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16. Abstract

The goal of this research project was to assess the effectiveness of the wide variety of frontage road–exit ramp and frontage road–U-turn yield treatments that exist in Texas. In meeting this goal, researchers collected field data at a number of sites around the state of Texas that represent the array of current yield treatments in practice. In order to assess the plethora of prevailing operating characteristics (i.e., variances in speeds, volumes, driveway densities, etc.), the research team utilized simulation modeling procedures to compensate for the impracticability of the data collection effort that would be required for every possible combination thereof. Several key operational and geometric features of each case study site were carefully collected and analyzed to produce a calibrated model for each case study condition.

Two levels of simulation analysis were used in this project. First, the research team developed a Level 1 procedure that involved selection of real-world sites for data collection, analysis, and simulation model calibration. After calibration of the model for each site, different yielding treatments were applied to each calibrated site. Comparisons were then made to determine if any one treatment performed better than the others. This procedure enabled researchers to look at some problematic sites that currently exist in the field and incorporate signal timing, current weaving patterns, speed and volume into the analysis. Since Level 1 analysis was limited to the geometric and traffic conditions at the selected sites, a Level 2 analysis was performed to consider the performance of various yield treatments on a wide variety of feasible scenarios/combinations of geometric and operating conditions.

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AN ASSESSMENT OF YIELD TREATMENTS AT FRONTAGE ROAD–EXIT RAMP AND FRONTAGE ROAD–U-TURN MERGE AREAS

by

Kwaku O. Obeng-Boampong, P.E.
Assistant Research Engineer
Texas Transportation Institute

Liang Ding
Assistant Transportation Researcher
Texas Transportation Institute

Russell H. Henk, P.E.
Senior Research Engineer
Texas Transportation Institute

James C. Williams, PhD, P.E.
Professor
University of Texas at Arlington

and

Phong T. Vo
Graduate Student
University of Texas at Arlington

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TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

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The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names may appear herein solely because they are considered essential to the object of this report.

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- Luis Ramirez, P.E.– (formerly with TxDOT Laredo District, who served as the PC until his retirement);
- Ismael Soto, P.E. – TxDOT Corpus Christi District;
- Scott Cunningham, P.E. – TxDOT Austin District;
- Pat Irwin, P.E. – Alamo Regional Mobility Authority (formerly with TxDOT San Antonio District – retired);
- Punar Bhatka – (formerly with TxDOT Traffic Operations Division); and
- Dustin Wiggins – TxDOT Traffic Operations Division.

Wade Odell, P.E., and Sandra Kaderka of TxDOT's Research and Technology Implementation Office were active participants in project management meetings.

TTI staff providing professional support included Gary Barricklow who was in charge of all the data collection activities and Bria Whitmire, student worker at TTI, who performed most of the data reduction work.

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CHAPTER 1. INTRODUCTION

BACKGROUND AND SIGNIFICANCE OF WORK

A very important element of traffic operations and safety within the freeway-frontage road interchange environment in Texas is that of yield treatments and related merging and weaving guidance. The current state-of-practice for such treatments in Texas varies widely and leads to operational inconsistency and driver confusion. To further understand the problem, a cursory review of relevant legislation and crash history pertaining to exit ramps and frontage roads was performed. In addition, previous studies on frontage road operations and the current guidelines for frontage road yield treatments were examined. Information on these topics is provided in the following sections.

Legislation

The main legislation that is concerned with the operation of the frontage road-exit ramp junction is found in Chapter 545 of the Texas Transportation Code. Specifically, §545.154 entitled "Vehicle Entering or Leaving Limited-Access or Controlled-Access Highway" states that "An operator on an access or feeder road of a limited-access or controlled-access highway shall yield the right of way to a vehicle entering or about to enter the access or feeder road from the highway or leaving or about to leave the access or feeder road to enter the highway" *(1)*. Essentially, this law requires all frontage road vehicles to yield to exiting vehicles regardless of the presence of a YIELD sign or any other traffic control device. Current field operations suggest that this law is not well understood by the motoring public.

Crash History

When a motorist fails to yield the proper right of way at a frontage road-exit ramp junction either by choice or due to miscomprehension, the end result is often a collision. Variables within the electronic crash database of Texas Department of Public Safety crash records can be used to attempt to isolate crashes occurring at exit ramp-frontage road intersections involving an exiting vehicle and a frontage road vehicle. A cursory assessment of the available data indicated that:

- 656 such crashes occurred in 1999,
- 548 such crashes occurred in 2000, and
- 581 such crashes occurred in 2001.

This preliminary assessment entailed only crashes where it was clearly stated that the collision took place between a vehicle from the exit ramp and the frontage road. Seldom do crash reports include the level of detail to make this assertion. In each year, approximately one-third of the accidents were reported to have occurred at locations where a YIELD sign was present.

Additional types of collisions are also expected at frontage road-exit ramp merge areas. Sideswipe collisions due to improper lane change or failure to yield the right of way often occur downstream of the actual junction. Rear-end collisions between frontage road vehicles also frequently occur when one frontage road vehicle chooses to slow dramatically or stop for an exiting vehicle but the following frontage road vehicle is unable to stop in time. In order to properly quantify the number of these types of crashes, a more detailed and updated crash record system would be key.

Previous Studies on Frontage Road Operations

Several previous studies have examined the frontage road-exit ramp merge areas as part of a larger effort to quantify frontage road level of service (LOS). In a 1988 Texas Transportation Institute study, Gattis, Messer, and Stover found that delays to frontage road vehicles yielding at an exit ramp increase as volumes on either the frontage road or exit ramp increase. In addition, the researchers identified the yielding maneuver to be complicated for drivers since the decision to yield (i.e., slow or stop) for an exiting vehicle has to be made based on the projection of the exiting vehicle's position relative to the frontage road vehicle's position at some point in the future. This projection is complicated by the fact that the exiting vehicle may or may not be changing speed and may or may not plan to immediately change lanes upon entering the frontage road *(2)*.

A TTI study in 1996 developed new criteria for fully characterizing the LOS of frontage roads and provided guidelines on exit and entrance ramp spacing. The study found that the LOS on the frontage road when one-sided weaving is present, such as an exit ramp followed closely by an entrance ramp (where weaving takes place typically with one lane change), is mainly based on the sum of the entering volumes from the frontage road and exiting volume. This finding is similar to that of previous studies. When examining two-sided weaving maneuvers, such as an exiting vehicle weaving all the way to the right lane (making two or more lane changes) in order to make a downstream right turn, density was found to be the controlling factor in determining the LOS. Furthermore, the study found that most drivers can complete the two-sided weaving maneuver within 360 feet of the exit ramp *(3)*.

A more recent study by TTI researchers Jacobson, Nowlin, and Henk examined the effect that driveways or intersections located close to the exit ramp have on the operations of the frontage road. Mathematical models were developed to determine the density within the weaving area on the frontage road between the exit ramp and the first driveway or intersection. These models were based on:

- the geometry of the frontage road,
- the exiting volume, and
- the frontage road volume.

A computer simulation was developed to analyze 1500 different geometric and volume combinations. Once this model was calibrated with field data, guidelines on appropriate spacing of driveways from exit ramps were developed *(4)*. These guidelines have subsequently been adopted into the Texas Department of Transportation *Roadway Design Manual* *(5)*.

U-turn lanes (or turnarounds) are fairly common in Texas but are infrequently found elsewhere. They provide an opportunity for drivers on the frontage road to connect directly to the frontage road running in the opposite direction on the other side of the freeway without having to pass through traffic signals at an intersection (diamond interchange).

Although little research has been conducted on U-turn lane operation, U-turn lanes share some of the operating characteristics of exit ramps. The U-turn lane enters the frontage road on the left, so the issue of weaving to nearby downstream driveways is the same, although U-turn traffic is typically lower than exit ramp traffic. Since the U-turn lane typically enters the frontage road immediately downstream from the diamond interchange, the issue of nearby downstream cross streets is not nearly as critical as it is for exit ramps.

Previous Studies on Yield and Gap Acceptance

"Critical gap" is the minimum time interval that a vehicle in the current lane takes to enter (accepted gap) between the traffic streams on the object lane (headway). A "rejected gap" is the time interval during which a subject vehicle fails to enter a main lane due to the main lane's vehicle obstacle flow.

Deterministic gap acceptance models are based mainly on capacity analysis and so are more focused on capacity analysis than on gap acceptance itself. Drew developed a regression method which uses merge angle and acceleration lane length *(6)*. An experimental equation is solved to determine the critical gap.

Other research has attempted to derive critical gap using gap distribution. This distribution uses logit or probit probability models and has the advantage of being detailed. However, it requires numerous variables and parameters and is time-consuming. Mahmassani and Sheffi used the probit model to estimate the mean and variance of critical gap at an uncontrolled intersection *(7)*. They noted that the model developed was affected by the number of gaps which are not critical gaps.

Wang performed a sensitivity analysis for gap acceptance data from different reference lines. The first reference line was on the major road and intended to record the arrival of the major road vehicles; the other one was placed on the minor road to reference the exact instant of the arrival and departure of the merging/crossing driver. He found that although different positioning of reference lines had little effect on the distribution of available gaps on the major road, it did affect the distribution and variance of accepted gaps to some degree. It was also shown that different positions of reference lines, on both major and minor roads, result in a difference in critical gap of about one second. Proper positioning of reference lines for a gap acceptance study was found to be critical in practice *(8)*.

Existing Guidance on Yield Treatments

Much of TxDOT's current policy regarding yield treatments on frontage roads stems from a 1988 memorandum to all district engineers from the Chief Engineer of Safety and Maintenance Operations *(9)*. The goal of the policy was to standardize the yield treatment applications throughout the state. In this memo, two alternatives for signing and marking exit ramp junctions with one-way frontage roads were presented.

The first alternative, which was identified as the preferred alternative, applies in situations in which the exiting traffic enters into their own lane on the frontage road. This can occur by adding an additional lane at the exit ramp (as shown in Figure 1) or by terminating a frontage road lane prior to the exit ramp merge (as shown in Figure 2). In both of these situations, double white line paint markings are provided for at least 80 feet beyond the painted gore. These markings are supplemented by the use of "DO NOT CROSS DOUBLE WHITE LINE" signs. In effect, this treatment encourages the gradual blending and merging of the frontage road and exit ramp traffic streams. A photograph where this type of treatment is used is shown in Figure 3. In this specific case, the option shown in Figure 2 is used to provide a separate lane for exiting traffic.

The second alternative for control of the frontage road-exit ramp junction consists of placing a YIELD sign with or without a supplemental TO RAMP plaque and a stop bar on the frontage road. This alternative, as illustrated in Figure 4, was developed mainly for those situations in which exiting vehicles do not have an exclusive lane on the frontage road. In effect, this treatment is a direct application of the law requiring frontage road vehicles to yield to exiting vehicles.

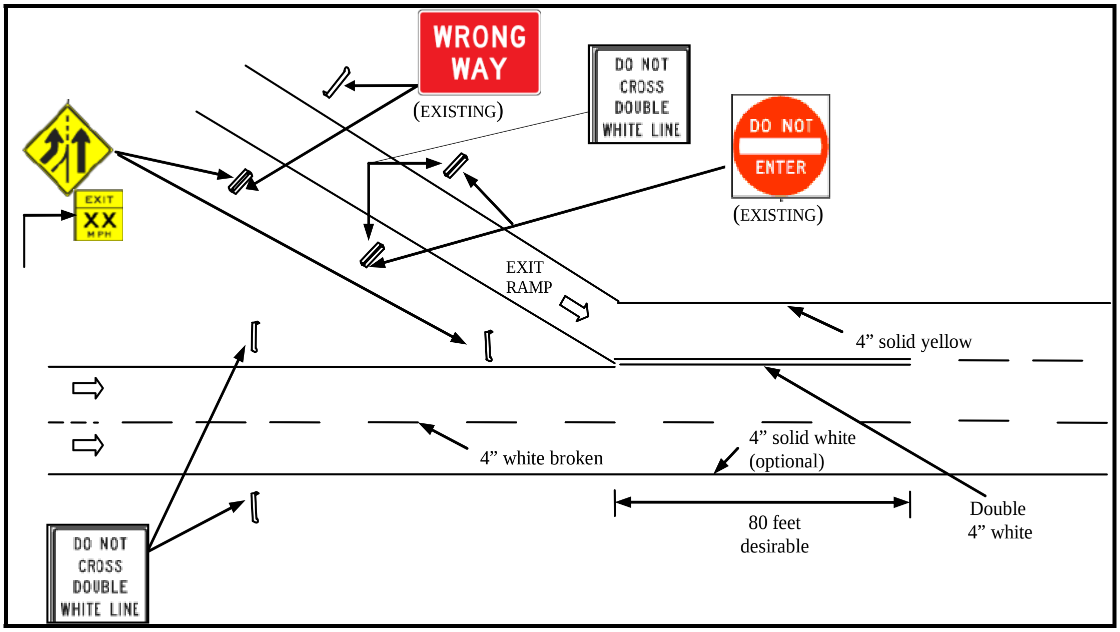


Figure 1. Preferred Exit Ramp Merge Treatment with Additional Lane Added (9).

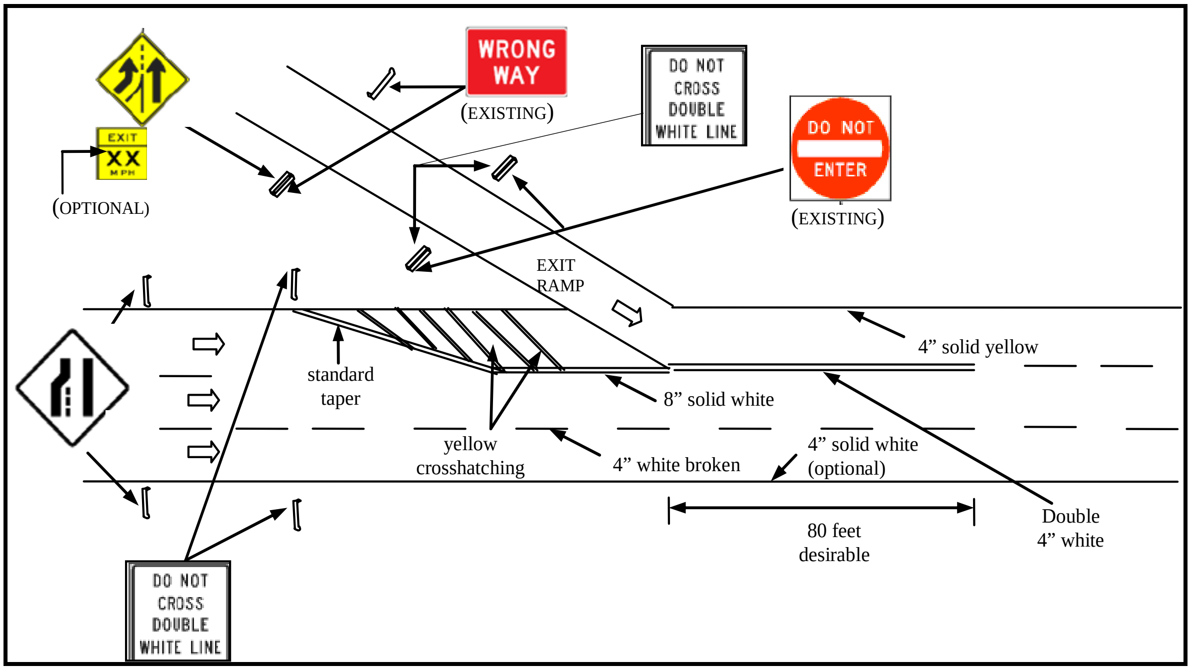


Figure 2. Preferred Exit Ramp Merge Treatment with Frontage Road Lane Terminated Prior to Exit Ramp (*9*).

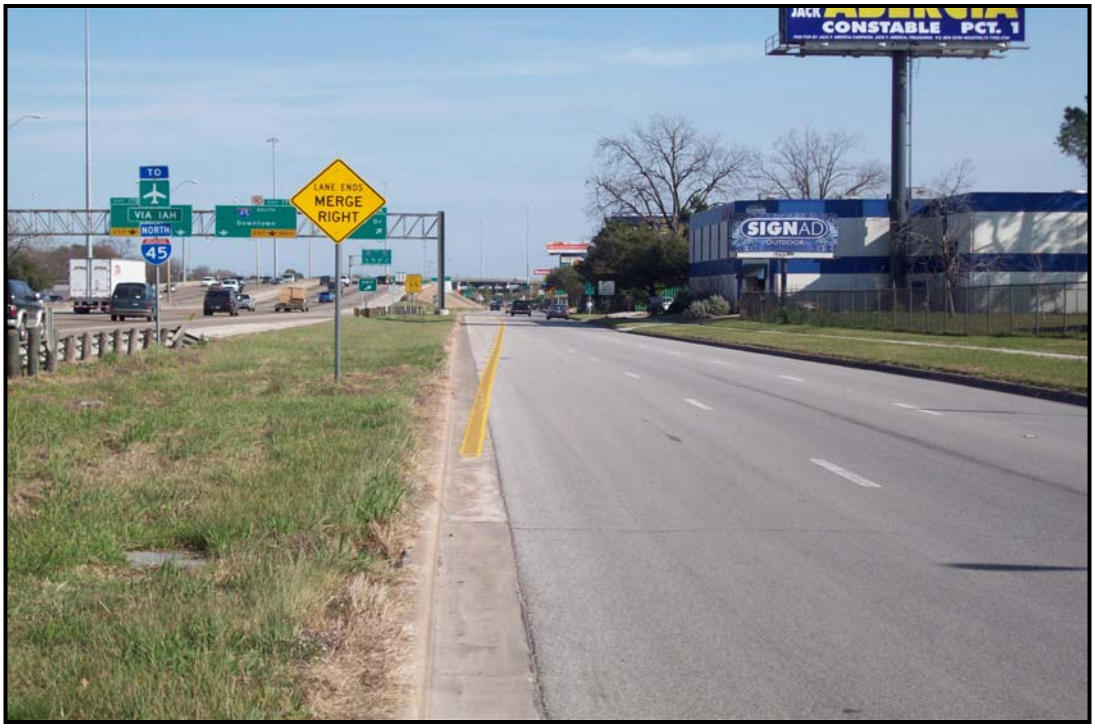


Figure 3. Example of Preferred Treatment with Frontage Road Lane Terminated Prior to Exit Ramp.

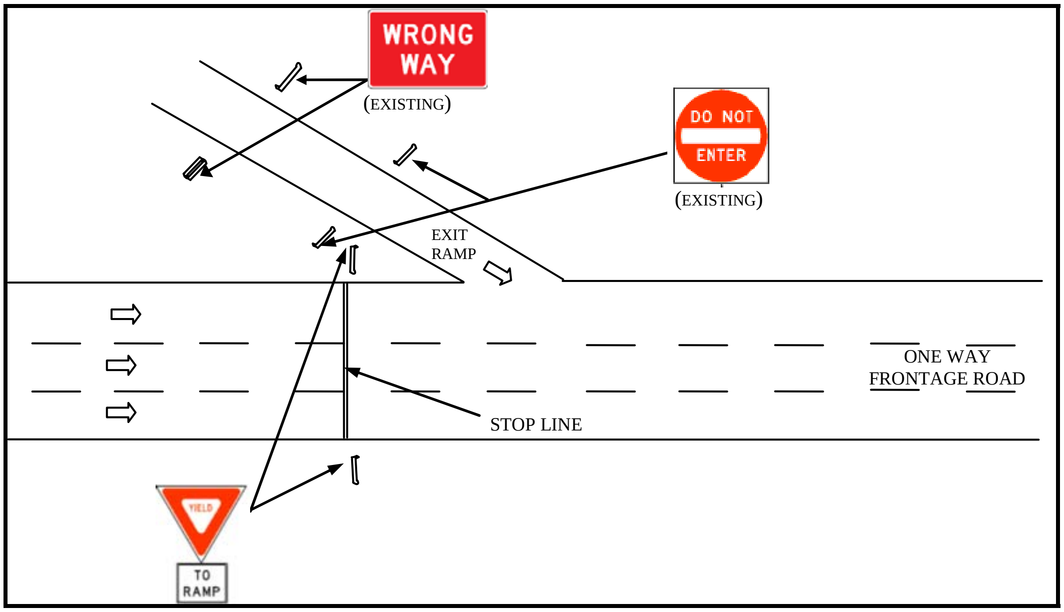


Figure 4. Alternative Exit Ramp Merge Treatment Used when No Exclusive Lane is Available for Exiting Traffic (9).

The previously presented guidelines have subsequently been included in the TxDOT *Traffic Operations Manual – Signs and Markings Volume*. In this document, guidance is provided that indicates that although the law requires frontage road vehicles to yield to exiting vehicles, a YIELD sign is not required where a free lane is available to off-ramp traffic *(10)*. Efforts to include these guidelines in the TxDOT Traffic Control Standard Sheets used by designers have also begun *(11)*. Finally, TxDOT research project 0-4170, Improved Signing for Urban Freeway Conditions, which was completed by the Texas Transportation Institute in 2003, includes similar guidelines in the *Freeway Signing Handbook*, which was published by TxDOT in 2008 *(12)*.

While the above guidelines provide details for the signing and markings required so that each application of a particular alternative is consistent, they have not prevented variations from occurring. Although the double white line alternative is listed as preferred, the engineer is allowed to use discretion when selecting which treatment to use. Guidelines taking into account distance to the nearest crossstreet, distance to the nearest driveway, ramp volumes, as well as other parameters may be needed to provide more uniformity in the merge treatments used throughout the state.

Examples of variations from the guidelines are readily available in the field. For example, both locations in Figure 5 consist of an exit ramp that flows into a short auxiliary lane on the two-lane frontage road. However, the application on the left is using the double white line alternative while the one on the right is using the YIELD alternative. Finally, the location in Figure 6 has a treatment in place that is actually a hybrid of the two previously discussed alternatives. At this location, a YIELD sign is present with a stop bar, but a double white line is also present.

Figure 5. Example of Variations of Merge Treatment Application with Short Auxiliary Lane Provision for Exiting Traffic.

Figure 6. Example of the Use of Both a YIELD Sign and a Double White Line.

Another new standard that has been incorporated into the latest *Texas Manual on Uniform Traffic Control Devices* is the use of "yield lines" instead of stop lines. These lines consist of a series of white triangles that point toward an approaching vehicle as shown in Figure 7. The main reason to use these yield lines is to emphasize that it *may not* be necessary to come to a complete stop *(13)*.

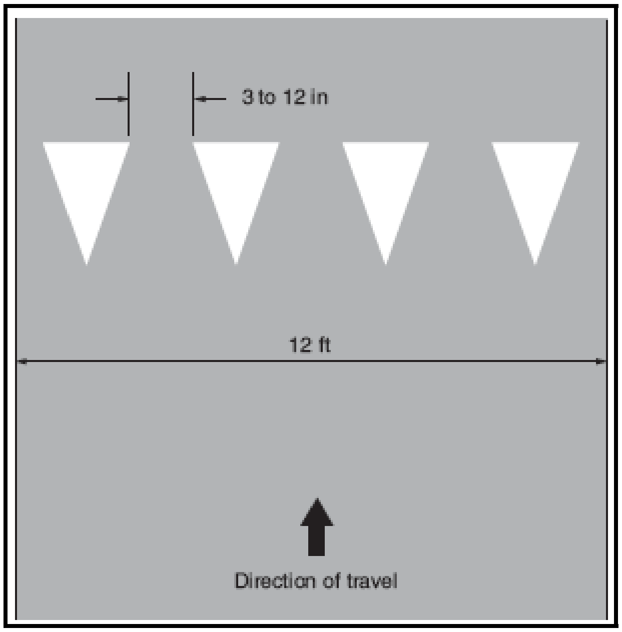


Figure 7. Example of a Yield Line Layout (*13*).

The use of yield lines (sometimes referred to as a "shark tooth" application) is relatively new throughout the United States, and these applications are only now beginning to appear in Texas (e.g., a recent deployment in Abilene). As such, knowledge of their effectiveness is currently very limited. One recent study examining the use of yield lines at mid-block crosswalk locations found that they were effective in reducing the number of vehicle incursions into the crosswalk when pedestrians were present *(14)*.

CHAPTER 2. DATA COLLECTION METHODOLOGY

Researchers collected data from two main sources and began the effort by focusing on an assessment of current frontage road--exit ramp yield treatments across the state of Texas. This first step involved the development of a survey sent out to various TxDOT districts. Then researchers focused on field studies, which included the selection of suitable sites and field data collection. Chapter 2 details both data collection efforts.

STATEWIDE SURVEY

Researchers conducted a statewide survey of TxDOT districts in January 2005 to determine the distribution of various frontage road-exit ramp yield treatments in the state of Texas. The survey was also designed to help provide information on which areas in the state to concentrate data collection efforts. Seven main yield treatment categories were identified and sent out to the districts. Respondents were asked to give an estimate of the distribution of frontage road–exit ramp yield categories existing in their district. Figure 8 and Figure 9 show the various frontage road–exit ramp yield treatments that were categorized in this survey. The categories shown in Figure 8 have no YIELD sign while those shown in Figure 9 have YIELD signs.

A similar survey was not developed for U-turn treatments as this was an additional task added after the initial survey was done. Based on field observations and input from the research panel, five basic categories were identified and described in the Field Studies section.

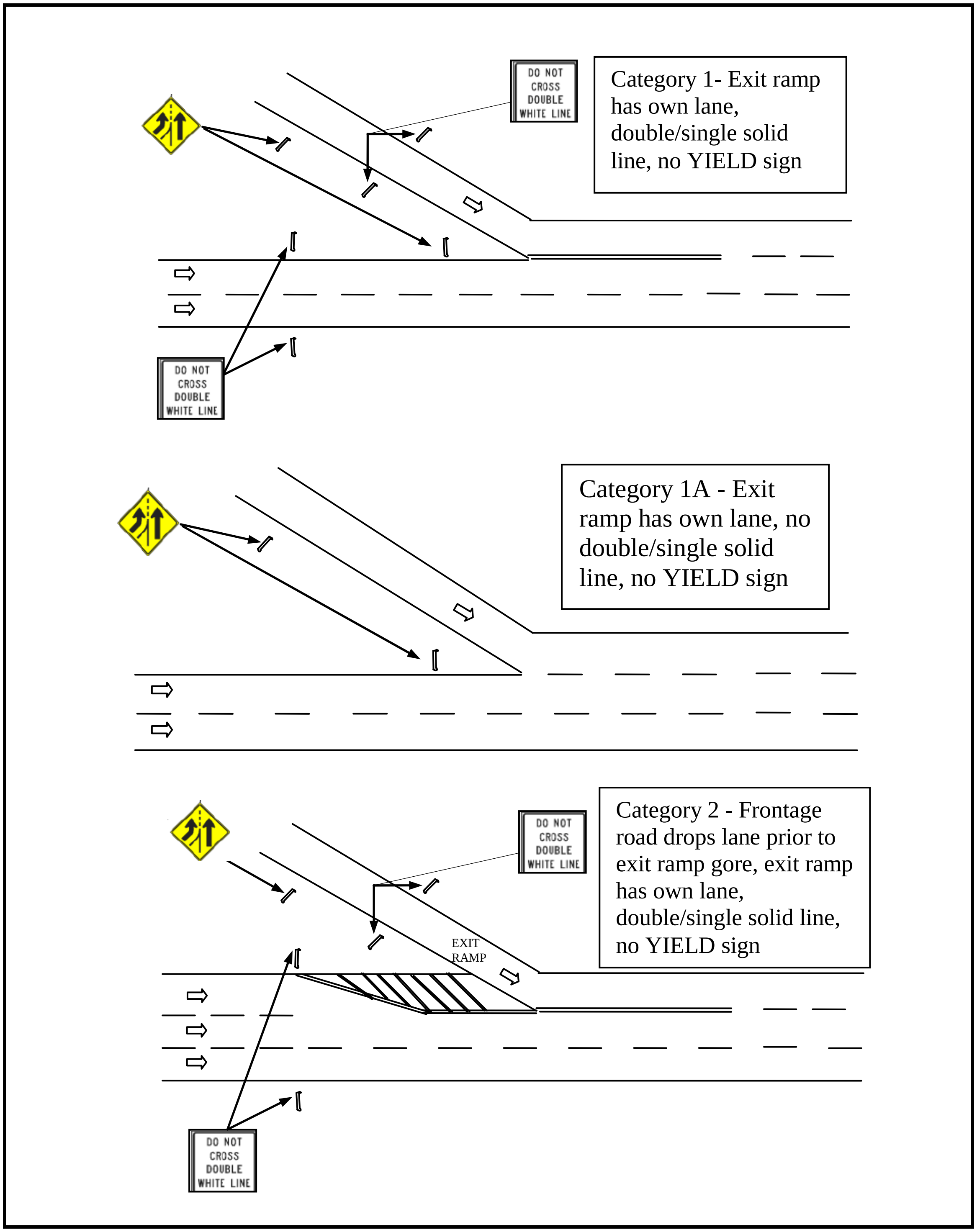


Figure 8. Frontage Road–Exit Ramp Yield Treatment Categories without YIELD Sign.

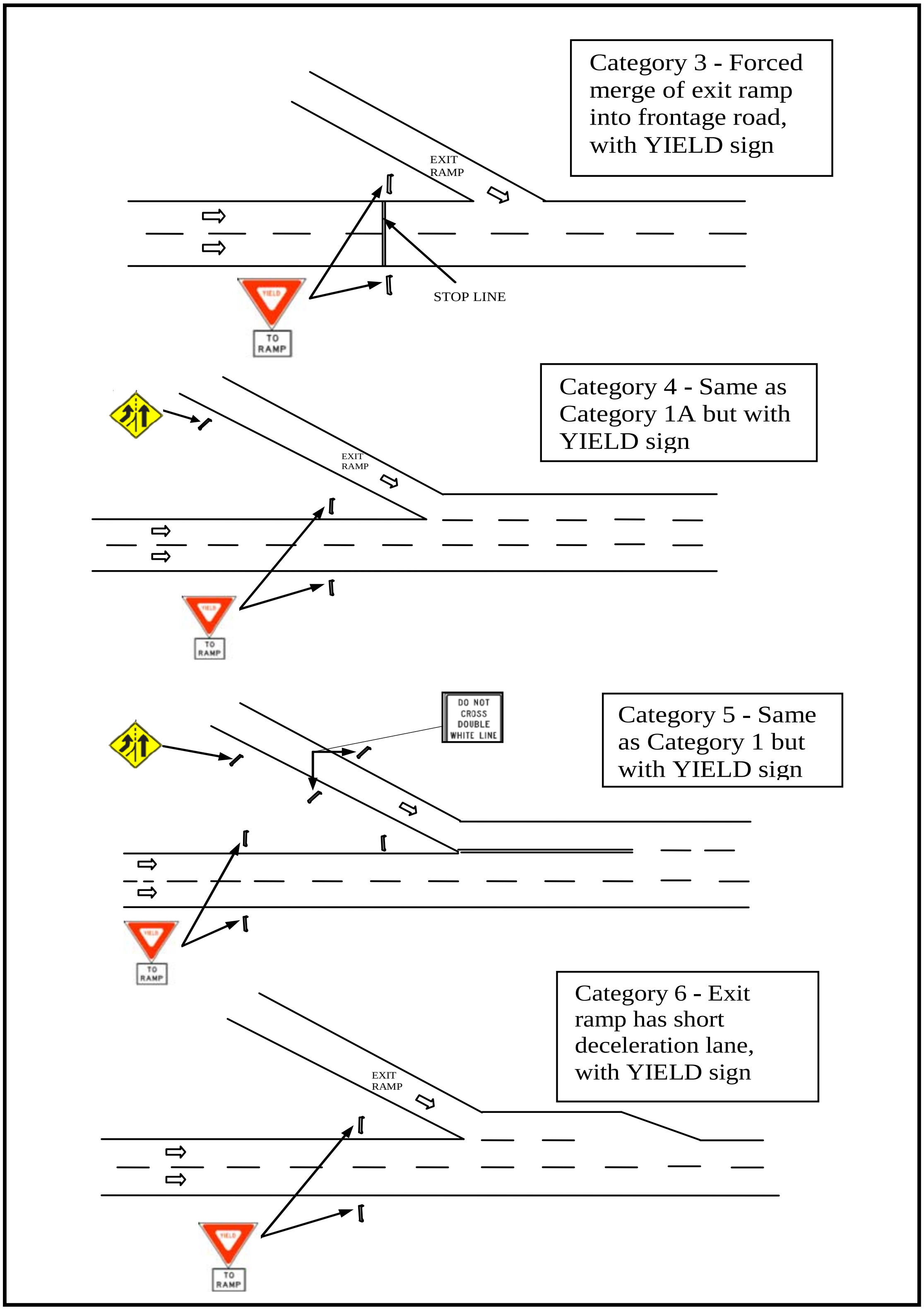


Figure 9. Frontage Road–Exit Ramp Yield Treatment Categories with YIELD Sign.

The results of the statewide survey are shown in Table 1. From the survey, the following observations were made:

- A total of over 2400 frontage road–exit ramp yield junctions exist in the state of Texas.
- A wide variety of frontage road yield treatments exist within particular cities or districts (such as in Corpus Christi and San Antonio).
- The results of this survey confirm the belief that too many frontage road–exit ramp yield treatments currently exist with few guidelines as to the efficacy or usage of these different types of treatment.

Table 1. Approximate Percentage of Various Yield Treatment Types in TxDOT Districts.

District	Category (See Figures 8 and 9) & Percentage (%)						
	1	1A	2	3	4	5	6
Abilene (n = 21)			86	9			5
Amarillo (n = 24)			18	40			42
Atlanta (n = 26)	9	90				1	
Austin (n = 156)		57	40	1	1		1
Beaumont (n = 100)	8		90		1		1
Bryan (n = 26)			100				
Corpus Christi (n = 90)			6	15	17	24	38
Dallas (n = 650)	40		35	20	5		
El Paso (n = 75)	95					5	
Fort Worth (n = 100)	10		53	1	36		
Houston (n = 550)	40		40	20			
Laredo (n = 11)	36		55			9	
Lubbock (n = 38)	15		75		5	5	
Lufkin (n = 32)			100*				
Odessa (n = 31)			65	35			
Paris (n = 40)			100*				
San Angelo (n = 25)				100			
San Antonio (n = 185)	5		30	15	45	2	3
Waco (n = 29)	5		50	30	5	5	5
Wichita Falls (n = 18)	5		10		75	10	

Notes: n = sample size
* Lufkin and Paris Districts operate their one-way frontage roads as shown in Category 2 without the far right lane (i.e., one dedicated exit lane and one dedicated frontage road lane resulting in a 2-lane downstream frontage road).

FIELD STUDIES

Frontage Road–Exit Ramp Sites

From the survey results obtained, eight sites across the state of Texas were selected as a basis for comparing the above-mentioned frontage road–exit ramp yield treatments. While an effort was made to select sites across the state of Texas, financial and time constraints as well as ease of data collection meant some cities or districts had more sites selected from them than others. San Antonio, with its wide variety of treatments and proximity to the core of the research team, provided almost half of the field sites selected. There was also a desire to select some problematic sites (an example is Northbound I-35 at Mann Road exit in Laredo) as well as sites with varying peak traffic volume levels. The data collection effort focused on the following areas:

- traffic volumes on frontage roads and exit ramps (by using pneumatic tubes to count vehicles and a video equipment trailer to record traffic count);
- speeds of vehicles from exit ramp and frontage road before gore and downstream of gore (by placing tubes immediately prior to the gore and approximately mid-way between gore and downstream intersection—see Figure 10);
- origin-destination (OD) pattern for frontage road vehicles and exit ramp vehicles (by noting the eventual turn direction either at a driveway or at the signal ahead);
- geometric configuration of location (by including frontage road–exit ramp yield type treatment, distance of driveways from exit gore, location of YIELD sign, distance to downstream intersection from exit gore, length and type of striping, etc.); and
- yielding behavior at the location (by using recorded video to estimate the minimum gap time as defined in VISSIM® simulation modeling tool).

Figure 10 is a data collection diagram showing the locations of pneumatic tubes for collection of volume and speed data at the various frontage road–exit ramp sites. Table 2 gives a summary of the data collection sites for the yield categories. Figure 11 and Figure 12 show photographs of the various field study sites.

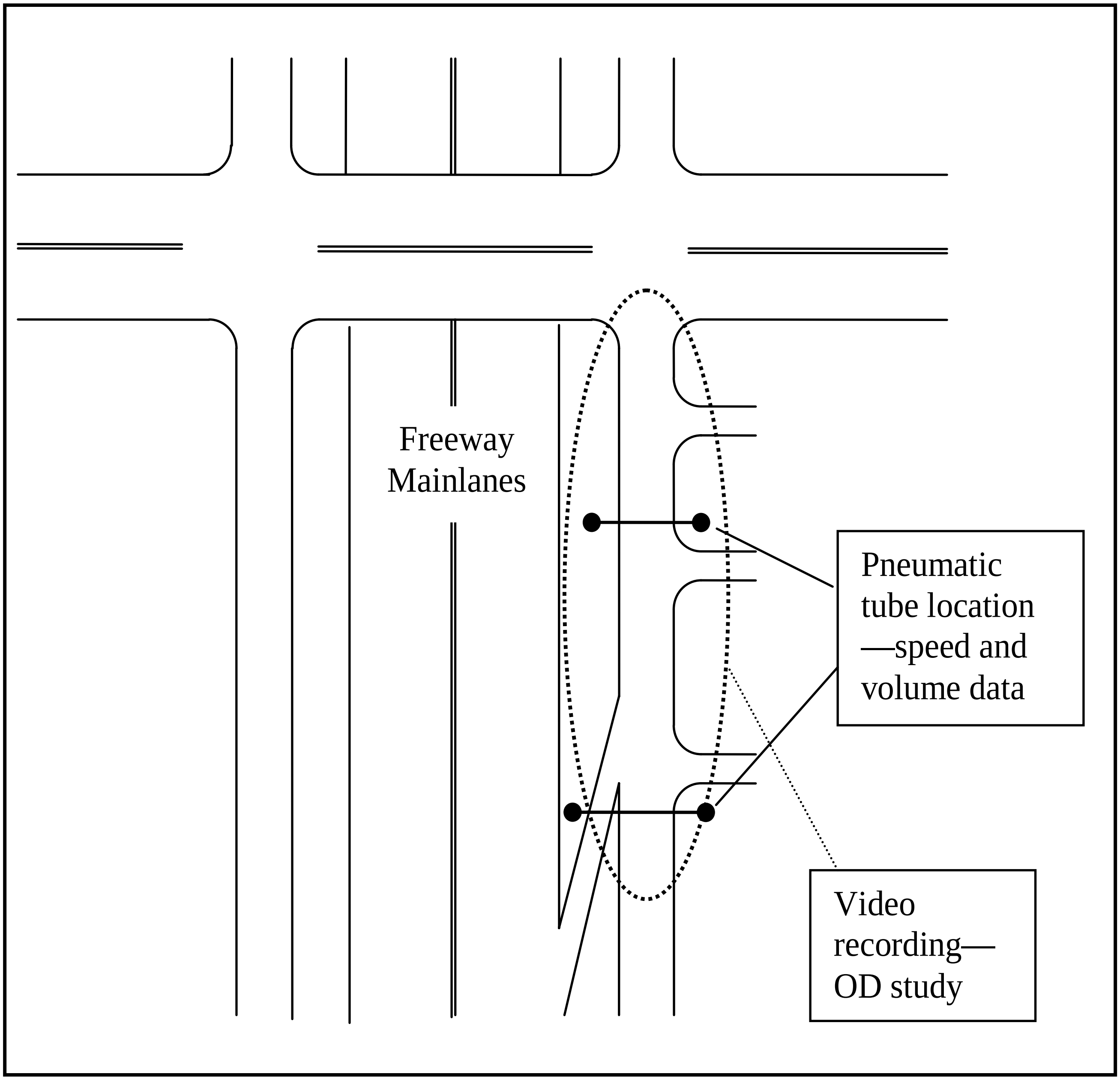


Figure 10. Data Collection Diagram for Frontage Road–Exit Ramp Field Studies.

Table 2. Summary of Frontage Road–Exit Ramp Field Study Sites.*

Characteristic	Site # 1	Site # 2	Site # 3	Site # 4	Site # 5	Site # 6	Site # 7	Site # 8
SITE CHARACTERISTICS								
Type of yield treatment	Category 1	Category 1A	Category 2	Category 3	Category 4	Category 4	Category 5	Category 6
Area type	Urban Residential	Urban Commercial	Urban Mix	Urban Commercial	Urban Commercial	Urban Commercial	Urban Commercial	Urban Commercial
Advisory speed limit on exit ramp (mph)	40	None	35	None	None	40	30	40
Posted speed limit on frontage road (mph)	40	50	45	45	50	40	45	45
GEOMETRICS								
Distance from exit gore to downstream intersection (ft)	950	880	450	450	690	1140	770	2200
Distance from exit gore to first driveway (ft)	290	330	100	90	490	110	55	480
Number of exit ramp lanes	1	1	1	1	1	1	1	1
Number of lanes on frontage road	2	3	3, dropped to 2 before exit ramp gore	2	2	2	2	2
Number of driveways[1]	2	2	2	3	1	6	4	4
Lane width (ft)	12	12	12	12	12	12	12	12
Presence of U-turn	Yes	No	No	Yes	Yes	Yes	Yes	Yes
TRAFFIC CHARACTERISTICS (EXIT RAMP VEHICLES)								
Peak volume (vph)	54	416	260	1047	751	952	793	370
Approximate truck percentage	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%
Volume of right-turning traffic[2]	31	105	74	270	35	752	363	195
Volume of through traffic[2]	0	156	18	81	94	87	164	64
Volume of left-turning traffic[2]	6	103[2]	168	585	597	98	77	58
Volume of U-turning traffic	17	52[2]	N/A	111	25	15	189	53
TRAFFIC CHARACTERISTICS (FRONTAGE ROAD VEHICLES)								
Peak volume (vph)	277	1891	440	326	151	1063	896	549
Approximate truck percentage	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%
Volume of right-turning traffic[2]	12	300	163	127	24	258	122	288
Volume of through traffic[2]	233	754	88	26	51	627	331	98
Volume of left-turning traffic[2]	9	557[2]	189	112	65	159	37	67
Volume of U-turning traffic[2]	23	228[3]	No U-turn	61	11	19	406	96

* Refer to Figures 11 and 12 for site names and sample site photographs

[1] Number of driveways between exit ramp gore and downstream intersection; [2] At driveways and downstream intersection;

[3] U-turn traffic does not have own lane; must make two left turns/no turnaround

All volume figures reported are in vehicles per hour (vph)

Site 1: Westbound I-410 at Honeysuckle Lane Exit, San Antonio, Texas

Site 2: Northbound US 183 at Loop 360 Exit, Austin, Texas

Site 3: Eastbound I-610 at Airline Drive Exit, Houston, Texas

Site 4: Eastbound I-410 at Perrin Beitel Exit, San Antonio, Texas

Figure 11. Frontage Road–Exit Ramp Yield Treatment Site Photographs–A.

Site 5: Westbound SH 358 at Rodd Field Exit,
Corpus Christi, Texas

Site 6: Westbound I-410 at Bandera Road Exit
San Antonio, Texas

Site 7: Northbound I-35 at Mann Road Exit
Laredo, Texas

Site 8: Eastbound Loop 1604 at Bandera Road Exit
San Antonio, Texas

Figure 12. Frontage Road–Exit Ramp Yield Treatment Site Photographs–B.

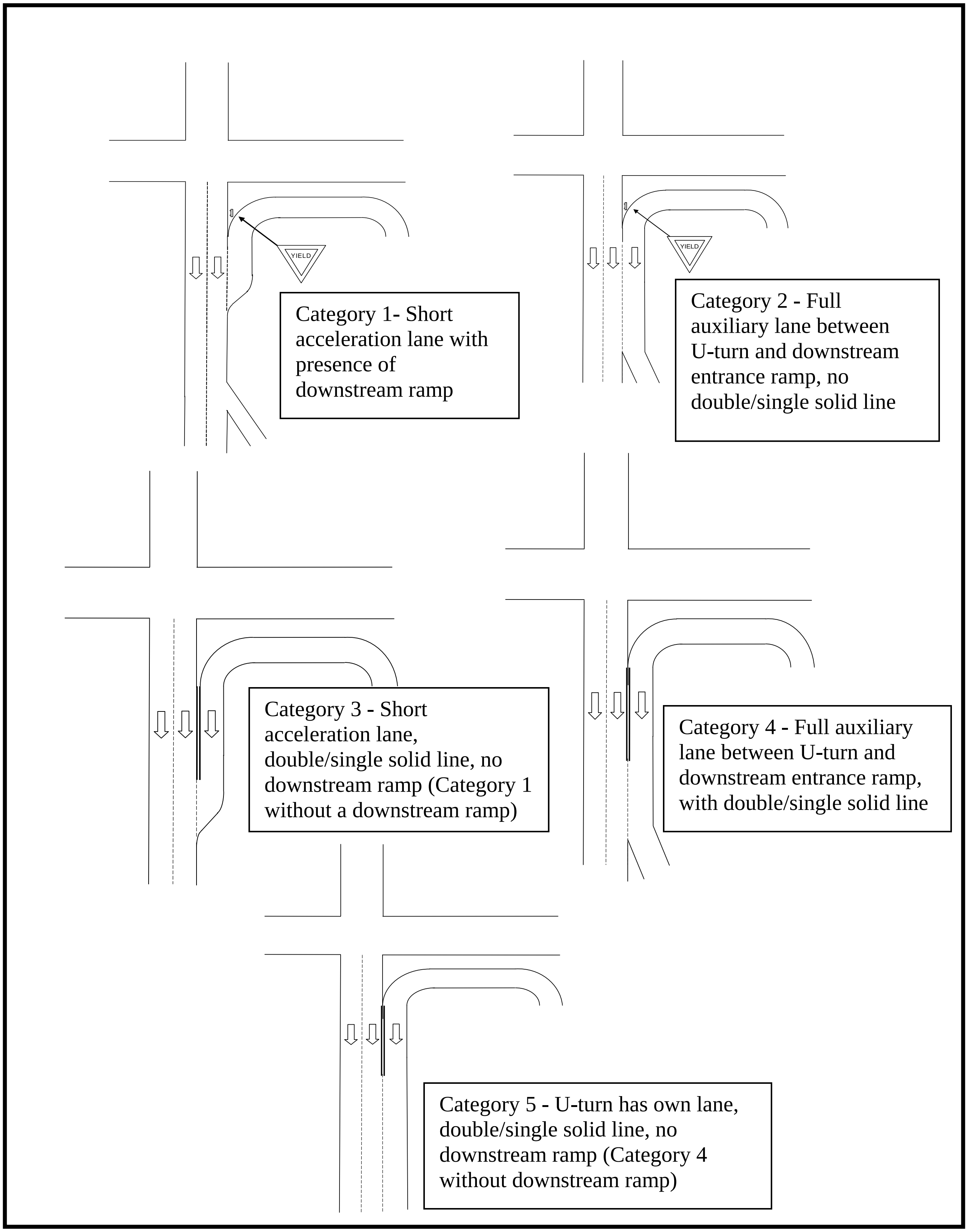
U-Turn Sites

Five U-turn yield categories were identified and analyzed in the study of yield treatments at U-turn locations. These categories are shown in Figure 13.

Six sites across the state of Texas were selected as a basis for comparing the above shown U-turn road yield treatments. While an effort was made to select sites across the state of Texas, financial and time constraints and ease of data collection meant some cities or districts had more sites selected from them than others. The data collection effort focused on the following areas:

- traffic volumes on U-turn lanes and frontage road;
- speeds of vehicles from U-turn and frontage road before gore and downstream of gore (by placing pneumatic tube counters immediately prior to the gore and approximately mid-way between gore and entrance ramp or downstream driveway--see Figure 14;
- origin-destination pattern for U-turn vehicles and frontage road vehicles (i.e., the direction of eventual turn either at a driveway or onto an entrance ramp);
- geometric configuration of location (including U-turn type treatment, distance of driveways from yield gore, location of YIELD sign, distance to the downstream driveways from gore, length and type of striping, etc.); and
- yielding behavior at the location (estimating the minimum gap time as defined in VISSIM® simulation modeling tool).

Figure 14 is a data collection diagram showing the locations of pneumatic tubes for collection of volume and speed data at the various U-turn sites. Table 3 gives a summary of the characteristics of the field study sites for the U-turn yield categories. The sites used for the U-turn study are shown in Figure 15 through Figure 17.



Category 1- Short acceleration lane with presence of downstream ramp

Category 2 - Full auxiliary lane between U-turn and downstream entrance ramp, no double/single solid line

Category 3 - Short acceleration lane, double/single solid line, no downstream ramp (Category 1 without a downstream ramp)

Category 4 - Full auxiliary lane between U-turn and downstream entrance ramp, with double/single solid line

Category 5 - U-turn has own lane, double/single solid line, no downstream ramp (Category 4 without downstream ramp)

Figure 13. U-Turn Yield Treatment Categories.

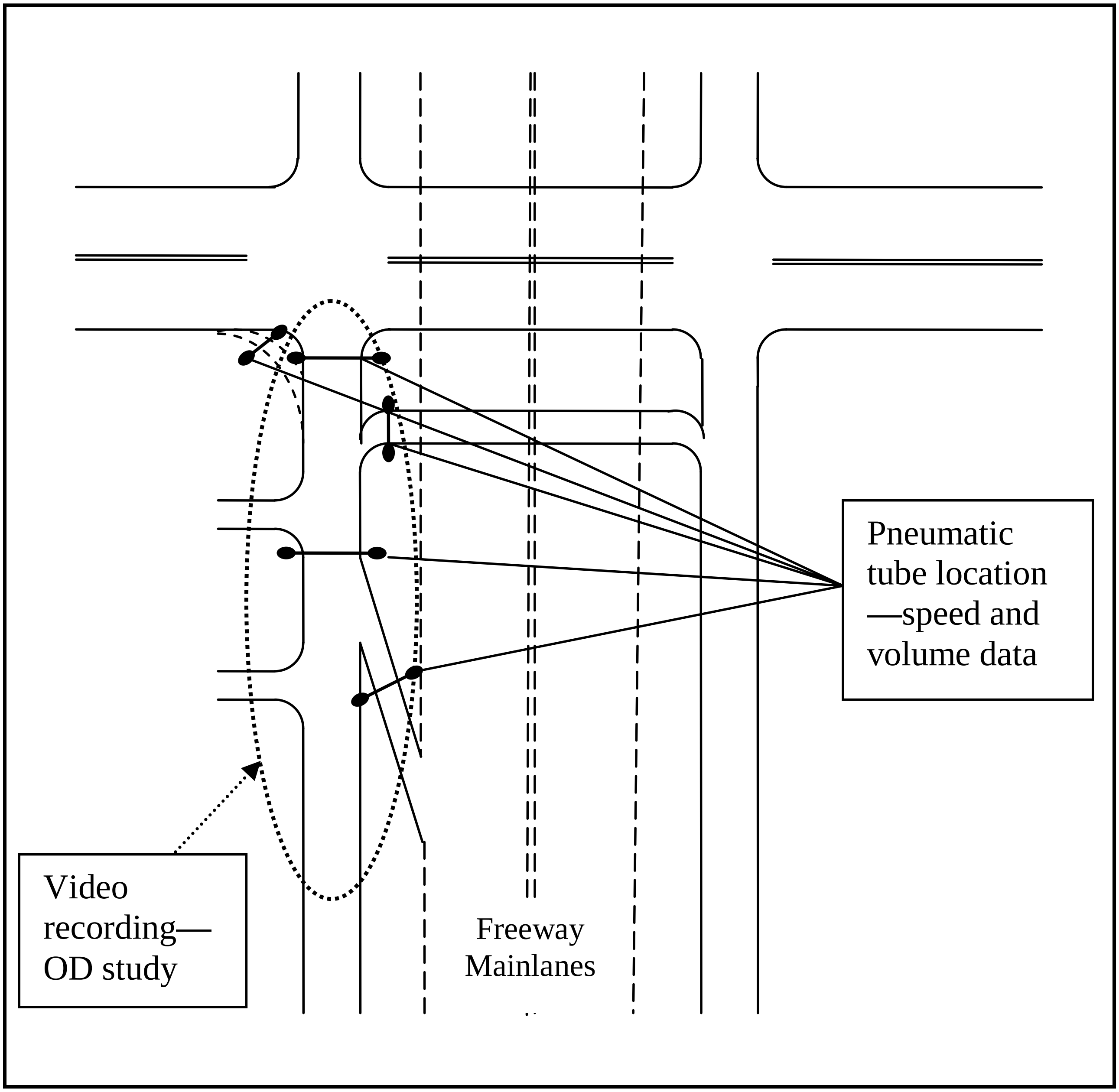


Figure 14. Data Collection Diagram for U-Turn Field Studies.

Table 3. Summary of U-Turn Field Study Sites.*

Characteristic	Site # 1	Site # 2	Site # 3	Site # 4	Site # 5	Site # 6
SITE CHARACTERISTICS						
Type of yield treatment	Category 1	Category 2	Category 4	Category 3	Category 5	Category 1
Area type	Urban Commercial	Urban Residential	Urban Commercial	Urban Commercial	Urban Commercial	Urban Commercial
GEOMETRICS						
Number of driveways*	3	2	3	4	2	4
Distance from yield point to first driveway (ft)	50	300	85	65	90	126
Presence of entrance ramp	No	Yes	Yes	No	No	Yes
Distance from yield point to entrance ramp (ft)	N/A	595	254	N/A	N/A	905
Number of lanes on frontage road	3	2	2	2	2	3
Lane width (ft)	12	12	12	12	12	12
TRAFFIC CHARACTERISTICS (U-TURN VEHICLES)						
Peak volume (vph)	255	53	604	454	659	364
Approximate truck percentage	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%
Volume entering first driveway	2	0	0	7	0	22
Volume entering second driveway	27	0	39	3	37	41
Volume entering third driveway[2]	35	N/A	9	9	17	64
Volume entering fourth driveway[2]	N/A	N/A	N/A	79	0	55
Volume continuing on frontage road	131	32	286	356	605	111
Volume entering entrance ramp[1]	N/A	21	270	N/A	N/A	71
TRAFFIC CHARACTERISTICS (FRONTAGE ROAD VEHICLES)						
Peak volume (vph)	1253	1477	1158	840	1208	1759
Approximate truck percentage	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%	Less than 5%
Volume entering first driveway	9	7	20	15	54	50
Volume entering second driveway	35	6	113	3	20	126
Volume entering third driveway[2]	17	N/A	25	8	13	134
Volume entering fourth driveway[2]	N/A	N/A	N/A	42	4	149
Volume continuing on frontage road	1192	836	504	772	1117	703
Volume entering Entrance ramp[1]	N/A	628	496	N/A	N/A	597

* Refer to Figures 15-17 for corresponding site names and sample site photographs

[1] Sites without entrance ramp have N/A; [2] Sites without 3 or more driveways have N/A

All volume figures reported are in vehicles per hour (vph)

Site 1: Northbound to Southbound US 183 at Anderson Mill, Austin, Texas

Site 2: Eastbound to Westbound I-410 at Bandera Road, San Antonio, Texas

Figure 15. U-Turn Yield Field Study Sites–A.

Site 3: I-35 at Mann Road, Laredo, Texas

Site 4: Eastbound to Westbound US 190 at FM 3470, Killeen, Texas

Figure 16. U-Turn Yield Field Study Sites–B.

Site 5: Northbound to Southbound US 183 at Braker Lane, Austin, Texas

Site 6: Northbound to Southbound US 281 at Bitters Road, San Antonio, Texas

Figure 17. U-Turn Yield Field Study Sites–C.

CHAPTER 3. EXPERIMENTAL DESIGN

SIMULATION MODELING AND CALIBRATION

Detailed descriptions of microsimulation modeling and the calibration process utilized in the process are described in detailed in Appendix A. The section gives a brief background on simulation modeling and a detailed description of the calibration process used to develop simulation models that more accurately reflected real-world scenarios.

The goal of the simulation modeling process was to identify if and/or when a certain type of merge or yield application may be more beneficial for operations and safety. The analysis was conducted on two levels—Level 1 and Level 2. These levels are discussed below.

FRONTAGE ROAD–EXIT RAMP YIELD TREATMENT

Level 1 Simulation Modeling Description

After calibration of the model for each site, as described in preceding sections, different yielding treatments were applied to each calibrated site. Comparisons were then made to determine if any one treatment would perform better than the others. Two main reasons for doing this kind of analysis were to look at some problematic sites that currently existed and to give a real-world experience incorporating signal timing and current weaving patterns into the analysis as much as possible.

This approach is a more straightforward utilization of the collected traffic information and geometric conditions as described in the previous section under Data Collection and Analysis and provides a basis for comparing frontage road–exit ramp yield treatments side by side. In Level 1, each yield treatment is applied to each site and the resulting Measures of Effectiveness (MOEs) compared. A brief outline of Level 1 simulation is given below.

- The purpose was to evaluate the performance of different yield treatments at each of the sites that had field data collection to find out whether the current local implementation at each site gives the best benefit.
- The methodology sought to test the performance of different treatments on each site by keeping the other model elements fixed and only changing the merge or yield treatment and running the simulation.
- Three runs were made for each scenario resulting in a total of 189 simulations (9 sites × 7 treatments × 3 runs = 189 simulations).

Note that a Level 1 analysis was not performed for the U-turn cases. Since the project results were to be based on the more extensive Level 2 analysis, researchers focused on this for the U-turn analysis.

Level 2 Simulation Modeling Description

Because Level 1 analysis was limited to the geometric and traffic conditions at the selected sites, the results might not be far-reaching enough to suggest its application to other sites. To analyze varying geometric and traffic volume and weaving conditions, a Level 2 analysis was required to consider the most feasible scenarios for frontage road-exit ramp yielding conditions including varying weaving distances to downstream intersection, number of driveways, weaving patterns, and the yield treatment. A brief outline of Level 2 simulation is given below.

- The purpose was to identify the performances of different treatments under varying traffic and geometric conditions not analyzed in Level 1.
- The methodology involved an advanced version of Level 1 to include performance of different frontage road–exit ramp yield treatments under varying demand and OD patterns, driveway density and weaving lengths. One typical site will be identified and various categories analyzed with varying demand and geometry conditions investigated. In this way, the performance under different scenarios for all treatments can be compared side by side.
- Three runs were made for each scenario developed.
- A total of 2268 combined models were developed. This total is a product of the general conditions [7 classes of yield treatment conditions, 1 class of vehicle mix, 3 classes of length of spacing to intersections, 3 driveway density classes (7 × 1 × 3 × 3 = 63)], volume scenarios [1 driveway flow class × 3 exit ramp flow classes × 3 frontage road flow classes (1 × 3 × 3 = 9)], 4 OD scenario classes, for 63 × 9 × 4 = 2268 scenarios, and 2268 × 3 runs per scenario = 6804 total simulation runs.

Frontage road yield treatment modeling scenarios were organized according to the following parameters:

General Conditions

1. Yield Treatment Condition (7 classes)
    - double white line, exit ramp with own lane, no YIELD sign (Category 1);
    - exit ramp with own lane, no double white line, no YIELD sign (Category 1A);
    - frontage road dropped lane, double white line, exit ramp with own lane, no YIELD sign (Category 2);
    - forced merge option (Category 3);
    - no double white line, exit ramp with own lane, YIELD sign present (Category 4);
    - double white line, exit ramp with own lane, YIELD sign present (Category 5); and
    - exit ramp with own lane, but dropped, YIELD sign present (Category 6).

2. Vehicle Mix – 95 percent auto, 5 percent truck “Normal Mix”

3. Spacing to Intersection (3 classes)
    - 500 feet (2 and 4 driveway count only);
    - 1000 feet; and
    - 2000 feet.

4. Driveway Density (3 classes)
    - 2 driveways (1 major, 1 minor);
    - 4 driveways (2 major, 2 minor); and
    - 6 driveways (2 major, 4 minor).

Volume Scenarios

1. Two driveway types were used together at each location to depict a real life scenario. Based on average trips from the Institute of Transportation Engineers (ITE) Trip Generation for a Gasoline/Service Station and Supermarket for low and high-volume driveways respectively for PM Peak Hour, the following was assumed.

    - 30 vehicles per hour (vph) in, 30 vph out (minor, low volume); 90 vph in, 90 vph out (major, high volume)

2. Three exit ramp flow levels were defined. The maximum ramp flow was assumed as 1400 vehicles per hour per lane (vphpl). This value was obtained from previous studies on managed lane ramps that examined ramps processing high volumes of vehicles with reasonable levels of performance. The signal downstream is likely to reduce the amount of volume likely to be processed by such ramps. The volumes obtained by using the percentages below were checked against actual volumes observed at each site to ensure a reasonable breakdown in to the three volume levels shown below.

    - 20 percent of maximum ramp flow—“low volume”;
    - 50 percent of maximum ramp flow—“moderate volume”; and
    - 70 percent of maximum ramp flow—“high volume”.

3. Three frontage road traffic volume levels were defined. The maximum frontage road approach volume assumed as 1200 vphpl derived by assuming an 1800 vphpl capacity for two lane frontage road and about a third of the cycle time being used to process the approach phase. The volume levels obtained using the percentages below were checked against actual volumes recorded at each site to ensure a reasonable breakdown into the three volume levels shown below.

    - 10 percent of nominal lane capacity—"low volume";
    - 30 percent or nominal lane capacity—"moderate volume"; and
    - 50 percent of nominal lane capacity—"high volume".

Origin-Destination Scenarios

Four OD classes for traffic exiting the freeway destined for the downstream intersection as well as traffic already on the frontage road destined for the downstream intersection are shown in Table 4.

Table 4. Origin-Destination Scenarios for Frontage Road–Exit Ramp Simulation Modeling.

Class 1					**Class 2**				
"Normal" Traffic Distribution					*"Normal" Exit Ramp Traffic, High Frontage Road Weaving Traffic*				
	To:					*To*:			
From:	UT[3]	LT[4]	TH[5]	RT[6]	*From*:	UT	LT	TH	RT
ExR[1]	10	30	30	30	ExR	10	30	30	30
FR[2]	15	25	30	30	FR	25	35	20	20
Class 3					**Class 4**				
High Exit Ramp Weaving, "Normal" Frontage Road Traffic					*High Exit Ramp Weaving and High Frontage Road Weaving Traffic*				
	To:					*To*:			
From:	UT	LT	TH	RT	*From*:	UT	LT	TH	RT
ExR	20	20	20	40	ExR	20	20	20	40
FR	15	25	30	30	FR	25	35	20	20

[1]ExR–exit ramp; [2]FR–frontage road; [3]UT–U-turn; [4]LT–left turn; [5]TH-through; [6]RT–right turn

U-TURN YIELD TREATMENT

A methodology similar to the Level 2 analysis adopted for the frontage road–exit ramp yield conditions was applied to the U-turn yield treatments. The goal of this analysis was to determine which U-turn treatment performs best under a variety of flow and geometric conditions. The levels of the various variables have been selected to include the specific field conditions studied. A brief outline of the Level 2 simulation performed is given below.

- The purpose was to evaluate the performance of different U-turn treatments with a range of traffic and geometric conditions.
- The methodology sought to test the performance of the identified U-turn treatments under a variety of geometric and flow conditions. The variable levels are shown below. The Measures of Effectiveness used to compare the treatments will include delay and average travel time on the frontage road. Average queue lengths in the U-turn lanes will also be noted.
- Three runs were made for each scenario developed.
- The total number of simulations developed was 1620. This is a product of general conditions, volume scenarios and OD scenarios [5 yield treatment conditions × 1 vehicle mix × 2 distance scenarios × 3 driveway flows × 3 frontage road flows × 3 U-turn flows × 2 OD scenarios] for 5 × 2 × 3 × 3 ×3 × 2 = 540 scenarios, and 540 × 3 runs per scenario = 1620 total simulation runs.

General Conditions

1. Yield Treatment Conditions (5 classes)
   - acceleration lane with downstream ramp (Category 1);
   - auxiliary lane between U-turn and entrance ramp (Category 2);
   - double white line with acceleration lane (Category 3);
   - double white line with auxiliary lane between U-turn and entrance ramp (Category 4); and
   - double white line with auxiliary lane without entrance ramp (Category 5).

2. Vehicle Mix

   - 95 percent auto, 5 percent truck

3. Distances from U-turn

   Two main scenarios were analyzed for distances from the U-turn to driveways and entrance ramp. The two scenarios were intended to capture a reasonable range of values for spacing of driveways from U-turn and entrance ramps.

   a. Scenario 1 (shorter weaving section):
      - distance from U-turn to first driveway (100 feet);
      - distance from U-turn to second driveway (300 feet); and
      - distance from U-turn to entrance ramp (400 feet).

b. Scenario 2 (longer weaving section):
    - distance from U-turn to first driveway (200 feet);
    - distance from U-turn to second driveway (500 feet); and
    - distance from U-turn to entrance ramp (600 feet).

Volume Scenarios

1. Driveway Flow (3 classes) —

    - Three different volume levels were defined. These are 30, 90, and 150 vehicles per hour. These are flows for driveway traffic entering the frontage road. Traffic entering the driveways from the frontage road will be determined by the OD matrix shown below. Note also that two driveways are assumed.

2. Frontage Road Flow (3 classes)

    - Three different volume levels were defined. These are 800, 1300, and 1800 vehicles per hour. These are the flows on the frontage road immediately upstream of the U-turn lanes. These flows will be controlled by the traffic signal at the upstream arterial crossing.

3. U-turn Flow (3 classes)

    - Three different volume levels were defined. These are 200, 400, and 600 vehicles per hour.

Origin-Destination Scenarios

The various OD pairs were developed for the U-turn scenarios and analyzed using the VISSIM simulation modeling tool. Two different conditions were used to depict different weaving levels from the frontage road to the freeway via the entrance ramp and from the U-turn to downstream driveways on the frontage road. The OD percentages are shown in Table 5 below.

Table 5. Origin-Destination Scenarios for U-Turn Simulation Modeling.

Condition 1									
No Ramp					*With Ramp*				
	To:					*To*:			
From:	DW[1]1	DW 2	FR[2]		*From*:	DW 1	DW 2	Ramp	FR
FR	5	5	90		FR	5	5	45	45
U-turn	5	5	90		U-turn	5	5	45	45
					DW 1	-	-	50	50
					DW 2	-	-	50	50
Condition 2									
No Ramp					*With Ramp*				
	To:					*To:*			
From:	DW 1	DW 2	FR		*From*:	DW 1	DW 2	Ramp	FR
FR	10	15	75		FR	10	15	37.5	37.5
U-turn	10	15	75		U-turn	10	15	37.5	37.5
					DW 1	-	-	50	50
					DW 2	-	-	50	50

[1]DW– driveway; [2]FR– frontage road

CHAPTER 4. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

The results of the field studies and computer simulations were used as the basis for the operations and safety analysis. The goal of this analysis was to identify if and/or when a certain type of merge or yield application may be more beneficial for traffic operations and safety. The safety analysis was correlated with the simulation analysis in order to provide an indication of safety characteristics (e.g., propensity/likelihood of crash rates) under varying geometric and operating conditions.

RESULTS ANALYSIS: FRONTAGE ROAD–EXIT RAMP YIELD TREATMENT

Data Analysis

A wide range of MOEs were generated. The challenge was to identify which MOEs to include in any comparative analysis of yield treatments. A total of 2268 simulation models and 29 MOEs were collected during each simulation. To simplify the results and enable a more effective comparison of the different scenarios developed, there was a need to reduce the number of MOEs. Researchers identified certain MOEs that were correlated or had little impact on the overall results.

Principal Components Analysis (PCA), one statistical tool in the factor analysis, was used to reduce the redundancy in the number of the variables and to define the underlying structure. The method begins by finding a linear combination of variables (a component) that accounts for as much variation in the original variables as possible. It then finds another component that accounts for as much of the remaining variation as possible and is uncorrelated with the previous component, continuing in this way until there are as many components as original variables. Our objective in this task was to extract a relatively large number of factors and identify independent variables, which captured both mobility and safety features, while discarding as little of the information in the original dataset of MOEs as possible.

In this study, eight variables or MOEs were pre-selected to perform the PCA analysis. They are:

- system total travel time;
- system average delay time;
- system average speed;
- average delay time group 1;
- average delay time group 2;
- average delay time group 3;
- average delay time group 4; and
- total surrogate crashes.

Vehicle Groups were defined as follows:

- vehicle group 1: vehicles exiting the ramp and making a right turn either at a driveway or at the downstream intersection (assumed to be weaving traffic);
- vehicle group 2: vehicles exiting the ramp and going through or making a left at the light or a U-turn (assumed to be non-weaving traffic);
- vehicle group 3: vehicles on the frontage road going through or making a right turn either at a driveway or at the downstream intersection (assumed to be non-weaving traffic); and
- vehicle group 4: vehicles on frontage road making either a U-turn or left turn at the downstream intersection (assumed to be weaving traffic).

From Table 6, two Principal Components (PCs) were estimated to address 80 percent of the variance. This implies that two of the variables can represent the whole data fairly well, and any additional variables will not have as much impact. The two PCs were determined through further analysis, as shown in Table 7, which shows that the first component is highly related to the average delay time. Although the factor loadings for average delay time for Group 1 and Group 2 are greater, the system average delay time was chosen to represent the first factor in all further analysis based on its representation of system-wide mobility measures. For the safety component, the PCA results show that total surrogate crashes total was highly related to the second component.

Table 6. Principal Component Analysis (Total Variance) for Frontage Road-Exit Ramp Data.

Component	**Initial Eigen Values**			**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**		
	Total	*Percent of Variance*	*Cumulative Percent*	*Total*	*Percent of Variance*	*Cumulative Percent*	*Total*	*Percent of Variance*	*Cumulative Percent*
1	5.371	67.142	67.142	5.371	67.142	67.142	3.536	44.200	44.200
2	1.044	13.050	80.191	1.044	13.050	80.191	2.879	35.991	80.191
3	0.809	10.107	90.298						
4	0.454	5.673	95.971						
5	0.172	2.145	98.116						
6	0.127	1.593	99.710						
7	0.018	0.227	99.937						
8	0.005	0.063	100.000						

Extraction Method: Principal Component Analysis.

Table 7. Rotated Component Matrix Analysis for Frontage Road-Exit Ramp Data.

Variable	Component	
	1	*2*
System Total Travel Time	0.549	0.480
System Average Delay Time	**0.875**	0.338
System Average Speed	-0.264	-0.871
Average Delay Time Group 1	0.949	0.217
Average Delay Time Group 2	0.916	0.279
Average Delay Time Group 3	0.572	0.637
Average Delay Time Group 4	0.550	0.670
Total Surrogate Crashes	0.173	**0.893**

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Numbers in bold show corresponding correlation factor for selected MOEs.

Summary Results

Table 8 shows the performance of the various yield treatments for the Level 1 direct site-specific comparison. In terms of traffic operations performance, Category 1A and Category 1 combined performed the best in six out of the eight sites (75 percent) analyzed. Safety-wise, these two categories combined performed best in five out of the eight sites analyzed (63 percent). See Appendix B of this report for detailed Level 1 operational and safety simulation results.

Table 8. Level 1 Results for Specific Frontage Road–Exit Ramp Yield Sites.

Site #	Description			Original Treatment	Best Operations Treatment	Best Safety Treatment
	Volume	Number of Driveways*	Distance, in feet, from ramp to intersection			
1	331	2	950	1	1A	1
2	2307	2	880	1A	1A	1A
3	700	2	450	2	2	5
4	1373	3	450	3	3	4
5	902	5	690	4	1	1
6	2015	6	1140	4	1	1A
7	1689	4	770	4	1A	1A or 5
8	919	4	2200	6	1A	6

*Number of Driveways from yield point to downstream intersection

Table 9 shows the performance of the various yield treatments for the broader Level 2 analysis respectively. From the results in Level 2, it becomes clear that the forced merging option (Category 3) is not a viable option for yield treatments. Also, Categories 4 and 5 had higher delay values (poor operational performance) compared to Categories 1 and 1A due to the forced yielding of vehicles on the frontage road.

Table 9. Level 2 Operational and Safety Performance Summary of Frontage Road–Exit Ramp Yield Categories.

Yield Category	Operations		Safety	
	Frequency Rated #1	***Percent Rated #1***	***Frequency Rated #1***	***Percent Rated #1***
1A	246	75.9	120	37.0
1	43	13.3	67	20.7
2	23	7.1	41	12.7
3	3	0.9	0	0
4	8	2.5	49	15.1
5	0	0	42	13.0
6	1	0.3	5	1.5
	324	100	324	100

Performance Index

In an effort to provide an overall performance measure for the various categories, a performance index was developed to combine the operational and safety performance measures. This index was a subjective undertaking based on:

- the data available (surrogate crash data vs. hard crash data);
- consultation with the TxDOT Project Monitoring Committee; and
- the experience of researchers.

The hypothesis assumed a simple linear function index of Average Delay (x) and Total Crashes (y) by weighting operations more than the surrogate crashes and deciding that zero Time Delay with two Total Crashes was equivalent to one unit Time Delay and zero Total Crashes. This assumption would then define the index as $I = 2x+y$. While this approach is simple, it afforded the researchers the chance to develop a reasonably sound overall Performance Index (PI) to combine the operational and safety performance of the various categories of yield treatment. This index is shown in Table 10.

Table 10. Results of Performance Index for Frontage Road–Exit Ramp Yield Categories.

Yield Category	Combined PI	
	Frequency Rated #1	***Percent Rated #1***
1A	130	40.1
1	70	21.6
2	43	13.3
3	0	0
4	42	13.0
5	36	11.1
6	3	0.9
	324	100

Detailed Results

The summary results shown in Table 10 gave a good indication of the overall performances of the various yield treatment categories. However, it was necessary to find out the performances of the yield treatment for specific traffic volume, weaving, and geometric layout scenarios including number of driveways and distance from yield point or gore point to downstream intersection.

To achieve presentation of the detailed results graphically would produce large quantities of charts or graphs, which has less usefulness to the practicing engineer or planner. The development of database software was thus initiated to incorporate detailed data from the results as well as the combined PI results for the various scenarios. The resulting program is intended to be a tool to enable TxDOT staff to analyze specific scenarios encountered in the field.

The database developed will not only provide the best yield treatment for particular scenarios, it will also provide practitioners with appropriate combinations of volumes, driveways, and distances to downstream intersections by providing actual performance index numbers. The database will also have a built-in mechanism warning for very high delays and high potential crash results.

Sample charts extracted from the current version of the database are presented in this report. The first two charts look at the performance of frontage road–exit ramp yield treatments when a short distance to downstream intersection is present (Figure 18) and when a high number of driveways exists (Figure 19). The last chart looks at scenarios with high frontage road and exit ramp volumes and high driveway density (Figure 20).

Figure 18 shows the performance of frontage road–exit ramp yield treatment types for a distance of 500 feet from exit gore (yield point) to downstream intersection. From the chart, Category 1A (frontage road with own lane, no solid line, and no YIELD sign) had the best performance (45 percent of cases). Category 1 had the best performance in few of the cases (2 percent). This result was primarily because the 80 feet of striped solid line prevents earlier changing of lanes and decreases the available distance to downstream intersection for weaving vehicles to maneuver. These results increase delays and reduce the headway (and thus the potential for crashes). As can be seen, Category 3 (forced merge option) did not perform best in any of the scenarios analyzed.

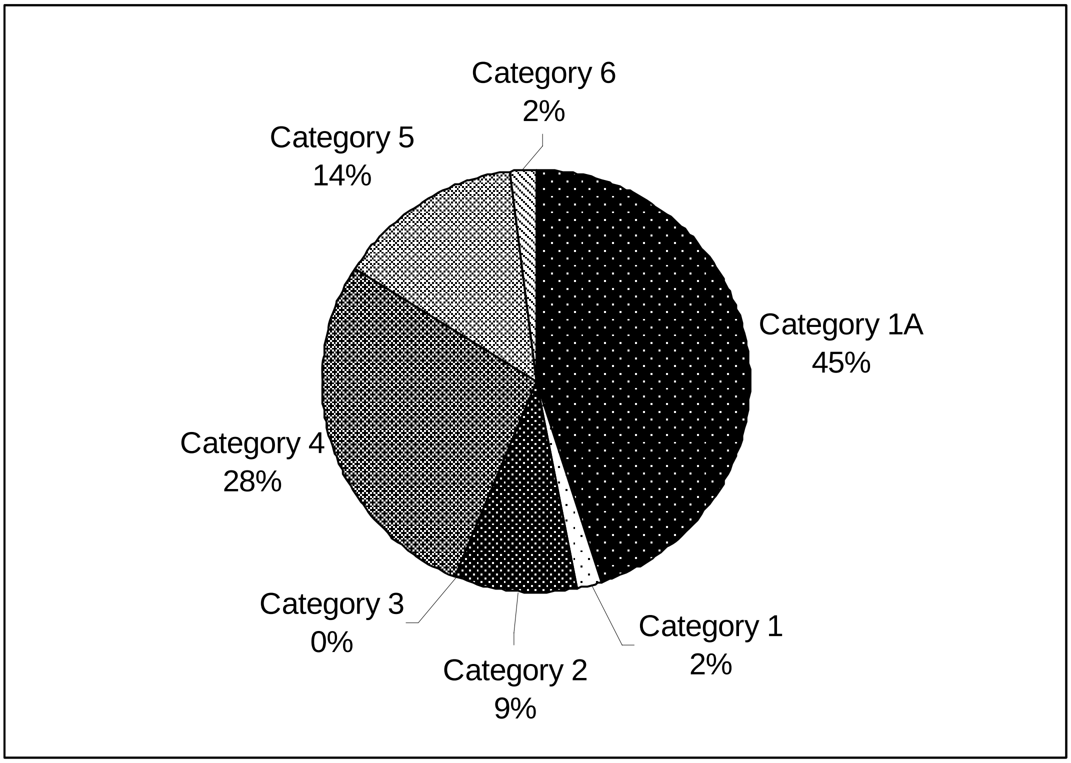


Figure 18. Performance of Frontage Road–Exit Ramp Yield Treatments (500 Feet to Downstream Intersection).

From Figure 19, the performance for various categories of frontage road yield treatment with six driveways between exit gore and downstream intersection are compared. Categories 1, 1A, 2, and 5 had roughly the same levels of success. The important observation here is that Category 3 (forced merge) and Category 6 (exit ramp with short deceleration lane) had no scenario in which they performed best.

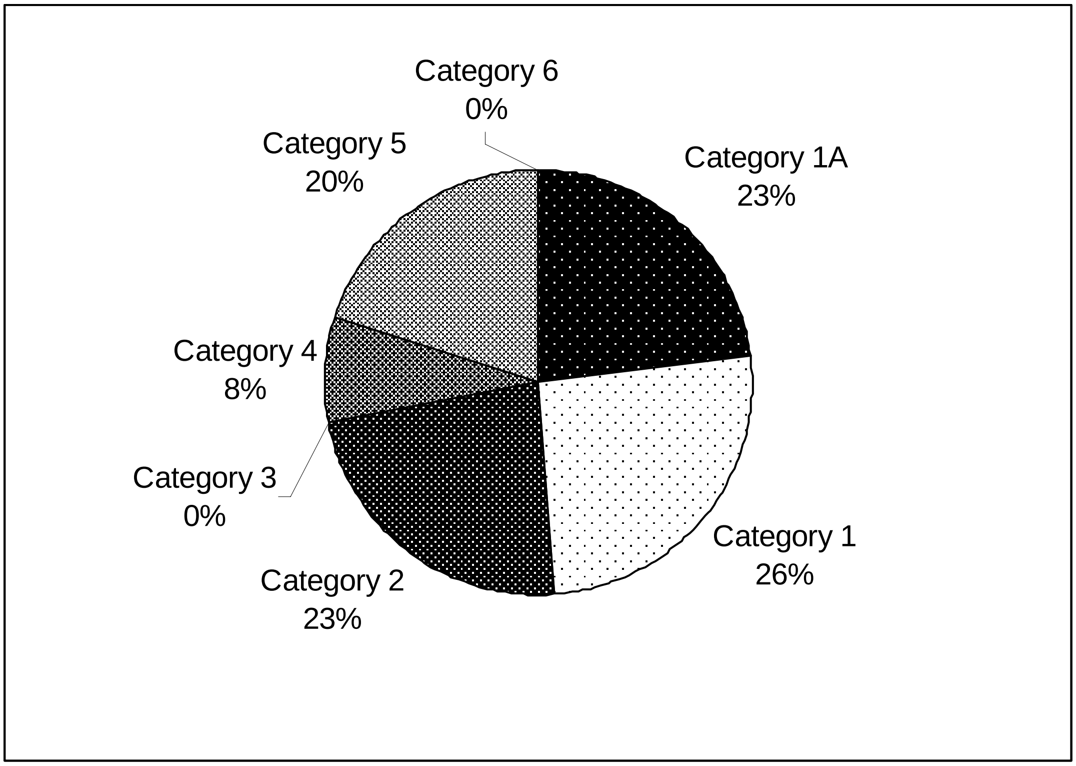


Figure 19. Performance of Frontage Road–Exit Ramp Yield Treatments with Six Driveways Located between Gore and Downstream Intersection.

From Figure 20, for a case with high volumes (greater than 2250 vehicles per hour combined frontage road and exit ramp volume) and high driveway density (greater than or equal to six driveways between exit gore and downstream intersection), the three categories without a yield sign (Categories 1A, 1, and 2) performed better than those with yield signs (Categories 3, 4, 5, and 6).

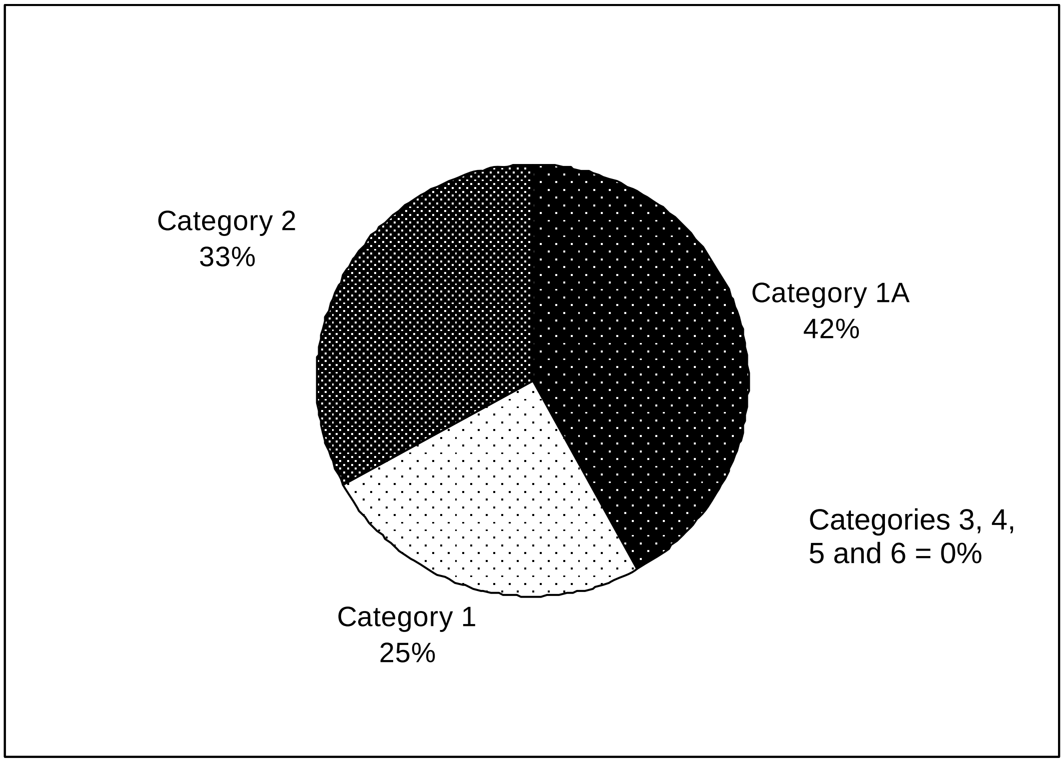


Figure 20. Performance of Frontage Road–Exit Ramp Yield Treatments for High Volumes and High Driveway Density.

RESULTS ANALYSIS: U-TURN YIELD TREATMENT

Data Analysis

Similar to the frontage road–exit ramp yield treatment analysis, a wide range of MOEs was generated (16 in this case). The challenge was to identify which MOEs to include in any comparative analysis of yield treatments. A total of 540 simulation models and 16 MOEs were collected during each simulation. To simplify the results presentation and enable a more effective comparison of the different scenarios developed, there was a need to reduce the number of MOEs. Researchers identified certain MOEs that were correlated or had little impact on the overall results.

Principal Components Analysis was used to reduce the redundancy in the number of the variables and to define the underlying structure. In this study, 11 variables were pre-selected to perform the PCA analysis. They are:

- total number of vehicles;
- average speed;
- average delay time;
- average number of stops;
- average stop delay;
- average density;
- lane 1 density;
- lane 2 density;
- lane 1 speed;
- lane 2 speed; and
- total surrogate crashes.

Lane 3 measures were not selected because some of the scenarios had no third lane, and the measure is not comparable across all scenarios modeled.

From Table 11, three Principal Components were estimated to address more than 85 percent of the variance. The three PCs were determined through further analysis as shown in Table 12 which shows that the first component is highly related to the average density, lane density as well as the total surrogate crashes from the Surrogate Safety Assessment Methodology (SSAM). See Appendix A for details on the SSAM process. Although the factor loading for the density measures was greater, a further analysis indicated a significant correlation between density and total surrogate crashes. For consistency with the previous analysis on frontage road-exit ramp yield treatment, the total surrogate crash measure was chosen to represent the first factor. The average speed and the average delay were chosen to represent the second and third factors as shown in Table 12.

Table 11. Principal Component Analysis (Total Variance) for Frontage Road-U-Turn Data.

Component	**Initial Eigen Values**			**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**		
	Total	***Percent of Variance***	***Cumulative Percent***	***Total***	***Percent of Variance***	***Cumulative Percent***	***Total***	***Percent of Variance***	***Cumulative Percent***
1	4.501	40.916	40.916	4.501	40.916	40.916	4.090	37.185	37.185
2	2.730	24.814	65.730	2.730	24.814	65.730	2.996	27.240	64.424
3	2.514	22.858	88.588	2.514	22.858	88.588	2.658	24.163	88.588
4	.557	5.063	93.651						
5	.335	3.045	96.695						
6	.176	1.601	98.296						
7	.100	.911	99.207						
8	.059	.532	99.740						
9	.014	.123	99.863						
10	.012	.111	99.974						
11	.003	.026	100.000						

Extraction Method: Principal Component Analysis.

Table 12. Rotated Component Matrix Analysis for Frontage Road-U-Turn Data.

Variable	**Component**		
	1	***2***	***3***
Lane 1 Speed	.039	.958	-.020
Lane 2 Speed	-.159	.963	-.023
Average Speed	-.141	**.964**	-.018
Lane 1 Density	.983	-.109	.026
Lane 2 Density	.953	.011	.024
Average Density	.966	-.145	.025
Average Delay	.010	-.066	**.974**
Average Stop Delay	.037	-.009	.871
Average Number of Stops	-.049	.016	.971
Total Surrogate Crashes	**.834**	-.421	.023
Number of Vehicles	.733	.086	-.069

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.
Numbers in bold show corresponding correlation factor for selected MOEs.

Summary Results

As already mentioned in the previous sections, there was no Level 1 analysis for the U-turn yield treatment analysis. The Level 2 results from the 108 scenarios for each of the five U-turn treatments were averaged and shown in Table 13. Table 14 shows the rankings of the various U-turn yield treatments for the operational and safety performance measures. The five U-turn yield treatment categories are shown in Figure 13.

Table 13. Average Operational and Safety Performance Measures of U-Turn Yield Categories.

Yield Category	**Operations**			**Safety**
	Average Speed (mph)	***Average Density (veh/mile)***	***Average Delay (sec/veh)***	***Number of Surrogate Crashes***
1	31.56	22	7.07	148
2	33.20	14	2.49	111
3	38.50	20	1.42	125
4	33.47	14	2.51	108
5	39.00	13	0.92	55

Table 14. Operational and Safety Performance Summary of U-Turn Yield Categories.

Yield Category	**Operations**				**Safety (Surrogate Crashes)**	
	Average Speed		**Average Delay**			
	Frequency Rated #1	***Percent Rated #1***	***Frequency Rated #1***	***Percent Rated #1***	***Frequency Rated #1***	***Percent Rated #1***
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	10	9.3	3	2.8	4	3.7
4	0	0	0	0	2	1.9
5	98	90.7	105	97.2	102	94.4
Total	108	100	108	100	108	100

Category 5 (U-turn enters as added lane, no downstream entrance ramp) is the overall best selection, with the highest average speed, lowest delay, and smallest number of crashes. In general, the delay and number of crashes are less than half the values for the other categories. This should not be a surprising result as the added lane for the U-turn greatly reduces the number of lane changes required by the ending of the U-turn lane (Categories 1 and 3) or by not having a downstream entrance ramp that would require traffic wishing to stay on the frontage road to change lanes (Categories 2 and 4).

One choice in the design of U-turn lanes is whether to end them with a YIELD sign and a short acceleration lane on the frontage road (Category 1) or provide a longer acceleration lane that would allow the U-turning traffic to merge with the frontage road traffic (Category 3). It would appear to be better to use an acceleration lane because Category 3 outperforms Category 1 in every measure. However, it should be noted that Category 1 includes a downstream entrance ramp, causing more of the frontage road traffic to be in the left lane, where the merging from the U-turn lane occurs, likely reducing speed and increasing delay and the number of crashes.

When a continuous lane is provided between the U-turn lane and the downstream entrance ramp, the engineer can choose to provide an acceleration lane (double white lines) for some of the length of the continuous lane to allow the U-turning vehicle some distance to match the speeds of the vehicles on the frontage road (Category 4) or to merely provide a YIELD sign, allowing vehicles to enter the frontage road immediately at the end of the U-turn lane (Category 2). It would seem that the former treatment (with acceleration lane) would provide better efficiency and safety. Yet the results of the simulation runs imply that there is virtually no difference in any of the MOEs evaluated. It should be noted that these two treatments were provided at (simulated) sites with similar geometric conditions. Provision of the acceleration lane resulted in a shorter distance for vehicles to change lanes (into or out of the left lane).

Detailed Results

Entrance Ramp Categories

To better compare U-turn yield treatments with similar geometry (with or without the presence of a downstream ramp), the categories were broken down into ones with and without a downstream entrance ramp into the freeway. Table 15 and Table 16 show the performance of U-turn yield treatment categories with and without a downstream entrance ramp respectively.

Table 15. Operational and Safety Performance Summary of U-Turn Yield Categories with Downstream Entrance Ramp.

Yield Category	**Operations**				**Safety (Surrogate Crashes)**	
	Average Speed		**Average Delay**			
	Frequency Rated #1	***Percent Rated #1***	***Frequency Rated #1***	***Percent Rated #1***	***Frequency Rated #1***	***Percent Rated #1***
1	1	0.9	0	0	3	2.8
2	12	11.1	71	65.7	36	33.3
4	95	88.0	37	34.3	69	63.9
Total	108	100	108	100	108	100

Table 16. Operational and Safety Performance Summary of U-Turn Yield Categories without Downstream Entrance Ramp.

Yield Category	Operations				Safety (Surrogate Crashes)	
	Average Speed		Average Delay			
	Frequency Rated #1	*Percent Rated #1*	*Frequency Rated #1*	*Percent Rated #1*	*Frequency Rated #1*	*Percent Rated #1*
3	10	9.3	3	2.8	4	3.7
5	98	90.7	105	97.2	104	96.3
Total	108	100	108	100	108	100

Category 4 (U-turn has added lane with no YIELD sign) performed best in terms of average speed and surrogate crashes of all the categories with a downstream entrance ramp option. The better performance of Category 2 (provision of a YIELD sign, allowing vehicles to enter the frontage road immediately at the end of the U-turn lane) versus Category 4 in terms of the average delay was not expected. Researchers found that at lower volumes, Category 2 performed slightly better (in most cases by just about half a second better) than Category 4. However, for higher volumes, Category 4 performed best in 58 percent of scenarios analyzed, as shown in Figure 21.

For the two categories not having a downstream entrance ramp, Category 5 (U-turn enters as added lane) outperformed Category 3 (U-turn has acceleration lane with double white line and no YIELD sign) in all measures.

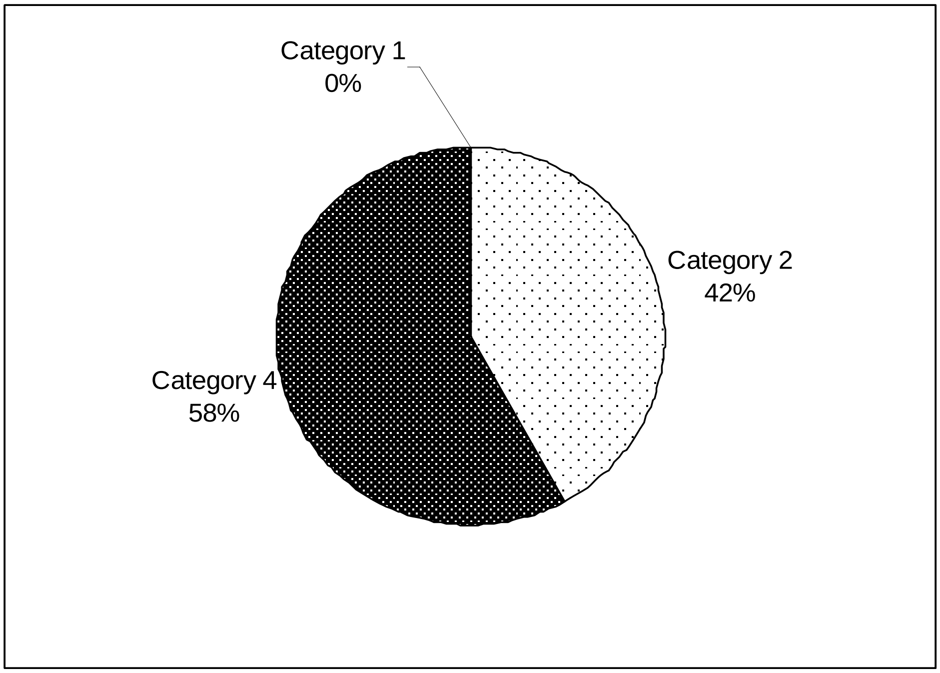


Figure 21. Average Delay Performance for High U-Turn and High Frontage Road Volume Scenarios for U-Turns with Downstream Entrance Ramp.

Performance Index

In an effort to provide an overall performance measure for the various categories similar to that developed for the frontage road-exit ramp yield categories, a performance index was developed to combine the operational and safety performance measures for U-turn yield treatment categories. This index was a subjective undertaking based on:

- the data available (surrogate crash data vs. hard crash data);
- consultation with the Project Monitoring Committee; and
- the experience of researchers.

The hypothesis assumed a simple linear function index of Average Delay (x), Average Speed (y), and Total Crashes (z) by weighting the operational performance measures (average delay and average speed) more than the safety performance measure (surrogate crashes). Due to much smaller delay values compared with the average speed (speed values were on average about 40 times the average delay values), operational measures weighted twice as much as the safety measure, and the fact that speeds have an inverse relation to the PI (the higher the speeds, the lower the PI), researchers assumed the following relation to define the performance index as: $I = 2(40x - 0.5y) + z$. The relation also sought to prevent the occurrence of negative PI numbers.

While this approach is simple, it afforded the researchers the chance to develop an overall Performance Index to combine the operational and safety performance of the various categories of yield treatment. The result of the combined PI is shown in Table 17 for categories with and without an entrance ramp.

Table 17. Result of Performance Index for U-Turn Yield Categories.

Yield Category	**Combined PI**	
	Frequency Rated #1	***Percent Rated #1***
With Entrance Ramp		
1	1	0.9
2	51	47.2
4	56	51.9
Total	108	100
Without Entrance Ramp		
3	5	4.6
5	103	95.4
Total	108	100

The results are similar to those obtained for the separated operational and safety performance measures with Category 4 slightly better overall than Category 2 for U-turns with a downstream entrance ramp. A more detailed analysis similar to that provided for the frontage road–exit ramp yield treatment results can be performed with the database program to be provided with this report. The impact of individual features (spacing of driveways or U-turn flow, etc.) can be evaluated to help answer specific design or operational questions.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions could be made from the analysis performed in this research for the yield treatment of frontage road-exit ramp and frontage road-U-turn merge areas.

Frontage Road–Exit Ramp Yield Treatment

- Category 3 (featuring a forced merge of exit ramp with frontage road) yield treatment and Category 6 (featuring a short deceleration lane for the exit ramp) produced the worst overall performance in terms of operations and safety.
- Category 1A and 1 (exit ramp has own lane with and without a DO NOT CROSS WHITE LINE sign and without a YIELD sign) consistently performed the best.
- Generally, YIELD signs caused increased delays at such intersections and were not found to increase safety.
- Retrofitting all current yield treatment options to either a Category 1 or 1A is recommended to provide uniformity to drivers and consistency in TxDOT districts. See Figure 22 for a sample illustration of recommended retrofitting from Category 3 (forced merge) to Category 2.

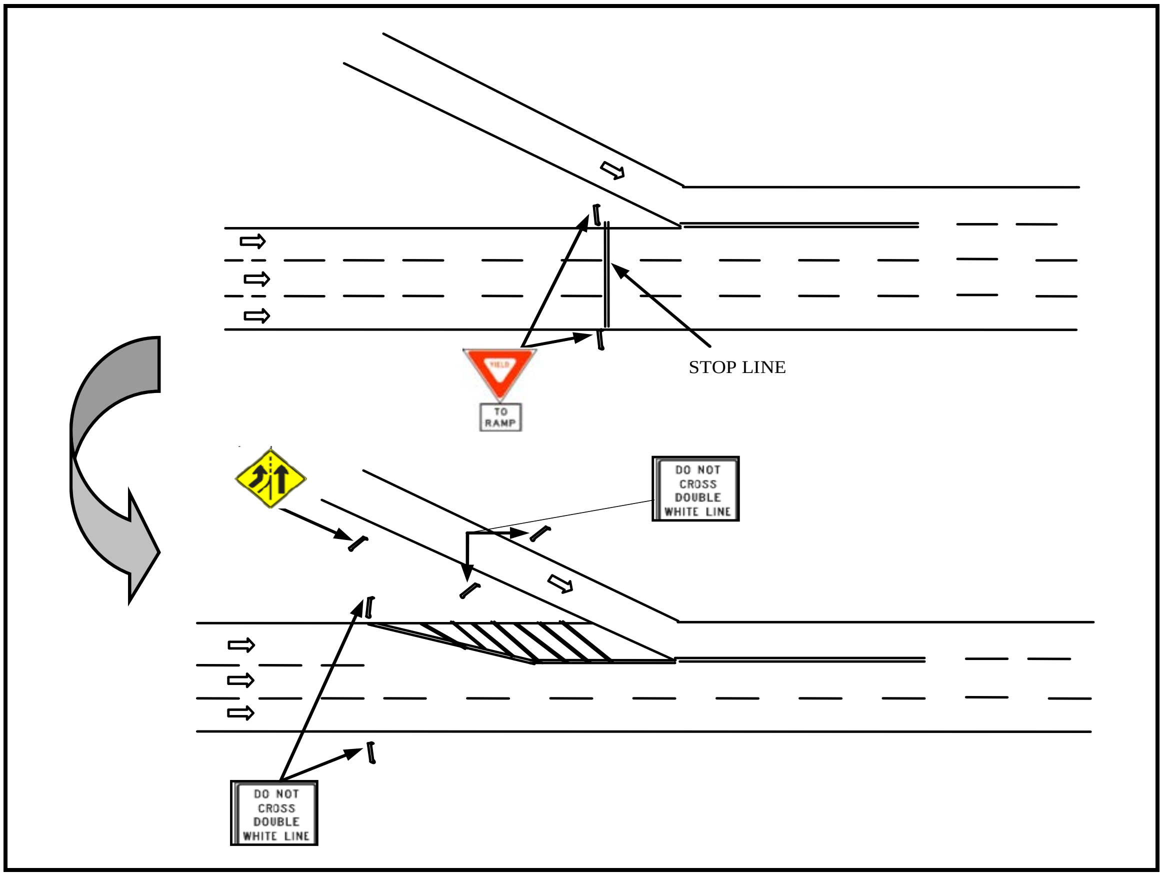


Figure 22. Illustration of Recommended Retrofit Yield Treatment.

Frontage Road–U-Turn Yield Treatment

The following conclusions can be derived from the U-turn analysis.

- With no downstream entrance ramp, Category 5 appears to provide the best overall performance. Provision of the continuous lane will result in better operation and safety (but the U-turn flows may not justify the addition of a lane).
- With a downstream entrance ramp, Category 4 seems to provide the best overall performance; however, Categories 2 and 4 are very close. Again, the provision of an added lane unsurprisingly results in improved efficiency and safety.
- The addition of a YIELD sign does not appear to improve safety, although the case of no YIELD sign without an acceleration lane was not considered.

FUTURE RESEARCH

Further analysis will be required to explore the impact of other geometric limitations such as grades on the yielding behavior of drivers. It might also be necessary to perform a similar analysis on driver yielding behavior in other states as driver behavior and comprehension of yielding might vary from state to state.

REFERENCES

1. *Transportation Code*. Chapter 545, §545.154. "*Vehicle Entering or Leaving Limited-Access or Controlled-Access Highway*." Acts 1995, 74th Leg., ch. 165, § 1, eff. Sept. 1, 1995 (most recent version is also found in *Texas Traffic Laws*, 2004 edition, Gould Publications.

2. Gattis, J.L., C.J. Messer, and V.G. Stover. *Delay to Frontage Road Vehicles at Intersections with Ramps.* Report FHWA/TX-86/402-2, Texas Transportation Institute, Texas State Department of Highways and Public Transportation. June 1988.

3. Fitzpatrick, K., R.L. Nowlin, and A.H. Parham. *Procedures to Determine Frontage Road Level of Service and Ramp Spacing.* Report FHWA/TX-97/1393-4F, Texas Transportation Institute, Texas Department of Transportation. August 1996.

4. Jacobson, M.S., R.L. Nowlin, and R.H. Henk. *Development of Improved Guidelines for Frontage Road Driveway Access Location.* Report TX-99/2927-1, Texas Transportation Institute, Texas Department of Transportation. September 1998.

5. *Roadway Design Manual*. Texas Department of Transportation. 2006. http://onlinemanuals.txdot.gov/txdotmanuals/rdw/index.htm

6. Drew, D.R. *Traffic Flow Theory and Control*, McGrawHill Inc., New York. 1968.

7. Mahmassani, H., and Y. Sheffi. Using Gap Sequences To Estimate Gap Acceptance Functions, *Transportation Research, Part B,* vol. 15, Transportation Research Board, National Research Council, 1981, pp 143-148.

8. Wang, Z. Effects of Reference Line Positioning on Gap Acceptance Data in *Road & Transport Research* website. http://findarticles.com/p/articles/mi_qa3927/is_200012/ai_n8922329/pg_1. Accessed January 15, 2006.

9. Hodge, B.G. "Traffic Control – Signing and Marking Exit Ramp Merging with One-way Frontage Roads." *Memorandum to All District Engineers*. June 9, 1988.

10. *Traffic Operations Manual: Signs and Markings Volume*. Texas Department of Transportation. November 1997.

11. Lopez, C. "Proposed Standard Sheets FPM (5)-2003, FPM (6)-2003 and FPM (7)-2003." *Memorandum to All District Engineers*. April 17, 2003.

12. Freeway Signing Handbook. Texas Department of Transportation. 2008. http://onlinemanuals.txdot.gov/txdotmanuals/fsh/fsh.pdf

13. *Texas Manual on Uniform Traffic Control Devices*. Texas Department of Transportation. 2006. http://www.txdot.gov/publications/traffic.htm#06%20mutcd

14. Van Houten R., J.E.L. Malenfant, and D. McCusker. Advance Yield Markings Reduce Motor Vehicle/Pedestrian Conflicts at Multilane Crosswalks with an Uncontrolled Approach. Center for Education and Research in Safety, Nova Scotia, 2002.

15. *VISSIM 4.10 User Manual*. PTV Planung Transport Verkehr AG: Karlsruhe, Germany, 2005.

16. Dowling, R., A. Skabardonis, J. Halkias, G. McHale, and G. Zammit. *Guidelines for Calibration of Mircosimulation Models: Framework and Application*, Transportation Research Record 1876, Transportation Research Board, Washington, D.C., 2004, p. 1-9.

17. Gettman, D., and L. Head. *Surrogate Safety Measures from Traffic Simulation Models*. Federal Highway Administration Report No. FHWA-RD-03-050, Washington, D.C., January 2003.

APPENDIX A–SIMULATION MODELING

BACKGROUND

Microscopic simulation (or microsimulation) has become an increasingly popular and effective tool in both quantifying and illustrating transportation problems and evaluating possible solutions to these problems. Simulation modeling tools now provide visualization of traffic flow on the transportation system for both current and proposed conditions. In addition, the vast array of design scenarios for different transportation alternatives can be simulated to assess and maximize operational performance.

Microsimulation is most useful when modeling multiple facility types where congestion is often an issue. The more complex the situation and the more detailed the results desired, the greater the advantage microsimulation can have compared to theoretical methods.

The simulation software market is dynamic. Developers are constantly releasing updated versions and additional plug-ins. The researchers chose VISSIM ® (German acronym for "traffic in towns – simulation") as the simulation tool for this study. Planung Transport Verkehr (PTV), Germany, developed VISSIM to model urban traffic and public transit operations based on microscopic time-step and behavior. The program can analyze traffic and transit operations under constraints such as:

- lane configuration,
- traffic composition,
- traffic signals,
- transit stops, and
- weaving behaviors, etc.

This flexibility allows the simulation tool to evaluate various alternatives based on transportation engineering and planning Measures of Effectiveness *(15)*.

VISSIM has a user-friendly graphical interface, which allows the creation of networks by importing background aerial photography or Computer Aided Design (CAD) layouts. The user can then "draw" the network and apply attributes (e.g., lane widths, speed zones, priority rules, etc.). The sophisticated vehicle simulation model allows the user to accurately mimic and analyze complex traffic interactions such as weaving sections and merges.

For presenting simulation results, users can customize their output data set by configuring in VISSIM before the simulation. Information contained in these files can include:

- detailed travel time and delay statistics;
- queue length statistics;
- detailed signal timing information;
- graphical output of space diagrams and speed profiles; and
- environmental indicators.

CALIBRATION

For any microsimulation study, the calibration procedure is always a crucial step. Model calibration is the procedure where model parameters are adjusted so that the model represents the local driver behavior and traffic performance characteristics. In other words, model calibration is the process to make sure that the model behaves the same as the observed traffic. This task is performed after all input data and model coding have been thoroughly checked.

Calibration is important because no single model is expected to have the ability to equally represent all possible traffic conditions. Even the most detailed microsimulation model has variables determined by real-world traffic conditions (*16*). Every microscopic simulation software package includes a set of user-defined parameters for the purpose of calibrating the model to local conditions. Even though the software developers suggest default values for these user-defined parameters, models that use these default values can rarely produce accurate results. The objective of calibration is to find the set of parameter values for the model that best duplicates local traffic conditions and behavior.

The calibration efforts focused on the use of observed data to calibrate the most critical parameters in the simulation. The calibration for a microsimulation study ultimately requires comparing simulated data with field-observed traffic data. Because the field observations vary from day to day due to the stochastic nature of traffic, the calibration objective was to re-construct the typical real-world traffic variation in the simulation.

Calibration Procedure

The major calibration effort in this project consists of four parts, and Figure 23 below depicts the process.

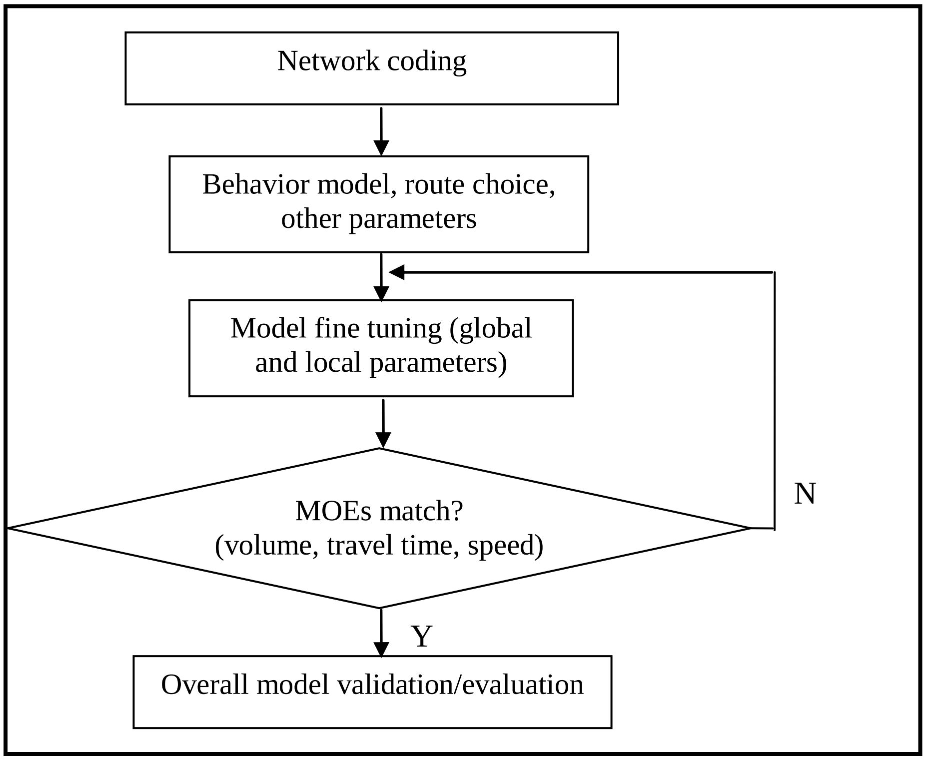


Figure 23. Calibration Procedure Flow Chart.

Network Coding

VISSIM networks are based on links and connectors. Links are used to define the width and number of lanes for a given roadway segment. There are five different link types, and each link type is represented by its driving behavior model. Connectors are used to connect the links at intersections and implicitly have the same type as the link from which they originate. Since this research focuses on frontage road operations, the link type for this model is urban (type 1). Links and connectors of the weaving area in this project are built on an aerial photograph downloaded from Google Earth™.

The network geometry and signal timing were coded in VISSIM with particular checks made to ensure they reflect actual field conditions. The network geometry is a major factor affecting vehicle behavior. To ensure accurate coding, certain issues need to be reviewed such as:

- roadway type;
- link and intersection locations;
- barred turns;
- closures and restrictions;
- lane usage and sign-posting numbers; and
- traffic volume data.

Roadway segment coding includes:

- freeway;
- frontage road;
- arterials, and
- the ramp and connectors.

Roadway sections within VISSIM are modeled as continuous links to the extent possible. The link breaks are only introduced in cases that involve the addition or subtraction of a lane due to lane drops/additions or an on/off ramp configuration. For each link, the user can specify various details such as the number of lanes, link type, lane width, gradient, among other factors. VISSIM visually presents the roadway curve perfectly by using intermediate points within a link. Connectors are used between links and in the case of a lane drop, a connector is used to link the ending lane to its merge lane, and yield rules are specified. In the case of a lane addition, a connector links the diverging lane to the added lane. Aerial photographs and site data collection of geometry (including distances from the exit gore to driveways as well as downstream intersection/entrance ramp) were used to code network geometry accurately.

Traffic volume includes:

- link count;
- turning count in the intersections;
- vehicle mix; and
- traffic route.

Traffic volumes collected from the field are entered into the network entry links. The traffic data collected includes the vehicle mix (percentage of trucks versus cars) which allows more accurate representation of the real-world vehicle operating characteristics within the traffic stream. Junction-specific allocation, such as turning movement specification, enables the traffic route choice function to be utilized. Within each trip origin, an array of routes can be defined to traverse different links.

Two sources of volume data were reduced. They both involved volumes from peak evening hour periods, which happened to be the highest volumes for all the study sites. The initial volume data was collected through the use of pneumatic tubes across the exit ramp, frontage road lanes, and U-turn lanes (see Figure 10 and

Figure 14). Twenty-four hour counts were obtained, and the peak hour was determined.

The other source of volume data was obtained from video recordings of each site. This volume source was used as input into the VISSIM model. The data were collected for two-hour slots, and the peak hour was determined from the resulting data. The tube count data were used as part of the calibration process to verify the volume of traffic output from the VISSIM model. The volume data were an important component of calibrating the VISSIM model. Speed data were collected at three main locations at each frontage road–exit ramp site:

- on the exit ramp about 100 feet in advance of the gore;
- on the frontage road about 100 feet in advance of the gore; and
- midway between the gore and the downstream intersection (see Figure 10).

The purpose of collecting these data was to further help in calibrating the simulation models for each site and to try and depict, to the fullest extent possible, real-life operations. The speed data were used to validate the model's calibration as they were compared to the performance output from the VISSIM models.

In this project, the traffic composition consists of 95 percent cars and 5 percent Heavy Goods Vehicles (HGV or trucks). Both vehicle types are set to enter the network with speed distribution number 70, which has a minimum speed of 42.3 mph and a maximum speed of 48.5 mph.

Decisions of Behavior Model, Route Choice, and Other Variable Parameters

Calibration allows researchers to find a set of model parameters that enable the model to produce as-close-as-possible results that match field measurements. Usually there are four categories of parameters that can be changed:

- travel demand;
- route choice;
- driving behavior; and
- other local link attributes.

In this study, the travel demand and route choice are fixed, so only the behavior model and link attributes could be adjusted. Video recordings collected OD data for vehicles coming off the exit ramp and vehicles on the frontage road. Vehicles exiting the ramp were tracked to determine if they:

- made a right turn into any driveway;
- made a right turn;
- went through or made a left turn at the downstream traffic signal; or
- made a U-turn.

Likewise, traffic that was already on the frontage road was tracked to determine their eventual turning movement. A similar process was used to collect OD data for vehicles coming off U-turns and vehicles on the frontage road coming from the intersection immediately upstream. U-turn vehicles were tracked to see if they continued on the frontage road, entered the entrance ramp, or weaved to enter a driveway.

This process enabled researchers to create an OD matrix as input into the VISSIM models developed for each site. It also ensured that the weaving pattern at each site was fairly accurately replicated in the VISSIM models. This information was also used as part of calibrating the simulation model.

Three basic models are implemented within VISSIM to control the movement of individual vehicles in the network:

- the car following;
- gap acceptance; and
- lane changing models.

The overall behavior of the model can be changed considerably by increasing or decreasing these parameters. Aside from changing the global behavior model parameters, it is possible to alter the local behavior parameters in the yield or priority rule as well. Researchers utilized this VISSIM capability to more accurately depict yielding behavior at merge areas.

Priority Rules in VISSIM

A critical aspect of modeling frontage road yield categories in VISSIM is the usage of priority rules. This feature translates to the yielding rules in real life, because this project dealt heavily with vehicles yielding or not yielding to each other at the point of the exit ramp and frontage road intersection.

In VISSIM, yield priority rule, gap acceptance time, and headway can be changed to fit the real-world condition. In this project, several sets of vehicle trajectories were selected from different sites, and the headway gap times of each trajectory were recorded. The final results provided a range for adjustment of behavior model parameters. Researchers used video footage to determine gap acceptance/rejection. The research team defined the difference in time between when the frontage road vehicle came to a certain point A at the gore and the time when the exit ramp vehicle arrived at the same point A as the gap time. If the frontage road vehicle did not yield, researchers recorded a gap acceptance; if the vehicle did yield, researchers recorded a gap rejection.

The gap rejections for each vehicle in each lane were graphed for each site and a range for the minimum gap time (as defined by VISSIM) was deduced. This minimum gap time was lane-specific and served as an input in the calibration process. Figure 24 illustrates how the gap time was determined, while Figure 25 shows a sample graph of gaps rejected at a site.

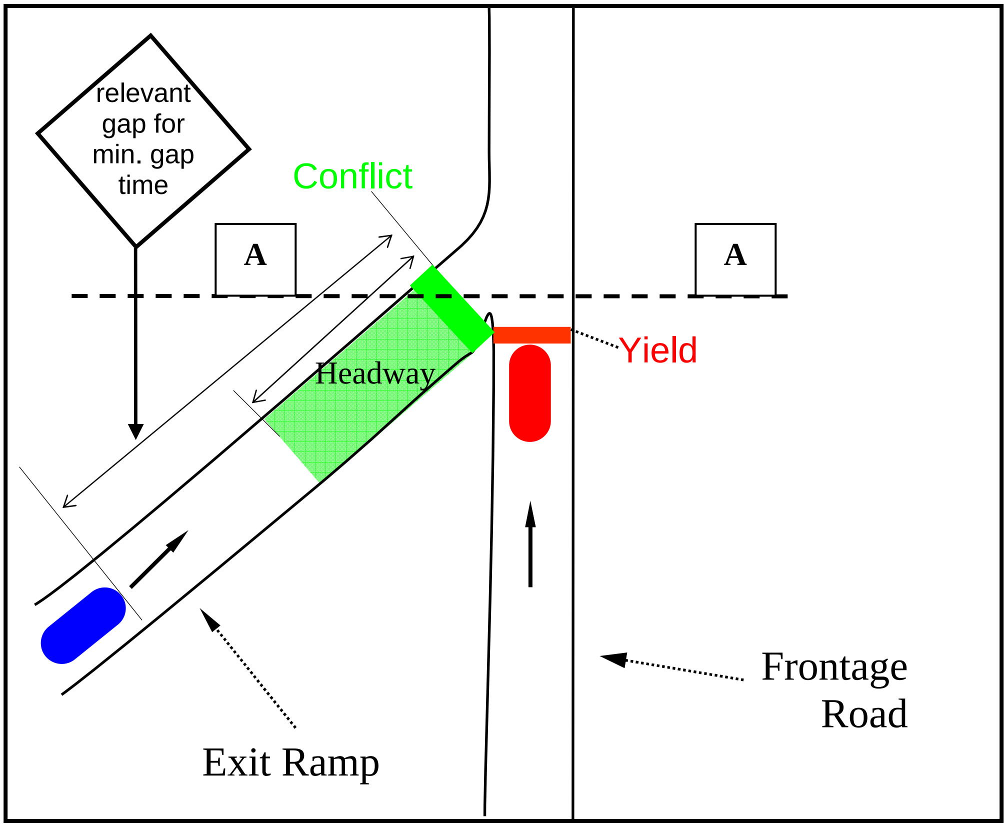


Figure 24. Yield Point Priority Rule.

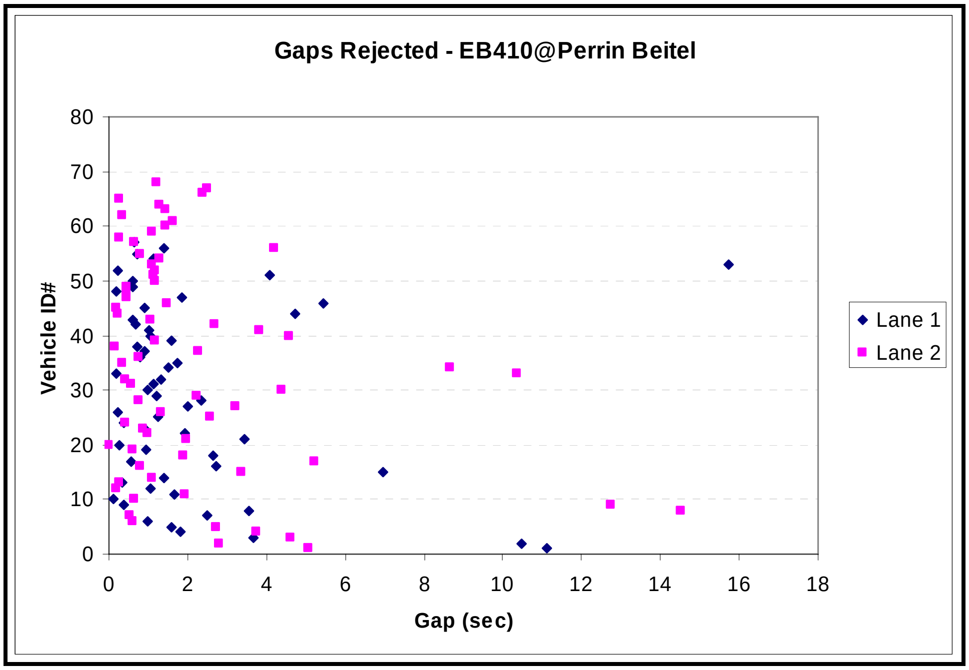


Figure 25. Graph of Rejected Gaps for Eastbound I-410 at Perrin Beitel Exit.

Goodness-of-Fit Measures

The objective of model calibration is to get the best match possible between model performance estimates and field measurements of performance. However, there is a limit to the amount of time and effort anyone can put into eliminating error in the model. There exists a point of diminishing returns where large investments in effort yield small improvements in accuracy. The analyst needs to know when a set of measures is selected and the performance from simulation is close enough to the field data in the chosen measures, the calibration effort can be considered accomplished.

Model Fine Tuning and Overall Evaluation

In the next step, researchers used aggregated traffic data to fine tune the established simulation model in order to reflect network-level congestion effects. The results from model fine-tuning provided feedback to previous stages and allowed researchers to modify the simulation model until the best matching with field data was achieved. The local attributes were fine-tuned using the trial-and-error method in order to reconstruct traffic variations and match the congestion pattern of the study network. The local attributes include the location of the YIELD sign, speed distribution, and the speed sign location.

The Texas Manual on Uniform Traffic Control Devices (TMUTCD) states, “The YIELD sign shall be located as close as practical to the intersection it regulates, while optimizing its visibility to the road user it is intended to regulate” *(13)*. Researchers observed that vehicles tend to yield slightly in advance of the yield sign proper, so they varied the location of the yield point in VISSIM by treatment and in different traffic conditions. For instance, in double white line cases, vehicles tend to yield farther up the frontage road closer to the termination of the double white line. Such observations from video data and general traffic observation governed the range of the yielding point in VISSIM.

Calibration Results and Analysis

Calibration for Frontage Road and Exit Gore Merge Area

Output statistics gathered by the model were checked for qualitative and quantitative validity. The simulation runs for the base conditions were evaluated with the data from the tube counters. The first analysis compared the model outputs to real-life traffic performance and specifically measured speed and flow data (see example data in Figure 26 and Figure 27). Then the detailed speed distribution was compared side by side with the field data distribution to validate the quality of the calibration (sample shown in Figure 28). Finally, a video audit was undertaken to compare queuing levels, site-specific driver yielding behavior, and weaving patterns of actual recorded peak time periods to those observed in the calibrated VISSIM models (see Figure 29).

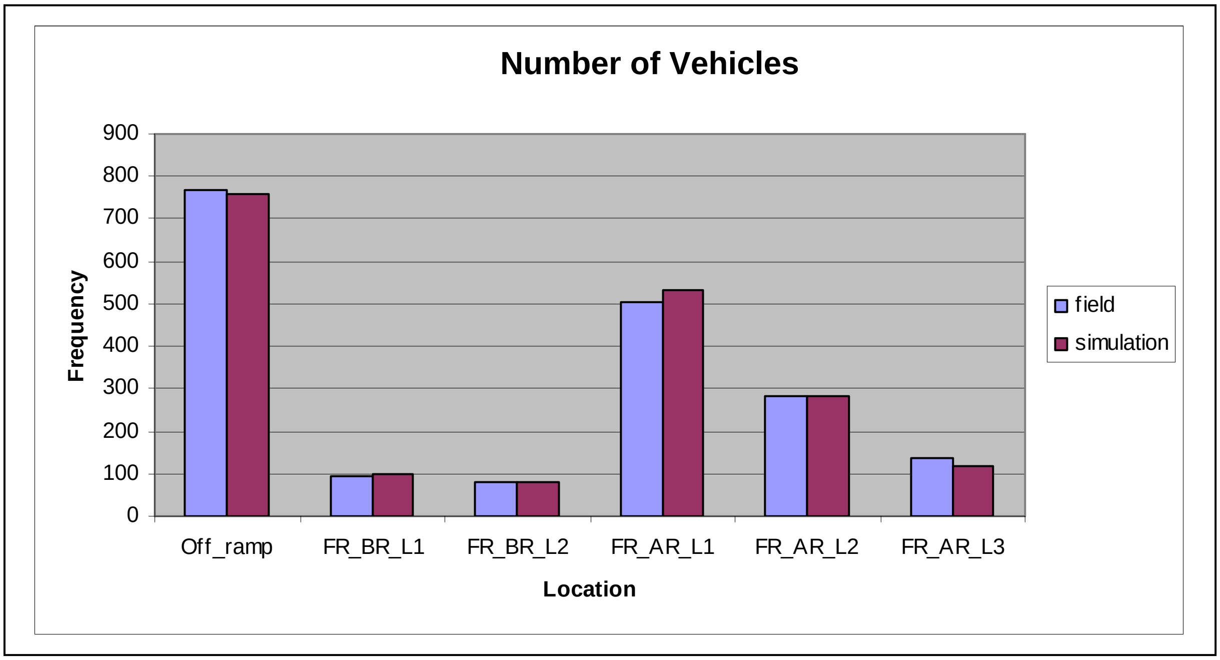


Figure 26. Calibration Data for Traffic Volume for Frontage Road–Exit Ramp Site Number 5.

<u>Legend for Figure 26 and Figure 27</u>

FR – Frontage Road
BR – Location before (upstream of) exit ramp gore
AR – Location after (downstream of) exit ramp gore
L1 – Lane 1 (left-most lane)
L2 – Lane 2 (next lane – from the left)
L3 – Lane 3 (right lane)

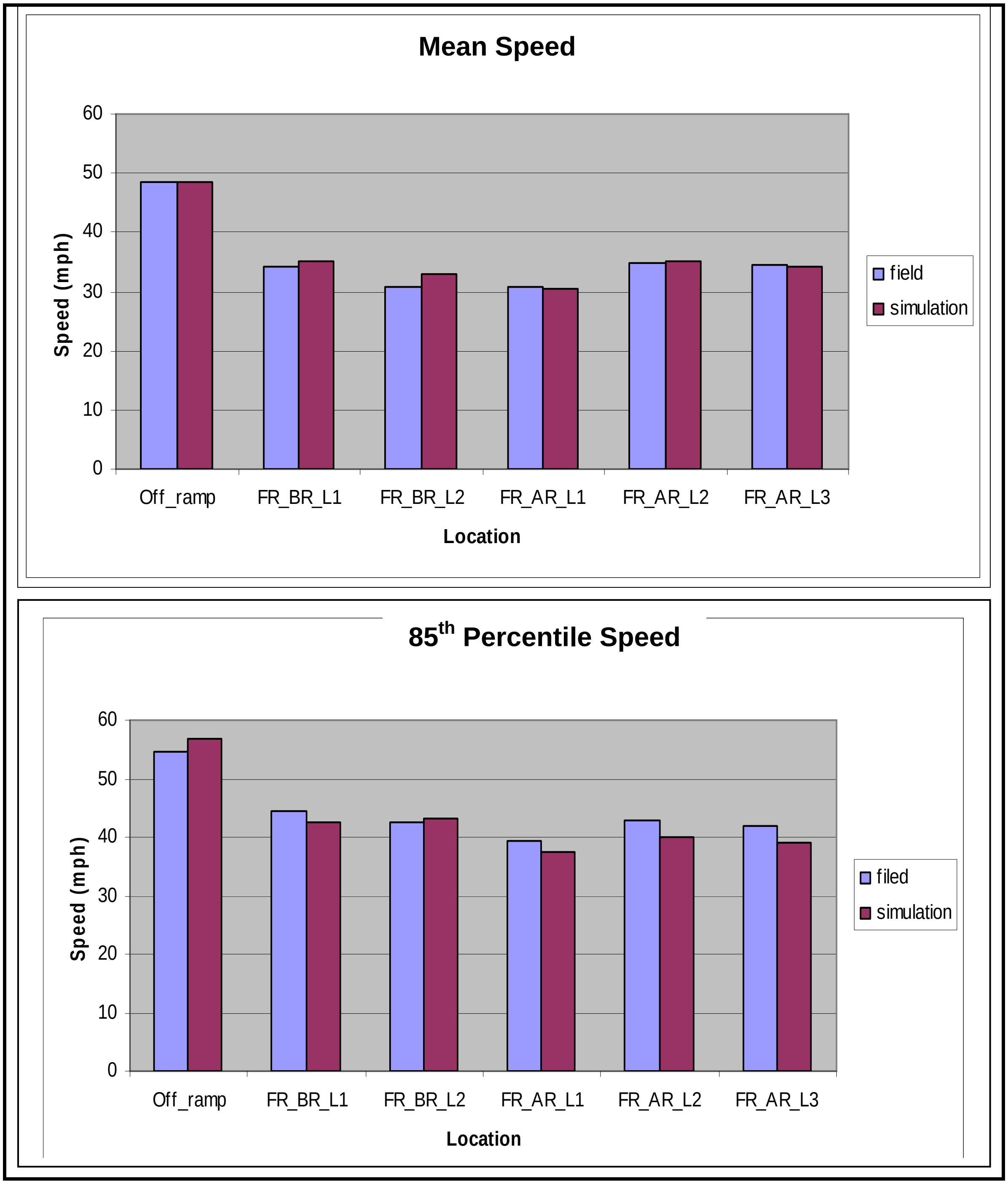


Figure 27. Calibration Data for Speeds at Frontage Road–Exit Ramp Site Number 5.

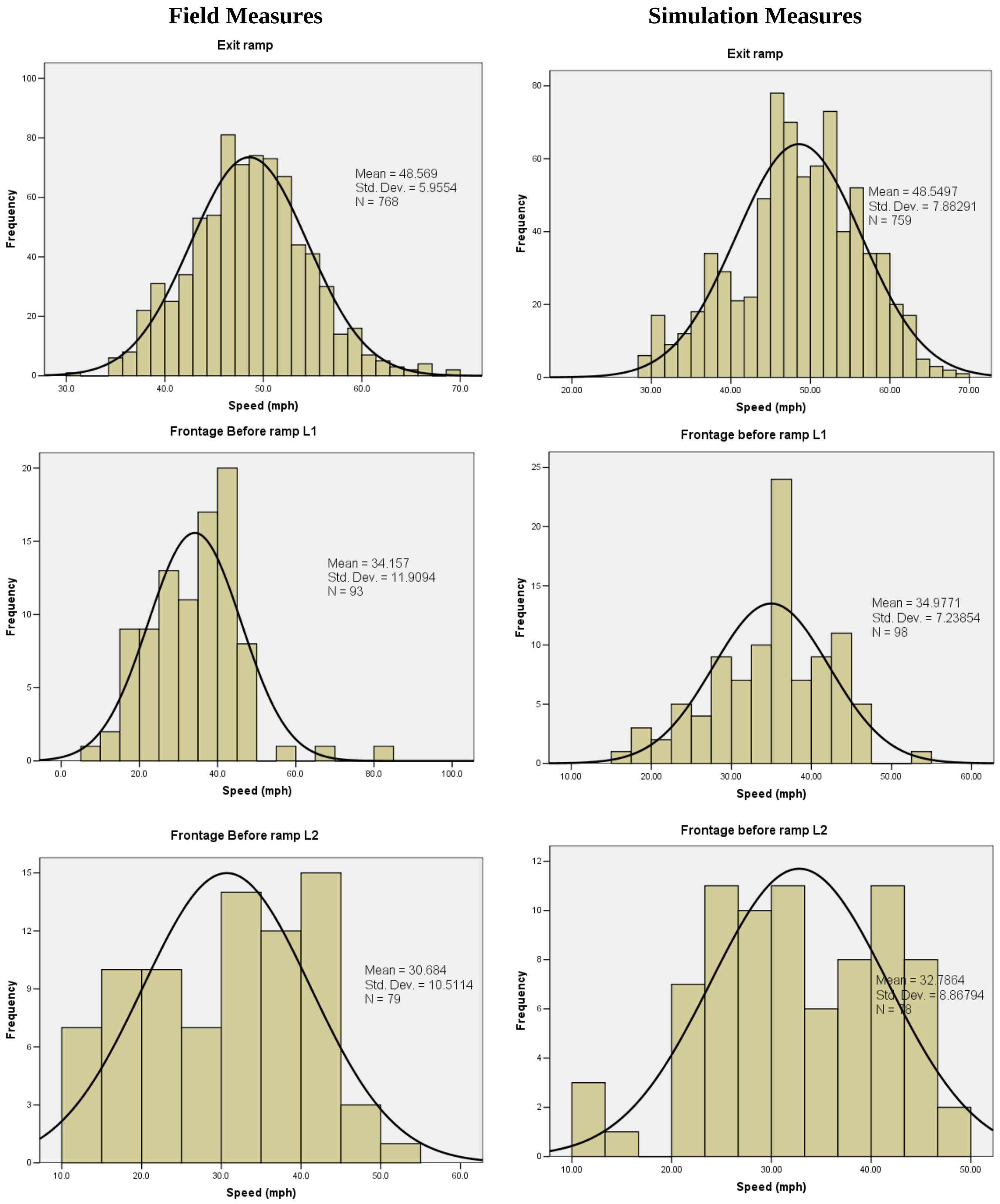


Figure 28. Calibration Speed Distribution for Frontage Road–Exit Ramp Site Number 5.

Figure 29. Video Audit of Calibrated VISSIM Models.

Calibration for U-Turn and Frontage Road Merge Area

VISSIM was calibrated for U-turns using data collected from two locations: US 281 at Bitters Road in San Antonio (no downstream ramp) and US 183 at Braker Lane in Austin (downstream ramp). Values of selected parameters were changed in different runs until the best-fit model was found. The parameter selection methodology consisted of iterated runs, visual evaluation, and speed comparisons.

A comparison of average running speeds between the calibrated model and the observed data for the US 281 site is shown in Figure 30. Note that speeds were measured at five locations where lanes 1 through 3 refer to the frontage road lanes (numbered from right to left) and were taken at sites immediately upstream of the point where the U-turn lane enters the frontage road ("Before" in Figure 30) and downstream from this point ("After" in Figure 30). Using this calibrated model, similar runs were made at the second site (US 183 at Braker Lane in Austin). The results of these runs are shown in Figure 31. In this figure, the locations are:

- right lane intersection: right lane of frontage road immediately upstream of U-turn lane (and just downstream of the intersection);
- middle lane intersection: middle lane of frontage road immediately upstream of U-turn lane (and just downstream of the intersection);
- left lane intersection: left lane of frontage road immediately upstream of U-turn lane (and just downstream of the intersection);
- right turn intersection: free right turn from cross street to frontage road upstream of U-turn lane;
- UT: U-turn lane;
- right lane UT (upstream): right lane of frontage road downstream of U-turn lane;
- middle lane UT: middle lane of frontage road downstream of U-turn lane; and
- left lane UT: left lane of frontage road downstream of U-turn lane.

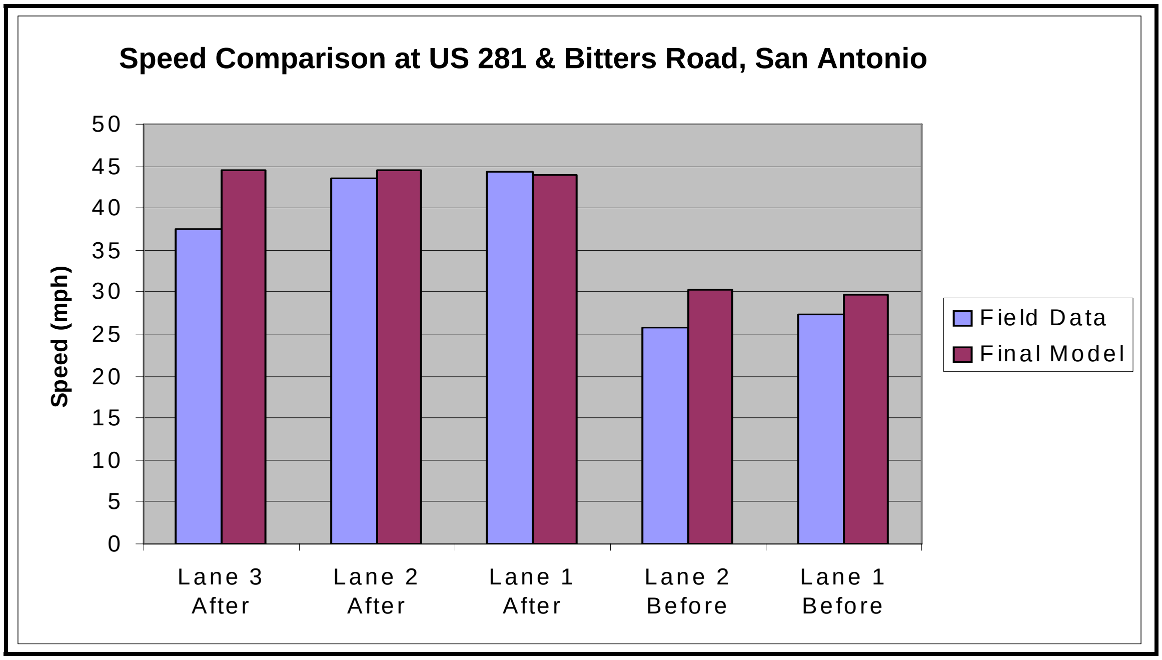


Figure 30. Sample Speed Calibration for U-Turn Site Number 5.

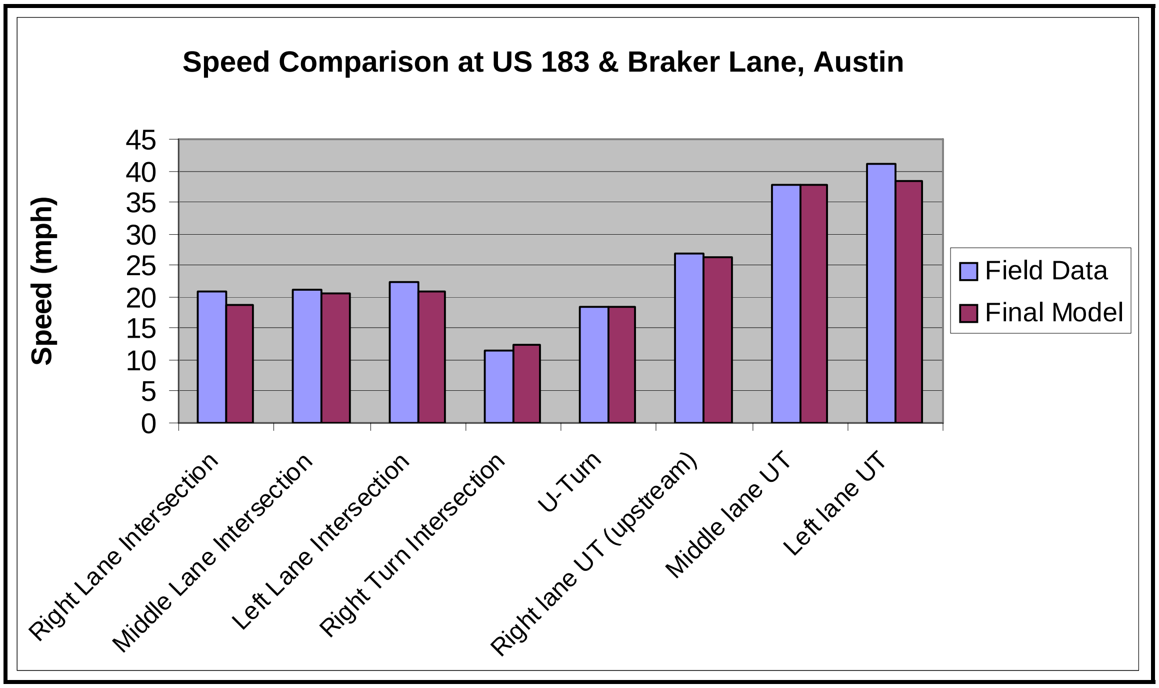


Figure 31. Sample Speed Calibration for U-Turn Site Number 6.

MEASURES OF EFFECTIVENESS

In selecting MOEs, it is important to usually ensure that the selected MOE:

- is able to reflect the changes of the different treatments;
- is independent of other measures; and
- enables data collection to be accomplished in VISSIM.

After considering the above criteria, researchers selected the below-listed MOEs for comparing the various scenarios modeled in the VISSIM simulation. The measures were divided into two broad areas:

- the system-wide measures of performance (an aggregated measure of the whole VISSIM model); and
- the weaving section measures of performance (a more detailed look at the impact on vehicles weaving on the frontage road).

Frontage Road–Exit Ramp Yield Treatment

System-Wide Measures of Performance

All vehicles released into the model were recorded for these performance measures:

- total system travel time (hours);
- average speed for vehicles in the whole system (mph);
- average delay time per vehicle in the whole system (seconds); and
- average number of stops of each vehicle in system.

Weaving Section Measures of Performance

To capture the performance of different yield treatments for frontage roads and exit ramp junctions, it was important to compare vehicle performance in the weaving sections. A total of four weaving sections or categories were created to detail weaving patterns of vehicles from:

- frontage road vehicles making a U-turn where U-turn lanes are present;
- frontage road vehicles going to the downstream intersection proper;
- exit ramp vehicles making either a left turn or through movement at the downstream intersection; and
- exit ramp vehicles making a right turn at a driveway or downstream intersection.

VISSIM has the capability of collecting the raw data of the various MOEs listed below through its evaluation module.

- vehicle number traverse the segment;
- average travel time for vehicles traverse the segment (seconds);

- average delay time per vehicle when they traverse the segment (seconds);
- average stop (standstill) delay time per vehicle when they traverse the segment (seconds); and
- average stop per vehicle when they traverse the segment.

U-Turn Yield Treatment

Likewise for the U-turn analysis, section measures of performance were defined as follows:

- The Average Running Speed is the average speed of the vehicles on the frontage road from the upstream intersection to a point 150 feet beyond the downstream entrance ramp (Categories 1, 2, and 4) or the last driveway (Categories 3 and 5). The average running speed is a space-mean-speed averaged over each lane of the frontage road.

$$S = \frac{n_1 + n_2 + \cdots + n_i}{\frac{n_1}{s_1} + \frac{n_2}{s_2} + \cdots + \frac{n_i}{s_i}} \qquad \text{(i)}$$

where:

S = average running speed in the U-turn section (mph),
s_i = average running speed in lane i (mph), and
n_i = number of vehicles in lane i.

- The Average Density is the average of the densities of each lane on the frontage road in vehicles per mile. The average density is taken over the same sections of roadway as the average running speed.
- Average Delay is calculated separately by VISSIM for each vehicle stream, where the vehicle streams are defined by the OD matrix specified by the user. Thus, the overall average delay is an average of the separate delays for each OD, weighted by the number of vehicles that traveled in each OD.

$$d_T = \frac{d_1 n_1 + d_2 n_2 + \cdots + d_i n_i}{n_1 + n_2 + \cdots + n_i} \qquad \text{(ii)}$$

where:

d_T = average delay per vehicle in entire section (sec/veh),
d_i = average delay on path i of the OD matrix (sec/veh), and
n_i = number of vehicles on path i of the OD matrix.

SURROGATE SAFETY DATA ANALYSIS

An important aspect of this research project was to look at the comparative safety of the discussed frontage road yield categories. The difficulties faced by the research team in obtaining hard copies of crash records from cities, coupled with the inadequacy of the state crash database, meant that surrogate safety measures had to be pursued to bolster the traffic operational analysis aspect of this project. Even though few measures can more accurately predict and evaluate safety than hard crash data, surrogate safety measures had to be employed in the modeling process to give some measure of comparative safety for the various types of yielding at the frontage road and exit ramp merge area.

Historically, safety has been difficult to assess for new and innovative traffic treatments, primarily because of the lack of good predictive models of crash potential and lack of consensus on what constitutes a safe or unsafe facility. The Federal Highway Administration-sponsored research project "Surrogate Safety Measures from Traffic Simulation Models" investigated the potential for deriving surrogate measures of safety from existing microscopic traffic simulation models. The process of computing the measures in the simulation, extracting the required data, and summarizing the results is denoted as the Surrogate Safety Assessment Methodology (*17*). The working procedure is shown in Figure 32.

Currently, VISSIM is one of the simulators cooperating with the project and supports the SSAM module by generating the vehicle trajectory data. The research team was given permission to use the SSAM module before its release to the public.

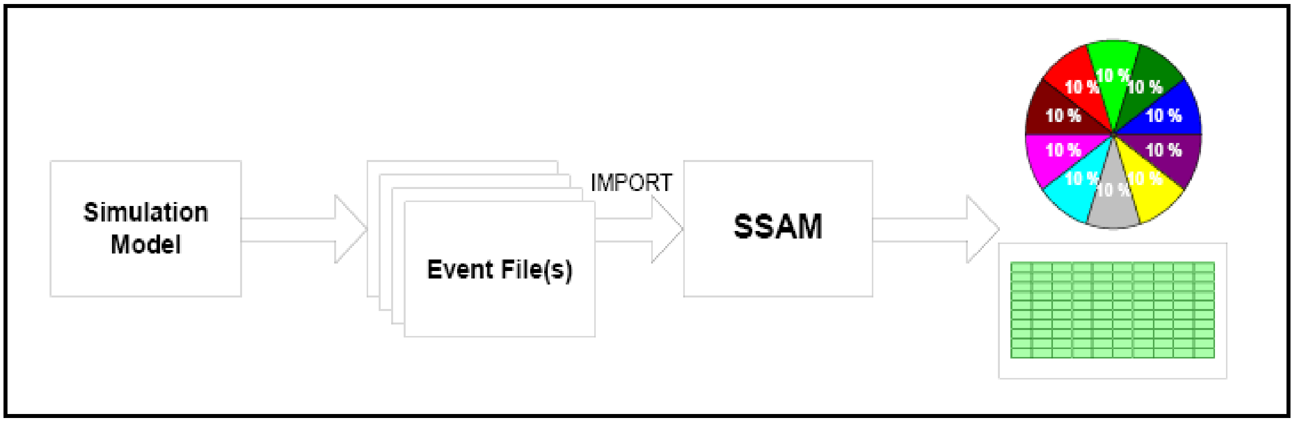


Figure 32. Work Flow for SSAM Module (*17*).

The two major surrogates used in the SSAM module and adopted for this project were (*17*):

- Post-Encroachment Time (PET): time lapse between end of encroachment of turning vehicle and the time that the through vehicle actually arrives at the potential point of collision; and
- Time to Collision (TTC): expected time for two vehicles to collide if they remain at their present speed and on the same path.

Conflict points define the situations where a crossing vehicle interrupts the progress of another vehicle, but the vehicles only interact at a specific point in space. Conflict lines describe the situations where two vehicles interact in the same lane for a period of time. Figure 33 depicts typical conflict points and conflict lines in the driving environment.

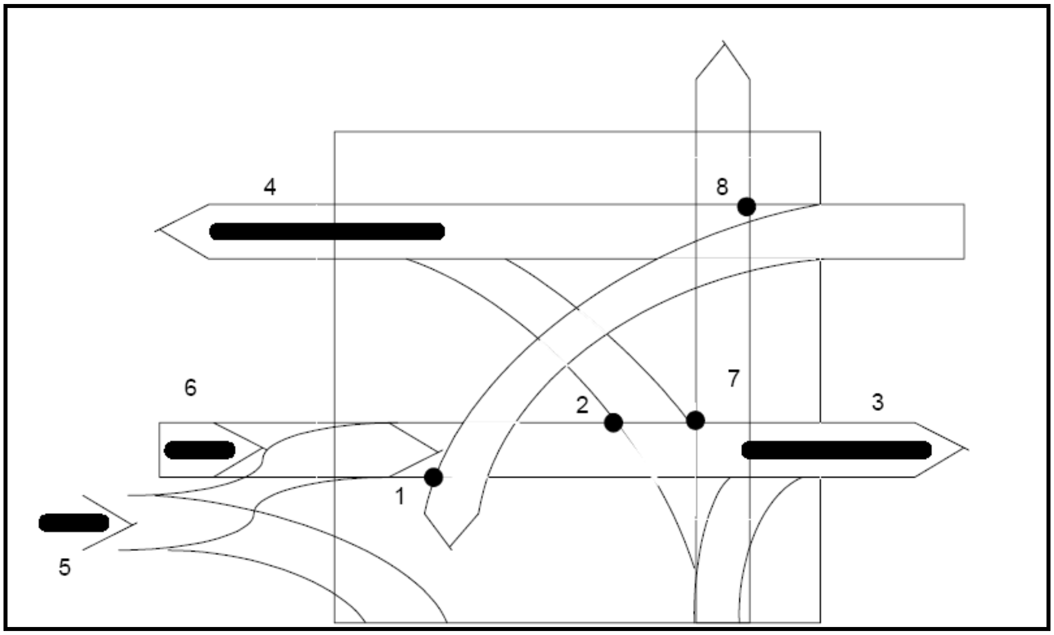


Figure 33. Conflict Point and Lines (*17*).

The SSAM module was used in this research to obtain surrogate crash data for the various frontage road–exit ramp yield treatment categories and frontage road–U-turn categories. These formed the second component of Performance Measures that were used for a comparative analysis of the various yield treatments at frontage road-exit ramp and frontage road-U-turn merge areas.

APPENDIX B-LEVEL 1 SIMULATION RESULTS

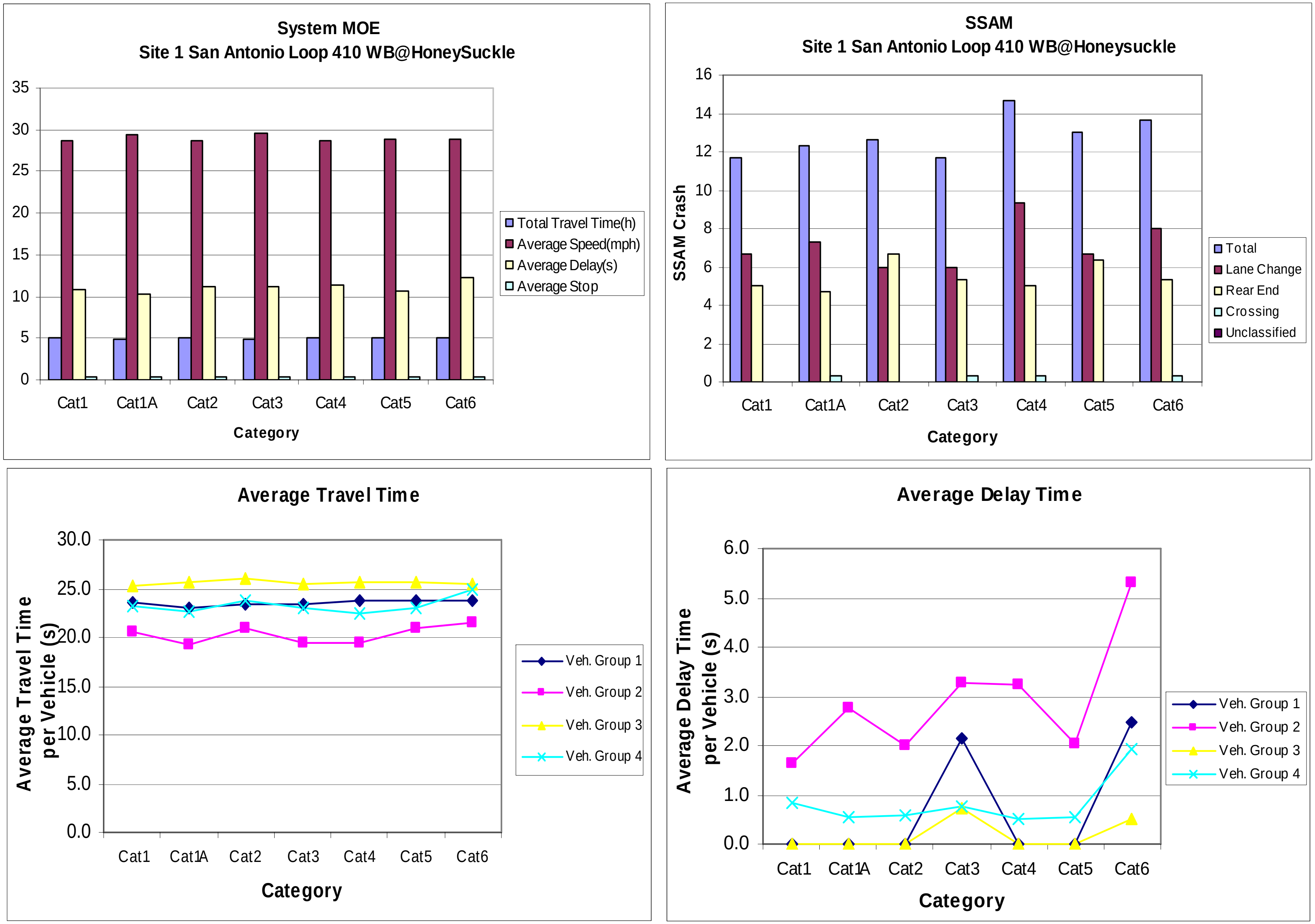


Figure 34. Simulation Results for Site 1 (I-410 WB @ Honeysuckle Lane, San Antonio).

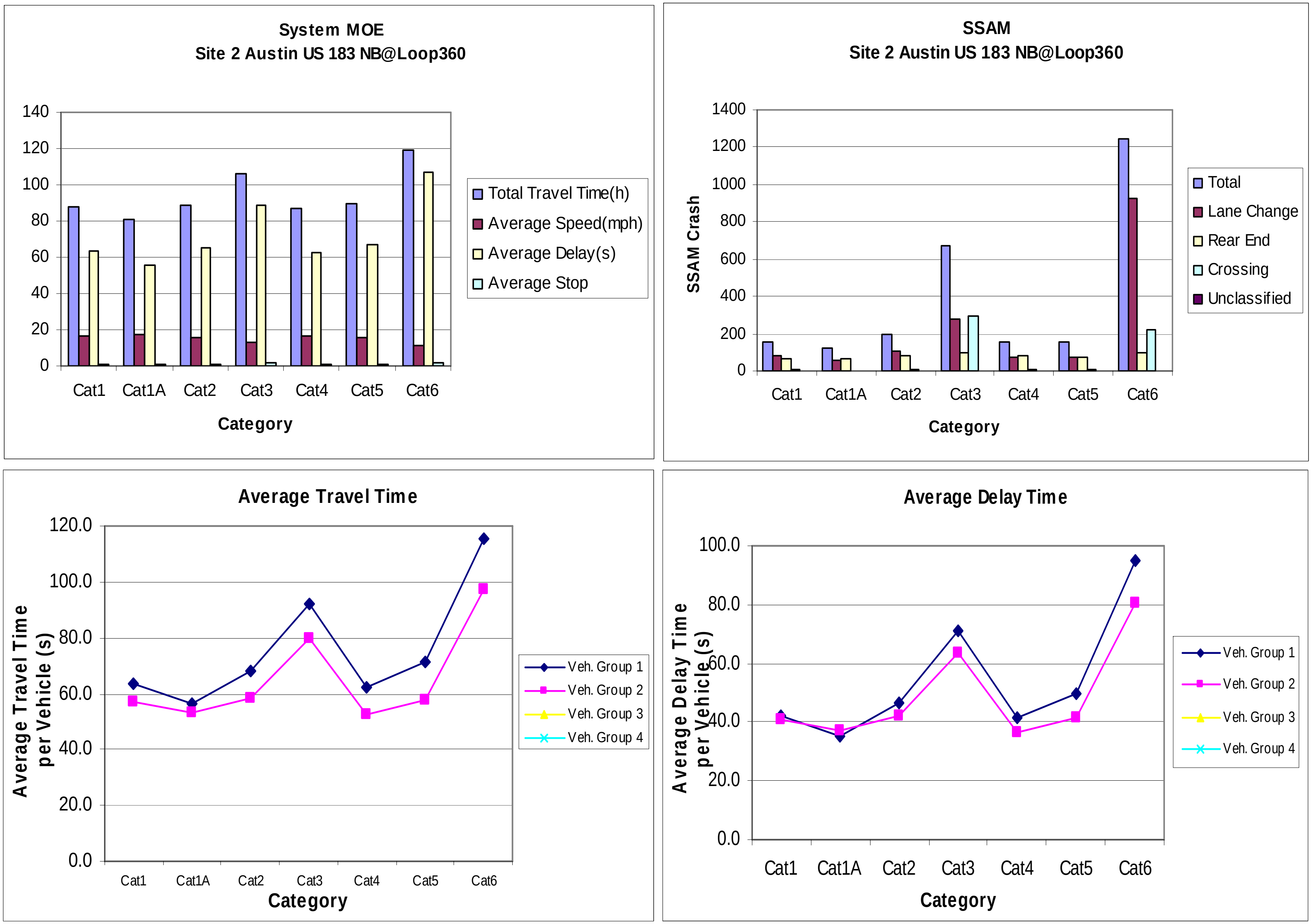


Figure 35. Simulation Results for Site 2 (US 183 NB @ Loop 360, Austin).

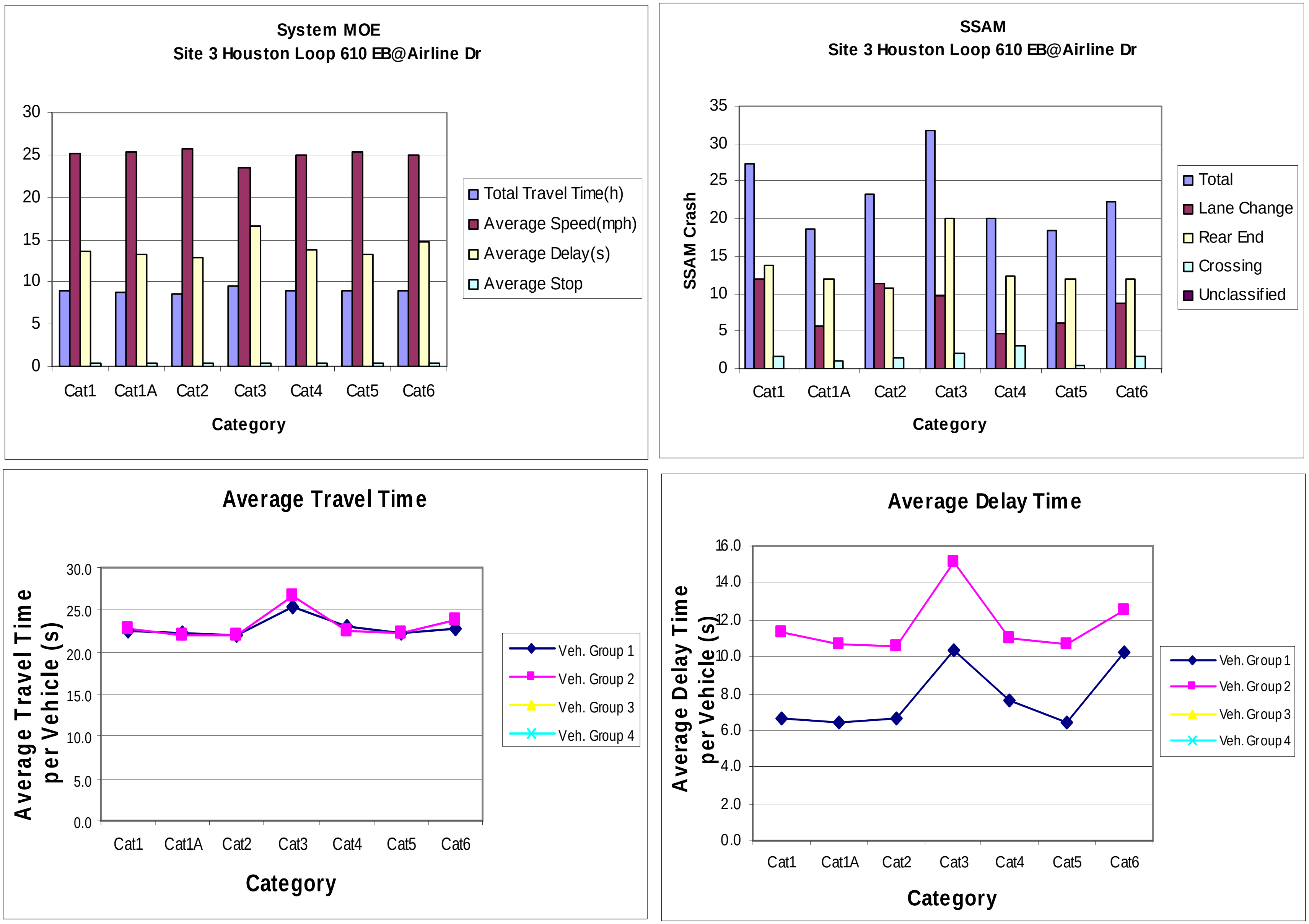


Figure 36. Simulation Results for Site 3 (I-610 EB @ Airline Drive, Houston).

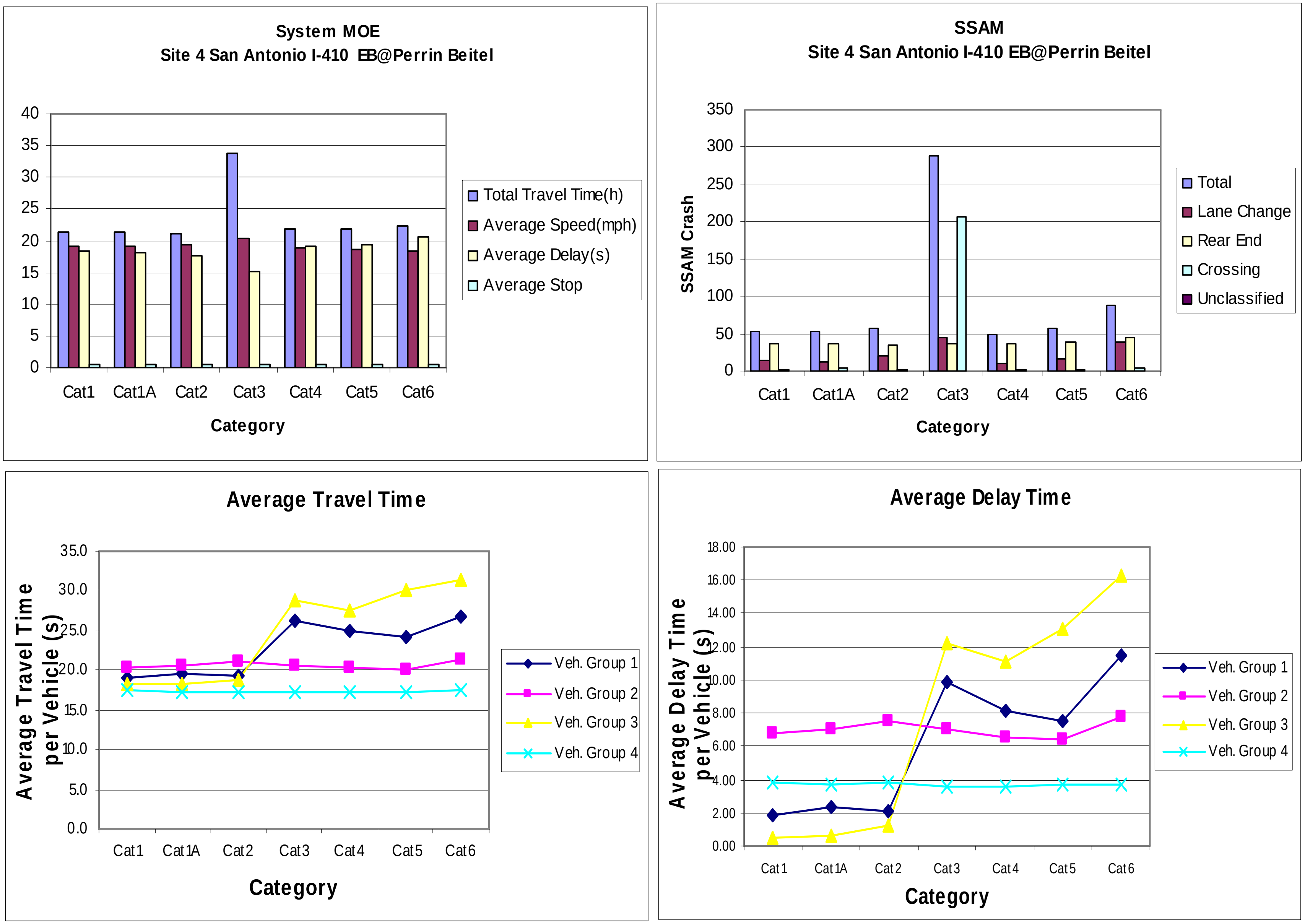


Figure 37. Simulation Results for Site 4 (I-410 EB @ Perrin Beitel, San Antonio).

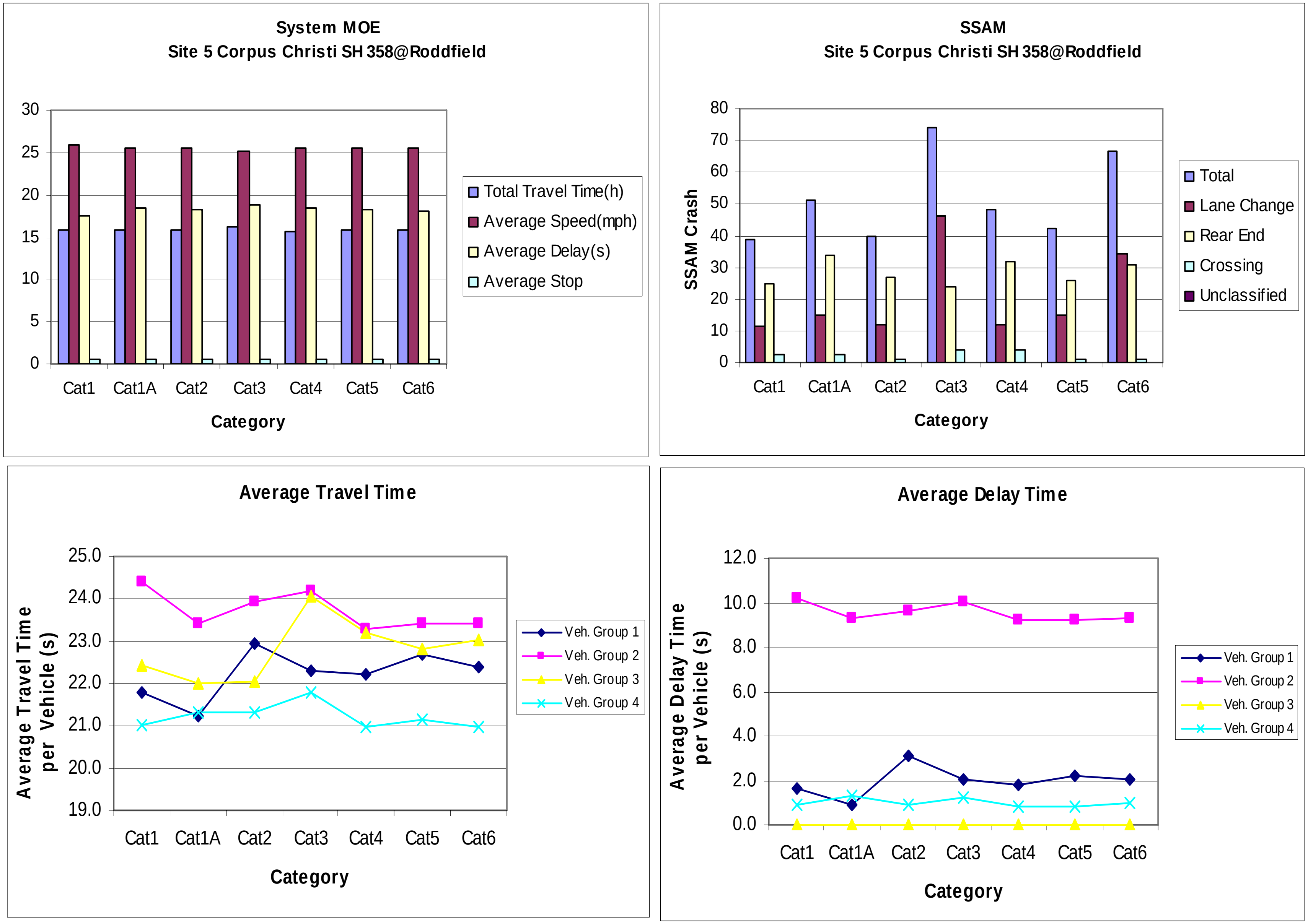


Figure 38. Simulation Results for Site 5 (SH 358 @ Rodd Field Road, Corpus Christi).

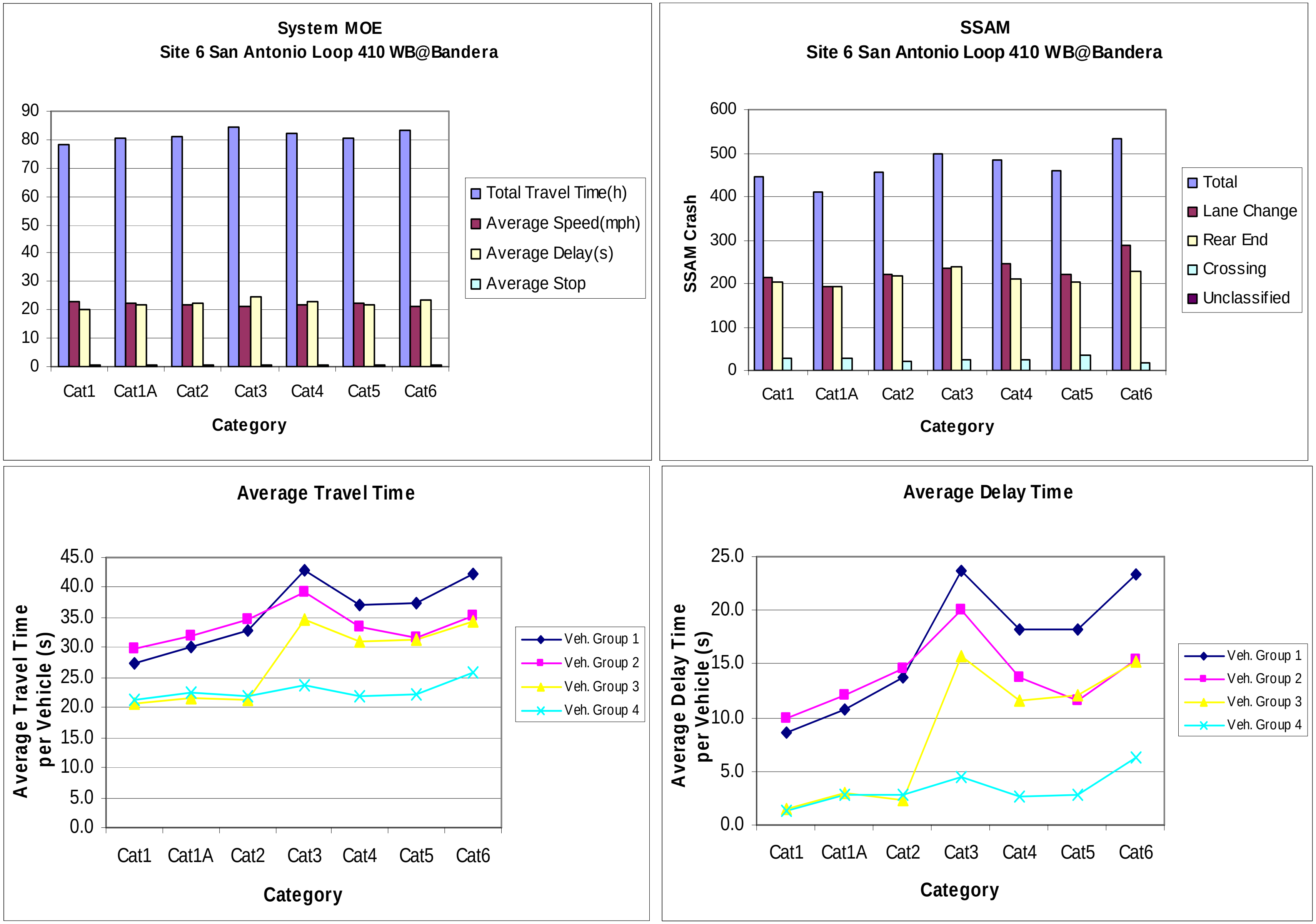


Figure 39. Simulation Results for Site 6 (I-410 WB @ Bandera Road, San Antonio).

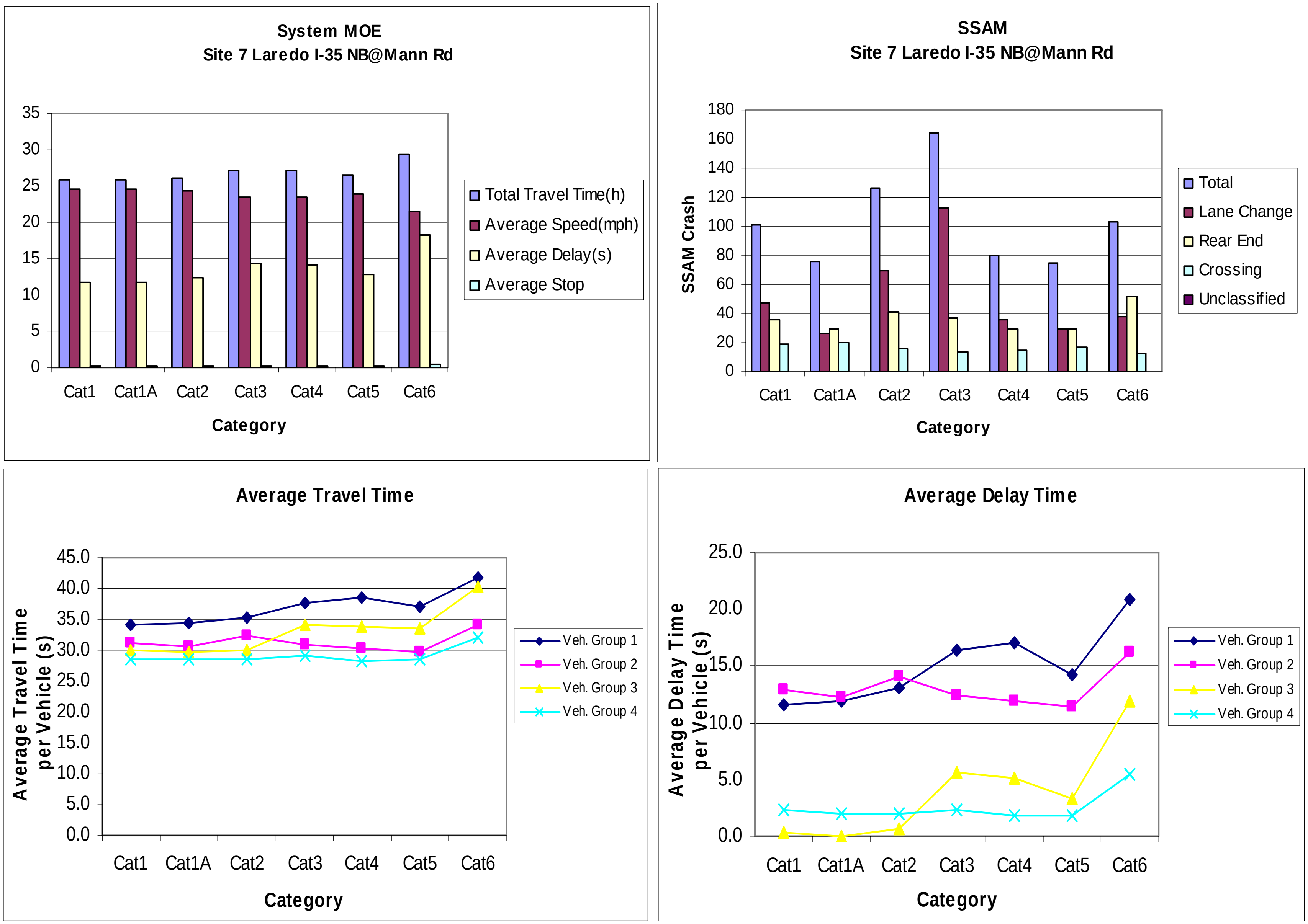


Figure 40. Simulation Results for Site 7 (I-35 NB @ Mann Road, Laredo).

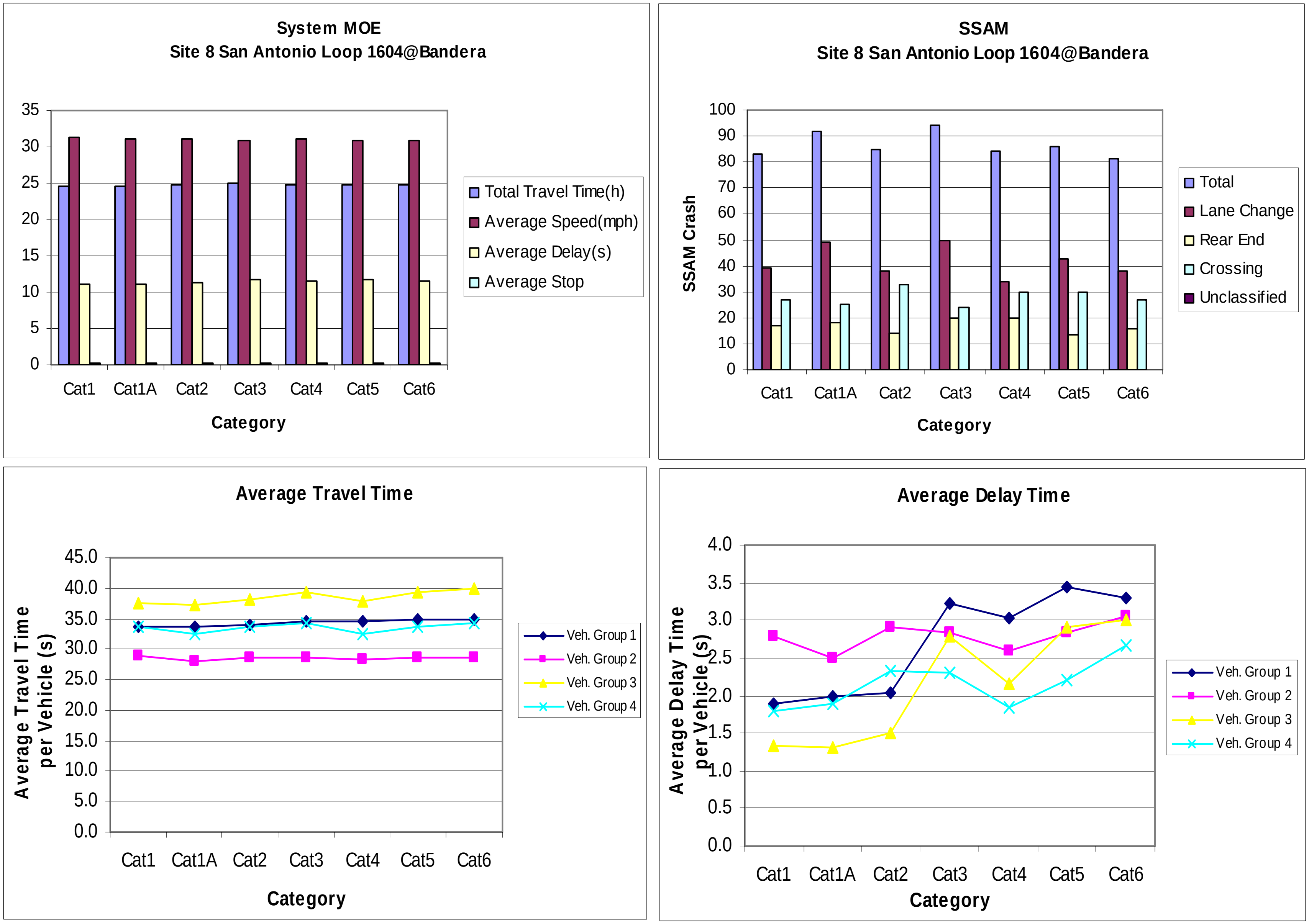


Figure 41. Simulation Results for Site 8 (Loop 1604 @ Bandera Road, San Antonio).