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Access Points And Weave Lengths For Automated Truck Lanes At Two Closely Spaced Interchanges

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Dedication

I dedicate my work to my family; my parents Ruben Jauregui and Alma G de la Garza, and to my brother Carlos Ruben Jauregui for all their unconditional support to everything I dream and accomplish. To my boyfriend, Rodolfo Arias, for the love and faith to always meet my goals and reach for success.

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by

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THESIS

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Abstract

The increase of traffic on major U.S. roadways has motivated the implementation of new technologies and better management of the transportation infrastructure, including managed lanes on freeways. Dedicated truck lanes, a type of managed lane, are increasingly attracting attention since truck freight is continuously increasing and trucks have greater impact on traffic flow relatively to cars. Truck-only managed lanes allow trucks to travel at their own speeds in an exclusive lane with no passenger vehicles on the way; likewise, vehicles on the main lanes of the freeway will have fewer trucks to travel with.

As truck-only managed lanes are being designed, Automated Trucks (ATs) are being considered as the only vehicles to potentially use this type of lane. ATs are vehicles equipped with devices capable to communicate with infrastructure and other vehicles and travel without human intervention. These trucks have been tested to travel long distances on highways, either by themselves or through the formation of platoons.

This research presents, through VISSIM microscopic traffic simulation, a series of scenarios to test possible design options for access point locations and weave length for Automated Truck Lanes (ATLs). The simulation testbed is located in El Paso, Texas along I-10 between two closely spaced interchanges, at Transmountain Drive and Artcraft Road. The freeway corridor consisted of the addition of an ATL and a third General Purpose Lane (GPL) to the existing design of I-10. Traffic volume data was projected to the year 2045. The design values are defined as x, to the distance between the freeway on-ramp or off-ramp to the ATL's access point, and y the length of access points for ATs to move in and out of the ATL. After simulation runs and analysis of results, the recommended values for x and y were 10,560 ft and 2,400 ft, respectively.

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Chapter 1: Introduction

1.1 Background

Travel has grown considerably over the last few decades (Bayliss, 2008) and since the start of the Interstate Era in the 1960's, roadway expansion to mitigate congestion has been very common. Recently, the U.S. Department of Transportation (U.S. DOT) has been pursuing new methods to improve the infrastructure capacity to mitigate congestion, and to manage traffic flow through the use of advance vehicle technology. Automated Trucks (ATs), capable to communicate through the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) paradigms, are already being developed and tested by vehicle manufacturers.

An Automated Truck Lane (ATL) is an exclusive lane for use by ATs only. An ATL is usually separated from General Purpose Lanes (GPLs) by a buffer or physical barrier. Feasibility studies for exclusive truck lanes have been conducted in Virginia and California in the U.S., and the United Kingdom and the Netherlands but no research has been done on geometric design standards (Kuhn, 2008). When planning and designing an ATL, access points and weave lengths must be provided for ATs to travel from an ATL to the GPLs and vice versa. Weaving is defined as "the crossing of two or more traffic streams traveling in the same general direction along a significant length of highway" (TRB, 2009). The weave length provides an opening along the buffer or barrier for ATs to make mandatory lane-changing maneuvers to reach the target lane (TRB, 2009). Access points are such openings.

1.2 Objective

The objective of this research is to test design options and to make recommendations for the locations of access points and weave lengths to allow ATs to travel from an ATLs to a freeway off-ramp, and from a freeway on-ramp to an ATL. The I-10 freeway in El Paso, Texas intersected by two closely spaced interchanges (Transmountain Drive and Artcraft Road) at approximately 1.75 miles apart, has been selected as the testbed and will be simulated with the use of the VISSIM microscopic traffic simulation tool. With the created network, the traffic data will then be entered to simulate the morning peak hour during a weekday in year 2045. A base network (with thee GPLs but without an ATL) plus ten ATL design scenarios will be tested. The ten scenarios have three GPLs and one ATL per direction of travel on I-10. They have different combinations of access point locations and weave lengths. From the simulation results, the location of the access points and weave lengths will be recommended.

1.3 Thesis Outline

This thesis is organized into chapters. Chapter 1 introduces the congestion problem on the U.S. highways, ATs, ATLs and defines the research objective. The literature review in Chapter 2 provides insights to the available resources for this topic and identifies the research gaps. In Chapter 3, the research methodology is presented along with the simulation model development and its assumptions. Chapter 4 presents the simulation results from VISSIM and the analysis of the results. Chapter 5 presents the findings and makes recommendations for future research.

Chapter 2: Literature Review

2.1 Managed Lanes

Due to increases in population, major urban areas are facing congestion on the highway systems. This trend is also seen in Texas where the transportation infrastructure does not have adequate capacity to support the massive demand of vehicle-trips generated in a day (Schrank et al., 2015). The strategies to relief congestion include adding lanes, managing the usage of lanes, and improving geometric designs (Lomax et al., 2013).

Managed lanes have increased in popularity among the transportation engineering community. Agencies have implemented managed lanes in the forms of High-Occupancy Vehicle lanes (HOV), High-Occupancy Toll lanes (HOT), exclusive truck lanes, and etc. Kuhn et al. (2004) defined managed lanes as "A managed lanes facility is one that increases freeway efficiency by packaging various operational and design actions. Lane management operations may be adjusted at any time to better match regional goals." This definition allows agencies in each state to create managed lanes according to their own needs and strategies.

In North America, managed lanes are commonly found in the form of HOV lanes. Studies have investigated the benefit of HOV lanes on traffic congestion and concluded that HOV lanes improved flows through bottlenecks by dampening lane-changing activities (Menendez, 2007). A study on carpool lanes, a form of managed lanes, showed a significant increase in speed in lanes adjacent to the carpool lanes (Cassidy et al., 2010).

An exclusive lane designated for use by one type of vehicle type is also a managed lane. Most exclusive lanes give access only to vehicles such as busses or large trucks to separate them from passenger car traffic. The physical separation of trucks from other traffic has the effect of

reducing conflicts between trucks and other types of vehicle which will have positive impact on creating and maintaining an uninterrupted flow condition (Kuhn et al., 2008).

An ATL has been proposed as an exclusive lane for use by ATs only. As a form of exclusive truck lane, an ATL provides a physical separation between ATs and the rest of the traffic. Thus, an ATL is expected to have similar benefit as an exclusive truck lane.

2.2 Automated Vehicles

The 2015 Mobility Scorecard (Shrank et al., 2015) states that a mobility solution to handle more freight and passenger travel on freeways is by implementing new technologies. Schrank et al. (2015) also mentioned that the advancements in connected and automated vehicles (e.g., cars, trucks, buses, trains) that communicate with each other and the transportation infrastructure will reduce traffic congestion.

General Motors first introduced the concept of automated vehicle in 1939 (Nowakowski et al., 2015). An automated vehicle is one that has the capability to operate by its own means, equipped with enough technology to drive without the active physical control of a human. Vehicles that have one or more safety technologies that provide driving assistance (e.g., lane assist or adaptive cruise control) but no ability to drive autonomously are not considered automated vehicles (Meyer, 2014).

The Society of Automotive Engineers (SAE) recently defined “levels of driving automation” to guide manufacturers and other entities in the safe design, development, testing, and deployment of automated vehicles (SAE, 2018). Below is a short description of the “six levels of automation”, from Levels 0 to 5. Levels 1 to 5 are also often known as the “five levels of automation”.

- Level 0 – No Automation: The human driver performs all the driving tasks.

- Level 1 – Driver Assistance: The driver assistance system executes either steering or acceleration/deceleration but the human driver performs all the remaining tasks.
- Level 2 – Partial Automation: The driver assistance systems executes both steering and acceleration/deceleration with the human driver performs all the remaining tasks.
- Level 3 – Conditional Automation: The automated driving system controls all the driving tasks with the expectation that the human driver will respond appropriately to a request to intervene.
- Level 4 – High Automation: The automated driving system controls all aspects of the driving task, even if a human driver does not respond appropriately to a request to intervene.
- Level 5 – Full Automation: The automated driving system has full control of all aspects of the driving tasks under all roadway and environmental conditions.

The updated visual chart is displayed in Figure 2.1.

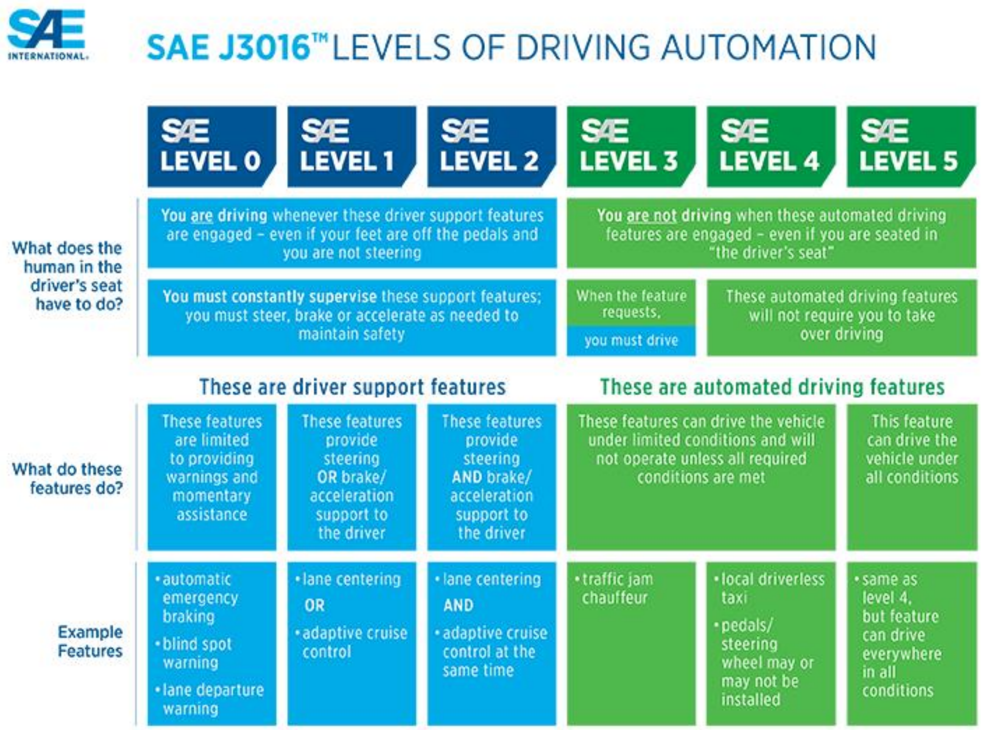


Figure 2.1: Levels of Driving Automation visual chart
(Source: SAE International, www.sae.org)

2.3 Truck Platooning

Truck platooning may be defined as grouping a number of trucks into a single entity (convoy) where one "lead" truck is followed by one or more "follow" trucks with smaller headways compared to regular driving (Shanmugavel et al., 2017). Trucks in a platoon can be treated as a single unit because they travel in the same lane at the same speed with a headway or gap between them. In relation to the levels of automation, the leading truck applies the Level 3 automation where driver has the ability to intervene and control truck maneuvers; while the following trucks use Level 5 automation where no driver has active control of the vehicles.

A platoon may be formed when trucks traveling along the same ATL "meet and join" through V2V communication. Once two or more ATs are traveling in an ATL in close proximity, the V2V communication system activates the vehicle control mechanisms in the ATs to form a

platoon. There are three phases that describe the interactions of ATs in a platoon: formation, maintenance, separation (Saeednia et al., 2016).

Research on truck platooning has been done on operational highways. The California Program of Advanced Transit and the Highway (PATH) piloted an experiment with three ATs traveling at a gap of 6 meters, with results showing a reduction in fuel consumption (Shadover, 2010). Other experiments made in Europe and the U.S. have noticed an increase in highway capacity of up to 9% (Kunze el al., 2009).

2.4 Simulation Software

VISSIM is a software tool that performs microscopic, time-stepping traffic simulations (PTV, 2011). It software is developed in Germany to model transportation infrastructure operations and to display visualizations of the coded simulation. The software is user friendly, providing a wide variety of menu options to recreate a network model representative of the actual system of interest. In this research, VISSIM was used to replicate a network with forecasted traffic volumes and to simulate ATs moving in platoons through ATLs, and as a single ATs in mixed traffic while entering and exiting ATLs.

VISSIM represents all the transportation infrastructure elements, plus every vehicle in detail. It uses links and connectors to represent the roadways at the lane level. Each link and connector has its own characteristics such as speed limit, usage of vehicles by type (e.g., ATLs), permissible turning movements at the downstream end. Sensors can be placed on any lane in any link to measure traffic conditions (such as volume and speed). VISSIM users can define different types of vehicles in the simulation model (for examples, passenger cars, trucks and ATs). Each type of vehicle can have its own driving behavior (for examples, minimum following headway, acceleration, and minimum gap to change lane). At critical locations, VISSIM modelers can

specify diving rules, such as priority rules, to resolve conflicts. During a simulation run, all the vehicles move from one time-step to another according to the behavioral rules that have been coded into the links and connectors, and vehicles.

VISSIM has been used by researchers to simulate all types of urban traffic networks in Texas and in other states. For example, Venglar et al., (2001) designed a variety of access and egress scenarios for HOV lanes in Texas cities with the help of VISSIM. A calibrated VISSIM model demonstrated the effect of crosswalk location and pedestrian volume on the entering capacity of a two-lane roundabout (Cheu and Duran, 2013). In addition, a double crossover diamond interchange (DCDI) was simulated using VISSIM to evaluate the feasibility of implementing a DCDI at an interchange with frontage road (Cheu and Martinez 2012).

In this research, VISSIM Version 5.40 was utilized to code the simulation testbed.

Chapter 3: Research Methodology

3.1 Current and Proposed Highway Designs

The I-10 freeway that runs through El Paso, Texas, currently has a two to four GPLs per direction. The I-10 segment from the New Mexico-Texas border in the west (milepost 0) to Mesa Street interchange (milepost 12) has two GPLs in each direction, as observed in Figure 3.1, with an additional two-lane frontage road in each direction.

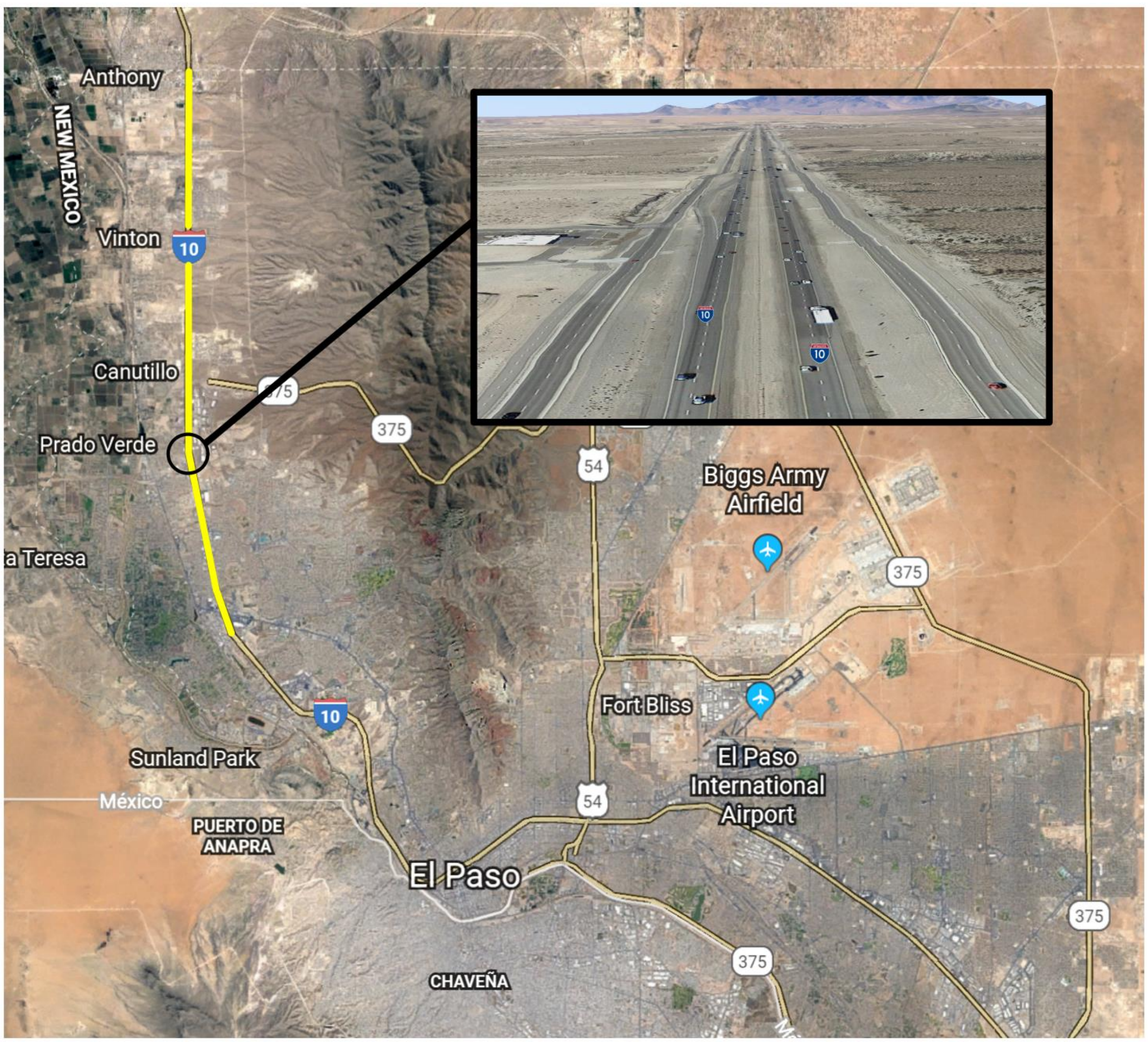


Figure 3.1: Existing I-10 in El Paso and testbed site
(Source: Google Earth)

This research assumed that ATLs would be designed to run along the freeway median, one lane per direction. There were several designs proposed by TxDOT El Paso District (see Figure 3.2). These four designs all have one ATL, three GPLs, and a frontage road with two lanes in each direction. Comparing the proposed cross-sections with the existing geometry, TxDOT El Paso District plans to add one GPL and one ATL per direction. The differences between the four proposed designs are the buffers between the ATL and the GPLs. The third design, i.e. "Alternative 3 – Adaptive Lane with buffer", has been recommended by TxDOT El Paso District for this research. This design has a buffer of 2 ft that separates the ATL and the GPLs.

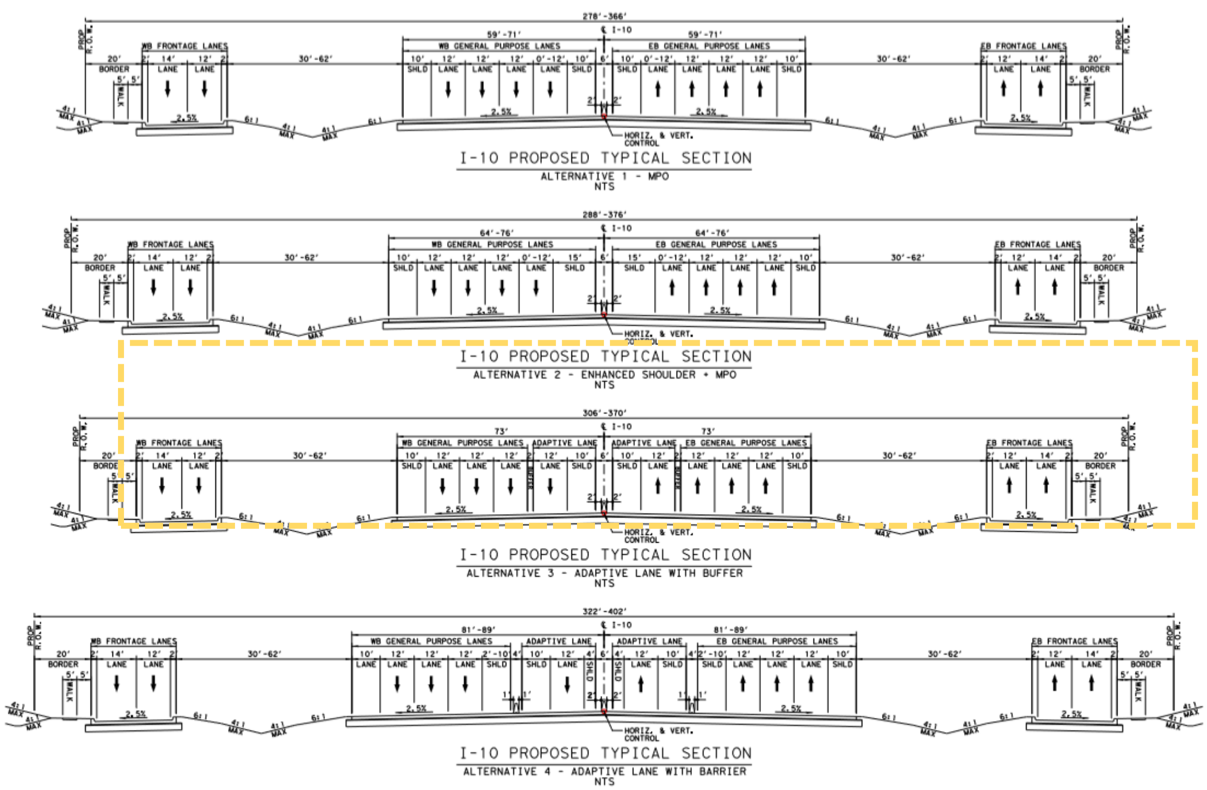


Figure 3.2: Cross-sections proposed by TxDOT El Paso District
(Source: TxDOT El Paso District)

3.2 Simulation Model Development

3.2.1: Site Location

This research used a portion of the I-10 in El Paso, Texas from Transmountain Drive in the west to Artcraft Road in the east as the testbed. Figure 3.3 shows a map of the chosen site. This location was selected since I-10 is the main freight corridor that connects the east coast with the Port of Los Angeles and the Port of Long Beach. Due to its importance in freight transportation, the I-10 Corridor Coalition has been formed between the States of Texas, New Mexico, Arizona, and California (https://i10connects.com/about/about-i-10-corridor-coalition). The Coalition will use technology to enable better passenger and freight movement, including connected vehicle information sharing and platooning. However, the design standards and guidelines are yet to be developed.

In addition to the I-10 Corridor Coalition, a group of Texas agencies formed The Texas Innovation Alliance (TIA) which is committed to address the Texas community's mobility challenges (http://txinnovationalliance.org/about-us). Part of TIA's work consists of identifying and facilitating real-world testbeds for automated vehicle operations.

The segment of I-10 in El Paso, as shown in Figure 3.3, has been identified as the ideal location for AT testbed in this thesis because this site has a large confluence of truck traffic on eastbound I-10 from California, Arizona and New Mexico as well as northbound traffic from the U.S. Mexico border.

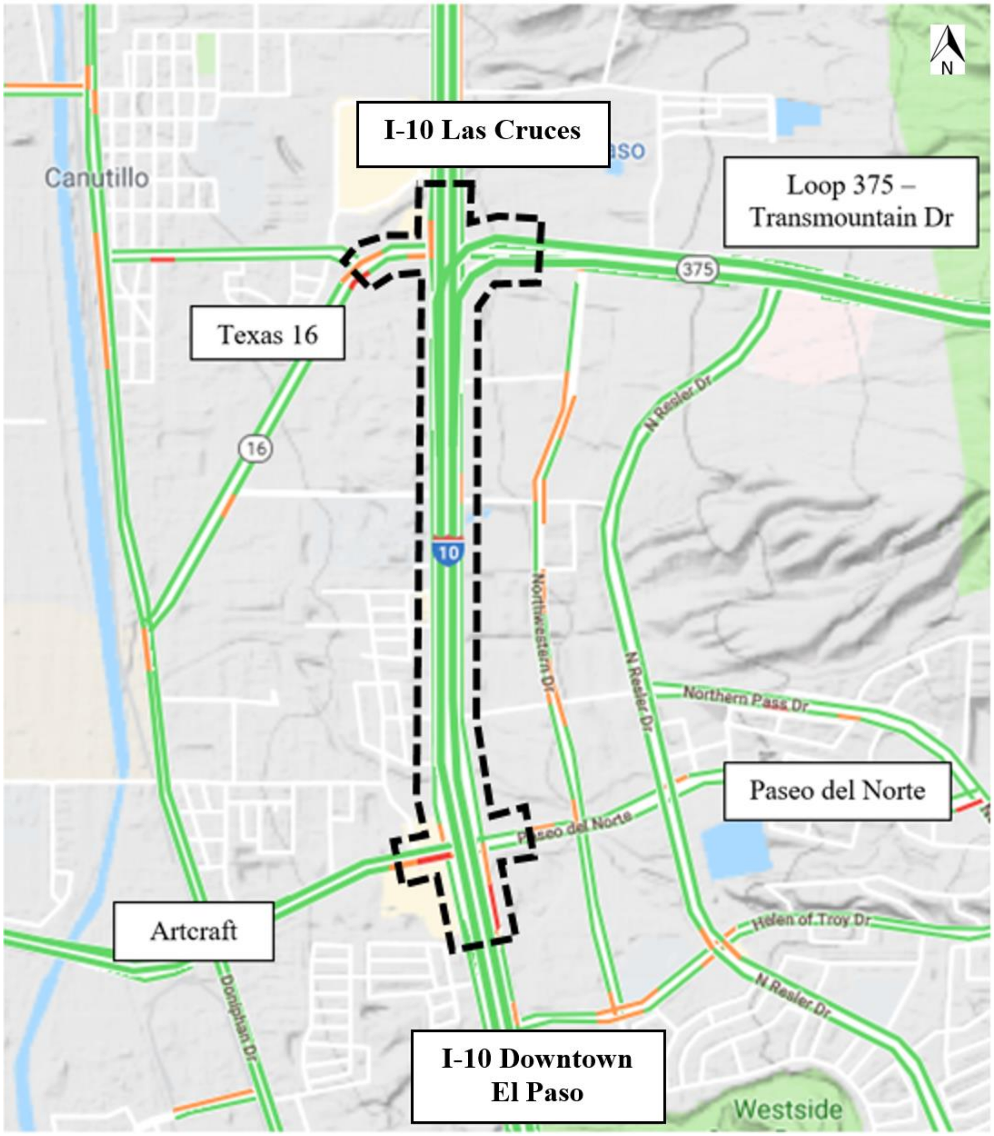


Figure 3.3: Simulation testbed
(Source: Google Maps)

3.2.2: Data Collection

Several meetings were held with the TxDOT El Paso District to obtain the required data. During the meetings, the concepts of operations of ATLs were discussed, the horizon year of 2045 was agreed and the cross-section of the geometric design was provided. The cross-section proposed, as shown in Figure 3.2 and discussed in the previous section, was used for the simulation model.

The El Paso Metropolitan Planning Organization (MPO) provided the traffic volume data. These volumes were already projected to the year 2045 in El Paso MPO's official Metropolitan Transportation Plan. The data specified the volume of passenger cars and trucks, as well as their origins and destinations through the entire testbed area. Table 3.1 displays the total volume for the whole simulation testbed, expressed in vehicles per hour, in the form of an O-D (Origin-Destination) matrix. The O-D matrices for cars and trucks are shown separately in Tables 3.2 and 3.3. These are the predicted volumes in the morning peak hour (7:00 a.m. too 8:00 a.m.) in the year 2045.

Table 3.1: O-D matrix for all vehicle types

Total Vehicles (veh/hr)		**To**					
		I-10 Las Cruces	Loop 375 Transmountain	Paseo Del Norte	I-10 El Paso Downtown	Artcraft Santa Teresa POE	Texas 16 Outlet Mall
From	I-10 Las Cruces	-	945	306	4855	0	513
	Loop 375 Transmountain	108	-	0	956	0	956
	Paseo Del Norte	590	0	-	789	1513	0
	I-10 El Paso Downtown	4492	123	300	-	1151	0
	Artcraft Santa Teresa POE	296	0	1810	1067	-	0
	Texas 16 Outlet Mall	417	1276	0	676	0	-

Table 3.2: O-D matrix for passenger cars

Cars (veh/hr)		To					
		I-10 Las Cruces	Loop 375 Transmountain	Paseo Del Norte	I-10 El Paso Downtown	Artcraft Santa Teresa POE	Texas 16 Outlet Mall
From	I-10 Las Cruces	-	605	184	3537	0	328
	Loop 375 Transmountain	71	-	0	546	0	546
	Paseo Del Norte	372	0	-	473	908	0
	I-10 El Paso Downtown	3149	79	192	-	737	0
	Artcraft Santa Teresa POE	189	0	1158	758	-	0
	Texas 16 Outlet Mall	304	931	0	493	0	-

Table 3.3: O-D matrix for all trucks

All trucks (veh/hr)		To					
		I-10 Las Cruces	Loop 375 Transmountain	Paseo Del Norte	I-10 El Paso Downtown	Artcraft Santa Teresa POE	Texas 16 Outlet Mall
From	I-10 Las Cruces	-	340	122	1318	0	185
	Loop 375 Transmountain	37	-	0	410	0	410
	Paseo Del Norte	218	0	-	316	605	0
	I-10 El Paso Downtown	1343	44	108	-	414	0
	Artcraft Santa Teresa POE	107	0	652	309	-	0
	Texas 16 Outlet Mall	113	345	0	183	0	-

There are two signalized intersections, at I-10 and Artcraft Road, and I-10 and Transmoutain Drive, in the simulation testbed. The City of El Paso provided the current traffic signal timing sheets for both intersections. The cycle time used for both intersections was 180 seconds with six signal phases per cycle during the morning peak hour (7:00 a.m.to 9:00 a.m.) on a weekday. The signal timing plans were coded into the simulation model.

3.2.3: Model Development

A base model of the testbed was developed as the do-nothing option. In this model, the I-10 freeway has three GPLs but no ATL in each direction. This model was given the projected traffic volume data in 2045 provided by El Paso MPO as stated previously. The current signal timing plan without modification was added to the intersections. All the data were entered into VISSIM following the procedures and guidelines from the VISSIM Version 5.40 User Manual (PTV, 2011). The systematic procedure of VISSIM modeling process is briefly described below:

1. After starting the VISSIM software to create a new model, the system of units was defined. The U.S. customary unit system was selected as the preferred system although the default units are the International System of Units.
2. A high quality image from Google Earth displaying the testbed area was imported into VISSIM and scaled as the background image. The image selected and imported represented the actual condition of the location in the current year.
3. Vehicle types were defined and modified to follow El Paso MPO's Metropolitan Transportation Plan. The plan has two types of vehicles: passenger cars and trucks. A new vehicle type was created to represent ATs. The vehicle specification for AT is shown in Figure 3.4. Figure 3.5 shows the 2D view of the 3D vehicle models.

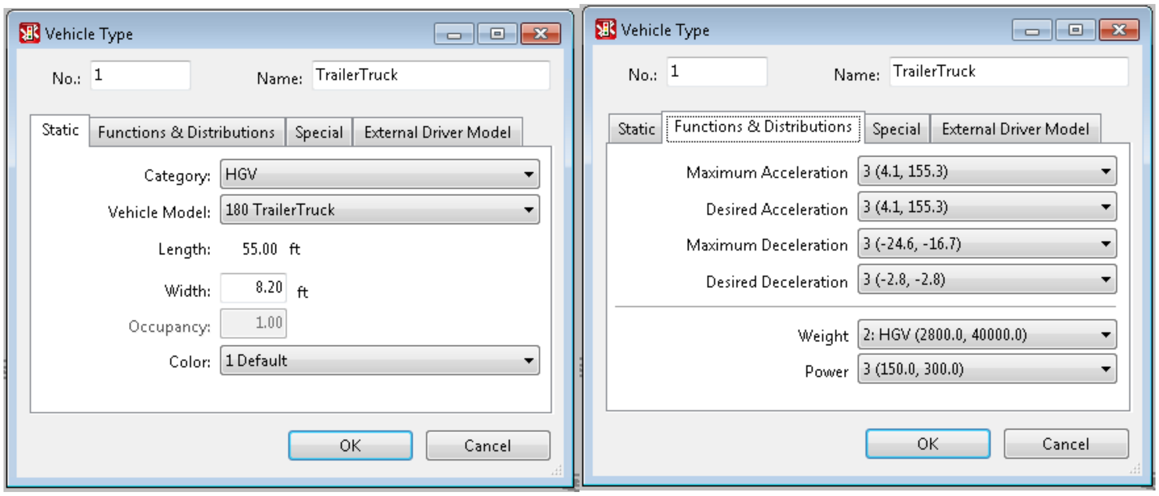
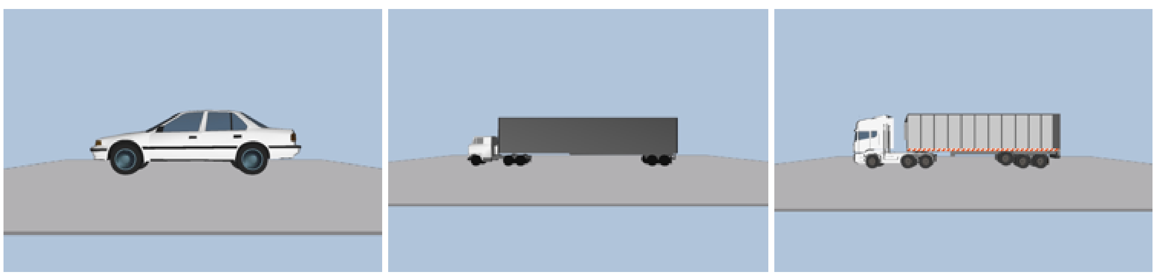


Figure 3.4: AT vehicle type specifications



a) passenger car b) heavy truck c) automated truck

Figure 3.5: 2D view of vehicle models

4. The driving behavior for all types of vehicles, i.e., passenger cars and heavy trucks, followed the default characteristics in the link's driving behavior parameter set. A new driving behavior parameter set, named Automated, was added to the list to controlled the driving behavior of ATs while traveling on the ATL, and to simulate AT's platooning behavior. Figure 3.6 describes the car-following parameter values for the AT's driving behavior. After repeated experimental runs, only the CC1 parameter was adjusted for ATs to have a "headway time" of 0.10 second (its default value was of 0.9

second). The other parameters, CC2 to CC9, remain unchanged. AT was set to have a "desired speed" of 62 mph (100 km/h). Therefore, the platooning headway of 0.1 second is equivalent to a gap of 9 ft (approximately 3 m). Obviously, the gap of 9 ft (3 m) is smaller than 6 m used by Shaldover (2010). This is because Shadover's experiment in California was conducted almost 10 years ago with the available technology at that time. Our model was based on the assumed 2045 scenario,

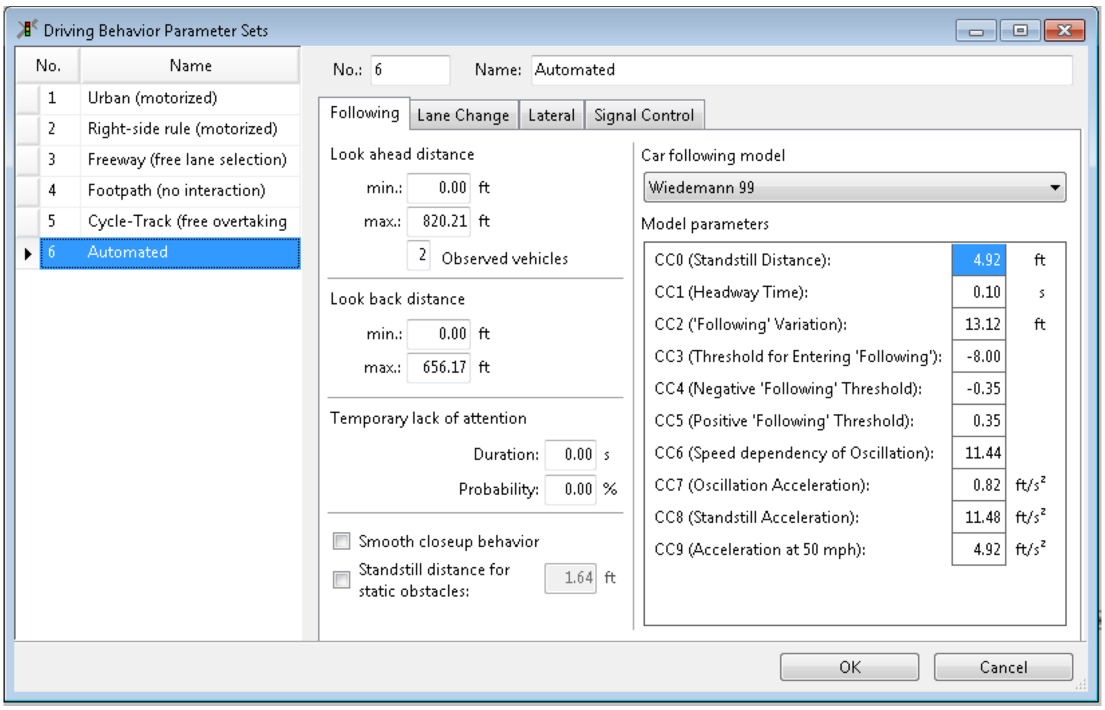


Figure 3.6: Driving behavior parameter sets for ATL

5. A base model (see Figure 3.7) was created using links and connectors.

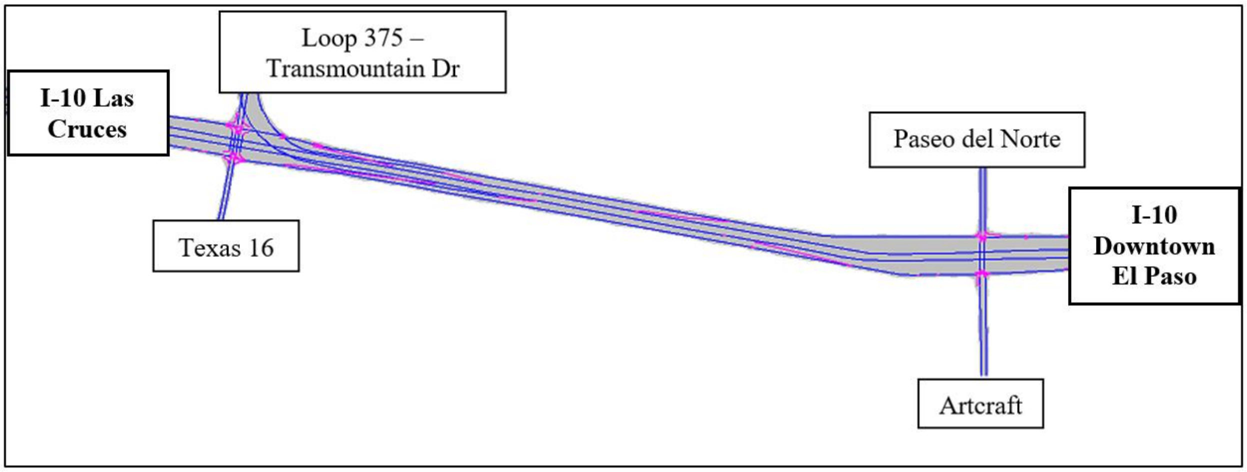


Figure 3.7: VISSIM base model

6. The traffic volume and vehicle composition were entered according to data as shown in Tables 3.2 and 3.3 The vehicle composition and the input volume of each type of vehicle must be defined for every origin (called entry link in VISSIM). An important property of each vehicle type is the desired speed. In this VISSIM model, the following desired speeds were assumed.
    a. Cars, Heavy Trucks and ATs on GPLs: 60 mph (95 km/hr)
    b. Cars, Heavy Trucks and ATs on frontage roads: 50 mph (80 km/hr)
    c. ATs on ATL: 62 mph (100km/hr)
7. After vehicles were added to the system, routing decisions were defined. For example, for a vehicle entering the testbed from the east (coming from Las Cruces, NM) and travel to Artcraft Road heading south, a specific route must be coded with specific turns along the route. A routing decision point may be placed in any link to define the directions and the percentages of vehicles could turn in each possible direction at a downstream intersection. When a vehicle crosses this routing decision point, VISSIM will randomly assign the direction of its next turn. From that point onwards, this vehicle

will try to change lane to get into the correct lane that allows it to make the turn. In the simulated testbed, 46 decision points have been coded for vehicles to make a total of 102 turns (left, though, right, and U-turn).

8. Twelve conflict areas were detected. They are located at the merge points between the on-ramps and I-10, and at the two signalized intersections. Vehicle conflicts in these areas were resolved by coding the two conflicting movements as yield and priority movements, respectively. For example, vehicles entering I-10 from an on-ramp was programmed to yield to the traffic in the GPLs.
9. Traffic signals were placed at each intersection. The signal time plans were set according to the City of El Paso's signal timing sheets.
10. Finally, to record the model's output, four sensor stations were defined at specific locations on the I-10 GPLs. Each sensor station has 3 "data collection points", one in each lane. VISSIM data collection points represent different types of sensors. Users can define what statistics every data collection points can measure. In this simulation model, the data collection points were assumed to be inductive loop detectors that measure volumes (veh/hr/ln) and average speed (mph). Therefore, there were 4 sensor stations and 12 data collector points. Of the 4 sensor stations, two stations were placed at the end of the weave length on the GPLs. The other two stations were placed before the weave length. An enlarged image depicting the locations of two sensor stations is shown in Figure 3.8. These are the locations where congestion caused by ATs moving in and out of the ATLs.

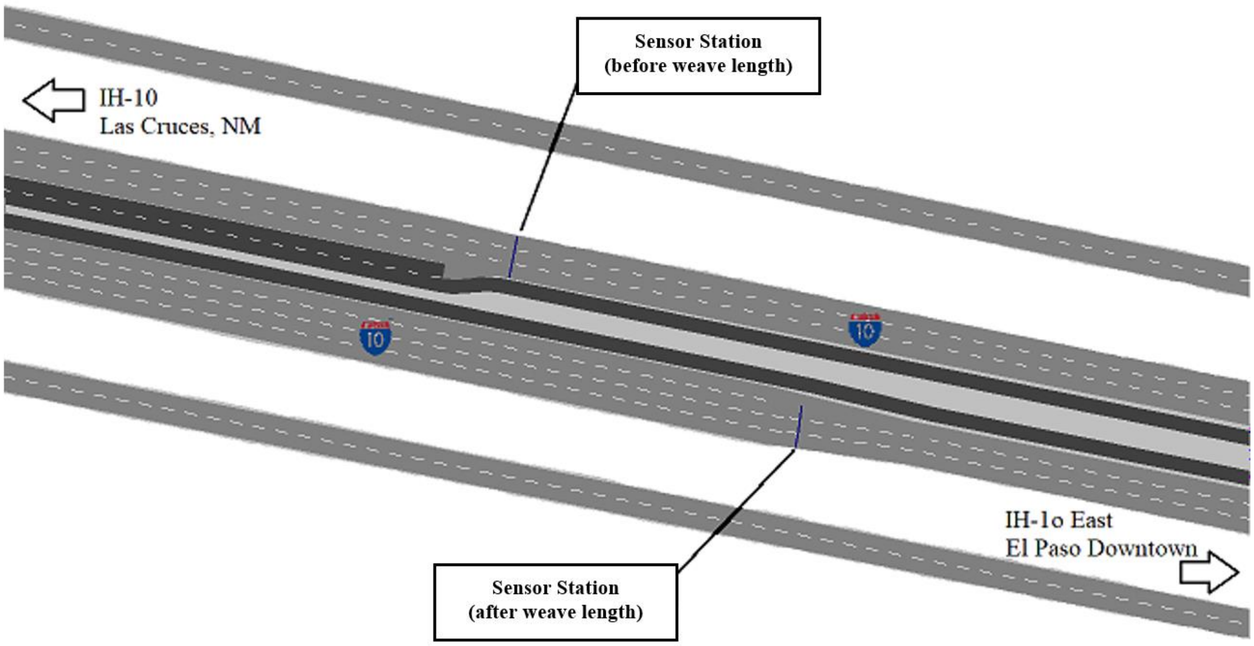
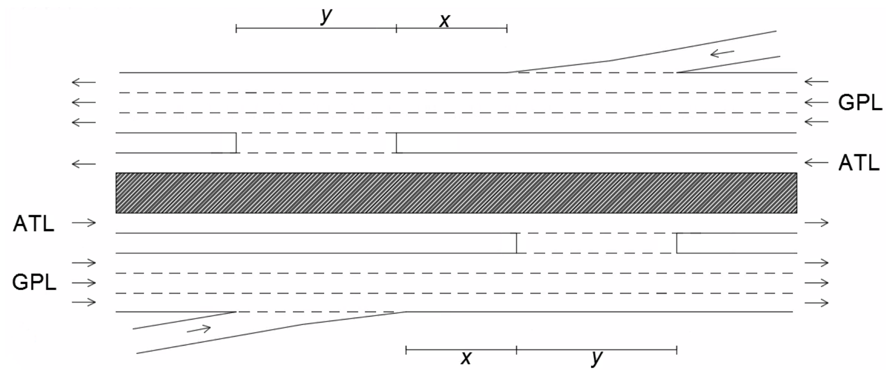


Figure 3.8: Sensor stations before and after weave length

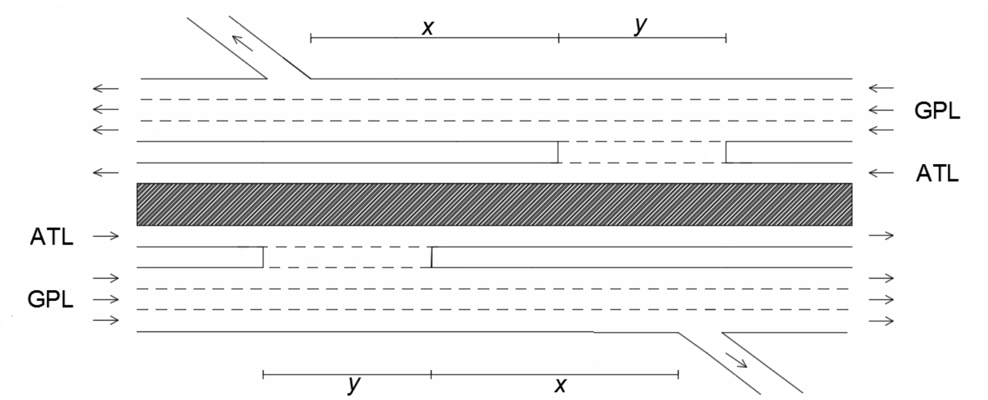
3.2.4: Simulation Plan

The base model has three GPLs per direction but without an ATL. It was replicated and modified to 10 different proposed design scenarios with an ATL per direction. These 10 scenarios were defined by varying the values of two critical design parameters, namely x and y. The parameter x is defined as the distance between the freeway on-ramp or off-ramp to the ATL's access point (see Figure 3.9). An access point is an opening between the ATL and the leftmost GPL for ATs to enter and exit the ATL. In other words, x is the maximum distance for an AT to change lanes from the leftmost to the rightmost GPLs or vice versa. It defines the location of an access point from the freeway on-ramp or off-ramp. The parameter y is the length of the buffer between the ATL and GPLs that is opened for ATs to move between the ATL and the leftmost GPL. For the entire length of y, a 12-ft wide auxiliary lane is constructed between the ATL and GPLs, in place of the 2 ft wide buffer. This auxiliary lane allows AT to decelerate or accelerate in

anticipation of a lane change. In this way, ATs that are entering or exiting the ATL will not interfere with the other ATs platooning at high speed. Figure 3.9 illustrates how the *x* and *y* values are measured.



(a) For ATs entering ATL



(b) For ATs exiting ATL

Figure 3.9: Definitions of *x* and *y*

Referring to Figure 3.9, it was assumed that for an AT to exit the freeway via the off-ramp or to enter the ATL from the on-ramp, the driver will be in full control of the vehicle. The parameter *x* is related to truck drivers' lane changing behavior. Without a national and state guideline to define the *x* and *y*, these distances were inferred from the placements of highway guide signs. In the Manual on Uniform Traffic Control Devices for Street and Highways (MUTCD), freeway off-ramp guide signs placement distance is the safe distance for vehicle to move from the leftmost lane

to the rightmost lane in time to turn into the off-ramp. For a full cloverleaf interchange, the first guide sign is placed two miles upstream of the interchange and for a diamond interchange this distance is only one mile (FHWA, 2009). Therefore, the *x* value was set to 1.0, 1.5, and 2.0 miles for the different design options.

On the other hand, the *y* value is viewed as the length of the opening of the buffer that separates the ATL and GPLs. It is created for ATs to travel in and out the ATL. Also, the *y* value may be seen as the equivalent of acceleration or deceleration lane found at ramp junctions or managed lane's T-ramp intersections. Assuming the worst case when an AT comes to a complete stop in the auxiliary lane while seeking a gap to change lane, the distances for a truck to accelerate from 0 to 60 mph are 2,405, 2,070 and 3,320 ft, at a 15^{th}, 50^{th}, and 85^{th} percentile values, respectively (Yang et al., 2016). Kuhn et al. (2005) recommended an acceleration and deceleration lane length of 2,400 ft for T-ramps in managed lanes having a speed of 65 mph. Based on this literature, the *y* values were set to be 1,800, 2,400, and 3,000 ft in the simulation runs. Table 3.4 lists all case scenarios with the assigned *x* and *y* values.

Table 3.4: Characteristics of cases

Case no.	*x* (ft)	*y* (ft)	Remarks
0	0	0	Base model, no ATL, do-nothing scenario
1	5,280	1,800	
2	5,280	2,400	
3	5,280	3,000	
4	7,920	1,800	
5	7,920	2,400	
6	7,920	3,000	
7	10,560	1,800	
8	10,560	2,400	
9	10,560	3,000	
10	0	0	ATL without access to interchanges, for pass through ATs only

There are 11 different cases that included a base model (case 0), 9 scenarios with possible design options (cases 1 to 9), and a scenario (case 10) in which the ATL is without an access point in the testbed area. For each case, the model was run 10 times (10 replications), each with initial random number seeds that varied between the runs.

The evaluation (output statistics) options were specified before running the models. In each simulation run, a 600 seconds of warm-up time (10 minutes) was followed by a 900 seconds (15 minutes) of data collection period.

3.3: Assumptions

Two major assumptions were made based on the observed initial simulation outputs. As the consequences of these assumptions, the VISSIM models were modified before making the complete set of simulation runs.

The first assumption covers the volumes at the approaches of the signalized intersections at the I-10 interchanges at Artcraft Road and Transmountain Drive. The signal timing plan provided by the City of El Paso did not have enough capacity to handle the projected traffic volume along Artcraft Road and Transmountain Drive in year 2045, as shown in the initial VISSIM simulation runs. For this reason, volume entering the intersections from Artcraft Road and Transmountain Drive were reduced in successive stages of 10% each until the queues at the intersection approaches no longer grew. It was determined that at 50% of the projected volume, the existing signal timing plan could handle the projected 2045 volume without the queue growing to infinity. Therefore, for all the simulation runs, the input volume from the origins (or VISSIM entry links named Loop 375-Transmountain, Paseo del Norte, Artcraft Santa Teresa POE, and Texas 16 Outlet Mall to all the destinations (see Tables 3.1, 3.2, and 3.3) were reduced by 50%.

The 50% of the vehicles that were “reduced” were assumed to be diverted to other streets in the city. It should be noted that this adjustment did not affected volumes on I-10.

The second assumption was regarding the truck volume. As advised by TxDOT El Paso District, it was assumed that in the year 2045, 50% of trucks would be automated and the other half would remain as the conventional trucks with active drivers. This 50% of conventional trucks travelled in GPLs.

Chapter 4: Analysis of Results

4.1: Chapter Introduction

The results of the simulations are presented and discussed in this chapter. The 11 cases created in Chapter 3 were each simulated for 10 replications or runs. The simulation outcomes were then analyzed. As part of this chapter, the following sections will describe the process of obtaining the necessary statistics to determine the results.

4.2: Sensor Stations

Four critical locations that were subject to possible congestion caused by ATs weaving out of ATL were selected as sensor stations to collect data for analysis (see Section 3.2.3). The traffic conditions at these four locations were potentially influenced by the activities caused by the ATL. They were at the access points, i.e., at the entrance or exit of ATL. The stations were labeled according to the direction of traffic flow and its function; SE1, SE2, SW1, SW2. For example, S stands for speed, E corresponds to the Eastbound, as W for Westbound, and the number represents the station number in the same direction as the traffic flow. Figure 4.1 shows the locations of the four sensor stations in the model. As seen on Figure 4.2, three data collection points were placed on each of the GPLs, creating a station. Each data collection point has the ability to measure volume and speed when a vehicle crosses the point. volume for trucks and passenger. The following sections analyze the results based on the average volume and average speed by senor stations. That is, the volume counted by the three data collection points at the same station over the same time interval were averaged. Similarly, the individual vehicle speeds counted by the three data collection points at the same station at the same time interval were also averaged. The average

volume and average speed in the following discussions use the station average values. This is consistent with the standard practice used by most of the traffic management centers.

Figure 4.1: Location of sensor stations

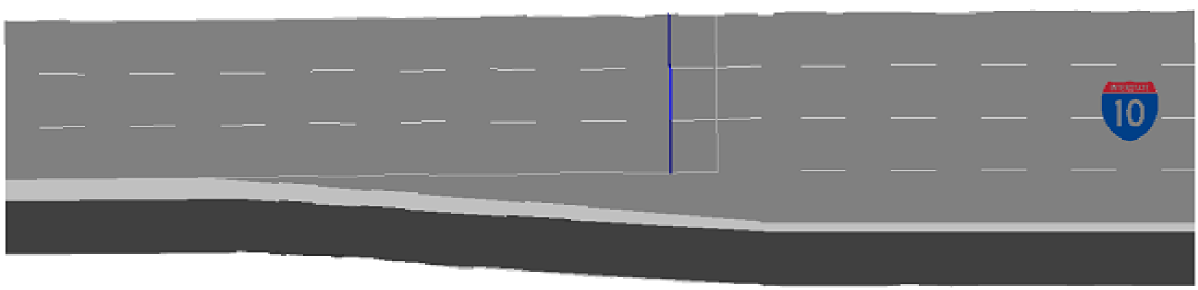


Figure 4.2: Sensor station SW1

4.3 Average Speed and Travel Time

As previously stated in the beginning of this chapter, each simulated case was replicated 10 times. The average values from the 10 replications were collected and are reported in Table 4.1. Table 4.1 lists the average speeds and Total Travel Time (TTT) for all the 11 cases simulated.

Table 4.1: Average speeds and total travel time for all cases

Case no.	***x* (ft)**	***y* (ft)**	**SE1 (mph)**	**SE2 (mph)**	**SW1 (mph)**	**SW2 (mph)**	**TTT (veh-hr)**
0	0	0	23	45	32	49	637
1	5,280	1,800	51	43	22	46	631
2	5,280	2,400	51	42	23	45	626
3	5,280	3,000	51	43	23	45	625
4	7,920	1,800	51	43	32	45	586
5	7,920	2,400	51	42	28	44	597
6	7,920	3,000	51	43	33	46	590
7	10,560	1,800	51	43	31	45	620
8	10,560	2,400	51	42	35	45	615
9	10,560	3,000	51	42	40	44	610
10	0	0	28	44	35	48	611

In Table 4.1, in cases 1 to 9 (when $x>0$ and $y>0$) the average speeds in sensor station SE1 were almost the same at 51 mph. The same condition is observed at sensor stations SE2 and SW2, respectively. This means that the *x* and *y* values had no effect on vehicle speeds at SE1, SE2, and SW2. There was a variation in average speed at sensor location SW1. At this location, the average speed ranged from 22 to 40 mph, but the trends with respect to *x* and *y* as was not evident.

The average speeds of the nine cases with $x>0$ and $y>0$ were then organized by stations as shown in Table 4.2. Table 4.3 shows the average volume at each station, and Table 4.4 the density at each station. Density is defined as the number of vehicles present at a given length of highway, in vehicles per mile per lane (veh/mi/ln). Density is calculated as average volume divided by average speed. The analysis based on the data in Tables 4.2, 4.3, and 4.4 focused on sensor station SW1. From Table 4.2, it was observed that as *x* increased, the average speed increased. However, the same could not be said for *y*.

Table 4.2: Average speed by stations

SE1	Speed (mph)	y (ft) 1800	2400	3000
x (ft)	5280	51	51	51
	7920	51	51	51
	10560	51	51	51

SE2	Speed (mph)	y (ft) 1800	2400	3000
x (ft)	5280	43	42	43
	7920	43	42	43
	10560	43	42	42

SW1	Speed (mph)	y (ft) 1800	2400	3000
x (ft)	5280	22	23	23
	7920	32	28	33
	10560	31	35	40

SW2	Speed (mph)	y (ft) 1800	2400	3000
x (ft)	5280	46	45	45
	7920	45	44	46
	10560	45	45	44

Table 4.3: Volume by stations

SE1	Volume (pc/h/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	1740	1754	1776
	7920	1756	1767	1751
	10560	1766	1778	1769

SE2	Volume (pc/h/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	1560	1678	1544
	7920	1663	1670	1686
	10560	1641	1677	1658

SW1	Volume (pc/h/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	1433	1476	1428
	7920	1665	1630	1643
	10560	1711	1765	1803

SW2	Volume (pc/h/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	1202	1233	1211
	7920	1272	1279	1256
	10560	1258	1280	1297

Table 4.4: Density by stations

SE1	Density (pc/mi/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	34	35	35
	7920	35	35	34
	10560	35	35	35

SE2	Density (pc/mi/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	36	40	36
	7920	39	39	39
	10560	38	40	39

SW1	Density (pc/mi/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	64	65	62
	7920	52	57	50
	10560	54	50	45

SW2	Density (pc/mi/ln)	*y* (ft)		
		1800	2400	3000
x (ft)	5280	26	27	27
	7920	28	29	28
	10560	28	29	30

In addition, the results were visualized by plotting the graphs of average volume against density and average speed against density, respectively (see Figures 4.3 and Figure 4.4).

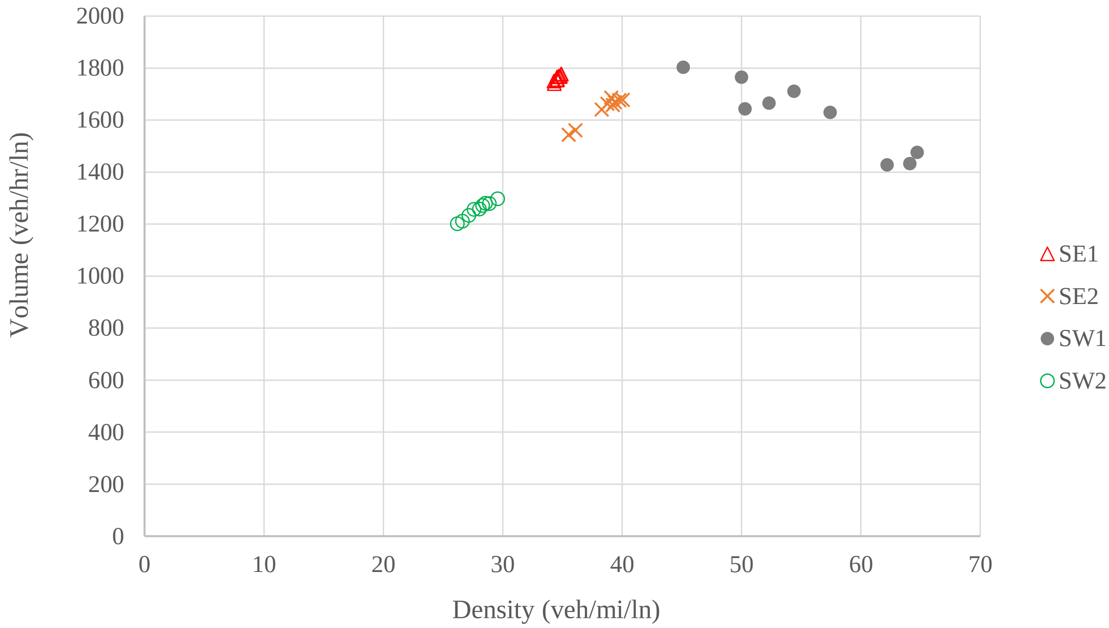


Figure 4.3: Average volume versus density

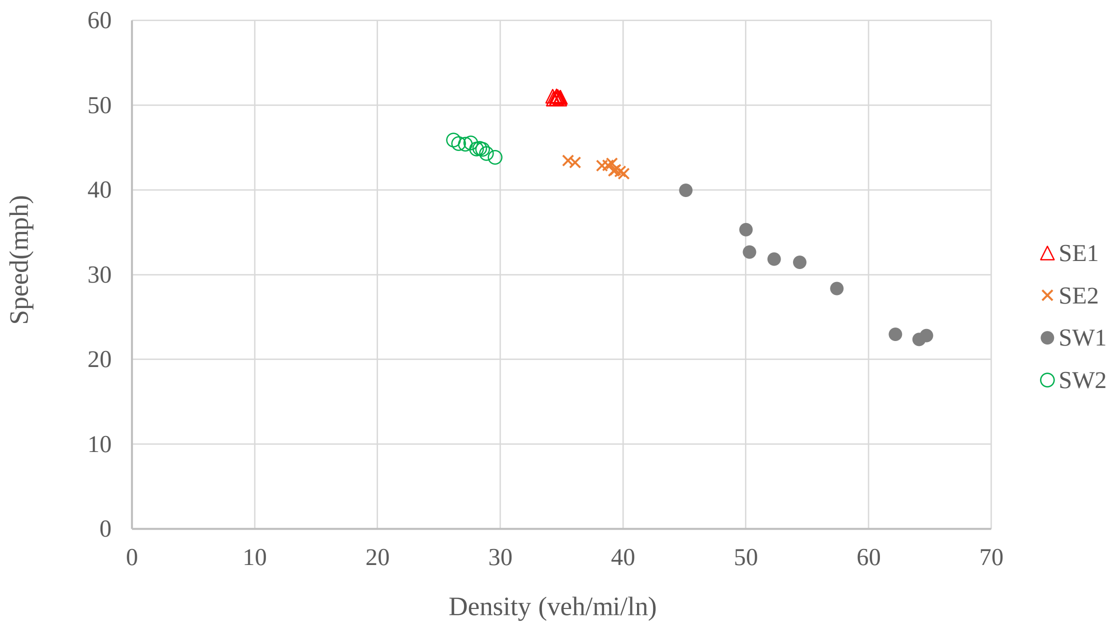


Figure 4.4: Average speed versus density

Figure 4.3 and 4.4 conveyed more information graphically. In these two figures, the 11 data points for the 11 cases at the same sensor station were plotted with the same color. It is obvious that the data points for SE1, SE2, and W2 clustered among themselves. While the data points in SW1 has average volumes of 1433, 1476, 1428, 1665, 1630, 1643, 1711, 1765, and 1803 veh/hr/ln, average speeds of 22, 23, 23, 32, 28, 33, 31, 35 and 40 mph, and density of 64, 65, 62, 52, 57, 50, 54, 50, and 45 veh/mi/ln.

Again, based on the clusters of data in Figures 4.3 and 4.4, it was concluded that at sensor stations SE, SE2, and SW2, the traffic conditions were very similar. This meant that the *x* and *y* parameters had little effect on the average speed, average volume and density. Since the average speeds at the GPLs at SE1, SE2 and SW2 were all greater than 40 mph, it can be concluded that all the *x* (access point locations) and *y* (weave length) were adequate to handle the ATs lane changing activities without disrupting traffic flow at the GPLs.

4.4 Traffic Speed Data

This section analyzed the variation of average speed with respect to the new variable $x+y$. Refering to Figure 3.9, $x+y$ is the maximum distance an AT must travel from the ATL to the I-10 off-ramp or from the I-10 on-ramp to the ATL. It represents the longitudinal distance in the GPLs occupied by the ATs to complete the movement between the ATL and the on-ramp or off-ramp. Figure 4.5 plots the average speed versus $x+y$. Like in the previous two figures, the data points for the same sensor location were marked with the same color. The same trend was noticed. That was, the average speeds at sensor stations SE1, SE2, and SW2 remained almost constant. The average speed at sensor station SW1 showed a positive correlation with $x+y$. This imply that as

x+*y* increased, the AT has more space to move between the ramps and ATL. They are not forced to slow down to change lane and decrease the speed of all the vehicles in the GPL.

The reason why station SW1 showed that *x*+*y* had an impact on the average speed at the GPLs was because traffic at or near SW1 was more congested. In Figures 4.3 and 4.4, the data points for station SW1 had higher density than the data points from other sensor stations.

Station SW1 was identified as the key station at which the data points were used to make decisions on the *x* and *y* values. At this station, case 0 had an average speed of 32 mph when no ATL was added to the network (see Table 4.1). An ATL with good *x* and *y* values should have a higher average speed in the GPLs. Case 10 showed an average speed of 35 mph when an ATL is present along the highway without an access point. That is, the ATL was for "pass-through" ATs only. With such a restriction, AT must use GPLs to access Transmountain Drive or Artcraft Road, increasing the volume in the GPLs and reducing average speed in GPLs. The ideal *x* and *y* design values from cases 1 to 9 should lead to higher average speeds in the GPLs than case 0 and case 10. Applying such criteria, good design values were *x*=10,560 ft or 2.0 miles, and *y*=2,400 ft or 3,000 ft. Between the two *y* values, 2,400 ft is preferred as it has lower construction cost due to the shorter auxiliary lane.

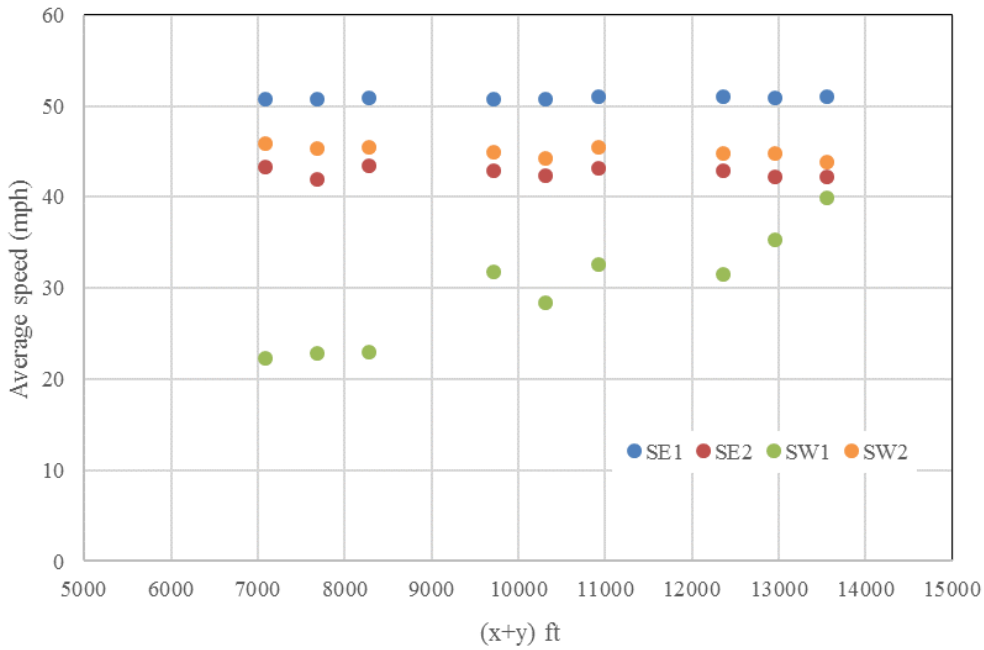


Figure 4.5: Average speed versus $x+y$

4.5 Summary of Results

This chapter analyzed the results of microscopic traffic simulation runs to recommend the value of two design parameters for ATLs: x and y. Parameter x, in feet, defines the maximum distance for an AT to change lanes from the leftmost to the rightmost GPLs, or vice versa, and y, in feet, determines the maximum weave length between ATL and the rightmost freeway GPL. The analysis procedure included the measurements of average volume and average speed at the GPLs at critical locations on the freeway immediately upstream or downstream from the ATL access points. The examination of the trends of average speed versus $x+y$ led to the recommended values of x=10,560ft and y=2,400 ft.

Chapter 5: Conclusions and Recommendations

5.1: Research Findings

Microscopic traffic simulation models of 11 cases were developed for the determination of the locations of access points relative to the on-ramps and off- (defined by *x*) and weave lengths (defined by *y*) of ATLs at a testbed along I-10 in El Paso, Texas. Based on the simulation results, the recommended values are x=10,560 ft and y=2,400 ft.

5.2: Contributions

There are two main contributions arising from this research:

- This is the first attempt to develop guidelines for the design values of *x* and *y*.
- A methodology that first uses microscopic traffic simulation to generate data for different design cases, followed by a procedure to analyze the data has been proposed and explored.

5.3: Future Research

The recommendations for future research are listed below. Most of them aim to address the limitations or assumptions made in the experiment that were performed in this thesis.

- All the simulation runs have so far used one set of input volume provided by El Paso MPO for the year 2045. More simulation runs should be made with different O-D and AT volumes.
- The percentage of AT was fixed at 50% of the total truck volume along I-10. The fraction of AT among the truck fleet should be varied in the simulation runs as well.

- VISSIM is developed in Germany using its own car-following and lane changing models. It is not known how these default behavioral models accurately represent the driving behavior of the drivers and ATs in U.S. The car-following and lane changing models in VISSIM should be calibrated or validated with U.S. data. However, these are not easy tasks.
- At the two signalized intersections, the approach volumes along the cross streets had been reduced by 50%. More investigation is needed to find out why the given volume exceeded the intersection capacity, and ways to improve the signal timing plans and make infrastructure improvement to increase the capacity.

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Vita

Ximena Jauregui was born in Torreón, Coahuila México. Concluding her high school education, she moved to El Paso, TX, where she continued to study at The University of Texas at El Paso (UTEP). Ximena graduated with a Bachelors of Science in Civil Engineering in December 2017. During her bachelor's degree, she worked as a web master in the Center of Instructional Design and Academic Technologies at UTEP. Additionally, Ximena participated in a student exchange program at the Czech Technical University taking courses in the Faculty of Civil Engineering which were credited to her degree at UTEP. During this time, Ximena participated in different student organizations such as the American Society of Civil Engineers (ASCE) and the National Society of Professional Engineers (NSPE). Also, she was an active member to the Chi Epsilon Civil Engineering Honor Society. Upon graduation, Ximena continued on pursuing her Master's Degree in Civil Engineering and is expected to graduate in August 2019. During her years as a master student, she worked as a Graduate Assistant for two courses: Transportation Engineering and Economics for Engineers and Scientists. In this past year, she became an intern at Walter P. Moore and Associates. Furthermore, Ximena joined the Institute of Transportation Engineers (ITE), serving as the Vice-President for the UTEP Student Chapter.

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