Also illustrated is instability in the system at the extreme ends of stress level. This suggests it is difficult to accurately predict how people will perform in hypo stressed and hyper stressed situations. In the middle levels drivers can adjust physically and physiologically to deal with stress so it does not affect their performance.

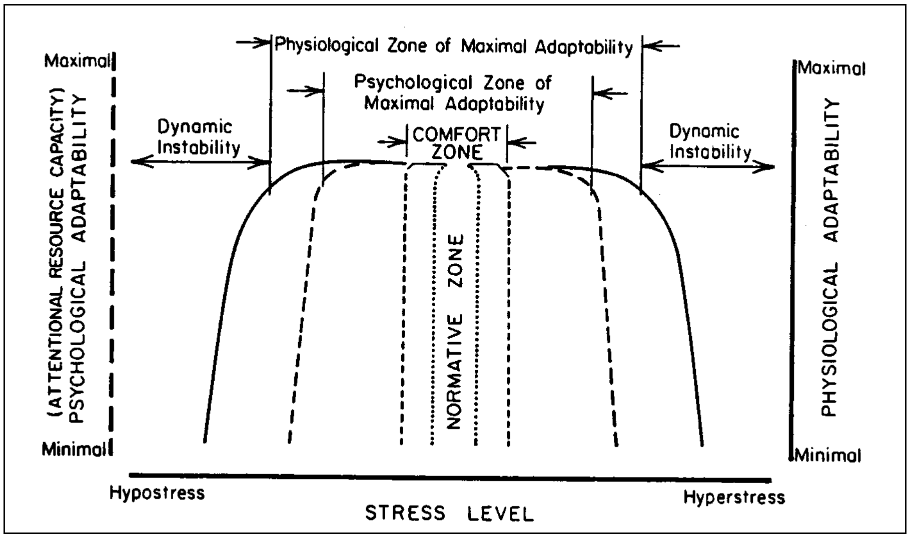


**Figure 2. Physiological and Psychological Adaptability as a Function of Stress**

## Mental Workload

The primary method for measuring driver stress, fatigue, engagement, and arousal level is through the construct of mental workload (*7*). Mental workload refers to the amount of effort and limited processing capacity required to interpret all of the stimuli provided to perform necessary driving and non-driving tasks. Mental workload is primarily measured using subjective, performance, and psycho physiological methodologies.

### *Subjective Measures*

These measures obtain a rating of mental workload based on the driver's assessment of the experience. Their scales are primarily defined by three different approaches. First, these assessments can occur immediately, retrospectively, or at both times. Second, subjective measures are either unidimensional or multidimensional. Third, subjective measures provide either an absolute or relative measurement.

The NASA-Task Loading Index (TLX) and the Subjective Workload Assessment Technique (SWAT) are widely used subjective assessments. The TLX and SWAT are measured immediately, are multidimensional, and provided an absolute rating. This type of measure is extensively used in a wide range of areas (*7*). The NASA TLX is widely used when assessing aircraft pilot mental workload (*8*).These measures are used because of to their ease of use, face validity, and driver acceptance.

*Performance Measures*

Performance measures use deterioration or erratic performance as an indication that workload is reaching an unacceptable level (*7*). This assumes that drivers have limited workload capacity and that as driver capacity is overloaded performance diminishes (*4*). Performance can be evaluated through the use of primary and secondary tasks. In the primary task method the driver's ability to perform the primary task of driving is measure directly (*7*). Using the secondary task method driver workload is measured indirectly through a secondary task. Drivers are instructed to focus on the primary task of driving and do the best they can on the secondary task. The driver's ability to perform the secondary task without jeopardizing the primary task performance provides a measure of the excess workload capacity remaining to the driver (*7*).

Secondary task measures are widely used in measuring driver workload. If driver performance on the primary task of driving were to falter then the testing environment would become dangerous. Through the use of secondary task performance measures a safe testing environment can be maintained. The use of performance measures can be intrusive and thus change the way the task of driving is performed. The use of word games and easy to reach secondary controls can elevate some of this intrusion.

With improvements in technology two types of performance measure are becoming more prevalent in the measurement of visual workload. These measures involve the use of eye tracking technologies and occlusion devises. These methods measure visual workload directly by looking at driver gaze patterns and visual need. These measures have been shown to be highly correlated with visual demand and the technologies making these measures possible have made the psychophysiological measure of blink rate more viable in the natural driving environment.

*Psychophysiological Measures*

Psychophysiological measures look at changes in driver physiology associated with cognitive task demand (*7*). Heart rate, blink rate, and brain activity have been used and associated with certain cognitive demands. Eye blink rate has been used extensively in driver workload measures of visual demand. Heart rate and brain activity have also been used while measuring workload in pilots.

Heart rate and brain activity measures have been shown to contain high variability, lag time, and the equipment is generally intrusive. This is to say the changes in heart rate and brain activity both tend to lag behind the actual increase in demand and there seems to be large viabilities between subjects making it difficult to measure. The equipment used in these measures can also interfere with the driver's ability to perform the task of driving, and in some instances raise the workload of participants not use to such equipment or uncomfortable with it.

**Sensory Input**

The five traditional senses are vision, hearing, smell, taste, and touch. Proprioception or kinesthesia describes driver's perception of body parts in relation to each other. Driver situational awareness is a function of these senses (*9*). For many years the visual sensory input level was assumed to account for 90% of the sensory input received by the driver. This number has been shown to have no empirical validation yet is still widely accepted (*10*). The research does suggest that visual input is the most important sensory input to the driver but until empirical evidence is found the value of 90% should not be used (*10*).

Besides visual input hearing, touch, and proprioception are considered inputs that are used by drivers while performing the task of driving. These senses combine to provide feedback to the driver about vehicle performance and the driving environment. Drivers have high sensitivity to changes in this feedback whether it is tactile, auditory, or vibratory (*9*). While drivers have been shown to have high sensitivity to changes in feedback they do not seem to be aware of this sensitivity (*9*). It is believed advances in vehicle technology could inadvertently remove situational feedback without drivers compensating for this change.

**Perception Reaction Time**

Perception reaction time is the amount of time it takes for a driver to detect a danger, recognize it as danger, decide on a course of action, and begin to take action. These judgments are a function of perceived following distance, perceived time to contact, and driver experience (*11*, *12*). Fambro and his colleagues confirmed that a 2.5s minimum AASHTO stopping sight distance encompasses most of the driving population (*13*). This time includes both the Perception Reaction Time and the time for vehicles to slow to a stop. These studies were conducted at speeds of 55 mph or lower.

**Perceived Risk and Risk Homoeostasis**

Part of perception reaction time is the driver's judgment of a dangerous situation. The driver's judgment is a result of their recognition of the perceived risk. Kruysse suggests a majority of dangerous judgments are made at the onset of the conflict (*14*). Risk homoeostasis theory implies that drivers have a level of risk in their driving which they are willing to accept and that as technologies improve vehicle safety drivers will perform more dangers driving maneuvers (*15*).

While risk homoeostasis is under debate, Fuller suggests there are three basic uses of the term risk (*16*). According to Fuller risk has been used to describe objective risk, subjective risk, and a feeling of risk (*16*). Objective risk is the statistical probability of being involved in an accident. Subjective risk is the driver's estimate of the objective risk. The driver's feeling of risk is an emotional response to threat such as a feeling of anxiety. These assessments of risk have been related to driver's feeling of control. This feeling of control is assumed to be the inverse of the difference between the demanded ability and capability of the driver (*16*). Thus, as demand increases or capability decreases the feeling of control decreases. This feeling of control is associated with the perceived risk of the situation.

**Driver Trait and State Factors**

Driver trait factors are related to the driver in general and state factors are related to the particular driving experience in question. A strong correlation between reckless driving behavior and the trait factors of aggressiveness and sensation seeking has been found (*17*). Angry drivers are also correlated with reckless driving behavior. Adolescent boys tend to have high ratings of sensation seeking, aggressiveness, and episodes of anger than adolescent girls (*17*). Driver age is another trait factor of concern. Drivers over the age of 65 have higher crash ratio's than drivers of other ages when performing left turns, gap acceptance, and lane changes (*18*).

**Speed Adaptation**

As driver's experience higher speeds for longer periods of time their estimation of lower speeds becomes less accurate (*19*). Schmidt and Tiffin found that as vehicles traveled at 70 mph for 20, 40, and 60 minutes total the driver's estimation of when the vehicle was traveling at 40 mph became less accurate. Drivers having traveled 70 mph for 20 minutes estimated 44.5 mph as 40mph, those going for 40 minutes estimated 50.5 mph as 40 mph, and those going 60 minutes estimated 53.4 mph as 40 mph (*19*). Speed adaptation is important to consider in the design of higher speed facilities because the effects at those speeds are unknown.

**Driver -Vehicle Interaction**

The modern vehicle has many components that compete for driver attention. Radios have been in vehicles for quite some time but recently MP3 players, blue tooth technology, navigation devices, and other intelligent transportation systems are beginning to find their way into the cab. These devices compete with other components of the vehicle, steering wheel and feedback instrumentation, necessary for proper vehicle operations. Vehicle size and driver placement within the cab also affect driver's ability to perform the primary task of driving such as maintaining proper following distance.

**Vision Occlusion**

Driver's judgment of following distance is based on the amount of road visible in front of the vehicle (*11*). The amount of road visible is affected by the size of the following vehicle's hood and driver eye height. One study looked at lead vehicles affect on this perception and no difference was found. Raising the driver's eye height thus allowing them to view more of the roadway did increase subjects' rating of following distance.

While larger vehicles may be on the conservative side of following distances this is not true of their blind spots. Larger vehicles have larger blind spots (*20*). Blind spots are locations around the vehicle that the driver cannot view with the use of mirrors and must change their gaze pattern to detect the presence of a vehicle. Even when the driver looks, some vehicles create blind spots so large that detecting another vehicles presence may be difficult or impossible (*20*).

**Driver Hand Placement**

Modern vehicles also contain more advanced devices for driver comfort such as electronically controlled mirrors, and seats. Many steering wheels now contain radio controls along with the cruise controls. While many of these features are intended to make driving more enjoyable, they are still competing for driver attention. The steering wheel is the primary method for vehicle trajectory control (*21*). A hand position of ten and two has been assumed to provide maximum vehicle controllability.

Survey data confirmed that drivers perceive a hand position of ten and two as providing more vehicle control than other hand positions (*22*). In a study comparing perceived risk and driver hand placement it was found that in situations where there is a higher perceived risk drivers place more hands on the top of the steering wheel (*22*). There does seem to be a difference between observed and reported typical hand placement. Drivers tend to overestimate themselves having more hands on top of the steering wheel.

**Driver-Vehicle Interaction with the Driving Environment**

As mentioned previously drivers primary method for interacting with the driving environment is through vision. Vision occurs through windows in the vehicle and the mirrors contained on the outside. Blind spots are dangerous points surrounding the vehicle where other vehicles are difficult to detect. Through the use of frequent mirror checks surrounding vehicles can be tracked and their presence in blind spots can be more easily discovered. On the German autobahn the use of the rearview mirror is strongly encouraged due to the approach of vehicles traveling at high velocities (*23*). Drivers of the autobahn are also encouraged to perform passing maneuvers quickly to limit their time next to other vehicles and passing on the right is never allowed (*23*). The right side of a vehicle has the largest blind spot (*20*).

**Mirror Check and Gaze Patterns**

Mirror checks are only a portion of a driver's gaze pattern. Driver gaze patterns involve all the objects inside and outside the vehicle that the driver fixates upon. Fewer mirror checks and longer fixations are often found in instances of higher workload (*24*,*25*,*26*,*27*). A report conducted for Transport Canada found the drivers spend 78% of their time looking forward when performing no cognitive tasks. As tasks of increasing difficulty were added the percentage of time drivers spend looking forward increased (*24*). In the same conditions the percentage of time checking mirrors decreased indicating a drop in this secondary task as cognitive demand increases. In another study it was found that as vehicle speed increases driver gaze patterns become narrower indicating an increase in driver workload (*27*).

**Perception of Forward Objects**

Forward objects are any obstacles that present themselves in front of the driver. The first step in avoiding a collision is to recognize the presence of an object, first step in perception reaction time. These objects must be detectable in both daylight and night time conditions. In most cases this object is another vehicle (*28*). Non-object characteristics of the roadway such as signs and curvatures also need to be recognizable to the driver (*29*, *30*, *31*, *32*). The number of cues available to drivers at night is relatively small in relation to the amount available during the day (*29*). During the nighttime hours, sign and pavement marking reflectivity are important for they provide the primary cues for roadway curvature and direction of drivers (*29*).

### Visual Demand

Visual demand is a portion of driver workload related to the amount of time a driver must fixate on an object or objects. Some roadway geometries require a longer fixation and thus increase visual demand (*30*,*31*,*32*). There is an inverse relationship between curve radius and visual demand (*32*).

### Sight Distance

As noted in the AASHTO *Green Book* (*33*), a driver's ability to see ahead is of the utmost importance in the safe and efficient operation of vehicle on the highway. Sight distance is the length of the roadway ahead visible to the driver. This distance should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in the path of travel. Stopping sight distance includes the distance travel by the vehicle during perception reaction time and the distance required by the vehicle to come to a complete stop. The 2004 *Green Book* uses values for driver eye height and object height identified in a mid-1990s study (*34*). Horizontal and vertical curve designs are based on these driver eye heights and object heights along with stopping sight distance.

### Time-To-Contact Estimations

When driving on multilane freeways the most common object encountered by vehicles is other vehicles (*35*). Time-to-Contact estimation is the driver's assessment of the time it will take for their vehicle to contact the lead vehicle if their velocities remain constant. It has been shown that drivers underestimate their time to contact judgments and that as closing speeds increase these estimates become more accurate (*35*,*36*). These studies paced a subject driver closely following a lead vehicle which suddenly braked. In these situations, as opposed to studies of object avoidance, drivers chose to brake rather than performing a lane change maneuver. Given a greater amount of time to choose their method of avoidance drivers will exhibit uncertainty and take more time to make their decision (*35*,*36*).

## DATA COLLECTION

All data collection procedures were approved by the Texas Transportation Institute Internal Review Board (IRB). All TTI personal involved in the collection and reduction of these data completed training required by the IRB for work with human subjects.

### Subjects

Fourteen subjects participated in an initial study of driver workload and visual capabilities at 70mph and greater speeds. The subjects had an average age of 48 years with a minimum of 20 and maximum of 71. The average number of years with a driver's license was 33 and four of the fourteen subjects were women.

These subjects were part of a test track following distance study and also drove the instrumented vehicle to or from the test track. An experimenter was responsible for shuttling the subject in whichever direction they were not responsible for driving. The intention was to have an equal number of subjects in both directions; however due to cancellations and no shows, ten subjects drove to the test track with only four driving the return trip.

The route chosen for the subjects between the test track and study headquarters was always the same and covered a stretch of interstate in west Texas were the posted speed limit changes from 70mph to 80mph in the west bound direction. When heading eastbound the speed changed from 80mph to 70mph in the same location

**TTI Instrumented Vehicle**

For the purpose of data collection the TTI Instrumented Vehicle was used. The Instrumented Vehicle is a Toyota Highlander equipped with multiple data collection systems synchronized by an onboard DEWE5000 made by Dewetron. This study used three synchronized camera views. Also synchronized with the cameras were an Assist Ware SafeTRAC device, Global Positioning System (GPS), Eaton Vorad Radar unit, and accelerometer. Data from each device were recorded every tenth of a second while subjects were operating the instrumented vehicle.

The available three camera views were out the front windshield, in cockpit, and of the driver's feet. These camera views can be seen in Figure 3. The Assist Ware SafeTRAC device collected data related to the instrumented vehicles position in the lane of travel. Lane potion was measured as offset from center of the lane of travel. Negative values are associated with an offset left of center and positive values an offset right of center.

**Figure 3. Cockpit (Upper Right), Driver's Feet (Lower Left), and Forward (Lower Right) Camera Views**

The Global Positioning System provided vehicle velocity and GPS coordinates with sub meter accuracy. The Eaton Vorad Radar provided distance and relative velocity for up to two different lead vehicles simultaneously. The radar had a maximum range error of 5% of the total +/- 3 feet and a maximum relative velocity error of 1% of the total +/- 0.2 mph.

## DATA REDUCTION

Dewesoft version 6.3 Rev. 7 was used to view the synchronized video, GPS, radar, and lateral offset data. All data reduced and analyzed in this paper are from the open road driving between the test track and study headquarters. The primary focus in this study was driver workload and behavior at high speeds, therefore non-interstate data were not reduced or analyzed. Two video coding runs were conducted and computer macros were used to reduce the collected data. The following explains the video coding methods used and assumptions made during data reduction.

### First Run Coding

The purpose of the first run coding was to determine the location of the Instrumented Vehicle on the interstate and the location of other vehicles in relation to the Instrumented Vehicle. The following are the event times recorded during the first run coding:

- Instrumented Vehicle Merges With The Interstate or Video Beginning
- Instrumented Vehicle Leaving the Interstate or Video Ending
- Other Vehicles around the Instrumented Vehicle
    - When neighboring vehicle appears in view
        - Vehicle Type
        - Vehicle Location
        - Vehicle Lane
    - When neighboring vehicle departs from view
- Instrumented Vehicle Lane Changes

If at any time one of the above events occurred all vehicles considered present at that time had their locations, lane, and type rerecorded. For example if a vehicle was already present and another vehicle became present, details about the first vehicle were recorded at the time the second vehicle arrived. In the same situation if the first vehicle left the presence of the instrumented vehicle details for the second vehicle were recorded at the time of the first vehicle's departure.

These event times do not cover the entire event but are only usable as reference markers. This was done so that future detailed analysis can be conducted on these data using consistent reference points. These coding methods were used to maintain high inter- and intra-rater reliability. What follows is a more detailed explanation of the codes used and event definitions.

*Lane Location Codes*

The same lane location codes were used for both the instrumented vehicle and non-instrumented vehicles.

- 1 = Vehicle located in the right lane
- 2 = Vehicle located in the left lane
- 3 = Vehicle performing a right to left lane change
- 4 = Vehicle performing a left to right lane change
- 5 = Vehicles located on an off or on ramp

*Vehicle Type Codes*

Vehicle codes only apply to non-instrumented vehicles.

- 1 = Motorcycle
- 2 = Car
- 3 = SUV or Van
- 4 = Pick-up Truck
- 5 = Flatbed truck
- 6 = RV
- 7 = Semi Truck
- 8 = Emergency Vehicle

Any Vehicle pulling a trailer other than a Semi Truck was given an additional coding of 1 in front of the number defined above. For example a motorcycle with a trailer was given a code of 11 and a car with a trailer a code of 12. All vehicles were given the coded they most closely resembled above unless it never came close enough to recognize. In these cases the vehicle received a vehicle code of 0.

*Vehicle Location Codes*

- 1 = Vehicle located in front of instrumented vehicle
- 2 = Vehicle located to the side of instrumented vehicle
- Vehicles behind the instrumented vehicle were undetectable and not coded

*Instrumented Vehicle Merging With and Exiting the Interstate*

The instrumented vehicle was considered as merging with the highway when the white line to the left of the vehicle was no longer visible through the forward viewing camera. An instance of this event can be seen in Figure 4. The first view shows the ramp gore line still present and the second view is the first instance where the line is no longer visible. The time where this second view occurs is the time recorded and all relevant event data were also be recorded such as the SUV present in front of the instrumented vehicle in Figure 4.

The instrumented vehicle leaving the interstate is coded similarly. When exiting the highway the time coded was the time when the end of the white line was no longer visible. Figure 5 shows this occurrence. The first frame is with the end of the gore markings still visible and the second is the first frame where it is no longer visible. The time where the second frame occurs was recorded along with any relevant data about other vehicles.

If these events do not occur then the first/last available synchronized video will be coded to mark what was occurring at the beginning/end of the available video.

**Figure 4. Instrumented Vehicle Merging with Interstate**

**Figure 5. Instrumented Vehicle Exiting Interstate**

*Presence of Other Vehicles*

Vehicles were considered present around the instrumented vehicle if they were visible through the driver side window, passenger side window, front window, or were picked up by the radar. The radar's maximum range is 500 ft.; however, accurate readings normally occurred within 450 ft. When the instrumented vehicle was not in the same lane as a leading vehicle there was a good chance, as the gap got smaller, that the radar would no longer register the lead vehicle. For this reason any vehicle within 160 ft, measured by the center skip line, was considered present even if the radar was not registering it.

Vehicles were defined as being present the first instance that any of the above occurred and times were also recorded when they changed locations around the instrumented vehicle. There are only three defined locations due to limited camera views.

- in front of the instrumented vehicle
- beside the instrumented vehicle (Left or Right)
- no longer present

Lane changes by other vehicles were not coded. If a vehicle changed lanes the change in location would not be coded until another event occurred. Vehicles present on on-ramps were only coded if the instrumented vehicle performed a lane changing maneuver or the vehicle on the on-ramp changed location around the instrumented vehicle. Vehicles were no longer considered present the first instant they were no longer visible through the passenger or driver side window or when they outdistanced the radar.

Figure 6 shows the instrumented vehicle passing another vehicle. In the left image we see the car in front of the instrumented vehicle. The instant the entire rear bumper was no longer visible to the front camera view that vehicle was considered to the side of the instrumented vehicle. The right image shows the car outside the passenger's side window. When no portion of the vehicle was present through that window the vehicle was no longer considered present.

**Figure 6. Instrumented Vehicle Passing a Car**

Vehicles approaching from the rear were considered first present when any portion of their vehicle was viewable through the passenger or driver side window. Vehicles are considered to be no longer to the side of the vehicle when the entire rear bumper is visible to the forward-viewing camera as seen in the left part of Figure 6. If this event occurred on the left side of the instrumented vehicle then the lane location for both the instrumented vehicle and vehicle present were given different codes but the qualifications for vehicle presence remained the same.

*Lane Changing*

Lane changes were only a coded event when the instrumented vehicle performed the lane change. Lane changes by vehicles around the instrumented vehicle were not coded. For example if a car passed the instrumented vehicle then changed lanes to be in front of the instrumented vehicle, this event was not coded. Non-instrumented vehicles changing lane during the coding of another event were given a lane location code for their destination lane. For example if a car moved from the left to right lane when another event occurred the vehicle changing lanes was given a lane location of right. During other coded events vehicles present have their location, lane of travel, and type recoded. At these times changes in lane by other vehicles would be accounted for.

Lane change time marks for the instrumented vehicle were obtained by placing the cursor at the highest or lowest peak that occurred during a lane change event. Figure 7 shows a lane change event demonstrated on the timeline by a spike in lateral offset and the cursor obtaining the time of this spike. The upper timeline demonstrates a right-to-left lane change event and the bottom timeline demonstrates a left-to-right lane change. These spikes occur at the point the lane tracker determines the lane of travel by the instrumented vehicle has changed.

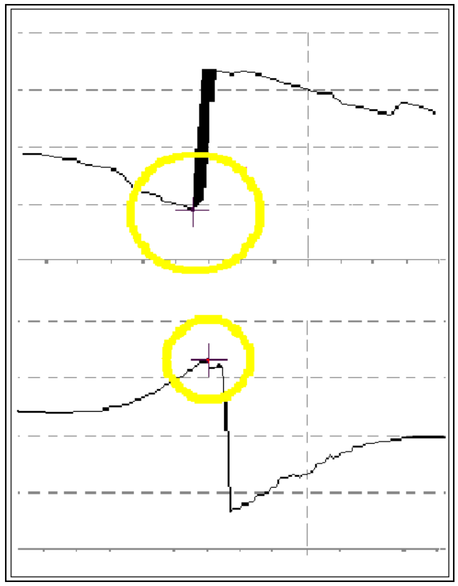

**Figure 7. Lane Changes Shown by Lateral Offset on Timeline**

**Second Run Coding**

The purpose of second run coding was to record the number and direction of non-forward glances made by drivers along with the location of their hands in 5 second intervals. This was a very time consuming endeavor and for this preliminary study only two 5 minute segments were coded. The segments were all tangents located in each of the two speed conditions allowing for comparison. These segments occurred approximately 15 minutes into each of the speed conditions.

*Coding Glance Rate & Head Movement*

Driver glance rates were primarily coded using driver head movement due to the video data quality. The coding of glance duration would have been difficult to achieve using the video available thus was not sought during this preliminary study. The direction of the head movement was coded from the driver's perspective and each glance was given only one direction. If a driver looked down and right it was given a code of down or right not both. The coded given was dependent on what the driver was perceived to be looking at. The following were the only movements recorded as glances during these coding runs:

- Glances at one of the three mirrors
- Glance at an object in the vehicle including other passengers
- Glances at the instrumentation panel or steering column. The only event coded as down.
- Blind spot checks

If a driver looks at the driver side mirror and then checks the blind spot, both events were coded even if their eyes never returned to a forward view between the two events. The same was true if a driver checks the rear view mirror and then proceeds to check the passenger side mirror in the same movement. In both cases if the coder can perceive two intentions by the driver than two events were coded.

In some instances drivers only moved their eyes and not their head. In the cases where these movements were visible they were given the proper coding that a head movement in that direction would be given. In the case of drivers with sun glasses, these types of coding were not possible.

*Driver Hand Placement*

Driver hand placement was recorded at the beginning and end of each five second segment. Each hand was coded separately and the following four codes were given:

- A driver's hand is considered on the upper half of the steering wheel if any portion of the hand is visible above the center of the steering wheel. The center of the steering wheel is defined by the top of the uppermost spoke connected to the hub. These events were given a code of (1).
- A driver's hand is given a code of (-1) if it is clearly visible to the driver view camera and is not grasping the steering wheel or another object.
- A driver's hand is given a code of (-2) if the hand is clearly visible to the driver view camera and it is grasping something other than the steering wheel.
- If a driver's hand does not meet any of the above criteria than it is given a coding of (0). A driver resting his/her hand on the shifter would be given such a code because the hand is not clearly visible to the available cameras.

**Dewesoft Exports**

The synchronized data from the Dewesoft program were exported into spreadsheets that contained all recorded data over the duration of the recording. These data from the coding were then incorporated into data files using the designed macros. Using the GPS coordinates from the file along with accelerometer data, the beginning and ending of horizontal curves were determined and everything in between was considered a tangent segment of roadway. These geometric data were incorporated into the spreadsheet files as well. The final spreadsheets in their raw form contained more than 60 variables and 40,000 synchronized data points.

**Final Data Reduction**

Final data reduction was conducted using macros that sorted these data files into separate worksheets by zone, lane, and geometry in order to develop exploratory results for this project in the form of charts and tables. If the Assist Ware SafeTRAC had a confidence of less than 90% those data points were eliminated from final analysis. These data were then made into five tables and nine charts exploring driver hand placement, lane position, and glace rates. To eliminate some bias due to lane changing events:

- Vehicles spending less than 30 seconds in a particular lane of travel and speed condition had their data for that segment removed before final analysis.
- Vehicles spending less than 15 seconds in a lane of travel within the zones were hand placement and eye coding took place had that section of data removed before final analysis.

These times were chosen because of the length of time a lane changing maneuver took and the proportion of the overall segment being analyzed. The results for this study are broken down into categories which correspond to the research questions being answered. All data are provided in both table and graph form.

**Lateral Offset & Lane Geometry**

Table 1 contains the lateral offset associated with the three geometric characteristic being broken down by lane of travel and speed zone. Table 1 also contains the standard deviation and total observations for each lateral offset. Figure 8 is a graphical representation of these data in Table 1. The first and last five minutes of observations were not included in these data. As noted previously negative values are offsets to the left of center in the lane of travel and positive values are to the right of center.

**Table 1. Average Lateral Offset by Lane and Lane Geometry**

| | Left Lane | | | Right Lane | | |
|---|---|---|---|---|---|---|
| Lane Geometry | Mean (in) | S.D. (in) | n | Mean (in) | S.D. (in) | n |
| 70mph Left | -10.79 | 15.78 | 4828 | -0.88 | 11.05 | 10776 |
| 80mph Left | -3.99 | 15.08 | 3581 | -3.55 | 11.22 | 13786 |
| 70mph Tangent | -9.49 | 15.69 | 33871 | -0.96 | 10.43 | 104826 |
| 80mph Tangent | -5.71 | 13.62 | 60910 | -2.34 | 10.75 | 178481 |
| 70mph Right | -8.42 | 16.13 | 4839 | 1.67 | 13.09 | 11045 |
| 80mph Right | -5.88 | 17.28 | 4887 | -0.69 | 13.56 | 15847 |

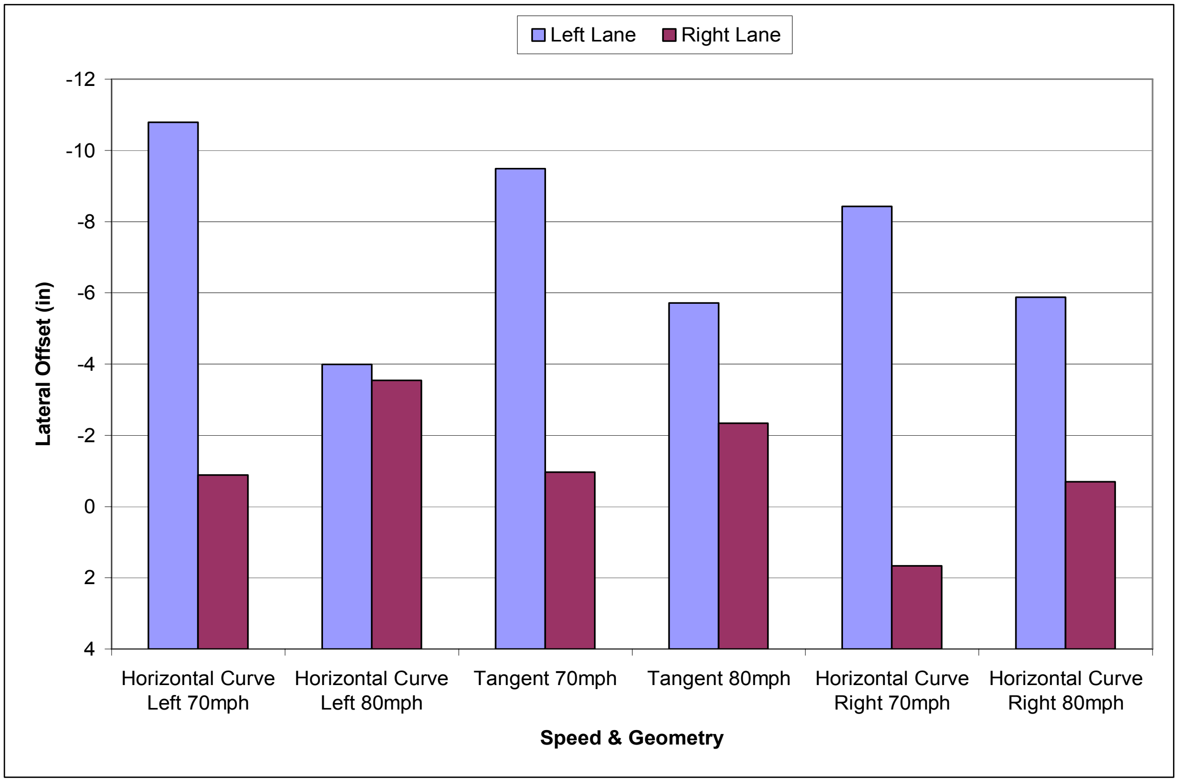


**Figure 8. Average Lateral Offset by Lane & Lane Geometry**

### Velocity & Lateral Offset

Table 2 contains the average velocity and lateral offset for the zones hand placement and head movements were coded. Table 2 also contains the standard deviation and number of observations for each measurement. Figure 9 is a graphical representation of the velocity data. Figure 10 is a graphical representation of the variance in velocity measure by standard deviation. Figure 11 is a graphical representation of the lateral offset broken by lane in each zone. Figure 12 is a graphical representation of the variance in lateral offset measured by standard deviation broken down by zone and zone by lane.

**Table 2. Average Velocity and Lateral Offset**

| | Velocity | | | Lateral Offset | | |
|---|---|---|---|---|---|---|
| Zone by Lane | Mean (mph) | S.D. (mph) | n | Mean (in) | S.D. (in) | N |
| 70mph Left Lane | 73.11 | 2.41 | 29442 | -8.49 | 15.63 | 29442 |
| 70mph Right Lane | 72.13 | 1.78 | 7462 | -1.17 | 8.91 | 7462 |
| 80mph Left Lane | 79.69 | 1.42 | 25487 | -7.89 | 16.59 | 25487 |
| 80mph Right Lane | 78.70 | 1.46 | 9075 | -2.00 | 10.89 | 9075 |

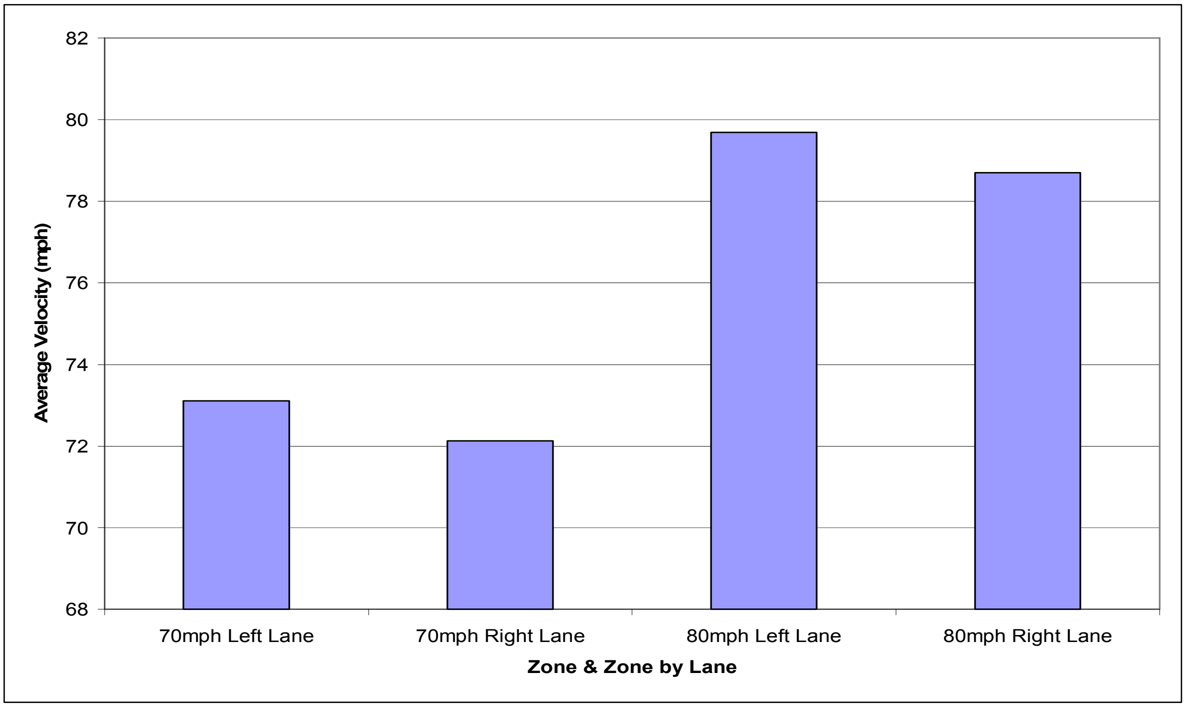


**Figure 9. Average Velocity by Zone & Lane**

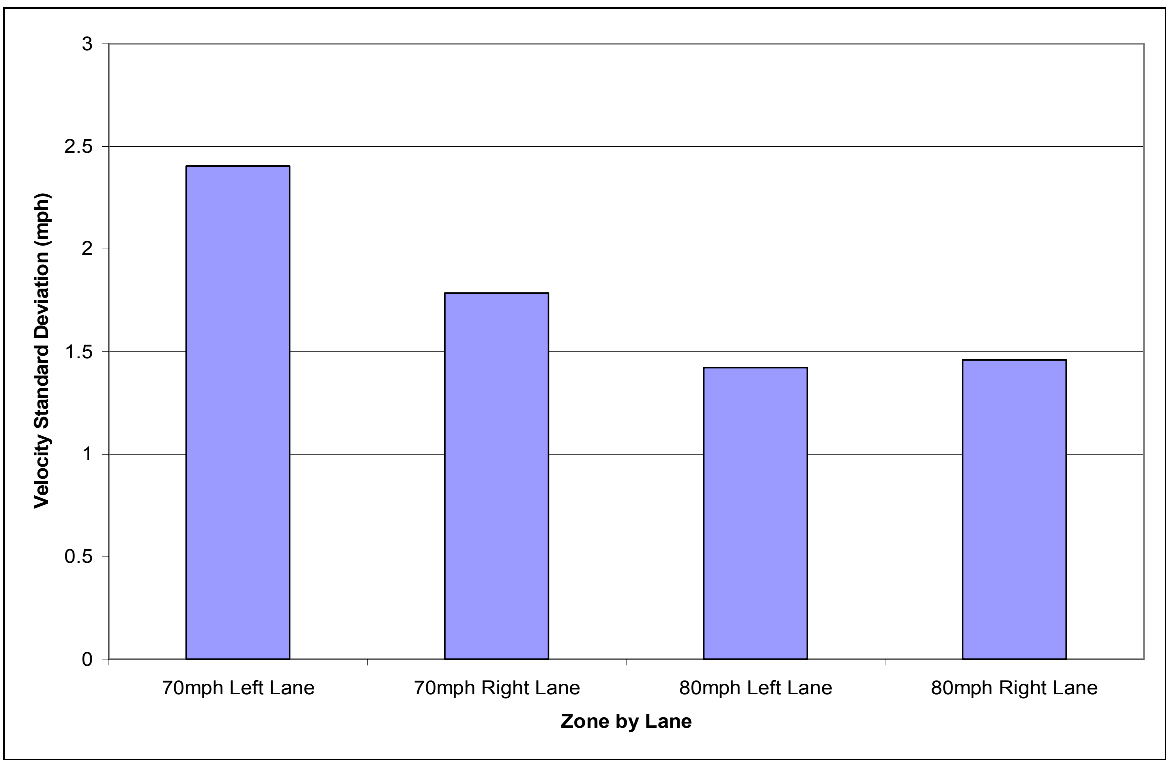


**Figure 10. Variance in Velocity by Zone & Lane**

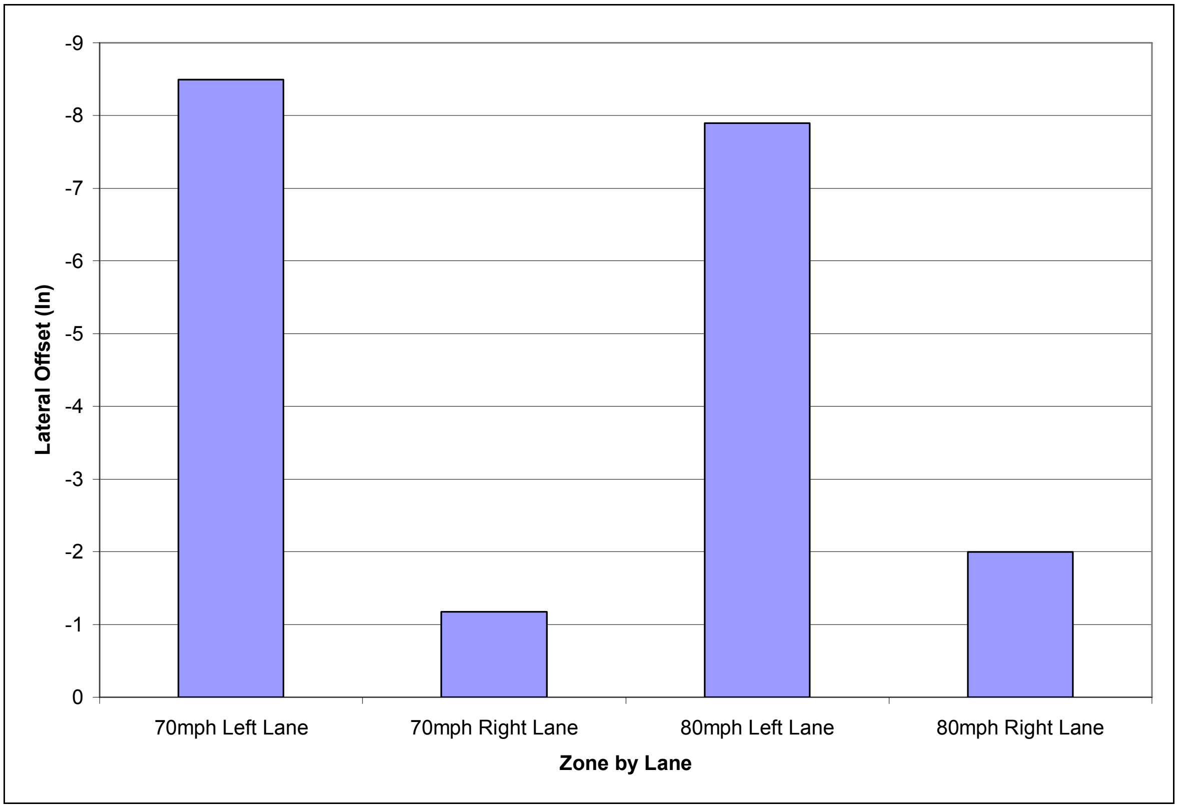


**Figure 11. Average Lateral Offset by Zone & Lane**

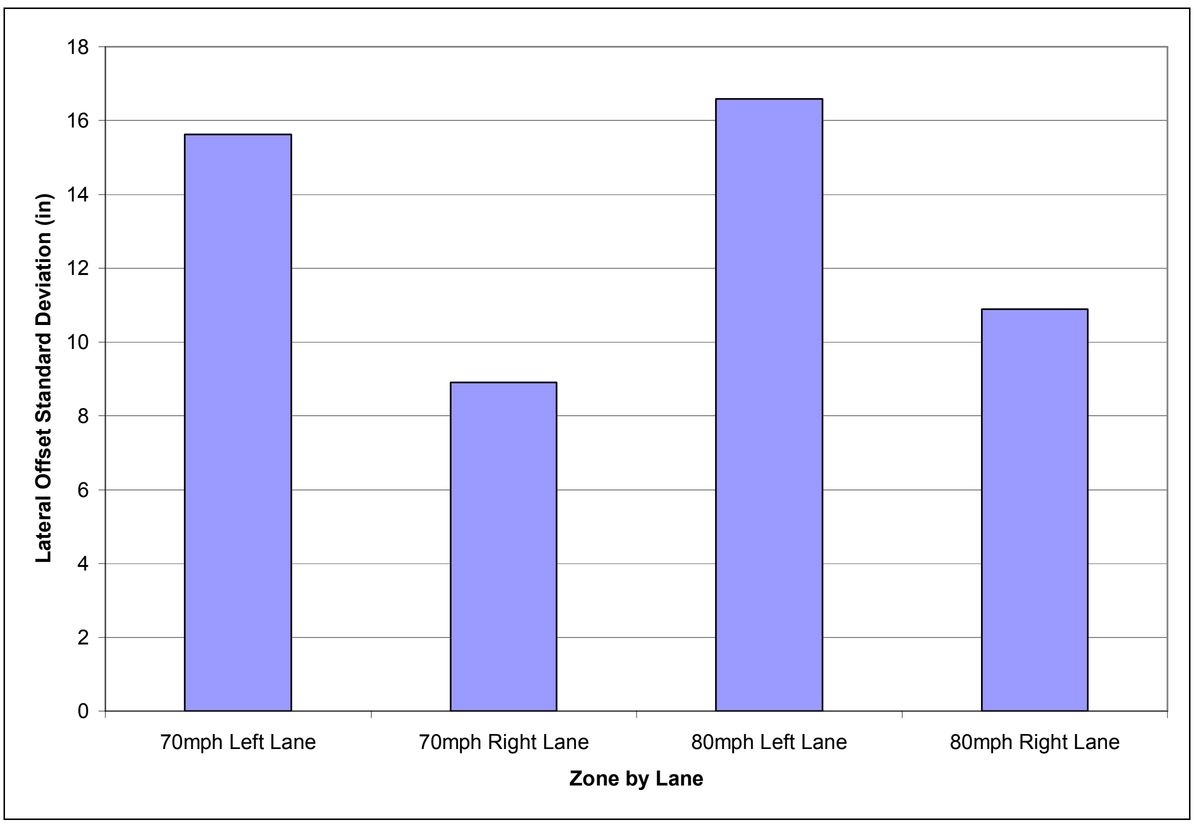


**Figure 12. Variance in Lateral Offset by Zone & Lane**

**Driver Glance Rate**

Table 3 contains the driver glance rate broken down by direction and zone by lane. Figure 13 is a graphical representation of these data. Forward glances were not taken into account in these observations.

**Table 3. Non-Forward Glance Rates by Zone & Lane**

| | Glances Per Minute | | |
|---|---|---|---|
| Zone by Lane | Left | Down | Right |
| 70mph Left Lane | 2.85 | 1.32 | 7.85 |
| 70mph Right Lane | 3.35 | 2.32 | 7.51 |
| 80mph Left Lane | 2.09 | 1.54 | 7.88 |
| 80mph Right Lane | 3.29 | 2.98 | 6.60 |

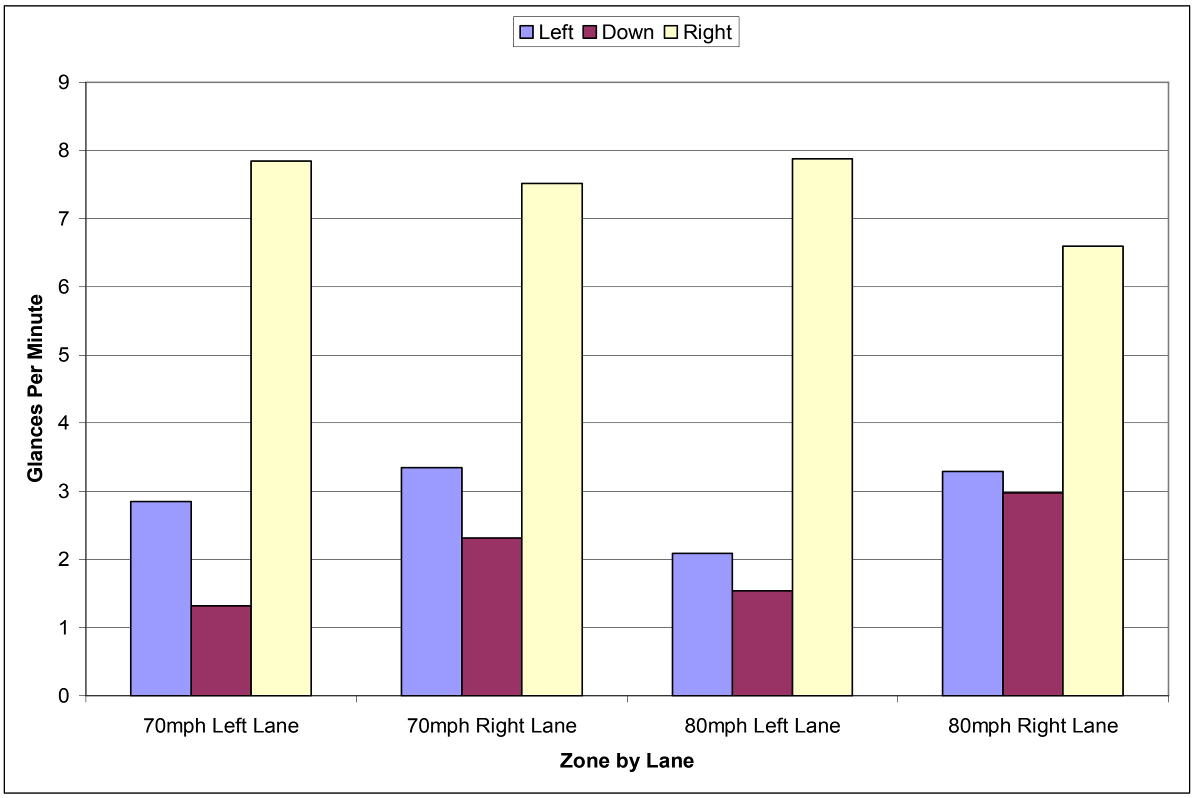


**Figure 13. Non-Forward Glance Rates by Zone & Lane**

**Driver Hand Placement**

Table 4 contains the percentage of time drivers' hands spent at the four coding location described above split by zone and lane. Figure 14 and Figure 15 are graphical representations of drivers' left and right hand placement, respectively, as a percent of total time. Table 5 contains the percent of total time that the driver had two, one, or zero hands on the top half of the steering wheel. Figure 16 is a graphical representation of Table 5.

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**Table 4. Drivers' Individual Hand Placement by Zone & Lane**

| Zone by Lane | Left Hand | | | | Right Hand | | | |
|---|---|---|---|---|---|---|---|---|
| | Top | Below | Off | Object | Top | Below | Off | Object |
| 70mph Left Lane | 73.92% | 22.30% | 3.76% | 0.00% | 45.21% | 49.08% | 5.71% | 0.00% |
| 70mph Right Lane | 77.97% | 17.98% | 4.04% | 0.00% | 30.21% | 62.64% | 6.99% | 0.17% |
| 80mph Left Lane | 67.63% | 25.62% | 6.75% | 0.00% | 28.76% | 66.22% | 5.02% | 0.00% |
| 80mph Right Lane | 63.17% | 30.70% | 3.97% | 2.16% | 47.86% | 45.65% | 5.63% | 0.86% |

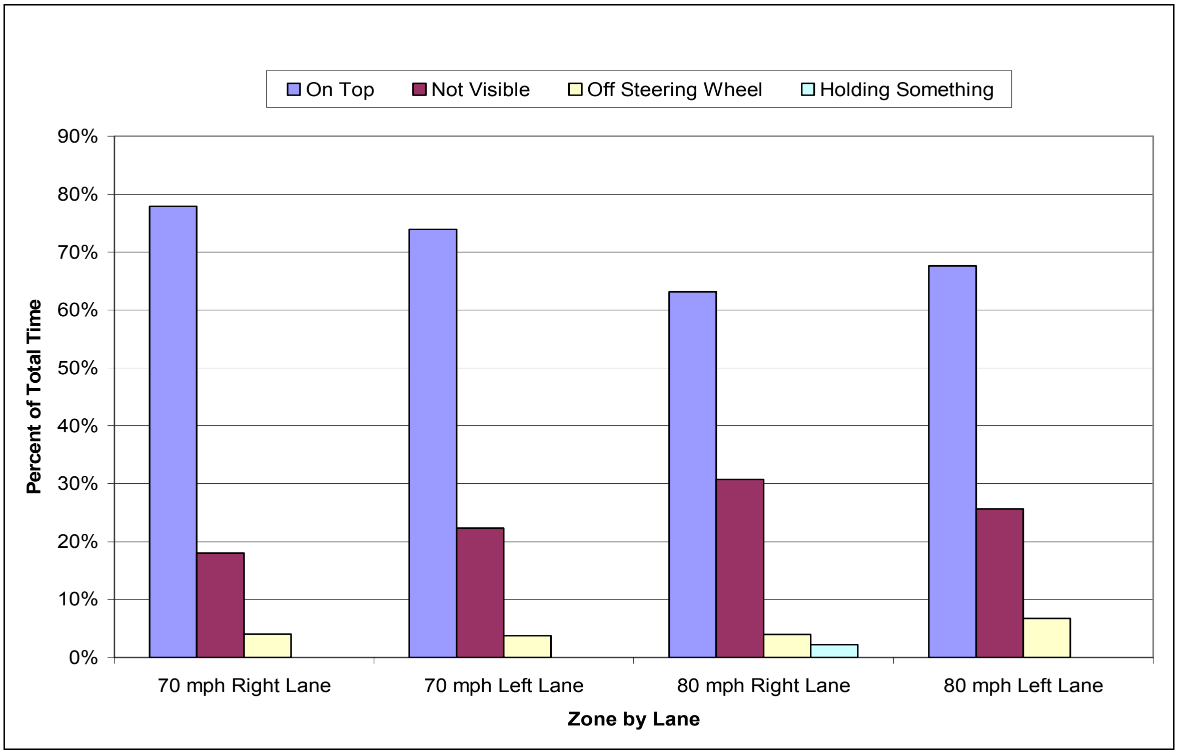


**Figure 14. Drivers' Left Hand Placement by Zone & Lane**

**Table 5. Number of Hands on Top Half of Steering Wheel by Zone & Lane**

| Zone by Lane | Hands on Top | | |
|---|---|---|---|
| | 2 | 1 | 0 |
| 70mph Left Lane | 36.43% | 46.27% | 17.30% |
| 70mph Right Lane | 31.26% | 50.35% | 20.74% |
| 80mph Left Lane | 26.15% | 44.10% | 29.75% |
| 80mph Right Lane | 32.67% | 45.53% | 21.81% |

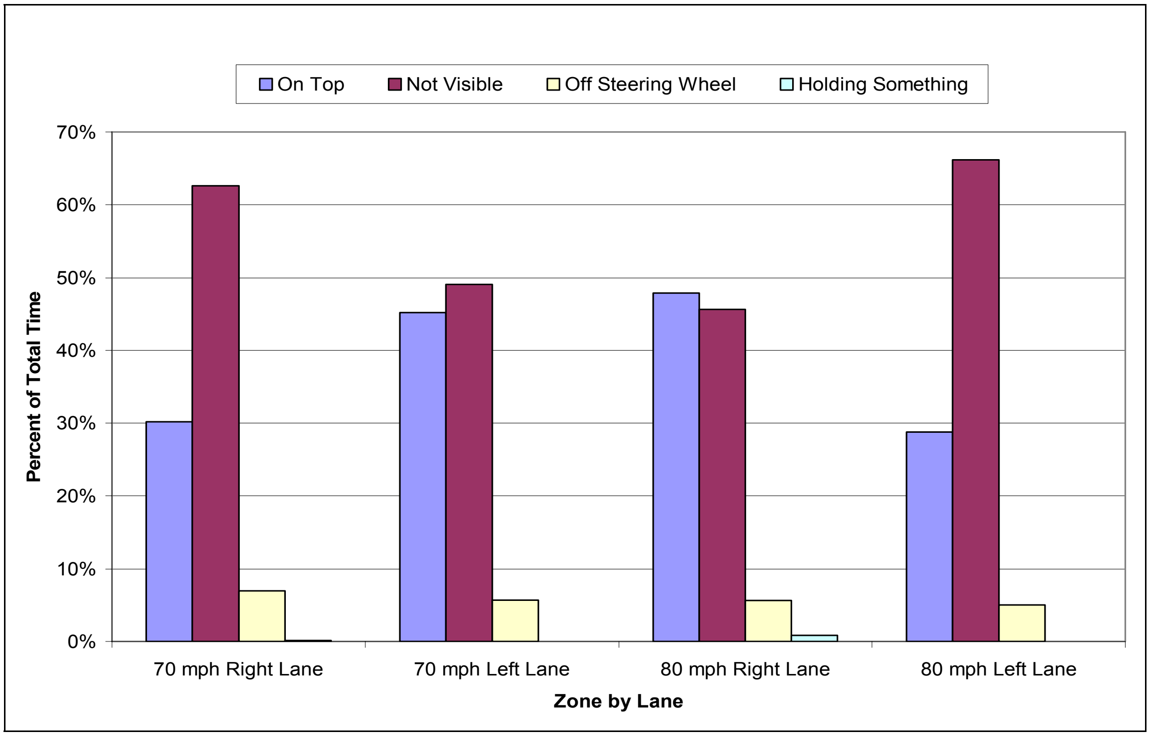


**Figure 15. Drivers' Right Hand Placement by Zone & Zone by Lane**

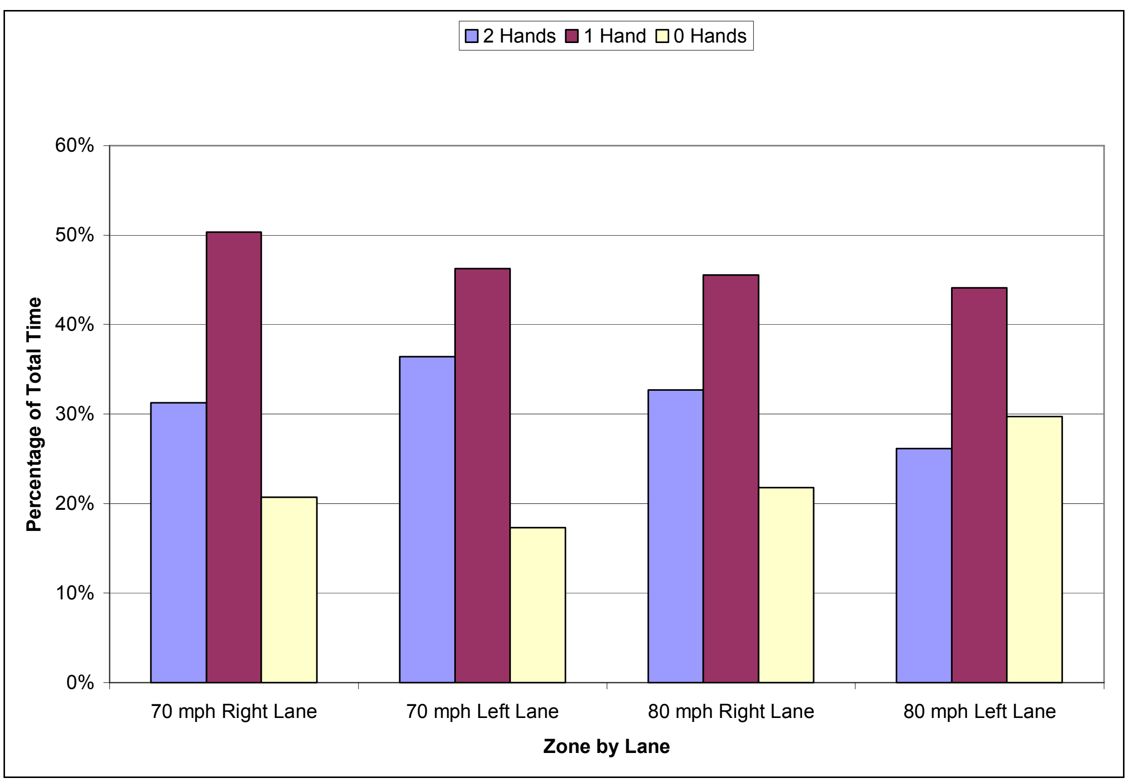


**Figure 16. Number of Hands on Top Half of Steering Wheel by Zone and Zone by Lane**

## CONCLUSIONS

For this study velocity results were considered to have practical implications if the difference in speed is greater than 2 mph. Lateral offset results were considered to have potential practical implications if the difference was greater than 6 inches or half a foot. Practical implications for hand placement and glance rates will be discussed in their respective sections.

### Lane Geometry and Lane of Travels Effect on Lateral Offset

Table 1 demonstrates practical difference between lateral offset and lane of travel. Within the 70 mph speed condition there were significant practical differences between vehicle lateral offset in the left lane verse the right lane in all geometric features investigated. This difference is not seen in any of the 80 mph geometries. However, there is a practical difference between lateral offset and negotiating a left horizontal curve in the two speed conditions.

These results suggest drivers going 70 mph are more willing to offset further to the left when traveling in the left lane than drivers at 80 mph in all geometries considered. These results suggest at 70 mph drivers may be more willing to travel close to the road's edge at these speeds than at 80 mph. More detailed analysis taking into account radius of the curves and remove of transition zones is desired to verify these results. The presence of other vehicles could be a contributing factor that was not considered in the development of these results.

### Lane of Travel and Posted Speed Limits Effect on Vehicle Velocity

While there seems to be statistical difference between vehicle velocity and variance in velocity they are not greater than the practical implication thresholds for velocity. One aspect of note is the average traveling speed for all drivers in the 80 mph condition was under the posted speed limit. This suggests drivers in the experiment may not have been driving as they normally do on such facilities.

While drivers not exceeding the speed limit could be an indication of unwillingness to travel at those speeds there are likely other reasons. They may have been driving differently because it was not their vehicle they were driving. Another factor in west Texas would be the enforcement of the 80 mph speed limit. As a prelude to getting permission to have posted speeds limits of 80 mph, stricter enforcement of these speeds was required. A speed study along the same corridor the subjects are driving would be desirable for comparison. Further analysis is desired taking into account other possible variables.

### Lane of Travel and Posted Speed Limits Effect on Lateral Offset

The lateral offset difference found in 70 mph tangents was also seen in the 70 mph tangent studied. Again the presence of other vehicles was not taken into account in these results. In the 80 mph coded segment there also seems to be a practical difference between offset and lane of travel. These differences suggest further analysis of other factors affect on lateral offset in the lane.

In both speed conditions the variance in lateral offset was also practically different. Vehicles traveling in the left lane seemed to have greater variation in their speed though this difference is smaller in the 80 mph condition. Further analysis needs to take into account the affect other vehicle have on these variances.

### Lane of Travel and Posted Speed Limits Effect on Driver Glance Rates

Drivers had higher glance rates to the right in all speed conditions and all lanes than the other two categories coded. There do not seem to be any practical differences in driver glance rates using the current methods. Future studies and analysis should use methods that obtain glance duration and can differentiate between a subject looking at a passenger in the vehicle and passenger side mirror.

### Lane of Travel and Posted Speed Limits Effect on Driver Hand Placement

Some general observations above driver hand placement can be made using data from Table 4 and Table 5. Data in Table 4 suggest drivers prefer having their left hand on the upper half of the steering wheel rather than their right. These data also suggest the right hand is normally in the driver's lap or gripping the lower portion of the steering wheel. The right hand also seems to be the hand most likely to clearly be off the steering wheel in all conditions.

Contrary to what would be expected drivers tend to place their hands on the upper half of the steering column less often in the 80 mph condition than they did in the 70 mph condition. This contradicts the idea that drivers would feel more at risk at these speeds and thus try to exert more control over the vehicle. As mentioned previously a hand position of ten and two has been shown to be associated with more vehicle control. This association may be true since in the 80 mph speed condition there was greater variance in lateral offset than the 70 mph condition as well.

So the question this raises is why did drivers exert less control over the vehicle in a condition that would seem to have a higher risk? One answer might be the driver's familiarity with the vehicle. Most observations had the driver going through the 70 mph section after having driving the vehicle for 15 minutes where in the 80 mph condition they had been driving for 45 minutes total. As driver familiarity with the vehicle became greater they would likely feel more comfortable in the vehicle no matter the small change in risk they perceive between the two speed conditions measured.

## RECOMMENDATIONS FOR FUTURE STUDIES

- Use of an eye tracking device that can obtain both glance rate and duration without further coding to reduce data reduction effort.
- Inclusion of a camera showing the entire steering wheel to differentiate between a hand in the driver's lap and a hand on the lower half of the steering wheel.
- Possible inclusion of steering wheel grip sensors to evaluate the intensity at which the driver's grip the steering wheel as a measure of workload.
- Development of more efficient computer macros to decrease data reduction effort.

- Inclusion of a camera showing the roadway behind the instrumented vehicle. On high speed facilities what is going on behind the vehicle can be just as important as what is going on in front of it (23).
- Obtaining roadway geometry data to measure the effects such as super elevation and curve radii in relation to lateral lane placement.
- Use the instrumented vehicles GPS system to obtain accurate GPS location for significant roadside objects such as Off Ramps, On Ramps, and Speed Limit Changes.

## REFERENCES


1. K. Fitzpatrick, K. Zimmerman, R. Bligh, S. Chrysler, and B. Blaschke. (2006) Criteria for Very High Design Speed Facilities. Draft FHWA/TX-07/0-5544-1.
2. D.B. Fambro, K. Fitzpatrick, and R.J. Koppa. (1997) Determination of Stopping Sight Distance. NCHRP Report 400. Transportation Research Board. Washington, D.C.
3. Dingus, T A, Klauer, S G, Neale, V L, Petersen, A, Lee, S E, Sudweeks, J D, Perez, M A;, Hankey, J, Ramsey, D J, Gupta, S, Bucher, C, Doerzaph, Z R, Jermeland, J, Knipling, R R, "The 100-Car Naturalistic Driving Study, Phase II - Results of the 100-Car Field Experiment." NHTSA Report HIS 810 593 April 2006 http://www-nrd.nhtsa.dot.gov/departments/nrd-13/driver-distraction/PDF/100CarMain.pdf
4. Kahneman, D. Attention and Effort. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973.
5. Simonov, P.V. "Emotional brain." Moscow: Science (1981) pp.140.
6. Hancock, P. A. "A Dynamic Model of Stress and Sustained Attention." Human Factors, Vol. 31, No. 5 (1989) pp. 519-537.
7. P. Tsang & G. F. Wilson, Job Design: Mental Workload. Chapter 13, pp. 113 -138
8. J. M. Noyes & D. P. Bruneau, A Self-analysis of the NASA-TLX workload measure. Ergonomics, Vol. 50 No. 4, 2007, pp. 514-519.
9. G. Walker, N, Stanton, and M. Young. Feedback and driver situation awareness: A comparison of Situation awareness measures and contexts. Transportation Research Part F, Vol. 11, 2008, pp. 282-299.
10. M. Sivak. The Information that Divers use: Is it Indeed 90% Visual? Perception, Vol. 25, 1996, pp. 1081-1089.
11. L. Evans & R. Rothery. The Influence of Forward Vision and Target Size on Apparent Inter-Vehicular Spacing. Transportation Science, Vol. 10, 1976, pp. 85-101.
12. R. J. Kiefer, D. L. LeBlanc, & C. A. Flannagan. Developing an Inverse Time-to-Collision Crash Alert Timing Approach Based on Drivers' Last-Second Braking and Steering Judgments. Accident Analysis and Prevention, Vol. 37, 2005, pp. 295-303.
13. D. B. Fambro, R. J. Koppa, D. L. Picha, & K. Fitzpatrick. Driver Perception-Brake Response in Stopping Sight Distance Situations. In Transportation Research Record: Journal of the Transportation Research Board, No. 1628, TRB, National Research Council, Washington, D.C., 1998, pp. 1-7.
14. H. W. Kruysse. The Subjective Evaluation of Traffic Conflicts Based on an Internal Concept of Dangerousness. Accid. Anal. & Prev., Vol. 23 No. 1, 1991, pp. 53-65.
15. G. Wilde, L, Robertson, and B Pless. Does Risk Homoeostasis theory have implications for road safety? Education and Debate, Vol. 324, 2002, pp. 1149- 1152.
16. R. Fuller. Towards a General Theory of Driver Behavior. Accident Analysis and Prevention, vol 37, 2005, pp. 461-472.
17. J. J. Arnett, D. Offer, & M. A Fine. Reckless Driving in Adolescence: 'State' and 'Trait' Factors. Accid. Anal. & Prev., Vol. 29 No. 1, 1997, pp. 57-63.

18. S. Chandraratna, & N. Stamatiadis. Problem Driving Maneuvers of Elderly Drivers. In Transportation Research Record: Journal of the Transportation Research Board, No. 1843, TRB, National Research Council, Washington, D.C., 2003, pp. 89-95.
19. F. Schmidit and J. Tiffin. Distortion of Drivers' Estimates of Automobile Speed as a Function of Speed Adaptation. Journal of Applied Psychology, Vol. 53 No. 6, 1969, pp. 536-539.
20. Missouri Department of Revenue, 2007, Missouri Department of Revenue Driver Guide. Department of Revenue, MO.
21. D. Walton and J. Thomas. Naturalistic Observations of Driver Hand Positions, Transportation Research part F, Vol 8, 2005, pp. 229-238.
22. J. Thomas and D. Walton. Measuring perceived risk: Self-Reported and Actual Hand Positions of SUV and Car Drivers, Transportation Research Part F, Vol. 10, 2007, pp. 201-207.
23. Getting Around Germany- The Autobahn: Brian's guide to getting around Germany, 2007, Available Online: http://www.gettingaroundgermany.info/autobahn.htm
24. J. L. Harbluk and Y. I. Noy. The Impact of Cognitive Distraction on Driver Visual Behaviour and Vehicle Control. Minister of Transport Report, 2002, Canada.
25. M. D. Wooldridge, K. Fitzpatrick, R. Koppa, & K. Bauer. Effects of Horizontal Curvature on Driver Visual Demand. In Transportation Research Record: Journal of the Transportation Research Board, No. 1737, TRB, National Research Council, Washington, D.C., 2000, pp. 71-77.
26. R Van Der Horst. Occlusion as a Measure for Visual Workload: an Overview of TNO Occlusion Research in Car Driving. Applied Ergonomics, Vol. 35, 2004. pp. 189-196.
27. S.D. Rogers, E. E. Kadar, & A. Costall. Gaze Patterns in the Visual Control of Strait-Road Driving and Braking as a Function of Speed and Expertise. Ecological Psychology, Vol. 17 No. 1, 2005, pp. 19-38.R Van Der Horst. Occlusion as a Measure for Visual Workload: an Overview of TNO Occlusion Research in Car Driving. Applied Ergonomics, Vol. 35, 2004. pp. 189-196.
28. D. B. Fambro, R. J. Koppa, L. Picha, & K. Fitzpatrick. Driver Braking Performance in Stopping Sight Distance Situations. In Transportation Research Record: Journal of the Transportation Research Board, No. 1701, TRB, National Research Council, Washington, D.C., 2000, pp. 9-16.
29. G. Schertz, G. Hawkins, P. Carlson, P. Hatzi, and K. Opiela. Workshop on Nighttime Visibility of Traffic Signs.
30. K. Fitzpatrick, D. B. Fambro, & A. M. Stoddard. Safety Effects of Limited Stopping Sight Distance on Crest Vertical Curves. In Transportation Research Record: Journal of the Transportation Research Board, No. 1701, TRB, National Research Council, Washington, D.C., 2000, pp. 17-24
31. D. B. Fambro, K. Fitzpatrick, & C. W. Russell. Operating Speed on Crest Vertical Curves With Limited Stopping Sight Distance. In Transportation Research Record: Journal of the Transportation Research Board, No. 1701, TRB, National Research Council, Washington, D.C., 2000, pp. 25-31
32. M. D. Wooldridge, K. Fitzpatrick, R. Koppa, & K. Bauer. Effects of Horizontal Curvature on Driver Visual Demand. In Transportation Research Record: Journal of the Transportation Research Board, No. 1737, TRB, National Research Council, Washington, D.C., 2000, pp. 71-77.
33. AASHTO. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials. 2004
34. K. Fitzpatrick, T. Lienau, and D. B. Fambro. Driver Eye and Vehicle Heights for use in Geometric Design. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1612, TRB, National Research Council, Washington, D.C., 1998, pp. 1-7.
35. R. J. Kiefer, D. L. LeBlanc, & C. A. Flannagan. Developing an Inverse Time-to-Collision Crash Alert Timing Approach Based on Drivers' Last-Second Braking and Steering Judgments. Accident Analysis and Prevention, Vol. 37, 2005, pp. 295-303.

36. R. J. Kiefer, M. T. Cassar, C. A. Flannagan, C. J. Jerome, & M. D Palmer. Forward collision warning requirements project: Task 2 and 3a final report. Report DOT HS 809 902. NHTSA U.S. Department of Transportation, Springfield, VA, 2005.