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16. Abstract

This report is a compilation of research papers written by students participating in the 2006 Undergraduate Transportation Engineering Fellows Program. The ten-week summer program, now in its sixteenth 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) identification of positive guidance deficiencies in urban interchange work zones; 2) driver comprehension of diagrammatic advanced guide signs and their alternatives; 3) performance evaluation of traffic responsive signal control; 4) internal trip capture estimation for mixed-use developments; 5) creating a process to identify a traffic fingerprint and correct altered data; and 6) evaluation of tripcal5 trip generation default models.

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COMPENDIUM OF STUDENT PAPERS:

2006 UNDERGRADUATE TRANSPORTATION

ENGINEERING FELLOWS PROGRAM

Participating Students (left to right):
Front Row: Geoffrey McDonald, Jonnae Hice, Eduardo Garcia
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Program Sponsored by

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Zachry Department of Civil Engineering
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PREFACE

The Southwest Region University Transportation Center (SWUTC), through the Advanced Institute 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 2006, the following six students and their faculty/staff mentors were:

STUDENTS	MENTORS
Mr. Eduaro Garcia Texas A&M University, Kingsville, TX	Dr. Gerald Ullman
Ms. Jonnae Hice Texas A&M University, Kingsville, TX	Dr. Sue Chrysler
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Sincere appreciation is extended to the following individuals:

- Mrs. Colleen Dau, who assisted with program administrative matters and in the preparation of the final compendium; and

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CONTENTS

DISCLAIMER

IDENTIFICATION OF POSITIVE GUIDANCE DEFICIENCIES IN URBAN INTERCHANGE WORK ZONES

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Eduardo Garcia will graduate in December 2006 with a Bachelor of Science degree in Civil Engineering at Texas A&M University at Kingsville. He is also a recipient of the South Texas Academic Rising Scholars scholarship and Dwight David Eisenhower Transportation Fellowship.

Currently, he is president of the American Society of Civil Engineers (ASCE) Kingsville student chapter, member of the Society of Hispanic Professional Engineers and Mexican-American Engineers and Scientists, Institute of Transportation Engineers (ITE), and establishing an Institute of Transportation Engineers Kingsville student chapter. He has worked at the Texas Department of Transportation - Laredo District lab during the summer of 2005 and Texas Transportation Institute San Antonio office in March 2006 and plans to attend graduate school at Texas A&M University upon graduating.

SUMMARY

Texas is the second largest state and has the second largest population in the United States. With the constant growth of its population and infrastructure, the demand for transporting goods and people efficiently and safely to their destinations is vastly increasing. Although Texas currently has over 300,000 paved miles of roads, there is frequent construction and maintenance on urban interchanges and freeways to keep up with the continuing growth of the state, population and impact of vehicles on the roadway. As work zones become ever present on the freeways, congestion and road signing will have an impact on the drivers' awareness in the urban work zone areas.

In this research the core steps of the positive guidance procedure are used and applied to urban interchange work zones to identify and characterize the types of conflicts and issues encountered within work zones. Data collected consisted of video and audio recordings from drive through various traffic movements at four urban freeway interchanges in Austin, Dallas-Fort Worth, Houston, and San Antonio.

By using the key steps of the positive guidance procedure, several deficiencies were detected and could be assessed. Such deficiencies include possible overload of guide signs with temporary traffic control signs, merging entrance ramps, exit ramp splits, and areas where motorists have to negotiate potential hazards.

TABLE OF CONTENTS

INTRODUCTION

The growth of metropolitan areas in the past two decades has had an impact on the highway infrastructure with the demand for extra lanes, and added emphasis on safety in the roadway. With the demand of a modified and improved highway system, the maintenance/construction area has become the second-highest rated concern to drivers after increased traffic congestion in the state of Texas (1).

The last census conducted in 2000 by the U.S. Census Bureau indicated that the population in Texas was close to 23 million people and specified that 82.5 percent of the population was situated in metropolitan areas (2). Such high population concentration brings traffic jams, and high volumes of vehicles during peak hours in cities such as Austin, Dallas-Fort Worth, Houston, and San Antonio. In addition, commuters are forced to coexist with the work zones on a daily basis. Work zones themselves have a significant impact on traffic. “In 2002, work zone fatalities reached a high of 1,181. More than 40,000 people are injured in work zone-related crashes each year (3).”

Currently, there are various guidelines that are used to appropriately setup and evaluate the work zones areas, The Manual on Uniform Traffic Control Devices (MUTCD) is the standard guideline used by the Texas Department of Transportation, and Federal Highway Administration (4). The MUTCD provides the guidelines and procedures on how to properly setup temporary signs and other traffic control devices for a limited number of “typical application” work zones. Presently, though, MUTCD is quite limited to guidance on establishing temporary traffic control in and around high-volume urban freeway interchange areas.

PROBLEM STATEMENT

Evidence exists to suggest that drivers often have difficulty in navigating through work zones that occur within the vicinity of complex urban freeway interchanges. The numerous existing guide signs, presence of short auxiliary lane segments, multiple lane exits, high merging traffic, and other conditions in the work zones present complex driving situations and place considerable work load on drivers. Driver work load and driving complexity increases even more when temporary travel paths configured with channelizing devices are in conflict with existing guide signs. It is often difficult to convey lane closure, path guidance, and other warning information using traditional temporary traffic control signs and temporary pavement markings. This research effort focused on urban interchange work zones because of the complexity of these locations from a driver’s perspective.

RESEARCH OBJECTIVES

The objective of the research summarized in this paper was to perform a positive guidance-based evaluation of work zone traffic control at a sample of urban freeway interchange work zones to identify, characterize, and quantify into potential travel path deficiencies and challenges that may lead to driver confusion, erratic maneuvers, and other undesirable consequences. The deficiencies were examined on the basis of types of driving movements such as exiting maneuvers, through movements throughout the interchange, and day and night conditions.

Both permanent and temporary signing were evaluated as well pavement markings and channelizing devices for lane closures, and lane shifts were assessed to determine if the guidance provided was conveyed properly.

LITERATURE REVIEW

The first report published on the topic of positive guidance by the U.S. Department of Transportation was in 1975 titled “Positive Guidance in Traffic Control” in which Alexander and Lunenfeld defined positive guidance from the guidance level to hazards, system failures, and applications in the highway. It was developed at first as a means to provide a “high pay-off, short-range way to enhance the safety and operational efficiency of substandard facilities (5)” but now applications of the procedure can be applied to various highway environments to ensure better operation and safety of the public on highways. The report explained in detail how “the control, guidance, and navigation levels of driver performance (5)” are the core upon which the positive guidance procedure is built upon. One of the main concepts of the positive guidance procedure involves the driving task, and is divided into three basic levels of performance (6):

- Control – involves the mechanics of the vehicle along with the information received by the driver.
- Guidance – decision process for evaluating lane position, maneuvering, and path identification.
- Navigation – deals with the location arriving at or departing from, this type of information usually be provided by maps, highway signs, or familiarity with the area.

In order of importance, these main levels provide the motorists with the vital information needed to guide them through both a work zone and non-work zone in rural and urban areas.

The report “A Users’ Guide to Positive Guidance” in 1990 provided more in depth detail on the positive guidance procedure and how to diagnose potential deficiencies in the road. In this report the procedure takes these factors into consideration such as, geometrics, traffic volumes, guide signs, and the environment to assess any errors and improve them to supply the drivers with the information they need to guide themselves to their destination or around any hazards. Provided in the report is a checklist that the reader can use to assess a particular hazard area, which might lack or have an absence of information or a difficult maneuver that is not advising properly with sufficient time. The checklist provides details from road information, signage, environment, location (rural or urban), interchange location, volumes and traffic patterns, accident history, geometric designs and more.

In work zone environments, Ullman and Schrock used positive guidance concepts to evaluate various work zones on Texas highways. An example of the data in Table 1 from their research stated that test subjects encountered at least one ambiguous location on the freeway once every 1.2 miles (4).

Even though there is no exact definition how many ambiguous locations per mile are required for the site to be considered non-confusing or distracting to the driver, it is apparent that even following the guidance currently available in the MUTCD can lead to a various potential path guidance challenges to drivers attempting to traverse a work zone location.

Table 1. Example of Frequency of Confusing Locations Per Site (*4*)

Site Number	Site	Site Location	Length (miles)	Number of Confusing Locations
1	I35 Northbound	Hillsboro	11.5	6
2	I35 Southbound	Hillsboro	11.0	10
3	Loop 410 Westbound	San Antonio	7.0	6
4	Loop 410 Eastbound	San Antonio	6.0	5
5	I35E Northbound	South of Dallas	4.0	5
6	I30 Westbound	Dallas	7.0	3
7	I30 Eastbound	Dallas	6.0	2
8	I35E Northbound	North of Dallas	3.0	6
9	I35E Southbound	North of Dallas	6.0	7
	TOTAL		61.5	50

Positive Guidance Procedure

The positive guidance procedure is designed to systematically consider potential hazards and information needs from the motorists' perspective, and to determine how that information should be best presented to motorists. This procedure can reduce or eliminate erratic driving maneuvers, provide efficient traffic control through a work zone and give the driver proper and clear path guidance information. The positive guidance procedure consists of eight steps to determine if a specific site meets the requirement for effective traffic control and proper path guidance. The procedure is as follows:

1. Site Definition
2. Problem Identification
3. Hazard Identification
4. Hazard Visibility Assessment
5. Expectancy Violation Determination
6. Information Load Analysis
7. Information Needs Specification
8. Current Information System Evaluation

In this research, steps four through seven were emphasized. The steps presented and provided in detail below.

Hazard Visibility Assessment

The objective of the hazard visibility assessment is to determine if a hazard can be adequately detected and perceived by drivers with sufficient time to be able to adjust his driving behavior and avoid or maneuver around the hazard. There are several types of fixed, moving and temporary objects in the work zone area. Some examples of possible work zone hazards are shown in Table 2 (4).

Table 2. Examples of Visible Hazards in Complex Work Zones (*4*)

TYPES OF HAZARDS	
LANE CLOSURES	DRIVEWAYS
CONCRETE BARRIERS	INTERSECTIONS
HORIZONTAL CURVES FOR LANE SHIFTS, DETOURS	BUMPS OR LIFTS
EXIT RAMPS AND BIFURCATIONS	UNEVEN LANES
ENTRANCE RAMPS	PAVEMENT DROP-OFFS
LANE DROPS, LANE ADDITIONS	ARROW PANELS, PORTABLE DMS, ETC.
	CONSTRUCTION EQUIPMENT AND MATERIALS
	CONSTRUCTION AREA ACCESS POINTS

Expectancy Violation Determination

Driver expectancy refers to any situation or particular location that a driver is accustomed to driving through on a daily basis or by prior knowledge of the area before. Consequently, an expectancy violation is characterized as any location that might "surprise" the driver. Some examples of expectancy violations from previous research include entrance/exit ramps that are temporarily closed due to construction at the location, traffic lane splits, etc.

Information Load Analysis

Under the goal of information load analysis step, the goal is to determine if amount of information from both formal and informal sources can be effectively processed by drivers to allow them to make appropriate lane choices or navigate decisions to their destination. An area is categorized as having "low, moderate, or high information load (6)" depending on how much information is presented at one time as the driver traverses the area. The type of information sources come from both permanent and temporary signing used in work zones, pavement markings, and concrete barriers and even other traffic itself. In work zones, there are locations that supply too much information, leading to the driver to feel anxiety or confusion in deciding what information deserves priority. Such anxiety and confusion, in turn, can increase the risk of wrong driving decisions and adverse operational impacts such as swerving, severe braking (to allow the driver more time to read and process the desired information), etc.

Figure1 demonstrates an example of high information load where the permanent, temporary, portable changeable message signs (PCMS), entrance/exit ramps, and traffic volume are all present within a short segment of the urban work zone. In this situation, the driver may find it difficult to determine which signs are greatest priorities to detect and process because the regulatory and guide signs are "drowned" in the vast amount of information provided.

Information Needs Specification

The objective of the information needs evaluation is to compare what information is needed in order to assess or avoid a hazard that is not adequately visible to approaching motorists to what and where that information is actually provided. Information may be needed to provide proper advance notice of a hazard that is not visible far enough upstream to provide enough decision sight distance to the driver. Information may also be needed to provide additional warning of locations where driver expectancy may be violated. Of course, the information provided must also be considered in relation to the other information sources presented at that same location (i.e., as part of the information load analysis at that location.).

Figure 1. Example of High Information Load

PROCEDURE

Literature Review

The first step in the data collection process was to select urban freeway interchanges to use in the analysis. TTI researches gathered maps from the cities of Austin, Dallas-Fort Worth, Houston, and San Antonio, and examined the overall geometric design and individual travel movements possible through several of the major freeway-to-freeway interchanges in those cities. A candidate list of interchanges was then identified. The sites were visited and video taped while providing audio commentary from the TTI staff that did the evaluation of the interchanges. Both day and night movements were done to provide a better detailed evaluation of the sites. All the possible movements were driven through in each interchange to acquire a complete evaluation of the potential deficiencies present within those segments.

After gathering the data from the drive throughs, 4 interchanges were selected based upon their geometric and work zone complexity. The interchanges selected for review were the following:

- Dallas: I30 – Loop 12 Interchange,
- Houston: I45 (North Freeway) – Loop I610 Interchange
- Houston: I10 (Katy Freeway) – Loop I610 Interchange, and
- San Antonio: I10 – Loop I410 Interchange.

After selecting the interchanges, the videotape drive throughs for each were reviewed. The information systems (both permanent and temporary signing, channelizing devices, and pavement markings) were mapped out from the beginning to the end of each movement for that interchange. In addition, the layout of entrance and exit ramps, horizontal and vertical curves, and other physical features were also denoted. The principals of positive guidance as described above (hazard visibility assessment, expectancy violation determination, information load analysis, and information needs specification) were then applied to each of the movements. A series of tables were generated to categorize the various issues and potential deficiencies identified. The primary results of the analysis are presented in the results section that follows. Detailed tables of some of the main issues identified are presented in the appendix.

RESULTS

In total, there were 46 day movements and 40 night movements. From these 86 movements, a total of 208 issues and deficiencies were detected. Figure 2 summarizes the distribution of deficiencies identified among the four main categories used in the positive guidance procedure. As would be expected, there is a correlation between the percentage information needs deficiencies and the percentage of the hazard visibility deficiencies. This correlation occurs because one of the main reasons for providing advance information to drivers is to warn them of a hazard they are approaching and will need to negotiate. If the hazard itself is not fully visible, and if information indicating that there is a hazard being approached and that a maneuver is required, both types of positive guidance deficiencies are the noted.

Based on the results of the overall analysis, one can conclude that providing adequate visibility to hazards within the work zone environment is one of the main challenges to work zone traffic control designers. More than one-third of all positive guidance issues identified through this analysis were hazard visibility related. The next most-common type of positive guidance issue was the absence of needed or useful information presented at the proper location for motorists. As noted above, many of these issues were directly related to the fact that hazards not immediately visible to drivers did not have advance signing or other information available to fully prepare the driver that a particular maneuver or response may be necessary. However, there were a number of other instances where temporary markings had either worn off or been knocked off the roadway, which then left the driver with no information as to where the limits of the lane were or should be traveling on.

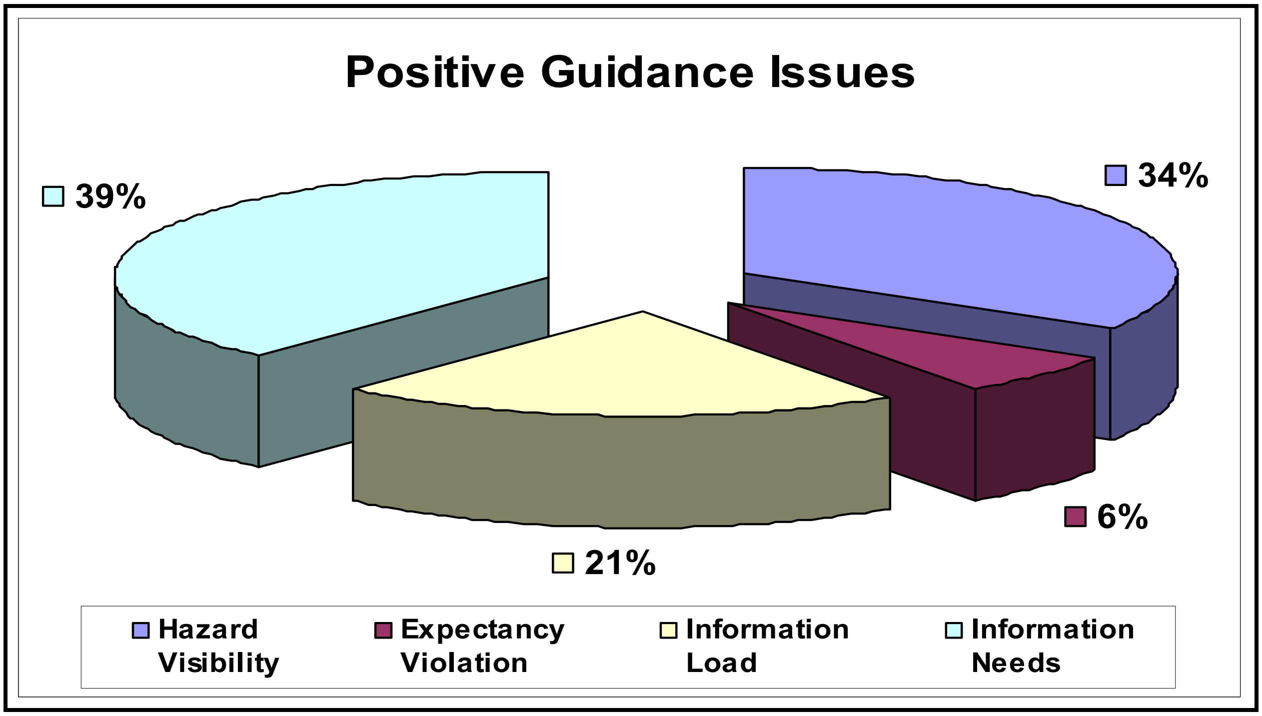

Figure 2. Percentage of Positive Guidance Issues

As also can be seen in Figure 2, 21 percent of the positive guidance issues identified were related to locations where the amount of information being presented exceeded the amounts recommended in the positive guidance procedures. Many of these were locations where a large number of permanent guide signs were installed (some locations having a high concentration of load information already) and where other temporary traffic control information was currently presented. Finally, only 6 percent of the positive guidance issues in the sample were encouraging, as it is believed that violations of driver expectancy can be particularly hazardous on high-speed, high volume facilities.

It should be noted that in many instances, a driver may be exposed to several types of positive guidance issues or deficiencies in a short driving distance. For example, Figure 3 from one of the interchanges examined indicates the presence of a hazard visibility issue at the end of the bridge and before merging with vehicles from the right side of the road. This situation creates a hazard because the traffic is merging from the right coming up a steep hill. When vehicles merge with the other lane, they travel up the hill fast and are forced to merge within a short distance of the lane closure and channelizing concrete barriers. Because of high traffic volumes, concrete barriers that create a narrow lane ahead and unexpected merging lanes that joined without any warning. With no advisory of the narrow lanes ahead and merging lanes, the drivers unsuspectingly are guided through merging traffic and lanes, and surprisingly a narrow lane, thus violating their expectancy. Before arriving to the location of the narrow lane, there is a high amount of information load that creates another positive guidance issue where motorists are required to observe, perceive, interpret and adjust their driving behavior to prepare for a sudden exit downstream of traffic. While trying to adjust their driving manner, the driver has to look overhead to identify the guide sign which is misleading because the guide sign states that there are two path lanes present yet only one lane is available. The sign advising of merging traffic never mentions merging lanes or narrow provides the driver with a warning for narrow lanes ahead. In this particular location the driver has to identify seven units of information within a 300 ft distance before encountering the narrow lane. Once in the narrow lane, it is difficult to assess how far the exit is located thus, leading to another expectancy violation. If a vehicle is behind of another vehicle, the driver will be unable to visually see the exit. Once at the split of the exit, it is difficult to read the signs at this location because of their size, and location at the split. Thus is it apparent that the information system for this location does not fully prepare a driver for the actual driver hazards present, violates the drivers expectancies with regards to following the information presented on the signs, and exceeds the desirable amount of information presented to the drivers at one time.

Another instance where multiple positive guidance issues were evident is illustrated in Figure 4. As the driver approaches the visible range of the overhead guide sign, it becomes unclear whether the exit is still open because of the temporary sign next to it stating that the lane ends ¼ mile away. The sign does not specify which lane ends and could lead the driver to believe that the exit is still open, which is contrary see because the reflective barrels used to control traffic for the lane shift also closes the exit. This situation provides an example of where a hazard visibility issue can lead to an expectancy violation within an urban work zone area.

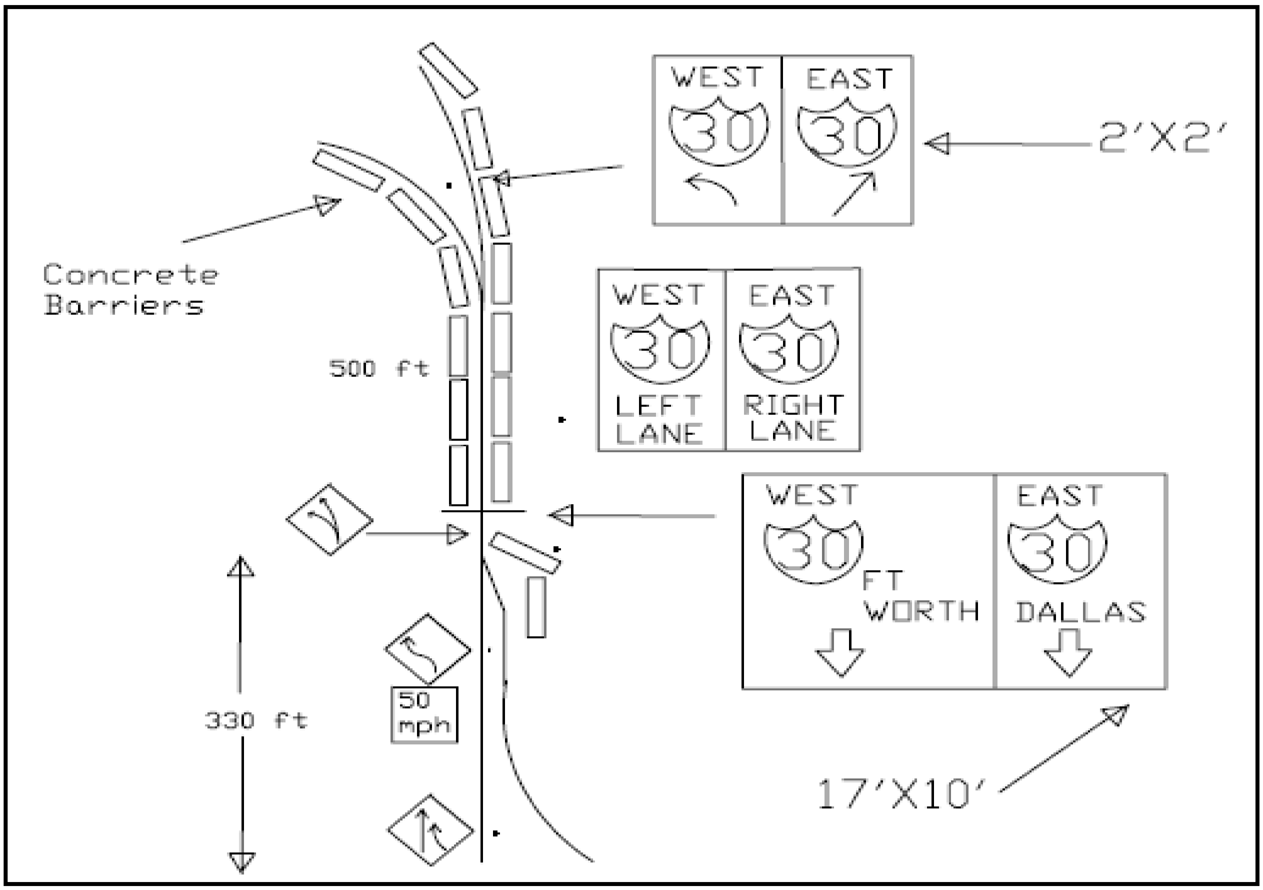

Figure 3. Dallas I30 – Loop 12, Movement # 3 South 12 – East 30

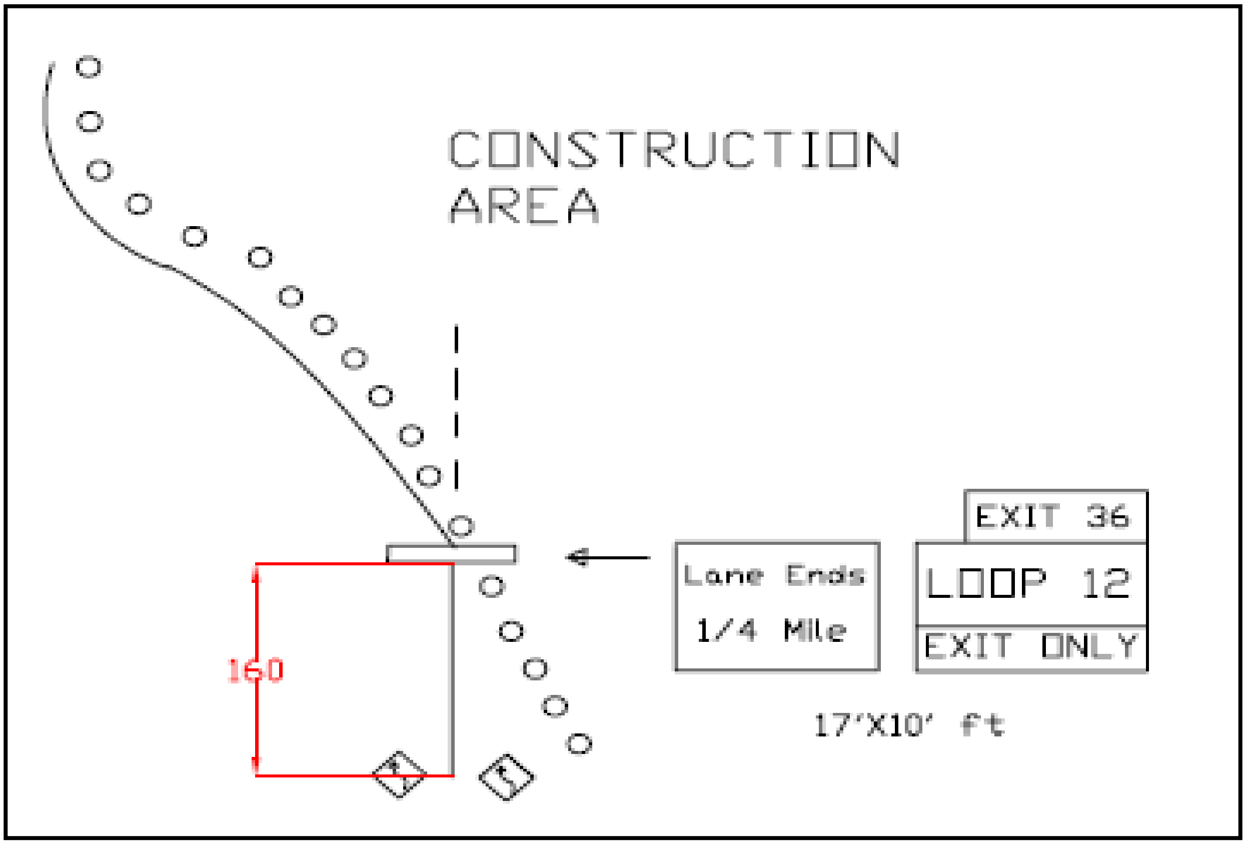

Figure 4. Illustration of a Combined Hazard Visibility-Driver Expectancy Issue

CONCLUSION

The purpose of this research was to use the positive guidance procedure to identify the potential conflicts encountered in urban interchange work zones and determine how well deficiencies could be identified by using the positive guidance tool.

Due to the limited time available during the research, only 4 interchanges could be evaluated within the time allowed. In the total 86 movements that were done, an average of 2.4 deficiencies was identified. The guidelines and procedures provided by the MUTCD to evaluate the work zone areas are the proper way to setup traffic control through typical highway environments, yet it is limited and not able to anticipate unique designs in all interchanges. Positive guidance is not developed for a single design evaluation purpose and can be applied to both work zone and non-work zone in rural or urban locations, thus giving it a broad application of the tool. Positive guidance was able to detect 208 potential deficiencies in four interchange work zones alone, and with more time to evaluate the other locales, more conflicts could be assessed and identified for further research. This will provide a broader scope of how this procedure is useful in all highway environments.

Overall, the positive guidance procedure has proved to be a useful tool in identifying and characterizing all potential conflicts within urban interchange work zones. With more research into positive guidance being used as a method of traffic control in construction and maintenance areas, a better understanding of how to evaluate safety and operations in these locations would prove itself valuable for future infrastructure.

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APPENDIX

Positive Guidance

Project # 5238

Notes for Interchange Video:
San Antonio I10 - Lp 410
Dallas I30 - Lp 12
Houston I45 - Lp 610
Houston I10 - Lp 610

San Antonio Interchange I10 - Loop 410

Time	Positive Guidance	Identification	Problems	Alternatives	Tape & #	D/N
1:05/ 1:17:22	Information Needs	Merging traffic from ramp.	No Warning is provided.	 sign placement upstream	San Antonio 1	D/N
1:12 1:17:29	Information Needs	Merging lanes.	No Warning is provided.	Placement of  sign	San Antonio 1	D/N
6:06/ 13:45	Expectancy Violation	Narrow Lanes	No warning of narrow lanes.	 sign before exit ramp.	San Antonio 1	D/N
6:17	Hazard Visibility	Pavement markings/condition	Path identification unclear.	Buttons needed.	San Antonio 1	D
7:20/ 1:14:40/ 17:22/ 22:05	Information Needs	Merging traffic from ramp.	No warning is provided.	 sign placement upstream.	San Antonio 1	D/N
7:29/ 17:32/ 1:09:55/ 22:16	Information Needs	Right Lane ends	No warning of lane ending.	 sign to provide adequate warning for drivers.	San Antonio 1	D/N
1:15:00/ 1:10:08	Hazard Visibility	Guide sign reflectivity	No reflectivity on guide sign	Improved reflectivity on sign.	San Antonio 1	N
12:48/ 1:24:56	Hazard Visibility	Sign indicates 2 lanes	Only one lane present, arrow partially covered. Potential problem is cover falls off.	Arrow removed or sign changed. Covering arrow with tarp is not a permanent solution.	San Antonio 1	D/N
22:38	Information Load	Ambiguous pavement sign.	Pavement sign does not correspond to geometric design. Pavement sign is misleading.	 pavement sign could be used instead. 5 sources of information present at location.	San Antonio 1	D
22:59	Information Load	90° turn sign on curve.	90° curve sign does not correspond to actual curve.	Sign is misleading to actual curve geometrics. 	San Antonio 1	D
23:11	Information Needs	No merging traffic sign.	Coming out of curve, there is no warning of merging with traffic.	 sign placement.	San Antonio 1	D

Dallas Interchange			**I30 -- Loop 12**			
51:51	Expectancy Violation	Sign provides little information of downstream path.	 Sign is misleading due to the fact that traffic splits. 50 mph sign at the bottom is not helpful since merging traffic into one lane slows down traffic.	Removal of speed sign and placing   sign might be better.	Dallas 1	D/N
51:54 1:00:52	Hazard Visibility	Misinformation of overhead guide sign.	Overhead guide sign states that there are two travel paths, but only one is present.	Covering of arrow could better help identify only one lane present. Warning of narrow lane ahead could help	Dallas 1	D/N
52:12 1:01:16 1:55:09 2:00:12	Information Needs	Sign is too small to read.	Sign can only be read when at the curve, difficult to read from a distance and at night. Difficult to maneuver through at night.	Bigger sign at exit could help at the road split.	Dallas 1	D/N
54:03/ 1:46:48	Information Load	Misleading sign	Sign indicates that the land ends a 1/4 mile away with a Loop 12 exit only sign next to it. The exit is closed off by barrels. At night this might cause confusion because of lane shift and the closed exit.	Covering up the sign or advising traffic about the exit being moved would be helpful to drivers.	Dallas 1	D/N
54:21/ 1:47:06/ 1:57:04	Information Needs	Sign appears a short distance from exit.	Sign gives little warning to exit and at night the sign has high glare reflecting from it.	Sign could be moved upstream to allow more maneuvering time.	Dallas 1	D/N
52:24/ 1:47:10/ 1:57:09	Information Needs	Exit sign cut and has barrels in front of it.	Exit sign is cut in half and laid standing on ground with another orange exit sign on top of it. Sign is placed behind barrels which block the view of the sign during the day and night.	Placing the sign in full view of drivers could give proper warning for exit.	Dallas 1	D/N
1:47:32	Hazard Visibility	Bright construction light at night.	The light used in construction areas at night is too bright and might affect drivers with sensitive sight or the elderly.	A cover on the light to protect drivers from glare on the interchange side.	Dallas 1	N

56:27 1:45:00	Information Needs	Exit 25 mph sign on 50 mph road.	Deceleration in speed can be seen at night for vehicles exiting, which cause vehicles in that same lane to decelerate also.	Advance warning of deceleration curve would benefit drivers to allow them to properly maneuver and decelerate with time and distance.	Dallas 1	D/N
58:38 1:57:32	Hazard Visibility	Sharp curve after exit.	There is a sharp curve with drop off where certain sections do not have barrels or delineators. During the night, there is a significance in visualization on the curve.	A sharp curve sign ahead, and more barrels and markers to allow for better path guidance information on curve.	Dallas 1	D/N
58:54 1:57:45	Information Needs	Number of lanes on bridge?	It is unclear whether bridge has both lanes available until half way through bridge.	Better warning with delineators and barrels to advise a single lane on bridge.	Dallas 1	D/N
1:59:33 1:05:10	Information Load	Too many signs.	There are 10 signs to read within 600 ft distance from exit ramp to entrance ramp. Plus the driver also has to pay attention to merging vehicles and the entrance ramp to interchange.	Placing the most important control and guidance signs first with the least important at the end.	Dallas 1	D/N
1:59:59 1:54:55	Information Needs	No sign of merging lanes or narrow lanes ahead	There is no warning sign for narrow or merging lanes ahead, and guide signs provide misleading information as well for available lanes during the night drive.	Placement of  and  sign could advise drivers of path guidance information.	Dallas 1	D/N

Houston Interchange I45 (North Freeway) - Loop 610						
1:34 1:12:12	Information Needs	No sign of merging traffic lanes and traffic.	There is no sign warning of merging traffic and lane with two other movements.	A warning sign of traffic merging from left and right side, but spaced so as to give the driver enough warning of location.	Houston 2	D/N
2:10 12:25 1:19:27 1:22:36	Expectancy Violation	Arrows on overhead guide signs are covered.	Overhead guide signs are still present with an orange guide sign displays path guidance information but it is placed overhead on the far right.	Placing sign in between guide signs would benefit all drivers on the road.	Houston 2	D/N
2:21 12:33	Information Load	"Left Lane Closed" intended for frontage road, not interchange.	"Left Lane Closed" sign is visible for vehicles on the right lane of the interchange but it is intended for vehicles on the frontage road.	Placing the sign lower or at an angle so drivers on the frontage road can visibly see the sign for them.	Houston 2	D/N
3:09	Information Needs	No warning of merging traffic and lanes.	There is no warning of merging traffic or lanes with two other movements.	A warning sign of traffic merging from left and right side, but spaced so as to give the driver enough warning of location.	Houston 2	D/N
1:14:39	Hazard Visibility	No reflectivity from guardrails or concrete barriers, poor pavement markings and buttons.	It is difficult to identify the travel path through this curve. Lane identification is also difficult to determine under the overpass.	Adding reflective markers and new buttons on pavement could help path guidance through this area.	Houston 2	N
8:40-45 14:04 1:15:53 1:21:19	Hazard Visibility	Difficult to determine travel path, no lane identification.	Solid white lines stop just after curve split and makes travel path difficult to identify due to lack of pavement markings.	Pavement markings or buttons would better help determine the travel path in this area.	Houston 2	D/N
8:53-9:00	Information Load	Road Work signs are ambiguous.	Before merging from 45 South to 610 West, sign stating "Road Work Ahead" then another sign after this reads "End Road Work" is visible.	Removal of inappropriate sign could help motorists to determine if there is a work zone ahead or not.	Houston 2	D/N

1:16:05	Information Needs	No warning of merging traffic.	There is no warning of merging traffic with 610 West, more useful at night due to lack of visibility by obstruction of trees.	Providing sign would better prepare drivers for merge.	Houston 2	D/N
9:57	Information Needs	No warning of merging traffic.	There is no warning of merging traffic from another movement.	Providing sign would better prepare drivers for merge.	Houston 2	D/N
11:25	Information Needs	No warning of merging traffic.	There is no warning of merging traffic from 2 other movements.	Providing sign would better prepare drivers for merge.	Houston 2	D/N
11:29 11:49	Information Load	Ambiguous signs, intended for frontage road.	Sign stating "Left Lane Ends" and "Lane Ends Merge Right" are meant for vehicles on the adjacent frontage road, but drivers on right lane of interchange might think these sign are intended for them.	Placing signs at an angle towards frontage road drivers might make signs less visible to drivers on the interchange.	Houston 2	D/N
1:18:40	Information Needs	No warning of merging traffic.	There is no warning of merging traffic from 2 other movements.	Providing sign would better prepare drivers for merge.	Houston 2	D/N
14:30 1:21:29 1:21:32	Hazard Visibility	No path guidance information on curve and poor lane identification.	There are almost no buttons or centerline pavement markings to determine if the curve is a two lane or one land curve.	Placing centerline markings or button, and reflective markers on guardrails could better help identify the path on the curve.	Houston 2	D/N
16:01 1:23:13 1:23:17 1:23:23	Hazard Visibility	No lane identification on curve, poor path guidance.	The curve has no lane identification or path guidance information, only the sign for the curve. It is a two lane curve but difficult to determine with no markings or buttons. Conditions are worse at night.	Placing buttons or pavement markings is necessary on this curve. Concrete barriers could use reflective markers at night	Houston 2	D/N

Houston Interchange I10 (Katy Freeway) -- Loop 610						
1:25:46	Hazard Visibility	Path guidance is difficult at night.	It is difficult to see the concrete barriers at night.	Adding reflective markers on the concrete barriers could improve path guidance for drivers.	Houston 1	N
1:27:42	Hazard Visibility	Barrels with no reflectivity markers.	Barrels in gore area are painted black and have no retro-reflectivity on them so drivers have difficulty visualizing them at night.	Adding the reflective markers would help the drivers see them.	Houston 1	N
30:28	Information Load	Dim lights on portable message sign.	The light on the portable message sign are very dim and difficult to read during the day. Important information might not reach drivers in time before a hazard or guidance location.	Brighter lights on the message sign or cover so day light will not affect the visualization of the information.	Houston 1	D
31:07	Hazard Visibility	Arrow indicating opposite movement.	Pavement arrow show a curve to the left upstream of traffic, but curves to the right downstream. This is dangerous since it contradicts and misleads the drivers.	Redoing the pavement sign to guide the appropriate direction.	Houston 1	D/N
31:31 1:37:44	Information Load	Signs at split difficult to read.	The signs at the split are difficult to read because of size and other signs in this location. Along with concrete barriers, split, and traffic, there is a high load of 7 information sources at once in the location.	Placing bigger signs that are visible or placing them before exit would help ease the high load information in this location.	Houston 1	D/N
33:20 39:26	Hazard Visibility	Ghost pavement markings.	Old pavement markings are visible during the day on exit. Could distract driver from path guidance.	Painting over or scraping of the pavement markings would be good.	Houston 1	D
33:55 1:39:52 39:57 1:35:36	Hazard Visibility	Difficult to see split from curve.	It is difficult to see the split from the curve because of limited sight distance and foliage.	Placing a warning sign for the curve upstream would better help guide the drivers through the split. Also showing how many lanes each direction contains can help advise the drivers because of lane split in the middle lane.	Houston 1	D/N

36:47 1:33:05 47:49 1:42:01	Information Load	Lane split appears from curve	The lane split appears from the curve but proper upstream pavement signing provides adequate warning, but split contains a high load of 5 information pieces. 2 sign, barrels, concrete barriers, 2 traffic lanes.	Warning of curve split and moving signs upstream could provide better guidance and lower the expectancy of the location.	Houston 1	D/N
48:08	Hazard Visibility	"Right Lane Closed" sign is posted in a one lane curve.	The sign is confusing since there is only one lane through the curve, but location gives the impression of merging traffic and an open lane.	Probably adding reflective barrels to show that there is no traffic merging or a second lane available would improve location.	Houston 1	D/N

DRIVER COMPREHENSION OF DIAGRAMMATIC ADVANCED GUIDE SIGNS AND THEIR ALTERNATIVES

by

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SUMMARY

The study of the Human Factors Group at the Texas Transportation Institute (TTI) analyzed driver comprehension of diagrammatic advance freeway guide signs and their text alternatives by assessing driver reaction and behavior to particular types of signs. The three types of guide signs tested were diagrammatic, modified diagrammatic, and text-only, which were presented in a manner of varying interchange types. Four different types of exits were tested: left optional exit (LE), left lane drop (LLD), freeway-to-freeway split with optional center lane (SPLT), and two-lane right exits with optional lanes (REO). From the data obtained, analysis of each individual sign was completed and driver inclination to each sign was calculated. While statistics are still pending, results showed that out of a general exit category (left exit, left lane drop, right exit only or freeway-to-freeway split) of signs, 1-2 specific signs are doing rather well. For the left exits the standard diagrammatic sign performed only slightly better than the text version. In regards to the right exit with optional lane, a modified diagrammatic sign, performed better than the text and standard diagrammatic sign. For the left lane drops, a modified diagrammatic sign did better as well. For freeway-to-freeway splits, text signs with two arrows over the optional lane performed better than either style of diagrammatic sign.

TABLE OF CONTENTS

INTRODUCTION

Diagrammatic guide signs are becoming ever more popular in the transportation world today. These advance freeway guide signs employ two methods of communication: words and symbols. A typical sign usually has a place name and some type of directional arrow. Though the signs are in practice in many places, few guidelines have been set regarding their design and presentation.

Freeway guide signs are often construed differently to different people; some people search for destination names whereas other people comprehend pictures and arrows with more ease. The generated signs in the Driving Environment Simulator allow for multiple representations of various types of exits. Since each distinctive interchange requires a unique system of signing, a variety of methods (i.e. diagrammatic, text-only, etc.) can be tested (*1*). For example, left exits can be put into operation with down arrows or highway splits can be implemented with an arrow representing the road map of the interchange. The variety of combinations will help to find a trend between drivers' behavior towards different signing. The results from analyzing driver behavior might possibly facilitate a standard type of diagrammatic guide sign to assure uniformity if more are designated to be put to use.

Although these guide signs are more elaborate, there is no assurance that they are not too complicated to comprehend while driving. More information just might lead to more confusion rather than offering additional assistance. In this situation, a diagrammatic guide sign falls short of serving its purpose in easing the direction process. Furthering research in this field can lead to an explanation of exactly how these signs affect a driver reaching a destination and may also offer insight into some useful alternatives *2*. Diagrammatic signs, which are larger in size due to the graphics and therefore require larger, more expensive structures, are generally costlier than most standard text-only signs (*1)*.

PROBLEM STATEMENT

Better guidance signs on freeways may aid drivers in judgment of interchanges, particularly unusual splits and exits. When drivers can recognize the layout of the freeway better, they can easily maneuver to their individual destinations and, in the process, may essentially eliminate any unnecessary lane changes. Alleviating extra lane changes should decrease the amount of erratic movements and possibly decrease the number of accidents at these atypical interchanges. Diagrammatic signs, pinpointing destinations with both the place name and some type of directional arrow, should help drivers reach their desired location with more ease. Because diagrammatic signs have so much information and appear to be so beneficial, it is necessary to evaluate driver comprehension before they are completely incorporated into use.

RESEARCH OBJECTIVES

The goals of this research were:

- To examine various advanced guide sign layouts,
- To observe different exits with optional lanes,
- To determine if diagrammatic, modified-diagrammatic, or text-only signs are preferred,
- To determine which set of guide signs was most effective for a particular type of exit,
- To determine a standard freeway guidance sign to use at atypical interchanges, and
- To determine any alternative guide signs to be used at atypical interchanges.

LITERATURE REVIEW

Increasing interest in diagrammatic guide signing has led to growth in research of driver behaviors towards these signs in different states.

National Cooperative Highway Research Program

The University of Massachusetts conducted a comprehensive study on alternative freeway guidance signs needed at atypical interchanges for the National Cooperative Highway Research Program (NCHRP) and the National Research Council. More specifically, this project addresses the Manual on Uniform Traffic Control Devices (MUTCD) in an assessment of alternative sign designs for two-lane freeway exits for a right exit with optional lane interchanges. Recently, more diagrammatic guide signs have been implemented into the freeway signing system; however, with no standard for these signs, the layouts of the lane drop and diagrammatic signing often approach similar geometries in inconsistent ways. The researchers designed an experiment consisting of four signs: the existing MUTCD sign configuration which was a diagrammatic sign, a modified diagrammatic sign, a text-only sign with a horizontal line dividing the names and the arrows, and a text-only sign without the horizontal line. This study was presented to 96 participants in a driving simulator. Based on the results of the data from the driving simulator as well as the information from the debriefing survey, the study concluded that a hybrid (a modified diagrammatic of the existing MUTCD configuration to clearly indicate the number of lanes on the approach) sign would be included in the MUTCD (*3*).

The scope of the University of Massachusetts research is very similar to the project here at TTI; the Human Factors group here took the hybrid results from the MUTCD project and applied it to determining what type of sign (diagrammatic, modified diagrammatic, or text-only) would be most effective here in Texas.

DATA COLLECTION & REDUCTION

Subject Selection

A total of sixty subjects were recruited for research and were mainly from the Bryan/College Station area due to the fixed-base simulator. The subjects were selected to represent the average demographic break up of licensed drivers in Texas. The age range of the subjects varies from 18-75 years old. Considering that many of the older drivers had problems with simulator sickness, the range was mainly young and middle-aged. Table 1 shows the demographics of the diagrammatic guide sign study (*1*).

Sign & Simulator Development

The freeway advance signs developed for the simulator were created using SignCAD. This program was used because of the easily accessible editing tools as well as the correct measure the program takes in developing a sign. The signs produced in SignCAD are accurate in that they resemble the existing signs on the roadway; however, to improve the quality of the signs, alterations were made using Corel DRAW. Unfamiliar destination names were chosen arbitrarily to avoid any familiarity for drivers; names were chosen at random from an atlas to avoid recognition.

HyperDrive Authoring Suite was used to generate a simulated world for the research. The signs developed in SignCAD were placed into a varying 4-6 lane highway with a median in the middle. Traffic and other cars in general were eliminated for ease and to also allow the driver to focus on the guide signs.

Table 1. Research Demographics

Demographic Group		Sample Characteristics	
		No. of Subjects	% of Sample
Gender	Male	31	52
	Female	29	48
Age	18-24	10	17
	25-39	18	30
	40-54	16	27
	55-64	8	13
	65-74	4	7
	75^+	4	7
Education	Some High School (HS)	31	52
	Some College (SC)	29	48

Study Administration

The study was administered in two parts: the laptop survey and the driving simulator. An example screen of the driving simulator is represented below in Figure 1, and an example of the prompt for the driving simulator is included in Appendix A. The signs tested are listed in Appendix B.

The Laptop Survey portion of the experiment included nine lane change questions, one multiple choice question, and five multiple choice questions. The survey was presented in the form of a PowerPoint presentation with the subject generally controlling the change of slides. However, the nine lane change questions were presented in a specific manner: the destination was prompted along with the question number, a picture was flashed for approximately three seconds, a question was asked regarding which lanes were a possible source to reach the destination, and then a second screen was flashed with the lanes numbered. The subject then had the opportunity to answer the question on the survey sheet, provide a confidence rating from 1-10, with 10 being the most confident, and also write down any comments about the signs displayed. In the case of the multiple choice questions, a subjective question was presented and the subject had room to circle the option preferred as well as write down any comments about the signs being displayed.

Figure 1. Screen shot of Driving Simulator in Progress

The simulator portion of the experiment consisted of two 25-minute drives (worlds) showing a series of 8-10 sets of guidance signs and was completed in TTI's Driving Environment Simulator. For continuity and a realistic feel, each sign was set at a certain distance from the gore, regardless of interchange/exit type. The markings denoting the distance between each sign are illustrated in Appendix D. For each set of guidance signs, an experimenter notified the subject to begin in a specific lane and then affirmed a destination; participants are essentially given a thru-route or an exit-route as a destination. Due to the numerous combinations of interchange layouts and sign configurations as well as the limited number of participants, a variety of signs were presented in different combinations to each subject. In general, half of the subjects would view the LLD and SPLT signs while the other half would view the REO and the LE signs; this break-up represents the A and B groups used in this experiment, respectively. The subject is then expected to maneuver accordingly to reach the destination with avoiding any unnecessary changes; sometimes the subject was already positioned in the correct lane to reach the destination and at other times the subject was required to make a lane change to reach the destination. As the driver changed lanes, the experimenter took notes regarding any general lane changes in addition to any unexpected movements or unnecessary lane changes. After the subject had passed the gore, the experimenter asked the subject to rate his/her confidence in direction to the destination on a scale of 1-5, with 5 being the most confident. This process was completed for every sign in both sections of the driving simulator portion.

A total of two simulator worlds were created for this experiment and the break-down can be seen below in Table 2 and Table 3.

Table 2. Sign, Route, and Start Lane Counterbalancing for the A Groups

	A 1			A 2			A 3		
	Sign	**Route**	**Start Lane**	**Sign**	**Route**	**Start Lane**	**Sign**	**Route**	**Start Lane**
α	REO9	T	R	REO8	T	R	REO7	T	R
	REO7	T	L	REO4	T	C	REO9	T	R
	REO1	E	L	REO2	E	L	REO1	E	L
	LE4	T	R	LE4	T	L	LE2	T	R
	REO2	T	R	REO1	T	R	REO4	T	L
	LE1	E	L	LE2	E	R	LE4	E	R
	REO9	E	R	REO7	E	C	REO7	E	R
	REO7	T	R	REO9	T	L	REO2	T	L
	REO4	E	R	REO8	E	C	REO8	E	R
	LE2	T	L	LE1	T	R	LE1	T	L
β	REO1	E	C	REO2	E	R	REO4	E	C
	REO8	T	C	REO4	T	R	REO8	T	R
	LE4	E	R	LE4	E	R	LE2	E	R
	REO2	E	C	REO7	E	L	REO2	E	L
	REO9	T	C	REO8	T	L	REO7	T	C
	LE1	E	R	LE2	E	L	LE4	E	L
	LE2	E	R	LE1	E	R	LE1	E	R
	REO1	T	L	REO2	T	C	REO1	T	C
	REO4	E	L	REO1	E	R	REO9	E	C
	REO8	E	L	REO9	E	L	REO4	E	L

Table 3. Sign, Route, and Start Lane Counterbalancing for the B Groups

	B1			B2		
	Route	Series	Start Lane	Route	Series	Start Lane
A	E	LLD1	C	E	LLD1	C
	T	LLD1	C	T	LLD1	L
	E	LLD2	L	E	LLD2	C
	T	LLD2	L	T	LLD2	C
	E	LLD6	C	E	LLD6	L
	T	LLD6	C	T	LLD6	L
	E	LLD9	L	E	LLD9	C
	T	LLD9	L	T	LLD9	C
B	E	SPLT2	R	E	SPLT2	C
	E	SPLT2	L	T	SPLT2	R
	T	SPLT2	C	T	SPLT2	L
	E	SPLT5	C	E	SPLT5	L
	T	SPLT5	R	E	SPLT5	R
	T	SPLT5	L	T	SPLT5	C
	E	SPLT6	R	E	SPLT6	C
	E	SPLT6	L	T	SPLT6	R
	T	SPLT6	C	T	SPLT6	L

DATA ANALYSIS & RESULTS

Method of Analysis

All of the data both from the surveys and extracted from the driving simulator computer was compiled into several separate Excel files. The information was divided into categories regarding demographics, comments, subjective based responses, and lane change distances. In evaluation of the sign alternatives process, the demographics, comments and subjective responses were used as a secondary source of information; the lane change distances were used as the main source of data.

To assess the lane changes for each subject a statistical approach was used. In the evaluation of the simulated world, a *hit* constituted a correct and necessary lane change. Similarly, any missed lane change would constitute a *miss* and no lane change when one was not needed would constitute a *correct rejection*. Considering that drivers approach various situations differently, there were unnecessary lane changes made and this is what needs to be clearly defined. To clarify the boundaries, responses denoting and unnecessary lane change, whether it be an additional lane change or just an initial unnecessary lane change, were classified as *false alarms (4)*. Table 4 explains how this process covers all possible responses to each prompt.

Laptop Survey Data

Data from the laptop survey has not been reviewed yet. Considering that the information drawn from this source is mostly subjective, it will be used to support the data from the driving simulator.

Table 4. Subject's Response

	YES	NO
SIGNAL PRESENT	HIT	MISS
SIGNAL ABSENT	FALSE ALARM	CORRECT REJECTION

Simulator Data

TTI's Driving Environment Simulator processes data from every drive and places it into Microsoft Excel files. The results from each simulated world (drive) for this experiment are stored into Excel files of roughly about 10,000 rows long and pertain to about 7 to 10 signs that a driver has observed. These files contain information regarding what lane the car was in, the car's position in the lane, lane changes denoted in relation to how many lanes exist at that time, detection of which turn signal was applied (if a turn signal was used by the driver), the position of the car in the simulated world, and a relative velocity. For each of the signs profiled in the Excel files, the only data needed are the lane change position and the position of the car in the simulated world. From a specific change in lane position (denoted by a -1.7 to a +1.7 or a +1.7 to a -1.7 regarding a left or right lane change, respectively), a driver's position in the simulated world can be determined, and, in turn, the distance from the gore can be calculated:

Lane Change Distance (from the Gore) = Position in Simulated World – Position of Gore

The units represented in the simulated world are meters, which allow for an easy comparison to the real world. When lane changes are addressed from the simulator data, they are placed into respective bins. Of the four bins existing, each represents a distance, in meters, from the gore. Figure 2 below illustrates the distance divisions and the bin markings. Once the lane change distance is established, the data for each subject can be concluded; hits, false alarms, and correct responses can be obtained and counted. Similarly, once the number of responses is recorded correctly, averages can be calculated and conclusions can be determined.

The horizontal lines dividing the interchange layout represent the different bins used in this research; starting with Bin 1 on the bottom denoting a distance greater than 1072 meters from the gore. Bin 2 represents a distance less than 1072m and greater than 576m. Bin 3 denotes a distance less than 536m and greater than 150m. The final section, Bin 4 represents a distance from the gore of less than 150 meters.

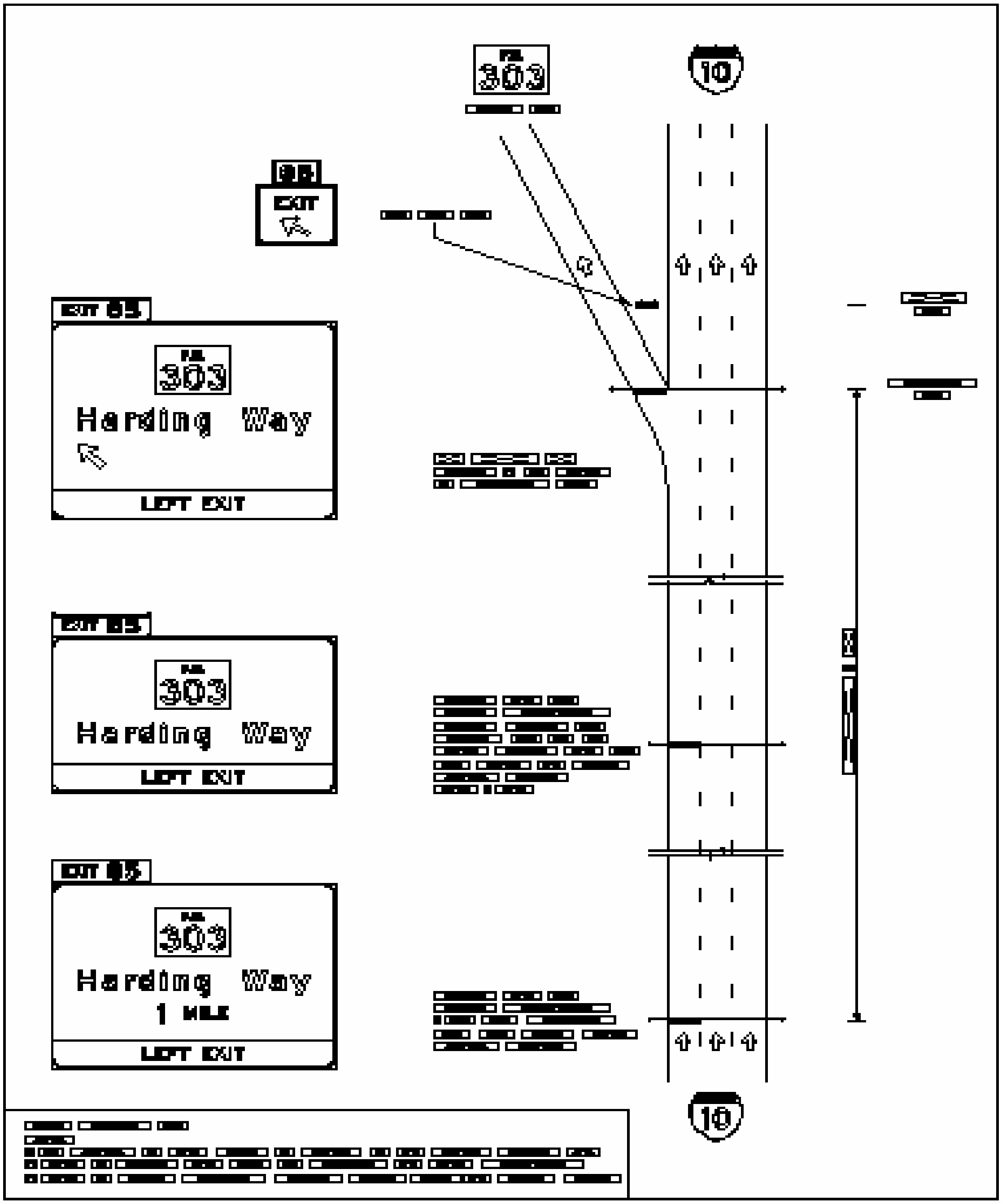

Figure 2. Bin Diagram

RESULTS

From the statistical review of the data collected by the simulator, a few signs stood out in different ways. In the freeway-to-freeway split interchange, the text-only sign without the yellow exit-only bar, SPLT6 (Refer to Appendix C), appeared to warrant attention; participants tended make lane changes sooner on this particular sign compared to the other two signs for this interchange. For the same interchange, the text-only sign with the yellow exit-only bar, SPLT2, seemed to have the most unnecessary lane changes out of all three signs in this category as seen in Figure 3 below.

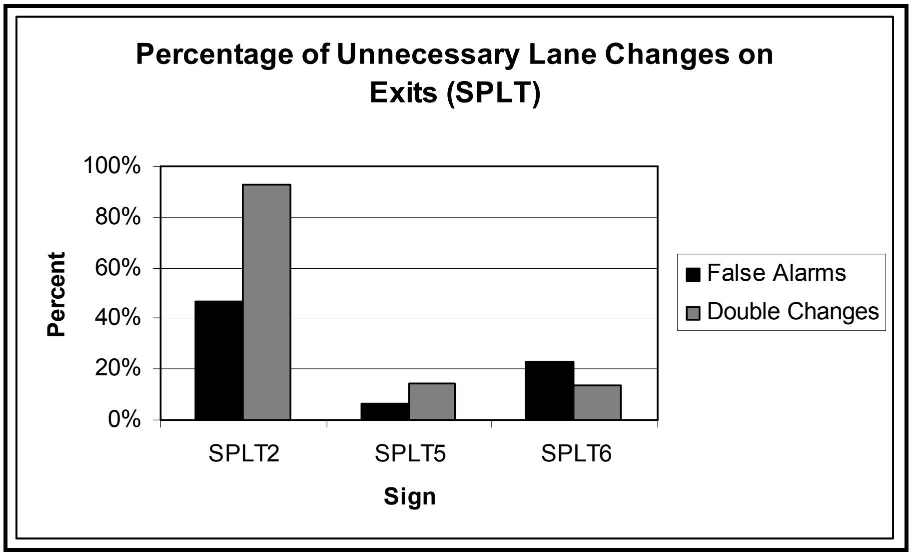

Figure 3. Unnecessary Lane Changes for Freeway-to-Freeway Splits

In the left exit interchange, LE1 seems to be the most successful in getting drivers to change lanes faster in comparison to the other two signs in this category. On a different note, there appear to be a lot of later lane changes in Bin 2 and Bin 3 with this particular type of exit in general. Table 5 below shows the number of lane changes per bin for the left exit interchange.

Table 5. Number of Hits for Left Exits

Left Exit				
Hits	**Bin1**	**Bin2**	**Bin3**	**Bin4**
LE1	3	18	6	1
LE2	1	11	13	1
LE4	2	18	5	2

Similarly, in the left lane drop interchange, there also appear to be a number of later lane changes in Bin 2 and Bin 3, particularly in Bin 2. Table 6 below illustrates the number of lane changes per bin for the left lane drop interchange.

Table 6. Number of Hits for Left Lane Drops

Left Lane Drop				
Hits	**Bin1**	**Bin2**	**Bin3**	**Bin4**
LLD1	1	11	1	2
LLD2	2	10	2	1
LLD6	1	12	0	2
LLD9	2	9	2	2

In the right exit optional interchange, REO4 and REO9 stand out slightly. These two modified diagrammatic signs have the longest lane change distance from the gore denoting the faster recognition by the subject in this type of interchange. Figure 4 below shows the average distances of lane changes made in the right exit optional interchange.

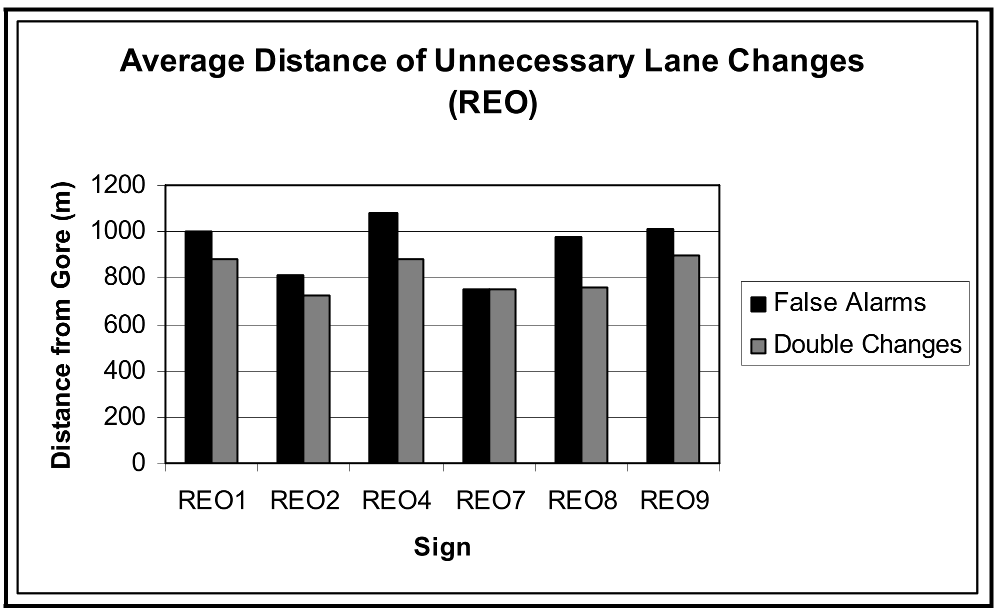

Figure 4. Average Distance of Unnecessary Lane Changes Made for Right Exit Optional

CONCLUSIONS

- REO's have a large number of late, unnecessary lane changes compared to other interchanges.
- The six signs that produced lane changes furthest from the gore: SPLT6, LE1, LLD6, REO1, and REO7.
- Overall, two diagrammatic, two text-only and one modified diagrammatic sign performed well.
- Though there was only one outstanding modified diagrammatic sign, this type of sign produced the lowest number of unnecessary lane changes when compared to the text-only and diagrammatic signs.

DISCUSSION

Although not included in this study for various reasons, further research on diagrammatic signing could include traffic in the driving simulator. Interaction between drivers allows for a more realistic simulated world and would most likely alter the statistics, possibly in a more beneficial manner. Further research for this study might focus more on driver preference than solely on driver behavior; an analysis of how drivers repetitively react to certain signs could be completed. The results for this might help account for drivers who just prefer to be in certain lanes rather than making unnecessary lane changes all of the time; bias is human nature. Additionally, the results from this further research might lead to conclusions surrounding that it's not just certain signs that people don't like, but that driver preferences may take priority.

ACKNOWLEDGEMENTS

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APPENDIX A

S19: *"Please maneuver to the* ***Right*** *lane. Your first destination is* ***50W to La Salle."*** After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 50W to La Salle?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C1 C2 R

Comments:

S20: *"Please maneuver to the* ***Left*** *lane. Your next destination is* ***73N to Lily."*** After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 73N to Lily?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C1 C2 R

Comments:

S1: *"Please maneuver to the* ***Left*** *lane. Your next destination is* ***15E to Tudor."*** After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 15E to Tudor?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C1 C2 R

Comments:

S2: *"Please maneuver to the* ***Right*** *lane. Your next destination is* ***47 N Mio."***
After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 47 N to Mio?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C R

Comments:

S3: *"Please maneuver to the **Right** lane. Your next destination is to continue on **47 N to Mio.**"* After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 47 N to Mio?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C1 C2 R

Comments:

S4: *"Please maneuver to the **Left** lane. Your next destination is **22 West to Trenton.**"* After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 22 West to Trenton?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C R

Comments:

S5: *"Please maneuver to the **Right** lane. Your next destination is **75 South to Daly.**"* After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 75 South to Daly?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C1 C2 R

Comments:

S6: *"Please maneuver to the **Right** lane. Your next destination is **73 North to Lily.**"* After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 73 North to Lily?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C1 C2 R

Comments:

S7: *"Please maneuver to the **Right** lane. Your next destination is **87 East to Martin.**"* After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 87 East to Martin?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C1 C2 R

Comments:

S8: *"Please maneuver to the **Left** lane. Your next destination is **33 North to Enid.**"* After the driver maneuvers through the intersection:

"On a scale of 1 to 5, with 5 being the most confident, how confident are you that you are heading on 33 North to Enid?"

1 2 3 4 5

Which lane was the subject in when they passed thru the intersection?

L C R

Comments:

APPENDIX B

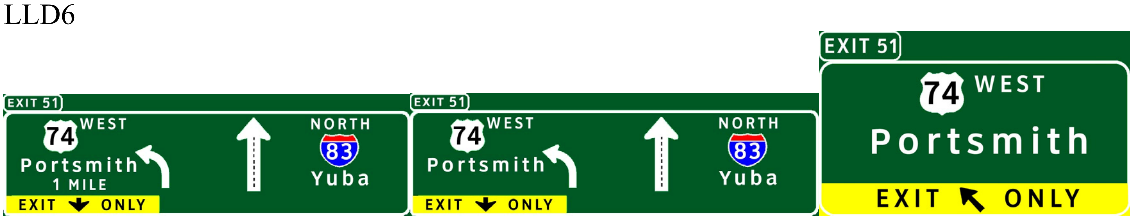
Advanced Guide Sign Layouts used in Driving Simulator

Left Lane Drops

LLD1

LLD2

LLD6



LLD9

Right Exit Optional

REO1

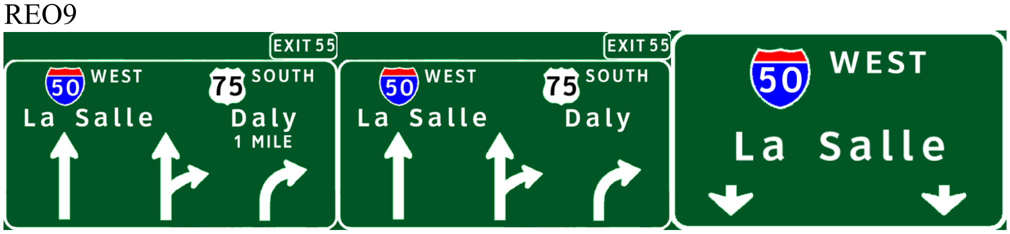
REO2

REO4

REO7

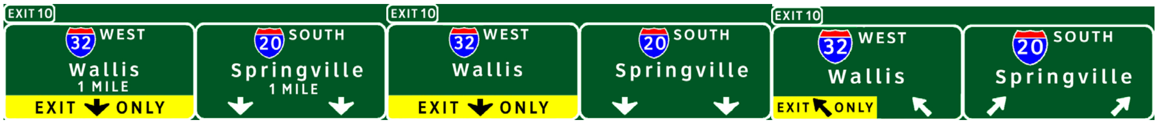
REO8

REO9



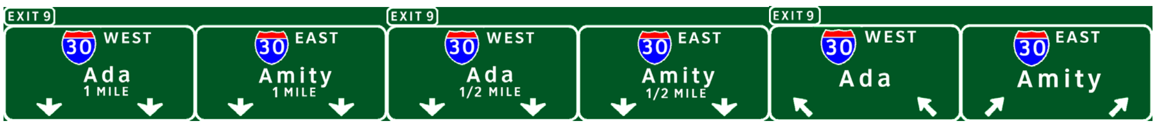
Freeway to Freeway Splits

SPLT2



SPLT5

SPLT6



Left Exits

LE1

LE2

LE4

PERFORMANCE EVALUATION OF TRAFFIC RESPONSIVE SIGNAL CONTROL

by

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SUMMARY

Traffic congestion in Texas, like in many other parts of the United States, has become an increasing problem. Traffic demands increase faster than the capacity of our roadway networks, which results in excessive travel times and delays. The Texas Department of Transportation and the Texas Transportation Institute are working together to find effective ways of improving traffic operations through better traffic control on our freeways and arterials. One important element of this effort is to improve the traffic flow at signalized intersections by implementing traffic responsive signal control. In traffic responsive control signal timing plans are selected in response to real-time changes in traffic demand. The traffic responsive plan selection (TRPS) mode can improve progression and reduce travel times and delays. This research focuses on the implementation and evaluation of TRPS mode on an arterial with three coordinated signals in Mexia, Texas. Prior to the implementation of TRPS mode, the signal system was operated on Time-of-Day (TOD) schedule. The two modes of signal control were compared based on travel times, delays and average vehicle speeds determined before and after the implementation of the TRPS mode. It was found that the TRPS mode significantly reduced travel times and delays, and improved progression. During the limited time period of this study the TRPS mode generally performed better than the TOD mode.

TABLE OF CONTENTS

INTRODUCTION

In Texas, like many areas of the United States, traffic volumes are increasing on a daily bases. In 2003, according to the Texas Transportation Institute (TTI), congestion in 85 urban areas added up to 3.7 billion hours of delay, or an annual delay per person of 43 hours. (*1*) As traffic volumes increase and roads become congested, delay also increases. This leads to an increase in vehicle stops, fuel consumption, and vehicle emissions. The congestion study TTI performed in 2003 estimated that the annual cost of delay and extra fuel was over $63 billion or $384 per person. (1)

The Texas Department of Transportation (TxDOT) has teamed up with the Texas Transportation Institute (TTI) to find better ways of improving traffic operations on arterial networks in Texas. The research focused on the coordination of traffic signals in a closed loop system with traffic responsive plan selection (TRPS) mode. The ultimate goal was to improve progression and decrease travel time, delay and the number of stops. Several field studies show that traffic responsive signal control systems can reduce peak period travel times by as much as 11 percent, while models estimate that fuel consumption can be reduced by as much as 13 percent. (1) In Kansas City, Missouri a signal timing effort along a 1 mile stretch of Bannister Road resulted in improved traffic flow, including an annual reduction of 101,000 hours in delay, and saving 346,000 liters (91,000 gallons) of fuel. This research, as part of TxDOT Project 5-4421, evaluates the performance of traffic responsive signal control mode on an arterial with three coordinated intersections in Mexia, TX.

PROBLEM STATEMENT

Coordinated traffic signals in arterial networks are typically operated on Time-of-day (TOD) schedule. TOD mode switches timing plans according to the time of day regardless of the actual traffic volume. It works well as long as variations in traffic demand follow the same or similar patterns over time. However, it may not be appropriate when there are frequent unusual changes in traffic volumes. In such cases, the TRPS mode is expected to perform better.

OBJECTIVE

The specific objectives of this research were to evaluate the performance of TRPS mode of signal operations and compare it to the performance of the TOD mode based on field observations at a study site in Mexia, Texas. To accomplish these objectives the researcher performed the following research tasks.

RESEARCH TASKS

First a literature review was conducted to better understand the operational characteristics of the TOD and TRPS modes, and to identify an appropriate tool and method for the performance evaluation of the two signal system operation modes. Then, the researcher conducted before and after studies to evaluate and compare the performance of both signal control modes. The evaluation was based on three operational measures of effectiveness (MOEs): travel time, delay, and average vehicle speed. First the performance of the TOD mode, which was operating at the beginning of this research, was evaluated. The researcher conducted field studies in mid-June 2006 to evaluate the TOD mode. In early August of 2006 the TRPS mode was implemented. After this implementation, the researcher again conducted field studies and evaluated the performance of the traffic responsive signal control mode. The performance of the TOD mode and TRPS mode were compared using the same MOEs. Statistical tests were also performed to determine the statistical significance in the differences between the MOEs.

LITERATURE REVIEW

Before the field studies and data collection, a literature review was conducted on three different topics. These topics included:

1. Closed loop traffic control systems
2. Travel time and Delay
3. Travel time studies using GPS technology

Closed Loop Traffic Control System

A closed-loop system consists of a master traffic signal controller connected to a series of traffic signal controllers using hard wire connections, fiber-optic cables, or spread spectrum radio. The on-street master supervises the individual intersection controllers and issues commands to implement timing plans stored at local controllers. The master controller can also report detailed information back to a traffic management center using dial-up telephone or similar communications channels for monitoring purposes. (2)

A closed-loop traffic control system can operate under:

- "Free" mode. In this mode, each intersection runs independently, usually under a fully actuated isolated signal control.
- Time-of-Day (TOD) mode. In this mode, all intersections are coordinated under a common cycle length. The timing plans are selected at specific times based on historical traffic conditions.
- Traffic Responsive Plan Selection (TRPS) mode. This mode is similar to TOD mode except that plans are switched in response to changes in some measures of traffic demand variation (e.g. volume and/or occupancy).
- Manual mode. Under this mode, the closed-loop system operates under a constant plan, unless changed by the system operator. This mode is rarely used. (3)

TOD mode is the most common closed loop mode used by Texas Department of Transportation (TxDOT) traffic engineers. TOD mode is easily setup and understood. TOD mode changes signal timing plans according to a predefined schedule. For example, if the programming is set to change timing plans at four o'clock pm Monday thru Friday, then at four o'clock the timing plan is changed from timing plan "x" to timing plan "y" regardless of the actual traffic volumes. TOD mode operates in this manner until the traffic engineer re-times/updates the signal control system.

Despite its easy set up, occasionally there may be some problems with TOD mode. First, as stated earlier, TOD mode switches timing plans according to the time of day, not according to the actual traffic conditions. This type of mode assumes a well-defined predictable traffic pattern. For example, Figure 1 illustrates a hypothetical daily variation of traffic volume on an approach to a signalized intersection. It shows a morning peak as well as an afternoon peak. At specified times of the day, the timing plans are changed. These changes are indicated by the vertical lines. If an abnormal traffic pattern occurs, such as the one in Figure 2, the TOD mode will NOT change timing plans and traffic could become congested if the scheduled timing plan can not handle the increased traffic demand.

Another potential problem with TOD mode is the need for frequent updates and retiming. TOD should be updated whenever there is a significant change in the usual traffic patterns. Volume data must be collected and analyzed and timing plans have to be updated according to the new traffic patterns. This process can get very expensive, time consuming, and many times, it does not happen. In 1997, Institute of Transportation Engineers (ITE) did a study and found that "75% of signals in the United States need to be retiming." (*4*) This means that traffic patterns are frequently changing and traffic engineers can not keep up with the adjustments.

TRPS is another less common signal systems operation mode. It is more detailed and complex then the TOD mode. TRPS mode switches traffic plans according to the actual traffic conditions (i.e., changes in traffic demand). Figure 2 highlights an abnormal surge in the volume of traffic that may be associated with a special event around the middle of the day. The TRPS mode can accommodate such abnormal traffic conditions. TRPS mode also reduces the need for frequent re-timing/updating of signal timing plans.

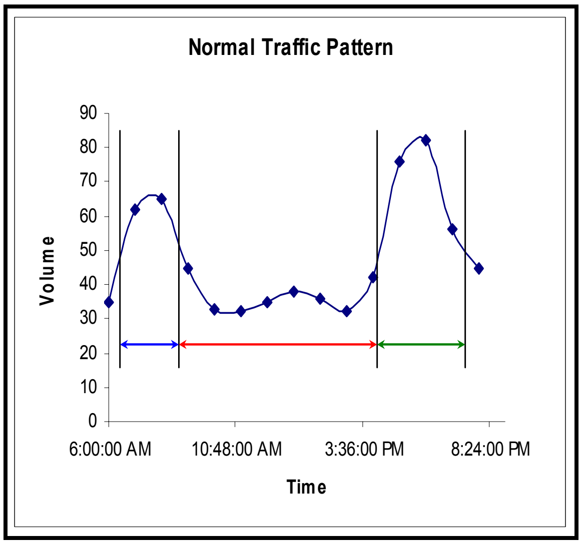

Figure 1: Normal Monday thru Friday traffic patterns

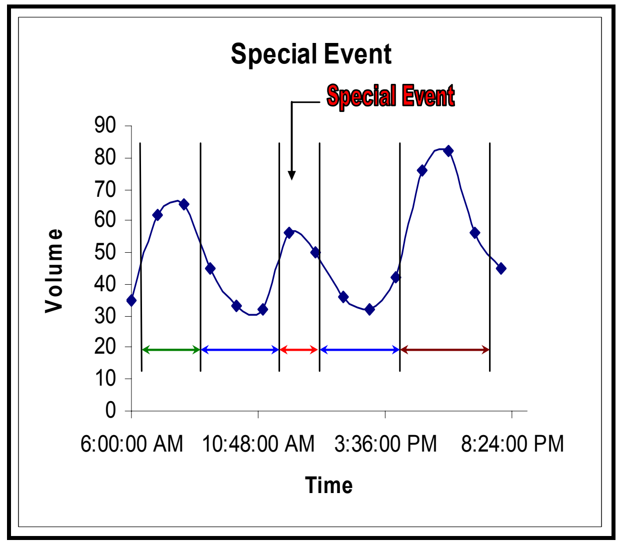

Figure 2: Abnormal traffic pattern during the week

Delay, Travel Time and Congestion

According to Pecheux, "…the use of delay as a measure of effectiveness for signalized intersections has been based on an average measure (whether stopped delay, control delay, or travel time delay). Although delay has been used as a measure of effectiveness for signalized intersections for nearly 15 years, little research has examined the distribution of delays at signalized intersections."(*5*). Advanced technologies, such as automated Distance Measuring Instruments (DMI), GPS receivers, Laptop computers and travel time software, has enabled researchers to more accurately assess the spatial distribution of delays along arterials with signalized intersections.

Travel Time Studies Using GPS Technology

Travel time studies are common methods of evaluating the effectiveness of various improvements in traffic operations and control. There are several methods to conduct such studies. These methods are (*6*):

- Average vehicle method
- Moving vehicle
- License Plate
- Direct observation, or interview method

While the first two methods require driving a vehicle, the other two can be performed remotely. The choice of the most appropriate method depends mainly on the purpose, the type and length of the road being studied, and the resources available to conduct the study. (1)

Since the early 1990s, the evolution of global positioning system (GPS) technologies for civil applications has provided a new powerful and cost-efficient tool for collecting travel data. The primary function of the GPS is to provide the user with a three-dimensional location (latitude, longitude and elevation) for any point on land, sea, and in the air. (1) As it provides real-time spatial and time measurements, it can be effectively used for conducting different transportation studies. Faghri and Hamad performed travel time, speed, and delay analysis on 64 major roads throughout the state of Delaware using an integrated GPS system, and found it an effective way of measuring congestion(1). They compared the results between GPS and manual travel time methods, and discovered that there were no statistically significant differences between the means and variances of travel times collected by manual methods and the GPS method. Faghri and Hamad concluded that "The main advantage of monitoring congestion using GPS is that real-time information on travel time and speed can be obtained in an accurate, economical, and expeditious manner." (1)

Based on the literature reviewed, it was decided to use a GPS receiver and travel time software installed on a laptop computer to conduct the travel time studies for the evaluation of the TRPS and TOD modes of signal operations. The GPS method requires only two people, a driver and a passenger to operate the notebook computer. Connected to the notebook computer is a GPS receiver, which feeds the data into a travel-time study software. The program TS/PP Draft 6.0, developed by Greg Bullock in Pacific Grove, California, was chosen for this study.(*7*) According to Robertson, this type of software can produce accurate reports and plots of travel time studies to measure the effectiveness of travel time and delay.(6)

PROCEDURE

Step 1: Select Study Site

The selected study site for this research was located in Mexia, TX, which is located approximately 30 miles east of Waco, TX. A map of Texas and Mexia can be seen in Figure 3.

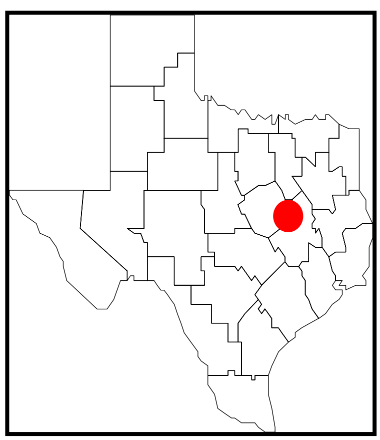

Figure 3: Dot represents the location of Mexia, TX

The study site was an approximately 4730ft long arterial with moderately high traffic volumes. The arterial traffic volume ranged from 1000 to 1800 vehicles per hour and the side street traffic volume ranged between 100 to 400 vehicles per hour. The intersection layout, shown in Figure 4, consisted of three intersections. These intersections, starting from the east, are Bailey, Ross and McKinney. The speed limit was 35mph between Bailey and McKinney and 30mph on the west side of McKinney.

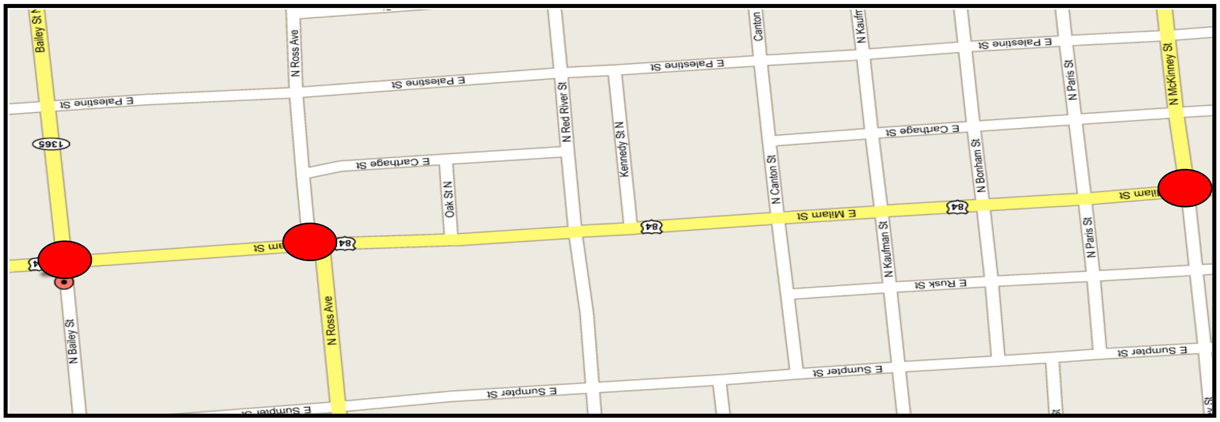

Figure 4: Intersections of study site

All intersections had the same geometry and lane configuration. The arterial roadway had two through and one left-turn lanes at each intersection. The side streets had single lanes for shared left-turn, through and right-turn movements. For example, Figure 5 shows the westbound approach to the intersection at Ross, and Figure 6 shows one of the side streets at the Bailey intersection.

Figure 5: Ross intersection looking West

Step 2: Test GPS and TS/PP Draft Software

Before conducting the travel time and delay studies at the selected study site, the GPS receiver and TS/PP Draft Software were tested through experimental data collection. These experimental runs were performed around Research Park on the Texas A&M University campus. The researcher used minor intersections, large trees, and other stationary objects, to simulate arterial intersections. The researcher then set up the computer software to simulate the arterial travel time and delay study. As the researcher explored the many software features, he became more familiar, comfortable and confident with the research approach and procedure.

Figure 6: Bailey side street facing North

Step 3: Data Collection

Data for this research was collected using a GPS receiver, laptop computer equipped with TS/PP Draft 6.0 software, digital video recorder, and visual observation. For the travel time and delay studies, the GPS receiver was placed on the roof of the study vehicle and powered by the cigarette lighter in the vehicle. The GPS then connected to the laptop through a serial port. This enabled data to flow between the GPS and TS/PP Draft 6.0. With this set of connections, travel time and delay studies were performed during the noon peak, 11:30am to 1:30pm and PM peak, 3:30pm to 5:30pm. During these time periods the researcher gathered data by traveling the arterial route approximately 10 times in each direction for each peak time period and for each signal control mode (TOD and TRPS). This data was then saved for each trip in the laptop computer for data analysis in the office. The GPS receiver and Laptop computer setup is shown in Figure 7.

Figure 7: GPS and Laptop set-up

While performing the travel time studies, the researcher also recorded the trips with a digital video recorder. This recorder was set up on a tripod located between the driver and passengers' seats. The researcher took this video to have a permanent record of each travel time run. The video recordings were also used for subsequent review of intersection layout, and to verify the reasons for stops and slowdowns observed from the travel time, speed and delay data.

While the GPS and TS/PP Draft software gathered data, the researcher also watched attentively for queues on the side streets, and noted the maximum queue length observed. Some queues were recorded on the digital video recorder while others were just noted.

Along with the travel time and delay studies, the researcher also counted the traffic volumes at each intersection at the study site.

RESULTS

Travel Time

The BEFORE study data was collected while the TOD mode was operating. After implementing the TRPS mode, the researcher used the same procedure to perform the AFTER study. Data from the travel time studies were analyzed using the TSP/Draft software and Microsoft Excel. Tables 1 and 2 summarize the average travel times in the eastbound and westbound directions, respectively. They also show the sample size, N, 95% confidence interval and percent differences in the average travel times between the TOD and TRPS modes. As indicated by Table 1, the travel times decreased for all time periods in the TRPS mode while traveling in the eastbound direction. In some cases, the travel time decreased as much as 23%. This decrease could be linked to the better performance of the TRPS mode. On the other hand, travel times increased with the implementation of the TRPS mode during the noon peak by 9%, as shown in Table 2. However, during the PM peak, while traveling in the west bound direction, the travel time decreased by 18%. The same results can be seen in the time-space diagrams shown in Figures 8 through 11. 8

Table 1. East Bound Travel Time

	TOD				TRPS				
	N	Average	95% C.I.		N	Average	95% C.I.		Difference
11:45am to 1:30pm	8	144.63	124.32	164.93	10	117.70	100.99	134.41	-19%
3:30pm to 5:30pm	13	150.69	133.89	167.49	9	115.67	99.45	131.89	-23%

Shaded cell indicates statistically significant difference at the 95% confidence level

Table 2. West Bound Travel Time

	TOD				TRPS				
	N	Average	95% C.I.		N	Average	95% C.I.		Difference
11:45am to 1:30pm	7	113.00	101.47	124.53	10	123.30	103.10	143.50	9%
3:30pm to 5:30pm	11	137.36	116.75	157.98	10	123.40	114.08	132.72	-10%

These Figures show the time-space relationship of travel times between the TOD mode and the TRPS mode. For example, in Figure 11, the travel time for the TOD mode, indicated by the upper line, was significantly decreased with the implementation of the TRPS mode. Overall, it was found that the TRPS mode's performance showed improvement in terms of vehicle travel time.

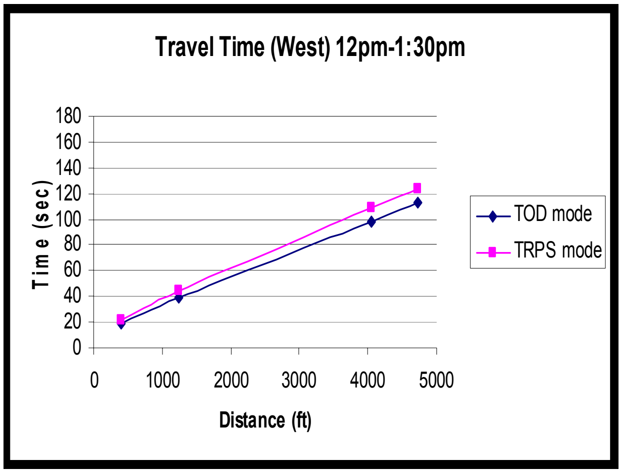

Figure 8. Travel Time for noon peak traveling west.

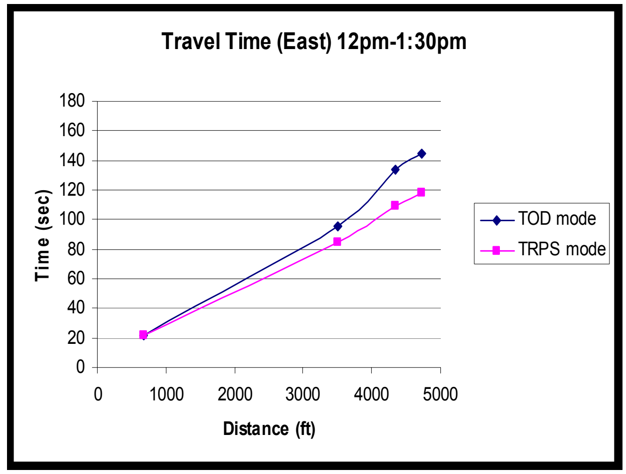

Figure 9. Travel Time for noon peak traveling east.

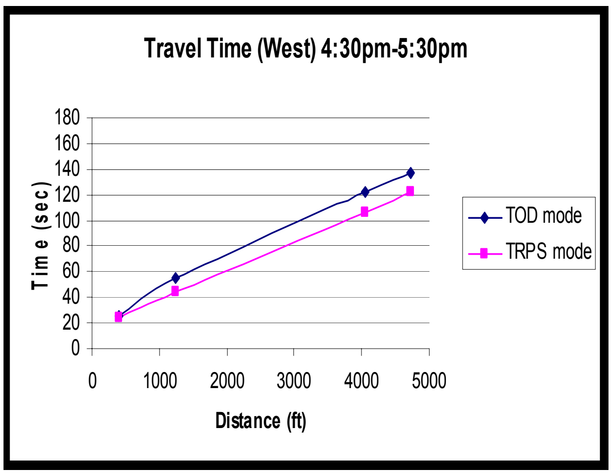

Figure 10. Travel Time for PM peak traveling west.

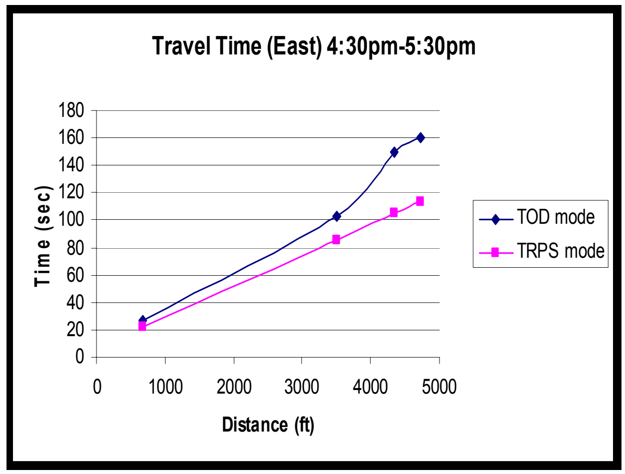

Figure 11. Travel Time for PM peak traveling east.

Delay

With the exception of the westbound traffic during the noon peak, the majority of the data indicated that the TRPS mode greatly decreased the delay. Table 3 and 4 show that the TRPS mode decreased the delay by 32%, as compared to the TOD mode, while traveling in westbound direction and as much as 62% while traveling in the eastbound direction during the PM peak. This significant change is linked to the TRPS mode's ability to respond to the change in traffic patterns. However, during the noon peak, the TOD mode performed better than the TRPS mode. Nevertheless, the TRPS mode performed more consistently over the study period. Note that there were relatively large variations in travel times as well as delays as indicated by the relatively wide 95% confidence intervals in Tables 1 through 4. This variation is primarily due to the relatively small number of runs that could be completed in each direction during the limited time.

Table 3. East Bound Delay

	TOD				TRPS				
	N	Average	95% C.I.		N	Average	95% C.I.		Difference
11:45am to 1:30pm	8	50.27	29.97	70.57	10	23.37	6.66	40.08	-54%
3:30pm to 5:30pm	13	56.31	39.51	73.11	9	21.27	5.04	37.49	-62%

Shaded cells indicate statistically significant difference at the 95% confidence level

Table 4. West Bound Delay

	TOD				TRPS				
	N	Average	95% C.I.		N	Average	95% C.I.		Difference
11:45am to 1:30pm	7	18.72	7.19	30.24	10	29.02	8.82	49.21	55%
3:30pm to 5:30pm	11	42.98	22.37	63.59	10	29.07	19.74	38.39	-32%

The delay profiles for the TOD and TRPS modes can visually be compared in Figures 12 through 15. These figures show the cumulative delay along the arterial route. The TRPS mode considerably decreased the delay for the PM peak time period. On the other hand, the TOD mode has less delay during the noon peak while traveling in the westbound direction.

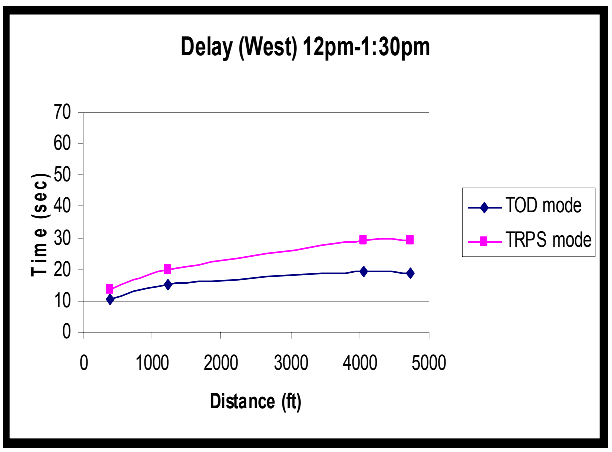

Figure 12. Delay for the noon peak traveling west.

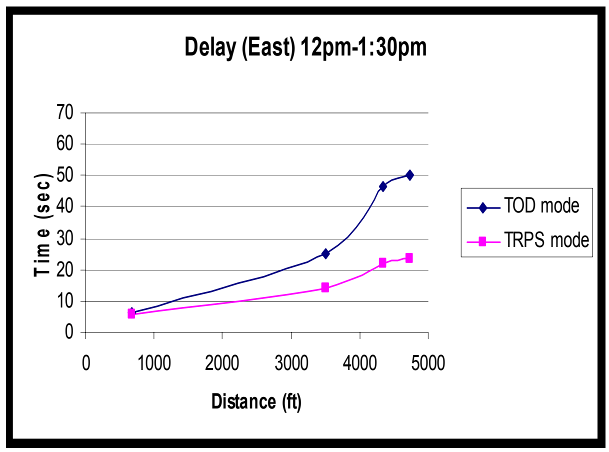

Figure 13. Delay for the noon peak traveling east.

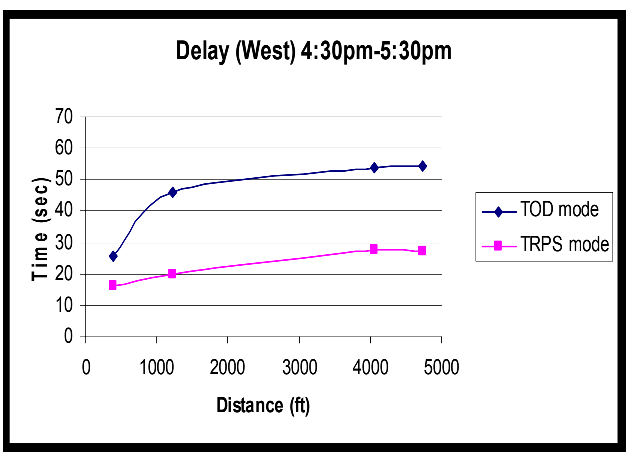

Figure 14. Delay for the PM peak traveling west.

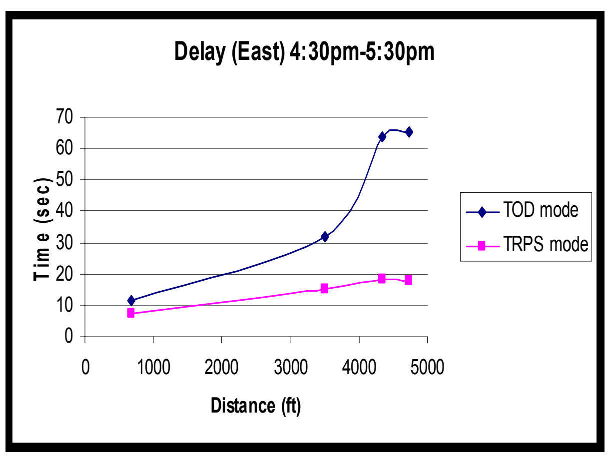

Figure 15. Delay for the PM peak traveling east.

As the above delay graphs highlight, the TRPS mode decreases the travel delay during most time periods.

Average Speed

Since vehicle speed is correlated to travel time and delay, the average speed between intersections increased during most time periods when the signal system was operated in TRPS mode. This measure of effectiveness can be seen in Figures 16 through 19.

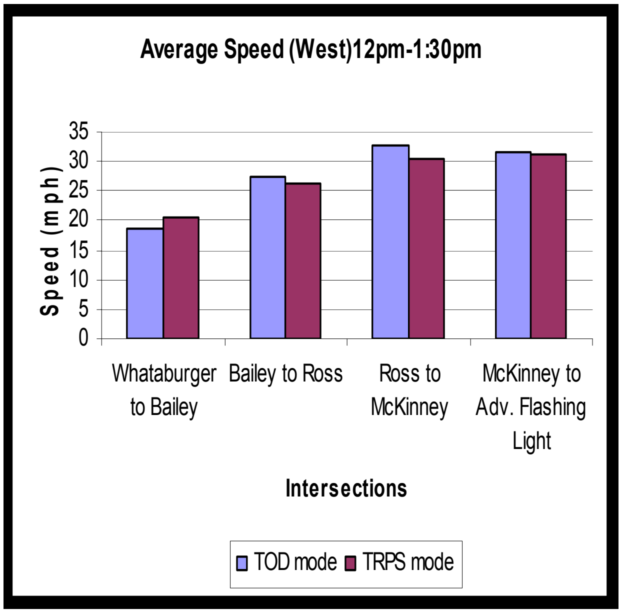

Figure 16. Average Speed for noon peak traveling west.

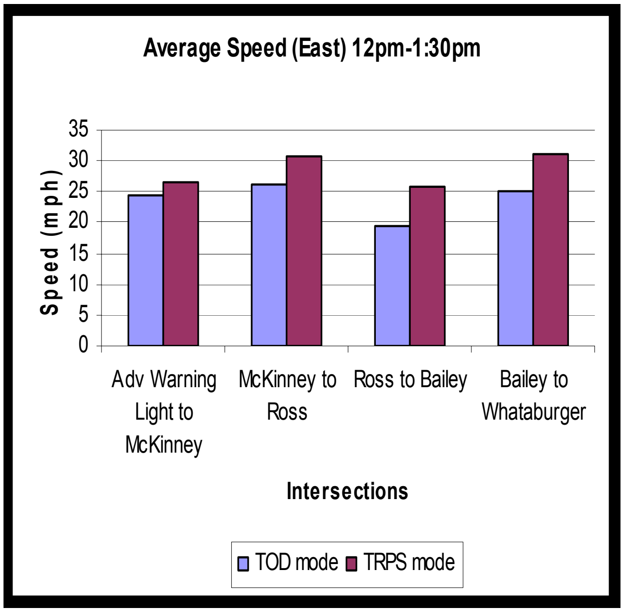

Figure 17. Average Speed for noon peak traveling east.

As Figure 16 indicates, for the TOD mode the average travel speed between Bailey and McKinney was higher than for the TRPS mode while traveling in the west bound direction. However, the TRPS mode increased the average speed between all intersections while traveling in the east bound direction. This is illustrated through the bar graph in Figure 17. Similar to Figure 17, the TRPS mode increased the average speed between all intersections for both directions during the PM peak, which is shown in Figures 18 and 19.

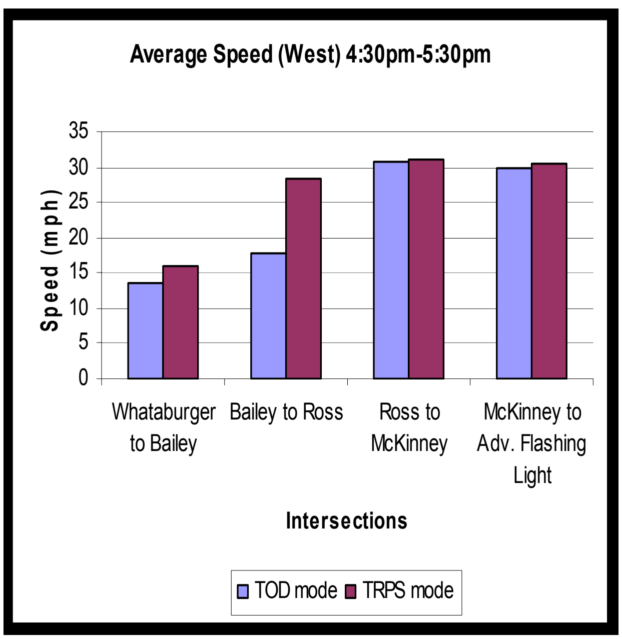

Figure 18: Average Speed for PM peak traveling west.

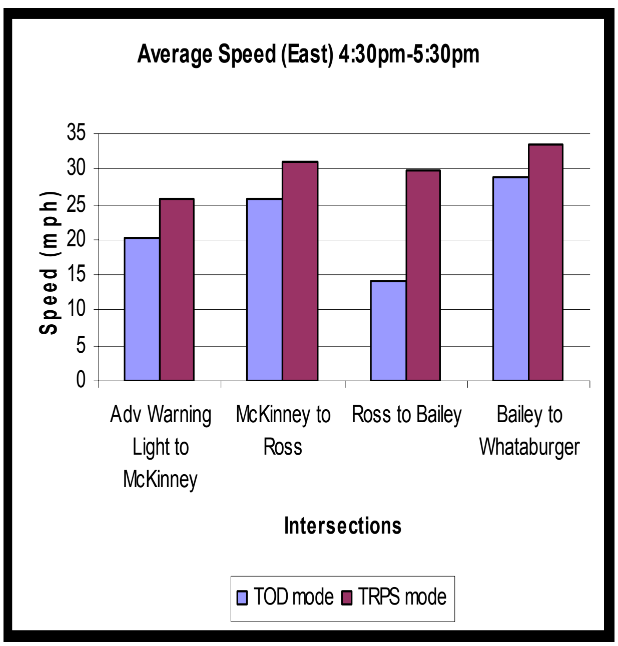

Figure 19: Average Speed for PM peak traveling east.

Between some intersections, such as Ross to Bailey, while traveling in the eastbound direction, the average speed for the TRPS mode was twice the average speed of the TOD mode. In some cases, the average speeds were unchanged between intersections. Overall, the average travel speed increased during all time periods and in all directions, except for the noon peak in the west bound direction.

CONCLUSION

This research was a small part of a much larger TxDOT research project. Due to a lack of time, the researcher was unable to analyze the traffic patterns and the performance of the TRPS mode for longer periods of time at the study site, in Mexia, TX. For a more complete evaluation of the traffic responsive signal control, the research must study the TRPS mode over a longer duration to see how it responds to unusual traffic patterns. During this program, the researcher was unable to measure the long term effect of the TRPS mode. However, the data collected during the limited time of the this research showed that the TRPS mode performed better than the TOD mode.

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INTERNAL TRIP CAPTURE ESTIMATION FOR MIXED-USE DEVELOPMENTS

by

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SUMMARY

The National Cooperative Highway Research Program contracted TTI to evaluate the current internal trip capture estimation method for mixed-use developments and improve the methodology if possible. Currently, the most widely used internal trip capture estimation method is from the ITE Trip Generation Handbook. This report focuses on the data analysis of two different mixed-use developments, Mockingbird Station and Atlantic Station. The data collected will be used in the future to develop an improved estimation methodology.

The preliminary results show that there is a correlation between the site characteristics and internal trip capture, but there is not enough data to make any definite conclusions at this time. The site characteristics that were primarily used to classify the mixed-use developments were internal synergy, proximity of uses, and internal connectivity. As more data is collected at different mixed-use developments, researchers will be able to more clearly define the different factors affecting internal trip capture.

Also, additional information was requested regarding mode of access and destination splits when using public transportation. This information is included in the report for the purpose of fulfilling those requirements.

TABLE OF CONTENTS

INTRODUCTION

The goal of NCHRP 8-51 is to improve the estimation of internal capture rates for mixed use developments. Accurate estimation methods for internal capture rates are necessary, because they are an important part of traffic impact studies. Developers need to know the amount of traffic to be expected in any development, but in mixed-use developments if the internal capture rate can be maximized the traffic impact will be lowered. Lowering traffic impact results benefits developers by decreasing construction costs; also the surrounding community avoids a more significant increase in congestion that would result from a comparably sized single use development. Therefore, a study is being conducted to determine what factors influence the internal capture rate and how it may be maximized.

Phase I of the study proposed an estimation methodology for internal capture rates. First, basic data about the development must be collected to determine the internal capture rate. The intended land uses, internal connectivity and proximity must all be known and classified using the charts provided in Phase I. These elements are used to estimate the initial site capture using the relationship provided in Phase I. Usually it is difficult to know the surrounding area of a development, because the surrounding area tends to be developed as well. However, if possible, the surrounding market area may be analyzed and competing opportunities in the area may be found. Using the equation found in Phase I, the adjusted internal capture rate can be found. Finally the internal capture rate needs to be balanced using the Trip Generation Handbook method.

Phase II of the project analyzes the data collected from at least two case studies of mixed use developments and compare the actual internal capture rates with the estimation methods proposed in Phase I as well as the current ITE method and data summaries. As part of NCHRP 8-51, TTI has already collected cordon counts, door counts and survey data for Mockingbird Station in Dallas, TX and will collect the same data for Atlantic Station in Atlanta, GA.

PROBLEM STATEMENT

Despite various previous attempts to create an accurate estimation methodology of internal trip capture, there is not enough data to make accurate estimations. Also, the current ITE method, generally accepted as the best currently available estimation method for site trip generation, does not take into account relevant data that is necessary to make accurate estimations. Therefore, this project:

- Determines relationships between the development's physical property and the effect on internal trip capture.
- Analyzes and refine a proposed estimation methodology for internal trip capture.
- Processes data for two mixed-use developments and add them to the internal trip capture database.

By using more information on mixed-use developments than previous studies, this project will help to determine a more accurate estimation methodology for internal capture rates.

RESEARCH OBJECTIVES

The objective of Phase II is to test the proposed estimation methodology described in Phase I. Two case studies were conducted to determine the actual internal capture rate. The focus of Phase II is:

- Refine and test the proposed estimation methodology
- Conduct pilot studies to test and verify the data collection and estimation methodology
- Create a database of mixed-use development information and internal capture rates

- Document the research findings and recommended procedures

The scope of Phase II was much larger than this report. This report focused on the data collection and analysis, so that in the future the estimation methodology may be refined.

LITERATURE REVIEW

A great deal of literature review was performed during Phase I of the project and therefore it was not really necessary to perform another one. However, a summary of the literature review from Phase I of the report will be included.

Need and Purpose of Internal Trip Capture Estimation

Internal trip capture is necessary to obtain a more accurate transportation impact study. The internal trip capture can be used to reduce the amount of external trips to and from the development and the amount of parking that is necessary.

Definitions

Several definitions are provided below to ensure a better understanding of this report:

Mixed-Use Development – There are varying definitions of mixed-use developments, but for the purpose of this project we will define it as being a development with more than one type of land use, which shares parking and provides internal pedestrian connectivity.

Internal Trip – The definition for an internal trip in this report is any trip that is made within a highly interactive area containing complementary land uses and convenient internal on-street or off street connections that may use short segments of major streets.

Internal Trip Capture (Site) Rate – Internal Trip Capture for a development is the percentage of internal trips that occur between two different land uses in that development during a specified time period.

Past Research Findings

Land Use Synergy

A study was conducted by the Urban Land Institute regarding land use synergy in mixed-use developments. Table 1 shows their results below. (*1*)

Table 1 shows the different rates of synergy from 1 and 5 between different land uses, with one being the lowest amount of synergy and five being the highest. Most land uses combinations show fairly high rates of synergy, but other factors can influence internal trips.

Table 1. On-Site Support and Synergy in Mixed-Use Projects

Land Use	Degree of Support/Synergy			
	Residential	Hotel	Retail/ Entertainment	Cultural/Civic/Recreation
Office	2	5	4	3
Residential	3	3	4	5
Hotel	5	3	4	4
Retail/Entertainment	5	5	5	4
Cultural/Civic/Recreation	4	5	5	3

Trip Capture

There is a section in the ITE Trip Generation Handbook that clearly defines how to estimate internal trip capture in mixed-use developments. Their estimation technique is base upon internal trip capture rates from data from three mixed-use developments in Florida. Tables 2 and 3 provide the percentages used to calculate internal trip capture using the ITE internal trip capture method. (2)

Table 2. Unconstrained Internal Trip Capture Rates for Trip Origins Within a Mixed-Use Development

From	To	Weekday Percent Trips Captured Internally		
		Mid-Day Peak Hour	PM Peak Hour of Adjacent Street Traffic	Daily
Office	Office	2	1	2
	Retail	20	23	22
	Residential	0	2	2
Retail	Office	3	3	3
	Retail	29	20	30
	Residential	7	12	11
Residential	Office	NA	NA	NA
	Retail	34	53	38
	Residential	NA	NA	NA

Table 3. Unconstrained Internal Trip Capture Rates for Trip Destinations Within a Mixed-Use Development

From	To	Weekday Percent Trips Captured Internally		
		Mid-Day Peak Hour	PM Peak Hour of Adjacent Street Traffic	Daily
Office	Office	6	6	2
	Retail	38	31	15
	Residential	0	0	NA
Retail	Office	4	2	4
	Retail	31	20	28
	Residential	5	9	9
Residential	Office	0	2	3
	Retail	37	31	33
	Residential	NA	NA	NA

The internal trip capture rates are used in conjunction with the estimated trip generation using the trip generation handbook and then are balanced to estimate the amount of internal trips in a mixed-use development. This method does not take into account the variation of site characteristics such as land use, proximity or connectivity.

Other Findings

TCRP Report 95, Chapter 15 contained a study that shows the relationship between proximity of land use combinations and the percentage of walking trips. According to the study, there is a close relationship between residential location and the percentage of residents who walk. Table 4 shows that relationship below. (3)

Table 4. Comparison of Shoppers Who Walk to Shopping with Percentages of Residents within ½ Mile of Shopping.

Traditional Shopping Area	Residents Living Within 1/2 Mile of Shopping Area	Percent Walking Trips	
		Weekday	Saturday
Rockridge - Market Hall (full array, restaurants)	30%	26%	28%
Rockridge - Alcatraz (grocery, specialty)	40%	38%	41%
Elmwood (convenience, specialty)	33%	28%	36%
El Cerrito Plaza (full array)	12%	10%	10%
Hopkins Specialty (food)	32%	23%	29%
Kensington (convenience, services)	58%	20%	27%
All Areas	32%	24%	28%

DATA COLLECTION

Purpose of Surveys

Surveys were collected at Mockingbird Station and Atlantic Station in order to get a sample of trips originating from the different land uses in the development. Surveys were necessary because both the origin and destination of each trip was necessary. The surveyors gathered internal and external trip information in order to find the internal trip capture of the development. Any other data collection method, such as daily journals, would not have been accurate enough for our purposes.

Mockingbird Station

Layout

Mockingbird Station is a relatively small mixed-use development. The farthest walking distance between land uses is 1000 feet, making it possible to walk around the entire development. A light rail station is located right next to it and even has a walkway connected to the Northeast side of the development.

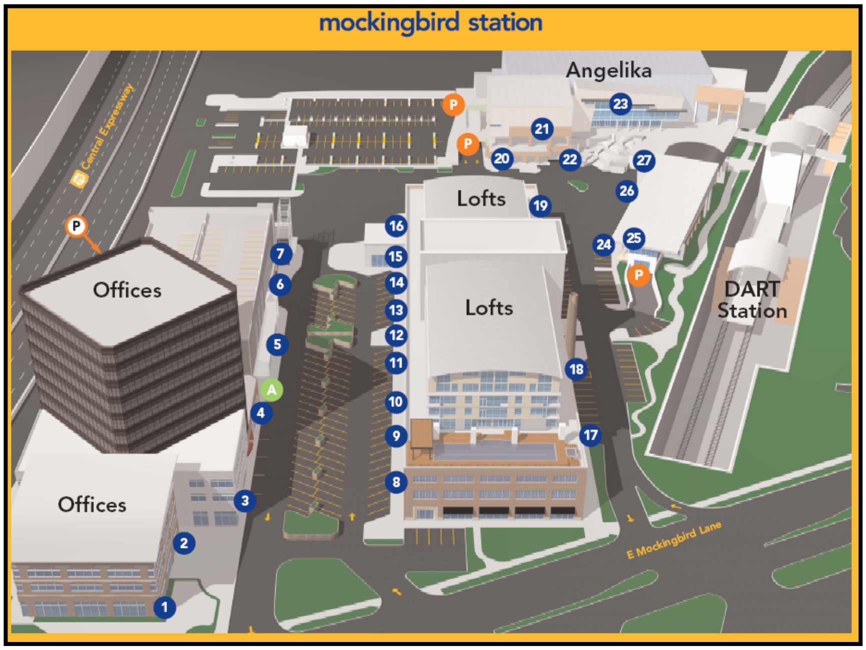

Figure 1. Mockingbird Station (4)

Survey Overview

The Mockingbird Station Data was already collected before this project was started. Brian Bochner oversaw the survey data collection, which was carried out by Pro Staff, a temp agency. The surveys were taken during four different peak periods. The peak periods were, May 16th from 3:00 PM to 7:00 PM, May 17th from 6:30 AM to 10:00 AM, May 17th from 3:00 PM to 7:00 PM and May 18th from 6:30 AM to 10:00 AM. There was a team of 40 surveyors doing four different types of surveys, which were cordon counts, door counts, exit interviews and transit center surveys.

The cordon counts were recorded at all of the possible entrances to Mockingbird Station. The door counts and the exit interviews were taken at all possible entrances to each land use. All of the data was broken up into 15 minute intervals so that the internal trip capture during the peak hour could be evaluated.

Other Data Collection

Much of the site characteristic data was readily available from the leasing agency, and the land use proximities were calculated using the site plans.

Atlantic Station

Layout

Atlantic Station has three different areas within the development, the Village, the Commons, and the District. The Commons are condos and apartments, the District is where most of the retail is located, as well as all the restaurants, the hotel, the cinema, and office building, and the Village contains the Ikea. Due to the large distance and relatively low connectivity between the other two areas, the Village was excluded from our survey.

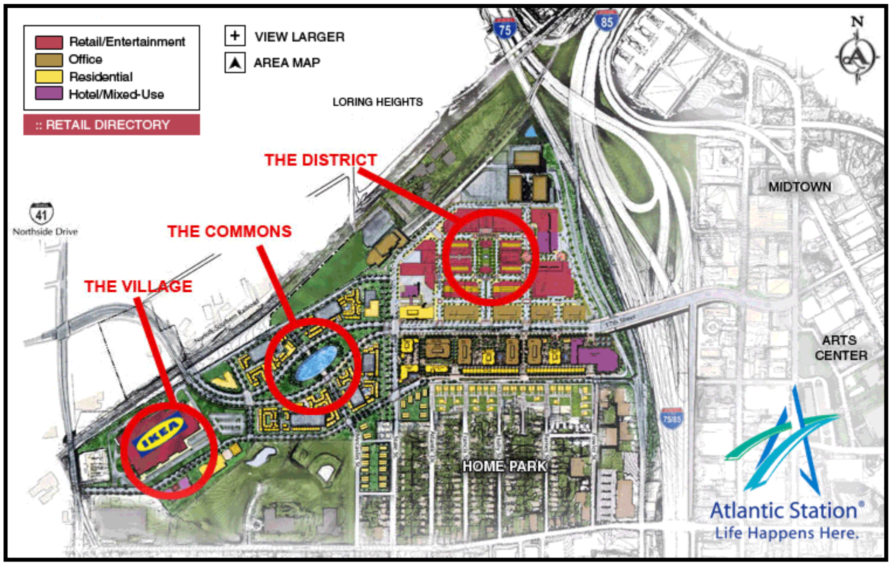

Figure 2. Atlantic Station (5)

Survey Overview

The Atlantic Station Data was collected over a period of three days from July 11th to July 13th. The peak periods were: July 11th PM peak, July 12th AM and PM peak, July 13th AM and PM peak. The surveys were collected by 43 survey personnel, also from Pro Staff, and consisted of cordon counts, door counts, exit interviews, and shuttle interviews.

Figure 3. The District (5)

DATA ANALYSIS AND RESULTS

Mockingbird Station

Data Analysis

Using the cordon counts from each entrance, the peak hour was determined. The number of people entering and exiting the development was counted at each entrance in fifteen minute intervals and was then used to find the peak hour of external trips generated by the development for each time period. The site AM and PM peak periods, along with the average cordon counts, door counts and surveys recorded during each period are shown below.

Table 5. Mockingbird Station Survey Information

Peak Hour	7:00-10:00 AM	3:00-7:00 PM
Persons Entering/Exiting Site	557 707	1380 1397
Persons Entering/Exiting On-Site Buildings	812	4350
Exit Interviews	123	263

Judging from the amount of exit interviews versus the amount of door counts and cordon counts, the reliability of a representative sample size was very small, especially for some of the land uses with less traffic. Hourly internal trip capture was plotted versus time and the variation from one interval to the next was quite significant, as can be seen below. Therefore, the decision was made to analyze the internal trip capture using the peak period instead of the peak hour, which yields a more stable result.

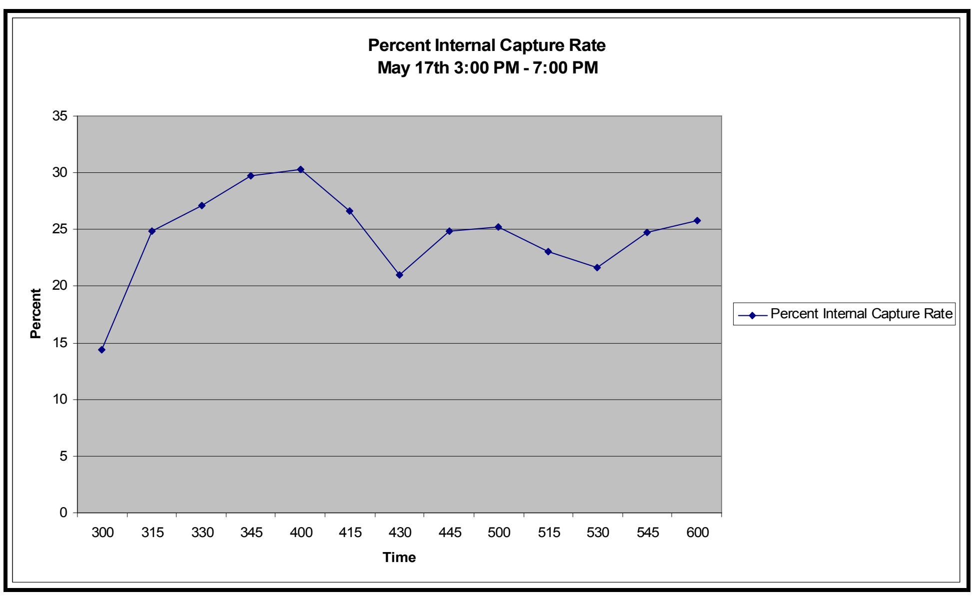

Figure 4. Internal Trip Capture Rate

Conducting exit interviews only yielded a sample of trips from each location. Therefore, in order to find a more accurate representation of the development, the exit interviews needed to be factored. The exit interviews were sorted by origin and destination and then multiplied by the number of persons counted exiting that land use over total number of trips originating from that land use. This produced a representation of all the trips occurring on-site. The results of these factored trips are shown below. Due to the relatively small sample size, there is a chance that the percentages of trip destinations could be inaccurate. A good example is the PM peak period trips originating from restaurant land uses. One day there is a high percentage of restaurant to retail trips, but on the next day there are very few.

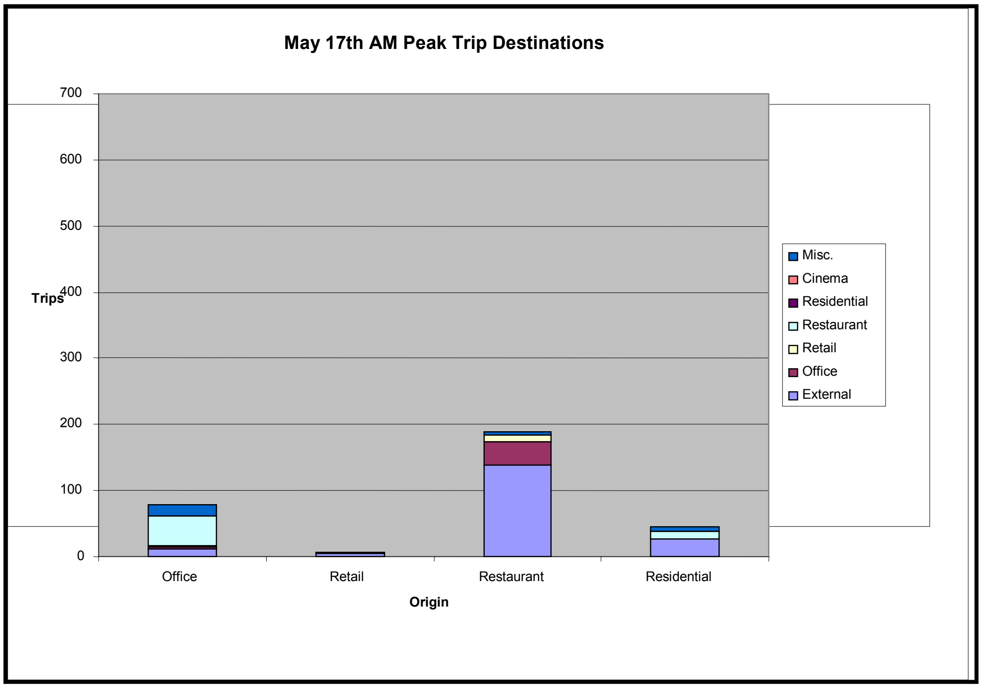

Figure 5. May 17th AM Peak Trip Distribution

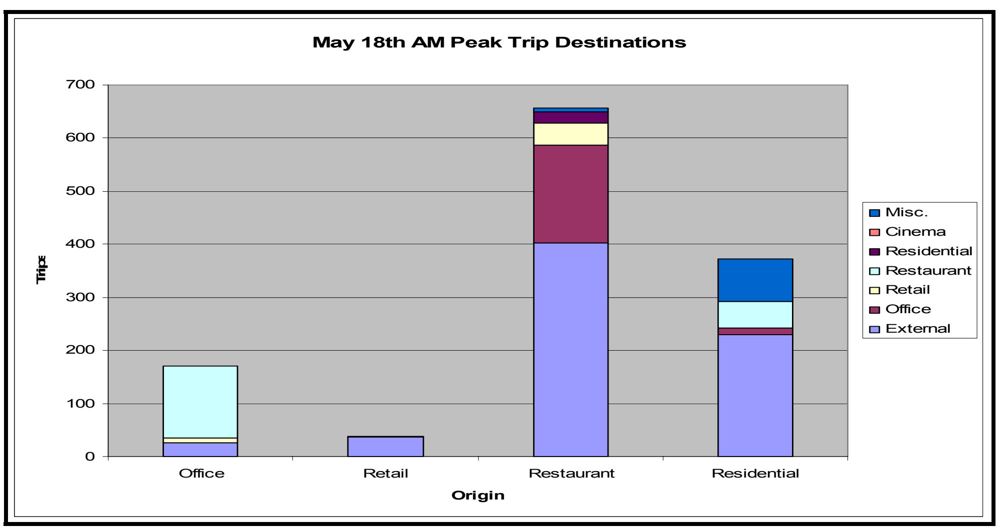

Figure 6. May 18th AM Peak Trip Distribution

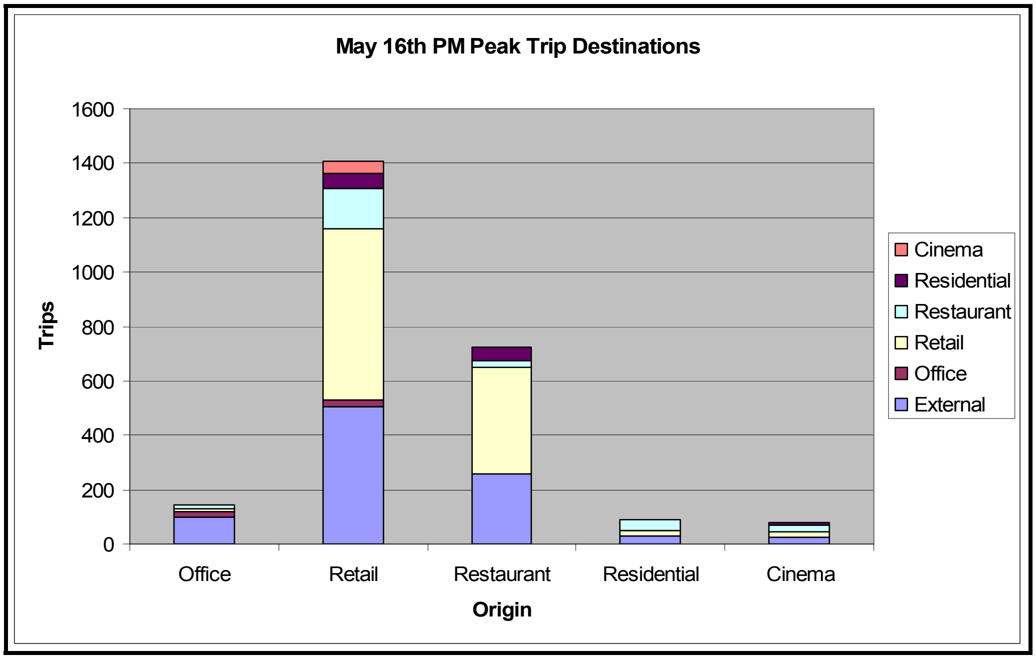

Figure 7. May 16th PM Peak Trip Distribution

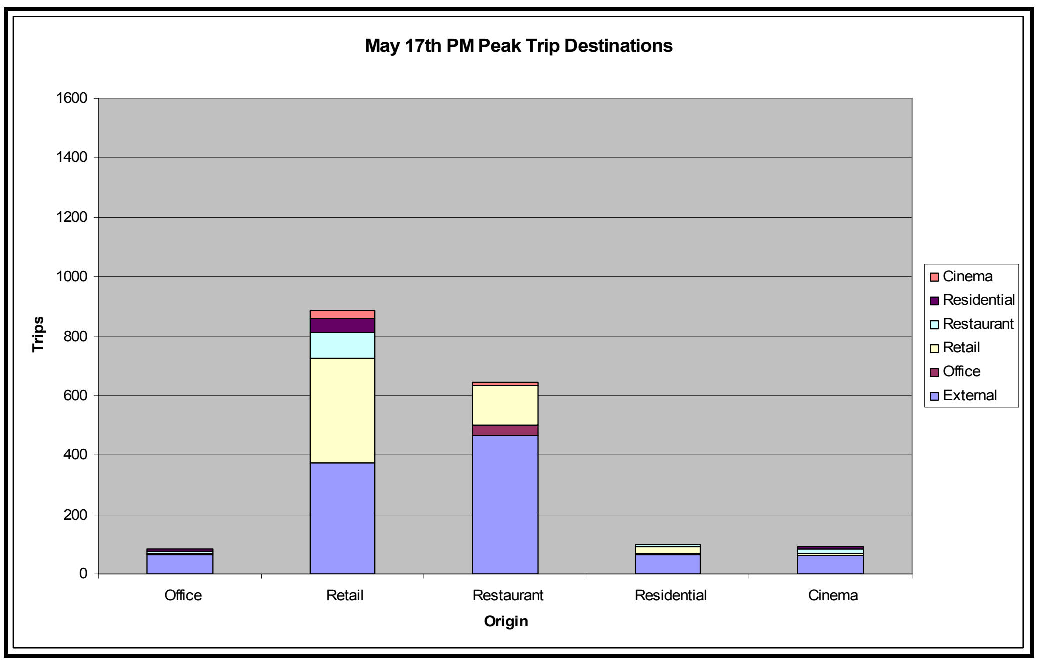

Figure 8. May 14th PM Peak Trip Distribution

During the morning peak hours, offices and restaurants showed a high rate of synergy because of the number of office building employees who visited Starbucks. Otherwise, there was no real activity because most of the businesses were closed. During the afternoon peak hours, only the retail to retail and restaurant to retail synergy was significant. But the internal trip capture applies solely to internal trips to other land uses, so any trip from one location to another of the same land use does not contribute to internal trip capture. The factored trips were then used to find the internal capture rates by taking the internal trips between two different land uses and dividing them by the total number of trips occurring during that time period. The internal capture rates calculated are as follows:

Table 6. Mockingbird Station Internal Trip Capture

May 17th	May 18th	May 16th	May 17th
7:00-10:00 AM	7:00-10:00 AM	4:00-7:00 PM	4:00-7:00 PM
33.33%	38.51%	40.88%	23.08%

Mode Split

As a part of the NCHRP project, the mode split of persons traveling to and from the development was calculated. The results are shown below.

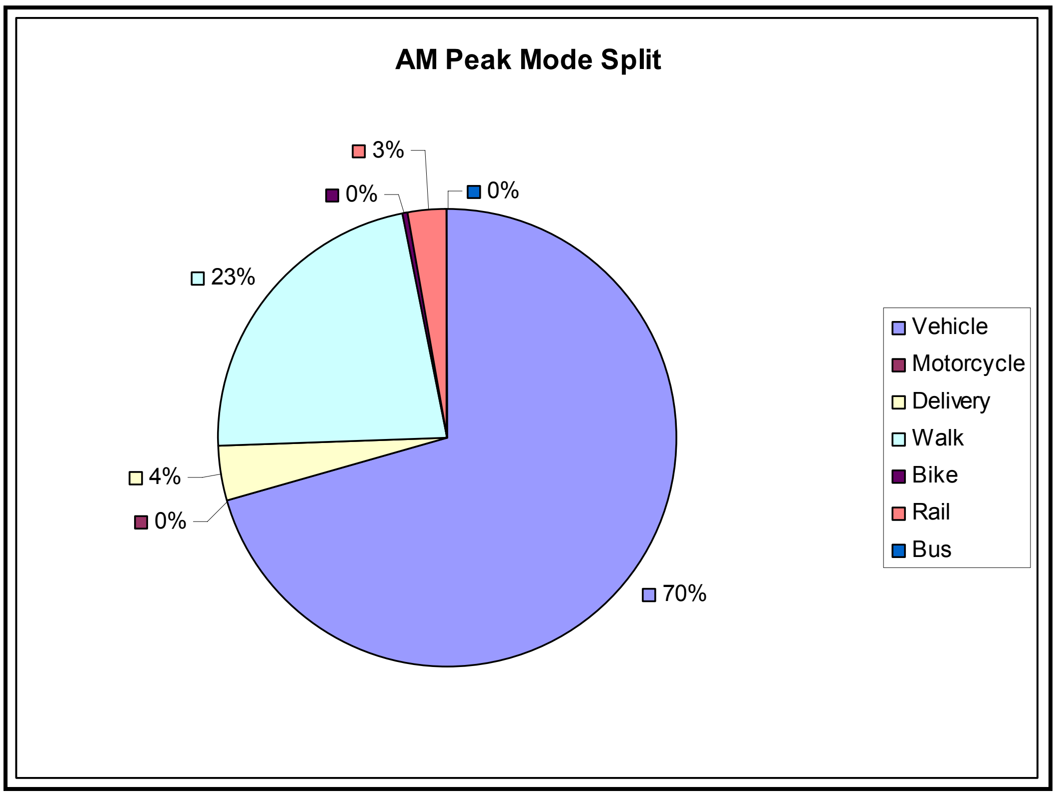

Figure 9. AM Peak Mode Split

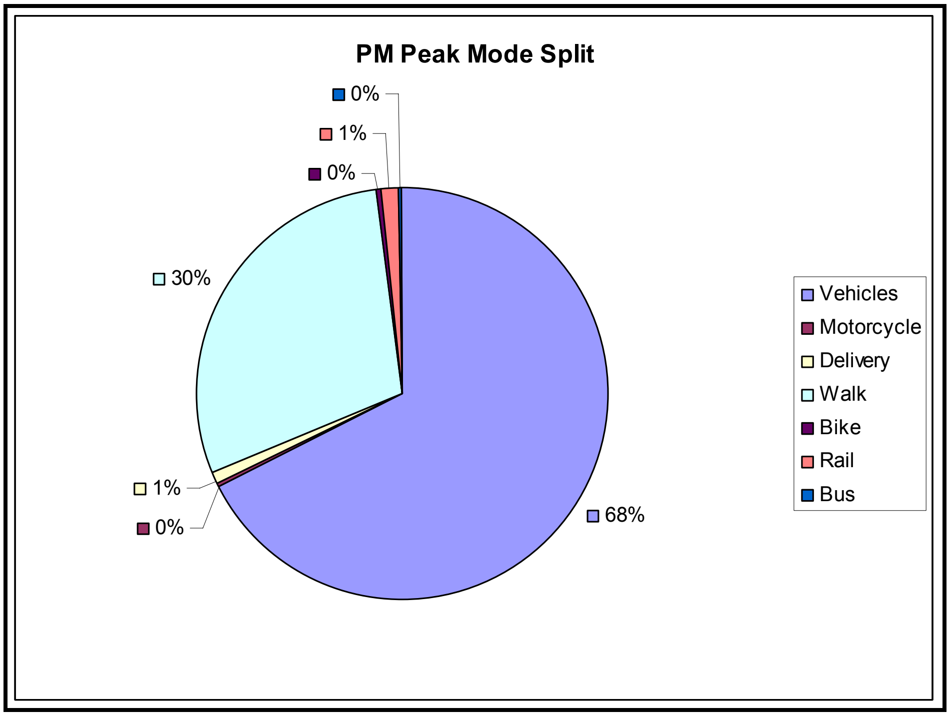

Figure 10. PM Peak Mode Split

Dart Interviews

Also, information was collected on the destination split for people using the Dart Rail. Below are the percentages of destinations for people using the Dart Rail. The high rate of external trips from the Dart Rail can be attributed to people walking to the Premier building just North of Mockingbird Station.

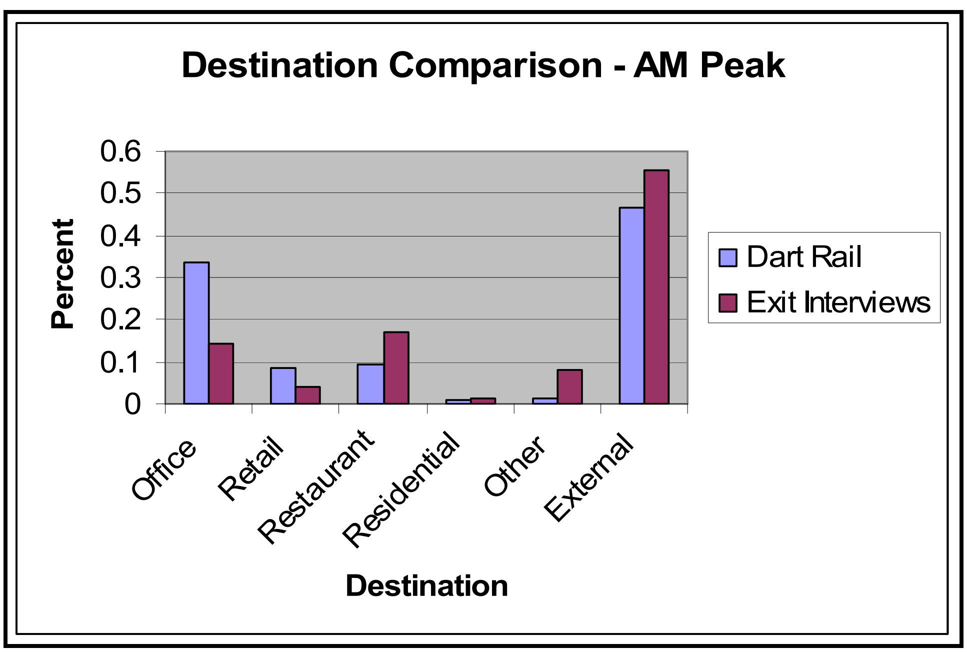

Figure 11. AM Peak Dart Rail Destination Comparison

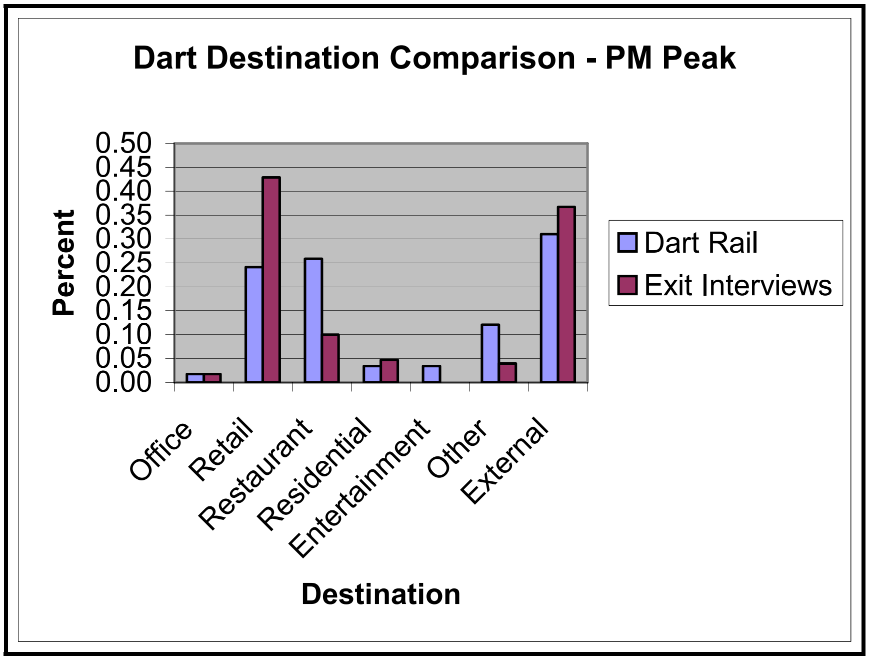

Figure 12. PM Peak Dart Rail Destination Comparison

Proximity Analysis

A proximity analysis was performed by taking all of the locations and calculating the distances between them. The combinations of locations was then sorted into bins and plotted versus the number of trips taken per land use combination. As the distance between locations get greater, the number of internal trips that occur decrease, suggesting that proximity does have play a factor in internal trip capture. The results are shown below. While there were more total trips as the proximity of the destination got smaller, there were also more trips per destination, suggesting that proximity does have an effect on internal trip capture.

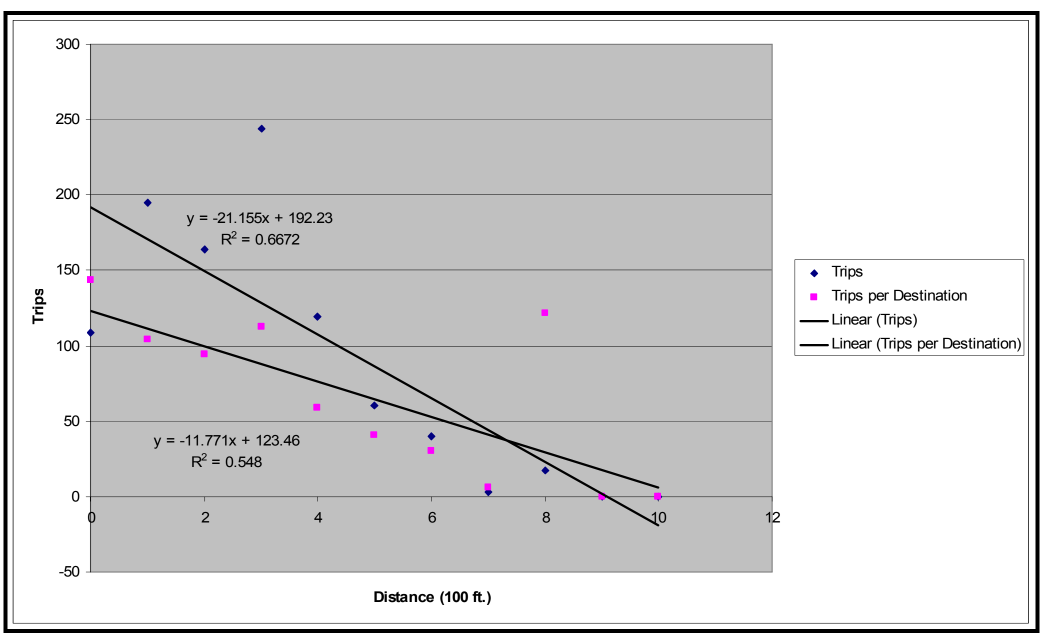

Figure 13. Proximity Analysis

Atlantic Station

Data Analysis

The data analysis for Atlantic Station was very similar to the analysis of Mockingbird Station. However, due to the amount of stores and restaurants in the district area, during the PM peak period the surveyors were not able to obtain exit interviews for each location. Therefore, after the exit interviews were factored by the persons exiting that location, the exit interviews were again factored by the amount of occupied square footage of each land use over the surveyed square footage of each land use. The results for each peak period were as follows.

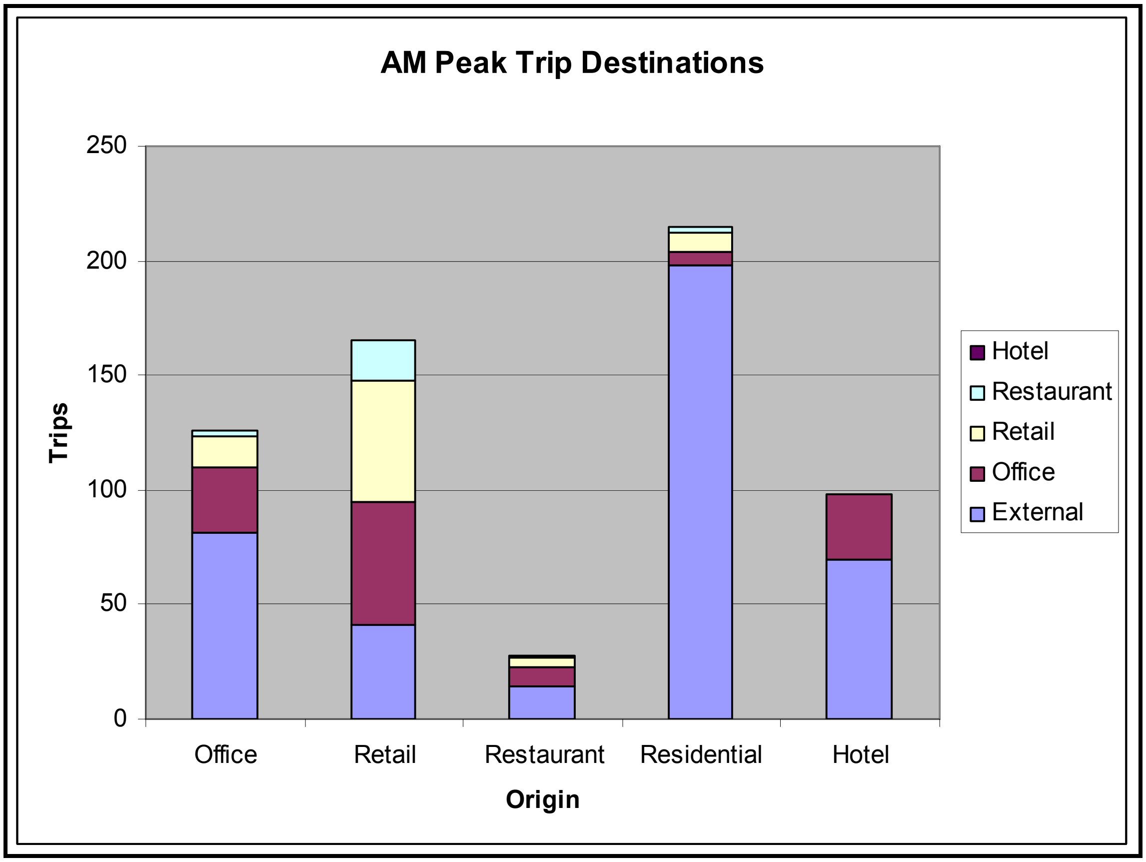

Figure 14. AM Peak Trip Distribution

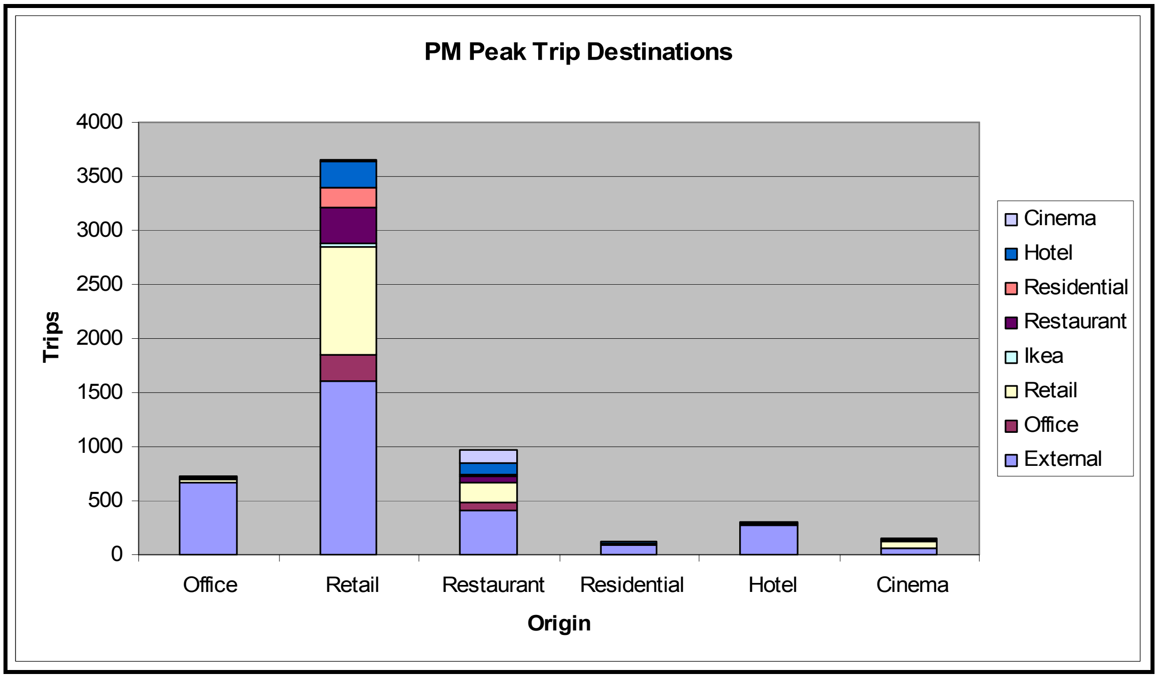

Figure 15. PM Peak Trip Distribution

The exit interviews were also analyzed with a more in-depth classification method. The grocery store and the department store were counted separately from the retail, and the bar, coffee shop and ice cream parlors were counted separately from the restaurants. The data clearly shows that there is a difference between those land uses, but for comparison reasons, classifying those stores in a more general land use category is necessary. The results from this analysis are shown in the figures below.

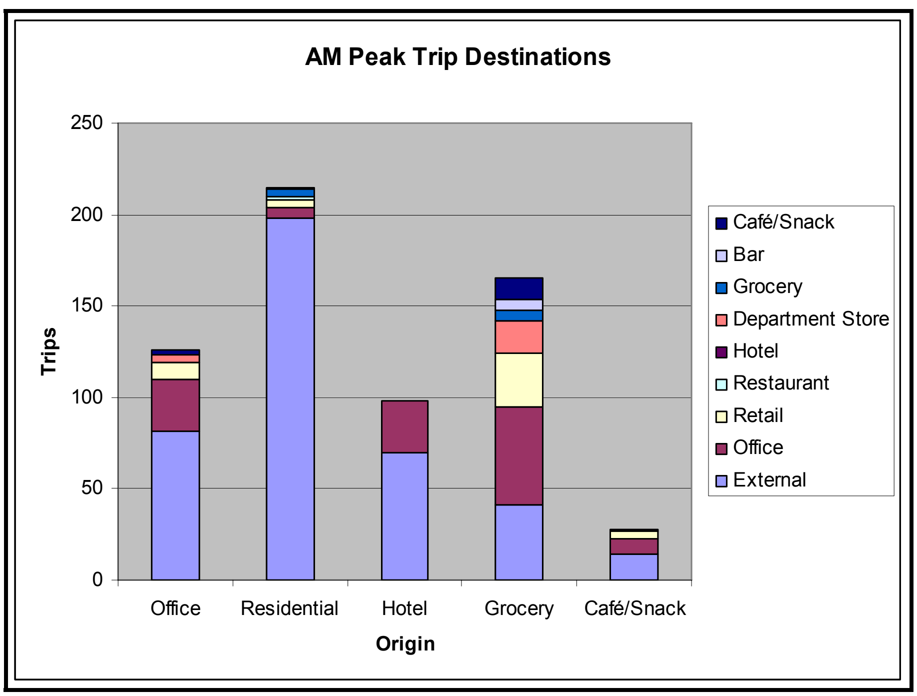

Figure 16. AM Peak Trip Distribution

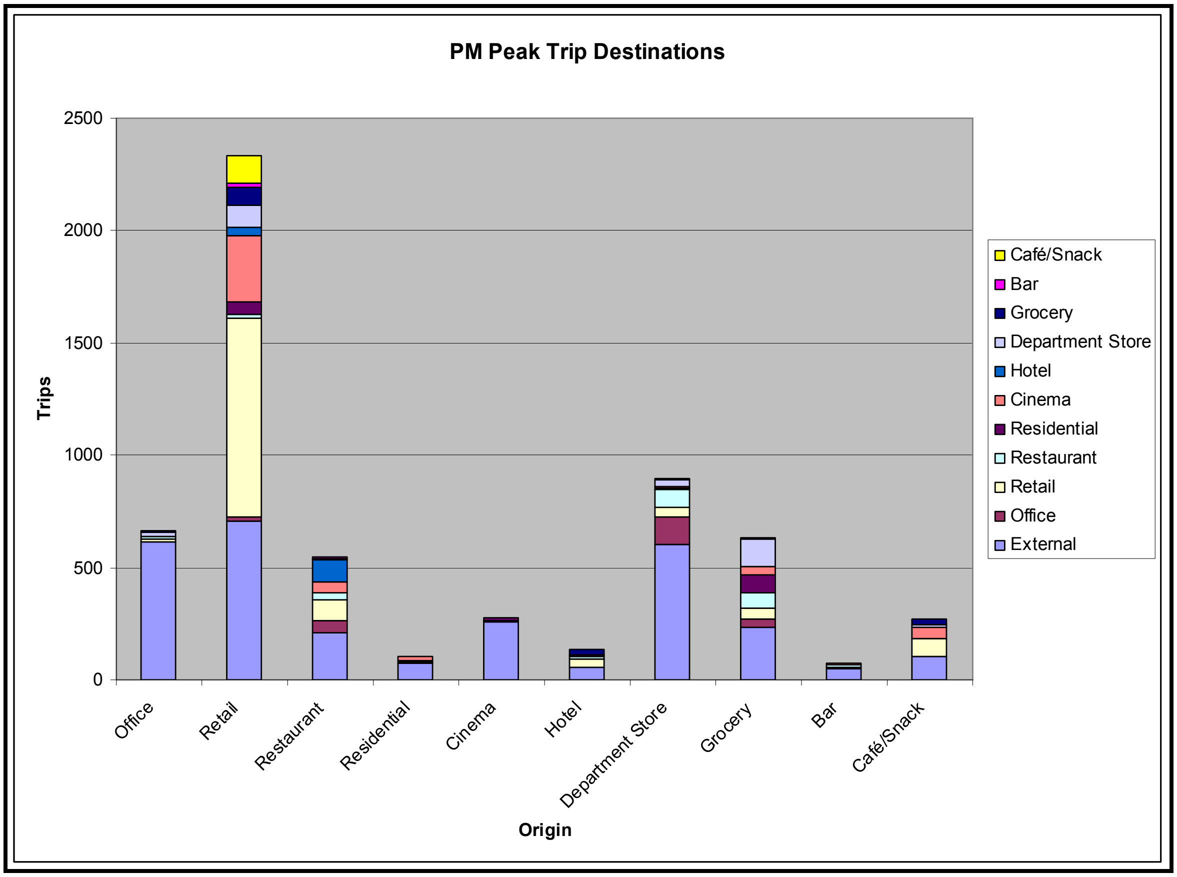

Figure 17. PM Peak Trip Distribution

Finally the internal trip capture, as a percentage of the total trips originating from that land use, is displayed below.

Table 7. Internal Trip Capture by Land Use

	Office	Retail	Restaurant	Residential	Hotel	Cinema
Office	0	5	2	0	0	0
Retaill	7	27	9	5	6	1
Restaurant	7	20	7	2	10	12
Residential	0	8	4	1	17	1
Hotel	0	3	1	3	0	0
Cinema	0	40	12	6	0	0

Mode Split

The mode split was collected and analyzed for trips going to Atlantic Station as part of the NCHRP project. The results of the mode split are shown below.

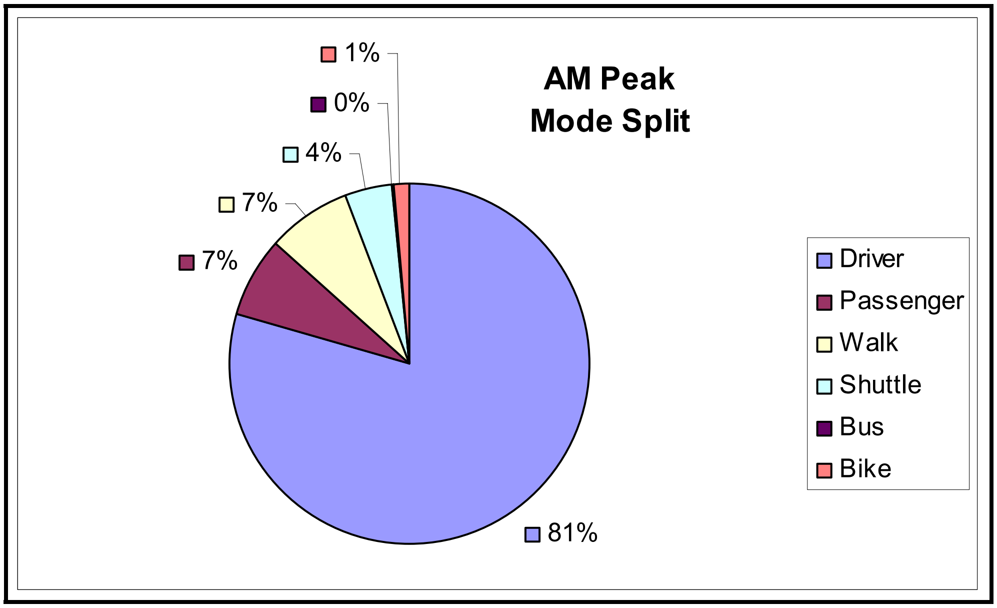

Figure 18. AM Peak Mode Split

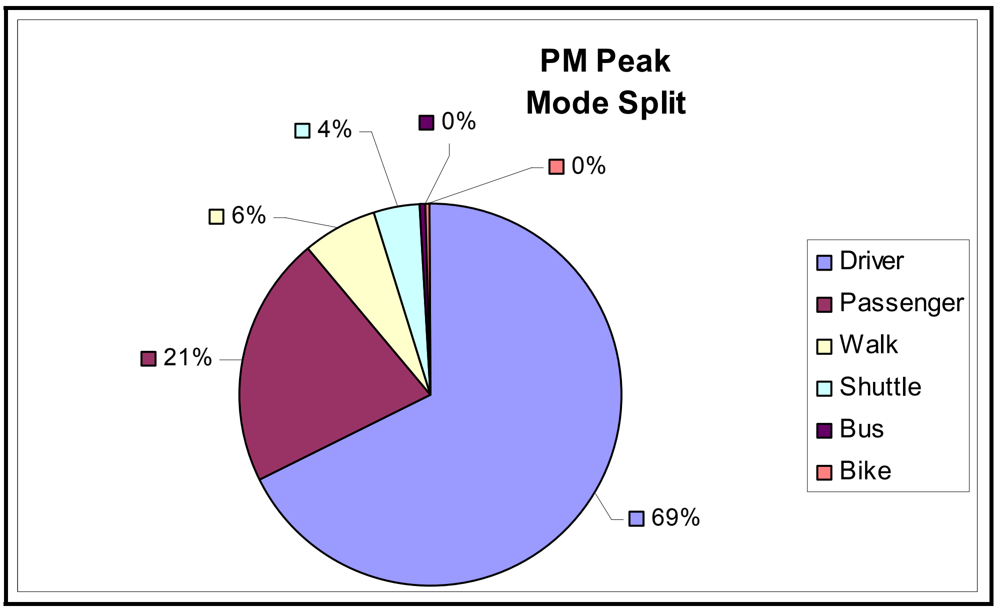

Figure 19. PM Peak Mode Split

Shuttle Interviews

Atlantic Station provides a free shuttle service from the MARTA rail station about a mile away. Shuttle interviews were conducted throughout the peak periods to collect data on where the shuttle users went. The results of the shuttle interview is available below.

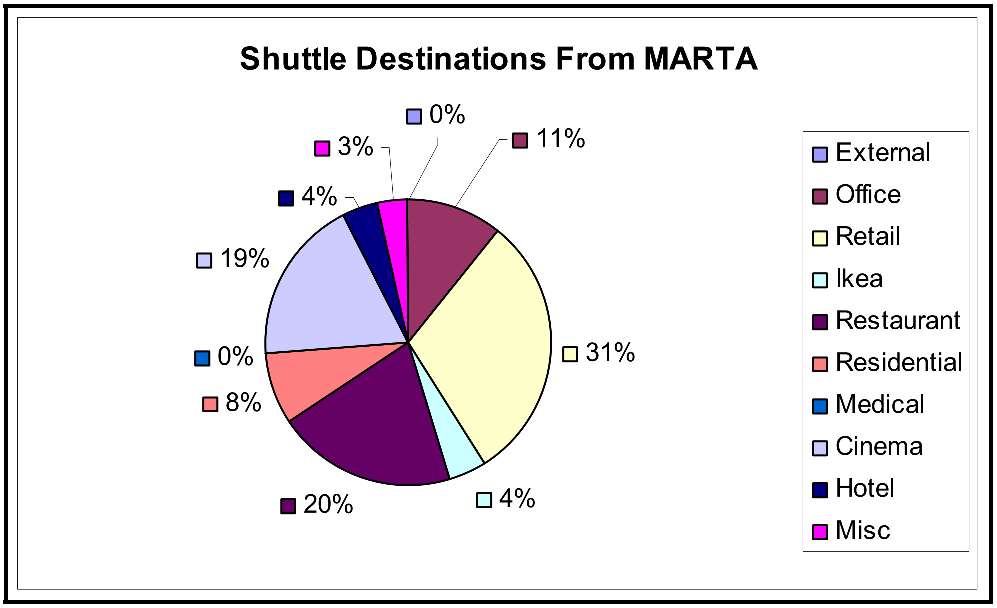

Figure 20. Shuttle Destinations From MARTA

Summary of Crocker Center, Mizner Park and Galleria Data Analysis

The Florida Department of Transportation conducted a study in March of 1995 of three different mixed-use developments, Crocker Center, Mizner Park and the Galleria. The study consisted of mechanical traffic counts, pedestrian counts and surveys with the intent of developing a way to calculate mixed-use development trip generation, including internal trip generation.

The surveys asked similar questions to our surveys so the report was analyzed for supplemental information regarding our project. Numerous problems were encountered when looking at the data. The way the survey was worded, accurate times and locations were not recorded by the surveyors. Therefore, this project's analysis was limited to finding an average internal trip capture percentage for the entire site over the course of a day. This information was already provided in the report, but upon closer inspection, the data analysis could not be completely reproduced. For each mixed-use development, the "browsing" category was drastically different. The data does not support the original analysis done by FDOT so the results from this project's analysis will be used.

The methodology used in finding the internal capture rate was mostly the same. All primary trips were counted as having 2 external trips, to and from the primary destination. The first internal trips for employees located in the mixed use development were multiplied by 1.5 to account for workers sometimes returning to work. However, the trips within a mixed-use development to the same land use do not count as an internal trip, so those were subtracted from the internal trips (6), (7), and 8.

Table 8. Crocker Center, Mizner Park and Galleria Internal Trip Capture

	Primary Destinations	External Trips	Worker Internal Destinations	Worker Internal Trips	User Internal Trips	Total Internal Trips	Total Trips	Percent Internal Trips
Crocker Center	650	1300	236	332	251	442	1883	23.5
Mizner Park	642	1284	128	171.5	545	569	2000.5	28.4
Galleria	556	1112	111	140.5	405	321	1660	19.3

Comparison of Mixed-Use Developments

After the internal trip capture was calculated for each development, the results were compared to find a correlation between site characteristics and internal trip capture. According to the preliminary information, there seems to be no correlation between the size of the development and internal trips. Mockingbird Station and Atlantic Station have roughly the same combination of land uses, so no conclusive results can be gotten regarding synergy. The only trip capture and site characteristics that could be compared between the different developments are those shown below.

Table 9. Internal Trip Capture Comparison for the PM Peak Period

		ITE	Mockingbird Station	Atlantic Station
from Office	to Office	1	7	0
	to Retail	23	6	5
	to Residential	2	4	0
from Retail	to Office	3	1	7
	to Retail	20	41	27
	to Residential	12	5	5
from Residential	to Office	N/A	3	0
	to Retail	53	18	8
	to Residential	N/A	0	2

Table 10. Site Characteristic Comparison

	Mockingbird Station	Atlantic Station	Percent Difference	MS Percent Internal	AS Percent Internal
Office	124146 RSF	509237 RSF	75.6	24	7
Retail	149803 RSF	486176 RSF	69.2	60	55
Restaurant	28883 RSF	66913 RSF	56.8	46	58
Residential	191 Units	627 Units	69.5	41	31
Cinema	8 Screens	16 Screens	50	53	58

The connectivity for Atlantic Station seemed to be somewhat higher, but the data does not show that connectivity had a great effect on internal trip capture. There are three different categories of connectivity used to analyze developments which are, fully integrated uses, internal outdoor walkways, and outside at-grade standard sidewalks systems. Both developments would be considered internal outdoor walkways and so according to our classifications there should be no effect on trip capture from connectivity. The internal trip capture seems to depend mostly on the high synergy of retail land uses with other land uses. Proximity did make a difference at Mockingbird Station, but the data collected at Atlantic Station was not properly recorded so no comparison could be made.

CONCLUSIONS

As of now, there are only five developments with usable data concerning internal trip capture, and only two that have been fully analyzed. Judging from the initial data however, the results suggest that the internal trip capture is significantly dependent on the combination of land uses used in the development and the proximity between the developments. Further studies are needed to make any accurate predictions. The capture rates for each land use were fairly similar amongst the two developments except for the office building which varied significantly. Despite the increase in square footage, there was no significant change in internal trip capture between Atlantic Station and Mockingbird Station. The proximity data at Atlantic Station could not be analyzed, so the data collected at Mockingbird Station could not be compared. The connectivity was fairly similar, and would fall into the same category using the Phase I categorization system, so no real comparison could be made that would examine connectivity's effect on internal trip capture. The synergy of land uses' effect on internal trip capture was very apparent. The retail to restaurant and restaurant to retail trips showed much higher rates of internal trip capture than other land use combinations. If there were no retail stores or restaurants in Mockingbird Station or Atlantic Station, there would be a significant drop in internal trip capture.

RECOMMENDATIONS

There is an obvious need for more studies to be conducted. The amount of information available is so small right now that any prediction can be wildly inaccurate. Also, the relatively low sample size for the peak hour when factored to match the door counts made the internal trip capture estimation too inaccurate to make any conclusions. The peak period had a much more stable sample size and is uniform at every development. The PM peak period had much more activity at both developments and was more helpful in learning about internal trip capture. If data was collected solely during the PM peak period, more surveys could be conducted for the same amount of money and the data would be more accurate.

As the database of surveyed mixed-use developments increases in size, the different land uses can be further sub-categorized to more accurately represent what is happening in the development. It is not very helpful to compare a department stores activity with the other development data if there is none, but in the future it will more accurately show the factors attributing to mixed-use developments. When there is a bigger database, the data must be compatible. Therefore, the data should be collected with the same purpose in mind, and sorted similarly so that when further study becomes possible, the data can be used again.

Another possibility is to use GPS tracking devices with some of the more habitual users of the development, such as workers and residents. With a GPS tracking device, much more data can be collected that will be very accurate as long as the subjects keep the device with them. The current technology does not make this option feasible, but in the future it could be a very useful data collection tool.

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APPENDIX A

Table A-1. May 16th 4-7 PM Mockingbird Station Cordon Counts

Cordon Site	Total In	Total Out	3:00	3:15	3:30	3:45	4:00	4:15	4:30	4:45	5:00	5:15	5:30	5:45	6:00
			Hour												
Office Garage	62	206	52	32	51	60	55	86	80	92	108	97	86	78	53
Frontage Road	671	687	249	263	283	296	287	301	310	294	343	385	435	505	479
Premier	113	72	52	57	62	57	57	58	58	56	47	49	35	30	29
Mockingbird East	294	280	100	153	167	137	136	145	145	146	157	181	191	202	181
Mockingbird West	643	332	146	207	255	215	219	240	240	267	323	339	322	336	296
Dart Bridge	267	334	74	95	128	114	119	144	144	162	204	231	241	229	143
Total	2050	1911	673	807	946	879	864	977	977	1017	1182	1282	1310	1380	1181

Table A-2. May 17th 4-7 PM Mockingbird Station Cordon Counts

Cordon Site	Total In	Total Out	3:00	3:15	3:30	3:45	4:00	4:15	4:30	4:45	5:00	5:15	5:30	5:45	6:00
Office Garage															
Frontage Road	353	389	82	168	231	308	307	310	325	336	353	372	388	398	386
Premier	81	14	10	23	33	35	43	44	37	39	24	12	13	17	18
Mockingbird East	334	277	43	93	140	169	173	169	172	179	196	189	174	187	199
Mockingbird West	544	376	78	145	216	292	228	210	243	244	316	354	340	327	298
Dart Bridge	310	938	73	183	271	351	378	348	386	416	454	470	448	395	343
Total	1622	1994	286	612	891	1155	1129	1081	1163	1214	1343	1397	1363	1324	1244

Table A-3. May 16th 4-7 PM Mockingbird Station Exit Interviews

						On-Site Destination						
Origin	1	2	3	4	5	6	7	8	Offsite	Total	Counts	Factored
1	4	3	3	0	0	1	0	5	93	143	597	4.174825
2	3	71	17	6	0	5	0	6	204	508	4491	8.840551
3	0	15	1	2	0	0	0	0	31	87	2252	25.88506
4	0	3	6	0	0	0	0	4	20	63	391	6.206349
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	2	2	1	0	0	0	0	8	25	291	11.64
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0

Table A-4. May 17th 4-7 PM Mockingbird Station Exit Interviews

						On-Site Destination							
Origin	1	2	3	4	5	6	7	8	1	Offsite	Total	Counts	Factored
1	1	1	2	3	0	0	0	6	0	100	152	382	2.513158
2	0	53	13	7	0	4	0	4	4	200	491	3272	6.663951
3	3	12	0	0	0	1	0	3	0	141	209	2372	11.34928
4	1	3	1	0	0	0	0	2	0	32	58	408	7.034483
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	1	3	1	0	0	0	0	1	38	54	331	6.12963
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX B

Table B-1. 7-10 AM Atlantic Station Cordon Counts

			Peak hour	Total
State		In	33	70
		Out	24	65
16th		In	58	132
		Out	41	126
District		In	12	70
		Out	14	45
Atlantic 1		In	49	136
		Out	57	178
Atlantic 2		In	23	53
		Out	50	106
Fowler 1		In	128	309
		Out	9	27
Fowler 2		In	65	215
		Out	43	115
Market 1		In	215	466
		Out	9	32
Market 2		In	131	361
		Out	49	139
Wachovia to 17th		In	43	100
		Out	1	2
Shuttle		In	65	139
		Out	15	37
Total		In	879	1951
		Out	313	870

Table B-2. 4-7 PM Atlantic Station Cordon Counts

			Peak hour	Total
State		in	237	507
		out	227	579
16th		in	74	200
		out	152	339
District		in	91	242
		out	90	216
Atlantic 1		in	52	183
		out	142	411
Atlantic 2		in	87	208
		out	39	102
Fowler 1		in	10	25
		out	84	251
Fowler 2		in	68	154
		out	92	237
Market 1		in	859	1921
		out	284	713
Market 2		in	89	250
		Out	32	67
Wachovia to 17th		In	1	16
		Out	13	83
Shuttle		In	44	182
		Out	28	146
Total		In	1612	3888
		Out	1183	3144

Table B-3. 4-7 PM Atlantic Station Exit Interviews

	external	1	2	3	4	5	6	7	8	9	Total	Outbound Counts	Factor	Square footage Factor
external	0	0	2	0	1	0	0	25	1	3	32	0	0	
1	9	0	9	1	4	0	0	0	0	1	24	84	3.5	1
2	89	23	94	3	32	18	0	22	2	14	297	2339	7.875421	1.229931
3	0	0	0	0	0	0	0	0	0	0	0	0	0	1
4	72	12	33	0	11	3	0	17	21	13	182	853	4.686813	1.121328
5	57	0	7	0	3	1	0	14	1	1	84	115	1.369048	1
6	0	0	0	0	0	0	0	0	0	0	0	0	0	1
7	85	0	3	0	1	3	0	0	0	1	93	281	3.021505	1
8	1	0	7	0	2	1	0	0	0	1	12	95	7.916667	1
9	16	1	41	0	13	0	0	3	0	5	79	0	0	1

CREATING A PROCESS TO IDENTIFY A TRAFFIC FINGERPRINT & CORRECT ALTERED DATA

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SUMMARY

Twice since 2004, traffic data for about 200 sensors on Loop 1 in Austin was reported at incorrect locations. From August 2004 to March 2005 and February through April in 2006, traffic data was shifted, such that it was reported at different locations than where it was collected.

A combination of methods was employed to correct the data by associating it with the location at which it was actually collected. This included hypothesis matching using total daily volumes, matching based on the emergence of patterns in the matches, and visual matching using time of day volume profiles. Finally, a statistical comparison was employed using both time-of-day volume and occupancy profiles.

Results show a shift of 52 positions in the 2004-2005 shift, believed to be caused by the removal of 52 detectors in August 2004. The February 2006 shift has a shift of 34 numerical positions with no obvious cause. The March-April 2006 shift was caused by the removal of eight detectors on February 23. Since the detectors were interspersed amongst all the detectors in the list, it is a progressive shift with the first hundred detectors being unaffected, and then the detectors after each removed detector being shifted one spot down the list.

TABLE OF CONTENTS

INTRODUCTION

Along many urban highways of the United States, loop detector sensors spaced typically every one-half mile apart collect data to report real-time traffic conditions for speed, occupancy, and volume every 20 to 60 seconds (*1*). This data is used to pinpoint trouble areas. In turn, authorities can respond quicker to clear accidents to restore traffic flow. It also creates a detailed collection of data that can be used to help planners and designers know how the highway is operating, compile long-term trends of congestion, and create better traffic models.

Many studies have covered the weekly, daily, and hourly variations typically seen in traffic volumes depending on the level of service of the highway and whether it is urban or rural setting (*2*), (*3*), and (*4*). Specifically, while the volume may change, the peak hour for a specific site will generally follow a set pattern each day (*5*). Further, when analyzing the validity of data collection, a simple principle to keep in mind is that all traffic entering a section of highway is equal to the volume of traffic exiting that section of highway, including all exits or entrance ramps along the way.

PROBLEM STATEMENT

Currently, there are 941 sensors in Austin, Texas collecting traffic data on the four major freeways for the Austin District of the Texas Department of Transportation (see Figure 1). In a review of the collected data in the spring of 2006, however, it was noticed that inconsistent data was reported for about 200 of those sensors along the northern section of Loop 1, denoted by the white arrows, from February through April in 2006. The same problem also occurred from August 2004 to March 2005. The inconsistency is that data that is being reported for a given location is actually being collected at another physical location.

From Figure 2, one can see that following a consistent line of traffic volumes, the numbers dropped considerably at the beginning of February 2006 before a brief rebound in March and April 2006. You can also see a similar shift of data took place for about seven months commencing in August 2004.

One possible cause of the shifts in the data is thought to occur when sensors are either added to or removed from the system. The system controller unit (SCU), which collects the data, does not recognize a change and continues to report the data to the central database as before, thus shifting data to be recorded as a different location than it really is. It is believed that since the SCU uses distributed databases, when the central database gets updated, the changes do not always carry over to the SCU database, especially if the traffic managers do not follow the correct sequence for updates.

RESEARCH OBJECTIVES

By the completion of this project, nearly 11 months of lost traffic data will have been recovered in order to fill the gaps of the historical traffic record for Loop 1. Additionally, a process will be in place to more easily correct such data shifts in the future, should a similar situation arise.

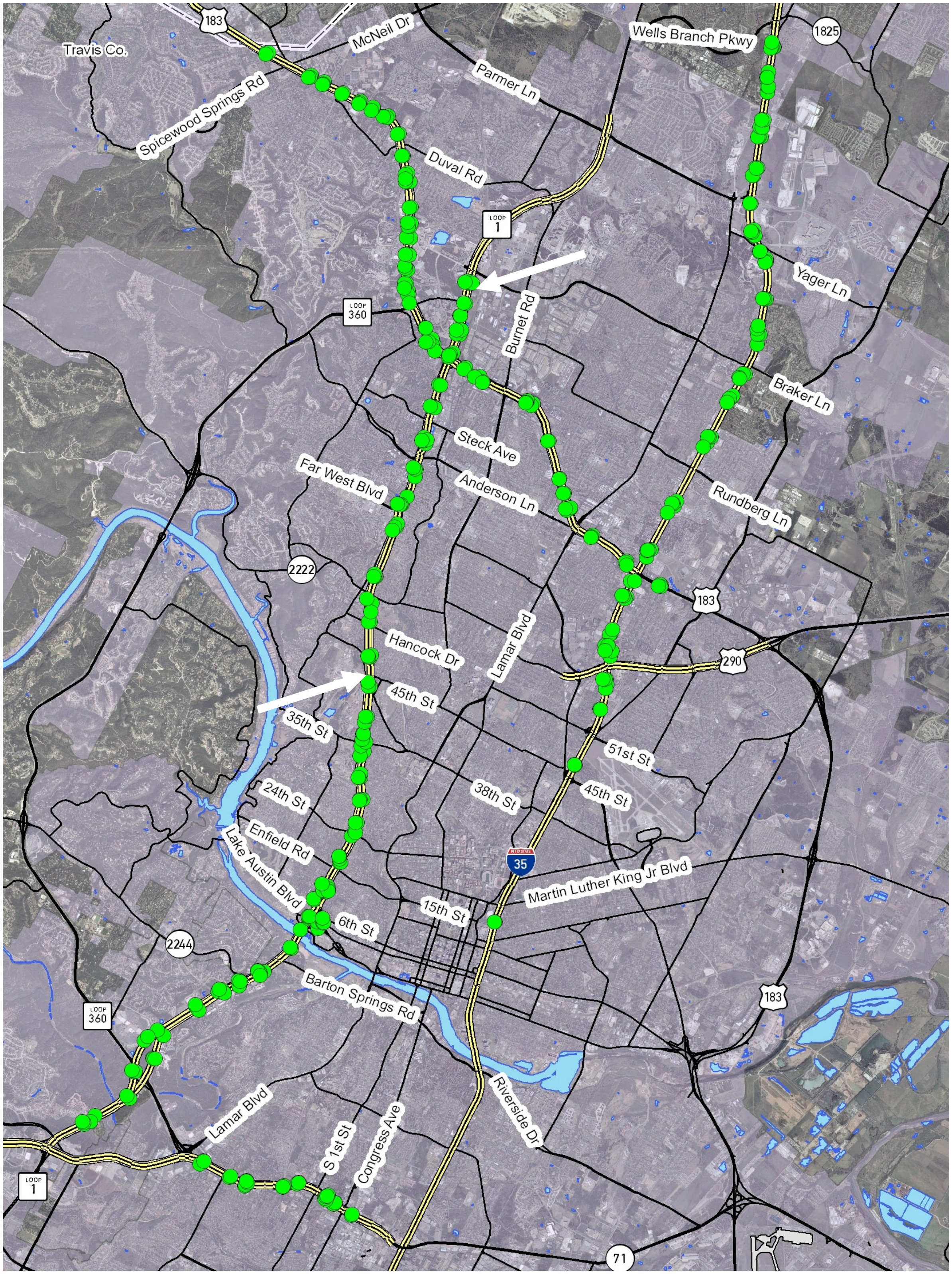

Figure 1. Locations of Austin Traffic Detectors and the Loop 1 Corridor

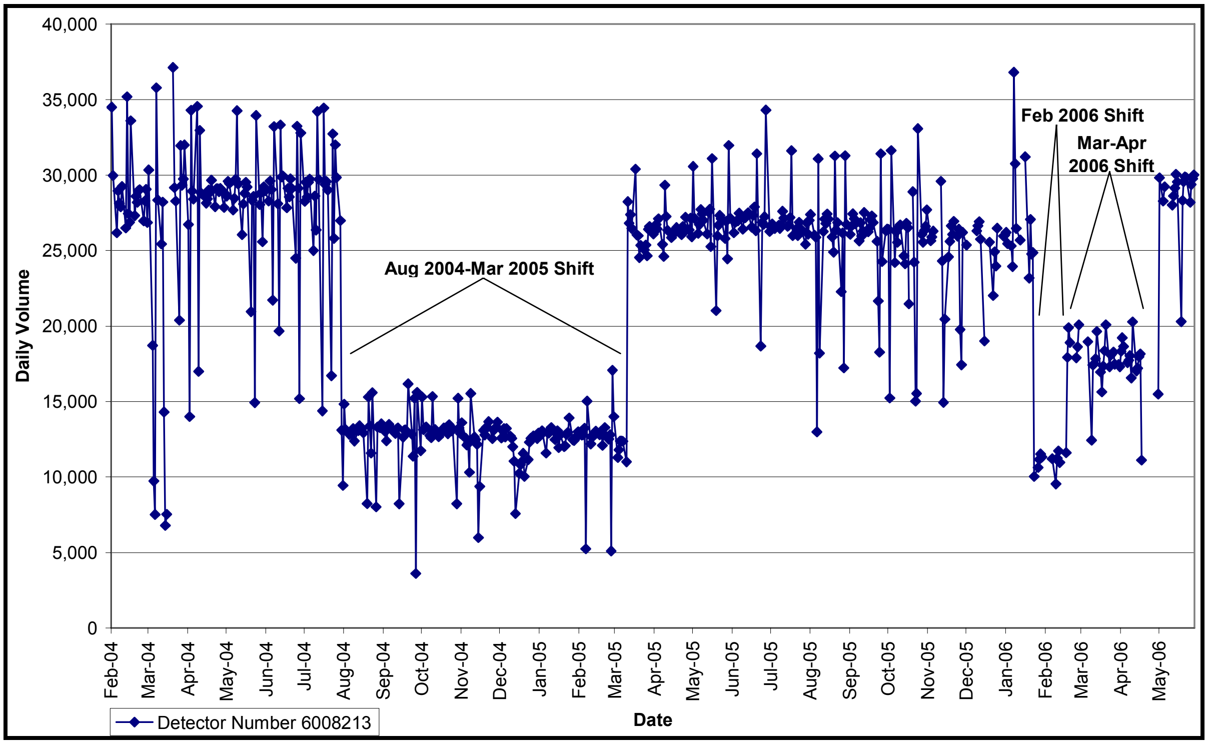

Figure 2. Example of Daily Traffic Volume Data from a sensor on Loop 1

MATCHING PROCEDURE

The first of three methods that were employed to match data, hypothesis matching incorporates any theories or suspicions held regarding the cause of the shift. This method investigates the relevance of presumed theories by examining the resulting arrangement of data. Hypothesis matching was employed for the March 2006 shift. With only minor exceptions, this shift was correctly believed to be adjusted based upon the removal of eight detectors.

After the preliminary matching, the first stage involved using average daily volumes to help confirm these matches. Total daily volumes for all detectors were examined before the March 2006 shift as compared with total daily volumes after the shift. From this, the emerging pattern of zero to zero and 16,100 to 15,900, for example, as one progresses down the list becomes apparent. The emerging patterns of matches help to pair up the remaining data.

Finally, the second stage is a visual technique which uses the more detailed time-of-day profiles to ensure that the hourly volume profiles are consistent with the shift. This type of matching is a good start if there are no obvious reasons for the shift; this was the first step toward matching the 2004-2005 and February 2006 data, since there was no indication as to their cause. First, put the graphs of two detector time-of-day profiles side by side for dates before and after the shift, and look for something close between them; key indicators include the position and magnitude of the morning and afternoon peak hours, the time between peak hours, and the overall magnitude of the curve. If two detectors appear a good match, investigate the next two respective detectors down the list, since detectors in Austin are reported in numerical order, and so on. Logically, with each consecutive "match," the likelihood of false matches decreases; the odds of similar curves not being matches despite being in the same order amongst the great diversity of curves are highly unlikely.

In Figure 3, time-of-day profiles for detector number 6007611 are shown for eight dates: two weekdays for dates before, during, and after the shifts. Based upon characteristics of the curves such as the time and height of morning and afternoon peaks, one can see the similarities between the curves for January 11-12 and May 24-25. However, it is apparent that the curves for February 8-9 is much shorter than those for January and May, while March 8-9 does not exhibit the same mid-morning slump in volume. These differences make plain the shifts that occurred in these times.

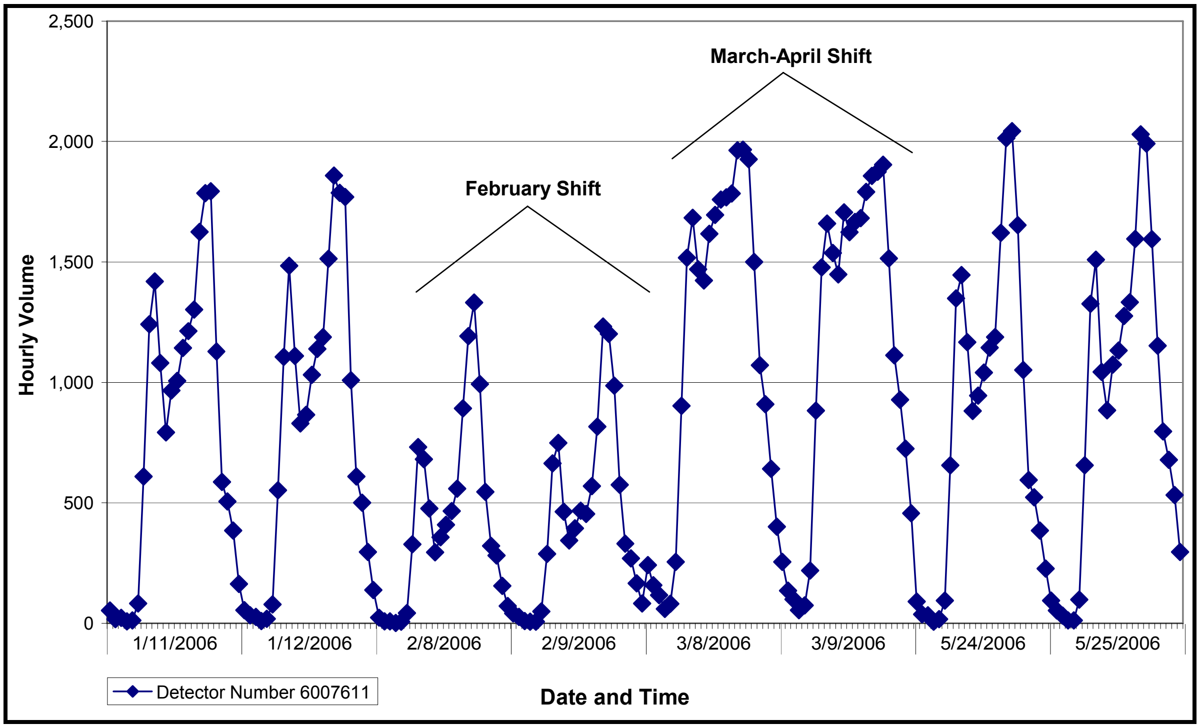

Figure 3. Example of single detector in 2006 before, during, and after shifts

Figure 4 shows the same time-of-day profiles as Figure 3, with the addition of its February match, detector number 6005224. Looking specifically at the time and height of the morning and afternoon peaks, alongside the mid-morning slump, one can see the similarities in the curves of detector number 6007611 (squares) for January 11-12 and May 24-25, and detector number 6005224 (diamonds) for February 8-9.

With the addition of an additional detector, number 6005224, Figure 5 shows the same time-of-day profiles as Figure 4, with the addition of its March-April match. Looking particularly at the time and height of the morning and afternoon peaks once again, alongside the mid-morning slump, one can follow the similarities in the curves of detector number 6007611 (triangles) for January 11-12, to detector number 6005224 (diamonds) for February 8-9, and next to detector number 6007142 (squares) for March 8-9, before returning to detector number 6007611 (triangles) for May 24-25.

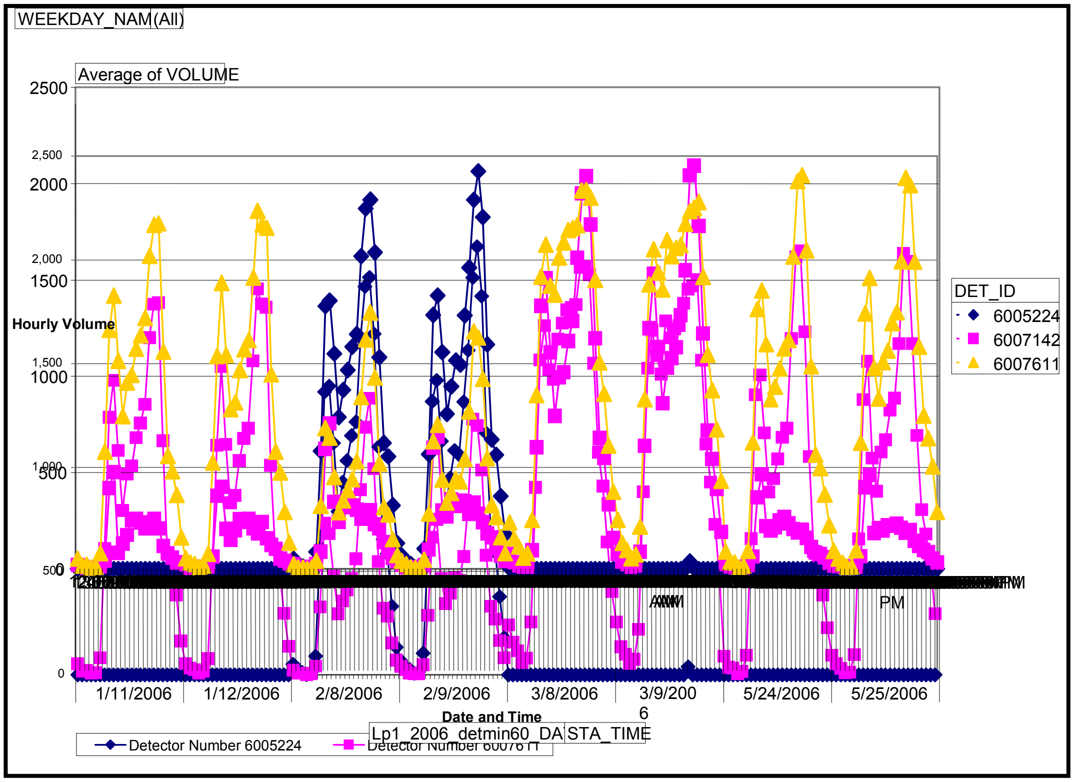

Figure 4. Detector in 2006 before, during, and after shifts (square) with its February match (diamond)

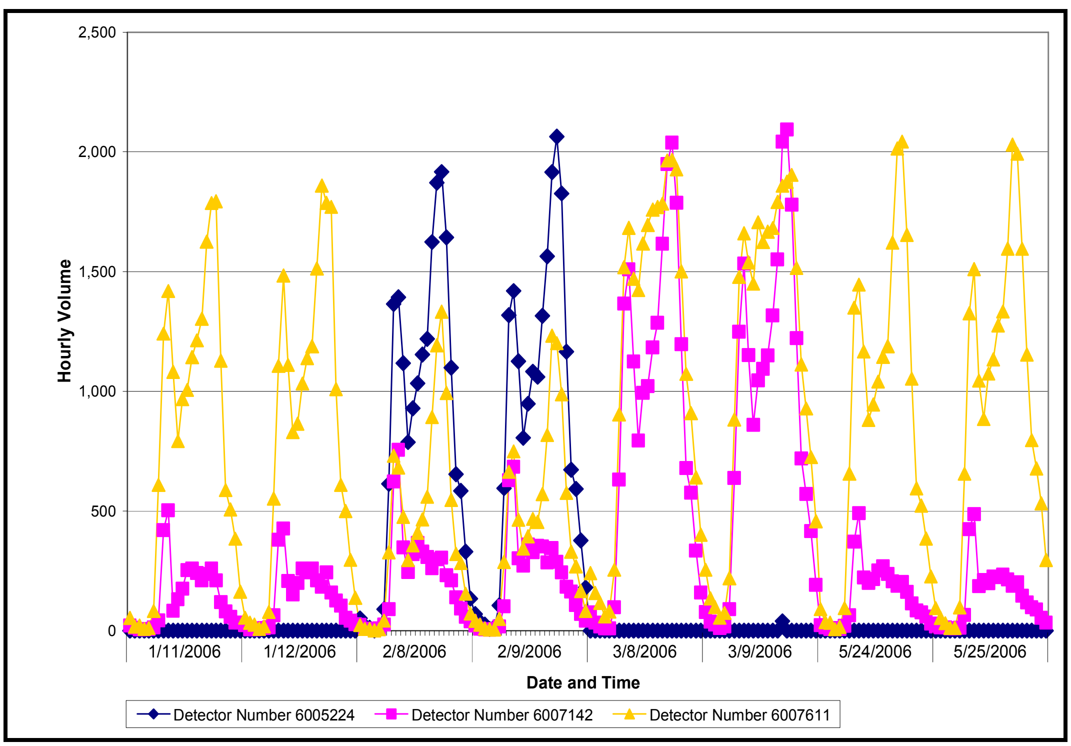

Figure 5: Detector in 2006 before, during, and after shifts (triangle) with its February (diamond) and March (square) matches

By removing all non-relevant curves from Figure 5, one is left with a complete time-of-day profile for detector number 6007611 in Figure 6. Using the same criteria as before to compare these curves, one can see that the matches shown are quite consistent. The gradual rise in individual curves from January through May can be explained by seasonal variation, a general increase in traffic in the Austin area from January into spring that is supported by permanent traffic count data from the Texas Department of Transportation (6).

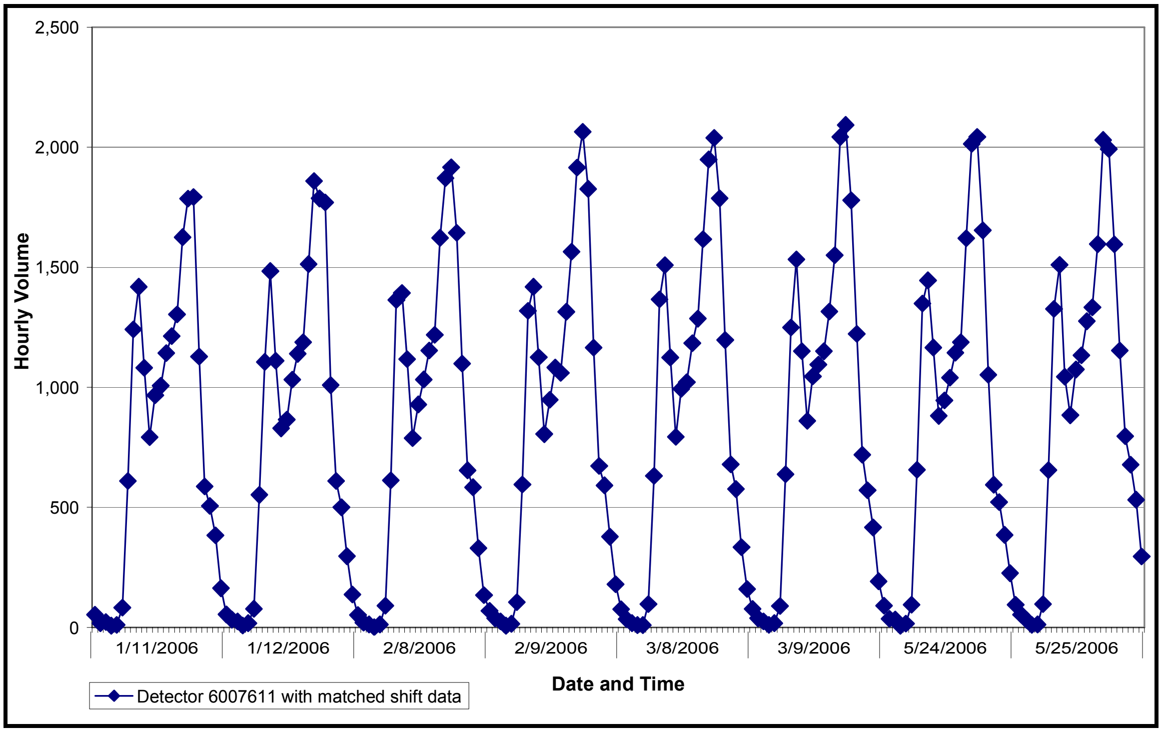

Figure 6: Final view of same detector in 2006 before and after shifts with its February and March matches

STATISTICAL ANALYSIS

Despite a high level of confidence in the visual matches that were made among the data, a final check was needed to help eliminate any human error. The comparison warranted a side by side analysis for each point on the time-of-day profile curve to ensure the distinctiveness of the matching curves. Thus, the sum of squared differences was chosen as the most effective means of accomplishing this goal.

Statistical analysis was implemented for the shifts in 2006 to verify the tentative matches that were made by the three methods. First, using Pivot Tables®, look at all detectors together to remove dates for which either incomplete or poor data was reported. Moreover, remove dates that might be affected by holidays, in this case, the week of New Year's Day, Martin Luther King, Jr. Day, President's Day, Good Friday, Easter Monday, and Memorial Day. Likewise, for each individual detector, remove additional dates for which inconsistent data was reported. For each detector, time-of-day volume profiles for multiple dates, Monday through Friday, were averaged together for a period of a month: January, February, March, April, and mid-May to the beginning of June; this resulted in an average of six to sixteen dates for each month. While all dates in March and April could be averaged together, they were done separately on the premise that too many dates would smooth out distinctive trademarks of the curve. Also, two months is a long span of time to average together when considering seasonal variations that could affect traffic patterns. On the other hand, February had a smaller range of dates to choose from, it being a shorter shift. Note that while it is not desirable to average too many dates, it is neither good to limit dates to a very low number. With too few dates, irregular occurrences due to accidents or weather, for example, could greatly affect the quality of the data and skew the average to make a poor control curve.

The average hourly profile for each month was lined up in columns by month to compare the control months (January and May/June) with the matches (February, March, April) for each detector. Each hour on the curves was then evaluated by taking the difference between each of the hours in the two columns and squaring that value. All hours were then summed together. The January to June sum for each detector was used as an empirical value; this was done on the premise that any seasonal traffic variations between the months would be greatest over this period of time, it being the longest period. Based on the quantity of data available from the months, the second shift was verified by matching April to May/June, and the first shift by matching February to March. This choice was based on the better quality of data available for May and June than January. Optimally, the sums for the February-March and April-May/June comparisons would be smaller numbers than the empirical value, due to the differences being smaller, and thus their profiles being more similar to each other. With 229 of 276 "matches" meeting this criteria, nearly 83% of the matches were confirmed.

For the matches that did not meet this criterion, the same procedure was applied using time-of-day occupancy profiles for the same dates. Time-of-day speed profiles would also have been a desirable alternative, however the recorded speed data available was much less complete than that for occupancy. Using occupancy profiles as a secondary statistical check for "matches" that were not confirmed by volume profiles, an additional 29 "matches" were confirmed. The overall matching confirmation after checks of both volume and occupancy thus exceeded 93%.

Whether it is necessary to employ occupancy time of day profiles as a secondary check is a matter of debate. On one hand, it is comforting to be able to confirm 60% of the matches that did not pass the initial check. However, the probability that the matches were not correct is greatly reduced, particularly since it was only a shift of data as opposed to random scattering of data. Thus, with more than 80% being confirmed after an initial statistical check, a second check could be deemed unnecessary.

Before implementing the statistical matching procedure, a test against false positives was run in which two profiles that were nearly identical were purposefully paired together incorrectly. The sum of differences squared for the false matches exceeded the empirical value for the vast majority of cases.

Even without graphically seeing the data, the statistical test could assist in the matching process. While incorrect matches had the sum of differences squared ranging from millions to billions, correct matches typically had values less than 100,000.

RESULTS

Results from the shift occurring from August 10, 2004 – March 21, 2005 showed a consistent shift of 52 positions with the detector numbers lined up side by side. The cause of this shift appears to have been caused by the removal of 52 detectors on August 4th. The straight shift encompasses numbers for detectors that had long ago been deactivated, and so data sent to these detector numbers was not recorded. To emphasize the seemingly erratic appearance of shifts, detectors removed on August 9th seemed to have no effect on shifting.

When this project began, it was thought that the shift from February to April of 2006 was a single shift. However, it was soon discovered that February had not been reporting bad data, rather was a unique second shift. Encompassing only a short period of time from February 3 – 21, it is a straight shift of 34 numerical positions with no obvious cause from the information available. It too incorporates non-reporting detectors.

Finally, the shift from March 1 – April 27 in 2006 was caused by the removal of eight detectors on February 23. These detectors were not grouped together, but interspersed among all the detectors in the list, so it is a progressive shift with the first hundred detectors being unaffected; then the detectors after each removed detector are shifted one spot down the list. Thus, data is shifted progressively from zero to eight positions. However, there are a couple oddities to this shift. First, beside each removed detector, another was added in its place on February 28, but apparently did not start reporting until May. Second, three consecutive detectors were added that recorded data for only one day before the number was changed to a lower number, moving it up the list. This change of detector numbers added a twist to the shift such that in order for a true "shift" to occur, one must view those three detectors in the position of their original numbers in the list. Additionally, one detector was removed and another added on March 1 with no affect on shifting. The shift was corrected on May 12.

Table 1: Example of Statistical Matching using Hourly Volumes

	Detector to Analyze: 6007611		February Match: 6005224	March-April Match: 6007142		Difference Squared		
	January Average	May Average	February Average	March Average	April Average	Jan-May	Feb-Mar	Apr-May
12 AM	57	85	57	77	71	793	414	209
1 AM	31	37	27	33	29	41	39	61
2 AM	26	33	19	33	25	47	173	60
3 AM	10	10	6	12	7	0	46	6
4 AM	17	14	17	14	13	8	5	2
5 AM	82	94	89	87	82	143	5	149
6 AM	569	628	598	637	638	3,488	1,488	106
7 AM	1,269	1,306	1,286	1,300	1,293	1,364	203	184
8 AM	1,451	1,470	1,403	1,422	1,464	361	391	33
9 AM	1,073	1,106	1,096	1,075	1,125	1,101	426	361
10 AM	835	882	824	852	856	2,227	788	682
11 AM	1,027	1,027	966	1,008	1,032	0	1,756	27
12 PM	1,092	1,137	1,074	1,115	1,143	2,031	1,744	31
1 PM	1,155	1,229	1,131	1,203	1,208	5,467	5,116	436
2 PM	1,314	1,288	1,288	1,366	1,357	650	6,077	4,710
3 PM	1,539	1,567	1,593	1,616	1,587	774	557	383
4 PM	1,779	1,939	1,878	1,913	1,873	25,820	1,198	4,400
5 PM	1,817	1,955	1,949	1,996	1,954	19,165	2,218	3
6 PM	1,668	1,583	1,726	1,659	1,640	7,289	4,413	3,201
7 PM	1,068	1,015	1,056	1,125	1,088	2,724	4,748	5,193
8 PM	575	656	592	633	738	6,652	1,708	6,607
9 PM	510	574	520	530	574	4,112	114	0
10 PM	375	434	333	357	384	3,474	607	2,488
11 PM	184	222	156	203	169	1,425	2,198	2,734
					SUM:	**89,157**	**36,432**	**32,068**

Note the intervals that sometimes appear between the removal of detectors and the actual shift or after the shift until quality data is again reported; these intervals before and after the March – April shift are February 24 – 28, April 28 – May 11 An explanation might include different fixes being attempted on the central database or SCU, but the data in intervals of a week or so before and after the 2006 shifts is irregular, incomplete, and unable to be used in the matching process.

CONCLUSIONS

With the completion of this project, 11 months of traffic data can be restored for the Austin congestion report and other future traffic studies. Also, TxDOT is now more aware of the causes of the problem and TTI checks the consistency of the Austin data on a weekly basis. Finally, there is a procedure in place to more readily correct similar shifts of data in the future.

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APPENDIX A

Detector Matches for August 2004-March 2005, February 2006, and March-April 2006 with Volume Confirmation Statistics

Detector Number	Aug 2004-Mar 2005 Matched Detector Number	Feb 2006 Shift - Matched Detector Number	Mar-Apr 2006 Shift - Matched Detector Number	2006 Shifts - Confirmation of Matches by Statistical Comparison with Volume Data		
				Jan-May	Feb-Mar	Apr-May
6002327	6000715	6000811	-	6,280	8,663	-
6002411	6000721*	6000812	-	361,947	51,923	-
6002412	6000722*	6000815	-	239,538	73,120	-
6002413	6000723*	6000816	-	150,990	49,142	-
6002415	6000724*	6000817	-	23,709	10,957	-
6002417	6000725	6000821	-	8,508	3,851	-
6002421	6000727*	6000822	-	375,593	94,400	-
6002422	6000731*	6000827	-	268,182	44,338	-
6002423	6000732*	6000828	-	0	0	-
6002424	6000733*	6000831	-	8,648	16,015	-
6002611	6000741	6000832	-	131,122	71,492	-
6002612	6000742	6000911*	-	-	-	-
6002613	6000743	6000912*	-	-	-	-
6002617	6000811	6000913*	-	-	-	-
6002621	6000812	6000915*	-	-	-	-
6002622	6000815	6000921*	-	-	-	-
6002623	6000816	6000922*	-	-	-	-
6002625	6000817	6000923*	-	-	-	-
6002811	6000821	6000927	-	189,664	65,790	-
6002812	6000822	6000931*	-	-	-	-
6002813	6000827	6000932*	-	-	-	-
6002815	6000828	6000941*	-	-	-	-
6002821	6000831	6000942*	-	-	-	-
6002822	6000832	6001027*	-	-	-	-
6002823	6000911*	6001711	-	480,868	44,126	-
6002827	6000912*	6001712	-	5,396	5,319	-
6003411	6000913*	6001713	-	117,723	69,941	-
6003412	6000915*	6001715	-	131,471	60,001	-
6003413	6000921*	6001721	-	183,564	48,722	-
6003417	6000922*	6001722	-	17,193	5,901	-
6003421	6000923*	6001723	-	308,586	97,854	-
6003422	6000927	6001727	-	219,006	62,758	-
6003423	6000931*	6001741	-	361,293	35,507	-
6003425	6000932*	6001742	-	2,596	468	-
6003427	6000941*	6002327	-	0	0	-
6003515	6000942*	6002411	-	75,775	3,777	-
6003525	6001027*	6002412	-	109,713	6,729	-
6003527	6001711	6002413	-	2,724	3,378	-
6003541	6001712	6002415	-	71,631	27,680	-
6003627	6001713	6002417	-	0	0	-
6003811	6001715	6002421	-	0	0	-

6003812	6001721	6002422	-	0	0	-
6003813	6001722	6002423	-	0	0	-
Detector Number	**Aug 2004-Mar 2005 Matched Detector Number**	**Feb 2006 Shift - Matched Detector Number**	**Mar-Apr 2006 Shift - Matched Detector Number**	**2006 Shifts - Confirmation of Matches by Statistical Comparison with Volume Data**		
				Jan-May	Feb-Mar	Apr-May
6003814	6001723	6002424	-	0	0	-
6003821	6001727	6002611	-	0	0	-
6003822	6001741	6002612	-	0	0	-
6003823	6001742	6002613	-	0	0	-
6003824	6001827*	6002617	-	0	0	-
6004311	6001831*	6002621	-	116,905	64,664	-
6004312	6001832*	6002622	-	34,123	45,201	-
6004313	6001841*	6002623	-	55,535	39,336	-
6004317	6001842*	6002625	-	6,289	3,421	-
6004321	6002327	6002811	-	327,761	83,935	-
6004322	6002411	6002812	-	257,475	38,532	-
6004323	6002412	6002813	-	611,600	30,216	-
6004325	6002413	6002815	-	15,875	16,281	-
6004611	6002415	6002821	-	132,372	69,942	-
6004612	6002417	6002822	-	63,032	38,695	-
6004613	6002421	6002823	-	107,270	33,894	-
6004615	6002422	6002827	-	11,094	10,515	-
6004621	6002423	6003411	-	794,344	79,443	-
6004622	6002424	6003412	-	441,217	35,051	-
6004623	6002611	6003413	-	690,173	24,759	-
6004627	6002612	6003417	-	58,404	10,638	-
6005211	6002613	6003421	-	17,987,111	13,620,127	-
6005212	6002617	6003422	-	12,926,828	15,143,626	-
6005213	6002621	6003423	-	22,155,405	4,610,439	-
6005214	6002622	6003425	-	1,794,987	2,024,038	-
6005221	6002623	6003427	-	11,422,269	4,591,309	-
6005222	6002625	6003515	-	41,270,541	6,104,855	-
6005223	6002811	6003525	-	35,063,453	16,479,202	-
6005224	6002812	6003527	-	0	1,115,938	-
6005515	6002813	6003541	-	164,878	5,396	-
6005517	6002815	6003627	-	2,723	2,578	-
6005518 (new 2/28/06)		-	-	-	-	-
6005519	6002821	6003811	Removed 2/23/06	-	-	-
6005525	6002822	6003812	6005518	356,801	29,197	53,688
6005711	6002823	6003813	6005525	91,512	43,932	43,584
6005712	6002827	6003814	6005711	83,518	38,913	31,262
6005713	6003411	6003821	6005712	46,719	16,934	21,455
6005721	6003412	6003822	6005713	109,561	110,040	137,255
6005722	6003413	6003823	6005721	165,150	33,315	107,066
6005723	6003417	6003824	6005722	180,063	12,388	49,383
6005727	6003421	6004311	6005723	119,620	53,516	90,976
6005741	6003422	6004312	6005727	8,778	15,010	12,864
6005742	6003423	6004313	6005741	10,871	8,273	17,919

6005743	6003425	6004317	6005742	1,580	2,823	8,337
6006811	6003427	6004321	6005743	103,452	61,392	42,319
6006812	6003515	6004322	6006811		38,743	
6006813	6003525	6004323	6006812	0	0	0
6006817	6003527	6004325	6006813	22,293	3,769	11,136
Detector Number	**Aug 2004-Mar 2005 Matched Detector Number**	**Feb 2006 Shift - Matched Detector Number**	**Mar-Apr 2006 Shift - Matched Detector Number**	**2006 Shifts - Confirmation of Matches by Statistical Comparison with Volume Data** Jan-May	Feb-Mar	Apr-May
6006821	6003541	6004611	6006817	1,832,075	142,967	85,163
6006822	6003627	6004612	6006821	661,914	28,670	80,595
6006823	6003811	6004613	6006822	361,373	15,636	36,894
6006825	6003812	6004615	6006823	10,849	14,246	41,167
6007111	6003813	6004621	6006825	101,657	44,835	42,102
6007112	6003814	6004622	6007111	42,466	27,800	24,876
6007113	6003821	6004623	6007112	34,337	24,415	22,058
6007115 (new 2/28/06)		-	-	-	-	-
6007116	6003822	6004627	Removed 2/23/06	79,905	-	-
6007121	6003823	6005211	6007113	131,493	111,973	77,419
6007122	6003824	6005212	6007115	216,782	36,105	62,890
6007123	6004311	6005213	6007121	38,343	15,604	49,472
6007125	6004312	6005214	6007122	16,189	11,793	19,834
6007141	6004313	6005221	6007123	6,202	4,603	18,391
6007142	6004317	6005222	6007125	3,723	7,770	5,890
6007143	6004321	6005223	6007141	13,383	8,066	9,435
6007611	6004322	6005224	6007142	89,157	36,432	32,068
6007612	6004323	6005515	6007143	50,905	27,120	25,070
6007613	6004325	6005517	6007611	222,361	17,529	25,788
6007617	6004611	6005519	6007612	14,749	5,940	6,617
6007621	6004612	6005525	6007613	146,844	102,165	92,028
6007622	6004613	6005711	6007617	228,840	25,939	106,235
6007623	6004615	6005712	6007621	49,522	9,887	20,201
6007627 (new 3/1/06)		-	6007622	-	-	-
6007647	6004621	6005713	Removed 3/1/06	-	-	-
6007911	6004622	6005721	6007623	36,073	35,499	27,890
6007912	6004623	6005722	6007627	1,121,287	2,189,038	241,295
6007913	6004627	6005723	6007911	61,633	211,633	29,066
6007917	6005211	6005727	6007912	3,054	18,953	2,658
6007921	6005212	6005741	6007913	116,246	77,212	58,090
6007922	6005213	6005742	6007917	154,275	24,323	74,008
6007923	6005214	6005743	6007921	32,659	16,707	32,073
6007925	6005221	6006811	6007922	7,312	10,545	19,320
6007931	6005222	6006812	6007923	9,227	3,970	2,302
6007932	6005223	6006813	6007925	4,118	783	5,773
6007941	6005224	6006817	6007931	3,180	897	2,330
6007942	6005515	6006821	6007932	1,955	1,813	8,351
6007943	6005517	6006822	6007941	2,999	844	1,366
6008211	6005519	6006823	6007942	24,092	122,070	17,529

6008212	6005525	6006825	6007943	29,816	117,169	21,565
6008213	6005711	6007111	6008211	547,828	84,023	34,429
6008217	6005712	6007112	6008212	0	0	0
6008221	6005713	6007113	6008213	229,177	60,939	52,355
6008222	6005721	6007116	6008217	0	0	0
6008223	6005722	6007121	6008221		2,487,973	
6008227	6005723	6007122	6008222	0	0	0
6008231	6005727	6007123	6008223	2,434,453	5,474,276	703,566
6008232	6005741	6007125	6008227	8,449	5,534	4,749
				2006 Shifts - Confirmation of Matches by Statistical Comparison with Volume Data		
Detector Number	***Aug 2004-Mar 2005 Matched Detector Number***	***Feb 2006 Shift - Matched Detector Number***	***Mar-Apr 2006 Shift - Matched Detector Number***	Jan-May	Feb-Mar	Apr-May
6008241	6005742	6007141	6008231	37,759	10,952	4,983
6008242	6005743	6007142	6008232	11,446	9,677	6,605
6008243	6006811	6007143	6008241	11,372	10,076	15,935
6008711	6006812	6007611	6008242	17,751	42,857	17,024
6008712	6006813	6007612	6008243	7,846	28,947	4,997
6008713	6006817	6007613	6008711	6,362	11,797	3,660
6008717 (new 2/28/06)		-	-	-	-	-
6008718 (new 2/28/06)		-	-	-	-	-
6008719 (new 2/28/06)		-	-	-	-	-
6008721	6006821	6007617	6008712	21,677	52,836	18,198
6008722	6006822	6007621	6008713	37,353	67,769	82,688
6008723	6006823	6007622	6008721	37,031	26,330	13,833
6008724	6006825	6007623	6008722	99,504	29,411	15,208
6008727 (reported only 2/28/06)			-	-	-	-
6008728 (reported only 2/28/06)			-	-	-	-
6008729 (reported only 2/28/06)			-	-	-	-
6008731	6007111	6007627	Removed 2/23/06	-	-	-
6008732	6007112	6007911	Removed 2/23/06	-	-	-
6008733	6007113	6007912	Removed 2/23/06	-	-	-
6009011	6007116	6007913	6008723	12,361	36,941	10,387
6009012	6007121	6007917	6008724	7,068	43,608	3,530
6009013	6007122	6007921	6008717	10,586	5,897	3,493
6009017	6007123	6007922	6008718	0	0	0
6009021	6007125	6007923	6008719	74,496	31,914	10,991
6009022	6007141	6007925	6009011	44,493	23,363	14,904
6009025	6007142	6007931	Removed 2/28/06			
6009027	6007143	6007932	6009012	9,092	1,128	24,396
6009041 (new 2/28/06)		-	-	-	-	-
6009131	6007611	-	Removed 2/23/06	-	-	-
6009311	6007612	-	6009013	9,048	-	6,309
6009312	6007613	-	6009017	6,987	-	6,472
6009313	6007617	-	6009021	1,791	-	1,078
6009315	6007621	-	6009022	0	-	0
6009321	6007622	-	6009027	45,742	-	26,144

6009322	6007623	-	6009041	28,830	-	20,053
6009325	6007647	-	-	7,972	-	
6009331 (new 2/28/06)		-	-	-	-	-
6009332	6007911	-	-	12,254	-	
6009333	6007912	-	6009312	5,381	-	6,279
6009341	6007913	-	6009313	0	-	0
6009342	6007917	-	6009315	474	-	317
6009343	6007921	-	6009321	1,903	-	1,407
6009825	6007922	-	6009322	4,651	-	963
6009827	6007923	-	6009325	0	-	0
6009911	6007925	-	6009332	9,542	-	8,217
6009912	6007931	-	6009333	9,497	-	14,937
6009913	6007932	-	6009341	41,514	-	50,100
				2006 Shifts - Confirmation of Matches by Statistical Comparison with Volume Data		
Detector Number	***Aug 2004-Mar 2005 Matched Detector Number***	***Feb 2006 Shift - Matched Detector Number***	***Mar-Apr 2006 Shift - Matched Detector Number***	Jan-May	Feb-Mar	Apr-May
6009921	6007941	-	6009342	200,450	-	152,857
6009922	6007942	-	6009343	115,988	-	103,498
6009923	6007943	-	6009825	42,221	-	34,453
6010311	6008211	-	6009827		-	
6010312	6008212	-	6009911		-	
6010313	6008213	-	6009912		-	
6010315	6008217	-	6009913		-	
6010321	6008221	-	6009921	179,735	-	122,355
6010322	6008222	-	6009922	97,697	-	109,965
6010323	6008223	-	6009923	41,003	-	33,276
6010327	6008227	-	6010311	68,924	-	80,430
6010331	6008231	-	6010312		-	
6010332	6008232	-	6010313		-	
6010333	6008241	-	6010315		-	
6010341	6008242	-	6010321	0	-	0
6010342	6008243	-	6010322	17,989	-	15,776
*reported to inactive detector number				Unconfirmed Matches:	26	20

APPENDIX B

Secondary Statistical Confirmation for Matches Unconfirmed by Volume, using Occupancy Data

Detector Number	Feb 2006 Shift - Matched Detector Number	Mar-Apr 2006 Shift - Matched Detector Number	2006 Shifts –Secondary Confirmation of Matches by Statistical Confirmation with Occupancy Data		
			Jan-May	Feb-Mar	Apr-May
6002327	**6000811**	-	1.87	1.03	-
6002424	**6000831**	-	1.66	4.00	-
6003527	**6002413**	-	1.58	0.60	-
6004312	**6002622**	-	26.96	25.43	-
6004325	**6002815**	-	2.20	3.26	-
6005212	**6003422**	-	798.29	982.41	-
6005214	**6003425**	-	127.79	138.46	-
6005721	**6003822**	**6005713**	1,084.95	188.58	63.64
6005741	**6004312**	**6005727**	23.35	2.48	2.44
6005742	6004313	**6005741**	46.32	9.72	3.90
6005743	**6004317**	**6005742**	3.96	1.44	2.74
6006825	**6004615**	**6006823**	48.24	2.16	13.50
6007123	6005213	**6007121**	208.37	52.15	91.70
6007125	6005214	**6007122**	94.90	33.09	77.28
6007141	6005221	**6007123**	1.38	1.25	17.02
6007142	**6005222**	**6007125**	2.34	1.87	16.50
6007912	**6005722**	6007627	1,071.26	415.96	13.02
6007913	**6005723**	6007911	101.25	329.55	8.62
6007917	**6005727**	6007912	0.37	0.62	0.21
6007925	**6006811**	**6007922**	1.79	1.14	4.10
6007932	6006813	**6007925**	0.96	0.09	1.36
6007942	6006821	**6007932**	0.51	0.50	1.44
6008211	**6006823**	6007942	5.09	4.44	1.66
6008212	**6006825**	6007943	6.98	6.04	1.66
6008222	6007116	**6008217**	0.00	0.00	0.00
6008231	**6007123**	6008223	271.62	319.51	1.10
6008243	6007143	**6008241**	2.52	0.30	5.21
6008711	**6007611**	6008242	1.45	1.54	0.57
6008712	**6007612**	6008243	1.07	0.88	0.48
6008713	**6007613**	6008711	1.49	0.53	0.24
6008721	**6007617**	6008712	4.09	2.94	27.70
6008722	**6007621**	**6008713**	121.37	13.26	63.98
6009011	**6007913**	6008723	0.59	0.72	0.22
6009012	**6007917**	6008724	0.58	0.50	0.29
6009027	6007932	**6009012**	1.16	0.29	1.59
6009333	-	**6009312**	0.93	-	2.70
6009912	-	**6009333**	1.31	-	0.63
6009913	-	**6009341**	3.54	-	1.85
6010322	-	**6009922**	705.62	-	750.01
6010327	-	**6010311**	1.22	-	1.89
Unconfirmed:	**26**	**21**		9	11

*Detector numbers in bold were not confirmed with volume comparison
**Numbers in yellow not confirmed with either occupancy or volume data

EVALUATION OF TRIPCAL5 TRIP GENERATION DEFAULT MODELS

by

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Currently a Junior at the University of Pittsburgh, Patrick anticipates graduating in 2009 with a degree in Civil Engineering, a minor in Music, and a certificate in Historic Preservation, after which he will likely attend graduate school to study transportation.

While at Pitt, he is also a student leader in the Collegiate Eagle Scout Association and the Urban Studies Association. Patrick hopes to use the research skills gained from this Fellows program to further the cause of old roads and conduct research on Historic US Highway 99.

SUMMARY

Transportation planning has a large influence on the built and natural environments, and similarly, the accuracy of software used in the travel demand modeling process is imperative for a successful result. TRIPCAL5 is a trip generation software developed in 1990 by researchers at the Texas Transportation Institute for the Texas Department of Transportation, and is disseminated to metropolitan planning organizations (MPOs) through the Texas Travel Demand Model Package. In order to develop distributions of households by household size, household income, and vehicle availability, the user may utilize default models within TRIPCAL5. These default models use a minimum of inputs to estimate distributions, based on a modified gamma distribution function. Although flexible and easy to use, there is no knowledge as to whether the default models currently estimate satisfactory distributions.

In order to evaluate the performance of the TRIPCAL5 default models, Census data from 1970 to 2000 for all MSAs in Texas were obtained and compared to estimated results from the default models. After determining improvements to the models that could be made, these revisions were then verified using Census data at the MSA level, and zonal data for a sample MSA. Both the household size and vehicle availability default models were replaced with individual regression equations, and the output of the income default model was adjusted based on a specific methodology. Overall, these revisions to the default models require fewer inputs and perform better than the current default models.

TABLE OF CONTENTS

INTRODUCTION

Transportation has an important effect on cities, towns, and their citizens, and the management of transportation is imperative to maintaining a high standard of livability. As part of a sound urban transportation planning process, travel demand modeling plays a vital role. Travel demand modeling forecasts quantitative values about travel on the physical transportation system, using a four-step process. During the trip generation step, certain socio-demographic information is used to determine trip productions and attractions at the zonal level. These traffic analysis zones (TAZ) can be as small as one city block, or as large as several square miles. A trip is considered one transportation journey, and has an origin and a destination; in general, trips are "produced" at the origin and "attracted" to the destination, except that any trip that begins or ends at home is considered to be "produced" in the home zone and "attracted" to the other zone. Once these productions and attractions are determined for each zone in an urban area, the trip distribution step determines how many of the trips produced in each zone are attracted to each of the other zones. Next, these trips are split by mode; i.e. single-occupancy vehicle, public transportation, bicycle, etc. Finally, a computer simulation is developed of the physical transportation system, with nodes standing for intersections and links between nodes standing for connections of travel. In this trip assignment step, each of the trips between zones is assigned a specific path. From this information, estimated amounts of traffic on each segment of the physical transportation system are obtained. This travel demand model can then be used to forecast future travel needs for the urban area, or predict the impact of a change in the transportation system, among other things.

Only the first step of the travel demand modeling process, trip generation, will be investigated during this research project. Trip generation supposes that there is a way to estimate travel using readily available census data and by investigating historical trends in travel. In general practice (*1*), the number of trips generated is correlated to several socio-demographic and socio-economic variables, particularly household income, household size, automobile availability or ownership, employment, and trip purpose. By definition, if a trip either departs from or arrives at the home, it is said to be "produced" at the home end and "attracted" to the other end; therefore production is dependent on residential or household characteristics, and attraction on employment. To determine the total trips produced for a zone, distributions of households by their characteristics (most frequently by household income, household size, and vehicle availability) are produced. These distributions are used in what are called "cross-classification" tables. An example of a cross-classification table is shown in Table 1. Trip rates can be developed through travel surveys to determine an average of how many trips are made by a household that fits the characteristics of each cell. The trip rates can then be multiplied by the distributions of households to come up with an aggregate total of the number of trips produced in each zone. Similarly, total trips attracted for a zone is calculated using cross-classification tables, trip rates, and employment information by sector. There are other considerations about trip generation, such as localized institutions with unique travel demands (called special generators), trips that begin and end outside of the study area (through-trips), and trips that have only one end in the study area (external-internal trips), but a discussion of them is not warranted at this time.

Table 1. Example Cross-Classification

TRIP RATES		# Autos Available		
		0	1	2+
Income ($)	0 - 14,999	3.0	4.9	9.0
	15,000 - 29,999	3.9	6.0	10.3
	30,000 - 44,999	5.1	7.5	11.5
	45,000+	5.6	8.5	12.7

TRIPCAL5, the current trip generation model used by the Texas Department of Transportation (TxDOT), was developed in 1990 with the intent of bringing the TxDOT modeling process into the state of the practice. Nearly all MPOs in the state use TRIPCAL5 as part of the Texas Travel Demand Model Package. The program is designed to allow flexible usage, particularly in developing distributions of households for use with cross-classification models. Users may choose from among three methods of developing distributions: input a user-specified model, input user-developed data, and/or utilize a built-in default model. These default models allow for a minimal input of user data (for example, the median income for a zone), and use a calibrated gamma distribution to calculate the household distributions (for example, the percentage of households in each income level). Because they are the most common selection by practitioners of TRIPCAL5, the default models deserve the most scrutiny and evaluation.

PROBLEM STATEMENT

The development of the default models used in TRIPCAL5 is well-documented (2). The models were developed, calibrated, and validated using Census data back to 1949, the most recent being from 1980. Since then, data from the 1990 and 2000 Censuses have been released, and there is no knowledge of whether the default models continue to estimate household distributions to a satisfactory degree. The purpose of this project is to evaluate the TRIPCAL5 default models to determine if they are performing satisfactorily in the present day, and to gather data to revise them if necessary.

In order to complete this project, Census data were collected from 1969/1970 to 2000 on specific household characteristics and analyzed for historical trends. At the same time, the Census data obtained were prepared and input into the default models; the estimated results were then compared to actual observed data, and statistical evaluation techniques applied. If it was necessary, the historical trends discovered were then used to develop improvements and revisions to the TRIPCAL5 default models.

RESEARCH OBJECTIVES

This research project is concerned specifically with the following objectives:

- Gather Census data since 1969/1970 and analyze historical trends for the following variables:
  - Household Size,
  - Household Income,
  - Automobile Availability;
- Evaluate TRIPCAL5 default models for satisfactory performance using 1990 and 2000 Census data;
- Update, calibrate, and validate TRIPCAL5 default models using recent Census data, if necessary.

PROCEDURE

Literature Review

The first step towards completing the research objectives as specified was a review of pertinent literature, to become introduced to the theoretical processes of travel demand modeling and specifically trip generation methodology. The results of this step are summarized primarily in the Introduction and sporadically throughout the rest of the paper.

Census Data Collection

For evaluation of the default models and analyses of historical trends, the following distributions of households were obtained:

- by household size,
- by household income,
- by vehicle availability.

In addition to these distributions, values were found for the following information:

- total population,
- total households,
- average household size,
- average vehicles per household,
- median household income,
- mean household income.

It was decided that any data collected must be from compatible sources to ensure comparability between years. As a result, the most reliable source for such data is the U.S. Decennial Census. For 2000, data were extracted from the Summary File 3 (STF 3), located online from the U.S. Census Bureau's American FactFinder (*3*). Similarly, data for 1990 were extracted from the STF 3 for 1990, also located online (*4*). Summary File 3 presents aggregate population and housing information collected from a 1-in-6 sampling rate and presented (in this case) at the metropolitan area level of detail. For 1980, no Summary File was available online, so Public-Use Microdata Samples (PUMS) were used (*5*). The PUMS are 5- and 1-percent samples of raw (untabulated and disaggregate) Census data particularly useful for creating unique collections and tabulations of data because they contain records at the person and household level. For 1970, data collection used library books containing the Censuses of Population and Housing for that year (*6*, *7*). Because all data were obtained from official U.S. Census Bureau publications, it was deemed reasonable that acceptable conclusions from analyses and comparisons of these data could be drawn.

Geographic Concerns

One major concern encountered when collecting census data was the geographic unit for which the data are presented. Although the flexible default models can be applied to any level of detail, including traffic analysis zone, census tract, or metropolitan area, it was determined that the models should be expected to perform very satisfactory at the metropolitan area level. Officially, metropolitan areas for a Census are comprised of one or more counties, with specific nuclear, population, and economic requirements. This level of detail is a reasonable balance between easily obtained data and widely applicable results. Once the default models performed positively at the metropolitan area level, they were then further validated by testing a sample of zonal data.

Over time, the official Census Bureau name for metropolitan areas has changed:

- MA: Metropolitan Area (used post-2000),
- MSA: Metropolitan Statistical Area (used 1990 and 2000),
- CMSA: Consolidated Metropolitan Statistical Area (used 1990 and 2000), signifying a collection of more than one related MSA,
- PMSA: Primary Metropolitan Statistical Area (used 1990 and 2000), signifying the MSAs that make up a CMSA,

- SMSA: Standard Metropolitan Statistical Area (used 1970 and 1980).

In this report, MSA will be the term used to represent the metropolitan area under consideration. A list of all MSAs in Texas, with their name changes over time, can be found in Appendix A.

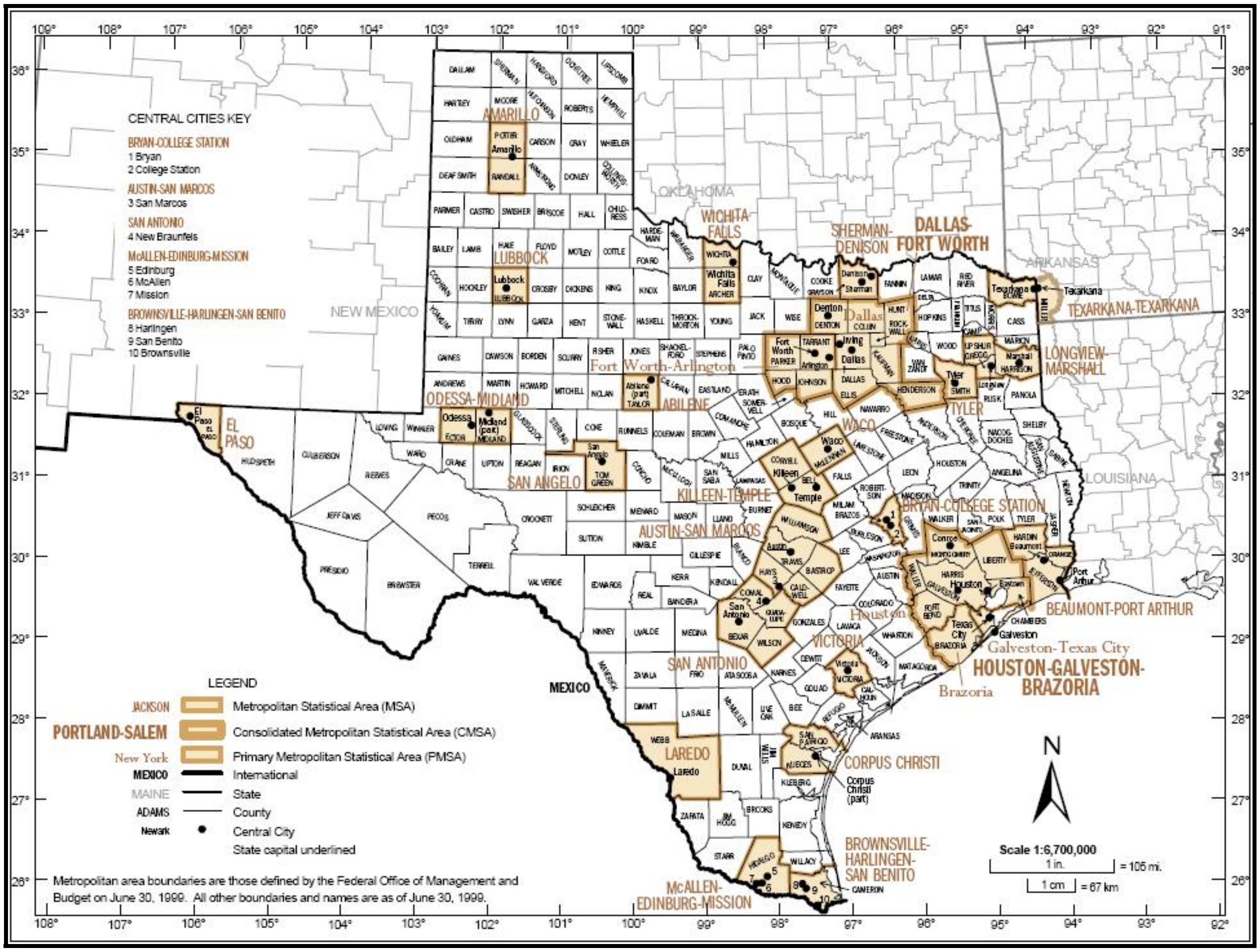


Figure 1. Map Showing MSAs in Texas, as used in the 2000 U.S. Census (*8*)

One problem encountered was that both Census redefinitions and changes in socioeconomic factors combine to create changes in MSAs between different Censuses, leading to possible incompatibility. It was decided that despite these changes, data would still be valid based on MSA definitions at the time of each Census, particularly because the information used to test the default models and examine historical trends would be looked at only in percentages (for distributions of households) and rates (e.g. vehicles *per* household). In addition, the counties that might be added or removed between Censuses contribute only a small proportion of population relative to the primary county, and so the changes would not adversely affect the use of the data.

Significant problems were encountered, however, when using the PUMS data for 1980. PUMS uses a different geographical system, organizing areas into County Groups (CGs) that may include a small portion of one county or several counties combined; the reason for this is sufficient security of data, since PUMS provide individual census records at the person and household levels. In 1980, several MSAs were grouped with nearby counties not in MSAs, while some MSAs were split between several County

Groups. In the cases of MSAs incorporating more than one County Group, data from these CGs were combined before extraction of relevant information occurred. For MSAs that were combined with non-metropolitan areas, if the MSA part of the county group made up 50-percent or more of the entire county group population, then it would be deemed acceptable to evaluate the county group as if it were the MSA. The reasoning behind this is that if the MSA counties contained the majority of the records, then the results of the analysis would be reasonably acceptable and not overly skewed by the inclusion of non-metropolitan territory. Unfortunately, this decision precluded the analysis of four MSAs (Corpus Christi, Sherman – Denison, Texarkana, and Victoria).

Other concerns over geography arose and were dealt with. In 1970, several current MSAs were not officially created yet, so data for those four (future) MSAs were collected from records of their composite counties. Finally, at some points between 1970 and 2000, MSAs representing Dallas – Fort Worth, Houston – Galveston – Brazoria, and Odessa – Midland were identified combined and separate. Because present modeling practice considers the combination of each of these composite areas, it was decided that although data would be collected for each part separately, final analyses and evaluations would use them combined. Please consult Appendix A for a chart detailing this complex geographic comparability.

Other Concerns

When collecting Census data and preparing the data for input, some data manipulation had to occur. For example, mean income was not directly listed in the Census records and was obtained by dividing aggregate household income by number of households. Also a concern, vehicle distributions were listed by occupied housing units rather than households; the difference between these two measures was found to be insignificant, especially since distributions were in percentages.

One thing that had to be dealt with often was the open upper range and its assigned value when calculating an average of the distribution (e.g. 3+ vehicles, $150,000+, etc). For vehicles, the value of the upper range (3+) in 2000 and 1990 was an average of 3.3, and so this number was used to obtain average vehicles per household for 1980 and 1970 (as well as for estimated distributions). For income, the average value of the upper range was between 1.6 and 1.7 times the lower limit of this range, and so this value for 1979 ($75,000 and up) was selected to be $125,000. This process was not necessary for household size.

Default Model Evaluation

Before any evaluation of the TRIPCAL5 default models could occur, applicable data had to be in the correct formats for input. The three default models were separated out from the primary program and made able to run in a DOS-mode on Windows; the inputs and outputs are so described:

- Size.exe – Household Size Distribution
  - Inputs: average household size;
  - Outputs: percentages of households by household size (one, two, three, four, five+).
- Inc.exe – Household Income Distribution
  - Inputs: consumer price index (CPI) relative to 1967, median household income;
  - Outputs: percentages of households by midpoint of income range (500 to 34,500 by 1000s, then 45,000, all in 1967 $), estimated mean income.
- Auto.exe – Vehicle Availability Distribution
  - Inputs: CPI relative to 1967, total number of households, total population, median household income;
  - Outputs: percentages of households by number of vehicles (none, one, two, three+), average vehicles per household.

Once all of the input data was prepared and ready, the three models were run for each MSA for each year, and the output file for each run (e.g. auto.out) was saved as a text file. The text files were then extracted into an Excel spreadsheet and the output data organized in an accessible and comparable form.

Gamma Distribution Function

As part of each default model, the underlying basis for the development of distributions of households is the use of a modified gamma distribution function. The probability density function (PDF) for a general two-parameter gamma distribution is:

$$f(x) = \frac{x^{\alpha-1} \cdot e^{-x/\beta}}{\beta^{\alpha} \cdot \Gamma(\alpha)}$$

where $\alpha =$ shape parameter, $\beta =$ scale parameter, and

$$\Gamma(\alpha) = \int x^{\alpha-1} \cdot e^{-x} dx = \text{ Gamma function.}$$

The mean of a general gamma distribution is $\alpha\beta$ and the variance is $\alpha\beta^2$.

An adjusted form of the PDF for a gamma distribution that is used in the TRIPCAL5 default models is shown below:

$$f(t) = t^{\alpha-1} \cdot e^{-\beta \cdot t}.$$

Note that in this case the mean is α/β. When alpha and beta are set equal to each other, the mean of the distribution becomes 1.00, very useful when calculating percentages. When they are not equal to each other, percentages can be easily obtained by dividing each $f(t)$ by the sum of all $f(t)$'s.

One theoretical concern with the use of the gamma distribution has to do with its continuous nature. Household size and vehicle availability are examples of discrete data, which can take on only certain values; income, however, is continuous or at least more continuous because there are nearly infinite values that it could take. The use of a continuous distribution to model discrete information is specifically of concern, and perhaps the basis for these models should be changed as a result.

Selecting a Performance Measure

In order to test the current performance of the TRIPCAL5 default models, estimated data obtained from running the default models were compared against observed data collected from Census records. In order for the performance of the default models to be determined, an applicable statistical comparison technique was selected. Because of its simplicity, ease of calculation, and universal comprehension, the correlation coefficient, r, was chosen, where r is calculated according to the following:

$$r = \sqrt{1 - \frac{SSE}{SST}}$$

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad SST = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

where

$y_i =$ actual value, $\hat{y}_i =$ predicted value, $\bar{y} =$ mean of actual values,

and where r^2 gives the value of the *proportion of explained variance*, with desirable values close to 1. In general, preferred values are 0.90 and above, and acceptable values are 0.80 and above.

The selection of r^2 as the performance measure produces some limitations to evaluation. Because it measures the error sum of squares (SSE) as a proportion of the total sum of squares (SST), data that deviate very little from the mean may produce poor values of r^2 even if the absolute errors are very small (as will be seen with average vehicles per household). It is therefore not valid to compare r^2 values between different tests and conclude that one has a better fit (e.g. comparing r^2 values from average vehicles per household and mean income). In addition, r^2 does not penalize models for including more variables than are significant; only an adjusted-r^2 or t-statistic could accomplish this. Taking this into consideration, no revised model will be proposed with more than two variables.

Specific Performance Guidelines

Using the performance measure of r^2, as explained above, the default models were evaluated by calculating r^2 for the following:

- Size.exe
  - For each MSA in each year, comparing the estimated household distribution percentages to the observed household distribution percentages.
- Inc. exe
  - For each MSA in each year, comparing the estimated household distribution percentages to the observed household distribution percentages;
  - For each year, comparing estimated mean income to observed mean income.
- Auto.exe
  - For each MSA in each year, comparing the estimated household distribution percentages to the observed household distribution percentages;
  - For each year, comparing estimated vehicles per household to observed vehicles per household.

Also, each default model was visually evaluated and compared to describe the data and verify the accuracy of the r^2 performance measure.

Revision and Validation

Once an evaluation of each default model's performance was complete, it was then revised using the observed historical trends. The methodology and proposed revised default models are described below. These revised models were then tested using similar inputs as the current TRIPCAL5 default models, and compared against the previously obtained results to demonstrate improvement. Finally, the suggested revised models were further validated against sample zonal data. The sample used was Amarillo, obtained from the 2000 Census Transportation Planning Package (CTPP), a tabulation of population and housing data designed for transportation planners and presented at the TAZ level (*9*). All three default models were evaluated for applicability at both the MSA and zonal levels before being recommended for implementation.

RESULTS

Household Size

Historical Trends

The average household size of Texas MSAs in 2000 was predominantly between 2.5 and 2.8 persons per household. Four geographic areas, however, displayed significantly higher average household sizes that were above 3.0 (Brownsville – Harlingen – San Benito, El Paso, Laredo, McAllen – Edinburg – Mission); notably these MSAs are all located on the Mexican border. This trend is similar in 1990 and 1980, with only four MSAs above 3.0 in 1990 and only five in 1980. A general trend to be noted in Table 2 is the slight decrease over time in average household size. 1970 data show a much larger average household size overall, with four MSAs under 3.0, three around 4.0, and the rest in the lower 3.0s. The cause of this dramatic decrease between 1970 and 1980 may be the result of different census definitions or sources (e.g. occupied housing units vs. households), but it is most likely the result of a decrease in fertility rates that took place during the 1970s.

Table 2. Average Household Size

Geographical MSA (name in 2000)	2000	1990	1980	1970
Abilene, TX MSA	2.543	2.612	2.678	2.975
Amarillo, TX MSA	2.549	2.548	2.642	3.005
Austin--San Marcos, TX MSA	2.569	2.480	2.609	3.020
Beaumont--Port Arthur, TX MSA	2.586	2.653	2.809	3.204
Brownsville--Harlingen--San Benito, TX MSA	3.407	3.469	3.555	3.922
Bryan--College Station, TX MSA	2.520	2.498	2.597	3.075
Corpus Christi, TX MSA	2.822	2.914	3.080	3.518
Dallas--Fort Worth, TX CMSA	2.694	2.634	2.718	3.103
El Paso, TX MSA	3.175	3.248	3.320	3.648
Houston--Galveston--Brazoria, TX CMSA	2.801	2.745	2.794	3.205
Killeen--Temple, TX MSA	2.725	2.745	2.846	3.047
Laredo, TX MSA	3.753	3.808	3.788	4.005
Longview--Marshall, TX MSA	2.574	2.606	2.751	3.049
Lubbock, TX MSA	2.514	2.618	2.765	3.195
McAllen--Edinburg--Mission, TX MSA	3.598	3.669	3.712	4.145
Odessa--Midland, TX MSA	2.701	2.750	2.807	3.297
San Angelo, TX MSA	2.523	2.607	2.669	3.004
San Antonio, TX MSA	2.774	2.814	2.973	3.390
Sherman--Denison, TX MSA	2.513	2.517	2.576	2.907
Texarkana, TX--Texarkana, AR MSA	2.500	2.618	2.744	3.022
Tyler, TX MSA	2.587	2.614	2.734	3.066
Victoria, TX MSA	2.749	2.802	2.957	3.425
Waco, TX MSA	2.588	2.587	2.653	2.925
Wichita Falls, TX MSA	2.498	2.547	2.632	2.959

In terms of the percentages of households in each size category, identifiable trends can be seen in Figure 2. One-person households decrease linearly as HH size increases, tapering off above 3.0. For two-person households, the trend is less clear, but still decreasing with increased HH size. Three-person households display a negative parabolic shape, centered around 3.25. The trend for four-person households is somewhat difficult to determine, but it is definitely increasing with larger household sizes. Five-person households show a very strong positive linear trend. These results make intuitive sense: as household size increases, the proportion of households in the higher size categories should increase, decreasing the other categories.

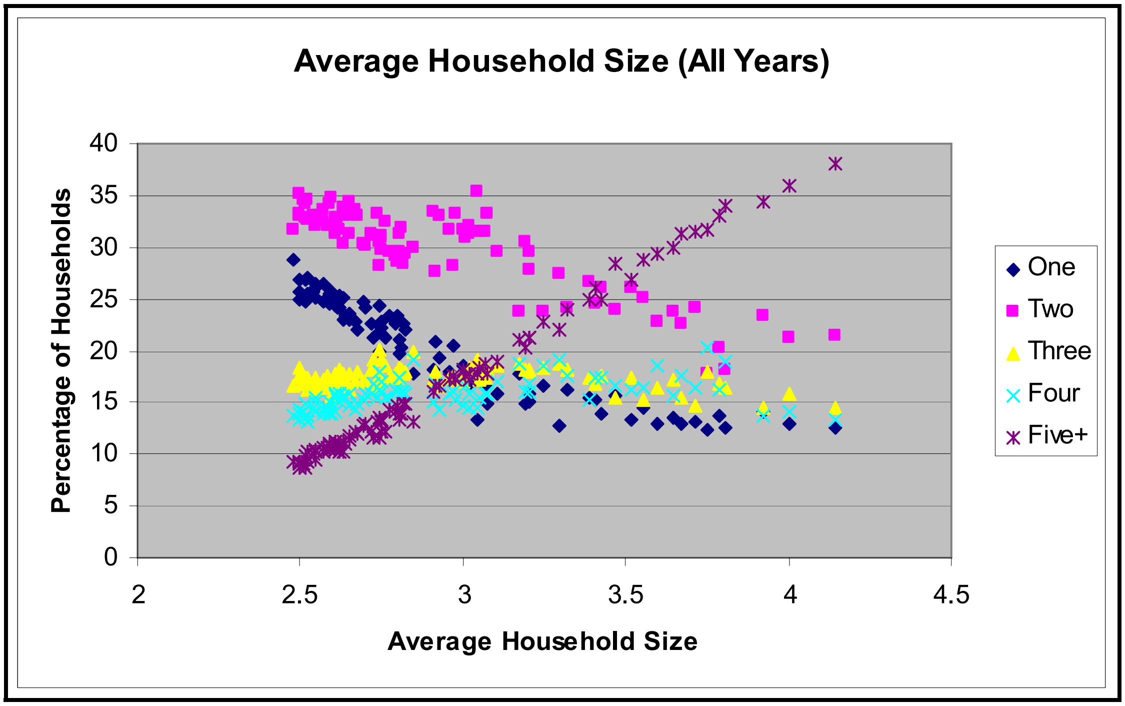


Figure 2. Household Size Categories

In order to better determine historical trends in household size distributions, the average household size categories were normalized by dividing by the overall average household size in each year, and then plotted. For two-, three-, and four-person households, this action concentrated the data and allowed trends to appear more easily. Yet when this was done for one- and five+-person households, the data from 1970 were separate from the other three data-year sets. A possible explanation for this is the comparatively high average household sizes for that year. Because of this disparity, it was decided that the 1970 data would not be used to evaluate or revise the default models, a decision that is justified by the fact that because of this year's larger historical separation from the present, it should have a lesser influence on future predictions.

Default Model Evaluation

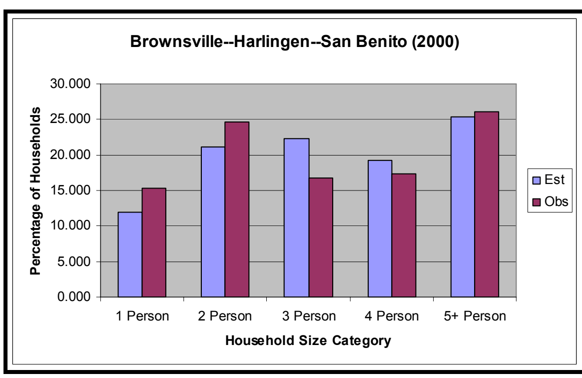
The default model that estimates household size distributions, Size.exe, is the simplest of the three default models being tested. Input into the model is the average household size (AHHS) for the area, between 1.005 and 4.750 persons per household. The program obtains preliminary estimates from a gamma distribution function, with shape (α) and scale (β) parameter set initially to 2.76. From this distribution is calculated an estimate of AHHS, and if not within 0.1% of input, beta is adjusted by a factor of estimated ÷ input, and a new distribution is calculated. This process repeats until the estimated AHHS is equal to the input value, and the estimated distribution is then output.

Estimated distributions were calculated for each MSA for all years, and an r^2 value was calculated for each MSA in each year, comparing the estimated distributions to the observed distributions. Table 3 displays these results. The overall r^2 value increased from 0.784 in 1980, to 0.847 in 1990, to 0.867 in 2000, and similarly most MSAs displayed increasing goodnesses of fit from 1980 to 2000; most MSAs had 0.79 or above in 2000, which is acceptable. Three MSAs (Brownsville – Harlingen – San Benito, El

Paso, McAllen – Edinburg – Mission), however, showed poor fits; these correspond to MSAs with very high average household sizes (above 3.0). Example distributions are shown in Figure 3.

Table 3. Household Size: r^2 Values

Geographical MSA (name in 2000)	R-squared values			
	2000	1990	1980	1970
Abilene, TX MSA	0.9019	0.8830	0.8707	0.6106
Amarillo, TX MSA	0.8877	0.8897	0.8616	0.6459
Austin--San Marcos, TX MSA	0.8841	0.9245	0.8809	0.6259
Beaumont--Port Arthur, TX MSA	0.9150	0.8845	0.8080	0.5254
Brownsville--Harlingen--San Benito, TX MSA	0.3890	0.3574	0.3845	0.3706
Bryan--College Station, TX MSA	0.9175	0.9091	0.8326	0.5752
Corpus Christi, TX MSA	0.7971	0.6206		0.4664
Dallas--Fort Worth, TX CMSA	0.8270	0.8934	0.8684	0.6409
El Paso, TX MSA	-0.0917	0.2471	0.3825	0.5334
Houston--Galveston--Brazoria, TX CMSA	0.7211	0.7688	0.7941	0.5260
Killeen--Temple, TX MSA	0.8759	0.8578	0.7733	0.5708
Laredo, TX MSA	0.8758	0.8342	0.6719	0.5510
Longview--Marshall, TX MSA	0.8982	0.9040	0.8946	0.5625
Lubbock, TX MSA	0.9246	0.8749	0.8558	0.5203
McAllen--Edinburg--Mission, TX MSA	0.6636	0.6365	0.4936	0.5083
Odessa--Midland, TX MSA	0.8145	0.7588	0.7997	0.6295
San Angelo, TX MSA	0.8967	0.8633	0.8388	0.5720
San Antonio, TX MSA	0.7856	0.7457	0.5773	0.3298
Sherman--Denison, TX MSA	0.8981	0.8978		0.6656
Texarkana, TX--Texarkana, AR MSA	0.9486	0.9047		0.6451
Tyler, TX MSA	0.8607	0.8749	0.7786	0.5562
Victoria, TX MSA	0.8140	0.7867		0.4948
Waco, TX MSA	0.8889	0.8947	0.8071	0.6262
Wichita Falls, TX MSA	0.9186	0.9025	0.8559	0.6446



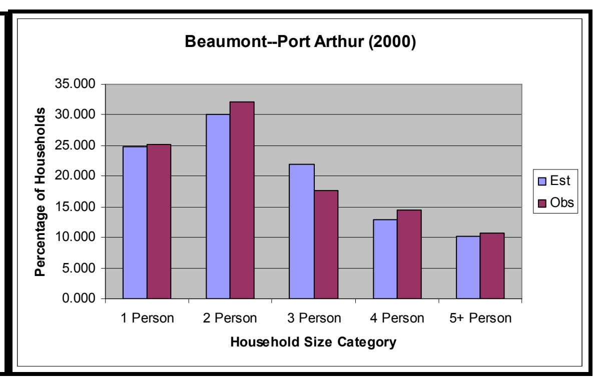


Figure 3. Example Distributions by Household Size

Each size category was graphed in Figure 4, comparing the observed values to estimated ones. For one-person households the model fits well, except for above 3.0 where it underestimates. The two-person results are consistently underestimated by 2-3 percentage points. The model significantly overestimates three-person households, by an average of almost 5 percentage points. Four-person households are underestimated below about 2.8, and overestimated above 2.9. Finally, 5+-person households are predicted with striking precision and accuracy.

Default Model Revision

To improve the performance of the household size default model, it was decided to attempt to replace the gamma distribution function and iterative routine with five separate regression models, one for each household size category. The reasoning for this was that the model consistently over- or under- estimated household size categories, especially for 2 and 3 persons. Using the Excel graphs of Figure 4, equations of best fit for data from 1980 to 2000 were found and are shown below, where y = percentage of households and x = average household size:

One-Person	$y = 132.4126 \cdot x^{-1.7604}$	$r^2 = 0.9518$
Two-Person	$y = 1.6496 \cdot x^2 - 20.6317 \cdot x + 74.9363$	$r^2 = 0.8903$
Three-Person	$y = -4.2216 \cdot x^2 + 25.5940 \cdot x - 20.7216$	$r^2 = 0.2884$
Four-Person	$y = -5.0971 \cdot x^2 + 34.6638 \cdot x - 40.7680$	$r^2 = 0.6766$
Five+-Person	$y = 2.3131 \cdot x^2 + 4.4586 \cdot x - 16.5452$	$r^2 = 0.9924$

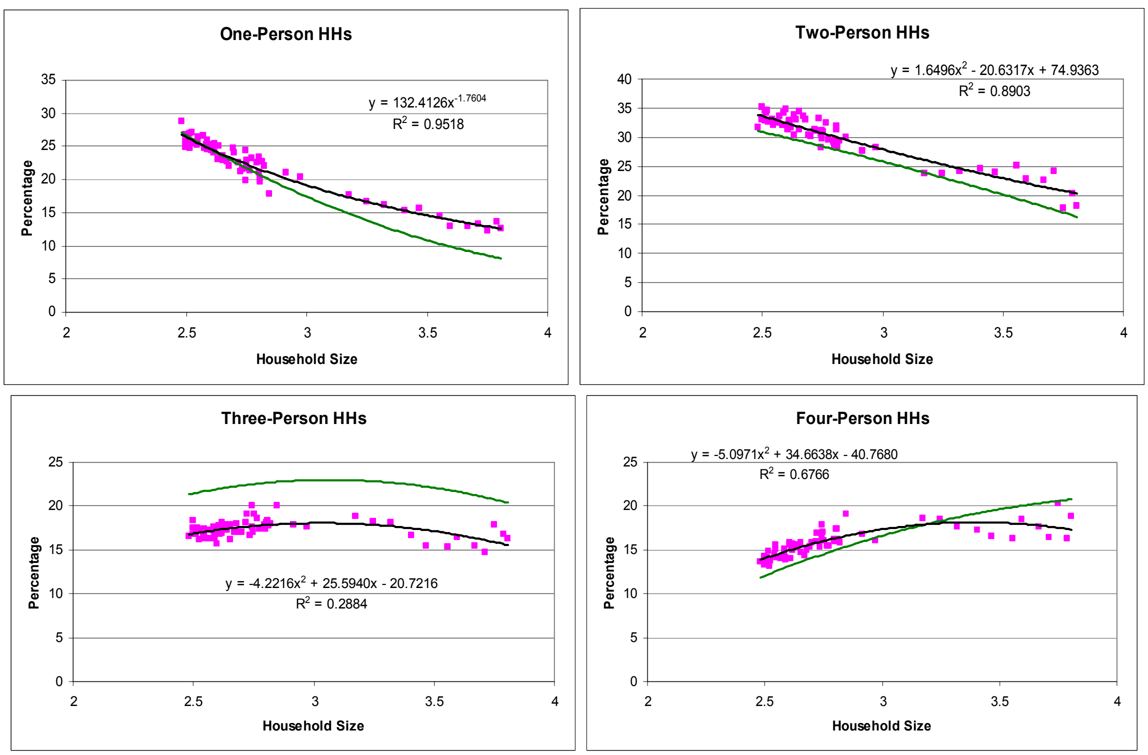


Figure 4. Graphs of Household Size Categories (pink are observed data points, green line is default model estimation, black line and equation is possible revision equation)

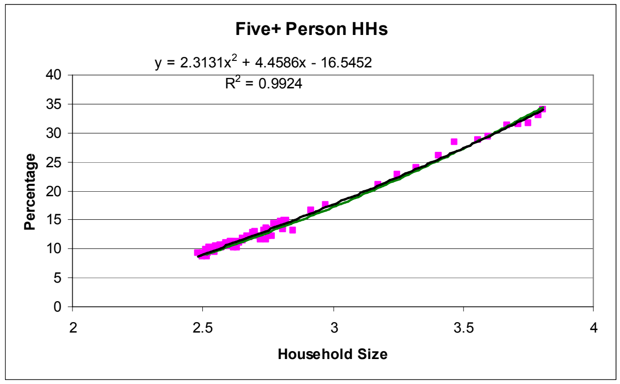


Figure 4 (Continued). Graphs of Household Size Characteristics

When investigating the results of testing the default model, a general trend was observed, that as household size increased (up to 3.00, above which no trend was observed), the r^2 value decreased linearly. It was hypothesized that perhaps the shape parameter (alpha) of the gamma function was related to household size. If a better-fit alpha value could be used in the model instead of a blanked value of 2.76, perhaps the model would demonstrate better performance. To test this, data from 2000 were run, and the best fit alpha values obtained. Indeed, a linear relationship was observed, especially for values below 3.00. A linear regression was performed and the following equation obtained:

$$\alpha = -0.6315 \cdot (HHSize) + 4.227 \qquad \text{with} \qquad r^2 = 0.5951 .$$

Verification

These two possible improvements to the household size default model were tested, the results of which are presented in Table 4. The alpha adjustment method in general showed slightly improved results, although the only MSAs that significantly improved were those that were previously performing very poorly. The individual regression equations, on the other hand, displayed incredible improvements for all MSAs, with most showing 0.99 or greater. Even the very poor performing MSAs improved to preferred levels (except for El Paso). Interestingly, the average household size obtained from the estimated distributions matched the input value significantly well, with an r^2 value greater than 0.96. These individual curve fits also performed similarly well against 1990 and 1980 data. As a result, they are recommended for revision of the default model.

Despite the positive performance of these replacement equations, it should be noted that they have limited application. Below 1.9 and above 5.1 persons per household the equations predict negative numbers, obviously wrong. In addition, because of the use of a quadratic equation, the four-person category decreases above 4.0, also counterintuitive. In order to test the applicability of these models to wider ranges of inputs, they were tested with 2000 Amarillo zonal data. The results are shown in Table 5.

Table 4. Household Size Evaluation, 2000 MSAs

2000 Geographical Name (in 2000)	Household Size		r-squared values		
	Obs	Est	Deflt. Mdl	Alpha Adj	Reg. Eqns
Abilene, TX MSA	2.543	2.544	0.9019	0.9022	0.9996
Amarillo, TX MSA	2.549	2.550	0.8877	0.8953	0.9930
Austin--San Marcos, TX MSA	2.569	2.569	0.8841	0.8946	0.9896
Beaumont--Port Arthur, TX MSA	2.586	2.586	0.9150	0.9183	0.9979
Brownsville--Harlingen--San Benito, TX MSA	3.407	3.274	0.3890	0.6355	0.9764
Bryan--College Station, TX MSA	2.520	2.522	0.9175	0.9115	0.9931
Corpus Christi, TX MSA	2.822	2.801	0.7971	0.8473	0.9913
Dallas--Fort Worth, TX CMSA	2.694	2.686	0.8270	0.8636	0.9807
El Paso, TX MSA	3.175	3.095	-0.0917	0.5748	0.6979
Houston--Galveston--Brazoria, TX CMSA	2.801	2.783	0.7211	0.8164	0.9540
Killeen--Temple, TX MSA	2.725	2.715	0.8759	0.8494	0.9684
Laredo, TX MSA	3.753	3.530	0.8758	0.9206	0.8936
Longview--Marshall, TX MSA	2.574	2.574	0.8982	0.8940	0.9973
Lubbock, TX MSA	2.514	2.516	0.9246	0.9282	0.9949
McAllen--Edinburg--Mission, TX MSA	3.598	3.417	0.6636	0.7763	0.9891
Odessa--Midland, TX MSA	2.701	2.693	0.8145	0.8507	0.9843
San Angelo, TX MSA	2.523	2.525	0.8967	0.9037	0.9907
San Antonio, TX MSA	2.774	2.759	0.7856	0.8441	0.9788
Sherman--Denison, TX MSA	2.513	2.515	0.8981	0.8925	0.9961
Texarkana, TX--Texarkana, AR MSA	2.500	2.503	0.9486	0.9433	0.9924
Tyler, TX MSA	2.587	2.587	0.8607	0.8578	0.9873
Victoria, TX MSA	2.749	2.736	0.8140	0.8256	0.9985
Waco, TX MSA	2.588	2.588	0.8889	0.9005	0.9915
Wichita Falls, TX MSA	2.498	2.501	0.9186	0.9199	0.9981
r-squared value		0.9630			

Table 5. Household Size Verification Results, 2000 Amarillo Zones

ENTIRE MSA DATA	Average HH Size	r-squared values	Distribution One	Two	Three	Four+	
Observed sum zones	2.595		26.4879	32.6021	16.2074	24.7027	
Est sum zones	2.570	0.9980	26.0865	32.5434	16.3840	24.9862	
			One	Two	Three	Four	Five+
Obs MSA	2.549		26.4824	32.5788	16.2760	14.1723	10.4905
Est MSA	2.550	0.9930	25.5072	33.0727	17.0927	14.4759	9.8515
Est sum zones	2.570	0.9980	26.0865	32.5434	16.3840	13.8483	11.1379

The individual results from each TAZ were varied, as would be expected, but when taking a weighted sum of the results from each zone, the model equations produce an amazingly accurate result, with r^2 close to 1.0. The results from estimating by zone also match well with the observed results previously found from MSA data. In addition, the model does a fairly accurate job of predicting average household size, although it begins to deviate slightly above about 3.5 as is shown in Figure 5. Despite this, the r^2 performance measure is a satisfactory 0.9093.

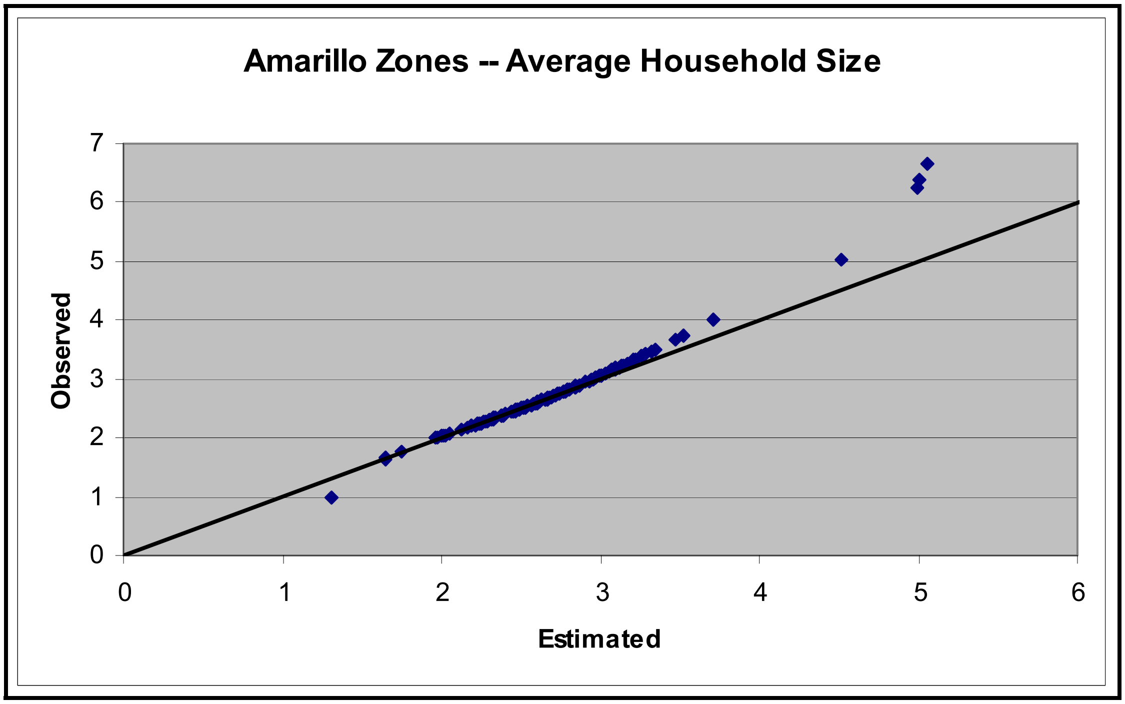


Figure 5. Average Household Size, Estimated vs. Observed, 2000 Amarillo Zones

Overall, these replacement regression equations perform very well at both the MSA and zone levels, although within a certain range of inputs. It is recommended that these models only be used between 2.0 and 5.0 persons per household. Luckily a high majority of the values observed fall within this range.

Household Income

Historical Trends

Overall, Texas MSAs are becoming more affluent, as shown by mean and median income in constant 1967 dollars in Table 6. Average mean income has continued to increase since 1979 (especially since 1989), while median incomes have generally increased slightly between 1979 and 1999, despite a large decrease in 1989. The reason for these results can be tied to economic conditions present in each year of the Censuses. In general, larger MSAs tend to have higher values of mean and median income. Mean and median income have also been shown to possess a linear relationship; see *Default Model Revision* below for more details.

In terms of distributions, all MSAs appear to follow a general shape, increasing to a left-centered peak, and gradually decreasing from there. The shape seems similar to a gamma distribution function, which is used in the model for estimation purposes. MSAs with higher incomes tend to have the peak shifted to the right more than those with lower mean or median incomes. Analyzing income distributions between years is a difficult procedure, because Census income ranges are not directly comparable due to changes in the value of money over time. When comparisons are performed, income values are converted to a constant dollar in 1967, using the Consumer Price Index (CPI).

Table 6. Median and Mean Income

Geographical MSA (name in 2000)	Median Income (1967 $)			Mean Income (1967 $)		
	1999	1989	1979	1999	1989	1979
Abilene, TX MSA	6821	6642	6628	9001	8575	8693
Amarillo, TX MSA	7150	6848	8015	9570	8797	9790
Austin--San Marcos, TX MSA	9810	7669	7362	12844	9899	9136
Beaumont--Port Arthur, TX MSA	7148	6859	8753	9359	8638	9913
Brownsville--Harlingen--San Benito, TX MSA	5241	4669	5501	7438	6695	7211
Bryan--College Station, TX MSA	5832	5497	5581	8673	8016	7515
Corpus Christi, TX MSA	7169	6720		9497	8701	
Dallas--Fort Worth, TX CMSA	9503	8841	8680	12800	11368	10534
El Paso, TX MSA	6223	6099	6540	8520	8005	8232
Houston--Galveston--Brazoria, TX CMSA	8970	8480	9642	12248	11112	11517
Killeen--Temple, TX MSA	7348	6383	5984	9231	7881	7596
Laredo, TX MSA	5631	4868	4894	8110	7001	6868
Longview--Marshall, TX MSA	6864	6571	7661	9134	8299	9130
Lubbock, TX MSA	6453	6552	7332	8960	8726	9179
McAllen--Edinburg--Mission, TX MSA	4983	4499	5307	7132	6513	7232
Odessa--Midland, TX MSA	6969	7203	8600	9564	9683	10448
San Angelo, TX MSA	6643	6558	6444	8849	8300	8448
San Antonio, TX MSA	7844	7027	6904	10338	9062	8581
Sherman--Denison, TX MSA	7451	6798		9645	8435	
Texarkana, TX--Texarkana, AR MSA	6461	6180		8796	7849	
Tyler, TX MSA	7444	6940	7824	10018	9053	9411
Victoria, TX MSA	7762	7257		10093	9264	
Waco, TX MSA	6725	6104	6247	9123	7980	7966
Wichita Falls, TX MSA	6833	6437	6902	8832	8200	8589

Default Model Evaluation

The default model that estimates household distributions by income, Inc.exe, uses a straightforward process slightly more complicated than the size default model. Input into the model are the CPI of the year under investigation and the median household income for the geographical area being studied. Converting this income to 1967 dollars, the model then estimates a mean income linearly related to the median income. This mean income is then used to estimate alpha, to which beta is initially set equal, for use in the gamma distribution function. These two linear equations, shown below, were developed using linear regression of 1980 Census data, as documented (2). An iterative process uses the gamma distribution to estimate distributions of households by income, calculating a mean income from the distribution, and comparing it to the estimated mean, adjusting alpha and beta as necessary until the means are within 1% of each other. Once this is achieved, the distribution of households into income intervals (in 1967 dollars) and an estimated mean income (in input year dollars) are output.

$$MeanInc = 1.0397 \cdot MedInc + 1355.02 \qquad \alpha = 0.000242 \cdot MeanInc - 0.3006$$

The default model was tested, and estimated distributions were obtained for 1999, 1989, and 1979; median income for 1969 was not available. The estimated mean incomes were compared to those observed, and r^2 values calculated for each year. To compare distributions of households by income, the 1967 income intervals had to be converted to the current year dollar amounts and adjusted to fit the observed income intervals. This methodology presumed that the distribution of households within each income interval was flat, so therefore the same ratio of households as the ratio of income was redistributed into the new intervals. For example, if an old interval was $1900 to $2300, 25% of the households would go into the new $1500 to $2000 interval and 75% of households into the new $2000 to

$2500 interval. Once this was completed, an r^2 value could be obtained by comparing the estimated distributions to those observed for each MSA in each year.

Table 7. Household Income Evaluation, r^2 Values and Mean Income

Geographical MSA (name in 2000)	r-squared values			Mean Income (99$)	
	1999	1989	1979	Obs	Est
Abilene, TX MSA	0.9444	0.9200	0.8945	44914	42147
Amarillo, TX MSA	0.9204	0.8996	0.9078	47756	43857
Austin--San Marcos, TX MSA	0.5149	0.7013	0.9241	64094	57654
Beaumont--Port Arthur, TX MSA	0.8253	0.7994	0.7971	46701	43846
Brownsville--Harlingen--San Benito, TX MSA	0.9934	0.9914	0.9679	37115	33954
Bryan--College Station, TX MSA	0.8477	0.9036	0.9411	43279	37020
Corpus Christi, TX MSA	0.8567	0.8328		47388	43954
Dallas--Fort Worth, TX CMSA	0.5361	0.5933	0.8921	63874	56062
El Paso, TX MSA	0.9797	0.9727	0.9579	42515	39045
Houston--Galveston--Brazoria, TX CMSA	0.3885	0.5048	0.7931	61115	53299
Killeen--Temple, TX MSA	0.9268	0.8636	0.9362	46061	44886
Laredo, TX MSA	0.9805	0.9847	0.9350	40467	35977
Longview--Marshall, TX MSA	0.9098	0.8541	0.8456	45580	42374
Lubbock, TX MSA	0.9408	0.8810	0.9484	44712	40237
McAllen--Edinburg--Mission, TX MSA	0.9781	0.9802	0.9690	35591	32611
Odessa--Midland, TX MSA	0.9011	0.8176	0.8572	47726	42915
San Angelo, TX MSA	0.9511	0.9300	0.9400	44156	41225
San Antonio, TX MSA	0.8070	0.8382	0.9476	51588	47455
Sherman--Denison, TX MSA	0.9022	0.8695		48129	45415
Texarkana, TX--Texarkana, AR MSA	0.9289	0.9014		43892	40279
Tyler, TX MSA	0.8496	0.8361	0.8592	49992	45384
Victoria, TX MSA	0.8639	0.6966		50365	47031
Waco, TX MSA	0.8675	0.9207	0.9598	45523	41653
Wichita Falls, TX MSA	0.9404	0.9449	0.9458	44072	42213
ALL MSAs Combined	0.8956	0.9031	0.9486		0.6143

Overall, as displayed in Table 7, the income distribution default model performed decently, although not well. Distributions showed decreasing goodnesses of fit from 1979 to 1999, with an overall r^2 decreasing from 0.949 in 1979 to 0.903 in 1989 and 0.896 in 1999. More noticeable than this decline was the poor prediction of mean income displayed in 1999, and to a lesser degree in 1989; mean income was in almost all cases underestimated by the default model. Also, despite the satisfactory overall performance of distributions in 1999, several distributions were not well estimated, as displayed by an r^2 value significantly lower than 0.800. Noticeably, these three MSAs (Austin – San Marcos, Dallas – Fort Worth, Houston – Galveston – Brazoria) are the largest MSAs in the state and had the three highest median incomes. In fact, it appeared that for median incomes above $8000 (1967 dollars), the model did not produce a distribution well.

Looking into the 2000 distributions in more detail (see Figure 6), it appeared that those MSAs with poor estimated distributions were differently shaped than other smaller, less affluent, better performing MSAs. The source of error was greatest in the large underestimation of households in the first income range, or first income "bin." This first bin underestimation was noticed in almost all the other MSAs, yet to a lesser degree. As a result, the model then overestimated the households in other income intervals, particularly between $50,000 and $100,000. Finally, because the gamma distribution approaches zero for very large inputs, the highest income intervals were also consistently underestimated.

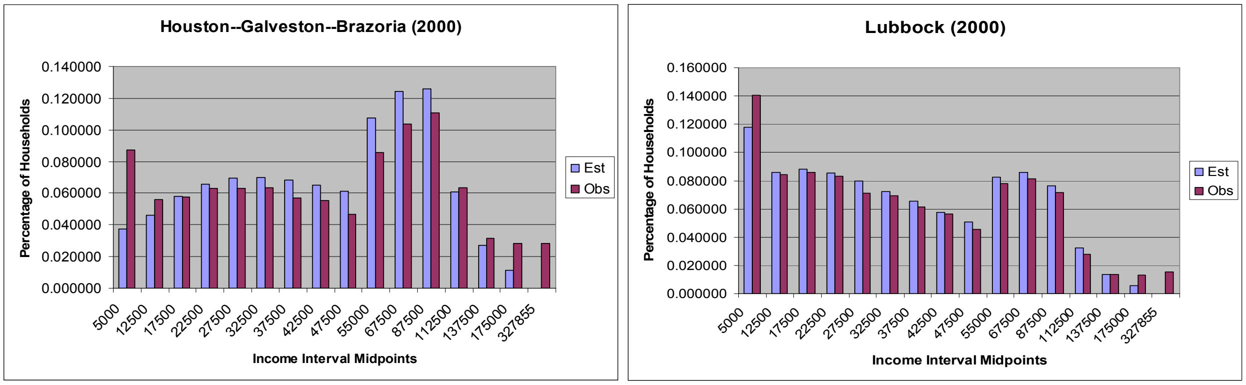


Figure 6. Example Distributions by Income, Estimated vs. Observed

Default Model Revision

One of the possible sources of error in the default model was the estimation of mean income from median income. The linear relationship assumed by the default model equation was tested by plotting mean income vs. median income for each year (using constant 1967 dollars). A strong linear relationship was found to be present, and a linear regression was performed for each year, yielding r^2 values of from 0.941 to 0.975, demonstrating strong correlation. A linear regression was also performed combining all years, with a resultant r^2 value 0.911, less than each individual year fit. Upon further review, the individual year fit lines showed an increasing slope and a decreasing intercept from 1979 to 1999. If plotted together as in Figure 7, they appear to all nearly intersect at about $4000 median income (1967 dollars). The best fit lines are shown in Table 8.

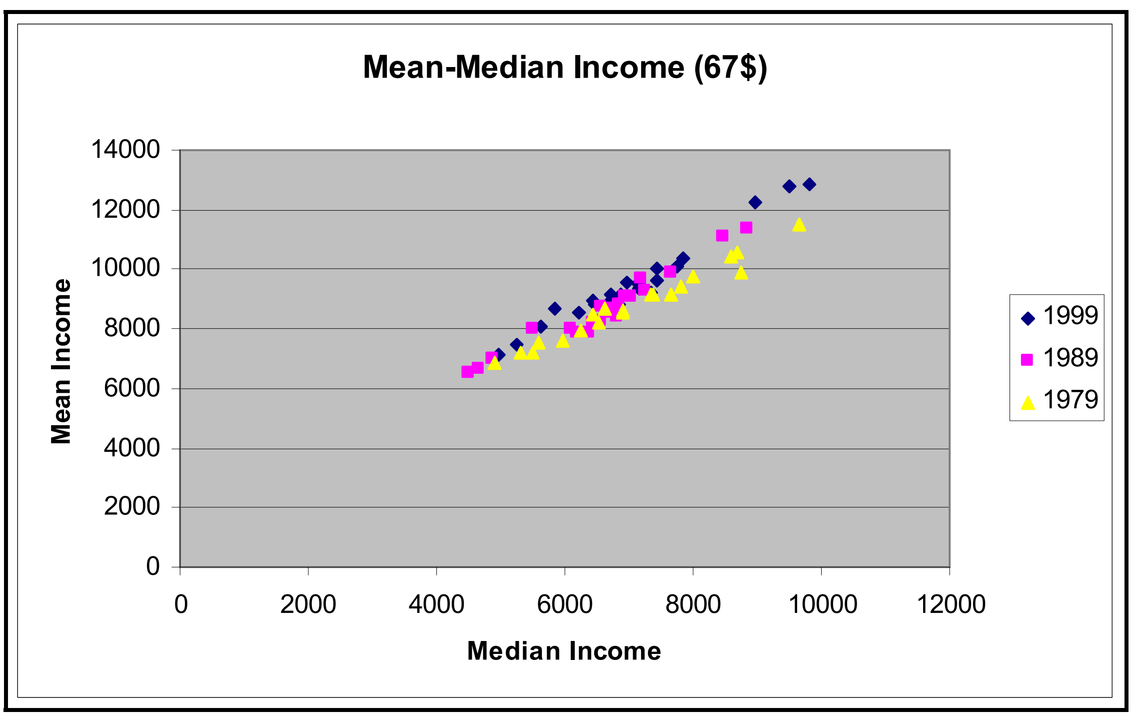


Figure 7. Mean vs. Median Income, MSAs 1979 – 1999

Table 8. Mean vs. Median Equations of Best Fit

Mean vs. Median Income (in 1967 dollars)					
	y =	m * x	+	b	r-squared
1999		1.1888		1106.12	0.960527
1989		1.0976		1373.29	0.940707
1979		0.9477		2127.87	0.975107
All Years		1.0839		1511.85	0.911132

The implications of this trend are not as easily grasped. The equations demonstrate that for a constant median income, mean income is rising over time, or that as median income increases at a constant rate, mean income increases at an increasingly greater rate over time. What this implies is that the proportion of aggregate income held by the top half of households is increasing; i.e. the rich are getting richer faster and proportionally more than the poor.

Although the societal implications of this trend are vitally important to study and observe, this trend may be used to better predict mean income from median income for use in the default models. Slope vs. year and intercept vs. year were plotted, and a second-order polynomial was fit to each of the data point sets (base year zero was set to 2000). The following show the resultant equations, and relevant extrema:

Slope $m(x) = \left(-2.9401 \cdot 10^{-4}\right) \cdot x^2 + \left(5.5868 \cdot 10^{-3}\right) \cdot x + 1.1946$ Max = 1.2212 at 9.50 (2009),

Intercept $b(x) = (2.4371) \cdot x^2 + (2.5281) \cdot x + 1106.21$ Min = 1105.55 at -0.52 (1999).

Perhaps these equations, accompanied by frequent attention to their validity, could be used to estimate mean income from median income. Sample median incomes were input and these equations projected the mean income in 2009 and 2019; in each income category over $5000 (the levels that normally appear) projected mean income increased slightly over time. This would be consistent with the observed trend continuing in the future.

Because one of the largest problems with the model was the underestimation of mean income, the default model was tested to see if errors in distributions were more the result of inaccurate predictions of mean income, or of the gamma distribution failing to adequately distribute households by income. Using the known model equation relating mean income to median income, an adjusted median income was input into the model that would produce the true observed mean income, and estimated distributions were obtained for all MSAs in 2000. Interestingly, these estimated distributions resulted in considerably poorer r^2 values when compared to the observed distributions. This makes intuitive sense, because a higher mean income shifts the gamma distribution to the right, where the default model was already overestimating. The implication of this is that the gamma distribution is not a perfect description of the distribution of households by income, but it works fairly well. Perhaps the resultant distributions could be adjusted in some way to improve estimation.

A possible improvement to the income default model comes as a result of the underestimation phenomenon observed at the extremes (first and last bins) of the distribution. By adjusting both the first and upper income intervals, and therefore taking away from the other overestimated intervals, it is hoped that the distribution will improve. The percentage of households in the first income range was plotted against median income (in 1967 dollars) for combined 1999 and 1989 data (converted to 1967 intervals), and a regression was performed, as shown in Figure 8. The resultant equation (listed below) was then used to estimate a new percentage of households in this first income bin. While this first bin was held steady, the other income intervals were adjusted to keep the overall distribution equal to 1. At the same time, the highest income range was adjusted to make the overall distributionally-estimated mean income equal to the mean income as estimated from median income. This mean income fitted to the distribution was previously decreased according to the equation below, because this entire process takes place in 1967 income intervals, and when those intervals are converted to current dollars, the estimated mean income of the distribution increases slightly. The final resultant distributions sum to 1, have the first income range values according to the equation, and (when converted to current dollars) produce mean incomes equal to those estimated.

$$\text{\% HHs in first 1967 income interval} = 46701.4149 \cdot (MedInc67)^{-1.5321} \qquad r^2 = 0.8238$$

$$\text{MeanInc67 to Fit Distribution} = 0.9298 \cdot (MeanInc67) + 389.95 \qquad r^2 = 0.9981$$

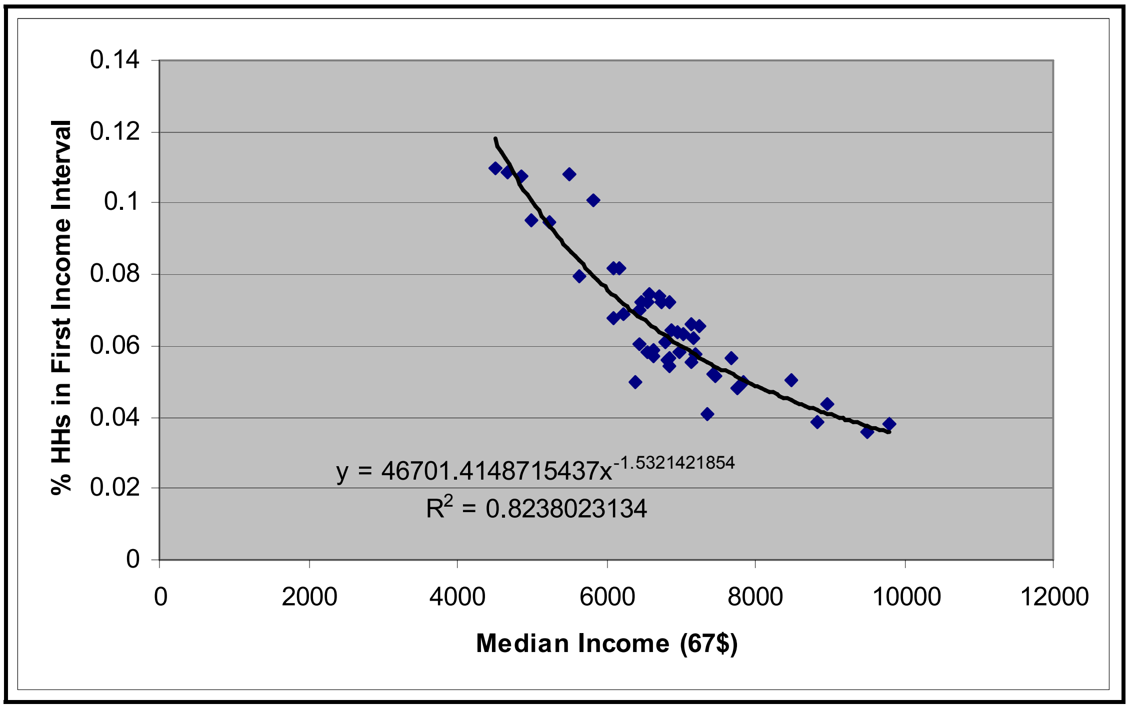


Figure 8. Percentage in First vs. Median Income, MSAs 1989 – 1999

Verification

The estimated distribution adjustment method was tested for each MSA in 2000, and the resultant new estimated distribution compared with the observed distribution. Table 9 displays the results of this evaluation, and example distributions are shown in Figure 9. Almost all MSAs (83%) showed an (albeit slight) improvement to their distributions, bringing most MSAs above an r^2 value of 0.90. Particularly impressive were the large improvements in those three previously-poor-fitting MSAs to at least the middle 0.80s. Of the four MSAs that did not improve, only one decreased more than slightly (Killeen – Temple); the reason for this is that the initial estimated distributions better predicted the value in the first bin than the estimated equation. All other MSAs were able to improve their distributions because this underestimation was eliminated and overestimations elsewhere in the distribution were resultantly lessoned. In addition, the estimation of mean income is much better than the current default models (r^2 = 0.9568 vs. 0.6143). This is a very significant improvement over the current default models, in both distributional fit and estimated mean income, and therefore these equations and methodology are recommended for revision of the default models.

Table 9. Income Distribution Verification Results

Geographic Name (in 2000) 1999	Mean Income (99$) Obs	Est DM	Est Adj	r-squared DM	Est-Adj
Abilene, TX MSA	44914	42147	46376	0.9444	0.9512
Amarillo, TX MSA	47756	43857	48319	0.9204	0.9884
Austin--San Marcos, TX MSA	64094	57654	63880	0.5149	0.8842
Beaumont--Port Arthur, TX MSA	46701	43846	48306	0.8253	0.9608
Brownsville--Harlingen--San Benito, TX MSA	37115	33954	37026	0.9934	0.9949
Bryan--College Station, TX MSA	43279	37020	40529	0.8477	0.9121
Corpus Christi, TX MSA	47388	43954	48431	0.8567	0.9812
Dallas--Fort Worth, TX CMSA	63874	56062	62097	0.5361	0.9047
El Paso, TX MSA	42515	39045	42841	0.9797	0.9888
Houston--Galveston--Brazoria, TX CMSA	61115	53299	58998	0.3885	0.8397
Killeen--Temple, TX MSA	46061	44886	49485	0.9268	0.8751
Laredo, TX MSA	40467	35977	39337	0.9805	0.9745
Longview--Marshall, TX MSA	45580	42374	46634	0.9098	0.9866
Lubbock, TX MSA	44712	40237	44198	0.9408	0.9961
McAllen--Edinburg--Mission, TX MSA	35591	32611	35497	0.9781	0.9775
Odessa--Midland, TX MSA	47726	42915	47249	0.9011	0.9834
San Angelo, TX MSA	44156	41225	45334	0.9511	0.9581
San Antonio, TX MSA	51588	47455	52398	0.8070	0.9853
Sherman--Denison, TX MSA	48129	45415	50089	0.9022	0.9752
Texarkana, TX--Texarkana, AR MSA	43892	40279	44246	0.9289	0.9814
Tyler, TX MSA	49992	45384	50051	0.8496	0.9740
Victoria, TX MSA	50365	47031	51925	0.8639	0.9681
Waco, TX MSA	45523	41653	45803	0.8675	0.9787
Wichita Falls, TX MSA	44072	42213	46449	0.9404	0.9376
r-squared values		0.6143	0.9568		

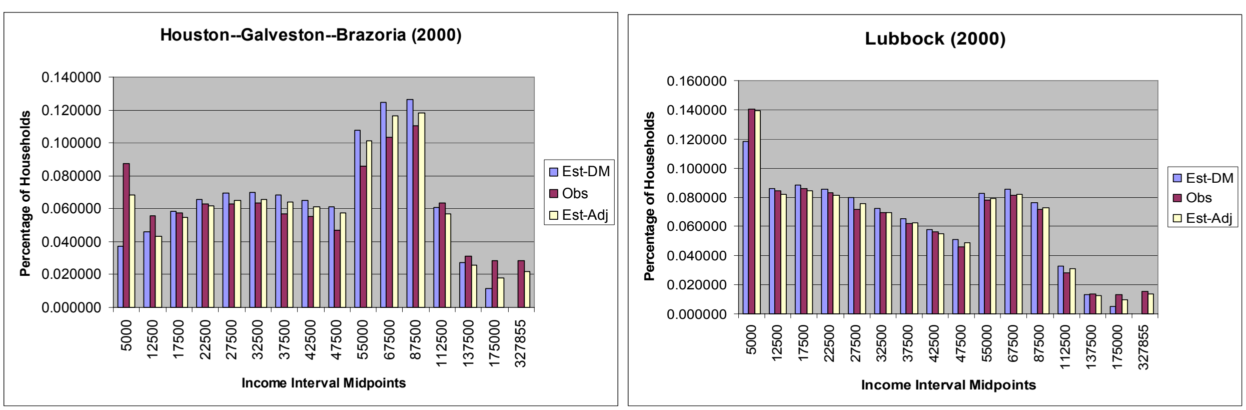


Figure 9. Example Distributions by Income

In order to further verify the performance of this revised income distribution model, it was tested against 2000 zonal data from Amarillo, the results of which are displayed in Table 10 and Figure 10. Although the distributions for each zone displayed a wide range of goodnesses of fit, overall the sum of the estimated weighted zonal distributions was somewhat close to that observed, with an r^2 of 0.7636. The estimated mean (obtained from the estimated distribution), however, is very high compared with that observed ($51,139 vs. $46,822). Surprisingly, when the current default model was applied to the same zonal data, it resulted in slightly better distributions (overall r^2 of 0.7805) and a much better estimated mean income ($47,806).

Table 10. Income Model Verification, 2000 Amarillo Zones

ENTIRE MSA DATA	MeanInc (from disb)	r-squared (distb)
observed sum zones	46822	
est sum zones	51139	0.7636
est default model	47806	0.7805
observed MSA	47756	
est default model	43857	0.9204
est revised	47933	0.9762

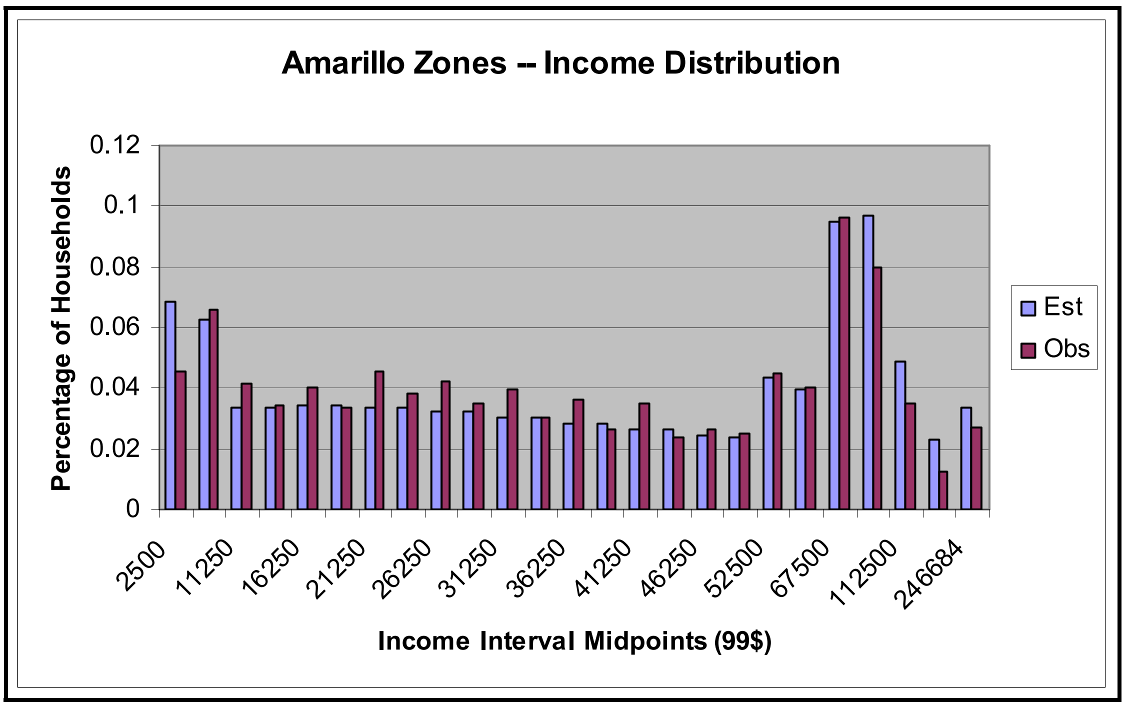


Figure 10. Distribution by Income, 2000 Amarillo Zones Overall

This result casts some doubt on the favorable revised default model. After analyzing the method and results, it is hypothesized that the reason for the better performance of the current default model is from the differences between the zonal characteristics of Amarillo and those observed for all MSAs. As can be seen in Figures 11 and 12, the overall relationship between mean and median income was slightly shallower for Amarillo zones than MSAs, and the percentage of households in the first income interval was in general less than that observed by MSAs. One cannot be sure if this surprising result is unique to Amarillo or would be found in other MSAs. Despite this result, because the default models must be able to perform well in many different situations around the state of Texas, they should provide adequate estimates and should not be expected to fit perfectly to an individual MSA. It is clear that the revised models perform better at the MSA level over a wider range of situations than the current default model. In order to make a similar determination for the zonal level, several more tests must be done of zonal data and compared; this extension unfortunately is beyond the time resources of this report, but should be undertaken before implementing the revised income default model.

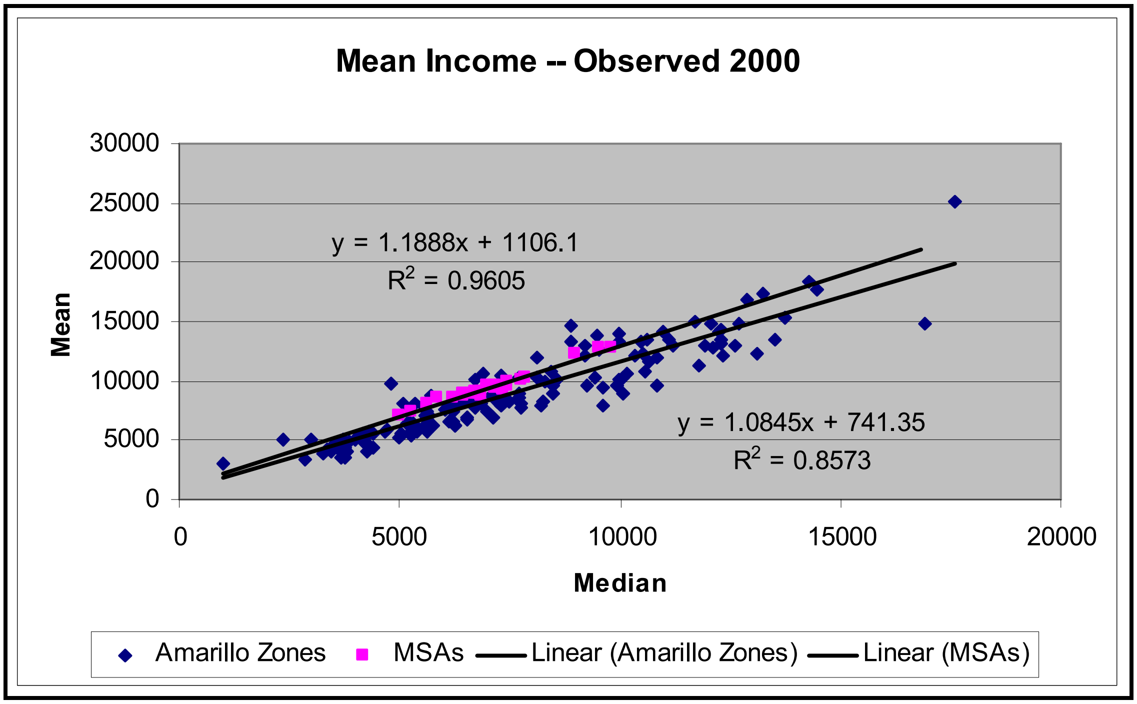


Figure 11. Mean Income, Comparison

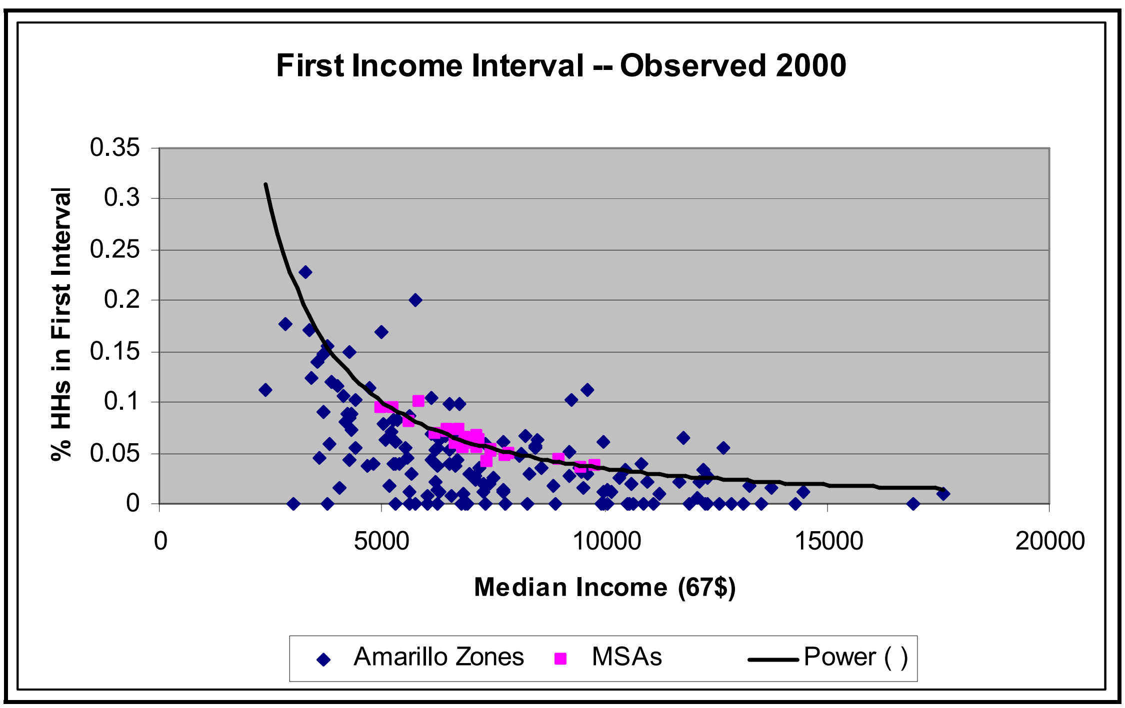


Figure 12. Percentage in First Income Interval, Comparison

Vehicle Availability

Historical Trends

The majority of MSAs in Texas had an average of between 1.60 and 1.80 vehicles per household in 2000, as shown in Table 11. Also, over time, the average vehicle availability is increasing, although slightly. In 1970, MSAs had an overall average of 1.41 vehicles, which increased to 1.79 in 1980. This number decreased to 1.68 in 1990, and increased slightly to 1.70 in 2000. The aggregate number of vehicles available continues to increase because of the continued increase in households.

Table 11. Average Vehicles per Household

Geographical MSA (name in 2000)	2000	1990	1980	1970
Abilene, TX MSA	1.692	1.743	1.851	1.414
Amarillo, TX MSA	1.735	1.741	1.883	1.538
Austin--San Marcos, TX MSA	1.732	1.660	1.780	1.441
Beaumont--Port Arthur, TX MSA	1.636	1.644	1.816	1.397
Brownsville--Harlingen--San Benito, TX MSA	1.543	1.443	1.588	1.161
Bryan--College Station, TX MSA	1.730	1.681	1.777	1.363
Corpus Christi, TX MSA	1.629	1.601		1.426
Dallas--Fort Worth, TX CMSA	1.734	1.747	1.844	1.484
El Paso, TX MSA	1.673	1.658	1.664	1.287
Houston--Galveston--Brazoria, TX CMSA	1.676	1.649	1.781	1.411
Killeen--Temple, TX MSA	1.716	1.648	1.725	1.321
Laredo, TX MSA	1.616	1.502	1.512	1.014
Longview--Marshall, TX MSA	1.736	1.696	1.883	1.294
Lubbock, TX MSA	1.666	1.719	1.863	1.499
McAllen--Edinburg--Mission, TX MSA	1.600	1.499	1.610	1.204
Odessa--Midland, TX MSA	1.698	1.740	1.952	1.644
San Angelo, TX MSA	1.671	1.713	1.870	1.421
San Antonio, TX MSA	1.667	1.635	1.713	1.339
Sherman--Denison, TX MSA	1.804	1.773		1.269
Texarkana, TX--Texarkana, AR MSA	1.672	1.722		1.215
Tyler, TX MSA	1.749	1.768	1.873	1.344
Victoria, TX MSA	1.729	1.718		1.467
Waco, TX MSA	1.679	1.730	1.781	1.396
Wichita Falls, TX MSA	1.733	1.723	1.792	1.352
ALL MSAs Combined	1.696	1.680	1.791	1.411

No very clear trend in the distribution of vehicles appeared, but there are several general trends noticeable in Figure 13. For households with no vehicles, the percentage generally decreased as vehicles per household increased. A similar trend was noted for one vehicle. Two vehicle households generally increased as vehicles per household increased, as did three-or-more vehicle households.

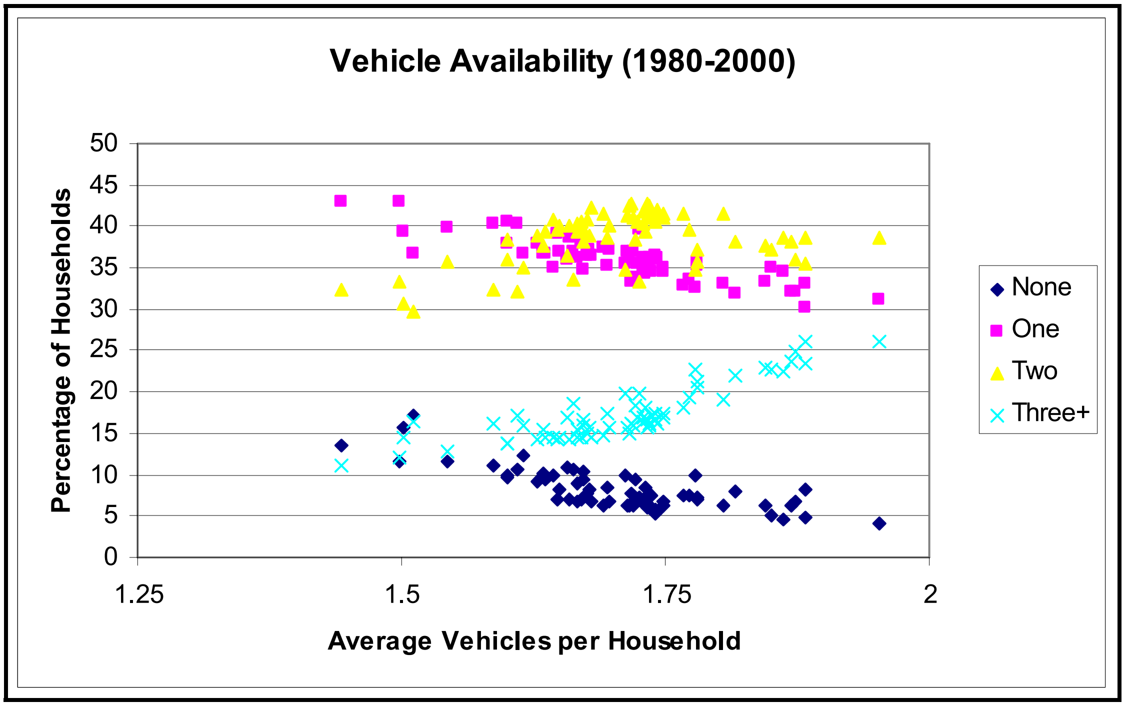


Figure 13. Vehicle Availability Categories

Default Model Evaluation

The default model that estimates distributions of households by vehicle availability, Auto.exe, is the most complicated of the models. Input into the model are the CPI value for the year estimated (where 1.00 = 1967), median household income, number of households, and total population. The model first converts the median income to 1967 dollars, and estimates a mean income according to the specified linear equation, finally converting the estimated mean back to 1980 dollars. Using the inputs, an estimated household size is also obtained; these values produce an estimated per capita income. Finally, an initial estimate of autos per household (APH) is calculated using the estimated household size and the natural log of the estimated per capita income.

At this point, the vehicle default model utilizes the methodology of the income default model; to obtain an initial income distribution, it uses the gamma distribution function, with alpha equal to beta, and alpha linearly related to the estimated mean income. This iterative process is continued until the distribution mean is within 1% of the estimated mean. The reason for first distributing households by income is because the model uses a built-in cross-classification table, showing relative distributions of households by vehicle availability in each 1967 income interval. For each income interval, an estimate of average vehicles per household is then calculated and proportionally aggregated over all the ranges to obtain the total vehicles for the zone; the output of average vehicles per household for the area uses this number divided by the total number of households. In addition, these partial distributions of households by vehicles in each income interval are also aggregated to obtain an initial distribution of households by vehicle availability.

Next, the model adjusts the initial distribution to fit the estimate of vehicles per household, according to a prescribed method. This method maintains the relative proportions of households on each side of the average, and only shifts households from one side to the other. Finally, a distribution of households by vehicle availability that matches the estimated vehicles per household is obtained and output.

Estimated distributions of households by vehicles and estimates of average vehicles per household were calculated for each MSA in 2000, 1990, and 1980. 1970 data were not tested because median income was not available for that year. Values of r^2 were calculated comparing estimated to observed distributions for each MSA in each of the three years, and also comparing the value for vehicles per household in each year. Figure 14 shows that the default model dramatically underestimates vehicles per household in all cases. As a result, any comparison of distributions is essentially meaningless, except to confirm that the model is performing very poorly.

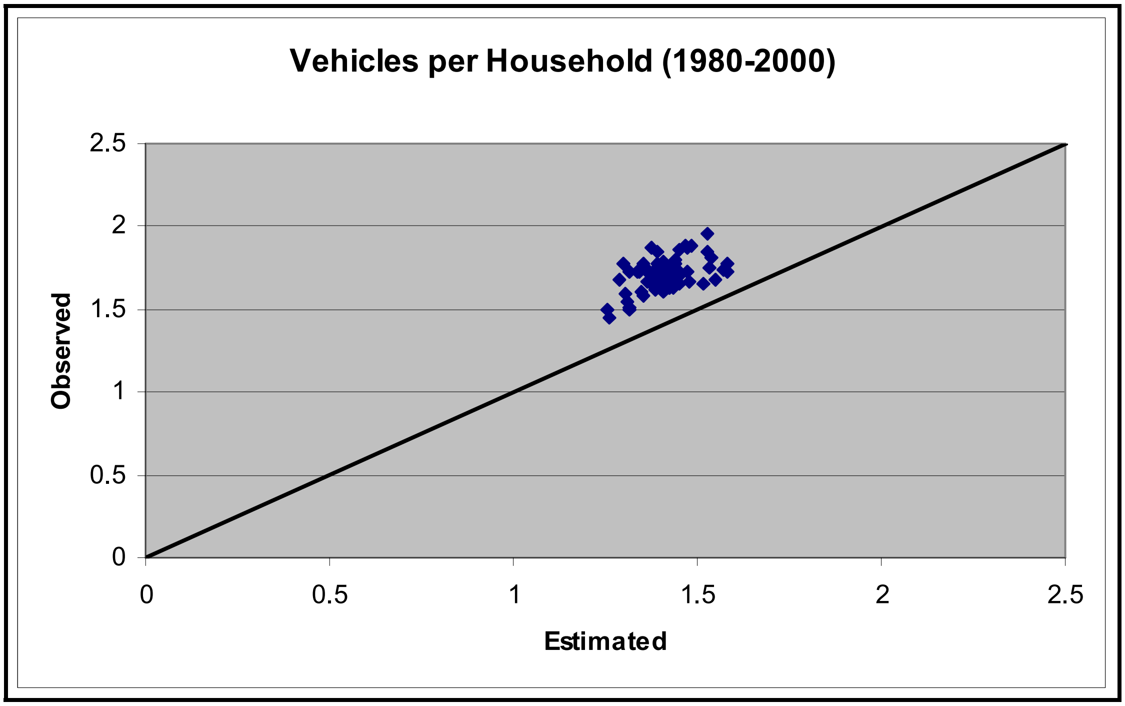


Figure 14. Vehicles per Household, Estimated vs. Observed

Default Model Revision

The first step to improving the default model was to more accurately predict a value for vehicles per household. In the model, the initial calculation of vehicles per household (from median/mean income and approximate household size) is actually not used as either the output value or to calculate distributions. During the revision process, it was decided that a similar initial calculation should at least be used to estimate distributions.

A review of several other vehicle availability models in use around the country (*10*) demonstrated that the most common independent variables used to estimate vehicle availability are natural log of household income and household size, with other less significant variables relating to employment or workers, accessibility, and the pedestrian environment sometimes used. Vehicles per household (VpHH) was plotted against both median income and household size, and although no trends were discernable for household size, as median income increased, average vehicles per household tended to increase as well, as shown in Figure 15. A logarithmic regression was performed to obtain the line of best fit:

$$VpHH = 0.3537 \cdot \ln(medinc67) - 1.4115 \qquad r^2 = 0.3858$$

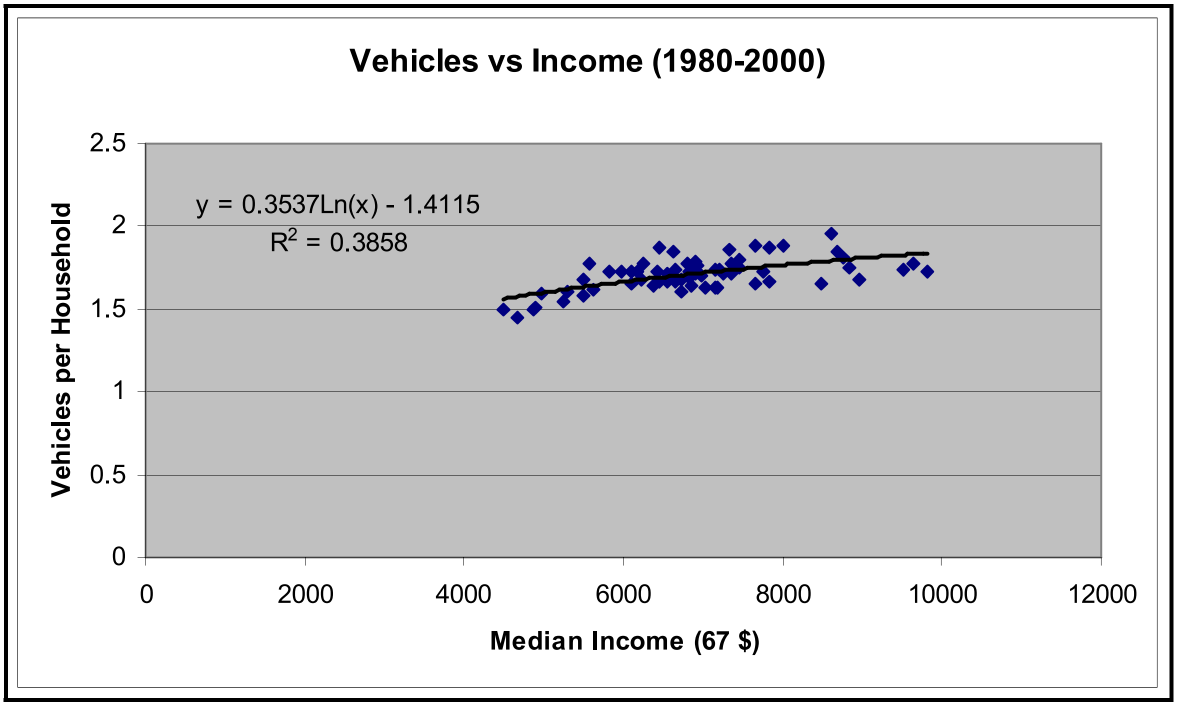


Figure 15. Estimation of Vehicles per Household

What was needed now was a method to distribute households by vehicle availability based on this estimate of vehicles per household. Each category was plotted against different variables, such as vehicles per household, VpHH normalized, and median income. The most distinct trends appeared under a special normalized scenario in Figure 16, where the value of each vehicle category (0, 1, 2, 3.3) was divided by each MSA's average vehicles per household. Because 1980 and 1970 data showed slightly different trends than the 1990 and 2000 data, two regression sets were done, one including data from all years and one with only 1990 and 2000 data, the results of which are displayed below.

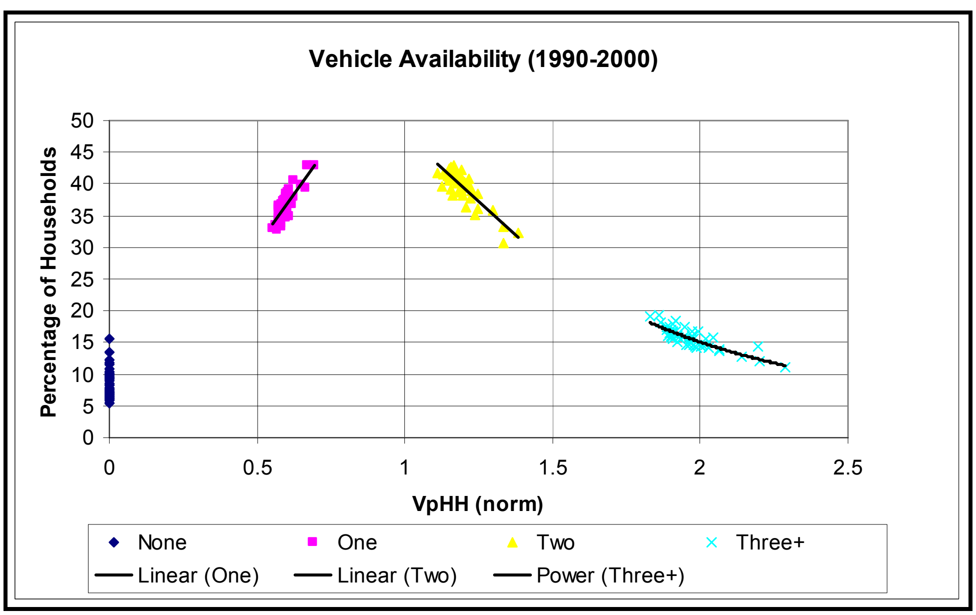


Figure 16. Distribution by Vehicle Category

	All Years Included	r^2	1990-2000 Only	r^2
One	$p_1(x) = 63.10 \cdot x - 0.593$	0.8287	$p_1(x) = 66.26 \cdot x - 2.985$	0.6984
Two	$p_2(x) = -21.46 \cdot x + 63.92$	0.6206	$p_2(x) = -41.53 \cdot x + 89.14$	0.7374
Three+	$p_3(x) = 179.0 \cdot x^{-3.600}$	0.9303	$p_3(x) = 64.79 \cdot x^{-2.104}$	0.7376
Zero	$p_0(x) = 100 - p_1(x) - p_2(x) - p_3(x)$		$p_0(x) = 100 - p_1(x) - p_2(x) - p_3(x)$	

where x = (vehicle category value) / (vehicles per household for MSA)

Verification

These possible improvements to the default model were tested using median income (converted to 1967 dollars) for each MSA in 2000, 1990, and 1980 (1970 data did not have median income information). The results of the 90-00 equations are displayed in Table 12. In addition, estimated values of VpHH are all relatively close to observed values, although with wide variations; 1980 values tend to be underestimated by the model. Despite the fairly low values of r^2, these estimates of vehicles per household are very significantly better than those currently obtained from the TRIPCAL5 default models.

Table 12. Vehicle Model Verification, 2000 MSAs

2000	Vehicles per Household			90-00
Geographical Name (in 2000)	Obs	Init. Est	Distb. est	r-squared
Abilene, TX MSA	1.692	1.711	1.706	0.9910
Amarillo, TX MSA	1.735	1.728	1.723	0.9973
Austin--San Marcos, TX MSA	1.732	1.840	1.836	0.9739
Beaumont--Port Arthur, TX MSA	1.636	1.728	1.723	0.9786
Brownsville--Harlingen--San Benito, TX MSA	1.543	1.618	1.613	0.9799
Bryan--College Station, TX MSA	1.730	1.656	1.651	0.9863
Corpus Christi, TX MSA	1.629	1.729	1.724	0.9694
Dallas--Fort Worth, TX CMSA	1.734	1.828	1.824	0.9793
El Paso, TX MSA	1.673	1.679	1.674	0.9800
Houston--Galveston--Brazoria, TX CMSA	1.676	1.808	1.804	0.9575
Killeen--Temple, TX MSA	1.716	1.738	1.733	0.9939
Laredo, TX MSA	1.616	1.643	1.638	0.9509
Longview--Marshall, TX MSA	1.736	1.713	1.709	0.9971
Lubbock, TX MSA	1.666	1.692	1.687	0.9896
McAllen--Edinburg--Mission, TX MSA	1.600	1.600	1.595	0.9914
Odessa--Midland, TX MSA	1.698	1.719	1.714	0.9952
San Angelo, TX MSA	1.671	1.702	1.697	0.9921
San Antonio, TX MSA	1.667	1.761	1.756	0.9699
Sherman--Denison, TX MSA	1.804	1.742	1.738	0.9878
Texarkana, TX--Texarkana, AR MSA	1.672	1.692	1.687	0.9930
Tyler, TX MSA	1.749	1.742	1.737	0.9992
Victoria, TX MSA	1.729	1.757	1.752	0.9985
Waco, TX MSA	1.679	1.706	1.701	0.9931
Wichita Falls, TX MSA	1.733	1.712	1.707	0.9987
r-squared		-0.1661	-0.0835	

These estimated values were then input into each of the distribution model schemes, and estimated distributions obtained and compared to observed distributions. The resultant r^2 values indicate an amazingly good fit in almost all cases, particularly in 2000. 1980 distribution estimates were further off than for 1990 and 2000, although still acceptable. The few cases where distributions had a poor fit were when vehicles per household was not well estimated (e.g. Bryan – College Station in 1980) or when an MSA had a significantly large portion of households with zero vehicles (e.g. Laredo). The scheme using only 1990 and 2000 data resulted in slightly worse fits for 1980 than the scheme using data from all years, as expected.

Before these distribution equations were deemed acceptable, it had to be determined if they accurately reproduce vehicles per household. A distribution should not be presented as accurate if it does not also predict an accurate value of vehicles per household. Estimates of vehicles per household were obtained from the distribution (using 3.3 as a value for 3+ vehicles, an average of what was observed), and compared to observed values, as shown in Figure 17. Values of r^2 indicated a somewhat less good fit than was initially estimated for 2000 and 1980, and very slightly better for 1990. Interestingly, the equations using only 1990 and 2000 data predicted vehicles per household better in each year than the model using all years' data. Because of this, these second equations are recommended for use in a revised default model.

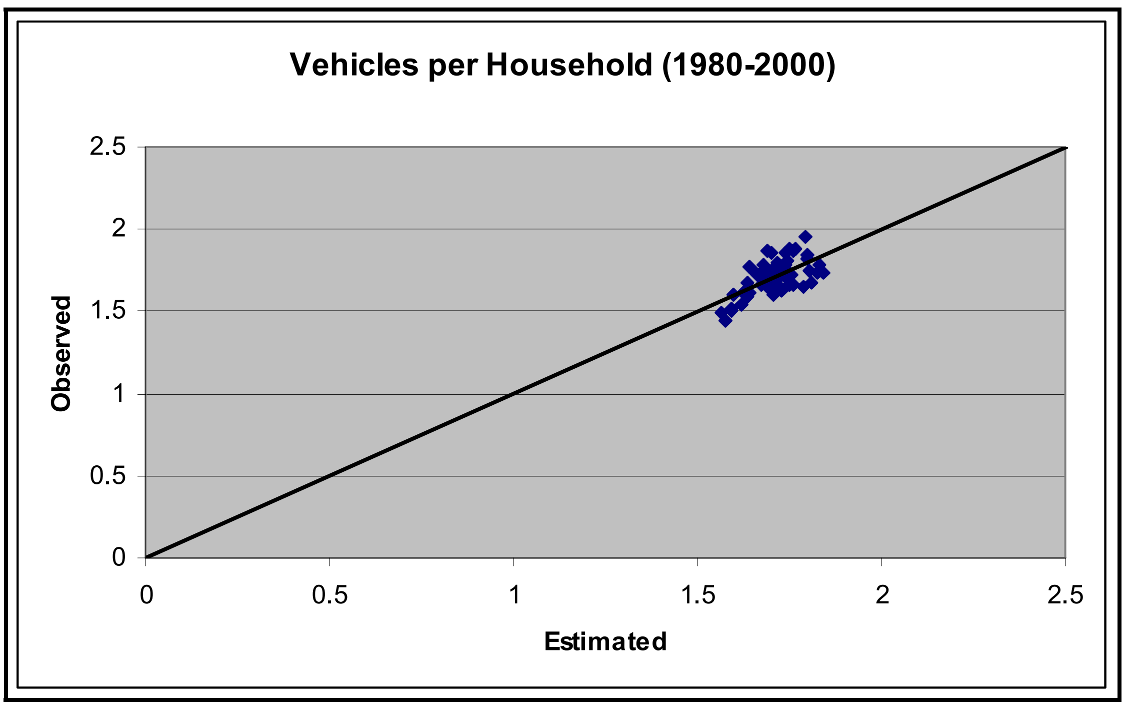


Figure 17. Vehicles per Household, Estimated vs. Observed

These equations to estimate vehicles per household and related distributions show dramatic improvement over the default model currently in use. It should be noted, though, that because some of these are linear equations, they have limited use. Below 0.70 VpHH, the models fail to estimate a valid distribution by predicting a negative number; this low value is obtained generally only in the very center of large urban areas, but at these low values the model highly underestimates the percentage of households with zero vehicles. More significantly, the model also obtains negative numbers above 1.9 vehicles per household, a threshold that many MSAs are approaching and many zones are likely above. Important to remember, also, is that it is median income that estimates vehicles per household, and so areas like dense downtowns with much higher median incomes relative to vehicles available will be significantly misrepresented as being similar to more residential or suburban areas.

In order to further validate the revised vehicle availability model, it was tested against 2000 zonal data from Amarillo, the results of which are displayed in Table 13. The estimated distribution (obtained from a weighted sum of each zonal distribution) is fairly close to that observed. Overall, the estimated vehicles per household is very close to that observed, but when looking at the individual zones (as in Figure 18), it becomes clear that the model generally overestimates below 1.7 and underestimates above 1.7.

Table 13. Vehicle Model Verification Results, 2000 Amarillo Zones

ALL MSA DATA	Average VpHH	r-squared values	Distribution None	One	Two	Three+
obs sum distb	1.728		5.9406	36.2501	41.6731	16.1362
est sum from distb	1.723	0.9993	6.9059	35.5997	40.7685	16.7258
obs from MSA	1.735	1.0000	6.0354	36.3085	41.5695	16.0866
est default model	1.421	0.9244	10.3530	47.8170	33.0140	8.8170
est revised	1.723	0.9994	6.9624	35.3619	41.0666	16.6091

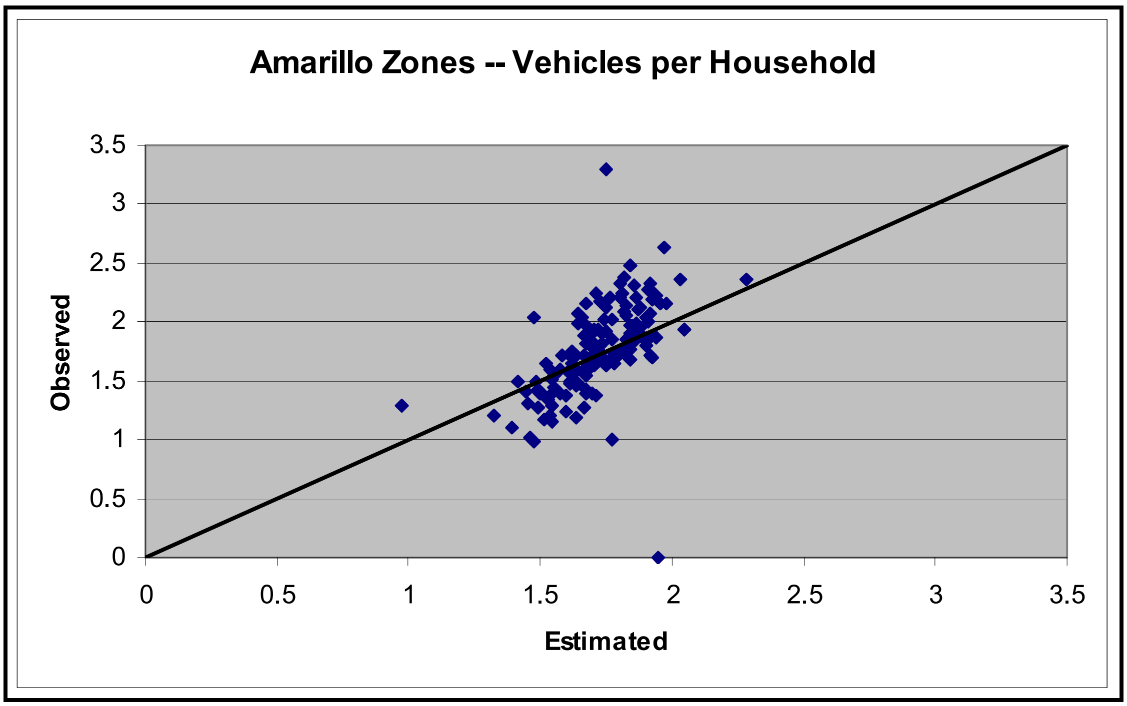


Figure 18. Vehicles per Household, Amarillo Zones

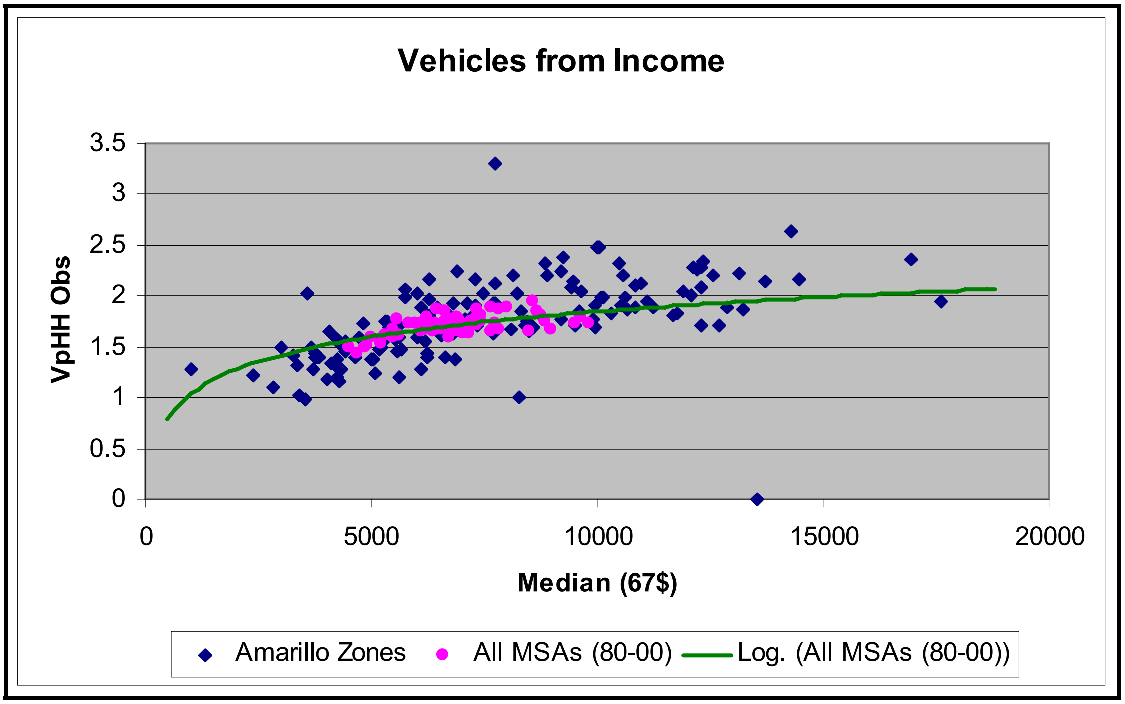


Figure 19. VpHH Estimation, Comparison

The reason for these inaccuracies is hypothesized to be the inadequate estimation of vehicles per household from median income, displayed in Figure 19. This conclusion is supported by Figure 20 showing vehicle categories by normalized VpHH. In all but One Vehicle, the equations derived from MSA data do a fairly good job at estimating the distribution percentages; maybe the one vehicle category should be adjusted to fit both the MSA and zonal data, but not without attempting other zonal data samples.

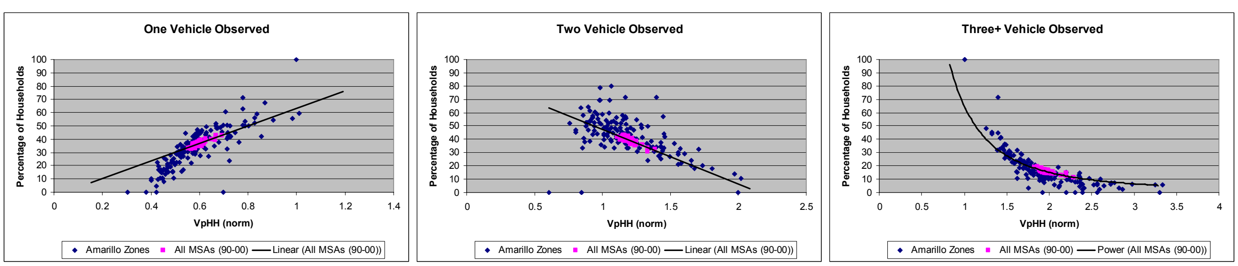


Figure 20. Vehicle Availability Categories, Comparison

Overall, the revised vehicle availability distribution model performs significantly better than the previous default model, and performs somewhat satisfactory as it now stands. A further study of a sample MSA's zonal data would significantly improve the model, particularly at its extremes. The addition of other variables to predict vehicles per household, particularly household size and employment density measures, would also be necessary to improve the estimation and widen the application of this model. Perhaps a further study could investigate the use of logit models to estimate vehicle distributions, which are commonly used today. Such extensions are beyond the time and resources of this research project, but are important for the reliability and future use of the model.

RECOMMENDATIONS

Developed and verified as documented above, the following revised default models are recommended for implementation into a new TRIPCAL trip generation program.

Household Size

- Input average household size
- Estimate initial distribution using regression equations:
  - $p_1(x) = 132.4126 \cdot x^{-1.7604}$
  - $p_2(x) = 1.6496 \cdot x^2 - 20.6317 \cdot x + 74.9363$
  - $p_3(x) = -4.2216 \cdot x^2 + 25.5940 \cdot x - 20.7216$
  - $p_4(x) = -5.0971 \cdot x^2 + 34.6638 \cdot x - 40.7680$
  - $p_{5+}(x) = 2.3131 \cdot x^2 4.4586 \cdot x - 16.5452$
    - where $x =$ average household size
- Adjust distribution by ratio of 100/sum.

Household Income

- Retain existing default model.
- Input median income and CPI (relative to 1967), obtain initial distribution.
- Calculate estimated mean income from median income according to time-dependent equations:
  - $m(x) = \left(-2.9401 \cdot 10^{-4}\right) \cdot x^2 + \left(5.5868 \cdot 10^{-3}\right) \cdot x + 1.1946$
  - $b(x) = (2.4371) \cdot x^2 + (2.5281) \cdot x + 1106.21$
  - $MeanInc67 = m(x) \cdot MedInc67 + b(x)$
    - where $x = 2000 - Year$
- Adjust estimated mean (so that it equals itself after converting to current dollars):
  - $fitMean67 = 0.9298 \cdot MeanInc67 + 389.95$
- Calculate estimated first income interval:
  - $\%First = 46701.4149 \cdot (MedInc67)^{-1.5321}$
- Adjust highest income interval to fit adjusted estimated mean income, while adjusting other values to maintain a distribution equal to 1.
- Convert income intervals to current dollar intervals (if necessary).

Vehicle Availability

- Input median income and CPI.
- Calculate estimated average vehicles per household:
  - $VpHH = 0.35373 \cdot \ln(MedInc67) - 1.4115$
- Divide vehicle category values (0, 1, 2, and 3.3) by estimated average vehicles per household and input into corresponding regression equations:
  - $p_1(x) = 66.2586 \cdot x - 2.9854$
  - $p_2(x) = -41.5323 \cdot x + 89.1404$
  - $p_{3+}(x) = 64.7950 \cdot x^{-2.1038}$

- $p_0(x) = 100 - p_1(x) - p_2(x) - p_3(x)$
  - where x = category value / VpHH
- Use estimated distribution to calculate final estimated average vehicles per household.

CONCLUSION

The estimation of distributions of households by household size, household income, and vehicle availability is a single task within the larger trip generation and travel demand modeling structures, but the accuracy of these estimates is vital to the usefulness and applicability of the entire process. By gathering Census data and comparing the observed values to those obtained from the TRIPCAL5 default models, it became clear that although the models performed decently in some cases, changes could be made that would significantly improve the results. The resultant revised default models now require overall simpler and fewer inputs and produce better and more accurate results. Despite this positivism, specific limitations do arise.

Replacing the gamma distribution function basis for the household size and vehicle availability models provides both improved results and eliminates the theoretical problem with using a continuous distribution to model discrete categories. But the use of regression equations introduces certain new problems. For example, the three-person household size equation produces negative values above 5.1 persons per household. Of course, such extreme values are rarely found even at the zonal level and are very difficult to predict when encountered; only an extensive and time-consuming data collection process would yield enough data to develop overall trends for these extreme data. Also, these regression equations assume the future continuation of the historic trends used in their development, an assumption that is the most valid practically, but which should continue to be investigated in the future in a process similar to the first portion of this report. In addition, future improvements to the default models should investigate including more variables into the estimation of average vehicles per household, and testing the revised income distribution model against more zonal data.

Just as these revised default models should by no means be taken as final, so should they be not be blindly applied. A satisfactory default model should apply well to all geographic areas around the State of Texas, because of the assumed inherent similarities in human characteristics, but cannot be expected to produce results as good as a locally-developed model. It should be emphasized that the use of default models should be a lower priority than developing localized distributions, should be tempered with some local validation of results, and should not be used in areas or for values where it does not satisfactorily perform, as documented in this report. In fact, this report may provide inspiration for methods to develop local models. Overall, the documented revisions to the TRIPCAL5 default models are a significant improvement to the default models currently in place and produce more accurate and reliable results.

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APPENDIX A

2000	1990	1980	1970
Abilene, TX MSA	Abilene, TX MSA	Abilene, TX SMSA	Abilene, TX SMSA
Amarillo, TX MSA	Amarillo, TX MSA	Amarillo, TX SMSA	Amarillo, TX SMSA
Austin--San Marcos, TX MSA	Austin, TX MSA	Austin, TX SMSA	Austin, TX SMSA
Beaumont--Port Arthur, TX MSA	Beaumont--Port Arthur, TX MSA	Beaumont--Port Arthur--Orange, TX SMSA	Beaumont--Port Arthur--Orange, TX SMSA
Brownsville--Harlingen--San Benito, TX MSA	Brownsville--Harlingen, TX MSA	Brownsville--Harlingen--San Benito, TX SMSA	Brownsville--Harlingen--San Benito, TX SMSA
Bryan--College Station, TX MSA	Bryan--College Station, TX MSA	Bryan--College Station, TX SMSA	Bryan--College Station, TX SMSA
Corpus Christi, TX MSA	Corpus Christi, TX MSA	Corpus Christi, TX SMSA	Corpus Christi, TX SMSA
Dallas--Fort Worth, TX CMSA	Dallas--Fort Worth, TX CMSA	Dallas--Fort Worth, TX SMSA	
Dallas, TX PMSA	Dallas, TX PMSA	Collin, Dallas, Denton, Ellis, Kaufman, & Rockwall Counties, TX	Dallas, TX SMSA
Fort Worth--Arlington, TX PMSA	Fort Worth--Arlington, TX PMSA	Hood, Johnson, Parker, Tarrant, & Wise Counties, TX	Fort Worth, TX SMSA
El Paso, TX MSA	El Paso, TX MSA	El Paso, TX SMSA	El Paso, TX SMSA
Houston--Galveston--Brazoria, TX CMSA	Houston--Galveston--Brazoria, TX CMSA	Houston--Galveston, TX SCSA	
Brazoria, TX PMSA	Brazoria, TX PMSA	Brazoria County, TX	Brazoria County, TX
Galveston--Texas City, TX PMSA	Galveston--Texas City, TX PMSA	Galveston--Texas City, TX SMSA	Galveston--Texas City, TX SMSA
Houston, TX PMSA	Houston, TX PMSA	Houston, TX SMSA (includes Brazoria County)	Houston, TX SMSA (includes Brazoria County)
Killeen--Temple, TX MSA	Killeen--Temple, TX MSA	Killeen--Temple, TX SMSA	Bell & Coryell Counties, TX
Laredo, TX MSA	Laredo, TX MSA	Laredo, TX SMSA	Laredo, TX SMSA
Longview--Marshall, TX MSA	Longview--Marshall, TX MSA	Longview--Marshall, TX SMSA	Gregg & Harrison Counties, TX
Lubbock, TX MSA	Lubbock, TX MSA	Lubbock, TX SMSA	Lubbock, TX SMSA
McAllen--Edinburg--Mission, TX MSA	McAllen--Edinburg--Mission, TX MSA	McAllen--Pharr--Edinburg, TX SMSA	McAllen--Pharr--Edinburg, TX SMSA
Odessa--Midland, TX MSA			
Midland County, TX	Midland, TX MSA	Midland, TX SMSA	Midland, TX SMSA
Ector County, TX	Odessa, TX MSA	Odessa, TX SMSA	Odessa, TX SMSA
San Angelo, TX MSA	San Angelo, TX MSA	San Angelo, TX SMSA	San Angelo, TX SMSA
San Antonio, TX MSA	San Antonio, TX MSA	San Antonio, TX SMSA	San Antonio, TX SMSA
Sherman--Denison, TX MSA	Sherman--Denison, TX MSA	Sherman--Denison, TX SMSA	Sherman--Denison, TX SMSA
Texarkana, TX--Texarkana, AR MSA	Texarkana, TX--Texarkana, AR MSA	Texarkana, TX--Texarkana, AR SMSA	Texarkana, TX--Texarkana, AR SMSA
Tyler, TX MSA	Tyler, TX MSA	Tyler, TX SMSA	Tyler, TX SMSA
Victoria, TX MSA	Victoria, TX MSA	Victoria, TX SMSA	Victoria County, TX
Waco, TX MSA	Waco, TX MSA	Waco, TX SMSA	Waco, TX SMSA
Wichita Falls, TX MSA	Wichita Falls, TX MSA	Wichita Falls, TX SMSA	Wichita Falls, TX SMSA

Table A1. Geographical Name Changes to MSAs, 1970 to 2000