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Automated Truck Lanes in Urban Area for Through and Cross Border Traffic

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Executive Summary

Automated trucks will soon be operational across our nation's highways. Yet, it is unclear how the design of our highway infrastructure should be modified to accommodate automated trucks, to enable them to operate in such a way to maximize the economic, capacity, and safety benefits. This report evaluated the existing design of interstate freeways in Texas for automated trucks. It demonstrated, through microscopic traffic simulations, the concept of operations of automated truck lanes along the interstate freeways. Using the I-10 Freeway in the El Paso, TX region as the testbed, the research team: (i) assessed the existing structural, geometric and traffic designs in handling fully automated trucks; (ii) performed microscopic traffic simulations at a simulated testbed site to develop recommendations on the access point locations and weave length; and (iii) conducted a preliminary cost estimation on such infrastructure improvements.

Automated vehicles may be defined as vehicles equipped with technologies that have the capability of operation or driving without the active physical control of a natural person. Five levels of automation have been defined. This research focused on fully automated truck at Level 5. The horizon year was 2045 when an automated truck lane will be constructed in the median in each direction for automated truck to travel in platoons. All the analyses were performed first at a physical testbed which was milepost 0 to 55 of the I-10 Freeway in the Texas Department of Transportation El Paso District. After assessing the existing structural and geometric designs of I-10 in accommodating automated truck platoons, the research team concluded no modification to the roadway geometric design is necessary. However, the future cross-section will require widening or replacement of nearly every structure for the addition of the truck lane.

The next phase of research was to use a selected site within the physical testbed as the simulation testbed to conduct experiments to develop recommendations on the geometric design of the automated truck lane. The locations of the access points and weave length were identified as the two critical design parameters. Using VISSIM to develop the models and perform experiments, the simulation findings indicated that the access points to the automated truck lanes should be 2.0 miles upstream from the freeway off-ramp, or 2.0 miles downstream of the freeway on-ramp, so that automated trucks have adequate distance to move between the ramps and the automated truck lane. The access point should have a weave length of 2,400 ft for automated trucks to change lanes between the automated truck lane and the leftmost general purpose lane.

Constructing the 110 miles of ATL (55 miles x 2 directions) would cost TxDOT \$220 million (in 2018 dollar). The barrier between the ATL and GPLs would cost another \$8 million.

Table of Contents

Automated Truck Lanes.....	i
Executive Summary	v
Table of Contents.....	vi
List of Figures	vii
List of Tables.....	viii
Section 1 Introduction	1
1.1 Background	1
1.2 Objectives and Scope	2
1.3 Research Methodology	3
1.4 Outline of Report	4
Section 2 Literature Review	5
2.1 Automated Trucks.....	5
2.2 Infrastructure Designs to Accommodate Trucks in Platoons	7
2.3 Concept of Operations	9
Section 3 Assessments of Existing Infrastructure Designs.....	11
3.1 Vehicle Characteristics	11
3.2 Evaluation of Geometric Design	12
3.3 Evaluation of Structural Design of Bridges	13
Section 4 Simulation Analysis.....	40
4.1 Selection and Description of Simulation Testbed	40
4.2 Coded Testbed Model in VISSIM.....	42
4.3 Design of Simulation Experiment.....	44
4.4 Collection of Simulation Outputs	47
4.5 Results	49
4.6 Section Summary	55
Section 5 Economic Impacts of Infrastructure.....	56
5.1 Infrastructure Costs.....	56
5.2 Economic Impacts	57
Section 6 Conclusions, Limitations and Future Research	60
6.1 Conclusions	60
6.2 Limitations	60
6.3 Recommendations for Future Research.....	61
References.....	62

List of Figures

Figure 3.1: Cross-section recommended by TxDOT El Paso District	13
Figure 3.2: Overview of structures on the I-10 testbed	14
Figure 3.3: Bridges on I-10 by maximum span length	16
Figure 3.4: Bridges on I-10 by structure length.....	17
Figure 3.5: Bridges on I-10 by bridge width.....	18
Figure 3.6: Bridges on I-10 by material	19
Figure 3.7: Bridges on I-10 by structural form	19
Figure 3.8: Bridges on I-10 by decade built	20
Figure 3.9: AASHTO design truck (Spec 3.6.1.2.2-1).....	21
Figure 3.10: HL-93 loading schematic	22
Figure 3.11: FDOT C5 truck axle configuration	23
Figure 3.12: Two-truck platoon with gap S_a	23
Figure 3.13: Example positive moment envelope - 100' SS bridge	25
Figure 3.14: Candidate bridge locations.....	26
Figure 3.15: Underside View of Redd Road Bridge.....	27
Figure 3.16: Moment demand for Redd Road existing configuration	28
Figure 3.17: I-10 and Cotton Ave bridge	29
Figure 3.18: 204 ft continuous girder span from Cotton Ave (section # in box)	30
Figure 3.19: 211 ft continuous girder span from Cotton Ave. (section # in box)	31
Figure 3.20: Moment demand envelopes for Cotton Ave - existing 204 ft continuous span.....	32
Figure 3.21: Shear demand envelope for Cotton Ave - existing 204 ft continuous span (absolute value)	33
Figure 3.22: Moment Demand Envelope for Cotton Ave - Existing 211 ft Continuous Span	34
Figure 3.23: Shear demand envelope for Cotton Ave - existing 211 ft configuration (absolute value)	35
Figure 3.24: Moment demand for Cotton Ave replacement span assumed at 150 ft.....	36
Figure 3.25: I-10 over George Dieter Drive.....	37
Figure 3.26: Moment demand envelope for the 102 ft span at George Dieter	37
Figure 4.1: Area map of the simulation testbed	41
Figure 4.2: Cross-section recommended by TxDOT El Paso District (source: TxDOT El Paso District)	42
Figure 4.3: Screenshot of the network in VISSIM.....	43
Figure 4.4: “x” and “y” distances	45
Figure 4.5: Locations of traffic measurement stations	48
Figure 4.6: Volume-density plots.....	53
Figure 4.7: Speed-density plots	53
Figure 4.8: Speed versus (x+y).....	55

List of Tables

Table 3.1: Weight and size limits of semitrailers..... 11

Table 3.2: Geometric design criteria 12

Table 3.3: Structural characteristics for candidate bridges..... 26

Table 3.4: Composite section properties for continuous spans 29

Table 4.1: Criteria for the selection of simulation testbed 40

Table 4.2: Origin-destination trip table of passenger cars 44

Table 4.3: Origin-destination trip table of all trucks 44

Table 4.4: Simulated cases 47

Table 4.5: Average speed and total travel time by simulation case..... 49

Table 4.6: Average speeds by the station..... 50

Table 4.7: Counted volumes by the station 51

Table 4.8: Calculated densities by the station 52

Table 5.1: Potential costs differences 57

Table 5.2: Description of automation and platoon benefits from selected literature..... 59

Section 1 Introduction

1.1 Background

The present system of driving on roadways requires, for psychological and safety reasons, a significant amount of lateral and longitudinal spaces between vehicles. The longitudinal separation increases as the speed of the vehicle increases, with bigger space for trucks. Such driving behavior limits the capacity of our highways. One way to increase the highway capacity is to have automated vehicles traveling in smaller distances apart at high speed, or even in platoons. Towards this goal, the California Department of Transportation (Caltrans) has funded automated trucks research such as the State Route 60 Automated Truck Facility. The Partners for Advanced Transit and Highways (PATH) has successfully demonstrated advanced vehicle and safety systems for both automobile and truck traffic (Tomizuka, 1997).

In response to the rapid automation of vehicle technology, the U.S. Department of Transportation (USDOT) has defined the following 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 system 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.

This research focuses on the design and operations of highways for Level 5 Fully Automated Trucks (FATs).

The research used the I-10 Freeway in El Paso, Texas, from the New Mexico border in the west to milepost 55 in the east (the boundary of Texas Department of Transportation (TxDOT) El Paso District), as the physical testbed. The I-10 Freeway is the nation's main freight corridor connecting west coast Los Angeles, CA to the east coast Jacksonville, FL. Because of its importance in freight movement, the States of California, Arizona, New Mexico, and Texas recently formed the I-10 Corridor Coalition for working together to facilitate safer and more efficient travel (I10 Corridor Coalition, 2019). It is expected that in the future, this freeway from California to Texas will have a common design and operating standards for automated vehicles. However, the design guideline is yet to be developed. Known scientific publications mainly focus on the dynamic control of automated trucks and buses. Such microscopic movements have only begun to be translated into the traffic stream characteristics such as capacity, at the macroscopic level.

Texas Innovation Alliance, a group of agencies in Texas formed to address future mobility challenges in Texas, has designated El Paso as the Automated Vehicle Proving Ground for freight (Texas Innovation Alliance, 2019). The 55-mile segment of the I-10 Freeway in the El Paso, Texas region has been identified by TxDOT and County of El Paso as the future testbed for FATs. This site is proposed as the testbed because there are four interchanges that connect the I-10 Freeway to Mexico, i.e., this segment is the confluence between the truck traffic coming from the west coast of U.S. and from the U.S.-Mexico border, thus serving as the most challenging test site along the I-10 Freeway in the State of Texas, and perhaps from coast to coast. Locally, this corridor serves the City of El Paso, El Paso County, and the international border crossings, making it a critical thoroughfare to the region and a multifaceted testbed.

1.2 Objectives and Scope

The objectives of this research project were to:

- O1.** Review the automated truck technology, predict the physical and operating characteristics of FATs, and propose a Concept of Operations (ConOps) of FATs for the urban I-10 Freeway corridor in Texas;
- O2.** Assess the existing highway's structural, geometric and traffic designs in meeting the physical and operating characteristics of FATs, and propose possible design improvements that would meet the requirements of the ConOps;
- O2.** Demonstrate, by means of microscopic traffic simulation in VISSIM, the ConOps with the various proposed design improvements and recommend a design;
- O3.** Perform cost analysis on the recommended design changes.

This project answered the following research questions:

- RQ1.** What would be the vehicle design of FATs and how will these FATs operate on major highways?
- RQ2.** Are existing structures (bridges), highway geometry and traffic control plans adequate to accommodate the FATs? If the answer is "no", what design improvements should be made? Are dedicated lanes for FATs feasible?
- RQ3.** How much will the proposed design improvements cost?

Due to time, budget, and geographical constraints, the scope of this research was limited to the following conditions:

- The testbed was along I-10 Freeway in Texas, from the New Mexico state line in the west to milepost 55 in the east. This 55 miles of I-10 Freeway is within the TxDOT El Paso District which includes the following counties: Brewster, Culberson, El Paso, Hudspeth, Jeff Davis, and Presidio.
- There were two versions of the testbed: physical testbed and simulation testbed. The physical testbed encompassed the 55-mile study site that was used to identify critical locations where highway for design improvements. The simulation testbed was limited to a selected location within the physical testbed. Multiple simulation models, before and after design improvements, were developed for the selected location within the physical testbed.

- The vehicles of interest were FATs. Such trucks might be traveling alone in mixed traffic, or in a platoon, in the design year.
- The vehicle of interest also included FATs coming from and going to Mexico via the following ports of entry: Santa Teresa, Bridge of the Americas, Zaragoza, and Fabens. The interchanges that connected these ports of entry with the I-10 Freeway with the ports of entry were part of the physical testbed.
- The facility design included a dedicated truck lane in each direction along the I-10 median (right-of-way), called Automated Truck Lane (ATL), its entrances and exits, and its structural and geometric elements at critical locations.
- The ConOps of ATL was demonstrated by means of microscopic traffic simulation at the simulation testbed.
- Based on the results of the recommended ConOps, a preliminary economic cost study was conducted to assess the potential infrastructure improvement cost.

1.3 Research Methodology

The research work was divided into four sequential tasks. The outcome of each task is written into a section of this report.

Task 1 – Literature review and concept of operations [Section 2]

This task reviewed recent research works on automated trucks on highways, including vehicle design, vehicle operations, and control, infrastructure requirement and policy. The findings were used to identify the most likely design vehicles for FATs and to develop the ConOps for FATs in the physical testbed.

Task 2 – Assessments of existing infrastructure designs [Section 3]

This task included the collection of structural, geometric design and right-of-way inventory data for the physical testbed. These data were used to evaluate the adequacy of existing testbed facilities in accommodating the design vehicle and ConOps for FATs. The evaluation included the structural designs of bridges and geometric designs of highway elements. The last assessment performed in this task was the identification of design elements that were critical for the FATs to operate in the ConOps.

Task 3 – Simulation analysis and propose design improvement [Section 4]

In this task, a section of I-10 Freeway was selected within the 55-mile physical testbed to form the simulation testbed. Simulation models were coded in VISSIM to evaluate the different designs identified in the last part of Task 2. Based on the simulation results, design guidelines for the ConOps were recommended.

Task 4 – Cost estimation [Section 5]

This task explored the potential costs and benefits of FATs and platoons both from an infrastructure perspective as well as a local economic perspective. The relative cost increase to accommodate FATs and platoons in the physical testbed was assessed. Also, the overarching effects of FATs and platoons on the economy (i.e., effects on jobs, job shortages, fuel economy, safety, congestion) were considered.

1.4 Outline of Report

The outline of this report is as follows:

- Section 1 explains the background of this project, the objectives, research methodology and tasks to accomplish the objectives.
- Section 2 reviews the automated truck technology, infrastructure, and structural designs to accommodate truck platooning. Based on the reviews, the ConOps for the ATL is proposed.
- The collection of geometric and structural data in the physical testbed is described in Section 3. This section also covers the evaluation of the existing geometric and structural designs in accommodating the platooned trucks.
- Section 4 describes the applications of microscopic traffic simulation models to experiment with different access points to the ATL and the weave length.
- Section five performs a cost analysis of having ATL in the physical testbed.

Section 2 Literature Review

2.1 Automated Trucks

2.1.1 Definition

Automated vehicles may be defined as vehicles equipped with technologies that have the capability of operating or driving without the active physical control of a natural person. This excludes vehicles equipped with one or more systems that enhance safety or provide driver assistance but are not capable of driving by itself (Meyer, 2016).

The concept of the automated vehicle was first introduced in 1939 by General Motors (Nowakowski et al., 2015). However, no experiment was conducted. Yang et al. (2018) chronologically listed the historical developments of automated vehicles since then to the 2014 Tesla autopilot model which has conditional automation.

The first automated truck experiment named “Chauffeur” was conducted with three trucks along the Brenner Pass through the Alps between Austria and Italy (Tsugawa et al., 2016) from the mid-1990s to early 2000s.

2.1.2 Levels of Automation

The Automated Highway System (AHS) research program was initiated in U.S. in 1991, as part of the Intermodal Surface Transportation Efficiency Act (ISTEA). Soon after, the National Automated Highway Systems Consortium (NAHSC) was created in 1994 (Nowakowski et al., 2015). The Society of Automotive Engineers (SAE) has defined five levels (sometimes referred to as six levels) of vehicle automation (SAE International, 2016):

- 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.

These five levels of automation are applicable to both cars and trucks. However, as in the current industry practice, trucks come in many sizes (dimensions), engine power, axles, and weight limits.

Moreover, two trucks with the same dimensions and engine power may carry different loads. These are factors to consider when designing algorithms to control a truck's dynamic movements.

2.1.3 Platooning

Along with the automation of trucks comes the concept of truck platooning. Truck platooning may be defined as grouping a number of trucks into a single entity (convoy) where one truck follows another in a smaller headway (or gap) compared to regular driving (Shanmugavel et al., 2017). Reich (2016) defined an automated truck platoon as two trucks following closely behind one another with the lead truck driven by a human driver while the following truck is without a driver. What is not clearly stated in the above, and many other definitions are (i) trucks in a platoon all travel in the same lane; (ii) trucks form a platoon when they follow each other with headways (or gaps) below a threshold value. Once a platoon has been formed, truck platooning may be viewed as a special case of truck-following, where the reaction time of the follower is almost zero. That is, the follower is able to accelerate and decelerate in response to the leader almost immediately, like a single unit. Therefore, in a platoon, trucks are able to travel at high speeds while maintaining small and almost the same headway (or gap).

Truck platooning has multiple benefits: (i) reductions in road space occupancy, or physical space; (ii) improvement in safety (by eliminating rear-end crashes); (iii) reduction in fuel consumption, (iv) reduction in emission (Aarts and Feddes, 2016; Berg and Greder, 2016; Bhoopalam et al., 2017; Boysen et al., 2018; Friedrich, 2016; Gheorghiu et al., 2017; Humphreys IV, 2017; Ihrén, 2017; Kockelman et al., 2016; Martin, 2015; Nunen et al., 2016; Shanmugavel et al., 2017; Thomas and Martinez-Perez, 2014; Tsugawa et al., 2016; Van de Hoef, 2016). However, truck platooning causes axle loads of multiple trucks to be closer to each other. These may have effects on pavement and bridges.

Automated truck platooning is most likely be implemented only on freeways. Trucks from different origins traveling to different destinations may form a platoon when they meet on the same section of the freeway. It is reasonable to assume that only certain parts of a state highway network be designated as "truck platoon segments" or ATL, perhaps due to geometry, crash history, etc. Once an automated truck has entered a truck platoon segment, it shall actively seek other compatible trucks to form a platoon, or to join an established platoon. Saeednia and Menendez (2016) presented three main platooning phases: (i) formation; (ii) maintenance; and (iii) separation.

2.1.4 Related Issues

From 2005 to 2009, a team of German researchers from the Aachen University automated a platoon of four trucks in a project named "KONVOI". The lead truck was driven by a human driver followed by three automated trucks without a driver at a gap of 10 m. The platoon speed was varied between 37 and 50 mph in German highways. It was found that the four-truck platoons increased the highway capacity of up to 9% and a fuel-saving of up to 10% (Kunze et al., 2011).

In the early 2000s, the California Program for Advanced Transit and The Highway (PATH) started its research on automated truck platooning. PATH researchers first conducted experiments with a two-truck platoon with gaps of 10, 8, 6, 4 and 3 m, and headways of 2 to 3 seconds. The results showed that fuel savings of 5% to 10% could be achieved for the front truck and 10% to 15% for the following truck (Bergenheim et al., 2012). In 2010 and 2011, a different experiment was performed with a three-truck platoon with a 20 ft gap and a speed of 53 mph. The results showed the first, second and third truck achieved fuel savings of 4.3%, 10% and 14% respectively (Tsugawa et al., 2016). Between 2008 and 2013, a project called “Energy ITS” in Japan studied fuel saving and CO₂ emission reduction by automated truck platooning. A platoon of three automated trucks was driven on a test track with a gap of 6 m at 80 km/h. They found that the trucks in the platoon achieved an average of 10% saving in fuel consumption (Tsugawa et al., 2016). Martin (2015) found 4.5% savings in fuel consumption for the lead truck and 10% saving in fuel consumption for the following truck, for a two-truck platoon traveling with gaps of 20 to 80 feet.

Automated trucks are expected to be safer than human-driven trucks because the technologies that provide the automation reduce the human errors and the crashes caused by such errors. Because automated trucks have not been used widely on highways, there are no statistics to compare the crashes before and after the implementation. Li et al. (2016) reviewed the technologies that could be implemented in automated vehicles (cars) and estimated the contributions of these technologies in reducing the different types of crashes, crash frequencies, and crash severities. From these judgments, they estimated that automated vehicles may reduce U.S. crash costs by at least \$126 billion per year and functional lost by nearly 2 million human-years.

2.2 Infrastructure Designs to Accommodate Trucks in Platoons

2.2.1 Bridges

The impact of platooned trucks on bridges has only been studied to a limited extent. The majority of recent research related to truck-bridge interaction has focused on extra heavy and overweight trucks, as well as superloads. As the trucks that make up a platoon are no different from standalone trucks in terms of geometry and typical axle weights, the primary concern, when focusing on platooning, is the spacing of the trucks.

Kuhn et al. (2017) presented a comprehensive study on truck platooning in Texas, funded by TXDOT, including a Level 2 Automation demonstration with truck platooning. The effect on bridges was considered in the identification of potential corridors, but the actual demonstration occurred on the Rellis Campus, did not include a bridge. In the consideration of bridges for potential automated truck corridor development, Kuhn et al. indicated that “typical bridge design...would not necessarily restrict where truck platoons may operate...” but they do not provide analysis to that effect (Kuhn et al., 2017). The controlling assumption is that as long as the trucks adhere to the FHWA Bridge Formula, then bridges shall be

sufficient. The U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC), in conjunction with Auburn University ([Anthony and Halleaux, 2017](#)) conducted a truck platoon test over an international crossing from Michigan to Canada. The purpose of this test was not to test the bridge itself, but rather the effects of the bridge superstructure on platoon technology. For the purposes of a demonstration, following distance in a platoon was a control variable.

[Lipari et al. \(2017\)](#) discussed infrastructure to vehicle solutions to manage vehicle gap in heavy trucks. This research presupposes that the structure has been identified as worthy for the investment required to manage vehicle gap, but does not provide analysis to that effect.

Similar to Texas, other states are in the process of addressing this question through research. Researchers from Rutgers University posited a similar question to New Jersey Department of Transportation ([Masceri, 2017](#)), but no further action has been taken.

The challenges from platooned trucks on bridge performance might best be likened to the effect of trains on rail bridge performance. There is a vast body of research in this area but the connection to platooned trucks on highway bridges is tenuous because of the differences in configuration, load level, speed, length of platoons, and the bridges themselves. As such, this resource shall be tapped when appropriate, but not presented herein.

2.2.2 Interchange designs

The only literature related to geometric and/or interchange redesign for automated truck platooning was [Chen et al. \(2017\)](#). They discovered that at some critical uphill grade (based on the trucks maximum acceleration capacity), the cooperative adaptive cruise control model becomes unstable, as the trucks fail to re-engage after the upgrade. This is related to the dynamic characteristics of trucks and their positions in a platoon.

Assuming that automated truck platooning only occurs on freeways. The interchanges of concern are freeway-to-freeway interchanges. Truck platooning may or may not be allowed when the trucks change direction from one freeway to another. The trucks may have to leave one platoon and join another platoon. A platoon of multiple trucks acts like an articulated truck. If platooning is allowed at freeway-to-freeway connectors, the geometry of the connectors must be analyzed for their abilities to accommodate a few trucks in a platoon while making turns. The literature on the analysis of horizontal curve and swept path associated with truck platooning has not been found.

2.2.3 Truck-Only Lanes

Truck-only lanes, as the name suggests, are lanes designed exclusively for trucks. Although the idea has been considered for many years, there are very few examples in the United States. None of those

restricts passenger cars from entering and traveling with trucks. California implemented truck lanes in two different portions of the I-5 Freeway. Segments in northbound and southbound in Los Angeles County and southbound in Kern County have two truck lanes per direction. Similarly, the New Jersey Turnpike has six lanes in each direction. Trucks are restricted to the three outer lanes while passenger cars can travel in all the lanes. Georgia plans to add truck-only lanes to the I-75 Freeway, with construction scheduled to begin in 2025 (GDOT, 2018). Forkenbrock and March (2005) estimated that additional truck-only lane costs \$2.5 million per mile per lane.

2.3 Concept of Operations

ConOps is a description of the operations of a proposed system. The ConOps of automated trucks has yet to be formulated at the state and national levels. Without a ConOps, it is very difficult, if not impossible, to conduct assessments on the existing highway infrastructure facilities in accommodating automated trucks. This subsection describes the ConOps of FATs and ATLS.

The ConOps is based on the following assumptions and scenarios:

- The ATL is on the left-hand side of the General Purpose Lanes (GPLs).
- The ATL has only one lane per direction.
- The ATL is separated from the leftmost GPL by a buffer or barrier.
- The ATL only runs parallel to the main highway. There is no dedicated connector that connects the ATL with another highway at any interchange. Therefore, a FAT that wishes to change its direction of travel at an interchange must (i) exit the ATL upstream of the interchange, move from the left to the right across the GPLs and then use the off-ramp or connector designed for mixed traffic to exit the original highway; or (ii) enter the rightmost GPL from an on-ramp or connector in mixed traffic, move from the right to the left across the GPLs and then enter the ATL.
- ATL has a higher speed limit than the GPLs.
- As the name ATL implies, only the FAT are allowed to use the ATL, and form platoons in the ATL. No other vehicle is allowed in the ATL.
- Every FAT still has a commercial driver in the cabin.
- When traveling with mixed traffic in GPLs, the driver is in full control of the truck.
- When a FAT is traveling in an ATL, the truck is operating in fully automated mode (Level 5).
- When a FAT is moving between the ATL and the leftmost GPL, it is said to be in the transition between the human-driven mode and fully automated mode. The control mechanism of the FAT during this transition is yet to be determined. In this research, it was assumed that the FATs is controlled by its driver at Level 3 automation.
- The leader of a platoon is controlled by a driver at Level 3 automation
- When entering or exiting an ATL, FATs are only allowed to move between the ATL and the leftmost GPL at designated weave areas of designated access points.
- To improve safer lane changing of FATs, an auxiliary lane is provided between the ATL and the leftmost GPL at every ATL's access point.

- When a FAT wishes to exit the ATL, it first separates from a platoon, decelerates and moves into the auxiliary lane to prepare for a lane change.
- When a FAT wishes to enter the ATL, it first moves from the leftmost GPL into the auxiliary lane, accelerates and then seeks an opportunity to merge into the ATL before joining a platoon.

Section 3 Assessments of Existing Infrastructure Designs

This Section assesses the current and future (proposed) highway infrastructure designs in meeting the operational requirements of anticipated FATs.

3.1 Vehicle Characteristics

Automated trucks are under various stages of development by companies such as Tesla, Volvo, Daimler, Waymo, TuSimple. These manufacturers’ websites provide many promotion videos and information about the ConOps, but none of them except Tesla has posted information on vehicle characteristics that relates to the geometric design criteria. Tesla’s automated trucks ([Tesla Semi, 2019](#)) is a semitrailer installed with four electric motors that drive the rear axle. It consumes less than 2 kWh/mi of energy, able to accelerate from 0 to 60 mph in 20 seconds and maintains 60 mph speed at 5% grade. Tesla truck can travel between 300 to 500 miles per charge. No information on the vehicle weight, width, height, and length is provided. Based on the video footages and still images found on the websites of the abovementioned manufacturers, automated trucks appear to have the same dimensions as conventional semitrailer trucks. This is most likely the case since any newly introduced vehicle into the existing transportation systems must meet the existing vehicle and infrastructure design criteria.

The vehicle characteristics that are associated with the bridge and highway geometric design criteria are: vehicle weight (or axle load), axle configuration, vehicle length, vehicle width, vehicle height, the height of driver’s eyes, acceleration rate, deceleration rate, and tire friction. The weight and dimension of vehicles are governed by the limits set by Federal and State laws (see **Table 3.1**). Acceleration rate, deceleration rate, and tire friction are vehicle specific, while the height of the driver’s eyes (commonly known as the h_1 value in vertical curve) should be replaced by the height of a forward-looking sensor.

Parameter	Federal limit at interstate highways	State of Texas
Reference	www.ops.fhwa.gov/freight/sw	www.txdmv.org/motor-carriers
Weight – gross weight	80,000 lbs	80,000 lbs
Weight – single axle	20,000 lbs	20,000 lbs
Weight – tandem axle	34,000 lbs	34,000 lbs
Length	No limit	59 ft
Width	No limit	8 ft 6 inches
Height	No limit	14 ft

Table 3.1: Weight and size limits of semitrailers

In summary, FATs are expected to be similar to semitrailers. The weights and dimensions of FATs should comply with the existing Federal and State laws.

3.2 Evaluation of Geometric Design

The existing geometry of I-10 Freeway within the 55-mile physical testbed was evaluated for its adequacy in accommodating automated trucks. This is because some FATs will be using the existing lanes along the I-10 Freeway to enter or exit the freeway, driven by a human driver. In Sub-Section 3.1, it was determined that FATs, with the expected ConOps, described in Section 2 were likely to have the same dimensions as the existing semitrailers. This means that FATs are able to operate on highways that have been designed to meet the standard for semitrailers. The task of geometric design evaluation for FATs thus became geometric design evaluation for semitrailers.

The as-built geometric drawings of the physical testbed were provided by the TxDOT El Paso District. A total of 128 drawings were provided. The geometric designs were checked against the guidelines in the TxDOT Roadway Design Manual (TxDOT, 2018). The manual provides two different sets of design criteria: (i) Chapter 6 Freeways and (ii) Chapter 8 Mobility Corridors. Their design criteria are listed in **Table 3.2**.

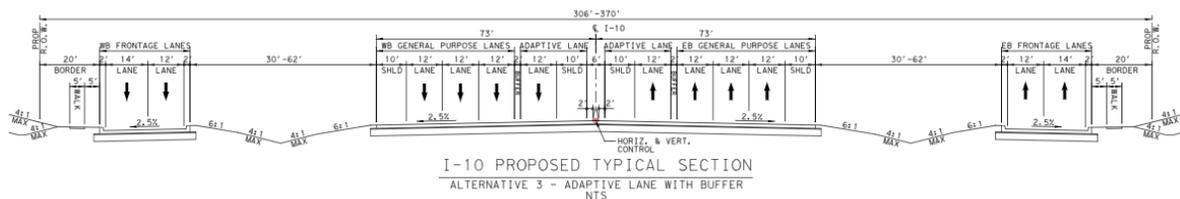
Components	Chapter 6 Freeways	Chapter 8 Mobility Corridors
Design speed	60 mph urban, 75 mph rural	85 mph
Lane width	Minimum 10 ft	Minimum 13 ft
Shoulder with (right)	Minimum 10 ft	Minimum 12 ft
Cross slope	2% recommended	2% recommended
Grade	Maximum 3%	2% to 3%
Horizontal curve radii (e=6%)	Minimum 3750 ft at 75 mph 2195 ft at 60 mph	Minimum 5615 ft at 85 mph

Table 3.2: Geometric design criteria

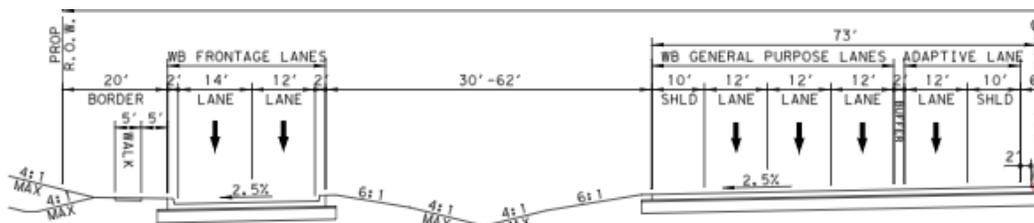
Texas mobility corridors have a minimum design speed of 85 mph. TxDOT Roadway Design Manual (TxDOT, 2018) states that the design speed can be lowered in urban areas. Given that the posted speed limit in the physical testbed is mostly 60 mph in the GPLs, the criteria with the design speed of 85 mph is conservative. That is, if the highway is designed to meet the criteria for 85 mph, it also meets the criteria for lower design speeds.

TxDOT Roadway Design Manual (TxDOT, 2018) states that freeway’s design speeds are 70 mph in rural areas, and 50 mph within urban areas. Since the 55-mile physical testbed of this project was constructed decades ago, the design speed is not known. Within the testbed, the posted speed limits vary from 60 mph to 75 mph. If one design speed is to be elected, it was believed to be 75 mph. With this design speed, the design criteria should exceed the values in column 2 of **Table 3.2** and lie between the values between columns 2 and 3. All the as-built drawings were checked against the modified design criteria of minimum lane width of 12 ft, minimum shoulder width of 10 ft; cross slope of 2% to 3%, maximum grade of 3%. All the designs met the applied criteria.

The evaluation was also performed for the known geometric data for the proposed I-10 Freeway in 2045 with ATLS. The cross sectional design alternatives were provided by the TxDOT El Paso District and are shown in Figure 3.1. The lane width (14 ft), shoulder-width (10 ft) and cross slope (2.5%) met the applied criteria.



(a) Both directions



(b) Single direction

Figure 3.1: Cross-section recommended by TxDOT El Paso District

3.3 Evaluation of Structural Design of Bridges

Automated trucks in a non-platooned configuration are no different than a regular semitrailer truck from the perspective of bridges. If anything, more control overload position could, in the long term, change how bridges are designed because it could reduce some of the uncertainty that is considered in design standards. It could also exacerbate wear on the driving surface. Trucks, automated or manually

operated, in a platooned configuration could have detrimental effects on bridges, however. This section presents an analysis of those potential effects for select structures along the physical testbed.

The 55-mile segment of I-10 Freeway that runs from the El Paso county line in the east to the New Mexico state line in the west includes 159 bridge structures. This number includes structures that carry the main travel lanes as well as several on-ramps and off-ramps. Per the ConOps, driver control is assumed when an FAT is leaving the ATL, so the analysis focused on GPLs, but a general overview of structures along the I-10 Freeway is provided below.

3.3.1 Overview of Bridges that Carry I-10 in El Paso County

Figure 3.2 illustrates the overall geography of the I-10 Freeway in El Paso County within the physical testbed. Bridges that carry the I-10 GPLs (red line) or adjacent ramps are indicated by blue dots. The southeastern corner of the El Paso county is more rural/agricultural, and this part of the I-10 Freeway is less traveled there. The resulting structures tend to be smaller. Once near Loop 375 to the southeast of the City of El Paso, the concentration of bridges increases and remains high until the state line at New Mexico.

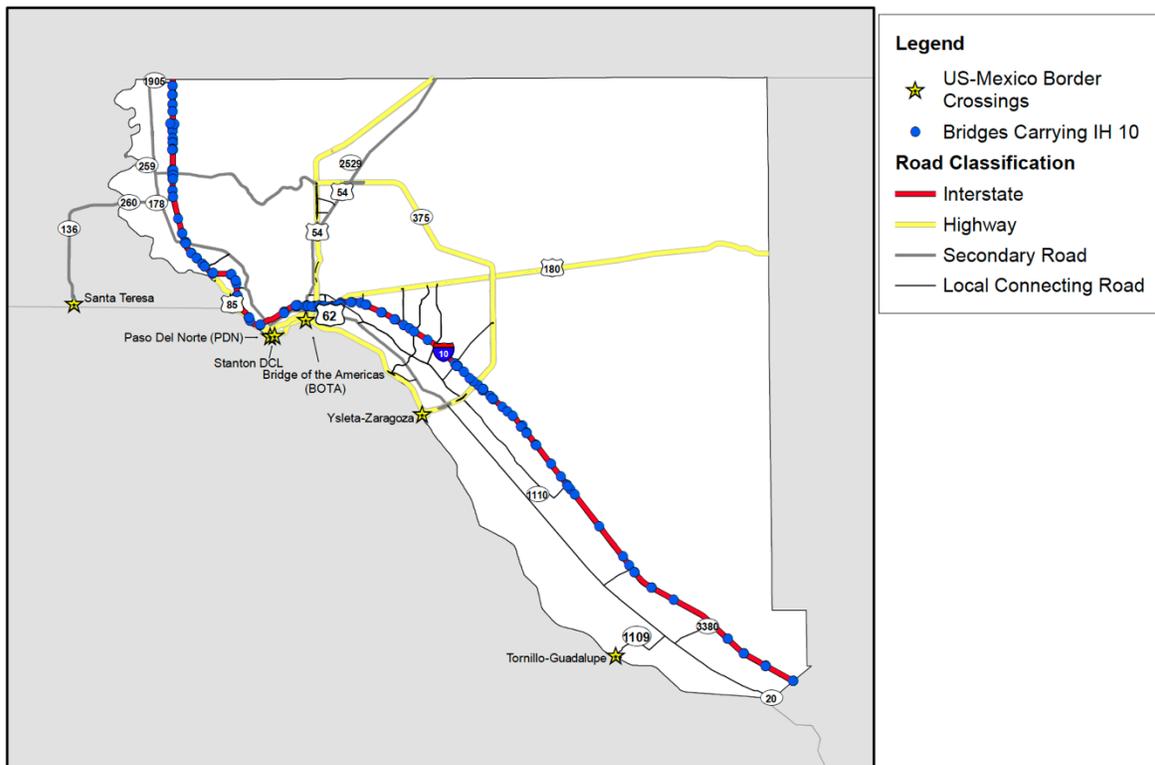


Figure 3.2: Overview of structures on the I-10 testbed

There are six international Ports of Entry (POEs) as indicated on the map. The city of El Paso manages the Paso del Norte (PDN), Stanton and Ysleta-Zaragoza (YZ) POEs, but only YZ carries commercial traffic. The Santa Teresa POE is managed by the New Mexico Border Authority and carries commercial traffic. The Bridge of the Americas (BOTA) POE near El Paso downtown is managed by the International Boundary and Water Commission. Finally, the Tornillo-Guadalupe POE is managed by the County of El Paso and has the capacity for commercial traffic but shut down commercial operations due to lack of demand. In summary, all commercial traffic in the greater El Paso region crosses either Santa Teresa, BOTA or Ysleta-Zaragoza POEs. The geographic dispersion of these three crossings and their ties into I-10 Freeway indicate that there is not a clear sub-region in which the bridge analysis should focus on.

Given the worst case scenario of trucks traveling in platoons, the key aspects for consideration of bridges are the length of the structure and the support conditions. Simply supported bridges, which are completely independent of adjacent spans, do not experience any load effects for trucks which are not on that specific span. Therefore, the key loading situation will be when a full platoon can be on the span at one time, exceeding the loading conditions for which the bridge was designed. This means that the longer the span, the more concern with platoons. **Figure 3.3** shows a histogram of the 159 bridges by maximum span length, per the National Bridge Inventory data. Most bridges (105 out of 159) are less than 60 ft maximum span length. This means that platoons will likely not have deleterious effects on the span. However, a small portion of the bridges have spans over 100' in length where platoons may be more problematic.

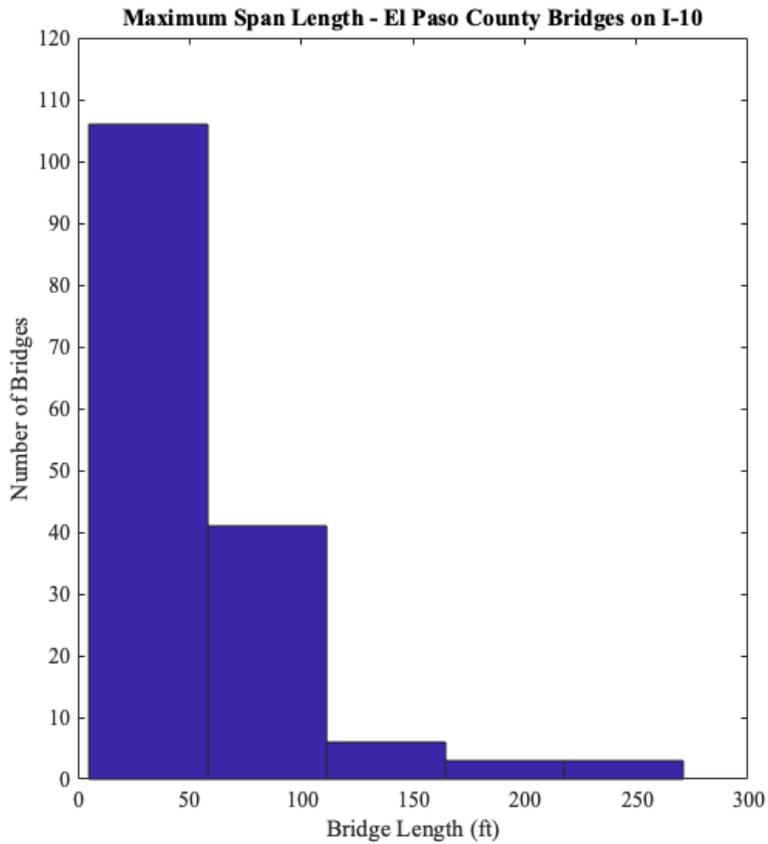


Figure 3.3: Bridges on I-10 by maximum span length

Figure 3.4 illustrates the bridges on I-10 Freeway in El Paso County by overall structure length. Again, most structures are 250 feet or less. Based on typical bridge designs, this indicates a one to three-span configuration, with either simple support or continuous boundary conditions.

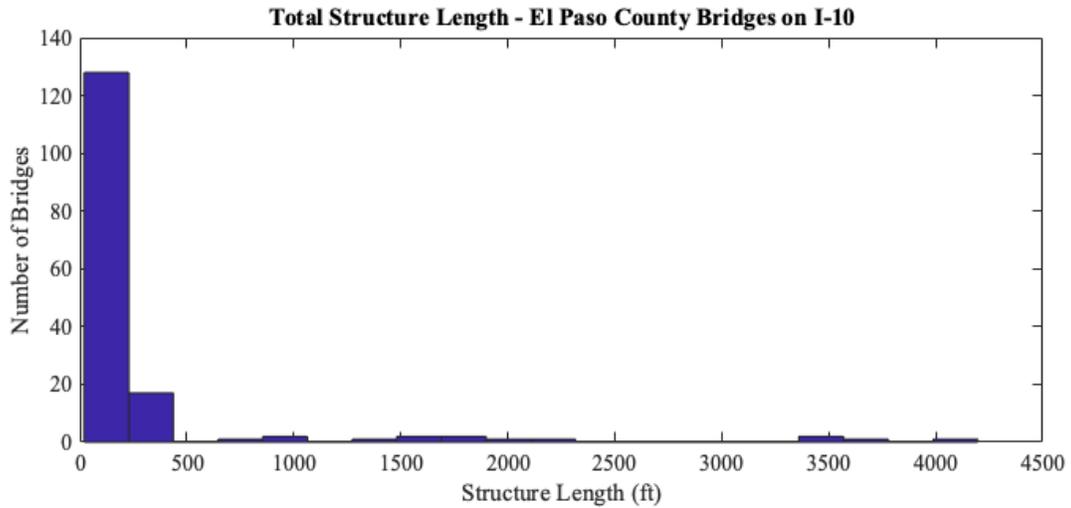


Figure 3.4: Bridges on I-10 by structure length

To facilitate this analysis, the TxDOT Bridge Design Standards ([TxDOT, 2019c](#)) will be used for standard design configurations that meet current design requirements. These design standards are provided by TxDOT for several structural configurations and lengths, binned by structure width. Most standard designs limit the bridge width at 44 feet. Figure 3.5 shows the range of bridge widths on I-10 Freeway in El Paso county. Most structures are between 30 and 50 feet in width, indicating that the design standards can be utilized when exploring future design options, though the proposed TxDOT roadway section will be slightly wider.

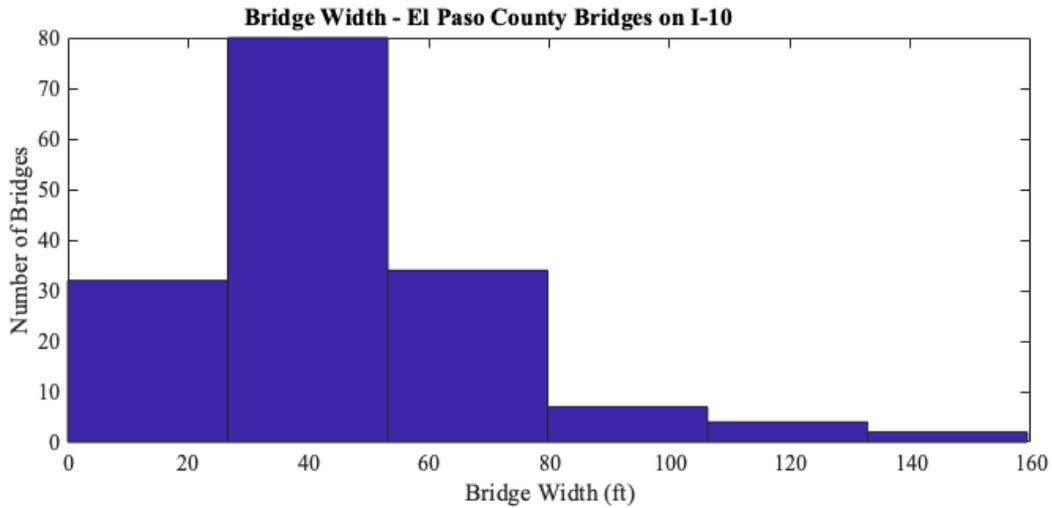


Figure 3.5: Bridges on I-10 by bridge width

The majority of the bridges on I-10 Freeway are concrete structures, with only 15 steel bridges in total, as shown in **Figure 3.6**. There are 59 concrete bridges, most of which are culverts and other small bridges. There are 39 continuous concrete bridges and 46 prestressed concrete bridges which are simply supported. The vast majority of the bridges are multigirder or multigirder box bridges (**Figure 3.7**).

Primary Materials - El Paso County Bridges on I-10

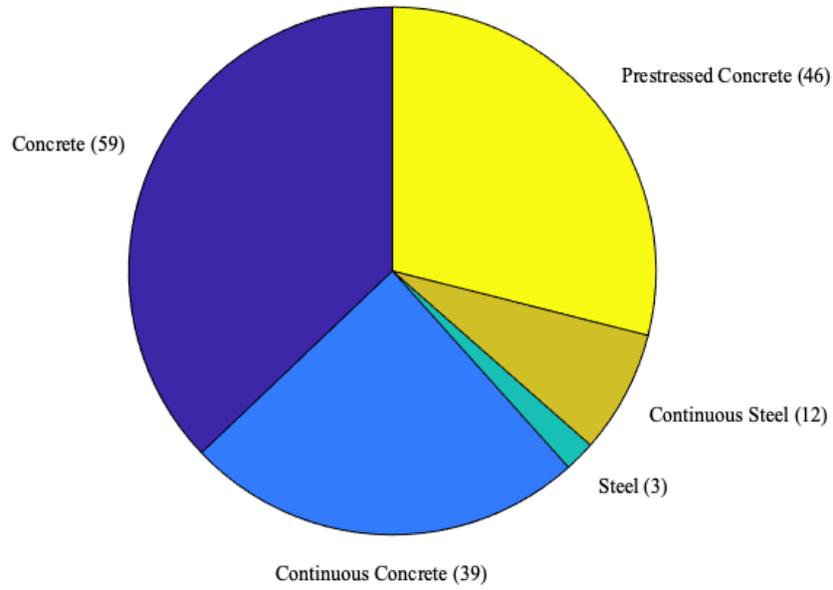


Figure 3.6: Bridges on I-10 by material

Structural Form - El Paso County Bridges on I-10

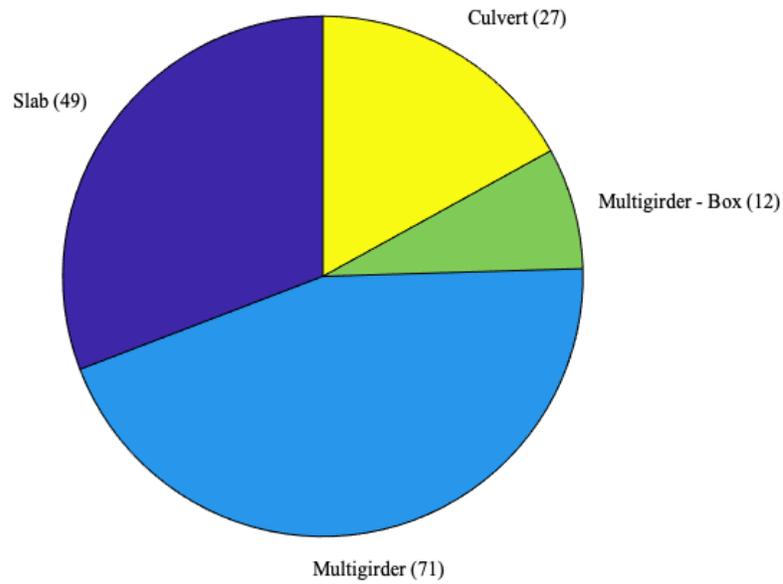


Figure 3.7: Bridges on I-10 by structural form

Finally, **Figure 3.8** shows the bridges on I-10 in El Paso County by the decade built. The majority of structures were built at the same time as the I-10 Freeway in the late 1950s and early 1960s. Later surges were tied to the construction of major interchanges with US Highway 54 and Texas Loop 375.

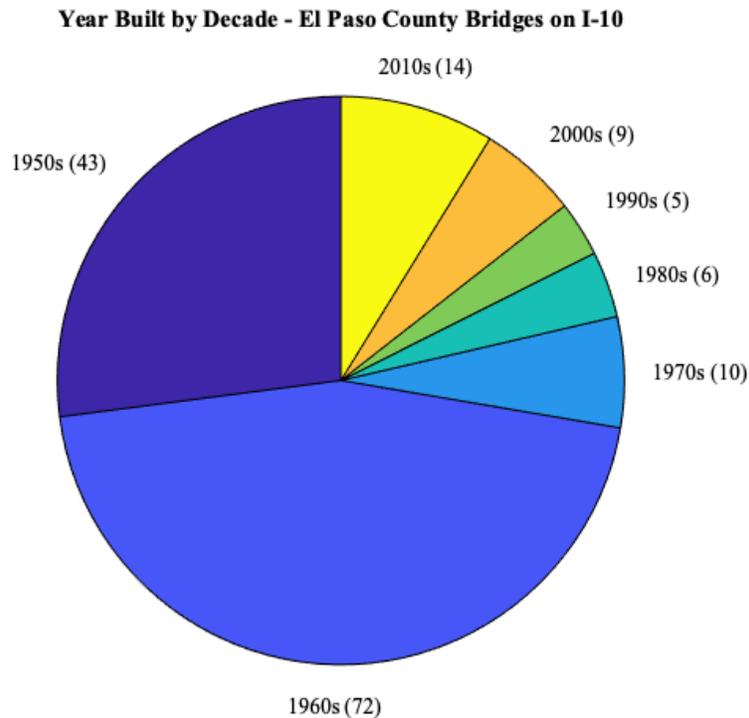


Figure 3.8: Bridges on I-10 by decade built

In summary, the bridges along I-10 have the following primary characteristics:

- Nearing the end of their design lives
- Generally made of concrete
- Generally simply supported with span lengths shorter than 100 ft
- Generally carrying three to four lanes of traffic with widths between 40 and 60 ft

In order for TxDOT to implement the proposed cross-section inclusive of the ATL, many if not all of the older bridges would be replaced, while some newer structures would be widened. Most bridges along the ramps would remain unchanged. New structures built after 1994 would have been designed using Load and Resistance Factor Design (LRFD), the prevailing design method in use today. Considering all this, the ensuing study will focus on LRFD designed bridges that adhere to the geometric constraints of the existing structures in terms of length, with the notable exception of the Cotton Avenue bridge, where

the steel superstructure and continuous configuration will be replaced with longer, simply supported concrete girders (Weidner, 2019). The specific bridges and configurations considered are presented later.

3.3.2 Loading Considerations

Bridges are designed according to the AASHTO LRFD Bridge Design Specifications (Spec). Design loads considered are generally broken into two categories, permanent and transient loads. Permanent loads include dead load, earth pressure, locked-in force effects, and post-tensioning effects, among others. Transient loads include blast, seismic, wind, ice, temperature, and of course, live load. Live load is the load that results from vehicles and pedestrians on the structure and is the focus of this study.

The LRFD Specifications define the HL-93 notional design load as a combination of one of two trucks, and a distributed lane load over the whole structure. The standard “design truck” is shown in **Figure 3.9**. It is a three-axle truck with a gross vehicle weight of 72 kips and is often referred to as the HS-20 truck, a vestige of prior design specifications. The rear axle spacing can vary from 14 to 30 ft in order to create maximum load effects on the structure. This is combined with a lane load of 0.64 klf. The other truck load considered is from the tandem axle, which consists of two axles carrying 25 kips each, placed at a spacing of 4 feet, which is also combined with the 0.64 klf lane load. These are the two primary considerations for simple spans. For continuous bridges, the same cases are considered plus a two-truck configuration with the design truck spaced at 50 ft axle-to-axle, along with the lane load, applied at 90%. The purpose of this case is for the negative moment region above interior supports on continuous bridges. These cases are summarized in **Figure 3.10**.

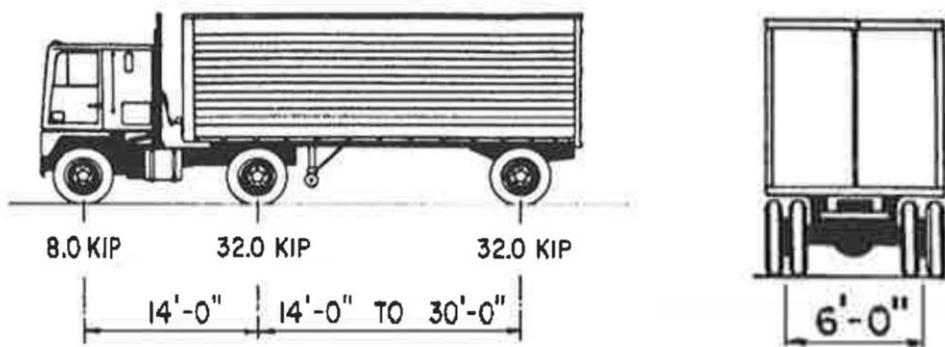


Figure 3.9: AASHTO design truck (Spec 3.6.1.2.2-1)

Simple Span

Continuous

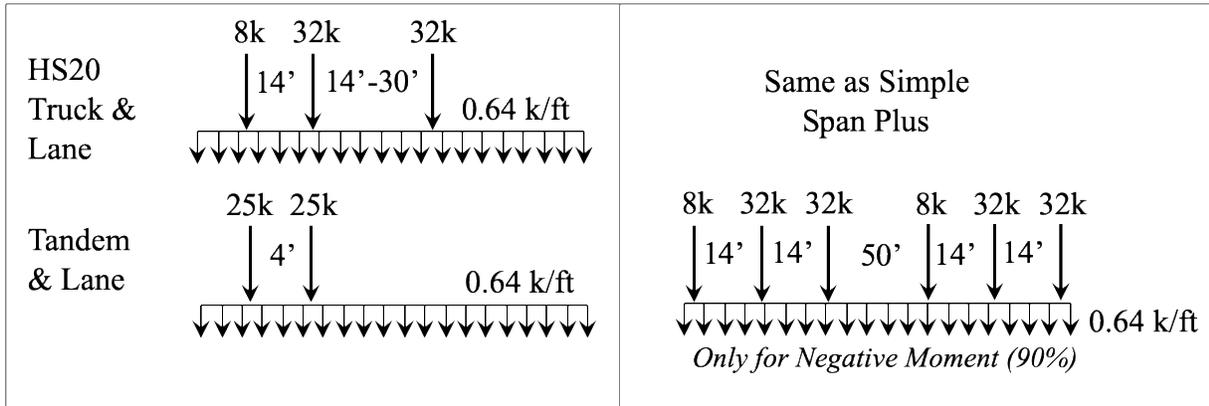


Figure 3.10: HL-93 loading schematic

The HL-93 notional loading scenario was developed to encompass the expected loading of traffic based on several experimental studies (Kulicki & Mertz, 1991; Nowak, 1995). These studies were conducted at a time when the gap between trucks was based on human reaction times and typical driver behavior. Automation and truck platooning will result in significantly smaller rear axle to front axle spacing between trucks in order to improve aerodynamics. The subsequent question to be addressed is “Will closely-spaced trucks in a platoon formation violate the HL-93 loading?” This is the primary question being addressed in this research.

The Federal Highway Administration provides the Federal Bridge Formula (Sivakumar et al., 2007) which specifies the maximum weight any set of axles may carry on the Interstate Highway System. This guideline is focused on the weight of the vehicle itself, providing a reference for a given set of axle dimensions regarding the maximum weight those axles may carry. Because of the potentially random and fluid nature of how truck platoons may form, and the potential variation in spacing, the bridge formula is a difficult tool to implement for guidance on bridges.

There are two existing studies that explore platoon effects on bridges. The Florida Department of Transportation (FDOT) explored the effects of two truck platoons some structures by scaling rating factors to represent platooned trucks (DeVault, 2016). FDOT adopted a two-truck platoon using the FDOT C5 truck with a GVW of 80 kips and axles spacings and weights shown in **Figure 3.11** Yarnold and Weidner adopted this same truck for the platoons considered but varied the axle spacing between vehicles as depicted in **Figure 3.12** (Yarnold & Weidner, 2019). This analysis consisted of three-span configurations (simple, two-span continuous, and three-span continuous) and assumed stiffness properties for steel construction, and compared loading specifications from the AASHTO Standard Specification, the LRFD Specification, and platoons of two, three, and four C5 Trucks.

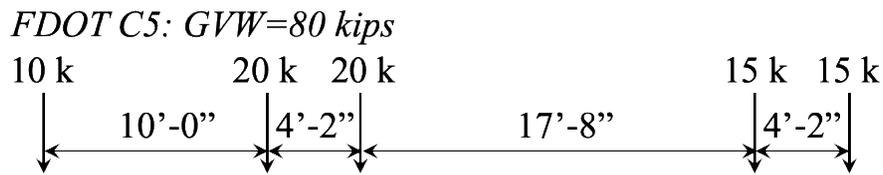


Figure 3.11: FDOT C5 truck axle configuration

3.3.3 Platoon Specifications for Structural Evaluation

The same platoon truck, the FDOT C5, was utilized for this research, with one notable exception. The gap between trucks was set to integer increments by 1 ft. This dramatically simplified the quasi-static analysis of the truck loading. The two-truck platoon configuration is depicted in **Figure 3.12**. The gap from the rear axle of the lead truck to the front axle of the follow truck, S_a , was varied from 20 to 50 in 1-ft increments. In addition, a similar platoon of HS-20 design trucks was also considered. Finally, the components of the HL-93 loading (i.e., the design truck, the lane load, and the tandem) were all implemented.

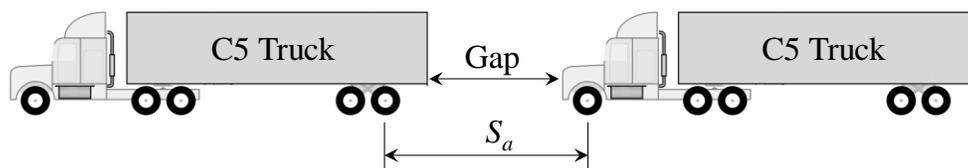


Figure 3.12: Two-truck platoon with gap S_a

3.3.4 Assumptions and Approach

There are many AASHTO-approved approaches to structural analysis for bridge design and assessment, but the most commonly used approach for common, multi-girder bridges is a single-line girder approach. In this approach, the transverse aspects of the structure are compressed to their proportional effects for a single girder, and loads are applied as point loads or distributed loads. That apportionment is achieved through the calculation of what is known as a distribution factor. AASHTO states that distribution factors do not vary between vehicles of the same wheel width (AASHTO, 2017).

Therefore, the distribution factor was assumed to be 1.0. Given the presence of a dedicated one-lane ATL in the physical testbed, it is logical to ignore the lateral position of the truck in other lanes.

The structural form for the analysis will be a single beam, with the requisite boundary and stiffness conditions applied based on the actual structure being considered. The analysis approach will be the finite element method in a Matlab-based code which incrementally steps each truck across the bridge in one-foot increments. The trucks (i.e., load cases) considered are as follows:

- Design truck with variable rear axle spacing at 1-ft increments (17 configurations)
- Design truck platoon with fixed 14' rear axle spacing and platoon gap from 20 ft to 50 ft (31 configurations)
- Tandem (One configuration)
- C5 Platoon with gap varying from 20 to 50 ft (31 configurations)
- Lane load (One configuration).

The result was 81 independent load cases, 80 of which must be incrementally stepped across the bridge. The analysis started when the first axle enters the bridge and continued as the truck moved across the bridge in 1-ft increments until the last axle left the bridge. For a typical, simply supported bridge in the order of 100 ft, this resulted in 100 ft plus the length of truck (f executions of the finite element solver for each of the 80 configurations—a total 14,754 individual solutions. This was the driving factor for developing a solution approach that was simple and fast.

For each positional iteration of each configuration of a truck, the moment and shear in the beam were extracted and stored in an array. From these results, peak response envelopes can be extracted by truck configuration. **Figure 3.13** shows a positive moment envelope for a simply supported 100 ft beam. Note that for all asymmetric load cases (i.e., non-tandem) the envelope is also asymmetric. This is because the analysis is unidirectional. For the purposes of this analysis, this is a justifiable assumption. If the trucks were run in both directions, an asymmetric envelope would emerge, but the peak values would not change. These component envelopes were then combined with the lane loading to create the HL-93 loading that serves as the comparison to the truck platoon. The lane loading must be patterned to create maximum effects.

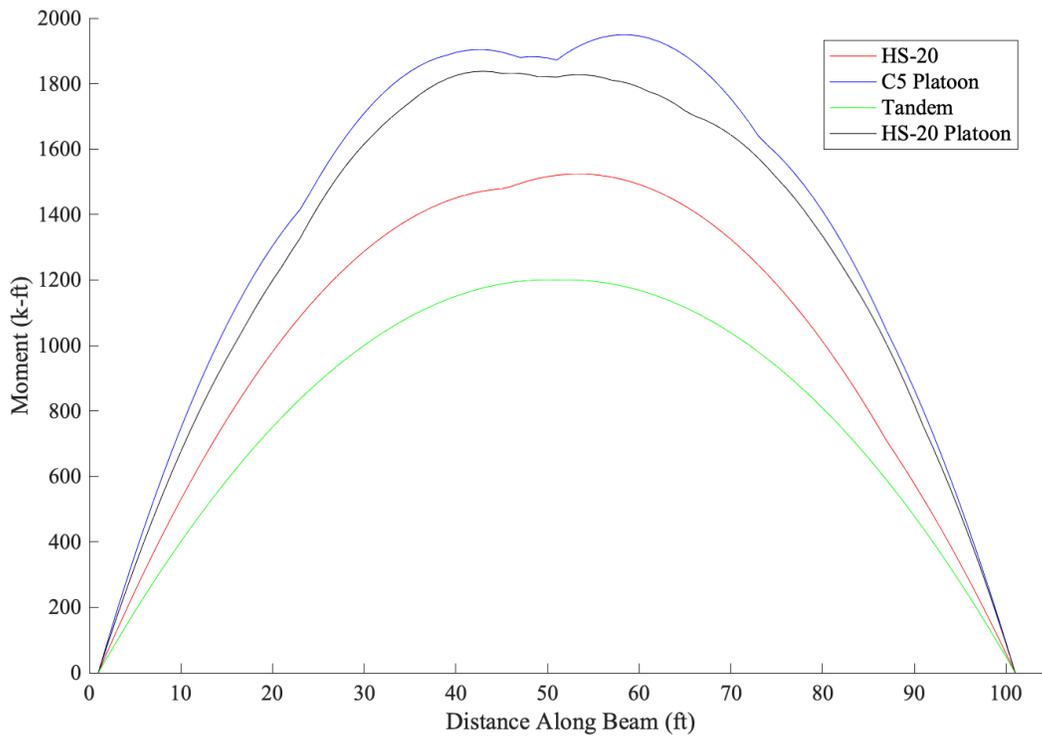


Figure 3.13: Example positive moment envelope - 100' SS bridge

3.3.5 Structures Considered

Three structures are considered in this analysis. These structures are I-10 over Redd Road, I-10 over Cotton Ave., and I-10 over George Dieter Rd. Each of these structures is relatively close to a connector to an international crossing. The bridges are dispersed throughout the city of El Paso along I-10, as seen in **Figure 3.14**. Summary properties of the bridges are provided in **Table 3.3**.

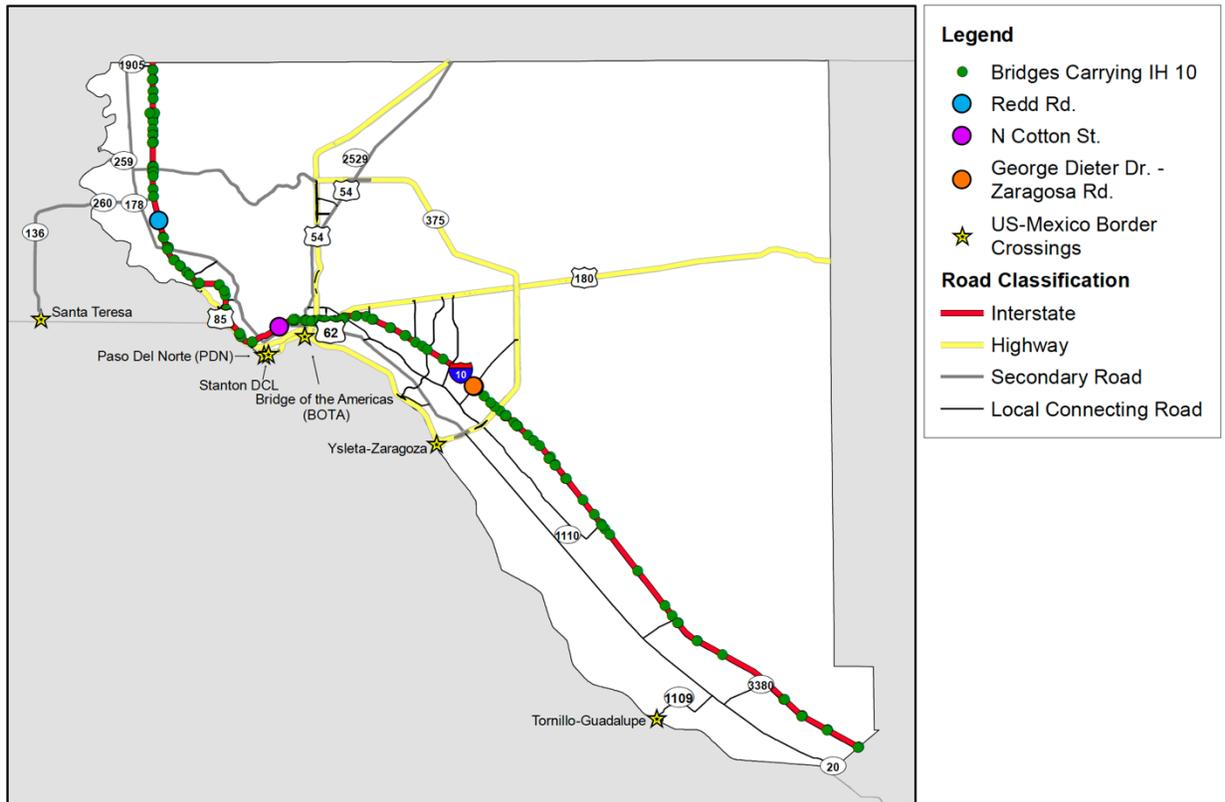


Figure 3.14: Candidate bridge locations

Characteristic	Redd Road	George Dieter Drive	Cotton Ave.
Structure Length (ft)	230	256	1850
Number of Spans	3	3	28
Twin Configuration?	Yes	Yes	Yes
Maximum Span Length (ft)	108	102	95
Structure Type	Concrete U-beam	Concrete Box Beam	Steel Multi-girder
Support Conditions	Simple	Simple	Continuous/Simple

Table 3.3: Structural characteristics for candidate bridges

3.3.6 Structural Analysis

In order to assess the readiness of I-10 bridges for the ATL and truck platoons, it is necessary to predict the structural form in the analysis year of 2045. TxDOT has standard designs available for many structural configurations (TxDOT, 2019c). These standard designs serve as a general reference. For a

better understanding of what is likely to occur, information was sought from the local TxDOT district office. Based on these resources, configurations for each of the three structures were selected.

Redd Road

The bridge that carries I-10 over Redd Road is a concrete U-beam with independent substructures for each beam, as seen in **Figure 3.15**. This structural form lends itself to widening. As such, it is likely that this structure would simply be widened to accommodate the expansion of I-10 for the ATL. This is a simply supported configuration which indicates that the girder level stiffness properties do not influence the load distribution. As such, the existing geometry can be considered for analysis.



Figure 3.15: Underside View of Redd Road Bridge

Figure 3.16 shows the positive moment demand envelopes for the C5 truck platoon and the HL-93 loading on the main span (i.e., the longest span of 108 feet). The HL-93 contains two separate envelopes. One is the design truck plus the 0.64 klf lane load, while the other is the tandem truck plus the lane load. Since this is a simple supported configuration, the truck to truck load case is not applicable. The HL-93 clearly exceeds the C5 Platoon demand, indicating that the structure in the current configuration will be adequate to carry the proposed platoon without any changes to the design approach.

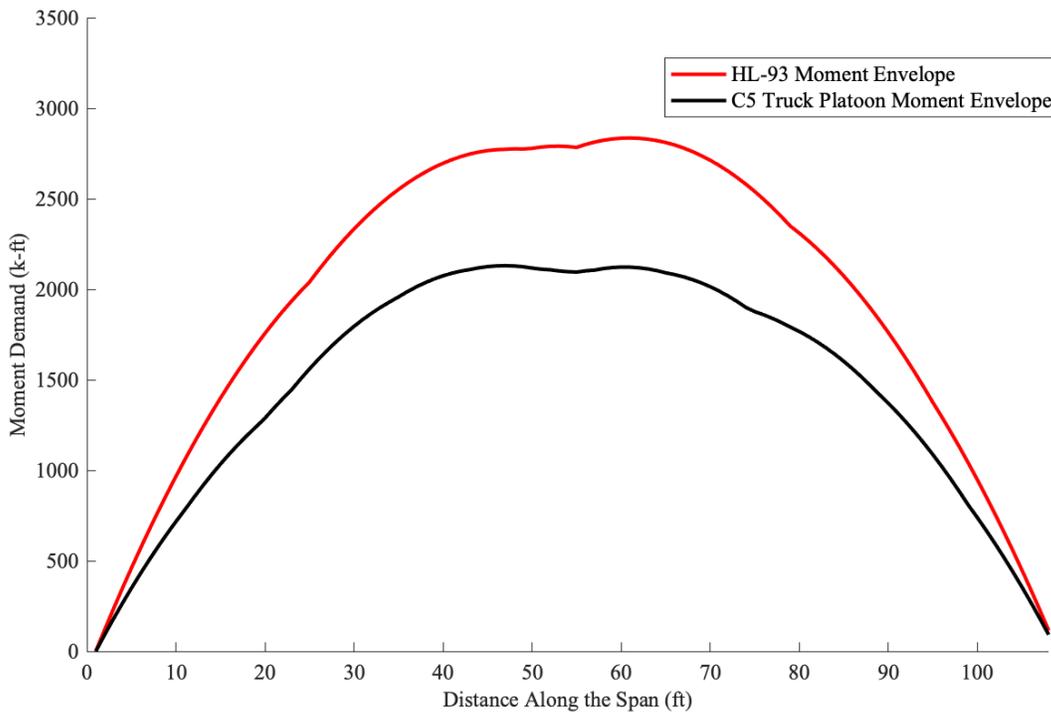


Figure 3.16: Moment demand for Redd Road existing configuration

Cotton Avenue

The Cotton Avenue bridge is a very large steel structure than spans across Cotton Avenue. The configuration is complex, accounting for the ground-level infrastructure (**Figure 3.17**). Cotton Avenue actually elevates to span an adjacent railway, increasing the required clearance height. Per a conversation with the TxDOT El Paso district, Cotton Avenue is already slated for replacement in the near future ([Weidner, 2019](#)). While the schematic design is not complete, it is expected that the new structure would be concrete multi-girder using TxDOT standard Prestressed I-girders. The number of spans would be reduced as would the number of substructures, again based on the ground-level infrastructure. The new spans would be simply supported. As discussed previously, the demand distribution in a simply supported configuration is not dependent on section properties. For this structure, a large simple span length is considered. Additionally, two continuous span configurations in the as-built structure are analyzed, as they represent a critical case if the bridge were not replaced prior to the introduction of truck platoons. These layouts, from the original as-built plans, are shown in **Figure 3.18** and **Figure 3.19**. The calculated composite section properties are tabulated in **Table 3.4**.

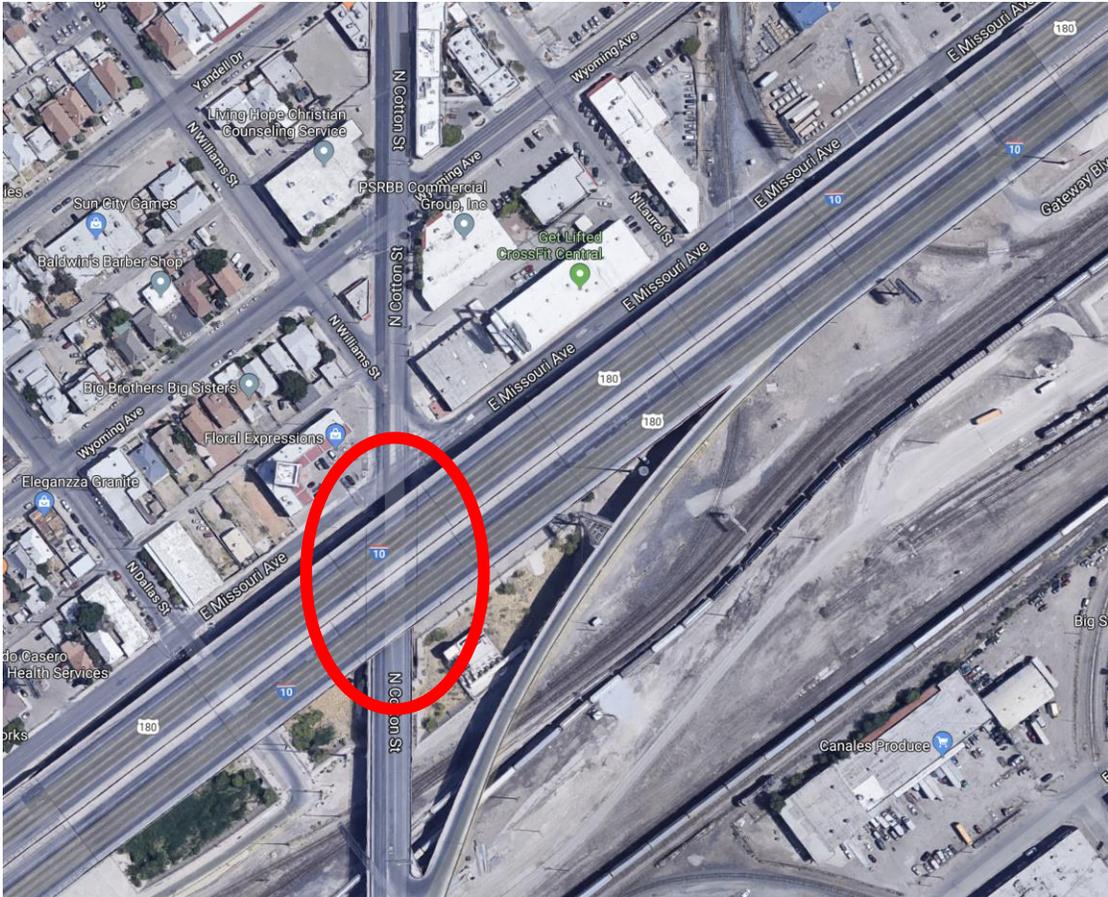


Figure 3.17: I-10 and Cotton Ave bridge

Section Number	Location	Moment of Inertia
1	All except noted	18980 in ⁴
2	Middle of 204' span	21562.5 in ⁴
3	Interior bent of 204' span	22991.2 in ⁴
4	Interior bent of 204' span	21922.1 in ⁴
5	Interior bent of 211' span	22280.1 in ⁴

Table 3.4: Composite section properties for continuous spans

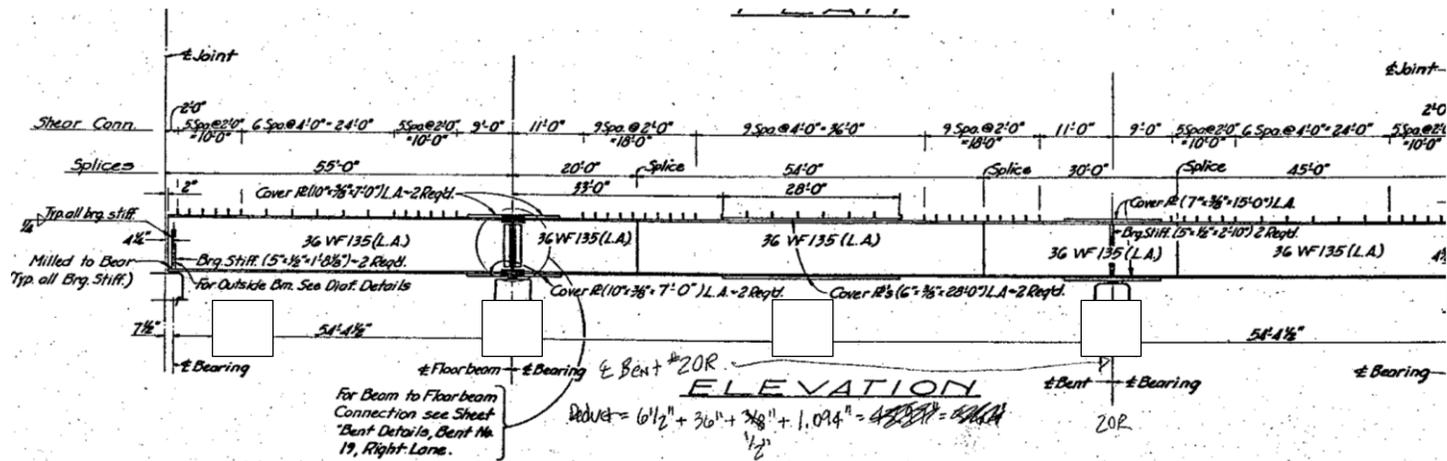


Figure 3.18: 204 ft continuous girder span from Cotton Ave (section # in box)

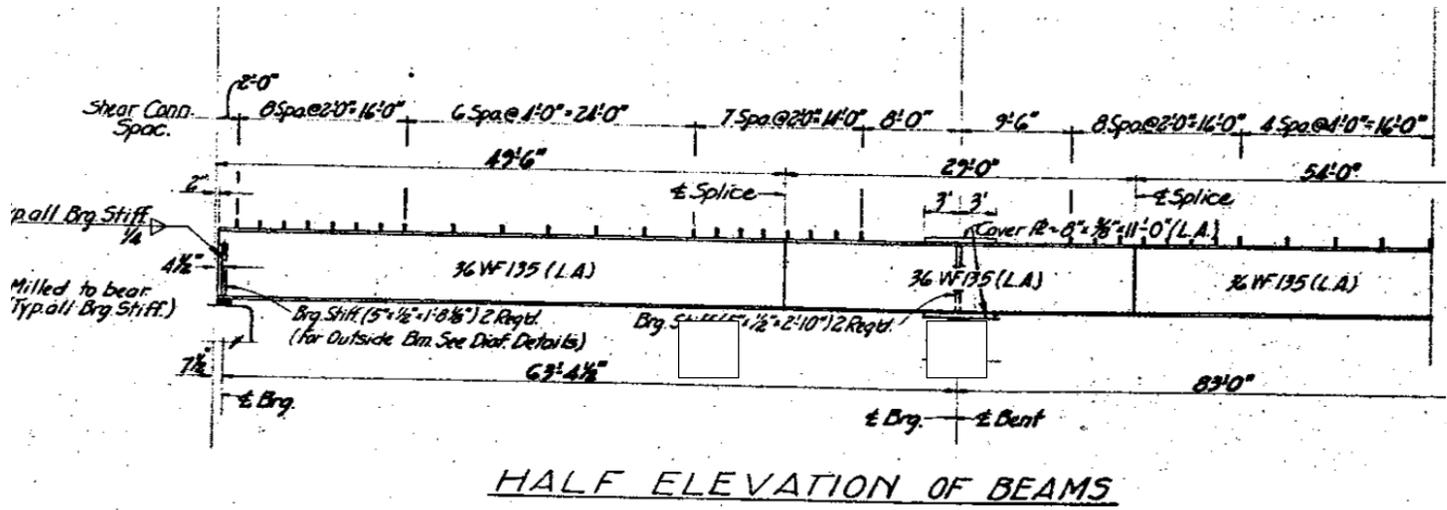


Figure 3.19: 211 ft continuous girder span from Cotton Ave. (section # in box)

Figure 3.20 shows the moment demand envelopes for the 204-ft three-span continuous existing configuration. **Figure 3.21** shows the shear demand envelope for the same structure. In both cases, the HL-93 notional design load exceeds the C5 Platoon loading, with one minor exception. Near the supports, the platoon has a slightly larger positive moment demand, but the controlling demand for continuous bridges at the supports tends to have a negative moment. This can be seen by comparing the absolute magnitudes of the positive and negative moments near 55 and 150 ft along the span. The absolute value of the negative moment is much greater than the positive moment at these locations. Effectively, these plots indicate that the proposed platoon, ranging from 20 ft to 50 ft spacing, would still fall within the HL-93 design loading.

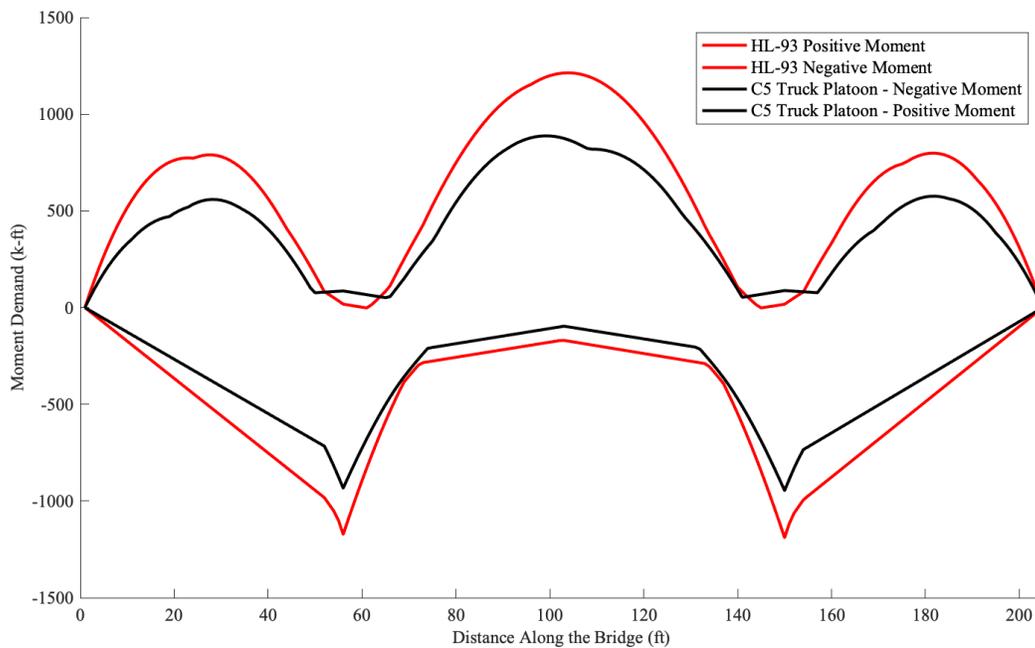


Figure 3.20: Moment demand envelopes for Cotton Ave - existing 204 ft continuous span

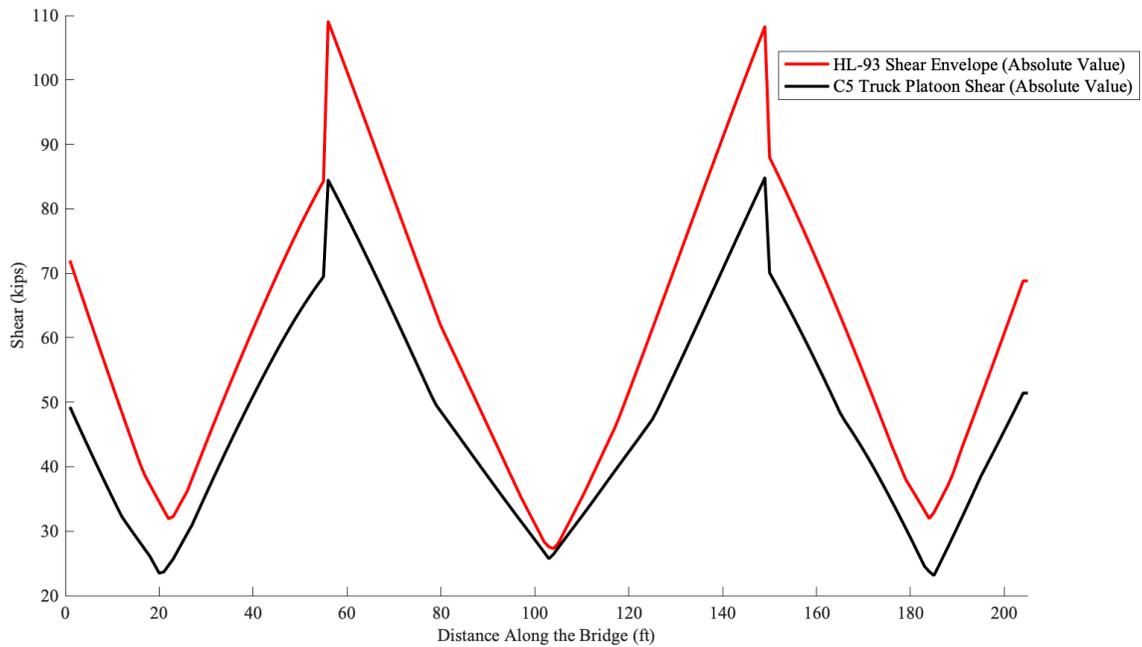


Figure 3.21: Shear demand envelope for Cotton Ave - existing 204 ft continuous span (absolute value)

Figure 3.22 shows the moment demand envelopes for the 211-ft three-span continuous existing configuration. **Figure 3.23** shows the absolute value of the shear demand envelope for the 211-ft existing continuous configuration. In both cases, the HL-93 exceeds the platoon demand.

The 211-ft configuration is marginally longer in total length resulting in longer side spans but a shorter middle span. In this case, the longer middle span of the 204-ft configuration results in a greater positive moment demand on the middle span, while the negative moment demand at the points is similar. Also, the 211-ft configuration presents a similar positive moment demand across all three spans.

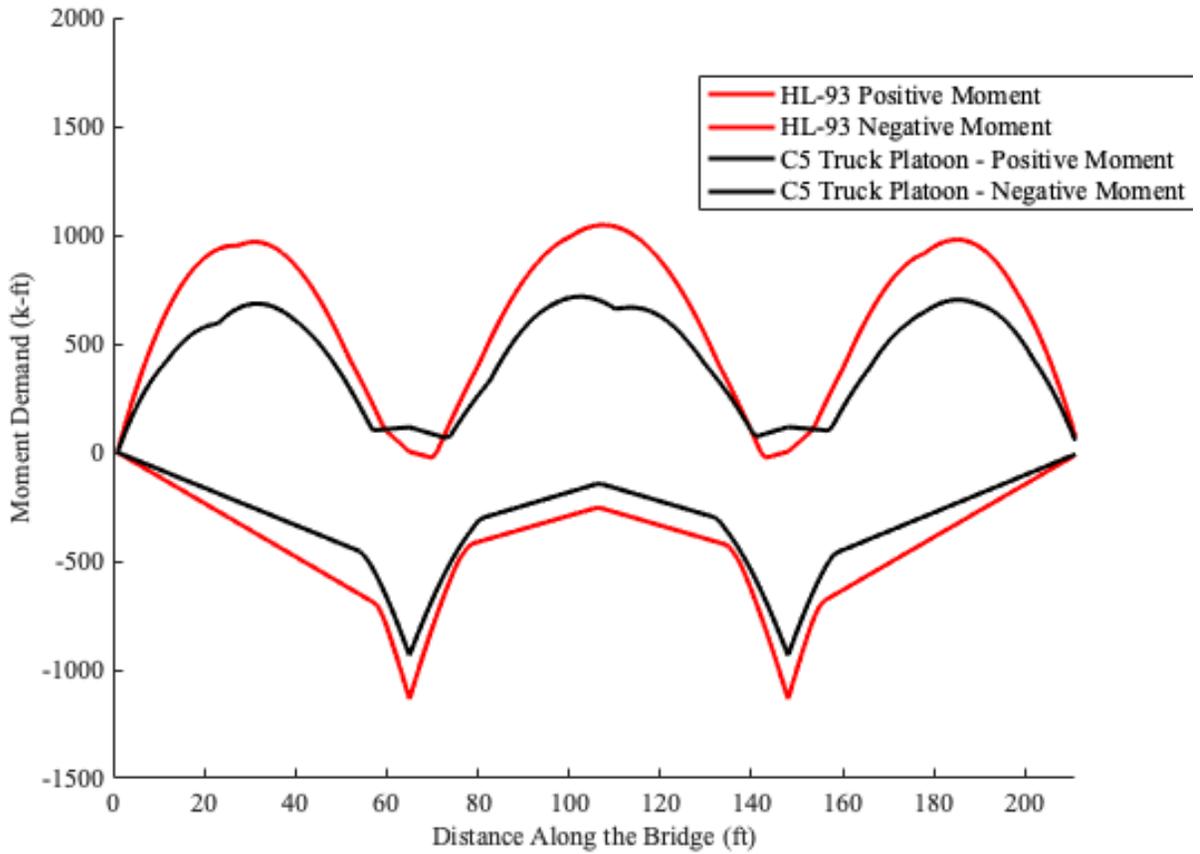


Figure 3.22: Moment Demand Envelope for Cotton Ave - Existing 211 ft Continuous Span

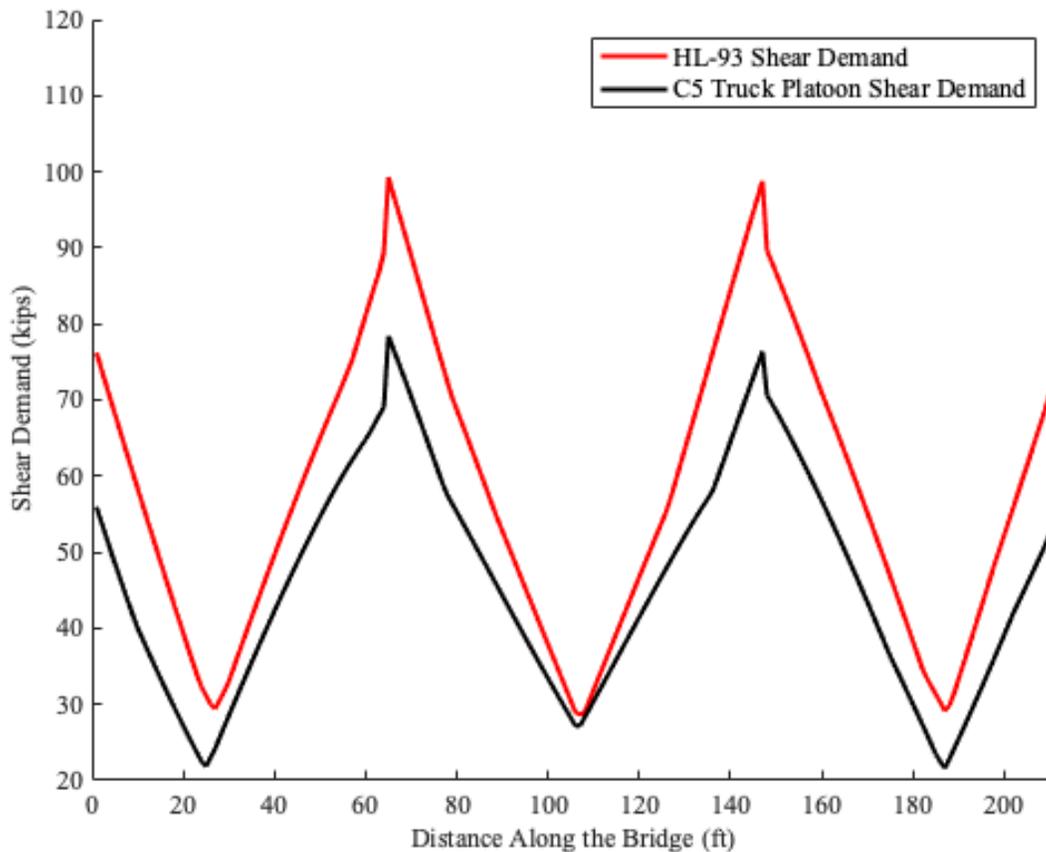


Figure 3.23: Shear demand envelope for Cotton Ave - existing 211 ft configuration (absolute value)

In the event of replacement, it is likely that the replacement spans would be simply supported, with new substructures. Assuming TxDOT would want to minimize the number of spans, one could assume that the longest span in the Standard Bridge Designs (TxDOT, 2019c) would be utilized. This investigation, assumed a length of 150 feet in a simply supported configuration. **Figure 3.24** shows the moment demand envelopes for this potential replacement configuration. Again, the HL-93 notional load exceeds the C5 Truck Platoon demand.

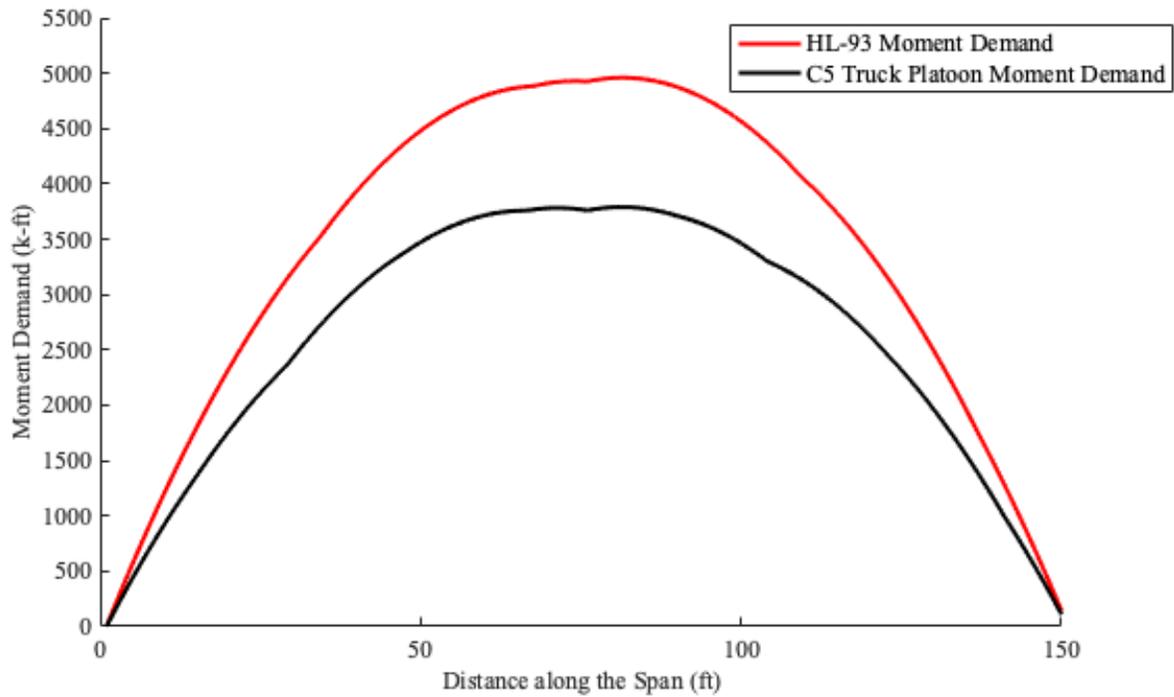


Figure 3.24: Moment demand for Cotton Ave replacement span assumed at 150 ft

George Dieter Drive

The bridge that carries the I-10 Freeway over George Dieter Drive is a pre-stressed concrete box beam configuration. This structure would also be widened and remain simply supported. Similar to Redd Road, this structure can be analyzed in its current configuration.



Figure 3.25: I-10 over George Dieter Drive

Figure 3.26 shows the positive moment demand envelopes for the C5 truck platoon and the HL-93 loading on the main span (i.e., the longest span of 102 feet). The HL-93 is shown as a single envelope that includes the design truck plus the 0.64 klf lane load, as well as the tandem truck plus the lane load. Since this is a simple supported configuration, the truck to truck load case is not applicable.

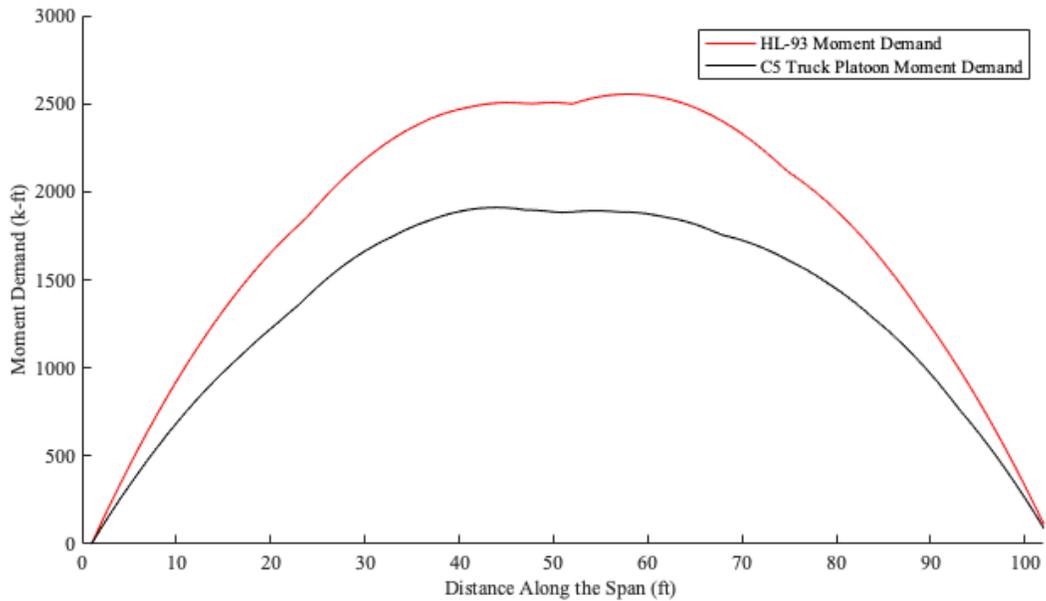


Figure 3.26: Moment demand envelope for the 102 ft span at George Dieter

3.3.6 Summary of Findings

The entire population of bridges on the physical testbed of I-10 between the New Mexico state line and the El Paso County line was analyzed. This population of 159 structures was explored to identify any trends that are related to truck platoon adequacy. It was found that most bridges are concrete multi-girder structures with simple supports, built in the 1960s, and have a maximum span length less than 100 feet. Three structures were identified for exploration of how truck platoons may exceed the load for which these bridges are or will be designed (if/when they are replaced). In all cases, the notional HL-93 load that is part of the AASHTO LRFD Bridge Design Specification is shown to be adequate.

In this study, the HL-93 was implemented piecewise and then superposed. The components include the design truck, the tandem axle, and the lane load. Considering the HL-93 notional load more specifically, it is likely that the lane load requirement, which is not present with the C5 Truck Platoon loading, makes a substantial part of the difference. Given the limitations on platoon configurations (i.e., two truck platoon) the gross vehicle weights in the two loadings scenarios are not very different, but only the HL-93 considers the lane load. The lane load effectively concentrates load on shorter spans that a platoon cannot. If a three or four truck platoon were considered, or a very small spacing axle to axle between trucks was permitted (e.g., longer than 20 feet), then the platoons may become more of a concern. However, as most of the spans are simply supported and under 100 feet, adding trucks to the platoon does not necessarily mean that more load will be experienced by the bridge at one time. As an example, the C5 truck platoon, at the shortest spacing of 20 ft axle to axle, is still effectively 92 feet long. The longer the truck platoon, the less likely it will have increasing deleterious effects on any given simple span because the platoon will tend to exceed the bridge span length.

However, additional studies should focus on the connector ramps. In El Paso, these include the US Highway 54 interchange, and the Loop 375 interchanges specifically. These structures tend to have long, curved continuous steel spans. The ConOps made the assumption that platoons would break when traveling over these structures, but if the goal were to allow automated and platooned action between major roadways, these structures should be analyzed.

From this study, it can be concluded that assuming TxDOT designs based on the AASHTO LRFD Bridge Design Specification and uses similar geometry to what is already in place when they replace structures in order to accommodate the addition of the ATL, then these new structures will be adequate for the platoon configuration considered here. While all the cases considered were adequate, the state of Texas is the steward for over 50,000 bridges. Many of these structures are old and are not slated to be replaced in the future, like the I-10 corridor. As truck platooning and automated travel become more ubiquitous and move away from major highways, these fringe structures will come into play. In those cases, comparison the HL-93 loading may not make sense, as the structure would have been designed for different loads. Currently, TxDOT is considering the effects of truck platoons on their infrastructure from

a broad perspective, inclusive of bridges. The Texas A&M Transportation Institute is leading TxDOT Project 0-6984 titled “Evaluate Potential Impacts, Benefits, Impediments, and Solutions of Automated Trucks and Truck Platooning on Texas Highway Infrastructure.” This project will take a broad approach to the entire population of bridges in the state, as opposed to a single corridor.

Section 4 Simulation Analysis

This section describes the application of microscopic traffic simulation to evaluate the proposed design options for the I-10 Freeway with ATL.

4.1 Selection and Description of Simulation Testbed

A simulation testbed was selected within the physical testbed. The simulation testbed must meet the following criteria:

- The I-10 Freeway at the site must have enough right-of-way for the addition of one ATL per direction.
- The I-10 Freeway at the site must be connected to a port of entry to Mexico.
- The port of entry is used by trucks, including FATs coming from and going to Mexico.
- The anticipated truck volume crossing the port of entry is high in the future year.

The following table (**Table 4.1**) lists the POEs and the conditions of the potential simulation testbed sites. Within the physical testbed, only the site at I-10 at Artcraft Road (Texas 178) leading to the Santa Teresa POE met all the criteria and therefore was selected. An area map of the selected simulation testbed is shown in **Figure 4.1**. A nearby interchange to Transmountain Road (Loop 375) is also included as part of the simulation testbed because its traffic has interactions with the trucks at the Artcraft interchange which will impact the ATL design and FAT operations.

Ports of entry (POE)	POE for trucks	Highway to I-10	ATL on I-10	Truck volume	Testbed Candidate
Santa Teresa	Yes	Artcraft Rd	Yes	High	Yes
Paso del Norte	No	El Paso Street	No	0	No
Stanton	No	Stanton Street	No	0	No
Bridge of the America	Yes	U.S. Highway 85	No	High	No
Zaragoza	Yes	Loop 375	No	High	No
Fabens-Tornillo	Yes	FM 3380	Yes	Low	No

Table 4.1: Criteria for the selection of simulation testbed



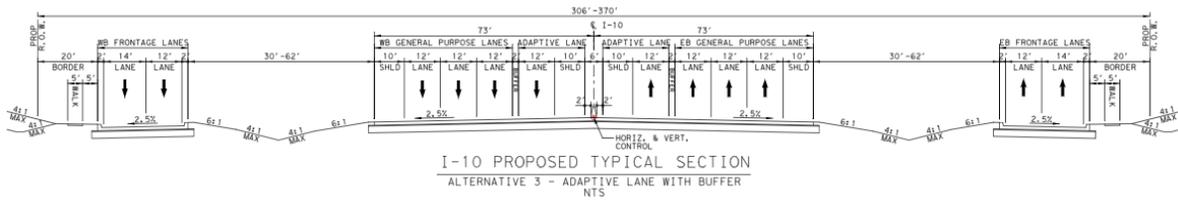
Figure 4.1: Area map of the simulation testbed

The geometric and traffic control characteristics of the selected simulation testbed may be summarized as follows:

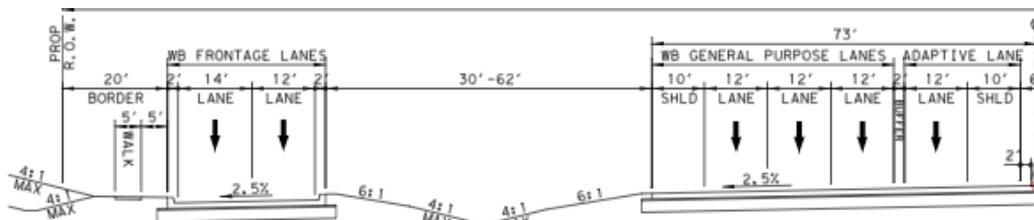
- I-10 interchanges = from Transmountain Road interchange to Artcraft Road interchange
- No. of ATL = 1 per direction
- No. of GPL = 3 per direction
- Posted speed limit = 60 mph for GPL, 65 mph for ATL
- No. of on-ramp = 2 per direction
- No. of off-ramp = 1 per direction
- No. of interchanges = 2 (Artcraft and Transmountain)
- No. of non-signalized intersections = 12
- No. of signalized intersections = 2 (1 at each of the interchanges)
- Signal timing plan = fixed time
- Signal cycle time = 180 seconds (7:00 a.m. to 9:00 a.m. on weekdays)
- No. of signal phases per cycle = 6
- Data source of signal timing plan: City of El Paso

The following figure (**Figure 4.2**), provided by the TxDOT El Paso District, shows the cross sectional design of the I-10 Freeway with ATLs. In each direction, there is an ATL (also known as adaptive lane) separated from the three GPL lanes by a two-foot buffer. On the right-hand side of the GPLs is a frontage road with two lanes. This cross-section depicts the part of the I-10 Freeway where trucks are not allowed to switch between the ATL and the leftmost GPL. At the section when lane changes are permitted,

we propose that the buffer be widened to 12 ft to provide an auxiliary lane (also known as weave lane) for the FAT to accelerate or decelerate while seeking a gap to change lane. In this way, the FAT that is exiting or entering the ATL will reduce its interruption with the traffic in the ATL and GPLs.



(a) Both directions



(b) Single direction

Figure 4.2: Cross-section recommended by TxDOT El Paso District (source: TxDOT El Paso District)

4.2 Coded Testbed Model in VISSIM

The highway network in the selected site was coded in Version 5.40 in VISSIM. The coded network had the following characteristics:

- No. of links = 73
- No. of connectors = 96
- No. of routing decision points = 26
- No. of routes = 60
- No. of conflict points = 12
- No. of data collection points = 18 (1 per lane; 3 lanes formed a station; the 4 stations were labeled SE1, SE2, SW1, SW2)

Figure 4.3 is a screenshot of a coded network in VISSIM.

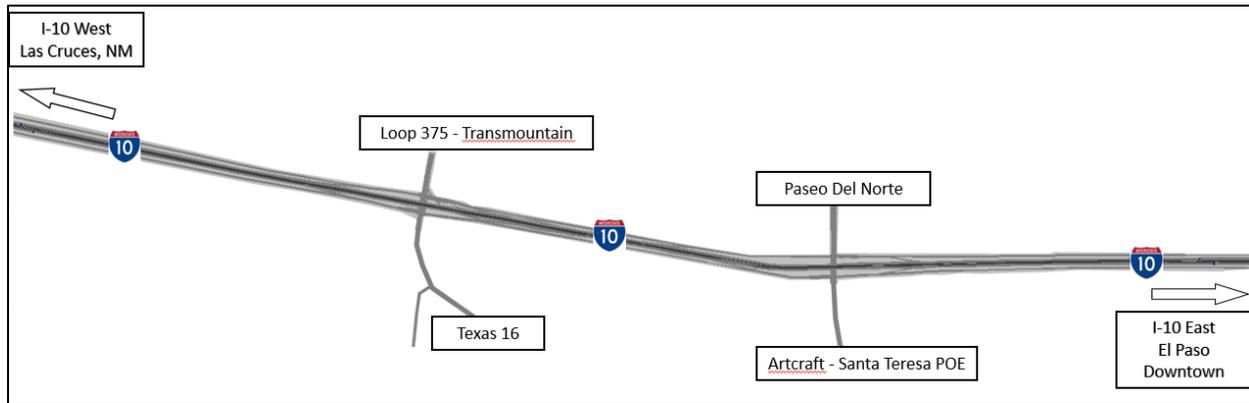


Figure 4.3: Screenshot of the network in VISSIM

The projected traffic volumes that were fed into the network was:

- Projected year = 2045
- Data sources = El Paso Metropolitan Planning Organization
- Hours of interest = 7:00 a.m. to 8:00 a.m. (highest peak hour as advised by El Paso MPO)
- Vehicle types = passenger cars and trucks (followed the El Paso MPO planning model). Trucks were further divided into 50% trucks with drivers and 50% FATs (as advised by TxDOT El Paso District)
- Passenger cars = type "Car", no. 100
- Trucks with drivers = type "HGV", no. 200
- FATs = defined as "TrailerTruck", which assumes the category of "HGV", vehicle model "180 TrailerTruck", dimension 55.00 ft by 8.20 ft

Tables 4.2 and 4.3 lists the traffic volumes between all the origins and destinations in the network, for cars and trucks respectively. These projected volumes in the year 2045 were provided by El Paso MPO.

O-D		To					
	Cars (veh/hr)	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 4.2: Origin-destination trip table of passenger cars

O-D		To					
	All trucks (veh/hr)	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	-

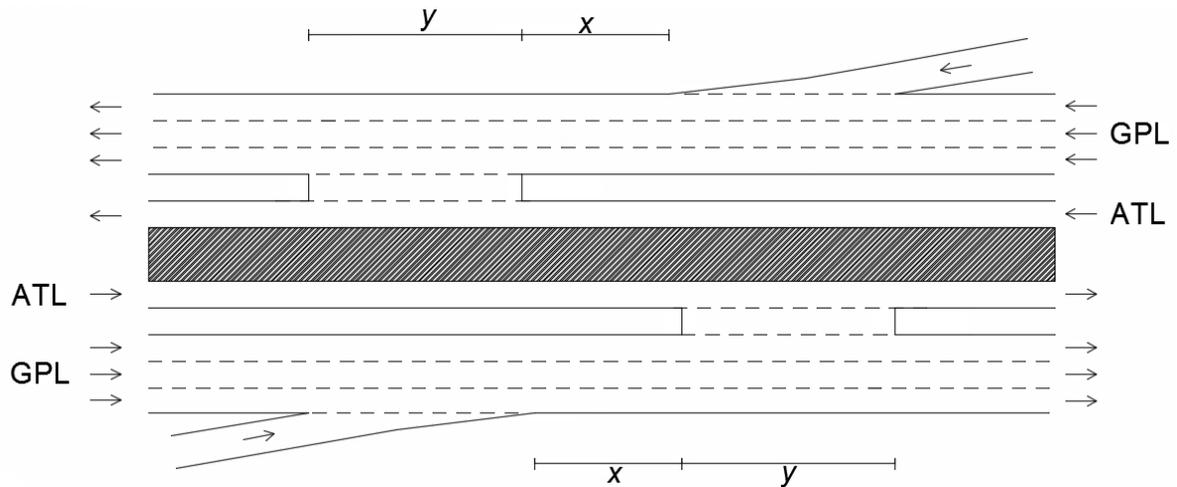
Table 4.3: Origin-destination trip table of all trucks

4.3 Design of Simulation Experiment

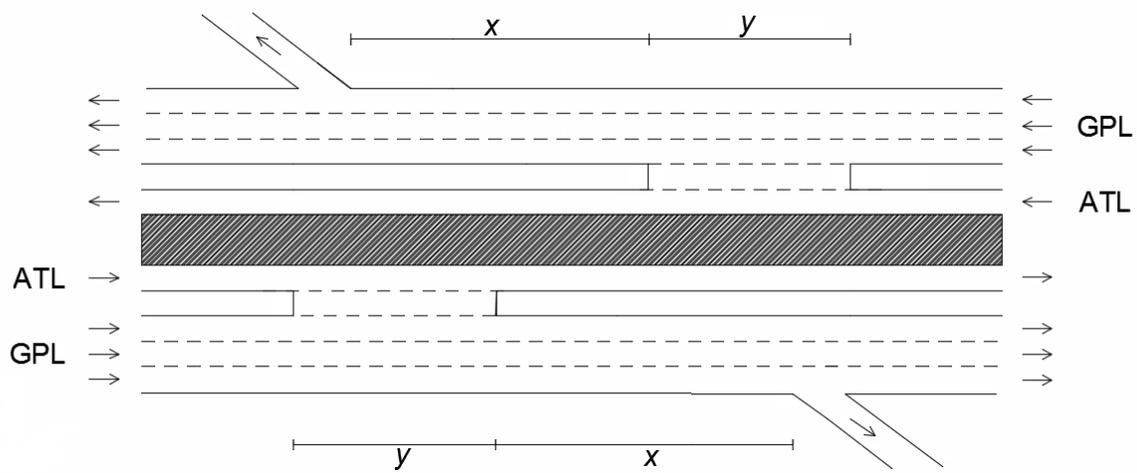
Simulated Scenarios

It was determined that the two critical design parameters of ATL were:

- x = maximum distance (in ft) for FATs to move across all the GPLs between an ATL's access point and the freeway's entrance or exit ramp.
 - y = maximum distance (in ft) for FATs to move between the ATL and the leftmost GPL.
- Figure 4.4** shows how the x and y values were measured.



(a) For FATs entering ATL from an upstream freeway on-ramp



(b) For FATs exiting ATL heading to a downstream freeway off-ramp

Figure 4.4: "x" and "y" distances

Refer to **Figure 4.4**, x was defined as the maximum distance for a FAT that has left the ATL, to move across the three GPLs to reach the exit ramp. This length is sometimes referred to as the weaving

distance (Kuhn et al, 2005). The ConOps presented in Section stated that while entering and exiting APL, the driver is in control of the trucks during the lane changes. Understanding the truck drivers' lane changing behaviors helped to define the possible x and y values. In the absence of a national and state design guideline for x and y , we used the placements of highway guide signs as the guidance. The distance between the most upstream guide sign and the exit ramp was considered as a safe distance for vehicles to move from the leftmost to the rightmost GPLs. The Manual on Uniform Traffic Control Devices for Street and Highways (MUTCD) (MUTCD, 2009) defines the national standard for the placement of guide signs. According to MUTCD (2009), for a full cloverleaf interchange, the first guide sign should be placed two miles upstream of the interchange. On the other hand, the distance for a diamond interchange was one mile. Therefore, the possible x values were set as 1.0, 1.5 and 2.0 miles in the simulation runs.

The value of y was defined as the maximum distance for the FATs to move between the ATL and the leftmost GPL. The y value may be viewed as the length of the opening of the barrier that separates the ATL and the GPLs. This opening is created for FATs to weave in or out of the ATL. Therefore, the traffic movements are similar to a weaving segment and the additional lane (with length y) at the opening may be regarded as the auxiliary lane. The y value may also be taken from the length of acceleration or deceleration lane commonly found at ramp junctions or managed lane's T-ramp intersections. Yang et al. (2016) determined the length of acceleration lane by analyzing field data and concluded that to reach 60 mph from a stop, trucks needed 2405, 2070 and 3,320 ft, at 15th, 50th and 85th percentile values, respectively. The managed lane guidelines can be used in defining possible values of y for our research. Kuhn et al. (2005) recommended that the length of acceleration/deceleration lane lengths for T-ramps, for managed lane having a speed of 65 mph was 2,400 ft.

Having conducted the above reviews, it was decided that the candidate x and y values be:

- $x = \{5280, 7920, 10560\}$ ft or $\{1.0, 1.5, 2.0\}$ miles
- $y = \{1800, 2400, 3000\}$ ft

Table 4.4 lists the 11 simulated cases, their x and y values.

Case no.	x (ft)	y (ft)	Remarks
0	0	0	No ATL, do-nothing scenario, all FATs used GPLs.
1	5280	1800	
2	5280	2400	ATL has 4 access points, 2 per direction.
3	5280	3000	Upstream access point: for FATs to leave
4	7920	1800	ATL.
5	7920	2400	Downstream access point: for FATs to enter
6	7920	3000	ATL.
7	10560	1800	
8	10560	2400	
9	10560	3000	
10	0	0	Continuous ATL without access point to interchanges, for pass-through FATs only, FATs used GPLs to access interchanges.

Table 4.4: Simulated cases

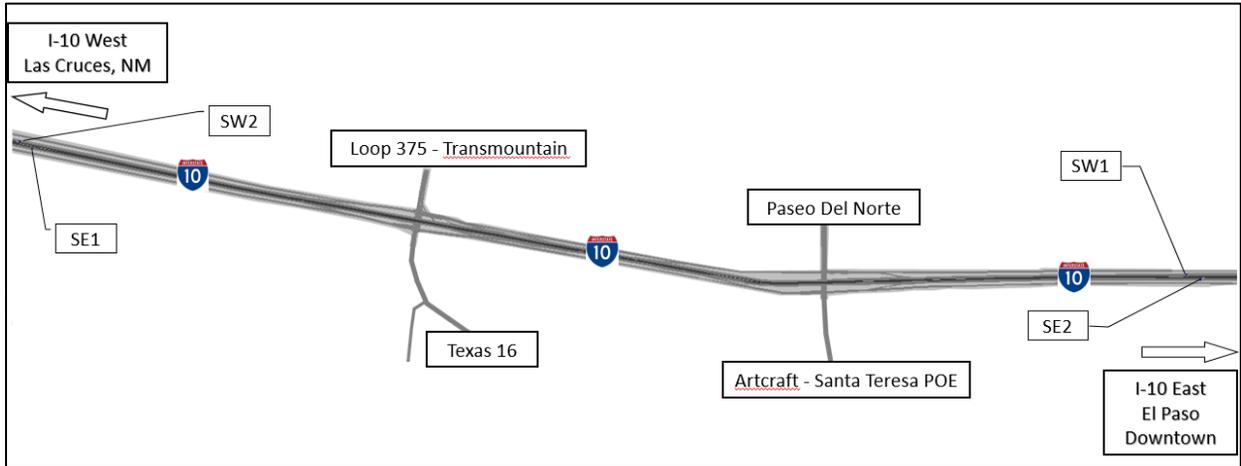
Simulation Settings

This subsection describes the simulation settings.

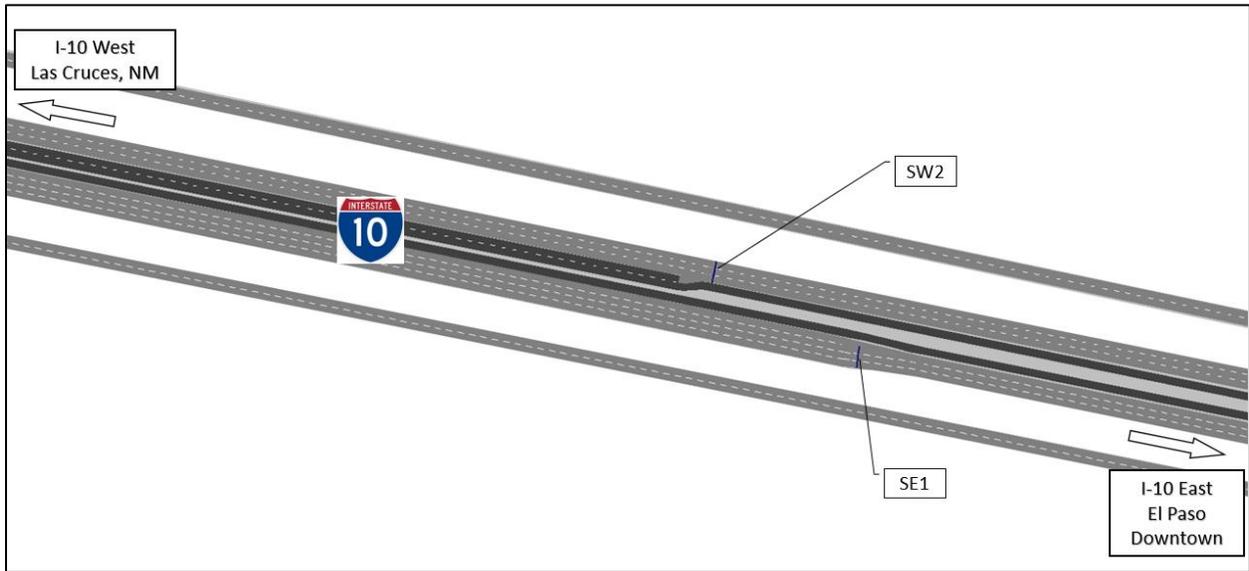
- No. of cases = 11 (Case 0 to 10)
- No. of repetitions for each case = 10
- Initial random number seed = 4885
- Simulation clock time = 1500 seconds
- Warm-up time = 600 seconds (10 minutes)
- Data collection period = from 600 second to 1500 seconds (15 minutes)

4.4 Collection of Simulation Outputs

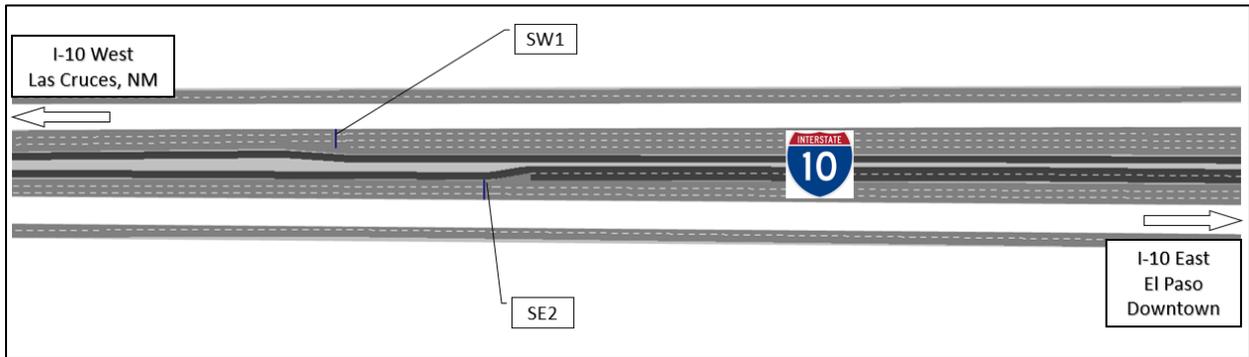
For every simulation run, statistics were collected to quantify the traffic conditions at critical locations in the network. Four locations along the GPLs along the I-10 Freeway were identified as the traffic measurement stations. At these stations, the average speed may be affected by FATs entering or exiting the ATLs. These stations were labeled as SE1, SE2, SW1, and SW2 respectively, in which S denoted speed, E represented eastbound, W meant westbound, and the numeric numbers were the stations. Their locations are indicated in **Figure 4.5**. At each station, sensors were coded in each GPL to measure volume and average speed of vehicles at each reporting interval. VISSIM outputted average volume across all lanes (in veh/hr/ln) and average speed across all lanes (in mph). The Total Travel Times (TTT) for all the vehicles in the network over the one-hour simulation period after the warm-up time was also collected.



(a) Entire network



(b) SE1 and SW2



(c) SE2 and SW1

Figure 4.5: Locations of traffic measurement stations

4.5 Results

Table 4.5 below are the average speeds and TTT for each case after 10 simulation replications. At station SE1, the average speed was the same for Cases 1 to 9. Based on the TTT alone, Cases 9 and 10 had the lowest TTT. It appeared that the x and y for Case 9 were long enough such that they had no impact on the TTT.

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	5280	1800	51	43	22	46	631
2	5280	2400	51	42	23	45	626
3	5280	3000	51	43	23	45	625
4	7920	1800	51	43	32	45	586
5	7920	2400	51	42	28	44	597
6	7920	3000	51	43	33	46	590
7	10560	1800	51	43	31	45	620
8	10560	2400	51	42	35	45	615
9	10560	3000	51	42	40	44	610
10	0	0	28	44	35	48	611

Table 4.5: Average speed and total travel time by simulation case.

Tables 4.6, 4.7 and 4.8 present the average speeds, volumes, and densities and with respect to x and y values, station by station. The density was calculated from the average speed and volume.

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

(a) SE1 – Speed (mph)

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

(b) SE2 – Speed (mph)

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

(c) SW1 – Speed (mph)

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

(d) SW2 – Speed (mph)

Table 4.6: Average speeds by the station

		y (ft)		
		1800	2400	3000
x (ft)	5280	1740	1754	1776
	7920	1756	1767	1751
	10560	1766	1778	1769

(a) SE1 – Volume (pc/h/ln)

		y (ft)		
		1800	2400	3000
x (ft)	5280	1560	1678	1544
	7920	1663	1670	1686
	10560	1641	1677	1658

(b) SE2 – Volume (pc/h/ln)

		y (ft)		
		1800	2400	3000
x (ft)	5280	1433	1476	1428
	7920	1665	1630	1643
	10560	1711	1765	1803

(c) SW1 – Volume (pc/h/ln)

		y (ft)		
		1800	2400	3000
x (ft)	5280	1202	1233	1211
	7920	1272	1279	1256
	10560	1258	1280	1297

(d) SW2 – Volume (pc/h/ln)

Table 4.7: Counted volumes by the station

		y (ft)		
		1800	2400	3000
x (ft)	5280	34	35	35
	7920	35	35	34
	10560	35	35	35

(a) SE1 – Density (pc/mi/ln)

		y (ft)		
		1800	2400	3000
x (ft)	5280	36	40	36
	7920	39	39	39
	10560	38	40	39

(b) SE2 – Density (pc/mi/ln)

		y (ft)		
		1800	2400	3000
x (ft)	5280	64	65	62
	7920	52	57	50
	10560	54	50	45

(c) SW1 – Density (pc/mi/ln)

		y (ft)		
		1800	2400	3000
x (ft)	5280	26	27	27
	7920	28	29	28
	10560	28	29	30

(d) SW2 – Density (pc/mi/ln)

Table 4.8: Calculated densities by the station

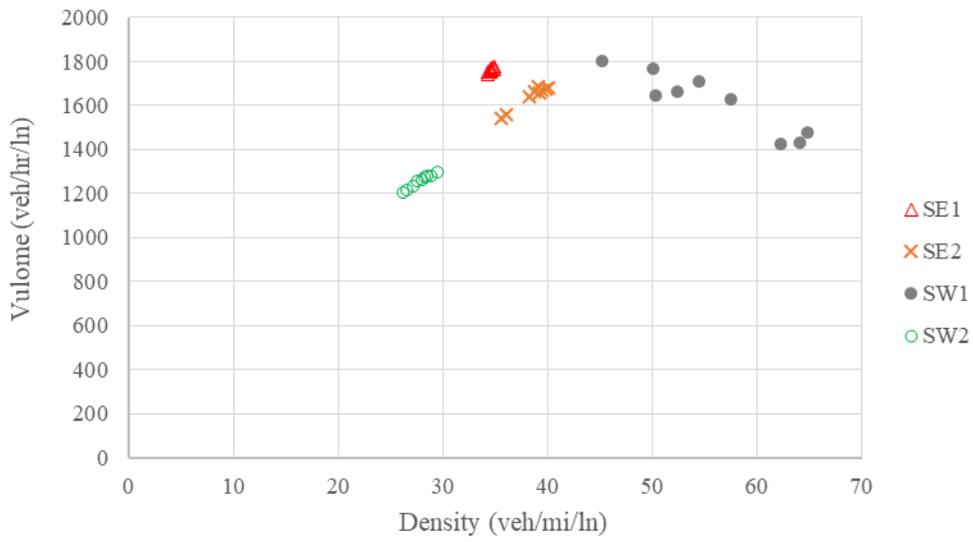


Figure 4.6: Volume-density plots

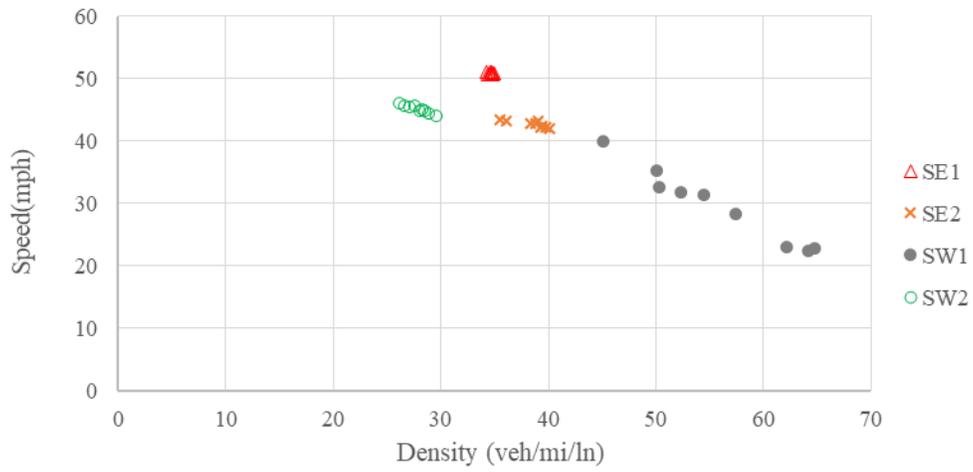


Figure 4.7: Speed-density plots

The data in **Tables 4.6, 4.7, 4.8** were used to plot **Figures 4.6 and 4.7**. From these two figures, it was clear that at stations SE1, SE2, and SE2, all the data collected at the same station fell in a very narrow range. This meant that at each station, the traffic condition was the same irrespective of the x and y values. In fact, the data points from each location exhibited an upward trend in **Figure 4.6**, indicated that they were on the left-hand side of each station's volume-density parabola, i.e., in the free-flow region. At these three locations, the x and y values were probably enough to cater to the design volumes. However, the data points collected at station SW1 showed a bigger spread. These data points in **Figure 4.6** appeared to fall into the right half of the volume-density parabola. This is the region where traffic is congested. In **Tables 4.6(c) and 4.7(c)**, when y was held to a constant value, the speed and volume increased with x . However, while x was fixed to a value but y increased, the volumes remained almost the same but the speed did not have a consistent trend. This suggested that while the speed and volume are sensitive to x but not y . Among the three candidate x value, the largest of $x = 10,560$ ft was recommended. The y value needed further investigation. Stations SE2 and SW2 were set up to capture the speeds in the GPLs at the downstream end of x and immediately upstream of y . A reduction in the speed at station SE2 and SW2 means some FATs had difficulties moving into the ATL, causing themselves to slow down and affecting the traffic in the GPL. The reason was unlikely due to the traffic congestion in the ATL. It was mostly due to the FATs having difficulties changing lanes from the right GPL to the left GPL. In the VISSIM simulation, under this condition, a FAT slowed down to look for a gap to change lane, causing congestion upstream.

The data presented in **Table 4.5** was next analyzed with respect to $(x+y)$. Refer to **Figure 4.4**, $(x+y)$ may be defined as the maximum distance for FATs to move from the ATL to the off-ramp (exit) or from the on-ramp (entrance) to the ATL. **Figure 4.8** plots the average speed against $(x+y)$. Again, one can observe that the average speeds of stations SE1, SE2 and SW2 remained almost constant. For SW1, the average speed increased with $(x+y)$.

The SW1 data plotted in **Figure 4.8** was used to determine the suitable $(x+y)$ value for the design volume. The average speed for Case 0 was 32 mph while for Case 10 was 35 mph. In Case 0 there was no ATL and therefore an ATL with good x and y values should have a higher average speed. Case 10 consisted of ATLs but only for pass through FATs, i.e., no entrance or exit. Because of this restriction, FATs that need to turn into and out of I-10 must use the GPLs, increasing the volume in the GPLs and reducing the average speed. The ATL with properly designed x and y values should have a higher average speed than Case 0 and Case 10. Based on these criteria, the recommended x value is 10,560 ft and the y values are 2,400 ft or 3,000 ft. This finding is for the design volume given. One additional consideration is construction cost. Extending y from 2,400 ft to 3,000 ft means adding 600 ft-lane of buffer between the ATL and GPLs. This provides the additional distance for traffic growth in the future but incurs additional construction cost.

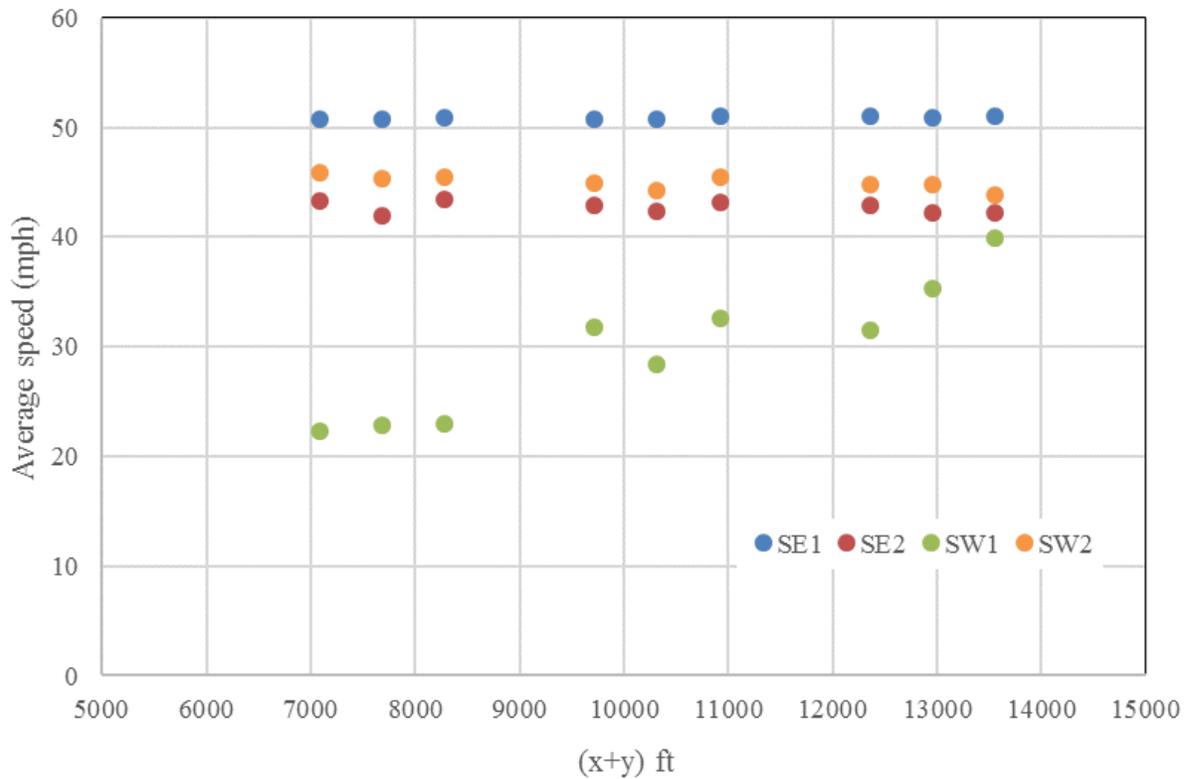


Figure 4.8: Speed versus (x+y)

4.6 Section Summary

This section used the microscopic traffic simulation approach to determine two important design parameters for an ATL:

- (1) x , the distance between the on-ramp or off-ramp (on the right or slow GPL) and the entrance or exit of the ATL;
- (2) y , the lane-changing section or weave length between the GPLs and ATL.

The analysis procedure included

- (i) Measuring the traffic volume and average speed of all the vehicles at critical locations at GPLs;
- (ii) Inspecting the data points in the volume-density and speed-density plots;
- (iii) Examining the trends of average speed with respect to x , y and $(x+y)$;
- (iv) comparing with the average speeds of limiting cases of no ATL (do-nothing case) and with ATL but without any entrance or exit (pass through FATs only).

From the analysis performed in this section, the recommended values $x=10,560$ ft and $y=2,400$ ft.

Section 5 Economic Impacts of Infrastructure

This section estimates the costs and benefits of infrastructure changes in order to accommodate automated or platooned trucks in the ATL per the ConOps. The goal is to determine the costs and economic impacts of providing/modifying infrastructure for automated vehicles to operate on I-10. All costs are in 2019 dollars.

5.1 Infrastructure Costs

Through collaboration with TxDOT and the primary contractor on the Reimagine I-10 project, it became clear that the entire corridor, as part of the project, would be altered according to the selected design alternative irrespective of the presence or lack thereof of automated or platooned trucks. Four alternatives were considered. They included:

1. Additional capacity
2. Additional capacity and an enhanced shoulder
3. A buffer-separated adaptive lane
4. A barrier-separated adaptive lane

TxDOT has not released an estimated cost for the project, but they have identified option #3 as the preferred option. For this study, we initially considered options 3 and 4 which are both equally capable of supporting automated and platooned trucks. From a cost perspective, however, there is little difference in options 1 to 3. There will be differences in striping, signage, traffic control, and other peripherals, but the main construction will be similar. The lane-mile cost only increases for Option 4 – which requires barriers. According to TxDOT unit cost information by district ([TxDOT, 2019b](#)), the Single Slope Traffic Rail most commonly used on TxDOT bridges costs approximately \$65/foot. If this detail were to be implemented for the entire project, it would be an additional \$18.8M dollars. No unit cost for roadway barrier was available.

The standard Continuously Reinforced Concrete Pavement (CRCP) costs range from \$45 to \$200 per square yard, with most projects using either a 9 inch (\$45/yard²) or 12 inch (\$58/yard²) design. Assuming a \$50/yard², the entire 55-mile stretch of I-10, if completely replaced, would cost \$220M for pavement alone, putting the barrier at approximately 8% of a total CRCP replacement. Given this cost and the lack of flexibility a permanent barrier would entail, it is likely that any adaptive lane would be buffered, supporting the assumptions for the ATL, and TxDOT's decision to pursue Option #3.

One additional cost which is not easily identifiable currently is enhancing vehicle communication along the entire route. In 2014, FHWA and the ITS JPO estimated that the total cost for dedicated short-range communications (DSRC) is approximately \$20K per site ([Wright et al., 2014](#)). Assuming a range of 1000m between DSRC terminals ([Bettisworth et al., 2015](#)), and zero redundancy, DSRC would cost \$1.7M for the entire corridor. This intuitively seems very low and calls into question both the estimate of site

costs for DSRC and the spatial dispersion required. TxDOT provides the of \$15,000 just for a 55 foot ITS pole alone, excluding sensors and equipment.

Finally, it is altogether more likely that 5G technology will drive automated vehicle operations, as opposed to local systems like DSRC. Identifying these costs without conducting a schematic design and cost estimation is very difficult. It would, however, be an additional cost beyond simply widening I-10, as per option #1 and #2.

Table 5.1 summarizes some potential costs differences between options relative to Option #1. These numbers are estimated (or qualitative) and are relative. It is clear that the adaptive lane option will be more expensive, so the question is one of the potential benefits. These benefits are discussed in the next section at a broader scale.

Option Number	Barriers	DSRC	Signage and Striping
1	\$ 0	\$ 0	\$ 0
2	\$ 0	\$ 0	\$ 0
3	\$ 0	+\$2M or more	+ ?
4	+\$18M	+\$2M or more	+ ?

Table 5.1: Potential costs differences

5.2 Economic Impacts

The presence of automated and platooned trucks stands to affect our economy in numerous other ways, beyond infrastructure costs. According to the Office of Employment Statistics (OES), El Paso in 2017 was home to over 22,000 transportation-related jobs out of 301,590 total jobs. Of that 22,000 jobs, 5,170 were “Heavy and Tractor Trailer Truck Drivers. The average salary for this position is \$38,000 which is very near to the median salary in El Paso, making it an attractive job. Surprisingly, there is a shortage of drivers in the region, so while in the long term, automated trucking may cost jobs, in the shorter term it may fill a need. Additionally, there are numerous support categories for trucking that may see benefits from autonomy.

As part of Reimagine I-10, TxDOT is proposing a connected network of parking locations where trucks can wait for assigned border crossing time window, which will help to mitigate congestion at the border (TxDOT, 2019a). The interaction of a system like this with automated and platooned trucks is not yet known, however, because there has been little research on automated or platooned trucks would

integrate into Customs and Border Protection (CBP) procedures at the border. This is an area that is ripe for research from an operational and logistics point of view as well as a security point of view. An international border provides challenges to automated vehicles that are not likely to be experienced in the contiguous United States, like changes in standards and specifications for communication equipment. Making the border automated-ready is a big challenge that should be addressed in order to take advantage of the ATL concept.

Generally speaking, automated and platooned trucks will relieve congestion, save money on fuel, and reduce collisions. Estimates of these effects vary greatly in the literature. The consensus is that platoons are more aerodynamic corresponding to a reduction in fuel consumption. The specifics of that reduction depend on myriad other factors. The ability of automated and platooned vehicles to travel at high speeds close together will help reduce congestion, at least initially. Finally, and perhaps most importantly, automated and platooned trucks will improve safety by drastically reducing collisions related to human error or fatigue. Over 35,000 people die in the U.S. each year in vehicle collisions, many of which involve trucks. It is difficult to put a cost-saving those lives. **Table 5.2** provides examples of cost estimates for these benefits from various sources of literature.

Reference	Congestion	Fuel	Safety	Other
(Kuhn et al., 2017)	Trucks account for 26% of the total cost of congestion	15-20% improved fuel economy	Accidents cost \$19B a year	Optimization of lane widths; Separate lanes at separate speeds by class; Optimization of infrastructure design
(Tsugawa, Jeschke, & Shladover, 2016)	NA	Up to 21% measured and 38% theoretical	Mean Time Between Failures for human drivers will improve dramatically when the driver is asleep or distracted	Dedicated lanes will enable shorter gaps and even greater fuel efficiency
(Lammert, Duran, Diez, Burton, & Nicholson, 2014)	NA	6% savings for a “team” of trucks is a reasonable assumption	NA	Determining national linehaul miles that re conducive to platooning is important; ATL would be conducive.
(Gordon, 2015)	Savings of 13 seconds over a 5.3-mile segment of interstate possible	NA	NA	Market penetration is critical to achieving the benefits of platooning
(McAuliffe, Croken, Ahmadi-Baloutaki, & Arash, 2017)	NA	14% savings at 17m separation	NA	Aerodynamic truck configurations make a big difference.

Table 5.2: Description of automation and platoon benefits from selected literature

Section 6 Conclusions, Limitations and Future Research

6.1 Conclusions

The 55-mile segment of I-10 Freeway in Texas from milepost 0 (New Mexico border) to milepost 55 (east end of the Presidio County) were used as the physical testbed.

TxDOT had identified the cross-sectional design of the automated truck corridor, in which there was one ATL per direction in the median. The ATL is separated physically from the leftmost GPL by a buffer or barrier. Openings were designated at locations to allow drivers to steer their automated trucks in and out of the ATL. These access points (locations) and length of the openings (weave length) were important design parameters which were tested via simulation analysis.

The existing geometric design and future cross-section of the physical testbed (using the Texas Roadway Design Manual as a guide) was evaluated against the expected dimensions of the FAT. No modification to the roadway geometric design is necessary.

The future cross-section will require widening or replacement of nearly every structure that carries the physical testbed. These structures will be designed according to the AASHTO LRFD Bridge Design Specification ([AASHTO, 2017](#)) and will generally have the same dimensions along the centerline of the testbed. As such, no modifications beyond those design parameters is required to implement the ATL.

The positions of the ATL access points relative to the I-10 on-ramp and off-ramp, and the weave length that permits lane changes between the ATL and leftmost GPL were tested via microscopic traffic simulation using a portion of the I-10 at Transmountain Road and Artcraft Drive interchanges as the simulation testbed. The simulation results indicated that the access point to the ATLs should be 2.0 miles upstream from the freeway off-ramp, or 2.0 miles downstream of the freeway on-ramp, so that FATs have adequate distance to move from the ramps across the GPLs and the ATL access points. The access point should have an opening of 2,400 ft for FATs to change lanes between the ATL and the leftmost GPL.

The future cross-section identified by TxDOT will accommodate the ATL within the adaptive lane framework. There may be additional costs related to signage and striping, but assigning that cost a priori is not feasible without a schematic design of the testbed. Accommodating the ATL according to the ConOps with physical infrastructure will not incur additional costs.

6.2 Limitations

As in all other research, because of time and budget constraints, assumptions were made and methodologies simplified. This section highlights important assumptions made, so that further research may be followed.

The ConOps in section 2 assumed that in a platoon, the leader operated in Level 3 automation while the followers were fully automated at Level 5. When automated trucks were moving in and out of an ATL, they moved by themselves (not part of a platoon) and was assumed to be driven in Level 3.

The simulation analysis in section 4 has assumed that:

- The FATs moved like human-driven trucks, and formed platoons in small and fixed headways;
- The O-D matrix for the year 2045 was given by El Paso MPO and used with some adjustments. The approach volume from Transmountain Drive and Artcraft Road was therefore reduced by 50%

The bridge analysis assumed that:

- The longitudinal (i.e., length) configuration would not dramatically change in order to accommodate the proposed cross-section;
- Any widening would be designed per the current LRFD standards;
- Loadings were assigned to individual beams at 100% of the truck to facilitate relative comparisons.

The limitations of estimating the cost include:

- The rapid rate of technology change made it difficult to confidently estimate costs for DSRC or 5G componentry;
- The relative benefits of addressing the current driver shortfall with the costs of job loss that could come with automation are not yet quantifiable;
- Fuel efficiency benefits appear to vary greatly in the literature, but will likely make up a major portion of the benefits of automated and platooned trucks.

6.3 Recommendations for Future Research

With the experience gained in executing the research tasks, the following activities are our recommendations to improve the specific components/tasks:

1. Calibrate VISSIM's car-following and lane-changing models for automated trucks;
2. Perform simulation runs for the afternoon peak hour;
3. Perform simulation runs with different sets of O-D matrices;
4. Evaluate bridge designs where dedicated truck lanes are designed specifically to meet platooned truck loading;
5. Evaluate existing structures outside of the testbed where replacement is not guaranteed, and older design standards prevailed;
6. Identify the bounds of platoon and bridge parameters were the LRFD Bridge Design Loading (HL-93) begins to be violated.

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