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Double Crossover Diamond Interchange with Frontage Roads

Jorge Alberto Martinez
University of Texas at El Paso, jamartinez5@miners.utep.edu

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JORGE ALBERTO MARTINEZ

Department of Civil Engineering

APPROVED:

____
Ruey Long (Kelvin) Cheu, Ph.D., Chair

____
Salvador Hernandez, Ph.D.

____
Raed K. Aldouri, Ph.D.

____
Patricia D. Witherspoon, Ph.D.
Dean of the Graduate School

Dedication

To my family, to all my real friends... to the world.

DOUBLE CROSSOVER DIAMOND INTERCHANGE WITH FRONTAGE ROADS

by

JORGE ALBERTO MARTINEZ, B.S. Civil Engineering

THESIS

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Chapter 1: Introduction

Increasing traffic congestion along major corridors in the United States has prompted engineers to develop new intersection designs that are being cost efficient and, they provide a better vehicular flow of traffic in congested areas. One fairly new design is the Double Crossover Diamond Interchange (DCD), also known as the Diverging Diamond Interchange (DDI). This new design has proven to be effective for certain traffic conditions. The intent of this research is to explore a new design for a DCD that caters to the through traffic movements at Frontage Roads (referred to as DCD-FR for the rest of the thesis) and compare the operational performance with a Conventional Diamond Interchange (CDI) with frontage roads.

1.1 Background

Most freeways in the United States have the CDI as the interchange design. This design is the most common across North America (Leisch, 2005). Typically, the CDI connects the freeway (in the north and south direction) to an arterial (in the east-west direction). In many cases the interchange is grade separated and the freeway can be either an underpass or an overpass. To access the arterial, drivers along the freeway use an exit ramp, and to enter the freeway from the arterial, drivers use an entrance ramp. In some designs, once a driver exits the freeway he/she only has the option to turn right or left at the intersection. Some states, like Texas, have service roads or frontage roads that allow drivers to proceed straight in the north-south direction through the intersections at the frontage roads. The CDI design accommodates freeways with and without frontage roads.

The first DCD known is found at Versailles, France and has been operational for more than 25 years (Edara, Bared, & Jagannathan, 2005). The concept of the DCD is relatively similar to the CDI. The major change is for traffic traveling on the arterial in the east-west direction above or below the freeway. Traffic traveling east or west will arrive at the first intersection at which the vehicles will cross to the opposite side of the divided roadway (hence the term “crossover”) and continue until they reach

the second intersection. At the second intersection the vehicles will cross back to the original side of the roadway and continue to their destinations. The original DCD design does not permit through vehicles movements on the frontage road. The movements along a DCD interchange design are illustrated in Figure 1.1.

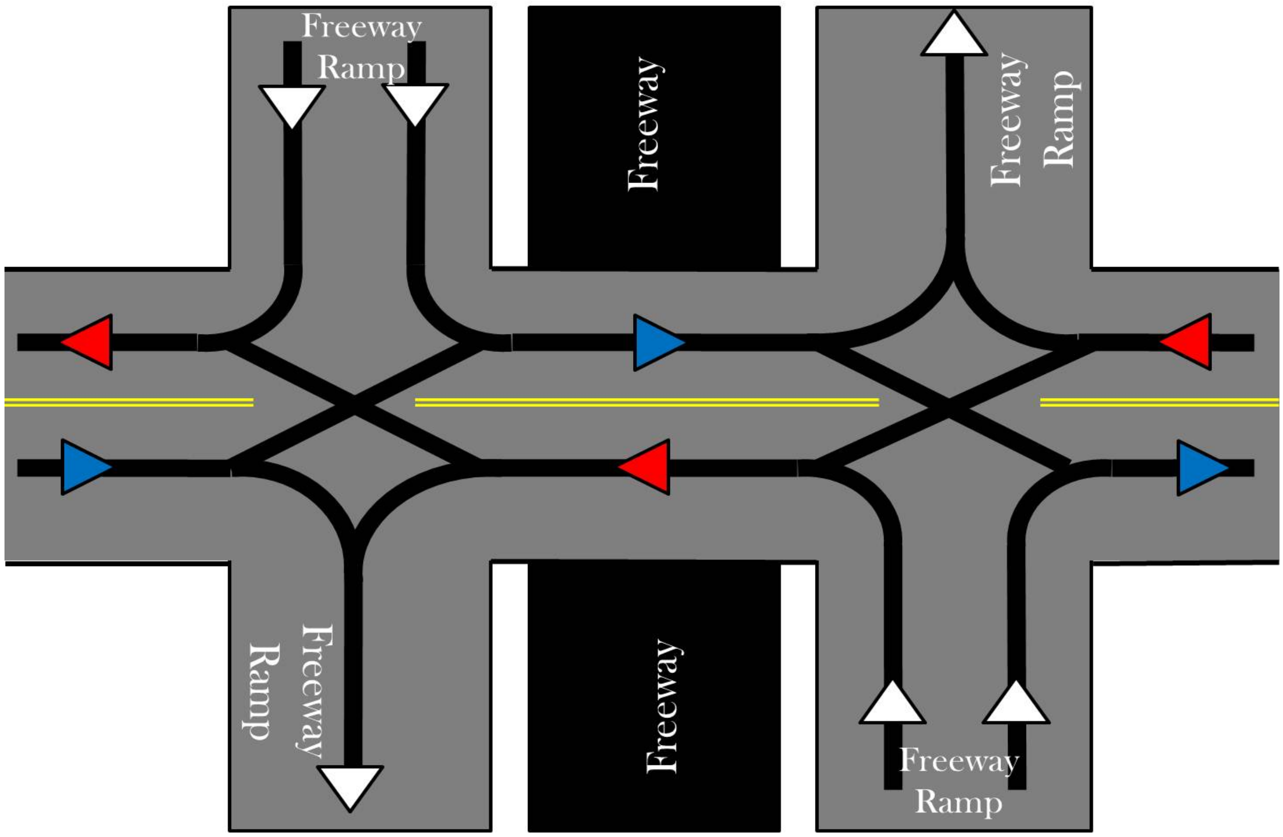

Figure 1.1: Typical Movements at a DCD.

No research has been done to accommodate and test the DCD design at freeway interchanges where through movements on frontage roads exist.

1.2 Objective

The objective of this research is to propose and test the functionality of the DCD with frontage roads against a typical design of the CDI. A particular interchange found in El Paso, Texas will be

replicated with the use of microscopic traffic simulation software. Once the network is created, it will be calibrated using actual traffic data from a typical day in El Paso. A signal phasing sequence will be proposed for the DCD-FR to accommodate the through traffic movements on frontage roads. Several traffic scenarios with symmetrical traffic demand were developed to compare both interchange designs and to determine the operational efficiency of each design. The Measures of Effectiveness (MOE) compared in this study are average intersection delay, Level of Service (LOS), section travel time and delay, and network total travel time and delay.

1.3 Thesis Organization

Chapter 1 of the thesis introduces the DCD and the need to study a DCD with frontage roads. The literature review is found in Chapter 2. Here, the available research to date about the DCD is presented and emphasis is made on the need of more studies related to DCD with frontage roads. Chapter 3 encompasses the research approach, the simulation scenarios and the assumption considered in this research. Chapter 4, describes the simulation software used as well as model development process. Moreover, this chapter describes the calibration process to obtain a base model. Chapter 5 describes the findings using Synchro, more specifically on the intersection LOS and average intersection delay. Chapter 6 describes the analysis performed with the use of VISSIM. This chapter compares section travel time, section delay and overall performance of the network between the CDI and the DCD-FR interchange designs. Finally, Chapter 7 presents the conclusions of this study, contributions of this research and recommended future research.

Chapter 2: Literature Review

2.1 Double Crossover Diamond Interchange

The DCD interchange is a fairly new interchange design in the United States presented by Chlewicki in 2003. The concept of the DCD originated from the thought of crossing drivers for a certain segment at an interchange to better accommodate left-turn movements. Chlewicki considered that a typical CDI would be the best design to modify or have vehicles crossover to the opposite side of the road (Chlewicki, 2003). Figure 2.1 illustrates the traffic movements along the DCD. Traffic traveling east or west (blue and red) will arrive at the first intersection on which the vehicles will cross to the opposite side (left-hand side) of the roadway and continue until they reach the second intersection. At this intersection vehicles will cross back to the original side of the roadway. Displayed in green are the two movements for drivers coming from the freeway exit ramps.

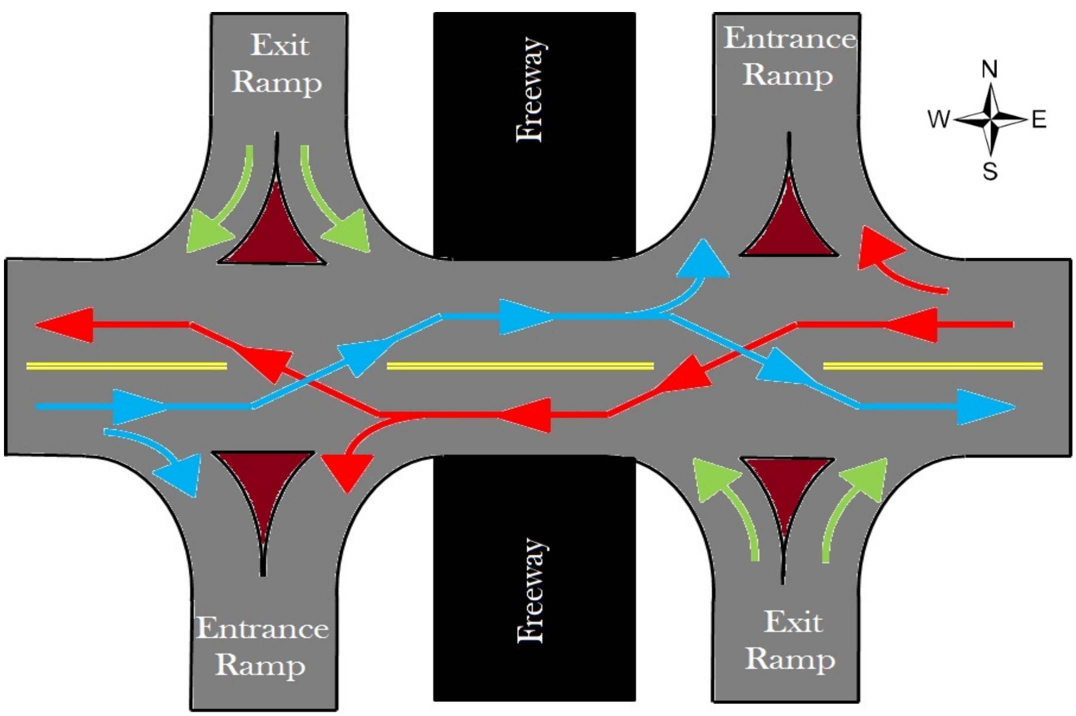

Figure 2.1: Double Crossover Diamond Interchange Movements.

On the other hand, shown in Figure 2.2 are the movements at a typical CDI. In this design, there is no crossover at the intersections. Vehicles traveling west will remain on the right-hand side of the roadway as would vehicles traveling east.

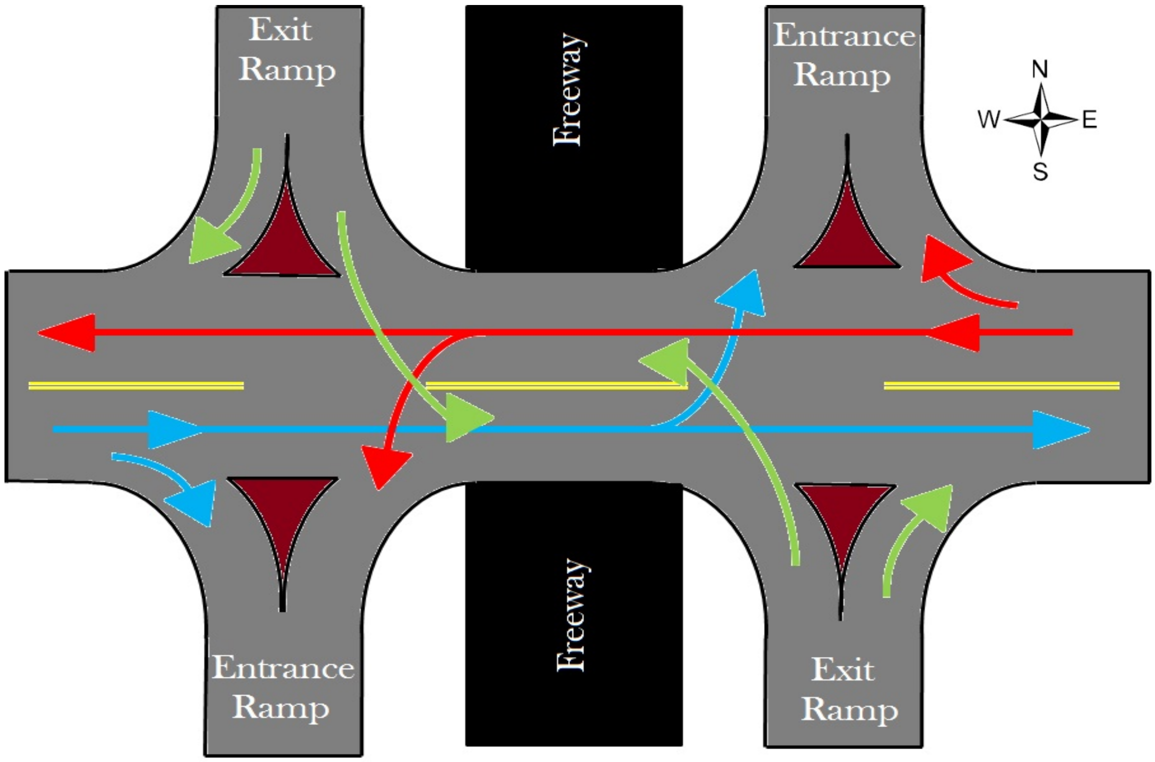

Figure 2.2: Conventional Diamond Interchange Movements.

Chlewicki pointed out that one of the benefits of his DCD design was that it eliminated the left-turn phase in the intersection signal timing plan. Each intersection needs only two signal phases to eliminate the crossing conflict. In addition, the DCD has fewer conflict points than the CDI. The conflict points eliminated by the DCD are the left-turn conflicts. In the DCD, since vehicles are in the left-hand side of the roadway between the two intersections, left-turn vehicles do not have a conflict with opposing or crossing traffic. Chlewicki used Synchro 5 (version 5) as the simulation tool to obtain his results. The traffic volume used during the simulation process was the a.m. peak hour volume at the intersection of U.S. 29 at East Randolph/Cherry Hill Road in Montgomery County, Maryland. The

results obtained by Chlewicki demonstrated that the DCD provided less delay and fewer number of stops as compared to the CDI (Chlewicki, 2003).

Based on the designed proposed by Chlewicki, a research was developed to further analyze the DCD under different traffic scenarios and test the performance of pedestrians (Edara, Bared, & Jagannathan, 2005). Two different cases were studied, a 4-lane and a 6-lane DCD. The research performed by Edara et al., tested the DCD against the CDI with 5 different traffic demand scenarios: low, medium, high 1, high 2, and high 3. The total demand in vehicles per hour (vph) was 1700, 3200, 5100, 5600, and 6100, respectively. This time, VISSIM was utilized as the simulation tool. It is important to note that the analysis performed by Edara et al. was done for conditions where the distance between the two intersections was 500 feet. The DCD showed a clear advantage over the CDI for all high traffic demand scenarios. In low and medium demand scenarios, both interchange designs have similar performances. Overall, the DCD offered lower delays, fewer number of stops and shorter queue lengths. In this research, Edara et al. noted that the DCD did not allow through movements. However, it allowed u-turn movements with fewer conflicts than the CDI.

In a similar approach as Edara, et al., Sharma and Chatterjee conducted research that compared the performance of the CDI and DCD. They followed a similar methodology and tested both CDI and DCD with different volume scenarios. They used VISSIM 4.3 as the simulation software to obtain their results. A key element of the research is that the volume scenarios allowed three options, equal through volume and equal mainline left-turns, unbalanced mainline left-turn volume and unbalanced through volume. The output provided by the simulation model in VISSIM indicated the same trends as observed by Edara, et al. The DCD has a better performance than the CDI, since it increases capacity for the left-turn movements and it has lower delays (Sharma & Chatterjee, 2007).

Another study performed by Stanek (2007) illustrated some advantages and disadvantages of several diamond interchange designs which included the DCD. Stanek uses as a case study of U.S. 50 at Cameron Park Dr. interchange in Cameron Park, California. The simulation tools used were Synchro and VISSIM. Synchro was used to optimize all traffic signal under their different designs with the similar traffic conditions, the preliminary design-year peak hour volume. Once optimized the designs

were replicated in VISSIM to further analyze the operations of the different interchange designs. By using a rating system, Stanek research results indicate that the DCD has good intersection capacity, construction and right-of-way cost. In addition, the research indicated that because of the possible driver unfamiliarity with the DCD, traffic safety and pedestrian/bicycle accommodation were acceptable (Stanek, 2007).

Due to its increasing popularity and benefits, the FHWA included a chapter in the *Alternative Intersections/Interchanges: Informational Report* that covered the DCD (Federal Highway Administration, 2009). The report identifies situation where the DCD is most applicable. These situations are: when heavy left-turns onto the freeway ramps exist, when moderate and unbalanced through volume on the east-west approaches on the arterial road occur, when moderate to very heavy off-ramp left-turn volume are present, and when there is limited bridge deck width availability. In addition, it cites the conclusions of Edara, et al. and Sharma and Chatterjee. as far as the performance when compared to the CDI. It also covers a segment describing the driver evaluation with the unfamiliar interchange design (this is reviewed in the next section). Moreover, the report indicates several benefits included with the two-phase signal operation of the DCD, the benefits of having a narrower bridge structure width, the lower cost, the fewer conflict points, the reduces vehicular delays, and reduced environmental impact of the design (Federal Highway Administration, 2009).

The results from the above studies suggest that the DCD has an overall better performance than the CDI. However, the DCD has not been studied or simulated at locations were frontage roads exist. This research is performed with the intent to answer the question of whether or not the DCD will show the common benefits when the through movements on the frontage road are present.

2.2 Driver Evaluation

While driving through the DCD, at the first intersection drivers have to change from the right side of the roadway to the left side of the roadway. When they reach the second intersection, they must switch back to the right side of the roadway or intersection, as can be seen in Figure 2.1. Because of its particular design, one of the frequently mentioned disadvantages of the DCD was the unfamiliarity of

the drivers with the design. Having this perceive disadvantage and a DCD proposed for the first time in the United States at Kansas City, MO, the FHWA took the initiative of assisting the Missouri Department of Transportation (MoDOT) to safeguard an effective implementation (Federal Highway Administration, 2009).

The FHWA decided to evaluate the human factors contained with the DCD design before the completion of the interchange. The approach taken was to build the intersection in the Highway Driving Simulator so that drivers, engineers and the Human Centered Systems team would have a direct experience of the DCD (Federal Highway Administration, 2009). The Highway Driving Simulator contained hardware and software that simulated roadways conditions with high fidelity output. One valuable asset of this simulator was the use of a 1998 Saturn SL1 chassis and a cylindrical screen to which three projectors were pointed to generate the driving simulation. With attention to have a more real-life experience, several parameters were calibrated to approximate the characteristics of a small passenger sedan. Variables of the vehicle dynamics such as speed, acceleration, throttle position, and brake force were recorded to have a reliable simulation (Federal Highway Administration, 2009). Furthermore, the simulation had several traffic control devices following the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD).

Once the simulation model was developed and approved by the engineers in both FHWA and MoDOT, the experiment was conducted. The main goals of the simulation was to test how drivers would navigate through the interchange and determine if the signs and markings used were redundant or required. The research approach executed by the FHWA used three simulated interchanges in the Highway Driving Simulator, the DCD as designed by MoDOT, another version of the DCD that removed some redundant signs and a CDI. Seventy-four licensed drivers from Washington, D.C. traveled through each interchange six times for the six different movements (Federal Highway Administration, 2009).

The MOEs evaluated in the research were wrong-way violations, navigation errors (when a participant followed a path to the assigned destination using a different route than the one assigned to follow), red-light violations, and speed reduction. For the first MOE no participants were observed

bearing right at the crossovers or turning into an oncoming traffic lane in the DCD model. As far as navigation errors, the study indicates that there was no significant trend in this error as a function of the design. Although the red-light violations were present in some cases for the three designs, there were no statistical differences. As for the last MOE (speed reduction), because of the geometry of the DCD the speed at the crossing points was about 8 mph less than the CDI (Federal Highway Administration, 2009).

Based on the test conducted by FHWA the DCD was proven to deliver its safety benefits. Moreover, because of the lower speed of the DCD if a driver would make an error that resulted in a crash, the severity of the crash is likely to be less severe than crashes in the CDI (Federal Highway Administration, 2009). In addition, the reported 11 minor injuries in the 25 year operational DCD in Versailles, France also serves as an indicator that a properly designed DCD is considerably safe (Bared, Edara, & Jagannathan, 2005).

2.3 Double Crossover Diamond Interchange in the United States

As mentioned before, the DCD was found originally in France. However, on June 22nd, 2009 the first DCD in the United States was completed at Springfield, Missouri. The DCD is located at the intersection of I-435 and East Front Street. For the time that this new interchange has been in operation, it has been a success and has performed better than what was originally thought and simulated (Chlewicki, n.d.). Figure 2.3 shows an aerial image of the first DCD in Springfield, MO provided by Missouri Department of Transportation (MoDOT). As can be seen in Figure 2.2, vehicles coming from the exit ramps are not able to make a through movement.

Figure 2.3: DCD in Springfield, MO (source: MoDOT)

Because of the success of the interchange, other DCD are under construction (Kansas City, MO and Maryland Heights, MO) or being planned and are now considered as an alternative design by other state agencies (Federal Highway Administration, 2009).

2.4 Simulation Software

Two popular and common simulation software packages were used to replicate and test the functionality of the CDI and the proposed DCD with frontage roads: Synchro 7 (version 7) and VISSIM 5.10 (version 5.10).

2.4.1 Synchro 7

Synchro is a traffic simulation software package that can analyze intersections based on simple parameters like traffic volume, lane configuration and cycle times. Synchro implements both the Intersection Capacity Utilization (ICU) 2003 method and the methods found in the 2000 Highway Capacity Manual (Albeck & Husch, 2006) .Synchro is a popular software used in the research and consulting communities. One of the major advantages of this software is that it can provide the user with intersection and movement LOS as well as intersection and movement delay. Both parameters play a significant role in determining the functionality of an intersection. Furthermore, Synchro offers the user the option to optimize cycle lengths, splits and offsets of a network. This tool can test different cycle lengths or signal phasing to determine the optimal timing plan for the specific scenario. In this research, Synchro 7 was used to optimize the signal cycle lengths and phase splits of the CDI and DCD-FR, and estimate the individual movement delays and intersection LOS.

2.4.2 VISSIM 5.10

VISSIM is a microscopic time stepping and traffic behavior-based simulation model that can simulate traffic and transportation systems such as individual or grouped intersections, freeways, transit corridors, etc. The software was developed in Germany and has gained popularity due to its flexibility in modeling transportation infrastructure networks as well as its visualization graphics. VISSIM uses a discrete, stochastic, time-step based model to replicate many roadway conditions. It has the option to simulate traffic flow based on different car following models such as Wiedemann 74 or Wiedemann 99 (PTV, 2007).

VISSIM offers a wide variety of tools and features to recreate highly detailed models. It can simulate several transportation modes like pedestrians, bicyclist, passenger vehicles, light or heavy duty vehicles, buses, and light or heavy rail. Each mode has specific parameters which can be modified to accommodate the conditions to be replicated.

Newer versions of the software are currently available. However, because the model validation was done using VISSSIM 5.10 in earlier part of this research it was determined to continue using this version.

Chapter 3: Research Approach and Simulation Scenarios

In order to test the functionality of the DCD-FR against the CDI, it was important to obtain critical information to develop an accurate traffic network models. Several steps were considered when developing the methodology to validate the new model. This chapter describes the approach taken and subsequent simulation scenarios generated to complete the research.

3.1 Research Approach

With the purpose of comparing the two interchange designs and their capabilities to accommodate different traffic demand, a basic methodology was developed. The methodology applied to this research follows the microscopic traffic simulation guidelines as established and recommended by FHWA (Federal Highway Administration, 2004). Figure 3.1 describes the research steps taken to ensure the validity of the microscopic simulation models.

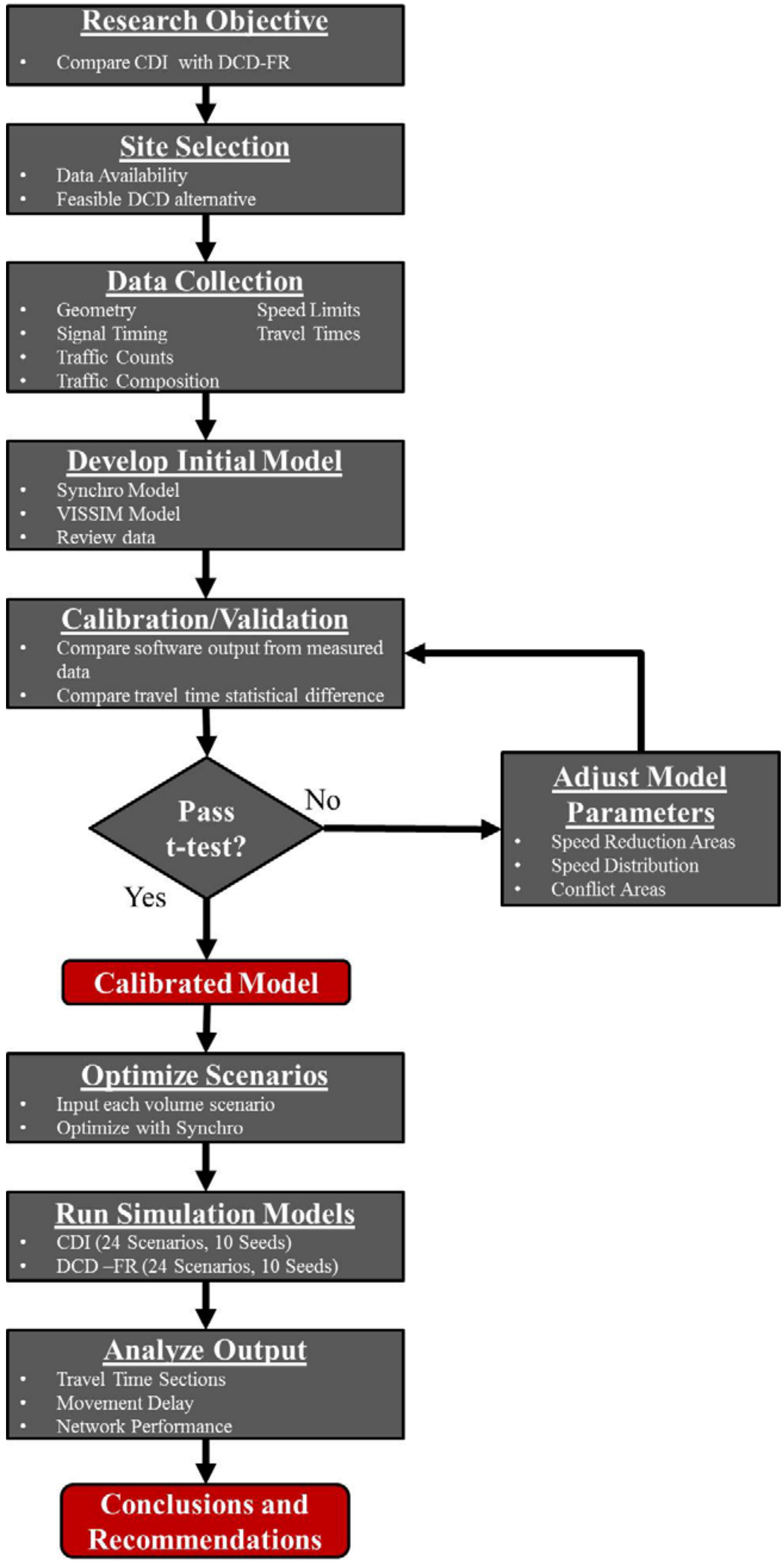

Figure 3.1: Research Approach Flow Chart.

The objective of this research is to compare two freeway interchange designs, the CDI with frontage roads and the DCD-FR. The main comparison will be travel time and delay of specific movements like east and west through and left-turn movements on the arterials, and the left-turns generated from the northbound and southbound frontage roads. Moreover, it was determined to use the software Synchro and VISSIM. Synchro was used to optimize the cycle length as well as the phase splits of each intersection. VISSIM replicated in high detail the intersection geometry, driving behavior, traffic patterns, signal timing and has various output parameters. In particular, VISSIM's section travel time feature was used extensively in model calibration. Furthermore, a site was selected based on the data available and based on certain geometry that can accommodate both types of designs.

The next step was to create the traffic simulation models. However, before any simulation was created and replicated certain data was collected from corresponding local and state transportation agencies, and by the author and his associates, to ensure that the model created had the necessary similarities to the existing site conditions. Once the data was obtained, both mentioned traffic simulation software was used to recreate the site selected for this study.

The third step, calibration, involved the use of the initial CDI models developed in Synchro and VISSIM, using all data collected. This model was carefully reviewed a number of times to ensure that all features and data collected was replicated as the existing site conditions. After several simulation test runs and by adjusting certain coding errors and software parameters, the final models were developed. During the calibration the average travel times of different sections (traffic movements) in VISSIM was used to compare against the corresponding measured travel times at the site. For each section, the t-test was used to determine whether the means of the average measured travel time and the average VISSIM output travel time were statistically different from each other. Throughout the process some adjustments to the speed limits and the use of speed reduction areas were coded and calibrated until the t-test was satisfied. The calibrated VISSIM model parameters were then translated to the equivalent parameters in the Synchro CDI model.

With the calibration phase completed, the new DCD-FR model was developed. The DCD-FR was derived from the calibrated CDI model. In addition, several simulation scenarios for both the CDI

and the DCD-FR were developed. Each scenario was then inputted into Synchro to obtain the optimized cycle length and phase splits for both models. The new signal timing and phase splits were then coded in VISSIM to be simulated. The output of the simulation runs was then analyzed and compared between the interchange designs.

3.2 Simulation Scenarios

As seen in the literature review, many of the scenarios modeled have a variation from low to very high traffic volume. For this study, the volume of certain traffic movements were kept consistent with Edara, et al. (2005), and some movements were tested with different volume. The volume of the frontage road through movement (X_1) as well as the left-turns (X_2) was increased. Figure 3.2 illustrates the typical movements of the interchange and indicates the movements that had fixed volume (blue arrows), and the movements which the volume were modified in the different scenarios (orange arrows). As the DCD was found to favor left-turns and the primary interest of this research is on the through vehicles on the frontage roads, the movements indicated by X_1 and X_2 were varied in the different scenarios.

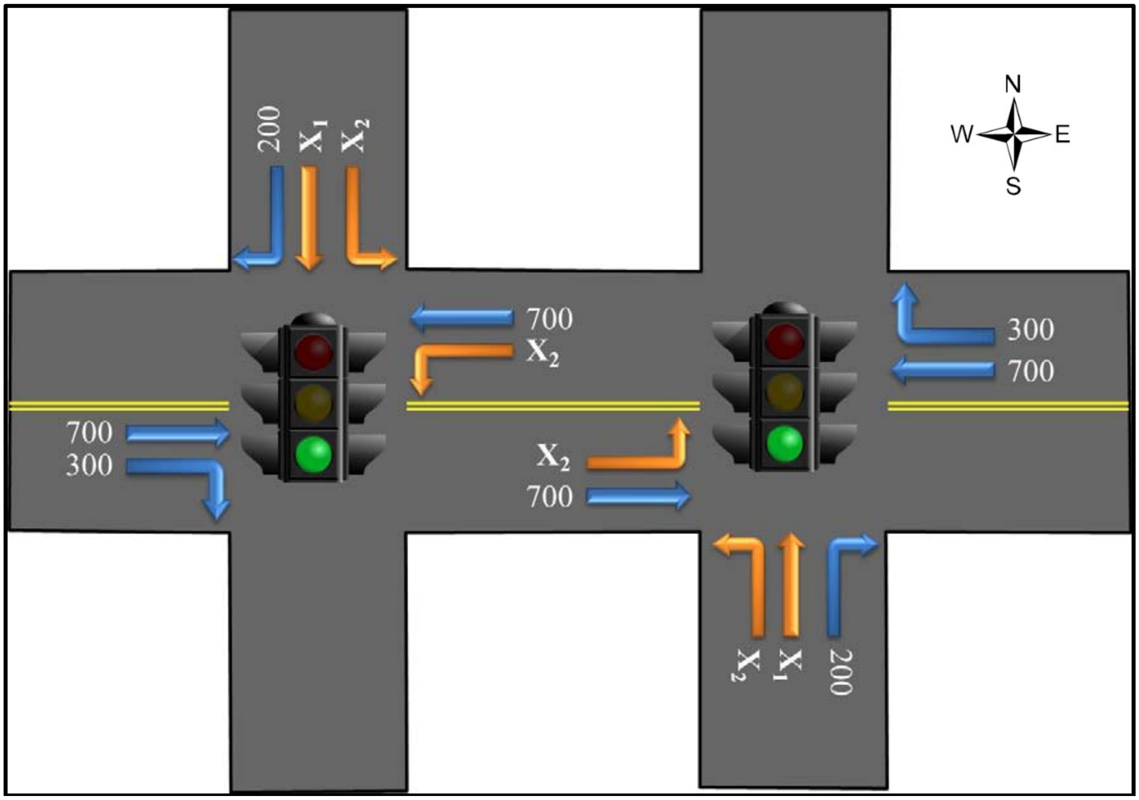

Figure 3.2: Intersection Volume Scenarios.

In addition, Table 3.1 clarifies the different volume scenarios used for the through and left-turn movements. The lowest traffic demand scenario modeled had 4000 vph while the highest traffic demand scenario modeled had a total of 5600 vph.

Table 3.1: Traffic Volume Scenarios for Through and Left-Turn Movements.

Through Volume X_1 (vph)	Left-Turn Volume X_2 (vph)
500	300
	400
	500
	600
	700
	800
600	300
	400
	500
	600
	700
	800

Through Volume X_1 (vph)	Left-Turn Volume X_2 (vph)
700	300
	400
	500
	600
	700
	800
800	300
	400
	500
	600
	700
	800

Each scenario in VISSIM was performed with ten random number seeds and the average value of each MOE from the ten simulation runs was used as the results for comparison. Twenty-four scenarios were developed for each intersection design and with ten random number seeds, two interchange designs, a total of 480 simulations were performed and analyzed.

3.3 Assumptions

Since this is an experimental study to test two interchanges, certain assumptions were adopted. The first assumption is the lane configuration for the interchange. On the north and southbound frontage road, left turns occur only from an exclusive left-turn lane. This was assumed because of two factors: data availability and software limitations. The video recording of the intersections did not allow the identification of how many vehicles where turning left from the shared left and through lane on the frontage road. In addition, because of angle and resolution of the video recording the lanes that vehicles followed when they turned left was not possible to identify. Moreover, Synchro showed inconsistencies while modeling a shared left and through lane on the proposed DCD-FR model. After modifying the

geometry several times the only functional geometry was to have one exclusive left-turn lane and two through lanes on the frontage road.

The second assumption adopted had to do with the vehicles that where traveling from the frontage road and would be performing a u-turn movement. The site selected had what is known as the Texas U-turn. This u-turn is separated by concrete sidewalk, curb and gutter from the east-west through movement, and allows both the north and southbound frontage road to u-turn. For this study, it was assumed that no Texas U-turn was available. The reason behind this assumption is based on the low traffic counts. The u-turn was not highly utilized at the intersection of interest. However, for the experimental scenarios developed some vehicles performed u-turn movements. Each modeled u-turn movement came from the frontage road, used the exclusive left-turn lane then merged to the left lane of the east-west arterial until it reached the second intersection at which it made the left-turns. In all of the simulated scenarios the volume of traffic coming from the frontage roads and making the u-turn movements was set to be 20% of the assigned left-turn traffic. Other percentages were considered. However 20% was selected to achieve a conservation of vehicles

Chapter 4: Simulation Model Development

In order to test the functionality of the new DCD-FR based on an existing CDI site in El Paso, Texas, it was important to obtain critical information to develop accurate traffic network models in Synchro and VISSIM. Several steps were considered when developing the methodology to test the new model. This chapter describes the model development and calibration process.

4.1 Site Selection

The first step of model development was to determine a location that would have the adequate site conditions to test both designs. Several potential interchanges in El Paso, Texas, were considered but due to the limited availability of traffic count data most of the sites were eliminated. The intersection selected for this case study was the interchange of Pellicano Dr. (the arterial running in the east-west direction) and Joe Battle Blvd (the frontage roads that serve Loop 375 freeway, running in the north-south direction). This intersection was selected because of its geometry and because it was the only intersection in El Paso that could be recorded with the existing traffic surveillance cameras nearby owned and operated by the Texas Department of Transportation (TxDOT).

Joe Battle Blvd serves as the frontage road for Loop 375 freeway. The freeway has an exit ramp upstream of the interchange and an entrance ramp downstream of the interchange in both the northbound and southbound directions. Figure 4.1 illustrates the selected study area.

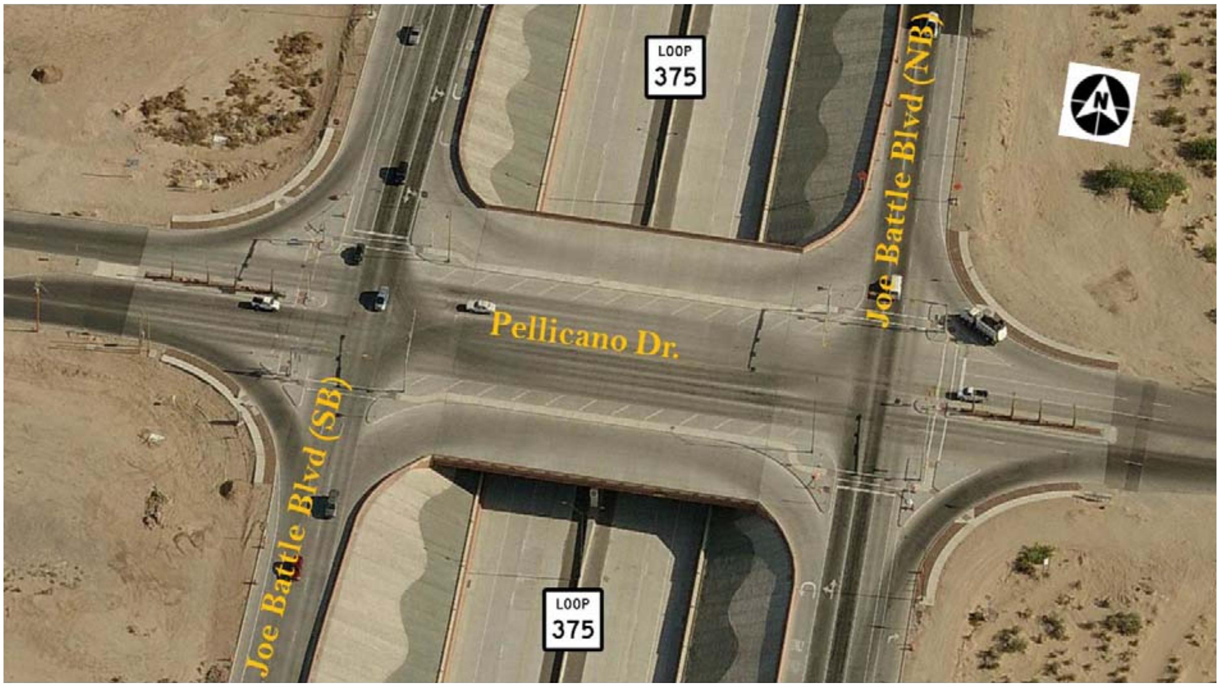

Figure 4.1: Case Study Site (source: Bing maps).

The two intersections that form the interchange are termed the east and west intersections, respectively. The frontage roads (Joe Battle Blvd) each have three lanes in both northbound and southbound directions. It has one exclusive u-turn lane (see Figure 4.1), one shared left-turn and through lane, and two through lanes. In addition, in each of the directions there is a channelized right-turn pocket. The east and west movements occur along Pellicano Dr. The eastbound direction starts with two lanes and then a left-turn pocket of approximately 170 feet is added before the west intersection. After crossing the west intersection, there is one exclusive left-turn lane and two through lanes. The two through lanes then merge to one lane at approximately 300 feet downstream of the east intersection. In addition, the northbound right-turn lane (from Joe Battle Blvd) merges into Pellicano Dr. before the two eastbound lanes merge to one lane. On the other hand, the westbound direction starts with two lanes and then a third lane is added. This third lane accommodates through traffic as well as right-turn movement at the east intersection. At the northbound frontage road at the east intersection follows the same lane configuration as the southbound frontage road at west intersection. In addition, the southbound right-

turn movement from Joe Battle Blvd merges in to the right lane of the two lanes on Pellicano Dr. Both intersection are approximately 320 feet apart from each other, center to center.

4.2 Data Collection

Once the site was selected the City of El Paso was contacted to obtain traffic counts and the signal timing data sheet. At that time no current traffic count data was available and only the signal timing sheet was provided. Since no traffic count data was available, TxDOT was contacted to request permission to use two existing traffic surveillance cameras nearby (along Loop 375 freeway) to record the intersections of interest. It is important to note that one camera recorded the east intersection while the other recorded the west intersection. Once permission was granted a 24-hour video was recorded on a weekday to determine the peak hour. After observing the traffic demand in the typical morning and afternoon peak hours in El Paso, that is 7:00 a.m. to 9:00 a.m. and 4:00p.m. to 6:00 p.m. respectively, it was determined to use the morning peak. Traffic in the morning had more presence than in the afternoon, especially between 7:00 a.m. and 8:00 a.m. Once the hour of interest was determined, a date was set to record the intersections and to perform a travel time study during the video recording process. The travel time study consisted of measuring the travel time along several sections (movements) at the interchange, the measured travel time sections can be seen in Figure 4.2. These sections included the through movements along the northbound and southbound frontage roads crossing the intersection of Pellicano Dr. (from points 1 to 2, and from points 3 to 4, respectively in Figure 4.2), the eastbound and west through movement along Pellicano Dr. crossing both intersections (from points 5 to 6, and from points 7 to 8, respectively in Figure 4.2), the left-turns from the frontage roads passed two intersections (northbound to westbound and southbound to eastbound).

Figure 4.2: Measured Travel Time Sections (source: Google Earth).

On December 10, 2009 the two cameras where set to record the morning peak hour traffic from 7:00 a.m. to 8:00 a.m. A team was organized to record the travel times for the selected movements by the floating car survey method. Subsequently, the video recording was downloaded from TxDOT's video server and a traffic count was performed in the laboratory. In addition, a distribution of the vehicle classes was determined. Only 4.20% of the traffic was heavy vehicles (buses, semi-trucks and trucks) while the rest of the traffic was passenger vehicles. The results from the traffic counts are listed in Table 4.1.

Table 4.1: Traffic Count Data.

East Intersection								
Street	**Joe Battle Blvd**			**Pellicano Dr.**				
Movement	**Right**	**Through**	**Left**	**Through**	**Right**	**Left**	**Through**	**U-Turn**
Vehicles (vph)	121	102	217	500	473	305	536	25
Trucks (vph)	10	2	12	20	45	7	23	1
Subtotal (vph)	131	104	229	520	518	312	559	26
Total (vph)	**464**			**1038**		**871**		**26**
West Intersection								
Street	**Joe Battle Blvd**			**Pellicano Dr.**				
Movement	**Right**	**Through**	**Left**	**Through**	**Right**	**Left**	**Through**	**U-Turn**
Vehicles (vph)	388	239	326	516	308	191	522	16
Trucks (vph)	5	4	18	11	6	13	23	0
Subtotal (vph)	393	243	344	527	314	204	545	16
Total (vph)	**980**			**841**		**749**		**16**

4.3 VISSIM Model

4.3.1 Development

With the purpose of comparing both the DCD-FR and CDI interchange designs, a base model, replicated after the existing CDI at Pellicano Dr. and Joe Battle Blvd was developed. This model was calibrated using the input traffic volume obtained from the survey (Table 4.1), signal timing data

provided by the City of El Paso as well as the observed geometry and traffic characteristics of the site. The data was then entered into VISSIM following the standard procedures described in the VISSIM 5.10 User Manual (PTV, 2007). The following list briefly describes the VISSIM modeling process:

1. The first step was to change the units from the International System of Units (SI) to the English system. Since VISSIM is software from Germany it has as default SI units.
2. A set of high quality images from Google-Earth were set and scaled on VISSIM to accurately represent the existing conditions of the site selected.
3. A speed distribution was created for each vehicle class (passenger vehicles and trucks) based on the posted speed limit.
4. The passenger vehicles characteristics such as acceleration, deceleration, power, torque, etcetera, were set as their default values. However, for the trucks two typical classifications used by TxDOT were defined, class 7 and class 8. Both of them represent semi-trucks and trucks as observed in the El Paso traffic.
5. The traffic composition was developed by using a distribution that matched what was seen on the video recordings, 4.20% trucks (out of which half was class 7 and half class 8) and the rest for passenger vehicles.
6. A basic network using links and connectors was then drawn to recreate the geometric layout of the intersection (see Figure 4.3).

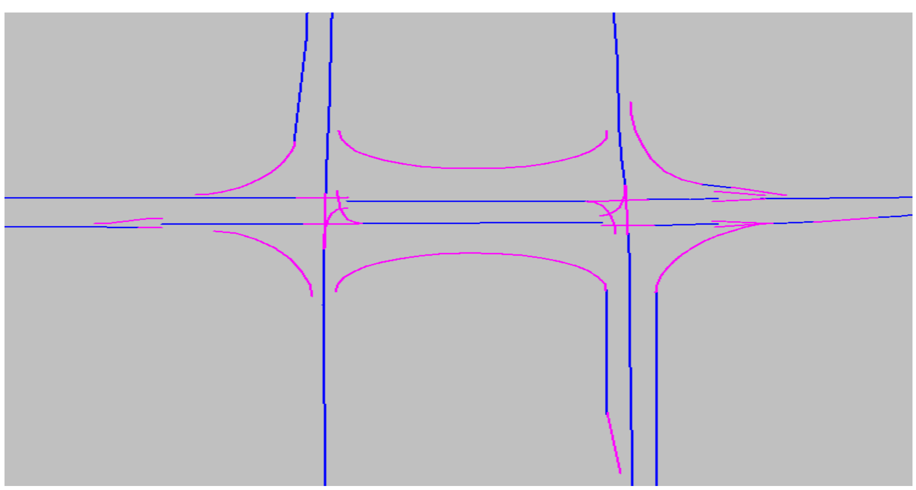

Figure 4.3: VISSIM Base Model.

7. Vehicle inputs were coded to have all vehicle compositions appear at the selected entry points.
8. Several routes were assigned to model the driving directions of the interchange. For instance, vehicles turning left would only use the left-turn connector to arrive to their destination. This same process was coded for all movements.
9. Conflict areas were used to model all yielding movements such as the channelized right turns.
10. After several test runs, further modeling parameters were then modified to achieve the final model. The use of speed reduction areas was critical to complete the model. The speed reduction areas are short sections on which an arriving vehicle is assigned a new desired speed, once it leave the speed reduction area the vehicle automatically accelerates to its original desired speed. Figure 4.3 illustrates the use of the speed reduction areas (green boxes) in the base model. A total of 54 speed reduction areas were used. The range of speed was from 20 mph to 25 mph

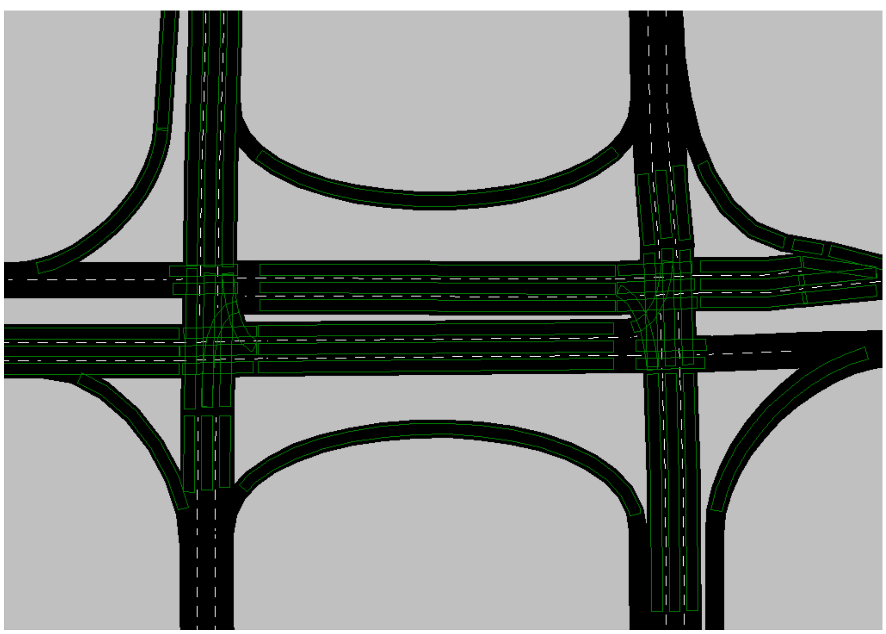

Figure 4.4: Speed Reduction Areas.

11. Finally, six travel time sections as described in section 4.2 and Figure 4.2 were designated to collect travel time and delay data for the movements of interest. Figure 4.4 is a snapshot of the final model.

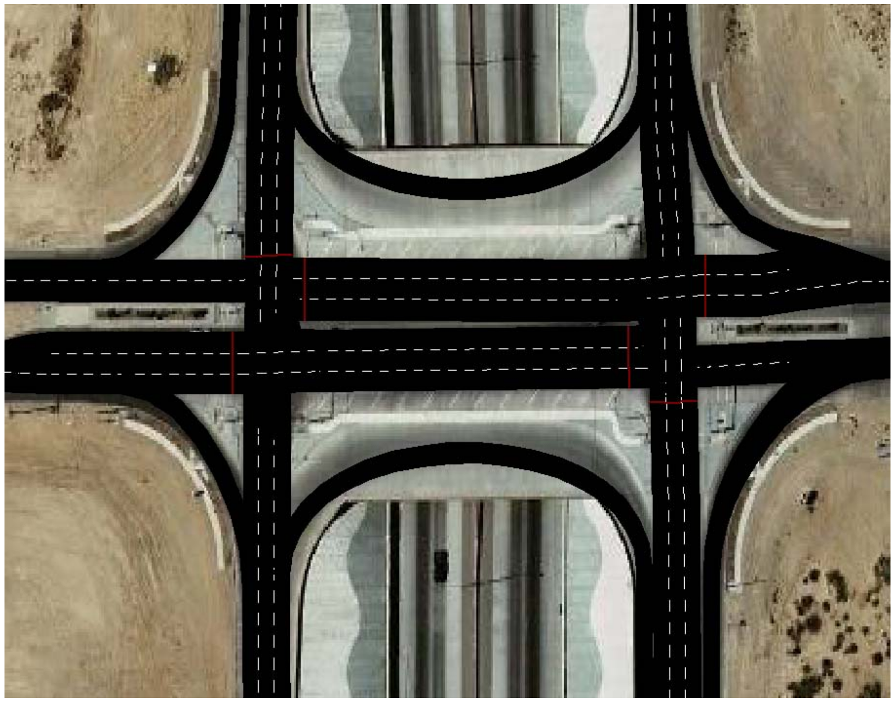

Figure 4.5: Final VISSIM Base CDI Model.

4.3.2 Validation

Once the existing conditions such as lane configuration, traffic volume, traffic composition, traffic routes, speed limit, and the signal timing plan were modeled in VISSIM, the base CDI model simulated the morning peak hour and using the through section travel times as the MOEs, the model was tested using the paired t-test. Essentially, the paired t-test tests if the average section travel time (from VISSIM runs with 10 random number seeds) is significantly different from the average section travel time obtained in the field data collection. After running the model for 10 random seeds and calculating the average travel time for each through section, the following results were obtained. Table 4.2 summarizes these results

Table 4.2: Results of Paired t-Tests.

Measured Travel Time (seconds)							
Northbound (1-2)		**Southbound (3-4)**		**Eastbound (5-6)**		**Westbound (7-8)**	
Average	126.90	**Average**	140.50	**Average**	152.09	**Average**	169.27
STDEV	16.17	**STDEV**	19.23	**STDEV**	41.78	**STDEV**	23.88
n	11	**N**	11	**n**	10	**n**	10
VISSIM Travel Time (seconds)							
Northbound (1 -2)		**Southbound (3-4)**		**Eastbound (5-6)**		**Westbound (7-8)**	
Average	145.44	**Average**	134.35	**Average**	140.04	**Average**	152.36
STDEV	83.31	**STDEV**	21.39	**STDEV**	31.97	**STDEV**	45.96
n	123	**N**	160	**n**	238	**n**	328
NB t-stat	**0.73**	**SB t-stat**	**-0.93**	**EB t-stat**	**-1.15**	**WB t-stat**	**-1.16**
t_critical	**1.97**	**t_critical**	**1.97**	**t_critical**	**1.97**	**t_critical**	**1.967**

All the calculated t-statistics are lower than the corresponding critical values. Therefore, the travel times produced by the VISSIM model are not significantly different than what were measured in the field. The results reflect that the base model has been calibrated to provide reasonable and comparable output.

4.4 Synchro Model

The Synchro model was created following similar steps as the model developed in VISSIM. It is important to note that some parameters specified in the final VISSIM validated model such as, the speed limits and speed reduction areas were set in the Synchro model. Since Synchro does not have an option to have speed reduction areas the speed limit between both intersections was lowered to match a similar effect. Illustrated in Figure 4.6 is the Synchro model.

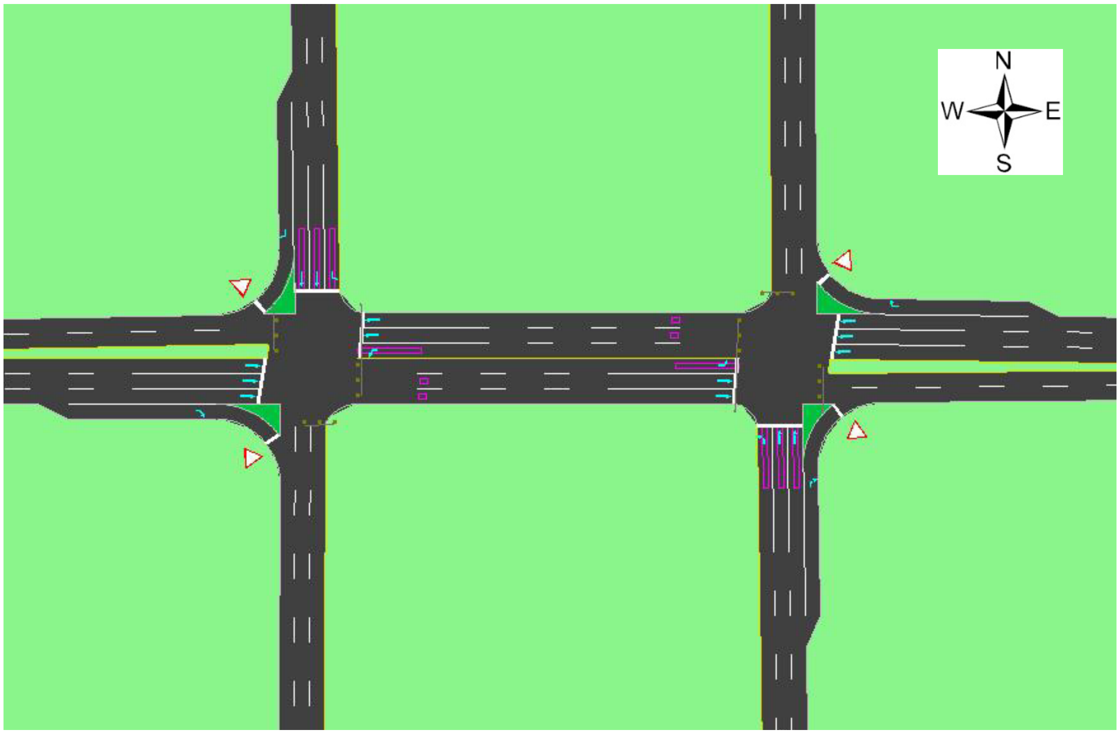

Figure 4.6: Final CDI Synchro Model.

The CDI model created in Synchro was then modified to replicate the DCD-FR interchange design. Because of the geometry and the crossing movement the DCD-FR model was a challenge. In order to create the DCD one must create a parallel link between the intersections. Once the DCD-FR model was developed several tests were done to ensure that the model had the correct performance and operations.

One of the problems encountered with the DCD-FR model was the creation of a shared left-turn and through movement lane. It was observed that under that configuration a fatal error occurred in Synchro. Synchro did not recognize that left-turn movement and stated that no receiving lanes were on the model. In other words, Synchro did not recognize the link where the arterial would receive the vehicles. Because of this limitations it was determined to use only one exclusive left-turn lane for this research. Figure 4.7 illustrates the DCD-FR model developed in Synchro.

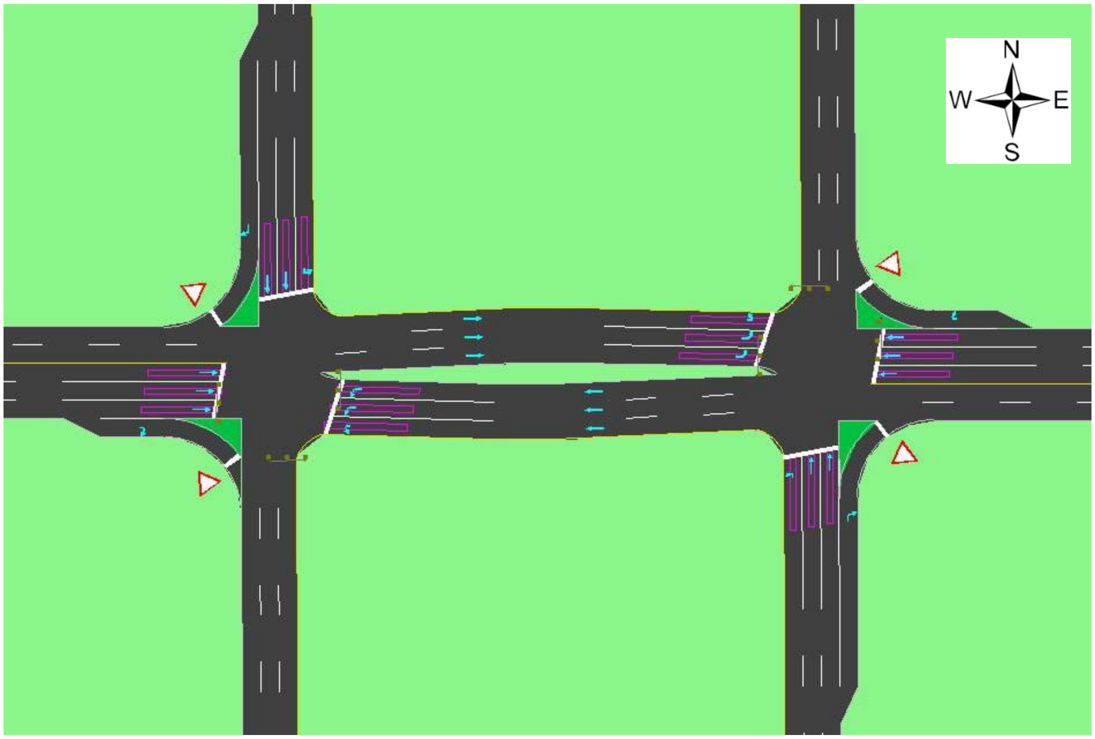

Figure 4.7: Final DCD-FR Synchro Model.

It can be observed how the directions of traffic between the intersections were coded to allow vehicles to drive at the opposite side of the roadway.

Chapter 5: Synchro Results

This chapter discusses the proposed signal phasing for the DCD-FR as well as the optimization performed for all volume scenarios. In addition, the results of Synchro evaluation are presented.

5.1 Signal Phases

The signal phase proposed allows all left-turns as free left. In other words, vehicles that perform a left-turn will only have to yield to incoming traffic on the right. The idea came about observing some intersections where the right turn has a small island that separates through traffic from the drivers that want to make a right-turn. In addition, the left-turn designs proposed by Chlewicki can be signal controlled or yield controlled (Chlewicki, 2003). Applying this concept to the intersection will have a significance impact since while some movements are waiting for the green light, vehicles turning left will have additional time to continue through the intersection. Illustrated in Figure 5.1 is the phasing layout as seen in Synchro for the DCD-FR with X_1= 500vph and X_2= 300 vph.

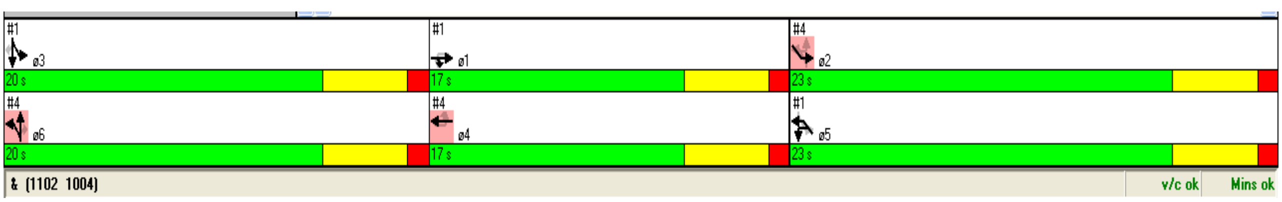

Figure 5.1: DCD-FR Signal Phase for the First Scenario.

The signal phase of the CDI was left to its standard phasing. It is important to note that during the optimization process in Synchro, the optimum signal phase and split were modified to accommodate an overlap to benefit one movement. An overlap is defined as when one phase of the traffic signal is given the green time while another phase is still active. Figure 5.2 illustrates the overlap provided to the CDI design. Synchro tends to give priority to the movements that have the highest volume. Even though the volume is symmetric it identifies one movement with high traffic and gives it more green time. The

overlap given is mainly of 5 seconds and is given to the southbound frontage road while the northbound frontage road is on.

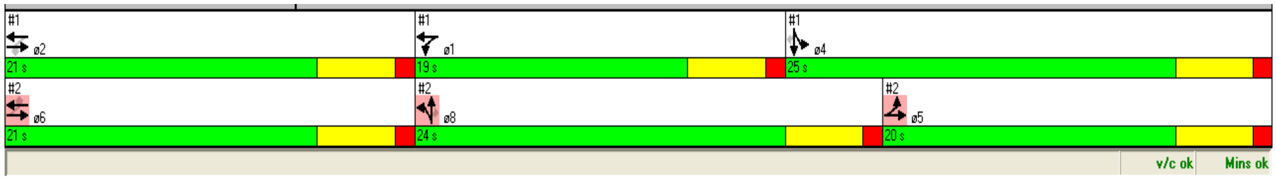

Figure 5.2: CDI Signal Phase for the First Scenario.

5.2 Optimization

Each scenario that was modeled first needed to be optimized in Synchro 7.0 to ensure that the optimum cycle length and phase splits was used. The optimization of a network coded in Synchro 7 was as follows. First, Synchro checked for different cycle lengths that might allow the network to have a better LOS or less delay. Cycle lengths from 60 sec to 120 sec with a 5 second increment were tested. These settings are the recommended settings performed by the City of El Paso. After the cycle length is determined, the option of optimizing the signal phase splits in Synchro was selected to help to minimize the delay for the heavy traffic movements. The final cycle lengths for each traffic demand scenario on both models are shown in Table 5.1. In general, DCD-FR has smaller or equal cycle lengths compared to CDI.

Table 5.1: Scenario Optimized Cycle Lengths.

Optimized Cycle Length			
Through Volume X_1 (vph)	**Left-Turn Volume X_2 (vph)**	**CDI Cycle Length (sec)**	**DCD-FR Cycle Length (sec)**
500	300	60	60
	400	65	60
	500	75	60
	600	75	60
	700	80	70
	800	80	80
600	300	60	60
	400	65	60
	500	75	65
	600	75	65
	700	75	70
	800	80	75
700	300	60	60
	400	65	60
	500	70	60
	600	75	60
	700	85	70
	800	85	75
800	300	60	60
	400	65	60
	500	65	60
	600	75	65
	700	85	80
	800	90	95

Once all the traffic demand scenarios were optimized by Synchro, manual adjustments to the phasing were done to help improve the intersection LOS. It is important to note that because no research has been done to a DCD-FR, a special three-phase sequence was developed.

5.3 Intersection Level of Service

The intersection LOS is an indicator of the overall traffic conditions of an intersection. It is highly used among researchers as well as public and private entities. The signalized LOS is defined in terms of the average total vehicle delay of all the movements allowed at an intersection (HCM, 2000). The most favorable conditions are designated with LOS A while the poorest conditions are indicated with LOS F. To better illustrate the concept of LOS given by the Highway Capacity Manual refer to Table 5.2. It is important to note that the City of El Paso accepts intersections with LOS C or better.

Table 5.2: Level of Service Criteria for Signalized Intersections.

Level of Service	Stopped Delay (sec/veh)	Description
A	≤ 10	Free flow conditions. Most vehicles do not stop at all
B	> 10 and ≤ 20	Stable flow. Some vehicles stop before getting a green signal.
C	> 20 and ≤ 35	Stable flow with acceptable delays. A significant number of vehicles stop and wait for a green signal.
D	> 35 and ≤ 55	Approaching unstable flow. Many vehicles have to wait through more than one signal cycle before continuing.
E	> 55 and ≤ 80	Unstable flow. Almost all vehicles have to wait through more than one signal cycle before continuing.
F	> 80	Forced flow. The number of vehicles entering the intersection exceeds the intersection capacity.

Since Synchro analyses the LOS of each intersection individually, the two intersections in the interchange are denoted as the east intersection and west intersection, respectively. To further understand the Synchro network, refer to Figure 5.2.

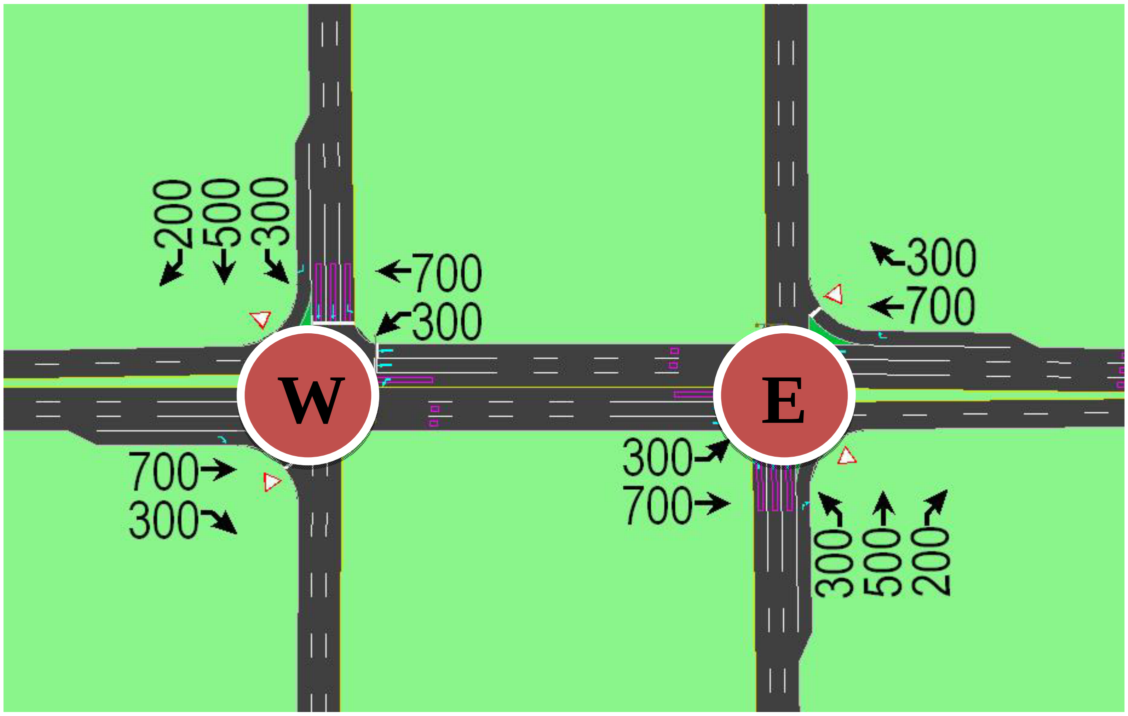

Figure 5.2: Scenario 1 in the CDI Synchro Model.

All scenarios for the CDI and the DCD-FR were coded in Synchro and optimized to obtain the best LOS. Since each traffic demand scenario had different traffic volume as well as different cycle lengths and splits each intersection had a unique intersection LOS. Table 5.2 shows the results obtained for both interchange designs under the same traffic demand. Highlighted in orange are the scenarios in which the intersection LOS is worse than C.

Table 5.3: Intersection Level of Service Results.

INTERSECTION LOS					
Through Volume (vph)	Left-Turn Volume (vph)	CDI OPTIMIZED		DCD OPTIMIZED	
		East Intersection	West Intersection	East Intersection	West Intersection
500	300	B	B	B	B
	400	C	C	B	B
	500	C	C	B	B
	600	D	D	B	B
	700	E	E	C	C
	800	F	F	C	C
600	300	B	B	B	B
	400	C	C	B	B
	500	C	C	B	B
	600	D	D	B	B
	700	E	E	C	C
	800	F	F	C	C
700	300	B	B	B	B
	400	C	C	B	B
	500	C	C	B	B
	600	D	D	C	C
	700	E	E	C	C
	800	F	F	C	C
800	300	B	B	C	C
	400	C	C	C	C
	500	C	C	C	C
	600	D	D	C	C
	700	E	E	C	C
	800	F	F	C	C

As seen in Table 5.3, the CDI starts with reasonable LOS but once the left-turn volume is 600 vph or higher the model starts to have worst LOS. Unstable flow starts to appear and in some cases the vehicles entering the intersection is higher than its capacity. On the other hand, the new DCD with

frontage roads shows that it keeps a fair LOS on any scenario modeled, having LOS C as the worst condition which is still acceptable by the City of El Paso.

5.4 Average Intersection Delay

Delay is a measure of the time spent by vehicles at any given intersection. It is measured from the time the vehicles arriving to the intersection until it leaves it. Some factors that contribute to high delay are: intersection geometry, traffic volume or queue, and signal timing. Shown in Table 5.4 are the average intersection delay results for both models under the coded scenarios.

Table 5.4: Average Intersection Delay Results.

AVERAGE INTERSECTION DELAY (seconds)					
Through Volume (vph)	Left-Turn Volume (vph)	CDI OPTIMIZED		DCD-FR OPTIMIZED	
		East Intersection	West Intersection	East Intersection	West Intersection
500	300	15.30	15.50	16.00	16.00
	400	20.20	20.30	16.00	16.00
	500	29.20	29.60	16.30	16.30
	600	45.40	46.10	17.50	17.50
	700	72.70	77.30	21.10	21.10
	800	107.80	115.50	24.60	24.60
600	300	16.30	15.90	17.20	17.20
	400	20.80	20.90	17.30	17.30
	500	30.70	30.50	17.90	17.90
	600	45.60	46.30	18.80	18.80
	700	74.30	74.40	21.40	21.40
	800	109.40	114.00	26.40	26.40
700	300	17.50	17.50	18.60	18.60
	400	21.60	21.50	18.80	18.80
	500	30.50	30.70	19.40	19.40
	600	45.80	46.80	20.50	20.50
	700	76.10	75.30	23.40	23.40
	800	104.70	119.10	29.40	29.40
800	300	18.60	18.40	20.40	20.40
	400	22.90	22.80	20.50	20.50
	500	30.80	34.70	21.20	21.20
	600	44.80	46.40	22.40	22.40
	700	73.60	73.60	26.40	26.40
	800	102.40	115.80	33.60	33.60

The CDI delay starts to get worse once the left-turn volume is 600 vph or higher. In addition, because of the way that Synchro optimizes the intersections at the CDI, the east intersection appears to generally have less delay when compared to the west intersection. The reason behind this behavior is because of the overlap given by Synchro to certain movements.

On the other hand, for the DCD-FR, no offset or overlap occur allowing the opposing movements to have green time simultaneously. In addition, as seen on Table 5.4 the DCD-FR keeps fairly consistent average intersection delays with the worst case being 33.60 seconds of delay per vehicle. This nature is due to the proposed phasing that allows cars to yield to the incoming traffic on any left-turn movement.

The network coded in Synchro 7.0 for both designs shows a clear advantage of the proposed DCD-FR when compared to the CDI. The key feature of the DCD-FR is the three-phase signal timing plan. This phase plan provides a more efficient intersection operation by requiring vehicles to make fewer stops and therefore, enabling a reduction in travel time and delay and an improvement in the intersection LOS.

5.5 Summary

The results obtained in Synchro show an overall better performance with the proposed DCD-FR. The CDI has high delays and its LOS varies from LOS B to LOS F. In contrast, the DCD-FR design shows lower delays and maintains at heavy traffic volume a LOS C.

Chapter 6: VISSIM Results

The use of VISSIM compliments the analyses performed using Synchro. Synchro allowed the signal timing plan to be optimized, the individual intersection's average delay time estimated, and intersection LOS analyzed. The optimized cycle length and phase splits were then coded in VISSIM to further analyze the interchange operations. The high detail modeling and the option to choose specific sections to evaluate the performance is valuable to most research projects. As mentioned before the validated model was used to simulate the CDI. On the other hand, by modifying its geometry, the new DCD-FR was developed. Seen in Figure 6.1 is the new DCD-FR model coded in VISSIM.

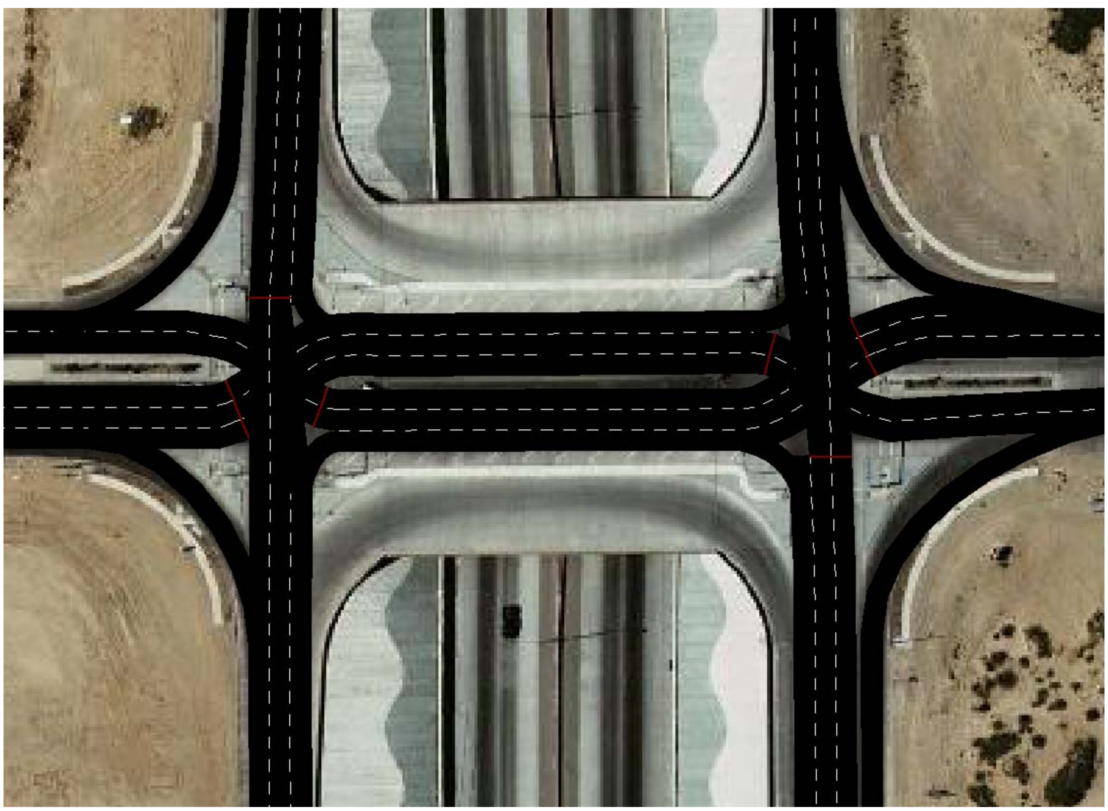

Figure 6.1: DCD-FR VISSIM Model.

6.1 Section Travel Time

One of the advantages of VISSIM is that one can set specific sections (each consists of multiple links) to be analyzed depending on the modeling needs. Each travel time sections consists of a starting and an ending point. Once a vehicle crosses the starting point the average travel time (which includes any waiting time) is calculated until the ending point is reached (PTV, 2007). The list of the travel time sections used in this study and as coded in the VISSIM models include:

1. The westbound movement turning left at the southbound frontage road.
2. The westbound movement crossing both intersections.
3. The eastbound movement turning left at the northbound frontage road.
4. The eastbound movement crossing both intersections.
5. The northbound frontage road turning left onto the westbound direction.
6. The southbound frontage road turning left onto the eastbound direction.

It is important to understand that even though the input volume is symmetrical, the travel time sections cover the symmetrical movements are not symmetrical. The reason behind this behavior is because of several factors. One factor is the basic skeleton of the VISSIM network. The links and connectors each have different lengths and different angles associated with them. This makes it difficult to specifically place the starting and ending points at exactly the same distance. Another factor that affects the section travel time results is the geometry of the existing site. Since VISSIM models the geometry in high detailed, certain existing lane configuration represent a problem under high volume. For instance, the eastbound movement has two conflict points that impact the simulation with high volume. The first conflict point is the left-turn pocket before the west intersection. This pocket is approximately 170 feet which can only accommodate about seven to eight passenger cars. Since some scenarios have high left-turning volume, the left-turn queue may spill back to the main lane. Another conflict point occurs at the eastbound movement east of the interchange. Once the eastbound vehicles have passed the east intersection they have to merge from the two existing through lanes into one lane.

Moreover, immediately upstream of the merging area, the northbound right-turn traffic enters the section that adds to the bottleneck. This geometry will tend to involuntary cause delay in the high volume scenarios.

While it has been explained that the travel time sections are not symmetrical for each movement with symmetrical traffic demand, each travel time section started and ended at the same position in both the CDI and DCD-FR models. Therefore, comparisons between the CDI and DCD-FR can be made for each travel time section. The results of the travel time sections are shown in the following figures. The y-axis is the travel time calculated by VISSIM and at the x-axis represents the corresponding left-turn volume scenarios.

Figure 6.2 and Figure 6.3 illustrates the travel time sections corresponding to the westbound vehicles. The section for the westbound movement turning left at the west intersection is also known as travel time section 1, while the section shows the westbound movement that travel straight through both intersections is also known as travel time section 2.

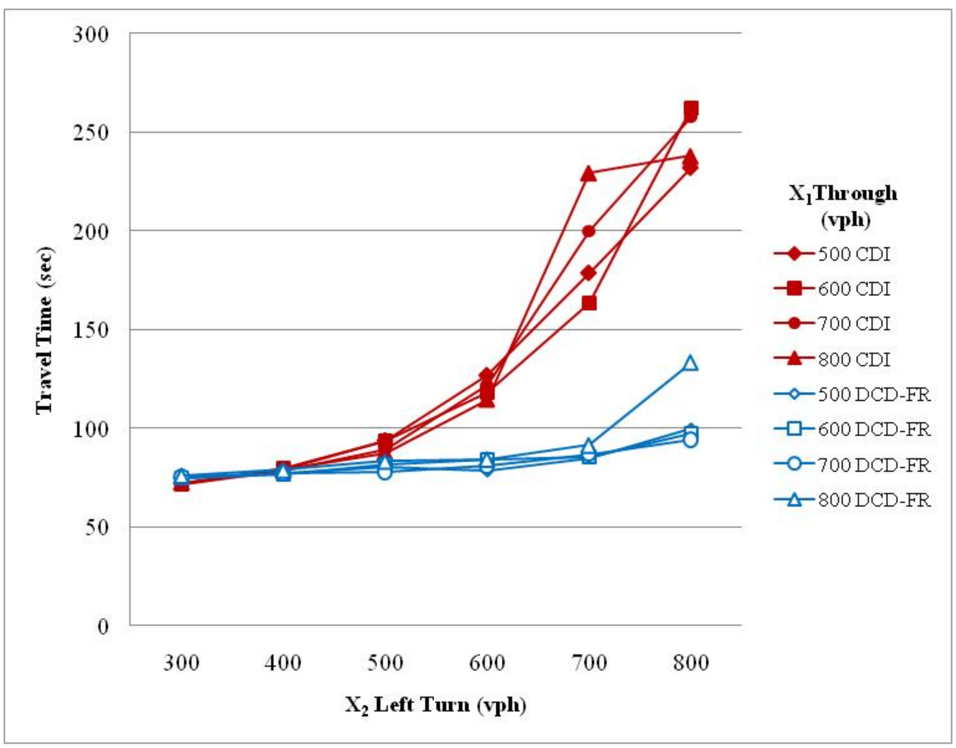

Figure 6.2: Average Section Travel Time of Westbound Movement Turning Left at the West Intersection.

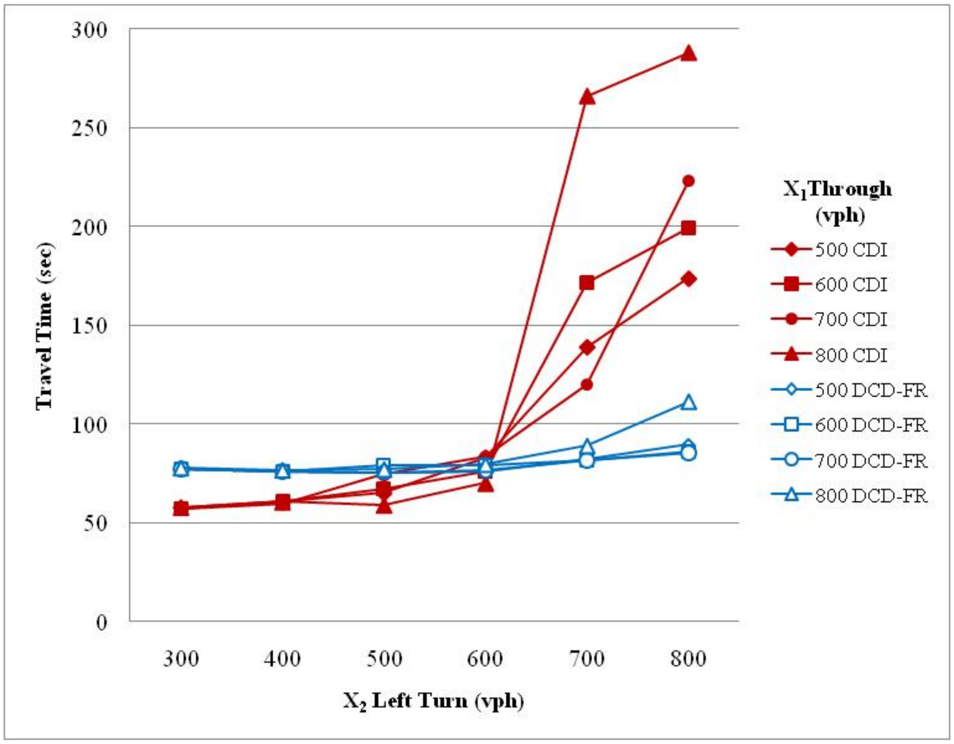

Figure 6.3: Average Section Travel Time of Westbound Through Movement.

The results for the first travel time section indicate how the proposed DCD-FR performs better than the CDI. The increase of the left-turn volume increases the travel time of the vehicles of the corresponding movement.

The results for the westbound vehicles show a similar trend as the first section. However, the DCD-FR shows a slightly higher travel time as compared to the CDI for the scenarios with low left-turn volume. This may be the result of the curvature and geometry of the layout. In a DCD-FR, for crossing from one point to the other requires vehicles to change to the opposite direction and then cross back to the original direction of travel. Even though this movement shows to a certain extent a higher travel time, throughout the different scenarios with different through volume the travel time is consistent.

Figure 6.4 and Figure 6.5 illustrates the average section travel time of the eastbound vehicles. The first figure shows the eastbound movement turning left at the northbound frontage road and the second figure shows the eastbound movement through both intersections. Bear in mind that this movement has the previously mentioned conflict points.

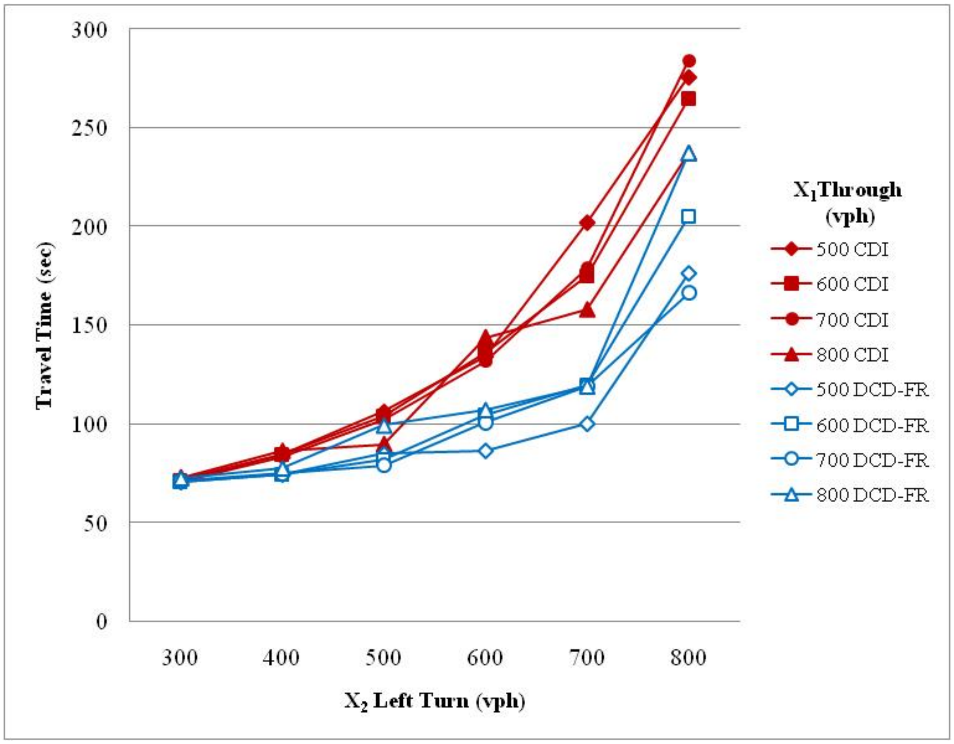

Figure 6.4: Average Section Travel Time of Eastbound Movement Turning Left at the East Intersection.

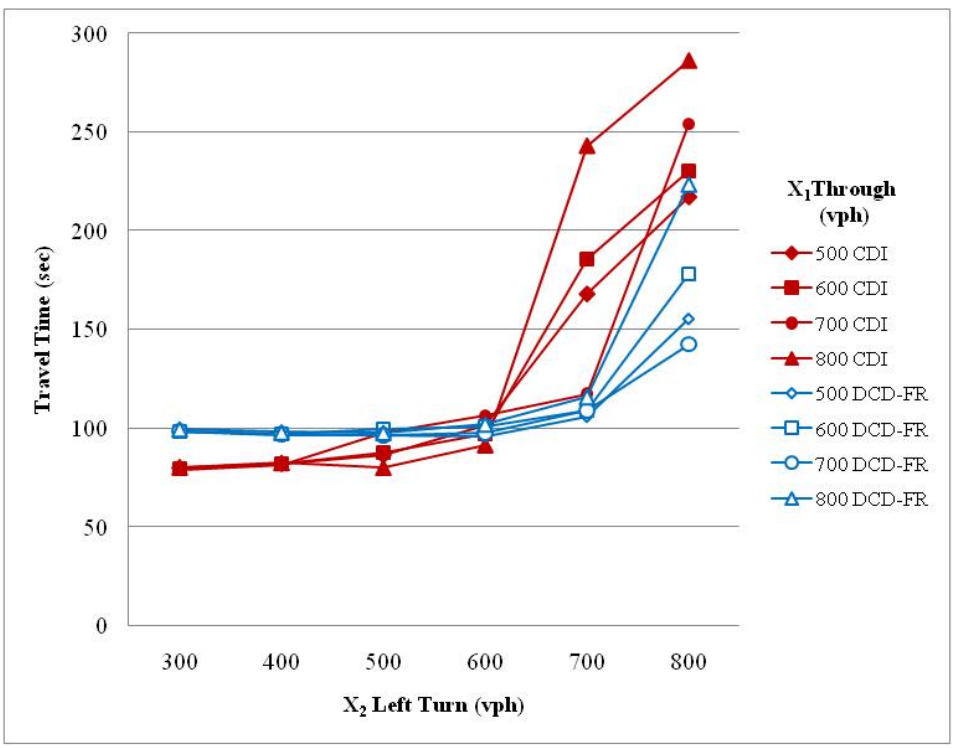

Figure 6.5: Average Section Travel Time of Eastbound Through.

Figure 6.4 is an indication of the conflicts occurring at the left-turn pocket at the west intersection. As the vehicles turning left increases more vehicles are set to use the desired lane. Nevertheless, the proposed DCD-FR design still shows less travel time when compared to the CDI. This is because of the free left-turn associated with the model.

The results illustrated in Figure 6.5 reflect a relatively similar pattern as the westbound vehicles. The curvature of the DCD-FR makes the CDI, at low left-turn volume, has slightly lower travel time than the DCD-FR. The only exception starts to occur when the left-turn volume is at its highest. Again, this could be caused because of the geometry of the existing conditions. As mentioned before, after crossing the northbound frontage road the two eastbound main lanes merge to one and the right-turns from the northbound frontage road also occurs at this point. Since the finishing point of this travel time section is present after the previously mentioned conflict, at the highest vehicular presence this geometry becomes a problem for the DCD-FR becomes obvious. Yet, the DCD-FR still shows better results as the CDI. Figure 6.6 illustrates the travel time section that corresponds to the northbound frontage road turning left to continue westbound.

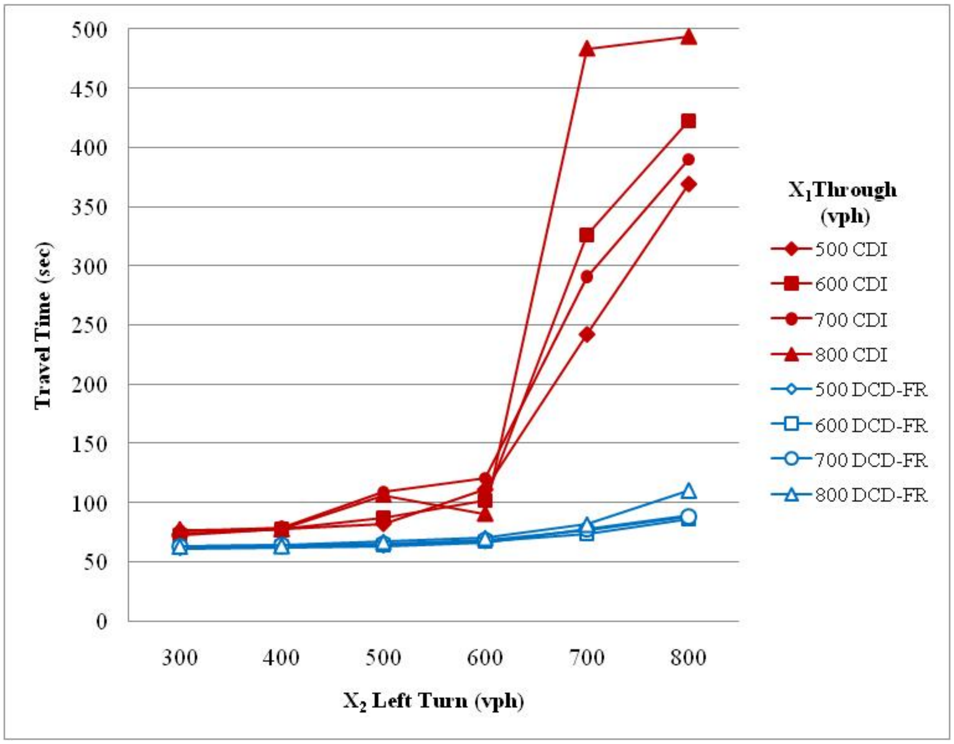

Figure 6.6: Average Section Travel Time of Northbound Movement Turning Left at the East Intersection.

The results Figure 6.6 show a significant improvement of the travel time with the proposed DCD-FR design. The DCD-FR keeps a consistent travel time along this route. On the other hand, as seen on Synchro, once the left-turn volume is 600 vph or higher the movement begins to jump to higher travel times.

The final segment analyzed was the southbound direction making a left turn to continue east. The travel time results for this section are illustrated in Figure 6.7.

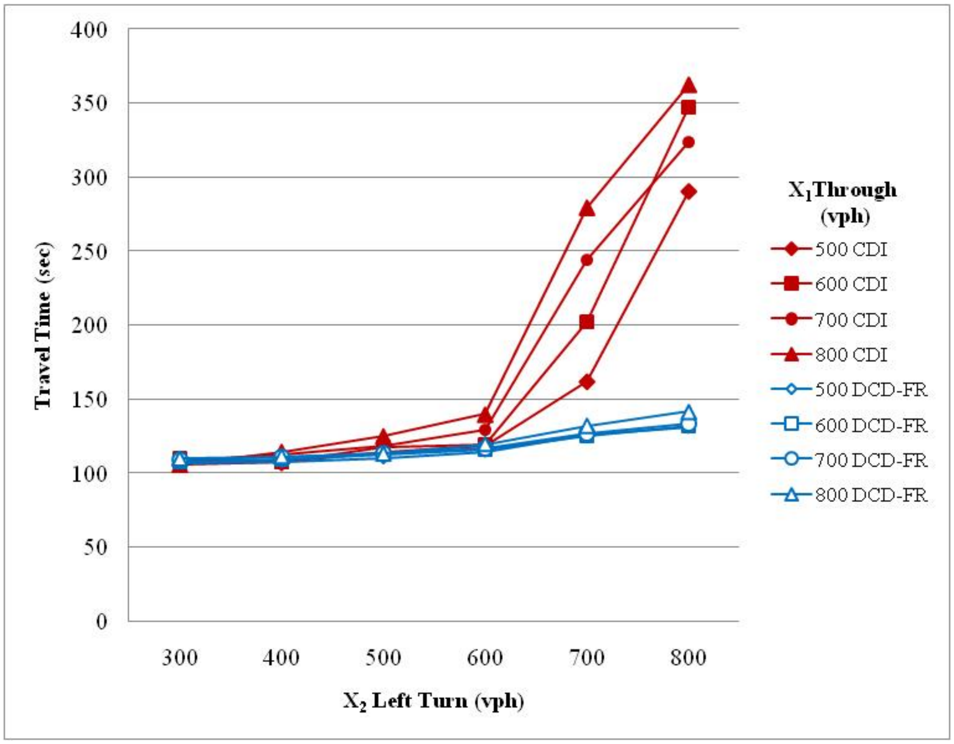

Figure 6.7: Average Section Travel Time of Southbound Movement Turning Left at the West Intersection.

The final travel time segment analyzed follows a similar pattern than the one shown in Figure 6.6. The advantage of the DCD-FR is noticeable for the left-turn movements coming from either the northbound or southbound frontage road. In addition, a pattern starts to be present for the CDI when the left-turn volume is of 600 vehicles or higher.

6.2 Section Delay

The delay in VISSIM is calculated by using travel time sections. Therefore, the travel time sections previously discussed are used to obtain the delay. The calculated delay follows the similar process as the travel time calculations. All vehicles that pass the travel time sections will generate a delay output file. All properties and conflicts discussed in the previous section apply to the results that will be presented in this section. The section delay results are shown in the following figures and have the same format as the travel time results.

Figure 6.8 and Figure 6.9 illustrates the section delay corresponding to the westbound vehicles. The first figure shows the westbound movement turning left at the southbound frontage road and the second figure shows the westbound movement through both intersections.

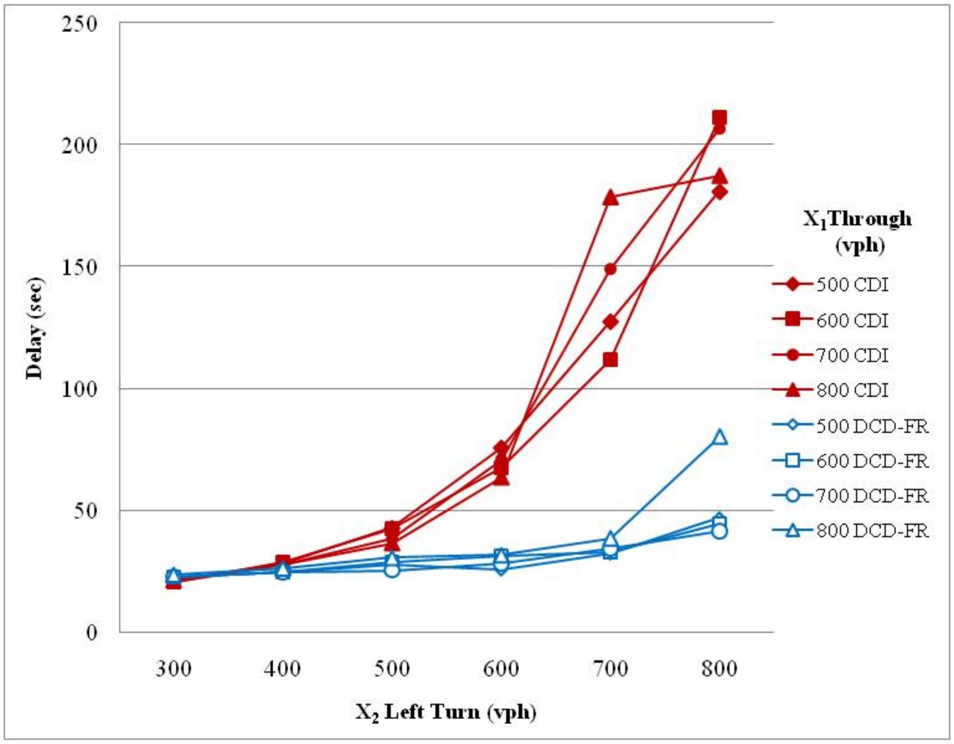

Figure 6.8: Average Section Delay of Westbound Movement Turning Left at the West Intersection.

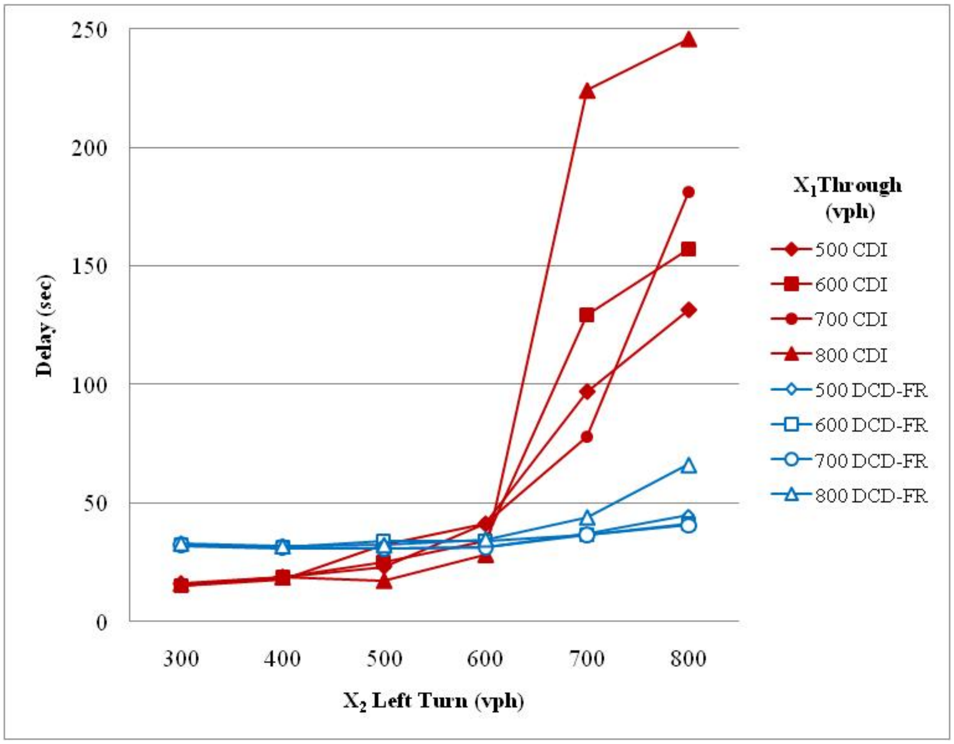

Figure 6.9: Average Section Delay of Westbound Through Movement.

The results illustrated in Figure 6.8 indicate how the proposed DCD-FR performs better than the CDI. The section delay stays fairly consistent in the proposed DCD-FR design. Moreover, the common denominator of the failing point of the CDI appears again when the vehicles turning left surpass 600 vehicles.

The results for the westbound vehicles show a similar interaction as the first section. However, the DCD-FR shows a slightly higher delay in the first scenarios as compared to the CDI. As previously discussed, this may be due to the lower speed of the DCD-FR, the curvature and geometry of the layout. Despite this behavior, the westbound section modeled in the DCD-FR shows to a certain extent a fairly consistent delay.

The eastbound movement turning left at the northbound frontage road and the eastbound movement through both intersections is shown in Figure 6.10 and Figure 6.11, respectively.

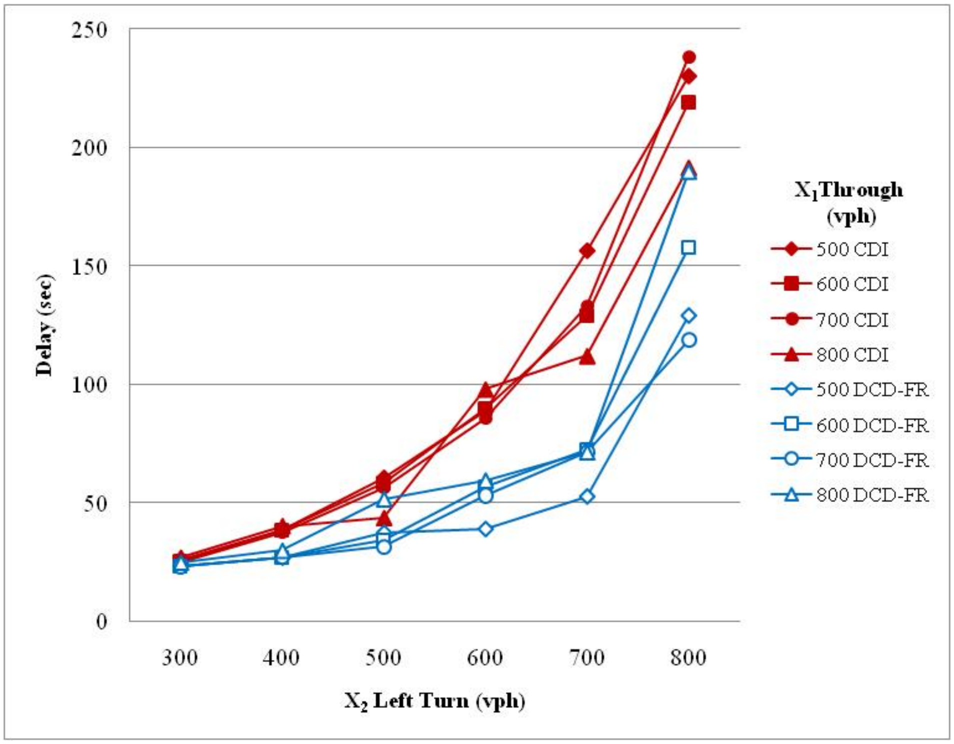

Figure 6.10: Average Section Delay of Eastbound Movement Turning Left at the East Intersection.

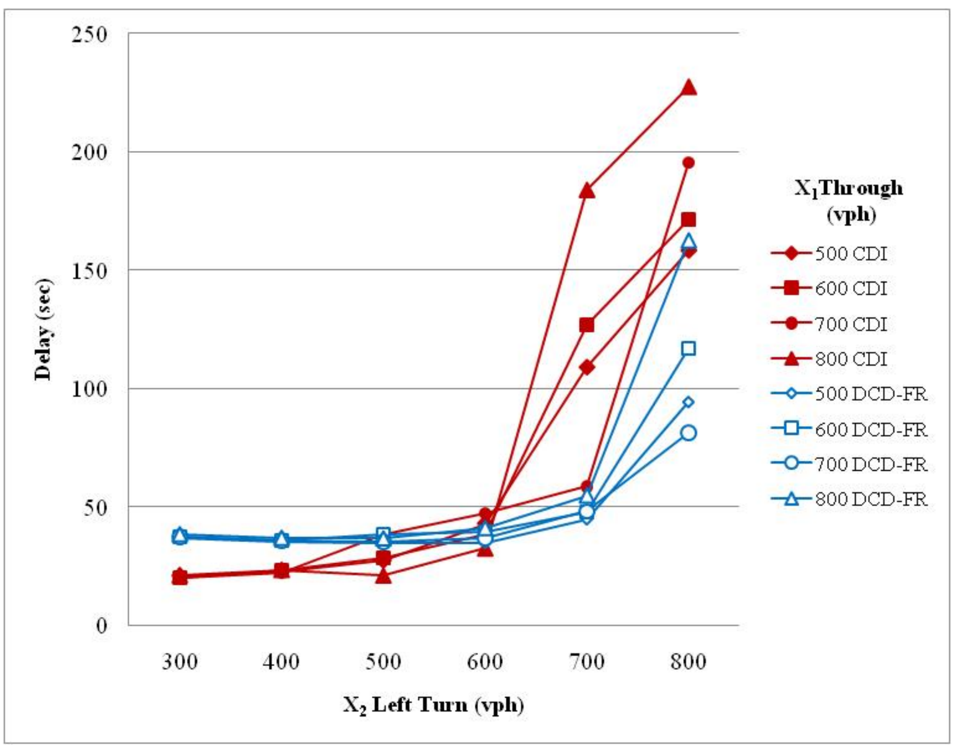

Figure 6.11: Average Section Delay of Eastbound Through Movement.

Once again, the conflicts occurring at the eastbound direction is shown in both figures. Figure 6.10 shows the effect of conflicts occurring at the left-turn pocket while Figure 6.11 depicts the effect of the conflicts after crossing the northbound intersection (lane merging). Nevertheless, the proposed DCD-FR design still shows less delay when compared to the CDI in Figure 6.10.

The results illustrated on Figure 6.11 reflect a similar pattern for the westbound vehicles. Once again, the curvature of the DCD-FR makes the CDI, at low volume, has slightly lower section delay better than the DCD-FR. Yet, for the most part the DCD-FR has less delay than the CDI.

Figure 6.12 illustrates the travel time section that corresponds to the northbound frontage road turning left to continue westbound. As expected, the results shown in Figure 6.12 depict a significant decrease in delay with the proposed DCD-FR design. The DCD-FR keeps a consistent delay along this route.

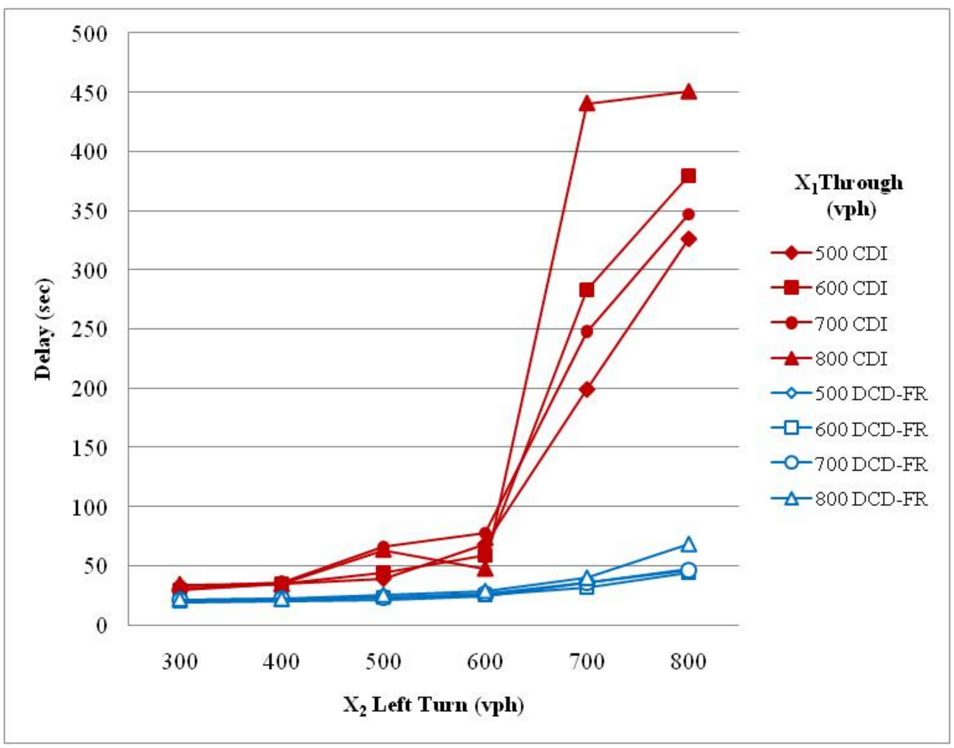

Figure 6.12: Average Section Delay of Northbound Movement Turning Left at the East Intersection.

The final segment analyzed was the southbound direction making a left-turn to continue east. The delay results for this section are illustrated in Figure 6.13.

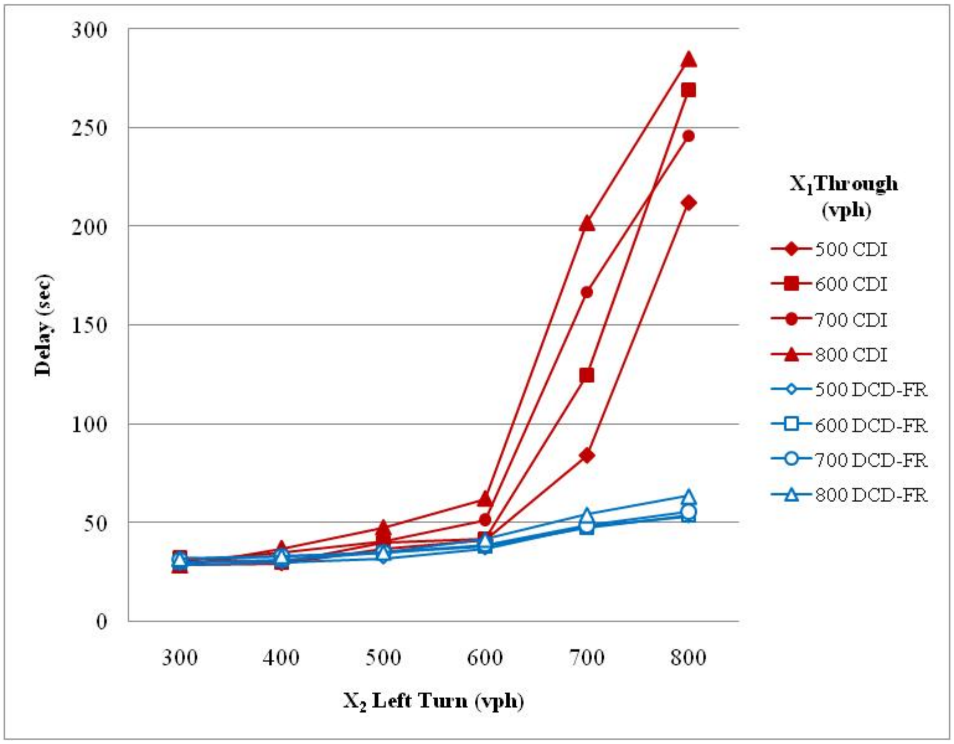

Figure 6.13: Average Section Delay of Southbound Movement Turning Left at the West Intersection.

This segment shows similar traffic behavior as the northbound frontage road making it clear that the proposed left-turn design for the DCD-FR has an advantage over the CDI. Moreover, the pattern seen on Synchro and on the travel time sections is present in the CDI when the left-turn volume is of 600 vph or higher.

6.3 Network Performance Parameters

VISSIM provides users with a good indicator of the performance of the complete network. This indicator is found under the Network Performance output. Certain parameters can be selected to evaluate the overall performance of all vehicles loaded to the coded network. In this case, the total travel time, total delay and number of stops was selected for analysis. It is important to mention that this output takes into consideration everything that is happening for the complete 3600-second simulation period. For instance, if one movement is experiencing high travel time or queue and another movement is at free

flow conditions it will not be reflected specifically. VISSIM will calculate the average MOE from every vehicle that is present in the network for the specified simulation time.

The first calculated MOE is the total travel time of both interchange designs. Table 6.1 specifies the average output result for each scenario.

Table 6.1: Total Network Travel Time Results.

Total Travel Time (hr)			
Through Volume (vph)	**Left-Turn Volume (vph)**	**CDI**	**DCD-FR**
500	300	189.31	191.49
	400	202.88	201.37
	500	221.12	212.84
	600	280.78	224.25
	700	442.20	242.60
	800	589.54	275.89
600	300	199.69	201.68
	400	213.49	211.72
	500	240.19	224.44
	600	279.37	238.57
	700	571.55	255.63
	800	729.39	292.73
700	300	210.29	211.95
	400	224.74	222.05
	500	279.25	233.13
	600	312.81	247.49
	700	505.36	266.83
	800	759.52	295.22
800	300	220.42	222.42
	400	236.00	232.61
	500	258.85	245.72
	600	285.00	260.39
	700	840.03	282.23
	800	966.17	346.46

It can be quickly identified that the new DCD-FR design has an overall better performance. The average total travel time of the DCD-FR is less than the total travel time experienced in the CDI.

The second parameter calculated by VISSIM is the total delay. As opposed to the travel time sections and movement delay, the total delay is not dependent of the total travel time shown in Table 6.1. Keep in mind that all vehicles, including movements beyond the interchange of before the interchange are tabulated in the output calculated by VISSIM. Table 6.2 shows the different delay experienced by all vehicles loaded to both interchange designs.

Table 6.2: Total Network Delay Results.

Total Delay Time (hr)			
Through Volume (vph)	**Left-Turn Volume (vph)**	**CDI**	**DCD-FR**
500	300	22.31	24.12
	400	27.39	25.39
	500	37.56	28.27
	600	95.76	31.24
	700	265.58	41.21
	800	413.11	68.24
600	300	24.01	25.67
	400	29.27	26.99
	500	49.58	31.18
	600	83.64	36.80
	700	400.20	45.71
	800	556.46	76.96
700	300	25.89	27.20
	400	31.96	28.73
	500	83.27	31.08
	600	110.91	37.06
	700	311.14	48.32
	800	581.60	69.88
800	300	27.31	29.02
	400	34.50	30.44
	500	49.69	35.68
	600	68.46	41.35
	700	679.00	55.19
	800	806.05	114.77

Once again, the proposed design of the DCD-FR shows a significant reduction in delay as compared to the CDI. This was expected due to the free left-turn movements that are associated with the DCD-FR design.

Finally, shown in Table 6.3 is the last MOE that was calculated from the complete networks, the number of stops. This parameter indicates the average total number of stops experienced by all vehicles

that entered the simulation model. The number of stops goes in hand with the total delay that was calculated and has also an impact on the travel time. In essence, the fewer number of stops the less delay vehicles will experience.

Table 6.3: Number of Stops Results.

Number of Stops			
Through Volume (vph)	**Left-Turn Volume (vph)**	**CDI**	**DCD-FR**
500	300	2,645	2,913
	400	3,137	3,010
	500	4,014	3,252
	600	8,588	3,525
	700	24,368	4,211
	800	42,539	6,626
600	300	2,848	3,101
	400	3,338	3,215
	500	4,899	3,511
	600	7,893	3,918
	700	37,080	4,631
	800	56,180	7,864
700	300	3,065	3,304
	400	3,654	3,422
	500	7,736	3,619
	600	10,545	4,140
	700	31,788	4,933
	800	57,144	7,041
800	300	3,253	3,428
	400	3,921	3,551
	500	5,786	4,019
	600	7,272	4,430
	700	62,052	5,273
	800	77,217	10,984

The number of stops experienced by all vehicles in the simulation is fewer in the proposed DCD-FR model. Since in the CDI vehicles have to wait for a signal phase to turn green or find a gap while the through movement is green, more stops are associated with this left-turn movement.

Overall, the calculated network parameters indicate that as a whole, the proposed DCD-FR design has a better traffic performance than the CDI.

Chapter 7: Conclusions, Contributions and Future Research

7.1 Conclusions

The objective of this research is to propose and test the functionality of the DCD-FR against the typical design of the CDI. A particular intersection found in El Paso, Texas was replicated with the use of VISSIM. Once the network was created and calibrated several traffic scenarios were developed and optimized to compare the CDI with the DCD-FR designs and to determine the operational efficiency of each design. Each scenario was first coded in Synchro 7.0 in order to optimize the cycle length and phase splits. Intersection LOS and average intersection delay was estimated by Synchro. In addition, once the signal timing plan of every single scenario was optimized, the timing plan was transferred to VISSIM to have a more detailed comparison on the average section travel times. The model used in VISSIM was first calibrated to ensure proper results would be generated. In VISSIM, section travel time and section delay was calculated as well as an evaluation of the complete network performance. Each scenario was simulated for ten random seeds for a 3600-second period. The average of the ten random seeds was calculated and used as the final output for analysis.

After comparing the performance measures of the interchanges under different volume scenarios, the following conclusions are established:

- The modification of the DCD-FR to include the through movement on frontage road is a feasible option. In this case, for two intersections are 320 feet apart (center to center).
- The proposed three-phase DCD-FR signal timing plan shows to have better overall performance benefits than the CDI, specifically for the left-turn movements. In addition, the optimized cycle lengths were shorted than the CDI.
- The DCD-FR showed lower average intersection delays and better or equal LOS under all traffic scenarios.
- For scenarios with medium left-turn volume, from 300 to 600 vph, both the CDI and DCD-FR models tend to behave fairly reasonable.

- For scenarios where the left-turn traffic is above 600 vph the CDI experiences unstable flow (LOS E or lower) while the DCD remains at a stable flow (LOS C or better).

7.2 Research Contributions

The contributions of this research are summarized in the following list:

- This research is the first to experiment with DCD with frontage roads accounting for through movements.
- This research proposes the three-phase signal design for the DCD-FR.
- This research has demonstrated that the DCD-FR improves the traffic operations compared with the CDI in terms of intersection LOS, average intersection delay, section travel times and delay, and network performance.
- The DCD-FR may be used by engineers in states that have freeway frontage roads (i.e. Texas and Minnesota) when considering interchange design.

7.3 Future Research

The presence of pedestrians may modify the operations of the DCD-FR and should be studied in more detail. In addition, further work is needed to model different traffic scenarios with higher volume or unbalanced volume, and different lane configuration (i.e. four-lane or six-lane). Moreover, a quantitative measure of the construction and right-of-way costs encompassed with the DCD-FR should be investigated. Furthermore, a Synchro software model that can accommodate the use of shared through and left-turn movements in the DCD-FR.

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Curriculum Vita

Jorge A. Martinez was born in El Paso, TX. He graduated from the University of Texas at El Paso in 2008 with a Bachelors of Science in Civil Engineering and then completed his Master's Degree in Civil Engineering in 2010. During his Bachelor's Degree he worked as a Research Assistant in the Laboratory for Advanced Dynamic Transportation and Urban Systems under the supervision of Dr. Yi-Chang Chiu. In addition, he then worked as a Research Assistant in the Border Intermodal Gateway Transportation Laboratory under the supervision of Dr. Kelvin Cheu. After completing his Bachelor's Degree he started his Master's Degree full time while working as an intern with Walter P. Moore and Associates. While in school, Mr. Martinez participated in different organizations such as Chi Epsilon Civil Engineering Honor Society, the Institute of Transportation Engineers (ITE) Student Chapter and the Civil Engineering Senior Class Organization (CESCO). He served as the Treasurer for Chi Epsilon and Vice-President for ITE Student Chapter. In addition, he was the President of CESCO for one semester. Mr. Martinez received different scholarships during his studies which include the Dwight D. Eisenhower Transportation Fellowship, the Louis Stokes Alliances for Minority Participation, and the Bridge to the Doctorate scholarship. Furthermore, Mr. Martinez joined a team formed by students from the University of Texas at El Paso and a Chinese research center, and obtained the bronze medal at the Daimler-UNESCO Mondialogo Engineering Awards 2010 in Stuttgart, Germany.

Permanent address: 6184 Thunder River Pl

El Paso, TX. 79932

This thesis was typed by Jorge Alberto Martinez.