Southwest Region University Transportation Center

Fuel Savings from Free U-Turn Lanes at Diamond Interchanges

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16. Abstract

The vehicle emission simulation feature of the TEXAS (Traffic Experimental Analytical Simulation) Model for Intersection Traffic in its Version 3.2 was used to demonstrate the potential fuel savings that can be realized from the provision of free u-turn lanes at diamond interchanges. More than 2000 runs of the model were made to compare the estimated amount of fuel consumed by u-turning vehicles using a free u-turn lane with that consumed by a similar number of such vehicles reversing direction through the two closely-spaced intersections of this type interchange. The observed traffic, geometric configuration, and traffic signal control at six existing diamond interchanges in Texas served as the basis for case studies in this research. Each interchange was evaluated over a range of traffic volumes and u-turn demand scenarios with, and without, free u-turn lanes.

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FUEL SAVINGS FROM FREE U-TURN LANES

AT DIAMOND INTERCHANGES

by

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DISCLAIMER

EXECUTIVE SUMMARY

There are hundreds of diamond interchanges operating in the State of Texas. This interchange configuration gets its name from the geometric diamond shape of the diagonal ramps connecting the freeway lanes to the crossing roadway at two closely-spaced intersections. The geometric configuration of diamond interchanges normally requires u-turning vehicles to pass through both intersections, making a left turn at each, in order to reverse direction. It is usually difficult to provide traffic signal plans that will accommodate a heavy u-turn traffic volume between the diagonal ramps on the same side of the interchange along with the other straight, left-turn, and right-turn movements. Consequently, traffic congestion, delay, wasted-time, pollution, and excessive fuel consumption frequently result from the u-turns being made through the two intersections. An alternative method of handling u-turning vehicles at diamond interchanges is the provision of separate free u-turn lanes in advance of the crossing roadway. Free u-turn lanes remove u-turning vehicles from the intersection demand and shorten their travel distance, thereby reducing delay, pollution, and fuel consumption at diamond interchanges.

The main objective of this study was to investigate any potential fuel savings that might be realize from the provision of free u-turn lanes at diamond interchanges. The emission processor of the TEXAS (Traffic EXperimental Analytical Simulation) Model for Intersection Traffic in its Version 3.2 (January 1993), a powerful simulation tool which allows the user to evaluate in detail the complex interaction among individually-characterized driver-vehicle units as they operate in a defined intersection environment under a specified type of traffic control, was used as the principal estimation tool for the research. Six diamond interchanges, with and without free u-turn lanes, were selected as case studies. Field surveys were made to gather information about the existing geometry, traffic volumes, and signal timing at each site. The observed signal timing at each diamond interchange was used throughout a series of more than 2000 runs of the TEXAS Model to examine fuel consumption by various combinations of vehicles using the interchanges in two experiments.

In one experiment, three levels of traffic demand volume on each external approach were used: high (observed level of traffic volume for the majority of the case studies), medium (70% of the observed traffic volume), and low (50% of the observed traffic volume). The u-turn demand volume was simulated as a percentage of the respective approach volume, and was held constant at the percentage observed in the field on each external approach during peak-hour traffic. For the other experiment, the high traffic volume (observed) was used for each external approach, and three levels of u-turn demand were simulated: low (10%), medium (20%), and high (30%). Each interchange was studied with and without free u-turn lanes.

The results of the experiments showed that the amount of fuel consumed by u-turning vehicles using a free u-turn lane is significantly less than that used by turning vehicles going through the two intersections of a diamond interchange. U-turning vehicles using a free u-turn lane typically consume about 60 to 80 percent less fuel, on average, than when traveling through the two intersections. This is partially due to the fact that vehicle drivers using a free u-turn lane can travel near their desired speed without incurring deceleration, idling, and acceleration caused by traffic signal control and by interaction with other vehicles.

Fuel consumed by u-turning vehicles going through the two intersections of a diamond interchange increased significantly as the total traffic demand increased. Similarly, the fuel consumed by these vehicles increased as the u-turn demand percentage increased. Traffic signal settings had a definite influence in these situations. Conversely, the average amount of fuel consumed by u-turning vehicles using a free u-turn lane was not affected markedly by changes in the overall traffic volume demand conditions, the percentages of u-turn demand, or by the traffic signal settings. However, the simulation results showed that fuel consumed by vehicles on a free u-turn lane varied among the different case studies, depending mostly upon the length of the free u-turn lane.

In addition to the fuel savings that can possibly be realized from providing free u-turn lanes at a diamond interchange, overall operational conditions can be improved. When free u-turn lanes were added, the total traffic volume processed on the inbound approach was higher. Another advantage of free u-turn lanes was the reduction of total delay and travel time for u-turning vehicles.

The capacity of a diamond interchange to process high u-turn demand through the two intersections is limited significantly by the traffic signal control. Signal settings must be adjusted to accommodate changes in u-turn demand. This is usually impractical to implement in a timely way. But, free u-turn lanes can handle large fluctuations in u-turn demand without affecting the normal operation of the two diamond interchange intersections.

Free u-turn lanes can be a desirable feature for diamond interchanges in many cases. The TEXAS Model for Intersection Traffic, Version 3.2 can be applied for comparing the relative effectiveness of specific alternative designs in terms of their potential traffic performance, fuel consumption, and vehicle emissions.

ABSTRACT

The vehicle emission simulation feature of the TEXAS (Traffic EXperimental Analytical Simulation) Model for Intersection Traffic in its Version 3.2 was used to demonstrate the potential fuel savings that can be realize from the provision of free u-turn lanes at diamond interchanges. More than 2000 runs of the model were made to compare the estimated amount of fuel consumed by u-turning vehicles using a free u-turn lane with that consumed by a similar number of such vehicles reversing direction through the two closely-spaced intersections of this type interchange. The observed traffic, geometric configuration, and traffic signal control at six existing diamond interchanges in Texas served as the basis for case studies in this research. Each interchange was evaluated over a range of traffic volumes and u-turn demand scenarios with, and without, free u-turn lanes.

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CHAPTER 1. INTRODUCTION

There are hundreds of diamond interchanges operating in the State of Texas. This interchange configuration gets its name from the geometric diamond shape of the diagonal ramps connecting the freeway lanes to the crossing roadway at two closely-spaced intersections. The geometric configuration of diamond interchanges normally requires u-turning vehicles to pass through both intersections, making a left turn at each, in order to reverse direction. It is usually difficult to provide traffic signal plans that will accommodate a heavy u-turn traffic volume between the diagonal ramps on the same side of the interchange along with the other straight, left-turn, and right-turn movements. Consequently, traffic congestion, delay, wasted-time, pollution, and excessive fuel consumption frequently result from the u-turns being made through the two intersections. An alternative method of handling u-turning vehicles at diamond interchanges is the provision of separate free u-turn lanes in advance of the crossing roadway. Free u-turn lanes remove u-turning vehicles from the intersection demand and shorten their travel distance, thereby reducing delay, pollution, and fuel consumption at diamond interchanges.

A methodology that engineers can use during planning, design, and operational-analysis to demonstrate the potential fuel savings that can be realized from providing free u-turn lanes at diamond interchanges is described herein. The TEXAS (Traffic EXperimental Analytical Simulation) Model for intersection traffic in its Version 3.2 (January 1993) [Refs. 1, 2] is used as the main tool for developing the methodology. Four representative diamond interchanges in the Austin area and two diamond interchanges in El Paso, Texas comprise six case studies for the experiment around which the methodology is developed and demonstrated. The fuel consumed by u-turning vehicles is evaluated over a range of traffic volumes, interchange geometric arrangements, and pretimed signal control.

1.1 BACKGROUND

1.1.1 Overview of the Fuel Consumption Problem

The United States transportation sector is almost totally dependent on petroleum-based fuels. More than 96 percent of the energy consumed in transportation comes from petroleum, which represents two-thirds of the total petroleum consumed in the nation [Ref. 3]. Highway networks account for nearly three-fourths of the total transportation energy used with about 80 percent by automobiles, light trucks, and motorcycles, and about 20 percent by heavy trucks and buses. The United States is heavily dependent on imported oil, nearly half of all petroleum consumed in the nation comes from foreign sources. The implications of this dependence became significant during the Arab oil embargo in 1973-1974, and the Iranian revolution in 1979. The unprecedented oil price increases and the market dislocations that accompanied them spurred major efforts in the industrialized world to reduce energy consumption, increase energy efficiency, and develop alternative energy sources.

As a result, the transportation sector has implemented several innovative projects to conserve energy and to improve air quality in major urban areas. The concept of transportation system management (TSM) has evolved to combat traffic congestion, improve air quality, and conserve energy by maximizing transportation system efficiency. TSM conservation energy measures include projects to increase vehicle occupancy, increase vehicle efficiency, system flow improvements, and alternative fuels use. Strategies to increase vehicle occupancy focus on promoting rideshare by transit services, implementation of carpools or vanpools, construction of exclusive lanes for high-occupancy vehicles (HOV), and others. Among the system flow improvements to conserve energy are optimization of traffic signal timing, increased capacity of existing facilities, improved intersection channelization, and telecommuting. In addition to the favorable impacts on the nation's fuel economy from implementation of these projects, average fuel economy has increased significantly as old vehicles have been replaced by new ones with more fuel-efficient engines. Since 1974, the average new car travels more than 10 miles farther on a gallon of fuel, and trucks transport the same number of ton-miles of freight on 20 percent less fuel [Ref. 4].

Despite the efforts to conserve energy, the transportation sector has failed to reduce its dependence on petroleum fuels as its main energy source. In 1973, transportation accounted for 51 percent of domestic oil consumption; by 1988 this figure had risen to 63 percent, an amount 23 percent greater than the U.S. oil production in that year. This shortfall is projected to increase to 41 percent in 2000 [Ref. 4]. As the number of vehicles on the highways increases, the domestic oil production declines, and the United States depends more on imported oil, the trend of energy consumption in transportation is becoming increasingly serious. Energy conservation may be the only feasible near-term alternative for reducing transportation oil consumption and US vulnerability to a disruption in oil supply. Furthermore, because transportation vehicles are major sources of urban congestion, pollution, and so-called greenhouse gases [Refs. 5, 6], saving energy in transportation has important social, economic, and environmental benefits.

As long as the main energy source for the transportation system is petroleum, energy conservation in the system will be a major national concern. The U.S. Department of Energy encourages states and localities to develop new transportation strategies for conserving energy. The task of transportation engineers is to develop efficient strategies to reduce fuel consumption.

Existing transportation facilities are being evaluated to identify sources of excessive fuel consumption. Furthermore, nationwide energy conservation programs to decrease fuel use are being implemented. As a consequence, practicable methodologies that engineers can use during planning, design, and operational-analysis to identify potential savings in fuel consumption and vehicle emissions by transportation are needed.

Traffic flow modeling and computer simulation provide a convenient tool for traffic engineers to analyze operation of the transportation system without costly, time-consuming field surveys. Currently, several traffic flow computer simulation programs feature fuel consumption and emission models among their features. Some of these models are PASSER II, NETSIM, MOBILE, and the TEXAS Model. In the study described herein, the emission simulator of the microscopic traffic simulation model, TEXAS Model for Intersection Traffic [Refs. 7, 8], is used to demonstrate the potential fuel savings that can be realized from the provision of free u-turn lanes at diamond interchanges.

1.1.2 Structure of the TEXAS Model

The TEXAS Model for Intersection Traffic is a powerful simulation tool which allows the user to evaluate in detail the complex interaction among individually-characterized driver-vehicle units as they operate in a defined intersection environment under a specified type of traffic control. The model performs microscopic simulation of traffic flow for both single intersections and diamond interchanges. The model allows its user to evaluate single-intersection and diamond-interchange performance under various geometric lane arrangements, traffic controls, and traffic demands. The TEXAS Model includes three data processors: GEOPRO (Geometry), DVPRO (Driver-Vehicle), and SIMPRO (Simulation). GEOPRO and DVPRO describe the geometric configurations, and the stochastically arriving traffic and the behavior of traffic in response to the applicable traffic controls. SIMPRO integrates all the defined elements and computes deterministically the response of each driver-vehicle unit.

GEOPRO defines the geometry of the intersection in the computer. It calculates vehicle paths along the approaches and within the intersection. The number of intersection legs, together with their associated number of lanes and lane widths, define the intersection size and the location of any special lanes. The azimuth for each leg and the associated coordinates define the shape of the intersection. The allowed directional movements of traffic on the inbound approaches and the allowed movements on outbound lanes define the directional use of the intersection.

DVPRO utilizes certain assigned characteristics for each class of driver and vehicle and generates attributes for each individual driver-vehicle unit. Each unit is characterized by inputs concerning driver class, vehicle class, desired speed, desired outbound intersection leg, and lateral lane position on the inbound leg. All these attributes are generated by a uniform probability distribution, except for the desired speed which is defined by a normal distribution. Each unit is sequentially ordered by queue-in time as defined by the input of a user-selected headway distribution. The total number of driver-vehicle units which must be generated by DVPRO is determined by the product of the input traffic volume, in vehicles per hour, and the minutes of time to be simulated.

SIMPRO simulates the traffic behavior of each unit according to the momentary surrounding conditions including any traffic control device indications which might be applicable. The premise is that each simulated driver will attempt to maintain safety and comfort while sustaining a desired speed and obeying traffic laws. At any time, a unit may maintain or change speed and retain or change lanes depending on the relative positions and movements of neighboring units and the effects of applicable traffic control devices. The instantaneous traffic behavior of each unit including speed, location, and time are recorded by the model for subsequent use in the emission processor (EMPRO). Statistics about the delays and queue lengths are also gathered by the model to evaluate the performance of the intersection.

A unique feature of the TEXAS Model is its vehicle emission post-processor, EMPRO [Refs. 7, 8]. EMPRO computes estimates of vehicle emissions and fuel consumption to help the user quantify the effects of the intersection geometry, traffic control, and traffic flow on vehicle emissions and fuel consumption. It incorporates models to predict the instantaneous vehicle emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and fuel flow (FF) for both light-duty vehicles and heavy-duty vehicles. EMPRO utilizes information from SIMPRO about the instantaneous speed and acceleration of each vehicle to compute instantaneous vehicle emissions and fuel consumption at all points along the vehicle path. For evaluation purpose, each lane on each approach is partitioned into a series of buckets, and the emissions and fuel flow are accumulated on a bucket basis to show the spatial variation of emissions and fuel consumption with respect to time. The intersection proper is treated as one bucket, which collects the emissions and fuel consumption values generated by vehicles crossing it from all approaches.

The TEXAS Model uses the emission models for CO, HC, NOx and CO_2 developed by the Environmental Protection Agency (EPA) for light-duty vehicles, referred to as the Modal Analysis Model. The models are represented in quadratic form of speeds for a steady state of vehicle motion, and in quadratic form of speed and acceleration for transient states. The fuel consumption model is expressed as a linear function of the amounts of HC, CO, and CO_2 emitted. The emission and fuel consumption models for heavy-duty vehicles use functions of engine performance, (engine torque and engine speed). EMPRO incorporates a subprogram that relates vehicle performance to engine performance for heavy-duty vehicles to estimate emissions and fuel consumption. These models were developed using experimental data. Development involved the combination of rational approximations of vehicle dimensions and operational characteristics with empirical data on engine performance. A detailed description of the emission and fuel consumption models used by EMPRO is described in references mentioned above.

A data file called POSDAT is needed for the TEXAS Model to run EMPRO. The POSDAT file is produced by the SIMPRO processor, and it contains detailed vehicle position data for every vehicle per unit of time. EMPRO uses POSDAT to calculate instantaneous vehicle speed, acceleration, and deceleration, which are the most important variables needed to predict vehicle emissions and fuel consumption by the TEXAS Model.

Among the output statistics produce by the TEXAS Model are speed, acceleration, delay and travel time for each individual vehicle along their travel path through an intersection or diamond interchange. The model also includes animated-graphics screen displays to assist the user in identifying any situation that may cause operational inefficiencies. This animated-graphics screen, along with statistics about fuel consumption and other measures of effectiveness produced by the model, provide a strong quantitative basis for evaluating and comparing the operational characteristics of intersections and diamond interchanges, and for demonstrating actual or potential energy savings.

1.2 PROBLEM STATEMENT

Excessive fuel is consumed in the vicinity of intersections due to the deceleration, idling, and acceleration of vehicles caused by geometric features and traffic controls. The current study addresses the problem of fuel consumption by u-turning vehicles at diamond interchanges. The geometric configuration of diamond interchanges normally requires u-turning vehicles to pass through two closely-space intersections, making a left turn at each, in order to reverse direction, Figure 1.1. This maneuver results in an additional amount of fuel being consumed by u-turning vehicles compared with the other straight, left, and right turn movements at a diamond interchange. Free u-turn lanes provide the turning vehicle with a smooth travel path as it reverses direction at the interchange, thereby reducing the incidence of sharp accelerations and rapid braking, and can potentially reduce fuel consumption at diamond interchanges.

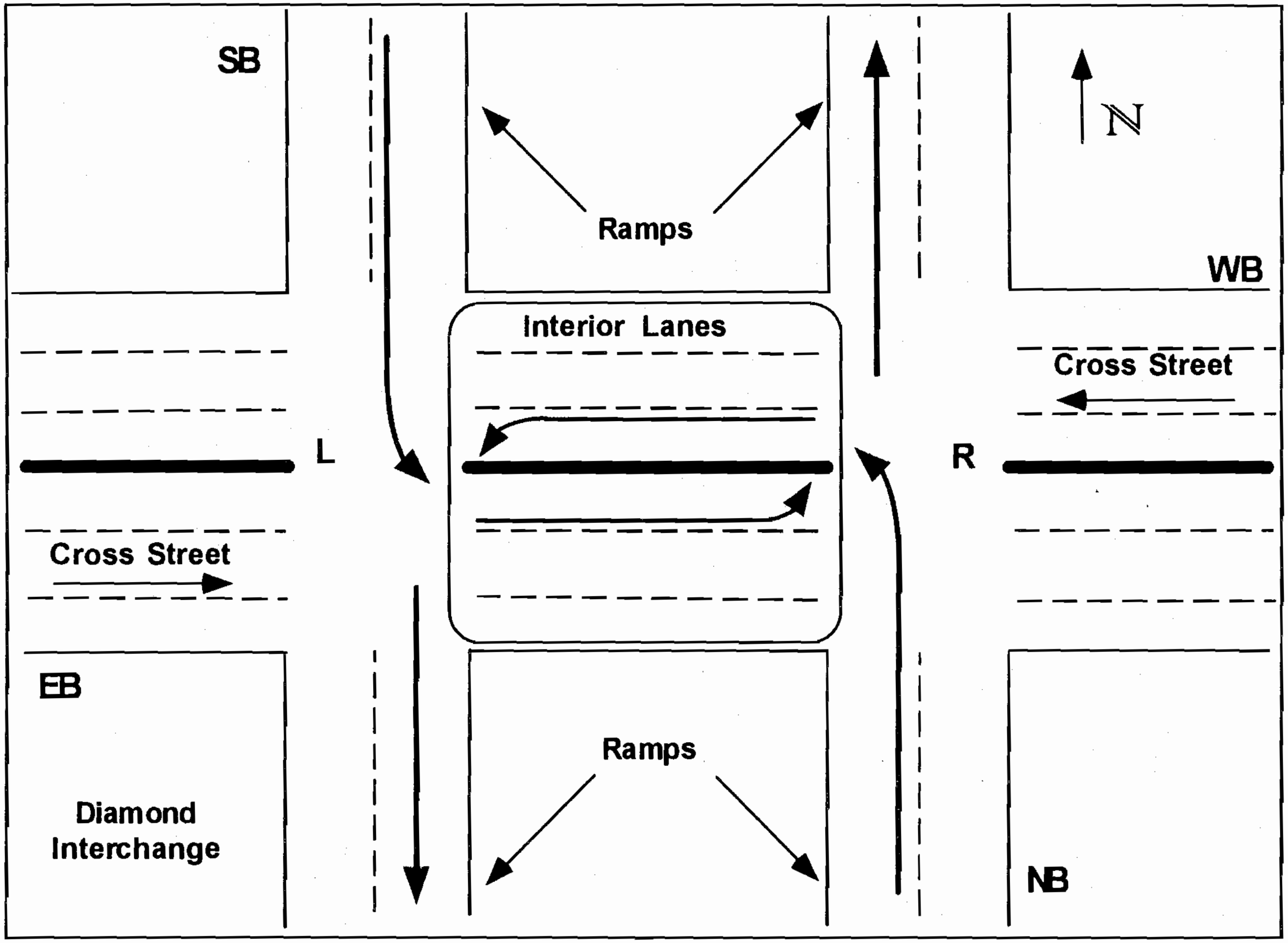

Figure 1.1 Path of u-turning vehicles going through the two intersections of a diamond interchange

As discussed previously, fuel consumption is a subject of continuous concern for governmental agencies as well as for communities in general, because of its direct relation to the demand and supply of energy. Congested urban areas are inherently a source of high energy consumption. Fuel consumed by vehicles can be represented by three components: (a) fuel consumed by vehicles traveling at a steady speed, (b) fuel consumed during speed-change cycles, which is the additional fuel consumed by vehicles slowing down and then returning to initial speed, and finally (c) the fuel consumed by vehicles while idling [Refs. 9, 10, 11]

Vehicles traveling at a steady speed experience better fuel economy than vehicles that experience speed-change cycles due to high traffic volume and traffic control at intersections. Sharp accelerations from passing or changing lanes, merging onto freeways from ramps, or leaving a signalized intersection impose heavy loads on the engine that result in excessive fuel consumption. Previous research has shown that repeated braking can account for as much as 15 percent of the fuel consumed during an urban driving trip. Also it had been estimated that, in a congested urban environment, aggressive driving with rapid accelerations can result in a 10 percent increase of fuel consumption [Ref. 3]. Furthermore, a vehicle that stops at a red traffic signal, idles for 30 seconds while waiting for the indication to change, and then accelerates to resume a speed of 60 km/h, uses about 70 milliliters more fuel than a vehicle which passes through the signal at a constant speed of 60 km/h [Ref. 9].

As u-turning vehicles approach a signalized diamond interchange without free u-turn lanes, they might decelerate to a complete stop at the first intersection with a red signal indication, idle the engine while waiting for a green signal, and then accelerate to cross the intersection. Before the vehicle reaches a desired speed, it might decelerate to perform a left turn at the second intersection, and then accelerate again to resume a desired speed for the completion of the maneuver. If adequate traffic signal progression between the two closely-spaced intersections is not provided, u-turning vehicles may undergo an additional cycle of deceleration, idling, and acceleration at the second intersection before the completion of the u-turn maneuver. This repeated cycle results in excessive fuel consumption for every u-turning vehicle, thus increasing the overall energy consumption at a diamond interchange. In the case of diamond interchanges controlled by stop signs, u-turning vehicles perform the same maneuvers as in the case of a signalized diamond interchange except that every vehicle is required to respond to the stop signs.

At a diamond interchange with free u-turn lanes, the u-turn maneuver is described as follows. The u-turning vehicle enters the free u-turn lane at a desired approach speed and continues to travel along the special lane, attempting to keep a constant speed. At the exit end of the lane, the vehicle either decelerates or stops, and then accelerates to a desired speed for completion of the maneuver. Figure 1.2 shows the u-turn maneuver through a free u-turn lane at a diamond interchange. The main part of u-turn maneuver can be performed without waiting for a green signal phase to cross the interchange or interacting with other traffic on conflicting paths. Free u-turn lanes potentially reduce the number of stops and the acceleration of u-turning vehicles, and thereby reduce the travel time, delay, and increase the overall capacity of a diamond interchange.

Although reduction of travel time and delay are expected from free u-turn lanes at diamond interchanges, no known attempt has been made previously to quantify the potential fuel savings that can be realized from the provision of these exclusive lanes. Traffic simulation computer models, such as the TEXAS Model, provide a powerful tool to aid in estimating vehicle fuel consumption. The subject of this study is the evaluation of traffic operations when free u-turn lanes are provided, and estimation of potential fuel savings that might be realized from the provision of such lanes at diamond interchanges.

1.3 OBJECTIVE

The main objective of this study was to estimate any potential fuel savings that might be realize from the provision of free u-turn lanes at diamond interchanges. The emission processor of the TEXAS Model was used to aid in this objective. A series of simulation experiments were developed to evaluate the u-turn characteristics at existing diamond interchanges. The objectives of the experiments were:

- To estimate the fuel consumed by u-turning vehicles at a diamond interchange without free u-turn lanes, and compare it with the fuel consumed by u-turning vehicles at the same diamond interchange provided with free u-turn lanes.
- To analyze the influence of the traffic flow conditions on the fuel consumed by u-turning vehicles at diamond interchanges.
- To analyze the fuel consumption of u-turning vehicles when the demand for u-turn traffic increases, and
- To analyze the operational characteristics of free u-turns, such as reduction in delays, reduction of vehicle travel time, and increase of diamond-interchange capacity.

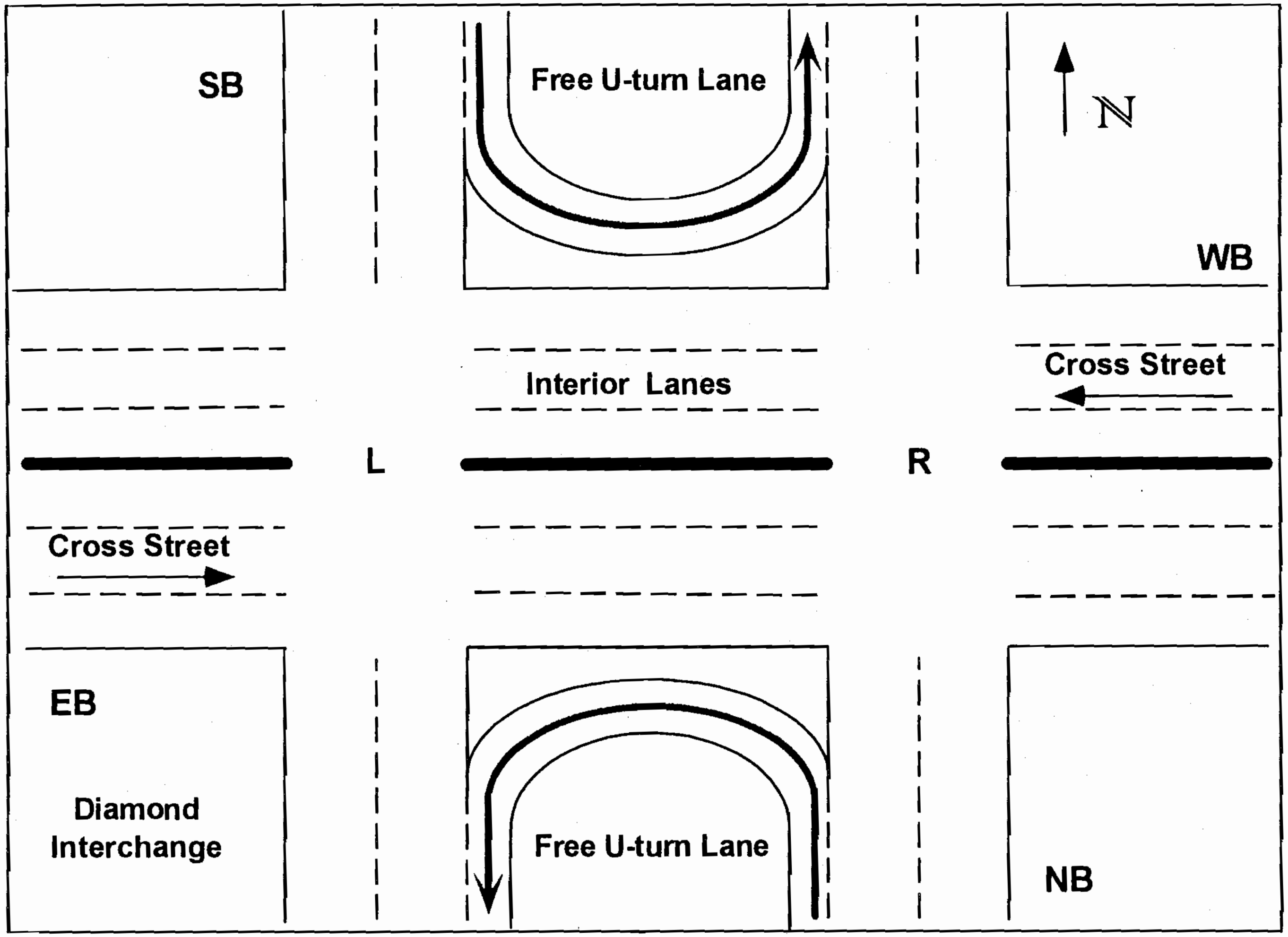

Figure 1.2 Path of u-turning vehicles going through a free u-turn lane at a diamond interchange

1.4 SCOPE OF THE STUDY

The scope of this study is to:

- Estimate the fuel consumption of u-turning vehicles at six case-study diamond interchanges,
- Estimate fuel consumption based on the output statistics of the TEXAS Model emission processor,
- Evaluate the effectiveness of pre-timed signal control at diamond interchanges in the series of case studies, and
- Use the existing traffic signal phasing plan at the selected interchanges in all experiments.

1.5 SIGNIFICANCE OF THE STUDY

The imminent fuel price increase and the scarcity of petroleum oil resources are motivation for traffic engineers and governmental agencies to encourage conservation of this product. It is urgent for the engineering community to evaluate their projects in terms of potential fuel savings. A reliable methodology for quantifying fuel consumption associated with current or proposed projects is needed. Several emissions and fuel-consumption simulators are available to aid transportation engineers in this effort.

In this study, the TEXAS Model for Intersection Traffic was used to evaluate free u-turn lanes at diamond interchanges and their potential benefits on fuel savings. In Texas there are a large number of diamond interchanges that handle high traffic volume daily resulting in a source of high fuel consumption. The provision of free u-turn lanes may significantly reduce the fuel consumption at a diamond interchange and improve overall interchange capacity. Such benefits can potentially justify the additional construction cost of free u-turn lanes.

CHAPTER 2. METHODOLOGY

2.1 SELECTION OF CASE STUDIES

Visits were made to sites in Austin and El Paso, Texas to identify representative diamond interchanges for the development of this research. The large number of diamond interchanges in these cities offered an ample range of alternatives for the selection of case studies.

It was observed that generally the operational characteristics of diamond interchanges were similar. However, the geometry, traffic flow, and the surrounding conditions varied; this made each diamond interchange an exclusive case study. Among the most important characteristics of diamond interchanges observed in the field were the following.

- Size of the diamond interchange - including the length of the interior lanes, number of approach lanes, lane width, median size, and curb radius.
- Geometric design - including the provision of free u-turn lanes, exclusive right-turn lanes, left-turn bays, and at-grade or elevated intersections.
- Traffic flow characteristics - including traffic volume, distribution of traffic movements, composition of traffic, and traffic control characteristics.
- Location and surrounding characteristics - this was influenced by whether the diamond interchange was located in a rural or urban area, or in a highly-developed or undeveloped area, or a commercial or residential area.

These characteristics were the basic criteria for the selection of case study diamond interchanges.

After studying the characteristics of several diamond interchanges, six interchanges were selected as representative case studies for the experiment. A variety of geometry, traffic flow, and surrounding characteristics are represented among the selected cases. All case studies are at signalized diamond interchanges. The selected case studies are listed in Table 2.1 at the end of this section. Figure 2.1 and Figure 2.2 are the maps of Austin and El Paso, Texas showing the geographical locations of the case studies. The case studies are described later in this chapter.

2.2 FIELD DATA COLLECTION

Once the case study sites were selected, the next step was to get detailed information about the individual diamond interchanges. Several visits were made to the sites for the collection of data. Among the data collected were the number of approach lanes, dimensions of the diamond interchanges, distribution of traffic movements, traffic volume, and traffic control characteristics.

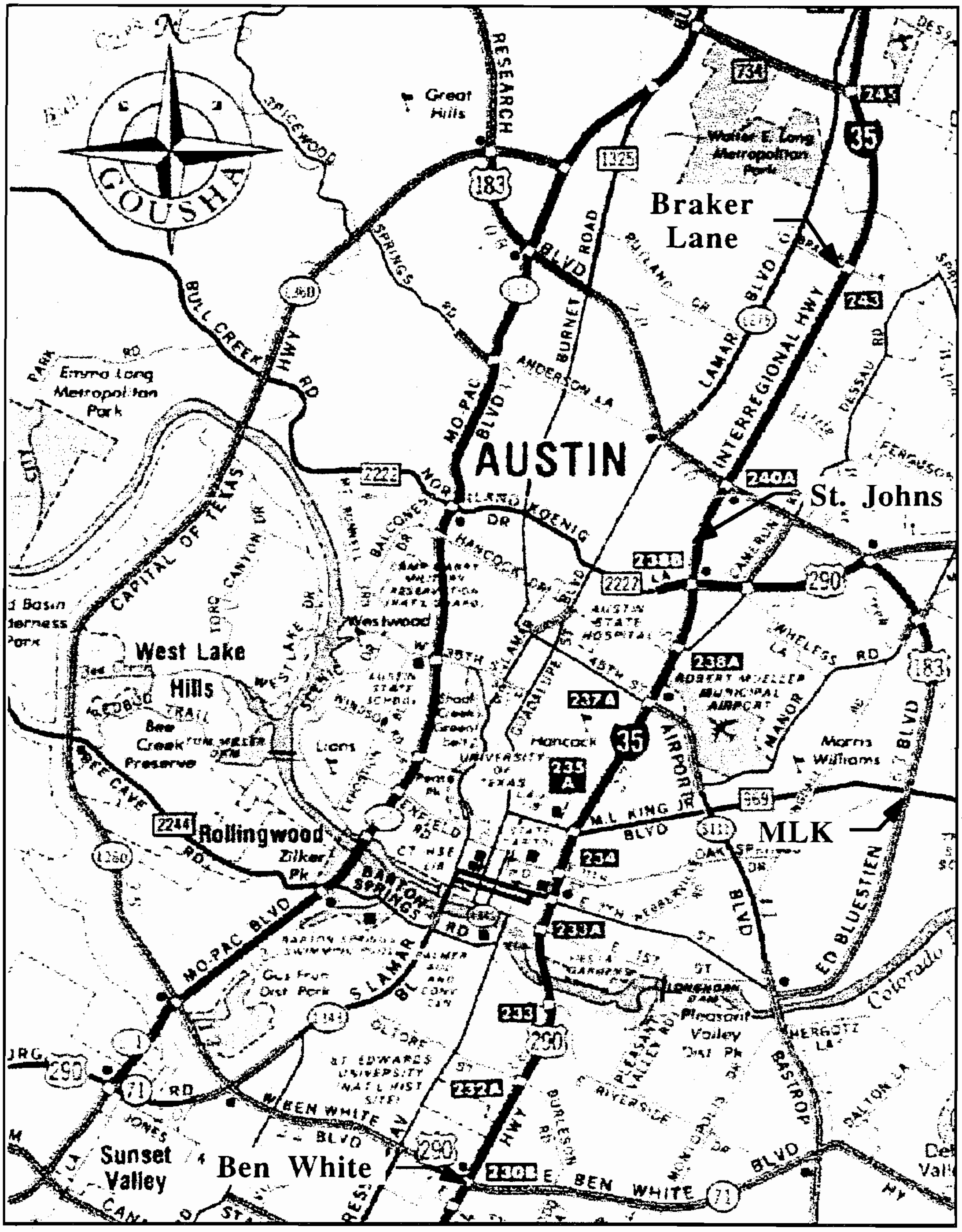

Figure 2.1 Geographical location of Braker Lane, St. Johns, BenWhite, and MLK diamond interchanges in Austin, Texas

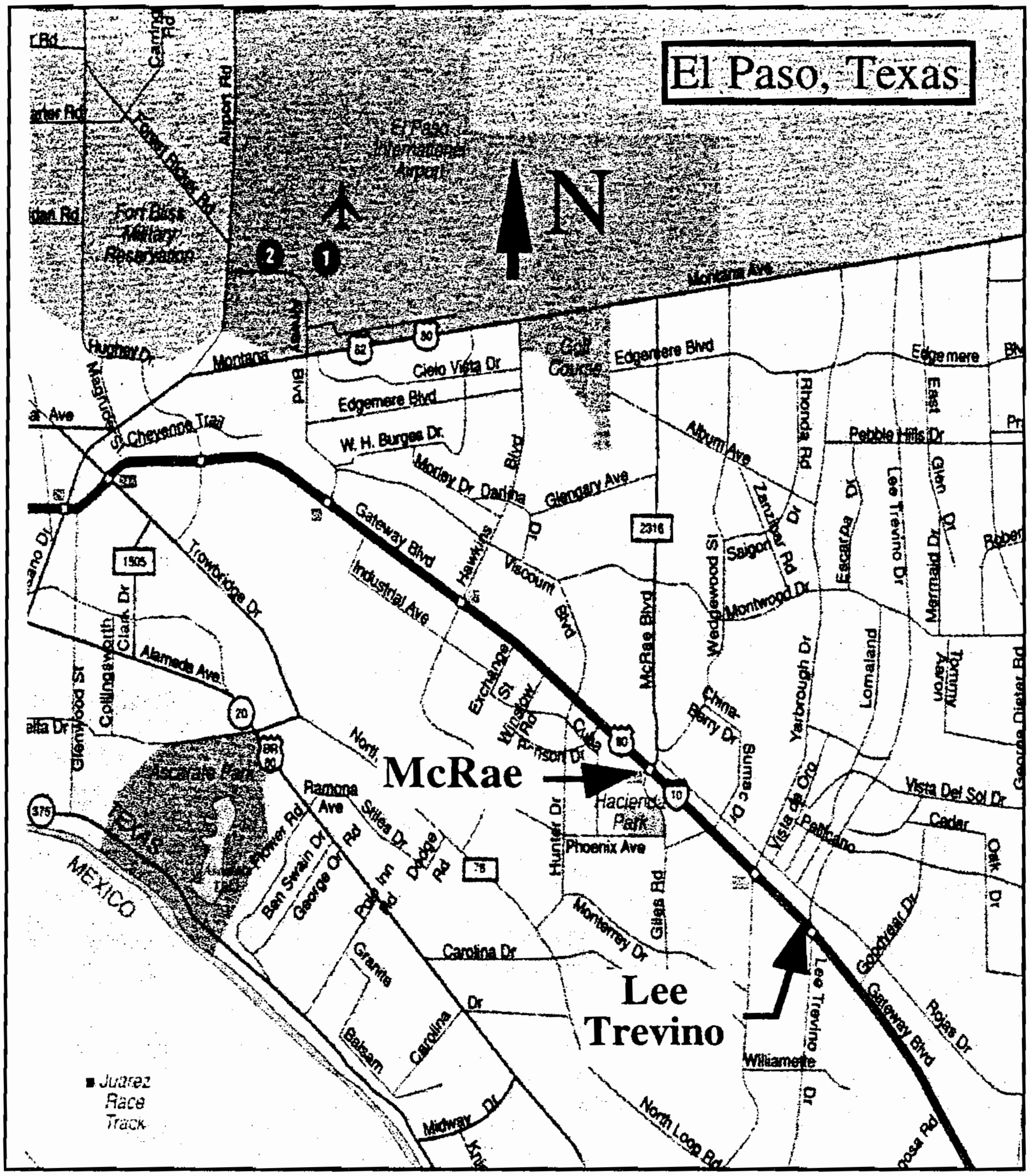

Figure 2.2 Geographical location of McRae, and Lee Trevino diamond interchange in IH-10 El Paso, Texas

TABLE 2.1 LIST OF CASE STUDIES

Case Study	Name	Location	No. of Free U-turn Lanes
1	Braker Lane	at IH-35, Austin	None
2	St. Johns	at IH-35, Austin	One
3	Ben White Blvd.	at IH-35, Austin	Two
4	Martin Luther King Jr.	at US 183, Austin	None
5	McRae Blvd.	at IH 10, El Paso	None
6	Lee Trevino Dr.	at IH 10, El Paso	None

The dimensions of the diamond interchanges were measured at the site. These dimensions included lane width, length of interior lanes, curb radius, and median dimensions. This information was supplemented with the geometry plan views of the diamond interchange, when they were available. The traffic signalization information such as timing and phasing patterns, were also gathered from field observation.

Traffic volume data were collected at each site, during the PM peak period of a typical weekday. In Austin, the PM peak period is usually between 4:30 pm and 6:00 pm, therefore, traffic volume data were collected for one hour during this time. For the cases in El Paso, traffic volume data was supplied by the Texas Department of Transportation district office in El Paso, along with the geometry plan views, and the signalization of the diamond interchanges selected for this study. The data used in the experiment represented the actual conditions at the time of the study.

2.3 DESCRIPTION OF CASE STUDIES

2.3.1 Case 1 -- Braker Lane at IH-35, Austin,Texas

Braker Lane is an arterial street located north of the Austin urban area. At the intersection of Braker Lane with IH-35, the through traffic of the freeway is separated from the turning traffic of the arterial street by an elevated diamond interchange (cross road above freeway). Figure 2.1 shows the geographical location of Braker Lane at IH-35. The geometric configuration of this diamond interchange does not include separated free u-turn lanes. The vicinity of the interchange consists of medium commercial development and residential areas. Along the frontage roads that connect the turning traffic of the freeway with the diamond interchange's ramps, are several commercial businesses that generate significant u-turn traffic demand. The total traffic volume of the northbound approach was 1200 veh/hr, which had a u-turn demand equal to 10 % of this traffic volume. The southbound approach had a u-turn demand of 19 % of the total traffic volume which was 900 veh/hr. The turning traffic movements at the diamond interchange are controlled by a four-phase signal pattern with two clearance phases [Ref. 12], see Appendix A. Figure 2.3 shows the geometric characteristics and traffic volume data collected at the site for this case study.

2.3.2 Case Study 2 -- St. Johns at IH-35, Austin, Texas

St. Johns is located north of Austin between the intersections of US 290 and US 183 on IH-35. Figure 2.1 shows the geographical location of the intersection of St. Johns and IH-35. At this intersection, a diamond interchange separates the freeway from the cross street. The interior lanes of the diamond interchange overpass the freeway through-traffic lanes. Its geometric configuration includes one separated free u-turn lane at the northbound approach of the interchange. The free u-turn lane was constructed as a separate bridge structure connecting the frontage roads located at both sides of the diamond interchange. The diamond interchange is located in a dense commercial business area that generates high traffic volume and high u-turn demand, specially on the northbound approach. The northbound traffic volume was more than 1500 veh/hr with a u-turn demand equal to 27 % of this traffic volume. The traffic volume of the southbound approach was 943 veh/hr with 13 % u-turn demand. The traffic signal control had a cycle length of 80 seconds. Both, the northbound and the southbound, approaches had 13 seconds of green time per cycle. The signal phasing pattern for this case study is shown in Appendix A. Figure 2.4 shows the geometric characteristics and traffic volume data of St. Johns diamond interchange.

2.3.3 Case Study 3 -- Ben White at IH-35, Austin, Texas

Ben White at IH 35 is a main diamond interchange located south of the City of Austin. This interchange is at the intersection of two principal arterial highways, IH-35 and US-71. The freeway through-traffic lanes of IH-35 overpass the two closely-spaced at-grade intersections of US-71. The geometric configuration of the diamond interchange includes two separated free u-turn lanes on the northbound and southbound approaches. It also includes a median left-turn lane provided for the storage of the left-turning vehicles at the right intersection of the interior lanes, and two exclusive right-turn lanes on the north side of the interchange. A wide median divides the

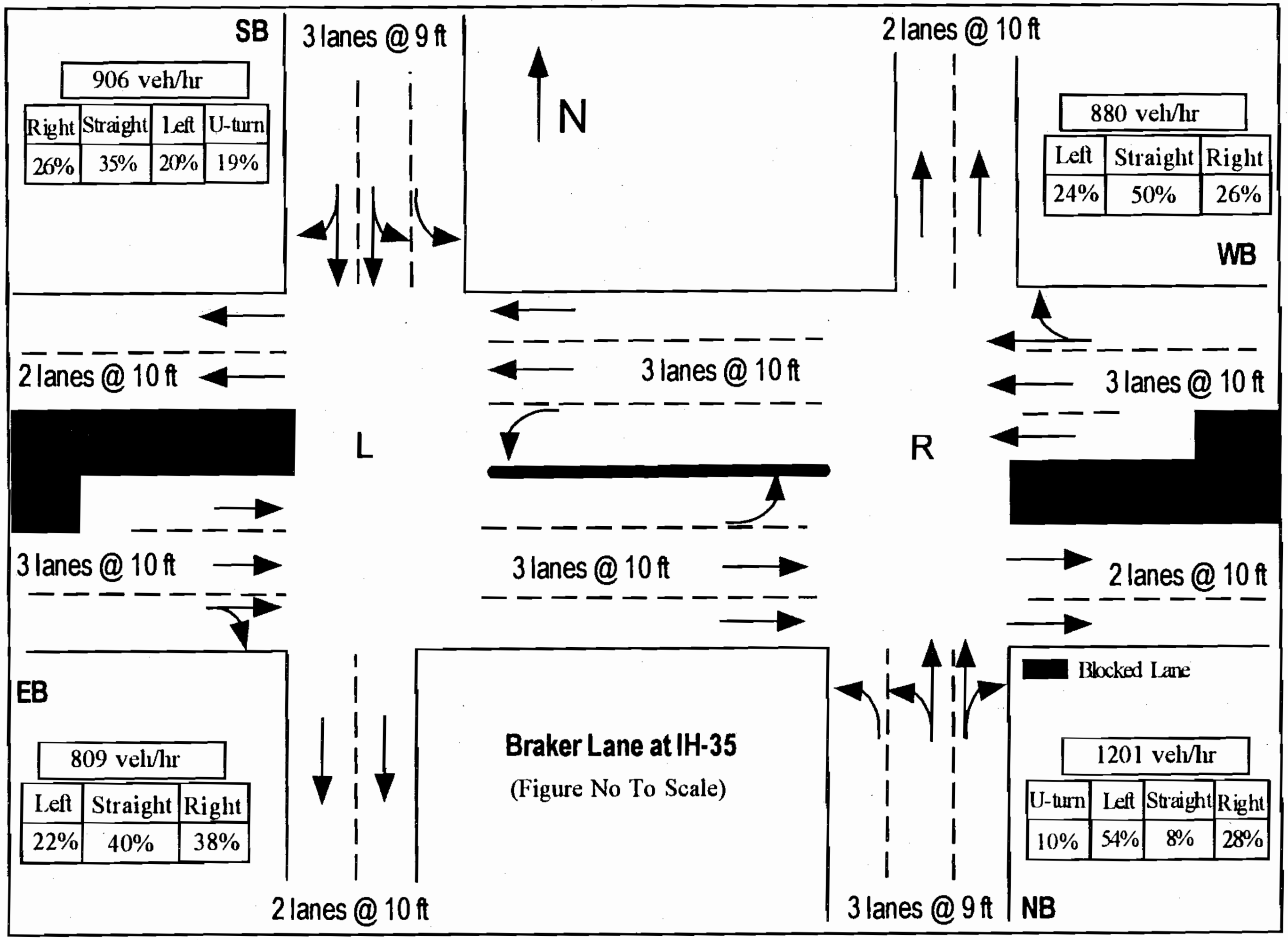

Figure 2.3 Geometry and traffic volume data for Braker Lane at IH-35 in Austin TX

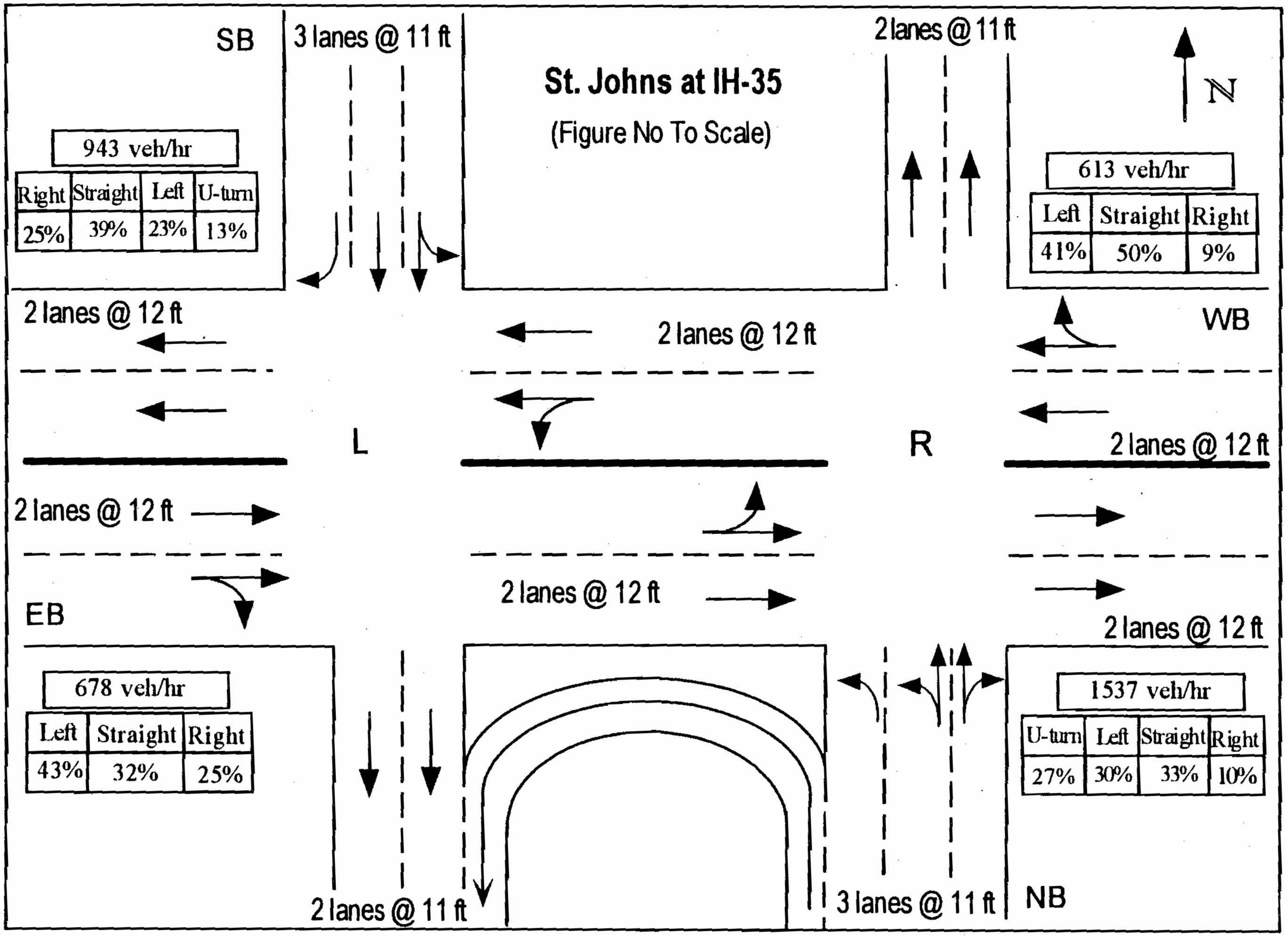

Figure 2.4 Geometry and traffic volume data for St. Johns at IH-35 in Austin TX.

westbound and eastbound through-traffic lanes on US-71. This diamond interchange is surrounded by a highly developed commercial and industrial area generating high traffic volumes and high u-turn demands. The northbound traffic volume was 1860 veh/hr with a u-turn demand equal to 27 % of this traffic volume, and the southbound traffic volume was 1190 veh/hr with 12 % u-turn demand. A four-phase signal pattern, with two overlaps and one clearance phase [Ref. 12], controlled the turning traffic at this diamond interchange, see Appendix A for details. A description of the geometric characteristics and traffic volume data is shown in Figure 2.5.

2.3.4 Case Study 4 -- Martin Luther King, Jr. at US-183

The freeway lanes of US-183 underpass the bridge structure of the diamond interchange at the intersection with Martin Luther King, Jr. (MLK). This diamond interchange is located east of Austin in a rural area. Its surroundings are undeveloped; therefore, its traffic volume was very low at the time of data collection. The main vehicle interaction at this diamond interchange was between the traffic flow of the crossing roadway and the left-turning vehicles coming from the freeway. Right-turning vehicles were handled by four exclusive right-turn lanes. The diamond interior lanes were about 400 ft long, being the largest diamond interchange configuration among the case studies. Its geometric configuration does not include separated free u-turn lanes. MLK was a special case of this study because the u-turn demand was equal or less than 1%. Despite its low u-turn demands, its geometric characteristics were interesting for this study. This diamond interchange was controlled by actuated traffic signal control. However, for purpose of this study a pre-timed signal control was set up for the simulation. The signal phasing and timing plan used in the simulation was determined from field observation of the actual signal performance. Details of the traffic signal control are in Appendix A. Figure 2.6 shows the geometric characteristics and traffic volumes of this case study.

2.3.5 Case Study 5 -- McRae Blvd. at IH-10, El Paso, Texas

The intersection of McRae Blvd. with IH-10 is located east to the City of El Paso. Figure 2.2 show the geographical location of this intersection. The frontage roads along IH-10 connect the turning traffic of the freeway with the crossing roadway at a diamond interchange. The through-traffic lanes of the main highway overpass the two closely-spaced intersections of the cross street at McRae Blvd.. Its geometric configuration does not include separated free u-turn lanes. Among the geometric features of this diamond interchange are three exclusive right-turn lanes, interior lanes of about 200 ft long, two 12 ft medians dividing the northbound and southbound traffic flow, and a small median of 2 ft width on the interior lanes. This diamond

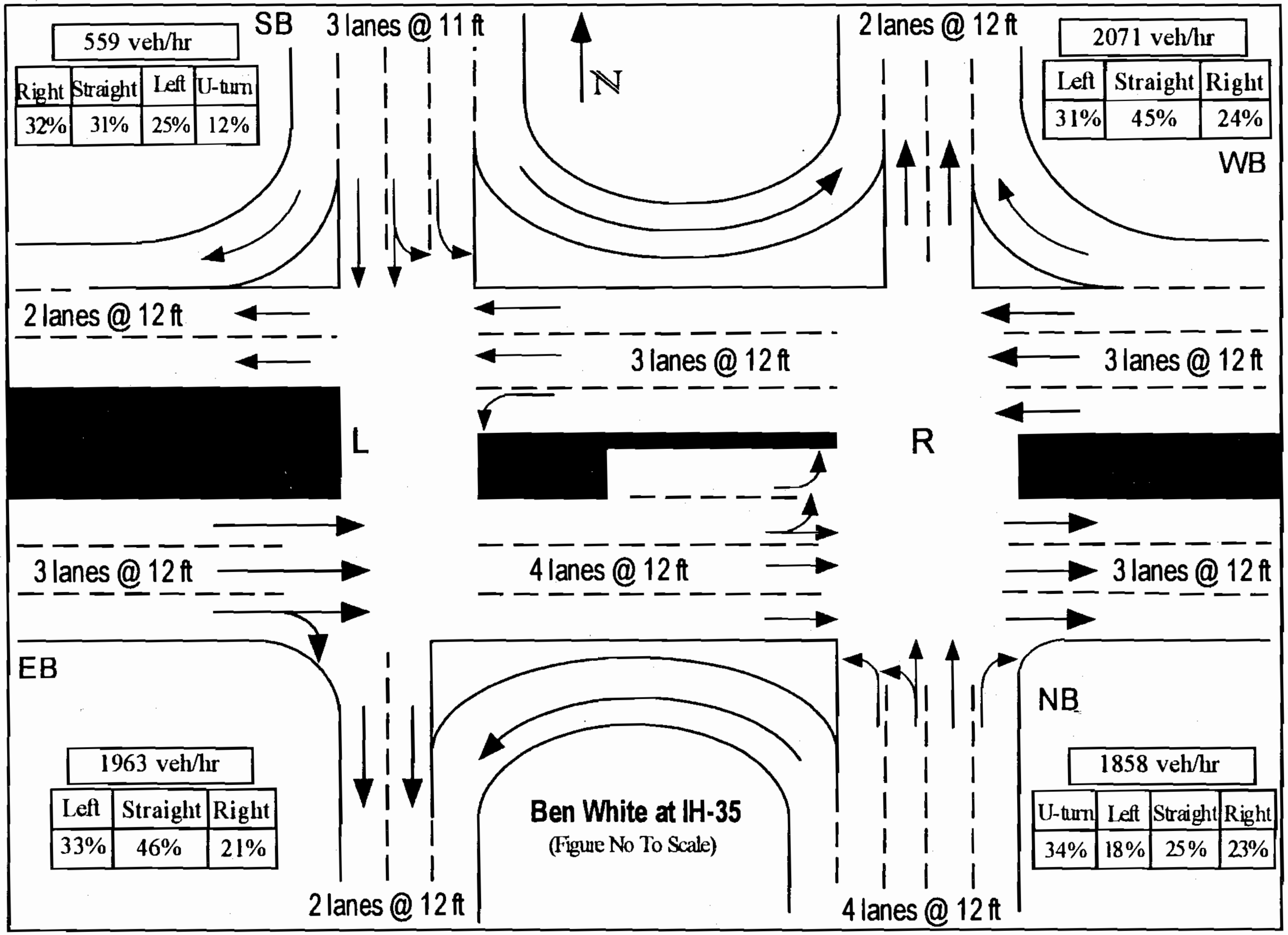

Figure 2.5 Geometry and traffic volume data for Ben White at IH-35 in Austin TX

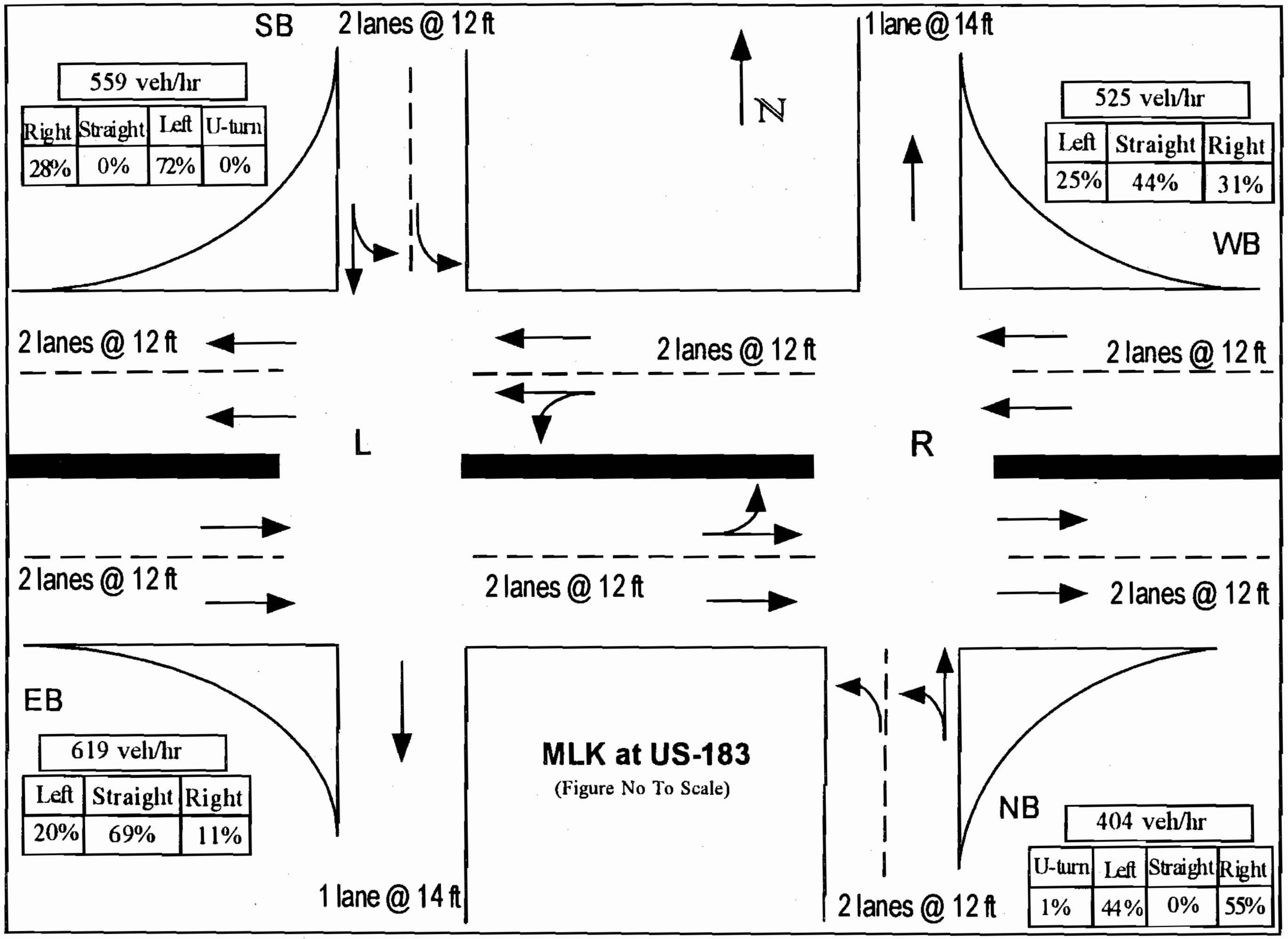

Figure 2.6 Geometry and traffic volume data for MLK at US-183 in Austin TX

interchange is located in a highly developed commercial area, which generates high traffic volume. However, the u-turn demands are less than 10 % of the approach traffic volumes. The high left-turn and straight traffic demand create a high interaction among the u-turning traffic and the other movements. The eastbound approach was equal to 2000 veh/hr and the westbound approach was 1230 veh/hr. This data shows that the eastbound approach were operating under conditions of over saturation traffic flow [Ref. 13]. Figure 2.7 shows the geometric characteristics and traffic volume data of McRae diamond interchange.

2.3.6 Case Study 6 -- Lee Trevino Dr. at IH-10, El Paso, Texas

Lee Trevino Dr. at IH-10 is an elevated diamond interchange without free u-turn lanes. This diamond interchange is located farther east from the McRae Blvd. diamond interchange. The two closely-spaced intersections of this diamond interchange are connected by a bridge structure that overpasses the through-traffic lanes of IH-10. The frontage roads of the freeway connect the ramps of the diamond interchange. Its geometric configuration includes four exclusive right-turn lanes, two dividing medians at the northbound and south bound approaches, and interior lanes longer than 200 ft. This diamond interchange is surrounded by a highly developed commercial area, which generates high traffic volume. Its u-turn demands were equal or less than 5 % of the approach traffic volumes. Similar to the case of McRae, the high left-turning traffic of the eastbound approach caused a high interaction of traffic for the u-turning vehicles. The traffic volume of the eastbound approach was 1780 veh/hr. The high traffic volume of the eastbound approach indicates that the approach was operating under saturated traffic flow conditions [Ref. 13]. Figure 2.8 shows the geometric characteristics and traffic volume data of Lee Trevino.

2.4 DESCRIPTION OF EXPERIMENT SCENARIOS

The purpose of this experiment was to evaluate the performance of u-turn movements through a diamond interchange. The main interests were to estimate the fuel consumed by u-turning vehicles, and to determine potential fuel savings from the provision of free u-turn lanes at diamond interchanges. For this purpose, a series of traffic simulation experiments were developed using the TEXAS Model as the main tool for the simulation.

As mentioned in previous sections, there were six case studies for this experiment. Each case study represents a diamond interchange that was evaluated under various scenarios. There were four basic scenarios describing the geometric and traffic flow characteristics of the case studies for the experiment. These experiment scenarios are listed in Table 2.2.

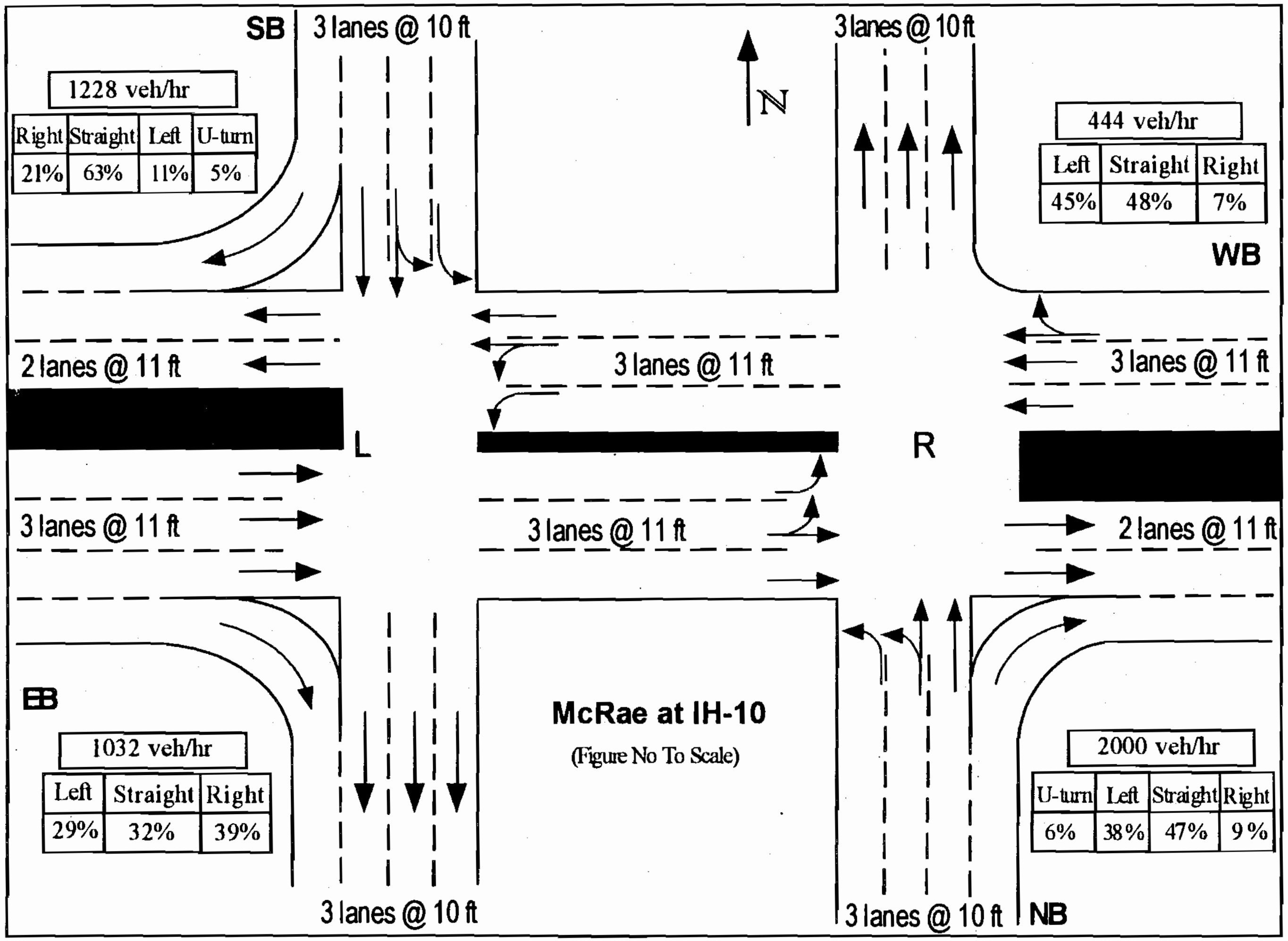

Figure 2.7 Geometry and traffic volume data for McRae at IH-10 in El Paso TX

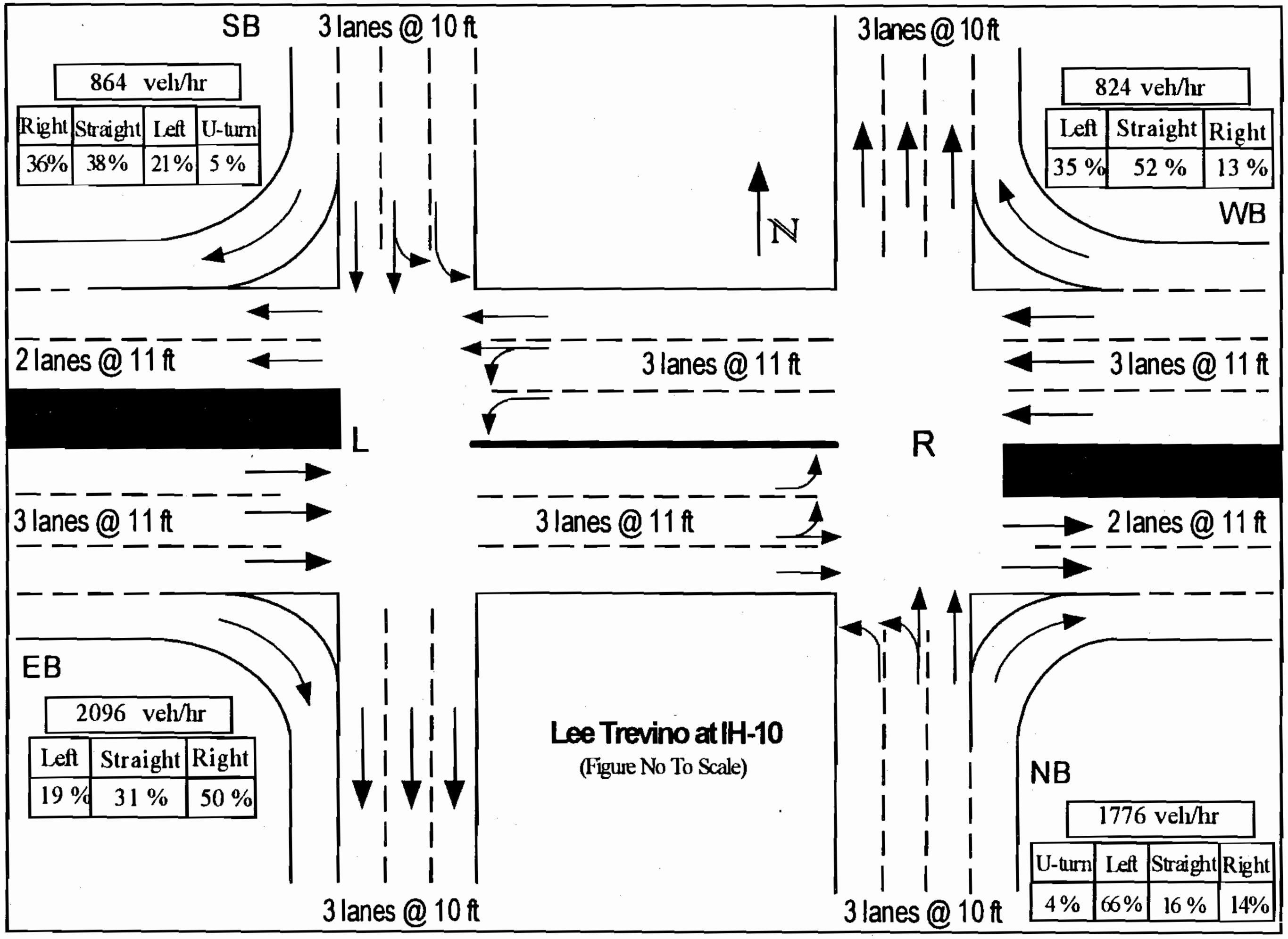

Figure 2.8 Geometry and traffic volume data for Lee Trevino at IH-10 in El Paso TX

TABLE 2.2 SUMMARY OF EXPERIMENT SCENARIOS

Free U-turn Lane Scenario	I	No
	II	One
	III	Two
Traffic Volume Scenario	I	High
	II	Medium
	III	Low
U-turn Demand Scenario	I	10 %
	II	20 %
	III	30 %
Traffic Control Scenario	I	Pre-timed signal control

2.4.1 Free U-turn Lane Scenarios

The free u-turn scenarios described the geometric characteristics of the diamond interchange. The actual geometric configuration of each diamond interchange was kept constant throughout the experiment, but free u-turn lane(s) was added or deleted as necessary to create the following scenarios.

- A diamond interchange without (No) free u-turn lanes
- A diamond interchange with only One free u-turn lane
- A diamond interchange with Two free u-turn lanes

All other geometric characteristics such as the number of approach lanes, length of interior lanes, lane width, curb radii, distribution of traffic movement, and in general the size of the interchange remained constant throughout the experiment. The purpose of these scenarios was to evaluate the fuel consumed by u-turning vehicles at diamond interchange with and without free u-turn lanes.

2.4.2 Traffic Volume Scenarios

The purposes of the traffic volume scenarios were to evaluate the fuel consumption of u-turning vehicles under various levels of traffic flow, and to determine how the traffic flow conditions directly affect the fuel consumed by u-turning vehicles. Furthermore, the traffic flow scenarios allow the estimation of total fuel savings per day, considering that the traffic flow conditions during a typical day are variable. Three scenarios of traffic volume were created for these purposes.

- ***High*** traffic volume scenario - For this scenario the total traffic volume of the inbound approaches was equal to the total traffic volume observed at the site.
- ***Medium*** traffic volume scenario - For this scenario the total traffic volume of the inbound approaches was 70 % of the high-traffic volume.
- ***Low*** traffic volume scenario - For this scenario the total traffic volume of the inbound approaches was 50 % of the high-traffic volume.

For the traffic volume experiment the proportion of left, straight, right and u-turn movements on the inbound approaches was kept constant throughout the three scenarios. In the case of MLK at US-183 the observed traffic volume data was considered to be equivalent to a low traffic volume level. In this case the low-traffic volume was multiplied by 1.4 and 2 to create the medium-traffic and high-traffic volume scenarios, respectively.

2.4.3 U-turn Demand Scenarios

The purpose of the u-turn demand scenario was to evaluate the performance of a diamond interchange at various levels of u-turn demand. Three scenarios were created for this experiment. These scenarios are described as follow.

- ***10%*** u-turn demand scenario - Ten percent of the total traffic volume on the off-ramp approaches performed a u-turn at the diamond interchange.
- ***20%*** u-turn demand scenario - Twenty percent of the total traffic volume on the off-ramp approaches performed a u-turn at the diamond interchange.
- ***30%*** u-turn demand scenario -Thirty percent of the total traffic volume on the off-ramp approaches performed a u-turn at the diamond interchange.

For this experiment the percent of left, straight, and right turn movements were redistributed using a weighted average of the remaining traffic volume. For instance, in the 10% scenario the other 90% of the traffic volume was redistributed within the other movements in proportion to the original data. The distribution of traffic data for the left, straight, and right movements used in this experiment is shown in Appendix B.

2.4.4 Traffic Control Scenario

All diamond interchanges used in this study were signalized. Only one traffic control scenario was used in this experiment. This traffic control scenario uses a pretimed signal. The phasing and timing data used in the experiment corresponds to the data collected at the site. The traffic-control data for each case study is shown in Appendix A.

2.5 EXPERIMENT DESIGN

The previous scenarios were combined to develop the experiment. There were two main experiments in this study:

- Traffic Volume Experiment, and
- U-turn Demand Experiment.

The traffic volume experiment was created to evaluate the fuel consumption of u-turning vehicles under various levels of traffic flow. For this experiment the traffic volume scenarios, the free u-turn scenarios, and the traffic control scenario were combined to create the experiment shown in Table 2.3.

The u-turn demand experiment was created by the combination of the u-turn demand scenarios with the free u-turn and the traffic control scenarios. Only two free u-turn scenarios were used. The objective of this experiment was to evaluate the fuel consumed by u-turning vehicles if the u-turn traffic demand was 10 %, 20%, or 30 %. The u-turn demand experiments are described in Table 2.4

Throughout the experiment, traffic control at the diamond interchange was not changed; neither were the traffic movements or the geometry of the interchange. Only the traffic demand was varied in each experiment, and the only change was the addition of free u-turn lanes.

TABLE 2.3 TRAFFIC VOLUME EXPERIMENT

	Traffic Volume Scenario	Free U-turn Scenario	Traffic Control Scenario
Traffic Volume Experiment	High	No One Two	Pre-timed Signal Control
	Medium	No One Two	
	Low	No One Two	

2.5.1 The Case of MLK at US-183

MLK at US-183 was a special case study because the observed u-turn demand was less than 1%; therefore, only the No free u-turn scenario was used for the traffic volume experiment. Thus, for this case there were only three experimental scenarios:

- *High* traffic volume *without free u-turn lane*
- *Medium* traffic volume *without free u-turn lane*, and
- *Low* traffic volume *without free u-turn lane.*

Since the observed u-turn demand was almost zero percent, it was not meaningful to run this experiment with one or two free u-turn lanes. The experimental scenarios of one and two free u-turn lanes were studied in the u-turn demand experiment. For this special case study, the experimental scenarios for the u-turn demand experiment are described in Table 2.5.

TABLE 2.4 U-TURN DEMAND EXPERIMENT

	Traffic Volume Scenario	Free U-turn Scenario	Traffic Control Scenario
U-turn Demand Experiment	10 %	No	Pre-timed Signal Control
		Two	
	20 %	No	
		Two	
	30 %	No	
		Two	

2.6 TEXAS MODEL SIMULATION DATA

The emission processor of the TEXAS Model was used as the main tool for the development of this experiment. A detailed description of the geometric and traffic control characteristics are required by the model to perform the simulation of diamond interchanges. The geometric and traffic flow data collected at site were used to create the GDVDATA and SIMDATA files of the TEXAS Model. The geometric and traffic control data for each case study is described in Section 2.2 and Appendix A, respectively.

In addition to these data the TEXAS Model required other parameters to perform a simulation. The simulation parameters used for the development of this research are listed in Table 2.6. These simulation parameters were used as default values for all the TEXAS Model simulations. The simulation parameters are independent of the diamond interchange characteristics, and are only for the purpose of simulation.

Table 2.7 describes the geometric characteristics of free u-turn lanes used in the simulation. For purposes of this research, the geometric characteristics of the free u-turn lane were the same in all the experiments, except in those cases where the existing geometric data were used. This way the characteristics of the free u-turn lanes were the same and a comparison of results could be made.

TABLE 2.5 U-TURN DEMAND EXPERIMENT FOR MLK AT US-183

	Traffic Volume Scenario	Free U-turn Scenario	Traffic Control Scenario
U-turn Demand Experiment	10%	No One Two	Pre-timed Signal Control
	20%	No One Two	
	30%	No One Two	

TABLE 2.6 TEXAS MODEL SIMULATION PARAMETERS

Simulation Parameter	
Start-up time, minutes	5.0
Simulation time, minutes	20.0
Step increment for simulation time, seconds	1.0
Speed below which xx miles/hr delay statistics is collected	10.0
Maximum clear distance for being in a queue, feet	30.0
Car following equation parameters	
l	2.8
a	0.8
m	4000.0
Headway Distribution	Negative Exponential
Length of approach lanes , feet	800
Type of intersection control	Pre-timed
Lane control for added lane to simulate right-turning	Yield
Lane control for added free U-turn lane	Yield
Permissive left-turning at internal approach	No

TABLE 2.7 FREE U-TURN LANE SIMULATION PARAMETERS

Parameters	Values *
Width of lane, feet	15
Space between outer internal lane and free U-turn lane, feet	10
Length of entrance lane, feet	200
Radius at entrance, feet	50
Length of exit lane, feet	200
Radius at exit, feet	50
Percent of U-turning traffic to use the free U-turn	100
Free U-turn traffic control	Yield

* In general, these values were used for the simulation of free u-turn lanes, but where existing conditions were different, the actual geometric characteristics were used.

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CHAPTER 3. RESULTS OF THE SIMULATION

For each case study, a bar graph is presented in Chapter 3 to show the estimated average amount of fuel consumed per u-turning vehicle as these vehicles reversed direction by traveling through the two intersections of the diamond interchange. The height of the bars represents the average fuel consumption for all such vehicles processed by the TEXAS Model during 15 minutes of simulated real time. The shaded bars show average values for u-turning vehicles as they traveled along the five path segments through a conventional diamond interchange that did not have separate u-turn lanes: (1) the 200 ft of the left-hand inbound lane in advance of the first intersection (x_{d1}), (2) the left turn path through the first intersection (x_{d2}), (3) the left-hand interior lane between intersections (x_{d3}), (4) the left turn path through the second intersection (x_{d4}), and (5) the 200 ft of the left-hand outbound lane beyond the second intersection (x_{d5}). Figure 3.1 ilustrates the path of u-turning vehicles going through the two diamond interchange intersections and its associated fuel consumption. The average fuel consumption per u-turning vehicle (grams/vehicle) that was processed by the TEXAS Model during the simulation time can be calculated with equation (1).

$$X_d = \sum_{i=1}^{n=5} \frac{x_{di}}{y_i} \qquad (1)$$

Where X_d = Average fuel consumption per u-turning vehicle that used the two intersections of the diamond interchange (grams/veh).

(x_{di}) = Fuel consumed on path segment, *i*, by each simulated vehicle that used the two intersections of the diamond interchange (grams)

y_i = Estimated number of vehicles that traveled on path segment, *i*, (vehicles).

The white and black bars show average fuel consumption values for u-turning vehicles as they reversed direction by traveling along the following path segments through a conventional diamond interchange where separate u-turn lanes were provided: (1) the entrance lane to the free u-turn lane (x_{u1}), (2) the free u-turn lane (x_{u2}), and (3) the exit lane after the u-turn lane (x_{u3}). For simulation in the TEXAS Model, both the entrance and the exit lanes were 200 ft long. Figure

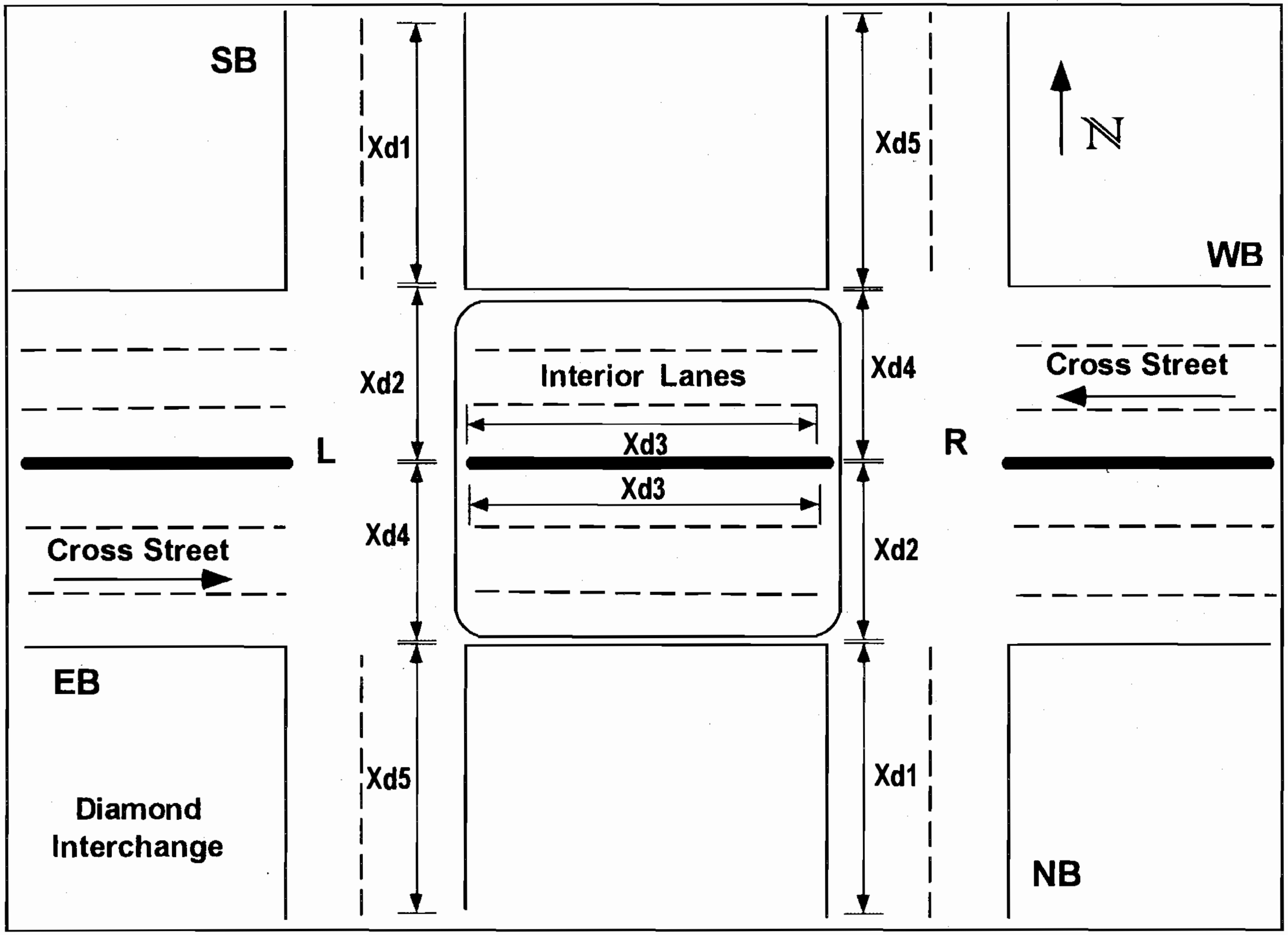

Figure 3.1 Fuel consumption of u-turning vehicles going through the two diamond interchange intersections

3.2 ilustrates the path of u-turning vehicles going through a free u-turn lane at a diamond interchange and its associated fuel consumption. The average fuel consumption per u-turning vehicle (grams/veh) that was processed by the TEXAS Model during the 15-minutes simulation time can be calculated with equation (2).

$$X_u = \sum_{i=1}^{n=3} \frac{x_{ui}}{y_i} \tag{2}$$

Where X_u = Average fuel consumption per u-turning vehicle along a free u-turn lane (grams/veh).

X_{ui} = Fuel consumed on path segment, i, by each simulated vehicle that used the free u-turn lane (grams)

y = Number of vehicles traveling through the free u-turn lane (vehicles).

The following sections of this chapter describe the fuel consumption results of the simulation experiments for each case study. In addition, there are three bar graphs describing the simulated traffic flow characteristics for each simulation experiment. These bar graphs represent the total traffic volume processed per approach, the average total delay per u-turning vehicle, and the average travel time per u-turning vehicle.

- *Total traffic volume processed per approach* - is the total number of vehicles that entered the diamond interchange via the specified inbound approach during the TEXAS Model simulation, in vehicles per hour, including all traffic movements from the approach: left, right, straight, and u-turn.
- *Average total delay per u-turning vehicle* - is the difference between travel time for a u- turning vehicle as it travels through the simulated diamond interchange and the time it would have taken the vehicle to travel the same distance at its desired speed.
- *Average travel time* - is the total time it takes a u-turning vehicles to travel through the simulated diamond interchange.

The average total delay and average travel time of a u-turning vehicle is calculated starting at the instant that the vehicle enters the simulated inbound approach lane. These values are the

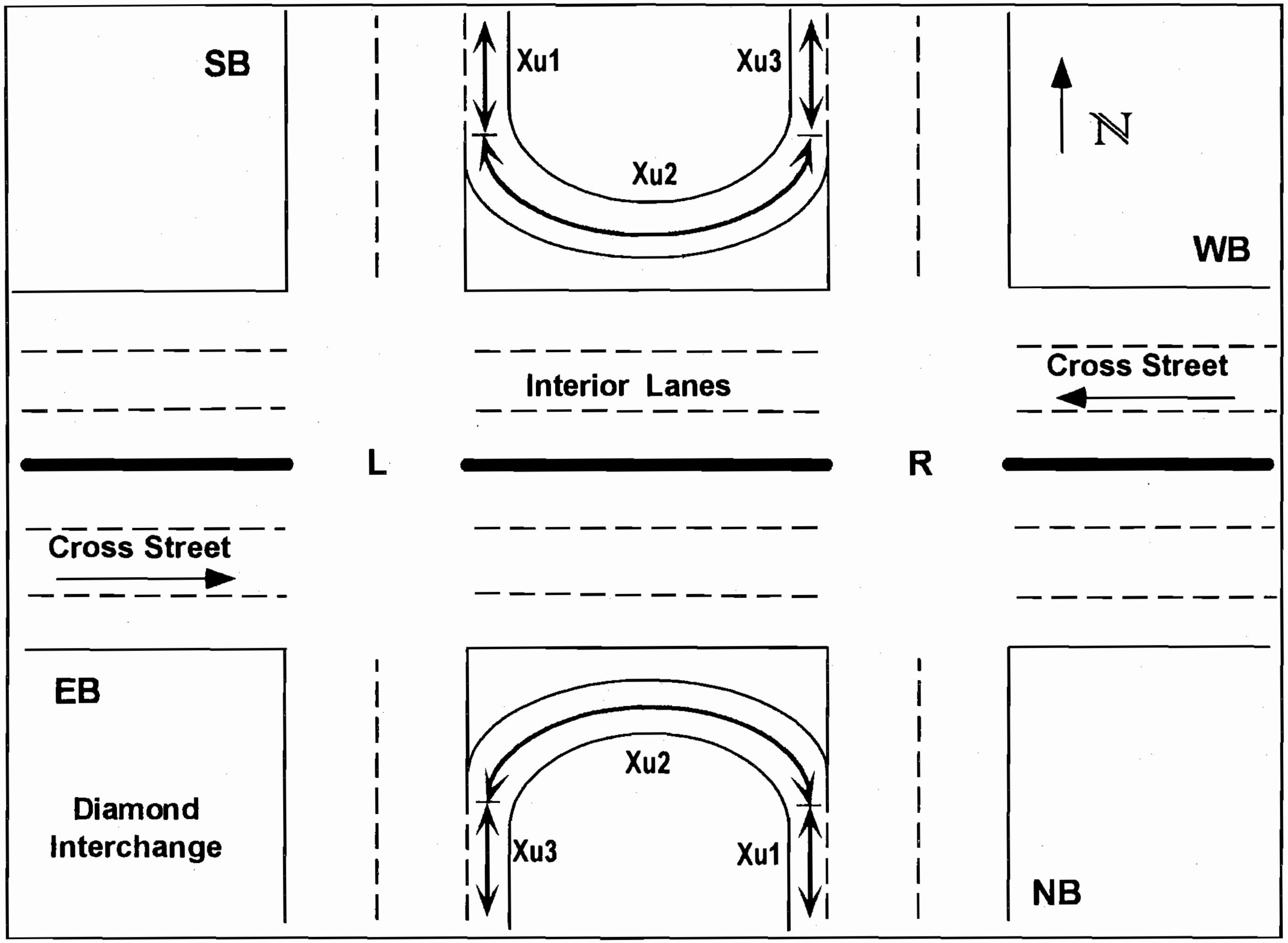

Figure 3.2 Fuel consumption of u-turning vehicles going through a free u-turn lane at a diamond interchange

sums of the delays and the travel times incurred by each vehicle as it travels along the following segments: (1) 800-ft length of the simulated inbound lane, (2) the two intersections of the diamond interchange, (3) the interior lanes or free u-turn lanes of the diamond interchange, and (4) 800-ft length of the simulated outbound lane. Appendix C includes the summary of the results for the two simulation experiments.

3.1 CASE STUDY 1 -- BRAKER LANE

As described in Chapter 2, the existing geometric configuration of Braker Lane does not include separate free u-turn lanes on any of its approaches. The total traffic volume observed on the northbound approach was near 1200 veh/hr during the peak hour, and it had a u-turn demand of about 10%. The total traffic volume of the southbound approach was about 900 veh/hr, with a u-turn demand of 19%. The observed cycle length of the traffic signal was 140 seconds. Approximately, 32 seconds of green time were allocated for the traffic movement on the southbound approach, and 39 seconds were allocated for the northbound approach. A summary of the simulation results for this case study is included in Appendix C, Tables C.1 and C.2. These results are described below.

3.1.1 Effect of Demand Traffic Volume

Figure 3.3 shows the simulation results for average fuel consumption by u-turning vehicles at Braker Lane under three traffic volume conditions, with and without (existing geometry) separate free u-turn lanes. These results indicate that maximum average fuel consumption on a free u-turn lane was 22 grams/veh, and the minimum value was 12 grams/veh for this diamond interchange. Both values resulted from the simulated low-traffic volume conditions on the southbound and northbound approaches, respectively. For the medium- and high-traffic levels average fuel consumption on the free u-turn lanes varied from 17 to 20 grams/veh. Meanwhile, the simulation results show that the maximum average fuel consumption by u-turning vehicles using the two intersections to reverse direction was 105 grams/veh, and the minimum value was 69 grams/veh. Thus, use of the free u-turn lanes represented savings in fuel of 75 and 81 percent, respectively, as compared to making u-turns through the two intersections.

Comparison of the data in Figure 3.3 for different approach directions shows that the fuel consumed by vehicles using the free u-turn lane was noticeably less than the fuel consumed by u-turning vehicles going through the two diamond interchange intersections. Change in demand volume did not affect the fuel consumption appreciably on either free u-turn lane for this case study. However, the fuel consumption for u-turning vehicles from the northbound approach that

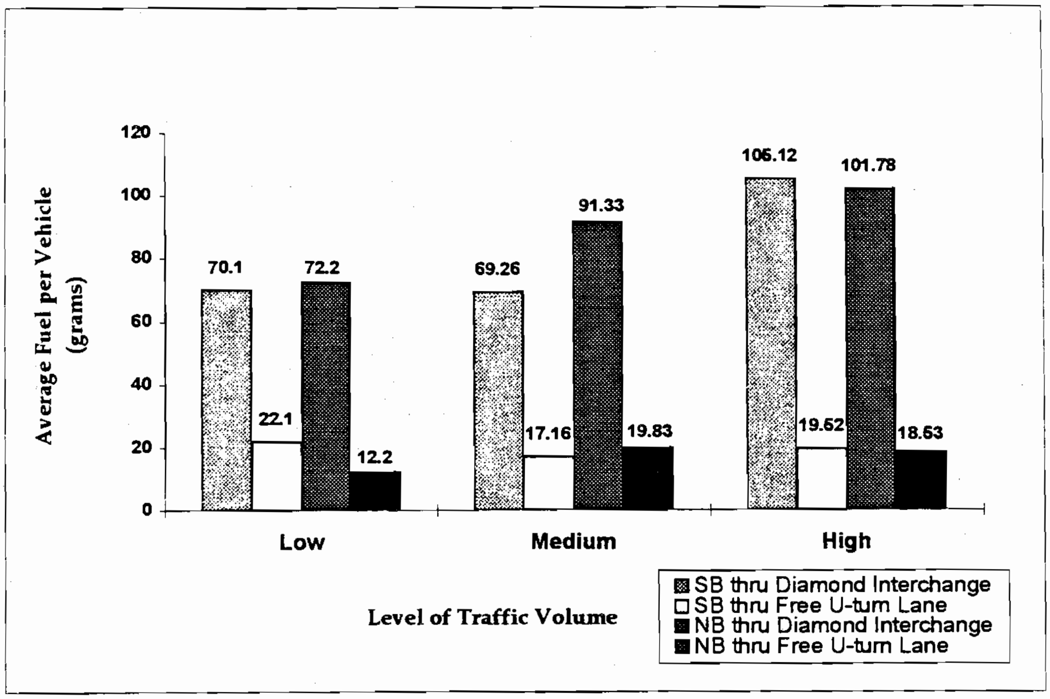

Figure 3.3 Average fuel per u-turning vehicle vs. volume Braker Lane at IH-35

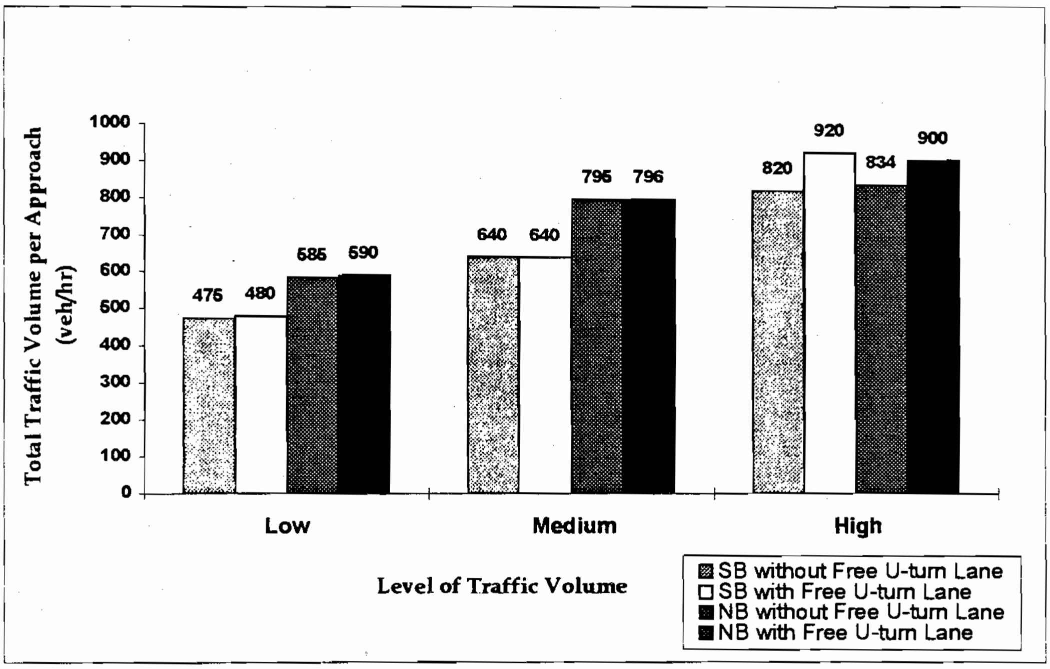

Figure 3.4 Total traffic volume processed per approach vs. volume for Braker Lane at IH-35

used both intersections of the diamond interchange increased as the level of traffic volume increased. Comparable u-turning vehicles from the southbound approach consumed about the same amount of fuel for the low and medium-traffic volumes, about 70 grams/veh, but this value increased to 106 grams/veh for the high-traffic volume level.

Figure 3.4 shows the number of vehicles processed for all demand traffic on the northbound and the southbound approaches at the Braker Lane interchange during simulation by the TEXAS Model. The results show that the number of vehicles processed for the simulated low and medium-traffic volume conditions did not change significantly with the addition of free u-turn lanes to the diamond interchange; the height of each bar in the pair is about the same. However, the number of vehicles processed during the high-traffic volume level was considerably larger when free u-turn lanes were provided. This indicates that the approach handled more traffic with the provision of free u-turn lanes. Comparison of these values with the traffic volume data specified for the simulation of this experiment, shown in Table C.1 of Appendix C, indicates that the total traffic volume processed on the approaches was less that the traffic volume specified for the high-traffic-volume condition. This resulted from the formation of long queues on the approach, which exceeded the 800-ft length of the simulated approach lanes. Consequently, the TEXAS Model discarded any vehicle that was unable to enter the intersection during the simulation, thereby reducing the total number of vehicles processed.

Figures 3.5 and 3.6 show the average total delay and average travel time for the u-turning vehicles under three traffic demand volumes at the Braker Lane interchange. The u-turning vehicles experienced very small delay when they used the free u-turn lane to perform the maneuver. An exception was the average total delay for the northbound approach at the high-traffic volume level. In this case the total delay was 184 seconds, more than 3 minutes of delay, when using the free u-turn lane. The total travel time was 254 seconds, more than 4 minutes. This indicates that at the high-traffic volume level the northbound approach experienced the formation of long queues. However, this delay was still appreciably less than when u-turning vehicles reversed direction through the two intersections of the diamond interchange when the average total delay for u-turning vehicles was 323 seconds, more than 5 minutes of delay, with a total travel time of 396 seconds, more than 6 minutes. The results show that under the simulated high-traffic-volume condition u-turning vehicles on the northbound approach saved more that 2 minutes of travel time and total delay when using the free u-turn lane.

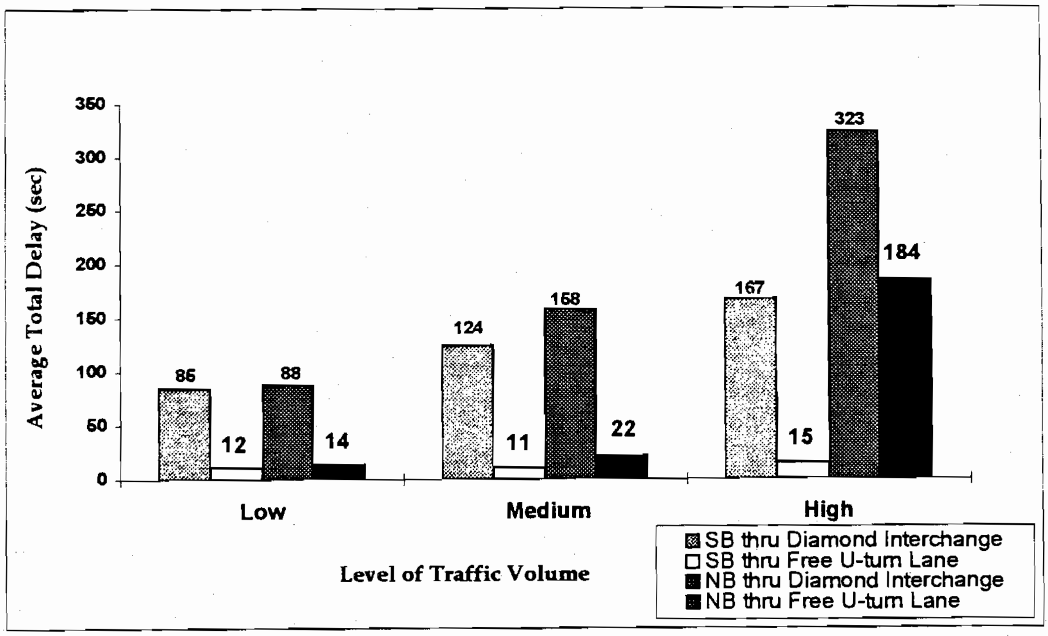

Figure 3.5 Average total delay per u-turning vehicle vs. volume for Braker Lane at IH-35

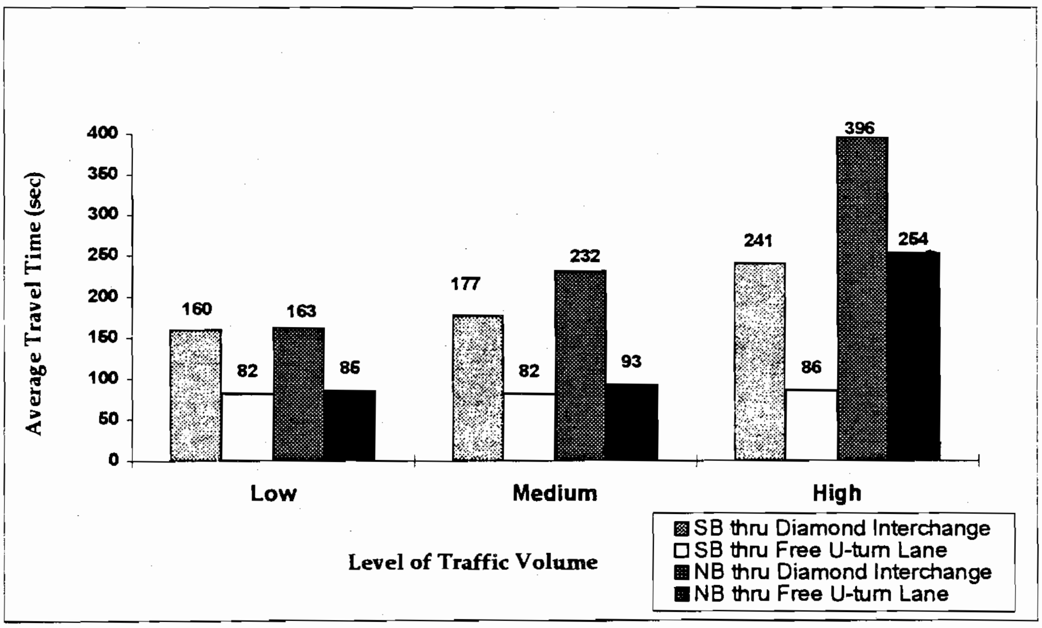

Figure 3.6 Average travel time per u-turning vehicle vs. volume for braker lane at IH-35

3.1.2 Effect of U-turn Demand

Figure 3.7 shows the effect of various u-turn traffic demand volumes on the average fuel consumption for u-turning vehicles when the Braker Lane interchange operated under a high level of traffic volume. Fuel consumed by u-turning vehicles going through the diamond interchange increased as the u-turn demand increased. For example, on the southbound approach, fuel consumed by u-turning vehicles on this path was 85, 106, and 125 grams/veh for the 10, 20, and 30 percent u-turn demands, respectively. Meanwhile, comparable values for u-turning vehicles using the free u-turn lane were 15, 17, and 17 grams/veh, respectively. This represented savings in fuel consumption of 83, 84, and 86 percent, correspondingly. The trends for the northbound approach were similar. Higher u-turn demand increased the average amount of fuel consumed by u-turning vehicles going through the diamond interchange; however, the average fuel consumed by u-turning vehicles using a free u-turn lane did not change appreciably with u-turn traffic demand.

Figure 3.8 shows the number of vehicles processed for traffic on the northbound and southbound approaches for three u-turn demand levels. Without free u-turn lanes the number of vehicles processed decreased as the u-turn demand increased. On the other hand, the number of vehicles processed on the inbound approaches increased as the u-turn demand increased, when free u-turn lanes were provided. Furthermore, the total number of vehicles processed during the simulation was consistently less than the observed traffic volume of 900 and 1200 veh/hr for the northbound and southbound approaches, respectively. As mentioned, this resulted from the formation of long queues on the approach, which exceed the 800-ft length of the simulated approach lanes. Table C.2 in Appendix C shows the total traffic volume and the u-turn demand processed by the TEXAS Model for this experiment. Comparison between the processed data and the specified data for the simulation indicates that this diamond interchange had problems in handling such high u-turn demand through the two intersections using the existing signal traffic control, specially on the northbound approach which had a higher traffic volume. However, when free u-turn lanes were added to the simulation the diamond interchange handled a high u-turn demand of 30 % without problems.

Figures 3.9 and 3.10 show the results of simulation for average total delay and average travel time for u-turning vehicles at three levels of u-turn demand. The maximum total delay through the diamond interchange was 356 seconds, almost 6 minutes, for the 30% u-turn demand level. This corresponds to an average travel time of 430 seconds, which is more than 7 minutes. Meanwhile, the average total delay to u-turning vehicles on the northbound approach decreased significantly as the u-turn demand increased. Those delays were 117, 55, 29 seconds

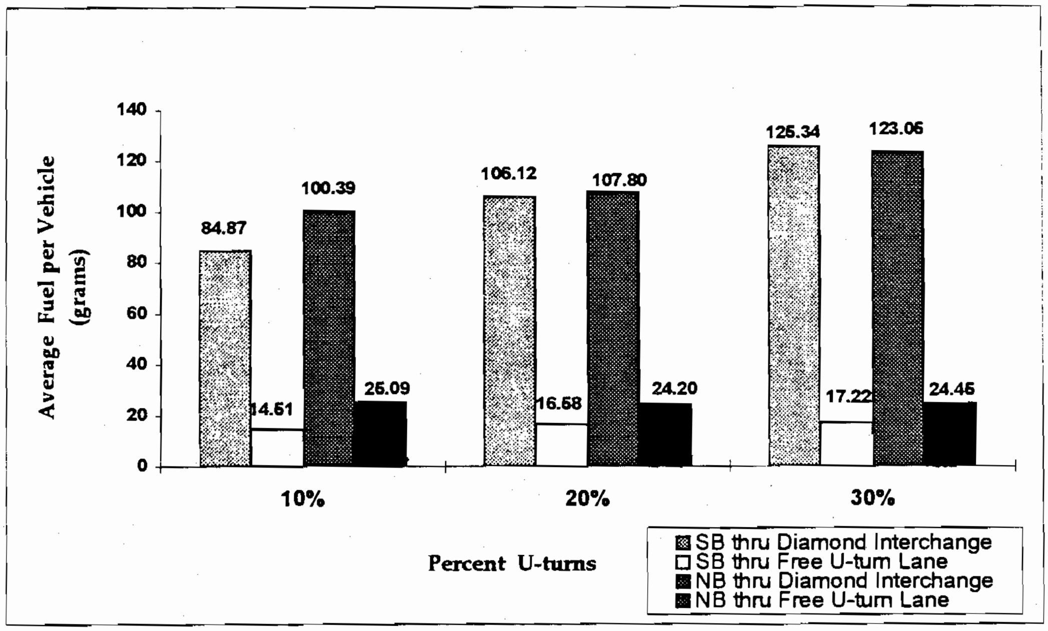

Figure 3.7 Average fuel per u-turning vehicle vs. percent u-turns for Braker Lane at IH-35

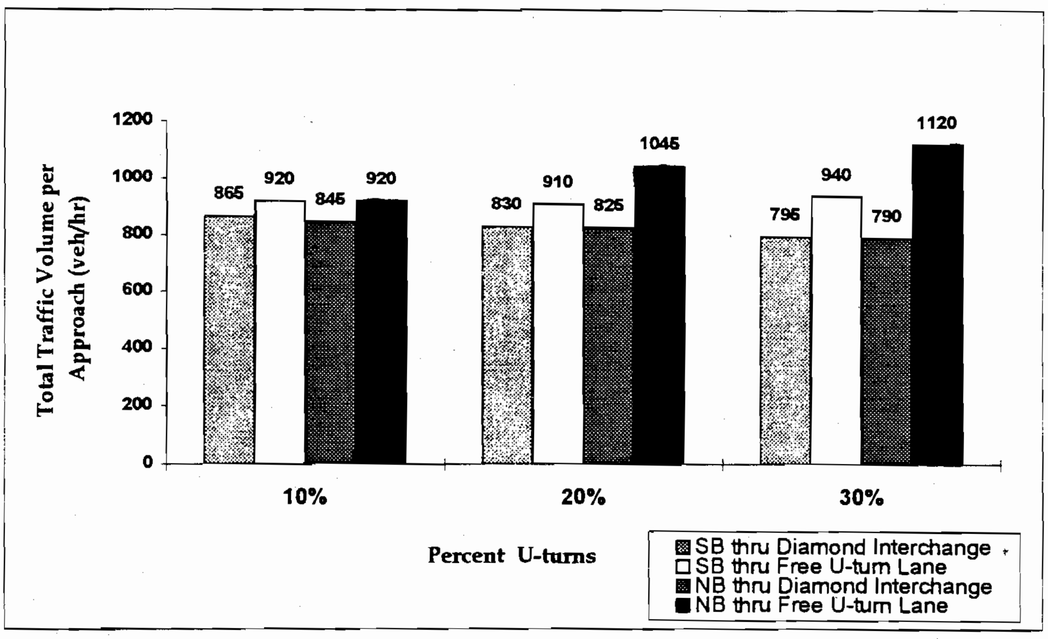

Figure 3.8 Total traffic volume proessed per approach vs. percent u-turns for Braker Lane at IH-35

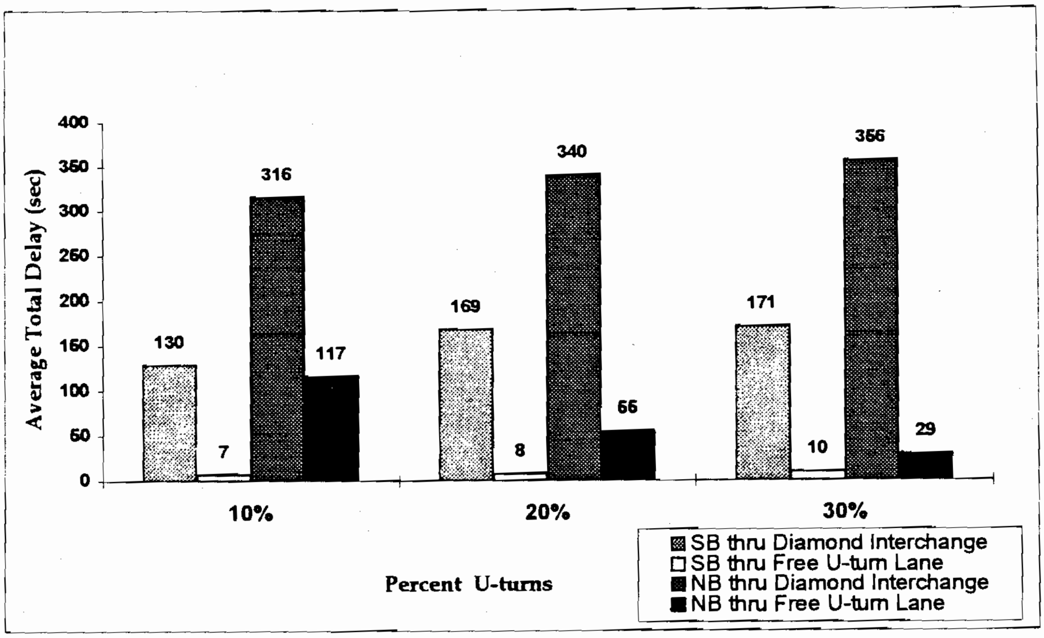

Figure 3.9 Average total delay pre u-turning vehicle vs. percent u-turns for Braker Lane at IH-35

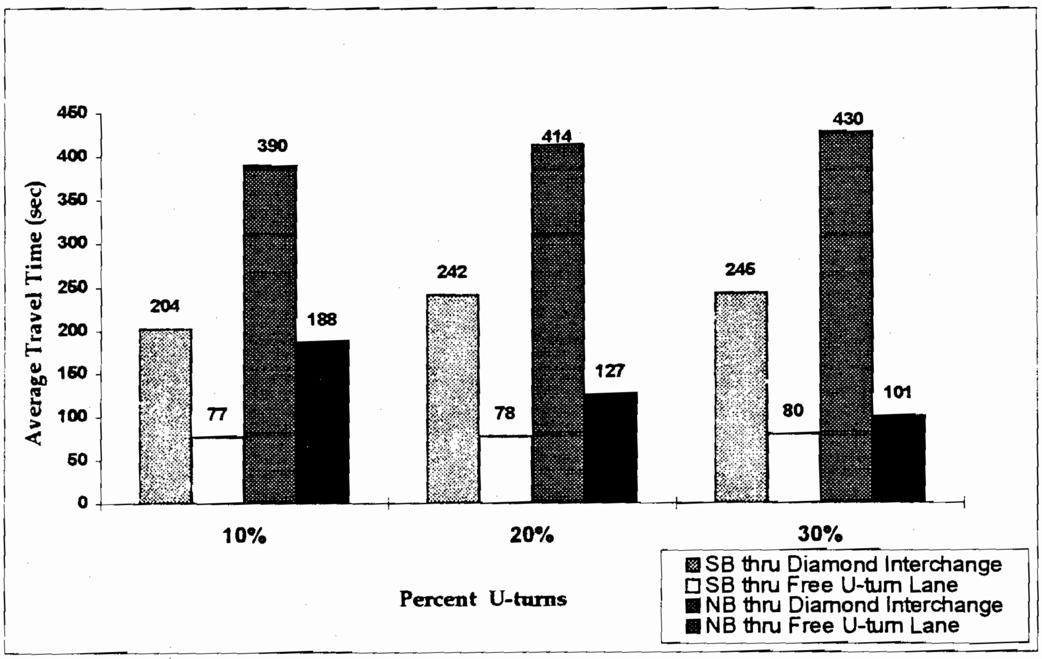

Figure 3.10 Average travel time per u-turning vehicle vs. percent u-turns for Braker Lane at IH-35

for the 10, 20, and 30 u-turn demand levels, respectively. This corresponds to an average travel time of 188, 127, and 101 seconds. These results indicate that the traffic signal control and other vehicles caused significant delay to the u-turn traffic, specially when the u-turn demand is small compared with the other traffic volume. Also, it demonstrates that free u-turn lanes significantly reduced the delay to u-turning vehicles.

3.2 CASE STUDY 2 -- ST. JOHNS

As described previously, St. Johns is a diamond interchange with one free u-turn lane on the northbound approach. The total traffic volume on this approach was 1537 veh/hr. Its observed u-turn demand was 27% of the approach volume. The total traffic volume on the southbound approach was 943 veh/hr, and it had a u-turn demand of 13%. The traffic signal cycle length on this diamond interchange was 100 seconds. Both, the southbound and the northbound approaches had a green time of 13 seconds. The traffic signal timing did not provide progression through the diamond interchange for u-turning vehicles on the northbound approach. This implies that u-turning vehicles were expected to use the free u-turn lane to perform this maneuver. Tables C.3 and C.4 in Appendix C summarizes the TEXAS Model simulation results for this diamond interchange. These results are discussed here.

3.2.1 Effect of Demand Traffic Volume

Figure 3.11 shows the simulation results for average fuel consumption by u-turning vehicles at St. Johns under three traffic volume conditions, with and without free u-turn lanes. The simulation results indicate that the average fuel consumption by u-turning vehicles using the two diamond interchange intersections to reverse direction increased with traffic volume. For instance, the average fuel consumed on the northbound approach was 91, 106, and 118 grams/veh for the simulated low, medium, and high-traffic volume conditions, respectively. On the southbound approach this value was 88, 101, and 120 grams/veh. On the other hand, the fuel consumption on the free u-turn lanes was 25, 21, and 24 grams/veh on the northbound approach, and on the southbound approach this value was 14, 20, and 19 grams/veh for the corresponding traffic volume conditions. Thus, use of free u-turn lanes represented savings in fuel of 73, 80, and 80 percent on the northbound approach, and 84, 80, and 85 percent on the southbound approach.

As mentioned before, the u-turn demand on the northbound approach was 27 % of the approach traffic volume. However, as shown in Table C.3 in Appendix C, the simulated percentage of u-turn demand processed through the two diamond interchange intersections was

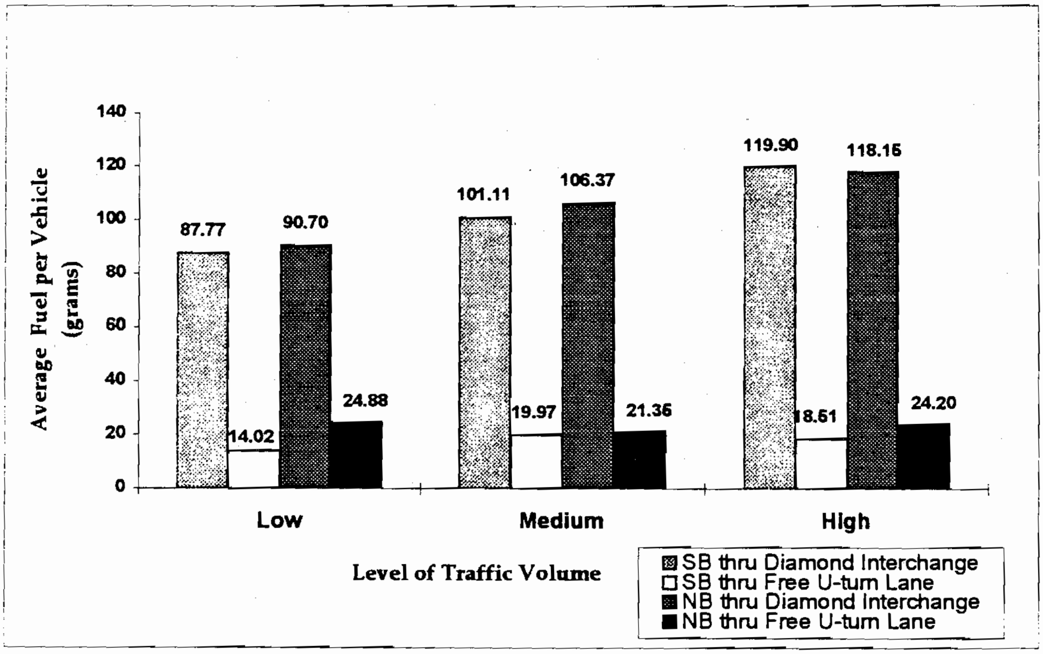

Figure 3.11 Average fuel per u-turning vehicle vs. volume for St. Johns at IH-35

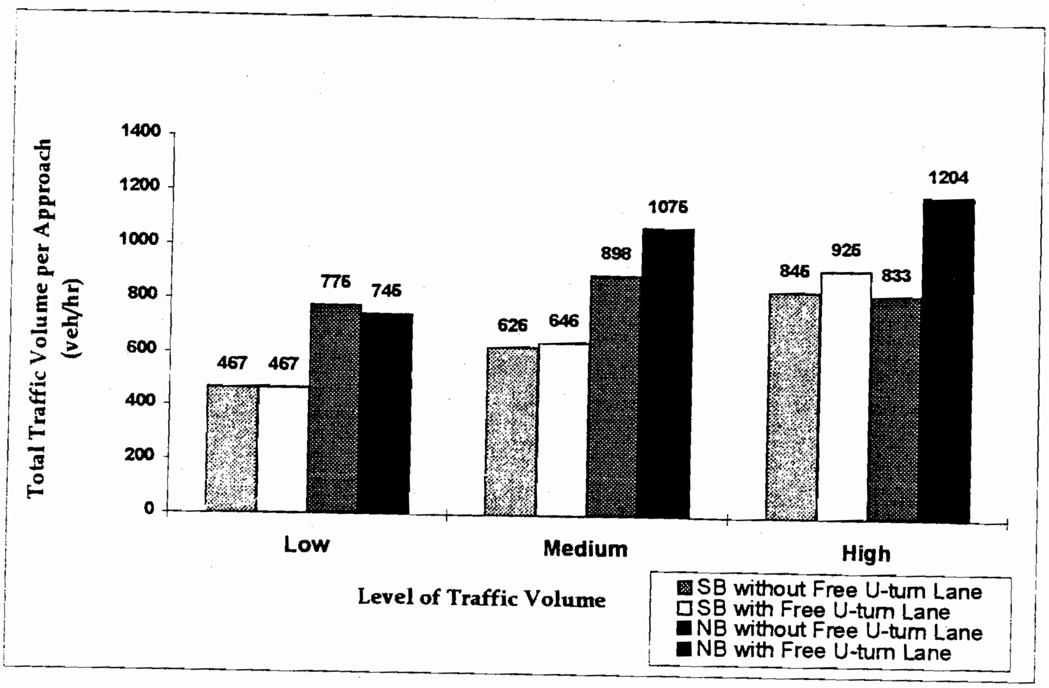

Figure 3.12 Total traffic volume processed per approach vs. volume for St. Johns at IH-35

only 20 percent for the high-traffic-volume level. For the simulated low- and medium-traffic volume conditions, this value was 26 and 24 percent. This indicates that as the traffic volume increased the capacity of the diamond interchange to process high u-turn demand through the two intersections decreased using the existing signal traffic control.

The number of vehicles processed for all traffic demand on the northbound and southbound approaches at the St. Johns interchange during the TEXAS Model simulations is shown in Figure 3.12. The number of vehicles processed during the simulation was higher when free u-turn lanes were provided. For instance, on the northbound approach this value was about 1200 veh/hr with free u-turn lane compared with only 833 veh/hr without the separate u-turn lane. Despite the increase in capacity resulting from the addition of free u-turn lanes, the number of vehicles processed for the high traffic level was less than the observed traffic volume on the northbound approach, 1537 veh/hr. This indicates formation of long queues on the approach lanes, which exceed the 800-ft length of the lane. Those vehicles attempting to join the back of the queue were discarded by the model during the simulation, thereby reducing the total traffic volume processed during the simulation. These long queues caused significant delays to u-turning vehicles on the approach.

Figures 3.13 and 3.14 show the average total delay and average travel time for the u-turning vehicles under three demand traffic volumes at the St. Johns interchange. The u-turning vehicles experienced very small delay when they used the free u-turn lane to perform the maneuver. An exception was the average total delay at the high-traffic volume level. The total delay on the southbound and northbound approaches was 49 and 95 seconds, when using the free u-turn lanes. The total travel times were 122 and 166 seconds, respectively, more than 2 minutes. At high-traffic volume level the northbound and southbound approaches experienced the formation of queues. However, this delay is appreciably less than for u-turning vehicles reversing direction through the two intersections of the diamond interchange. The average total delay in these cases was 291 and 369 seconds, about 5 and 6 minutes. The total travel time was 367 and 445 seconds, more than 6 and 7 minutes, respectively. U-turning vehicles saved more than 4 minutes of delay and travel time by using the separate u-turn lane.

3.2.2 Effect of U-turn Demand

Figure 3.15 shows the effect of various u-turn traffic demands on the average fuel consumption for u-turning vehicles when the St. Johns interchange operated under a high traffic volume level. The simulation results indicate that the average fuel consumed by u-turning vehicles going through the two intersections of the diamond interchange increased as the u-turn

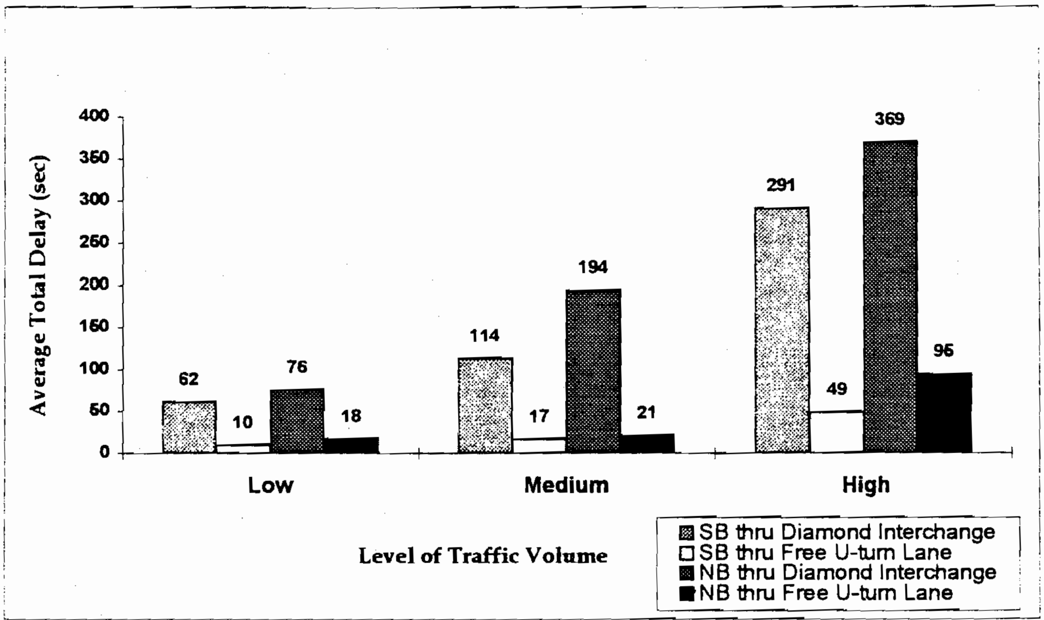

Figure 3.13 Average total delay per u-turning vehicle vs. volume for St. Johns at IH-35

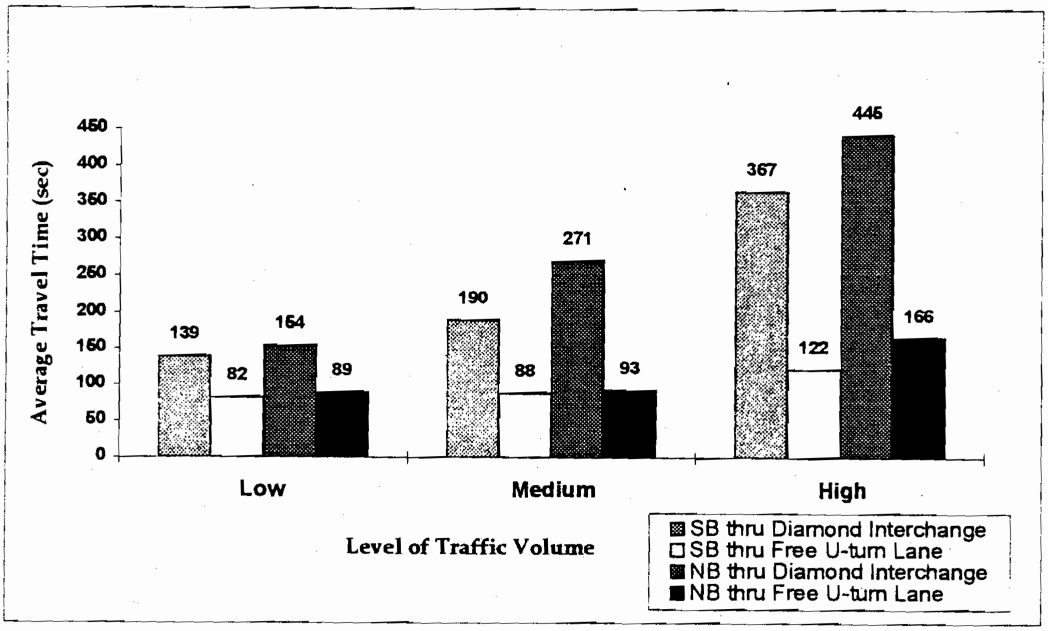

Figure 3.14 Average travel time per u-turning vehicle vs. volume for St. Johns at IH-35

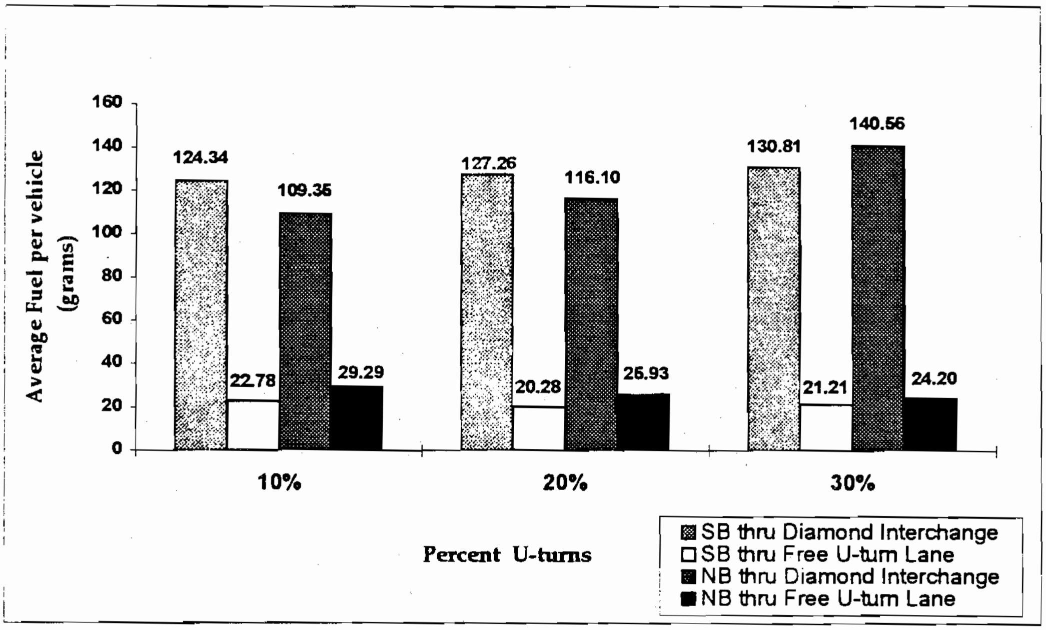

Figure 3.15 Average fuel per u-turning vehicle vs. percent u-turns for St. Johns at IH-35

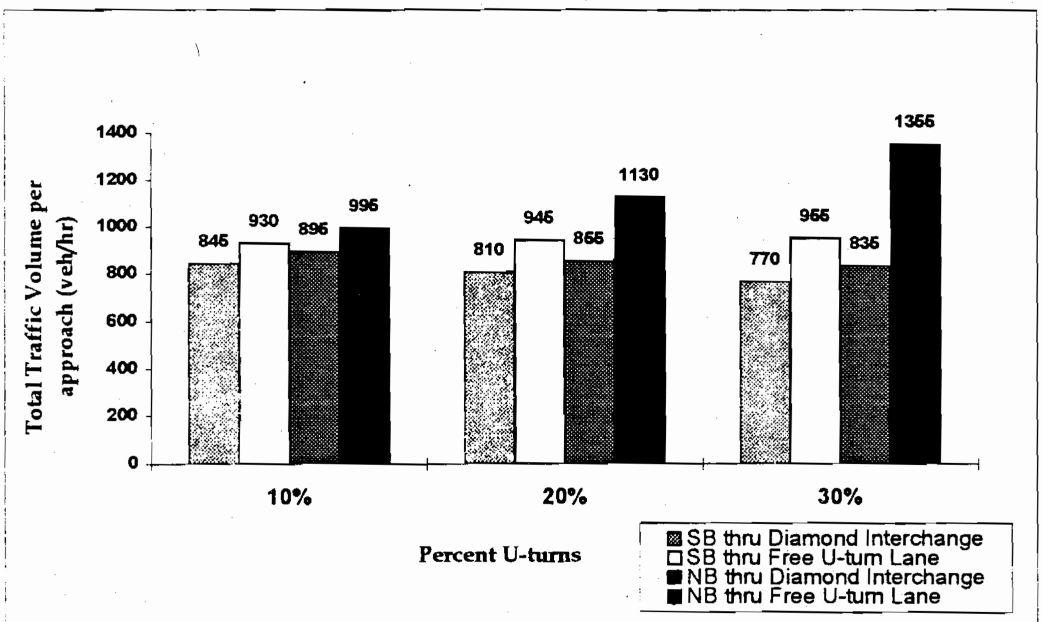

Figure 3.16 Total traffic volume processed per approach vs. percent u-turns for St. Johns at IH-35

demand increased. For instance, on the northbound approach, fuel consumed by u-turning vehicles on this path was 109, 116, and 140 grams/veh for the simulated 10, 20, and 30 percent u-turn demands, respectively. Meanwhile, comparable values for u-turning vehicles using the separate u-turn lane were 29, 26, and 24 grams/veh, respectively. As shown in Table C.4 in Appendix C, these values represented fuel savings of 73, 78, and 83 percent, correspondingly. The trends for the southbound approach were similar. Higher u-turn demand increased the average amount of fuel consumed by a u-turning vehicle going through the diamond interchange; however, the fuel consumed by a u-turning vehicle using a free u-turn lane did not change appreciably with u-turn traffic demand.

Figure 3.16 shows the number of vehicles processed for traffic on the northbound and southbound approaches for three u-turn demand levels. Without free u-turn lanes the number of vehicles processed decreased as the u-turn demand increased. Conversely, when free u-turn lanes were provided, this value increased as the u-turn demand increased. However, as shown in Table C.4 in Appendix C, the simulated percentage of u-turn demand processed through the two intersections of the diamond interchange was less than the specified u-turn demand for the simulation. For instance, on the northbound approach the u-turn demand processed was 8, 16, 22 percent of u-turn demand, and on the southbound approach this value was 9, 14, 19 percent for the 10, 20, and 30 percent condition, when using the existing signal traffic control. The maximum u-turn demand processed through the two diamond interchange intersections was about 20 percent of the approach traffic volume. On the other hand, there was not any problem to process high u-turn demand through the free u-turn lanes. The capacity of the diamond interchange to process high u-turn demands at the high-traffic volume with the observed signal settings level was limited, while free u-turn lanes did not show limitations.

Figures 3.17 and 3.18 show the average total delay and average travel time for u-tuning vehicles at three levels of u-turn demand for the St. Johns interchange. The simulation results indicate that u-turning vehicles reversing direction through the two intersections of the diamond interchange experienced appreciably higher total delay and travel time than u-turning vehicles using the free u-turn lanes. For instance, on the northbound approach the average total delay of u-turning vehicles going through the diamond interchange was 350, 358, and 380 seconds, about 6 minutes. The travel time was 425, 434, and 456 seconds, more than 7 minutes. Meanwhile, the average total delay for u-turning vehicles using the free u-turn lane was 169, 95, and 55 seconds on the northbound approach for the 10, 20, and 30 percent of u-turn demand, respectively. Comparable values on the southbound approach were 13, 9, and 12 seconds, respectively. The u-turning vehicles on the northbound approach experienced significant delays

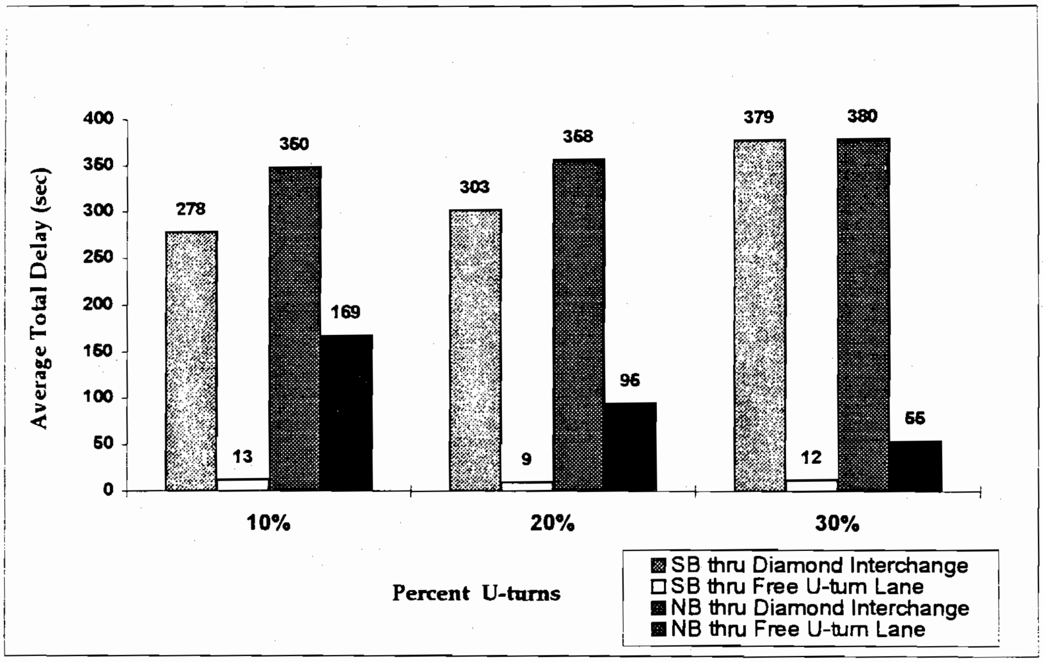

Figure 3.17 Average total delay per u-turning vehicle vs. percent u-turns for St. Johns at IH-35

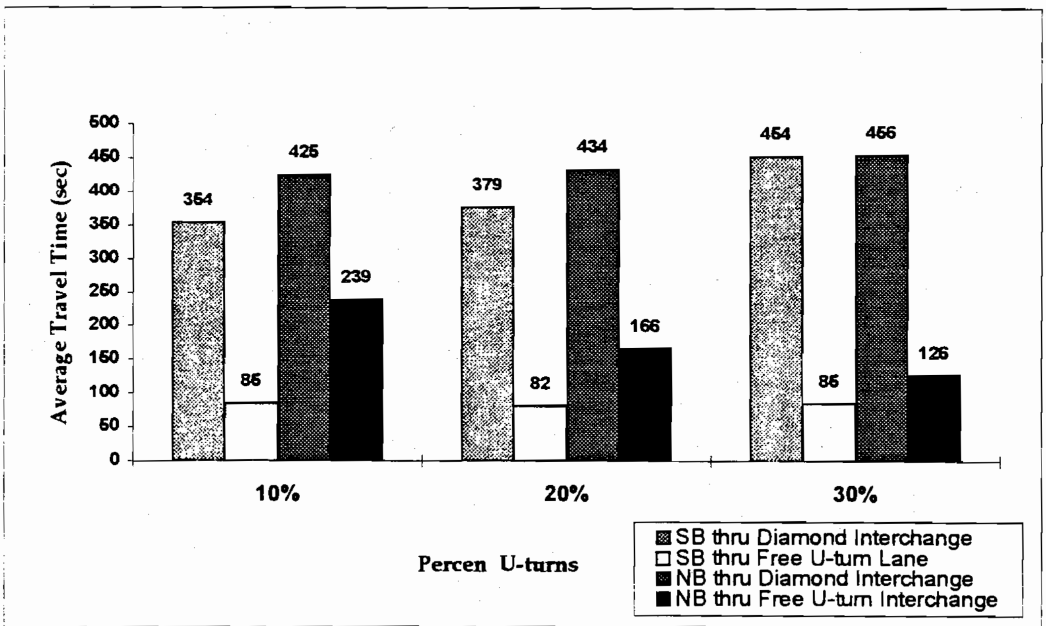

Figure 3.18 Average travel time per u-turning vehicle vs. percent u-turns for St. Johns at IH-35

caused by formation of long queues on the inbound lanes. The simulation results shown that the total delay for u-turning vehicles using a free u-turn lane decreased as the u-turn demand increased.

For the u-turn demand experiment, the total traffic volume of the approach was kept constant while the percentages of the other traffic movements were decreased as the u-turn demand increased. Therefore, when free u-turn lanes were provided the total delay for u-turning vehicles decreased as the u-turn demand increased, because the queue length on the inbound approach decreased as the percentage of the other traffic movements decreased. The results show that when the traffic volume on the inbound approach was high enough to form long queues on the approach, u-turning vehicles experienced significant delays. For instance, the total delay on the northbound approach were significantly higher than the total delay for u-turning vehicles on the southbound approach. Despite the high average total delay on the northbound approach for u-turning vehicles using the separate u-turn lane, this delay was still appreciably less than for u-turning vehicles reversing direction through the two intersections of the diamond interchange.

3.3 CASE STUDY 3 -- BEN WHITE

Ben White is a large diamond interchange with two free u-turn lanes. The total traffic volumes of the northbound and southbound approaches were 1858 veh/hr and 1188 veh/hr, respectively. Correspondingly, the u-turn demand for these approaches was 27% and 12%. The traffic signal cycle length was 160 seconds. The green times allocated for the traffic movement on the northbound and southbound approaches were 25 and 16 seconds, respectively. The observed signal traffic timing provided limited progression through the diamond interchange for u-turning vehicles going through the two intersections. However, field observation showed that about 7 percent of the total traffic volume on the northbound approach used the two intersections to perform this maneuver. This situation was not simulated for this study. Tables C.5 and C.6 in Appendix C summarizes the TEXAS Model simulation results for this diamond interchange. These results are discussed below.

3.3.1 Effect of Demand Traffic Volume

Figure 3.19 shows the results for average fuel consumption by u-turning vehicles at Ben White under three traffic volume conditions, with (existing geometry) and without free u-turn lanes. The maximum fuel consumption on a free u-turn lane was 45 grams/veh, and the minimum value was 30 grams/veh for this diamond interchange. These values resulted from the simulated high and low-traffic volume conditions on the southbound and northbound approaches, respectively. For the other conditions, average fuel consumption on the free u-turn lanes varied from 32 to 43 grams/veh. These values are noticeably higher than for the other case studies. Meanwhile, the simulation results show that the maximum average fuel consumption by u-turning vehicles using the two intersections to reverse direction was 247 grams/veh, and the minimum value was 148 grams/veh. Thus, use of the free u-turn lanes represented savings in fuel of 73 and 86 percent, respectively, as compared to making u-turns through the two intersections.

The simulation results indicate that the average fuel consumption of u-turning vehicles using the free u-turn lane was noticeably less than the fuel consumed by u-turning vehicles reversing direction through the two intersections of the diamond interchange. The fuel consumption was not appreciably affected by change in demand volume on either free u-turn lane for Ben White interchange. However, the fuel consumption for u-turning vehicles going through both intersections of the diamond interchange on the northbound approach increased as the level of traffic volume increased. Comparable u-turning vehicles on the southbound approach consumed slightly more fuel for the medium traffic demand level than for the low and high traffic demand conditions. This was about 174 grams/veh for the medium traffic demand level compared with 148 and 165 grams/veh for the low and high demand conditions.

Figure 3.20 shows the number of vehicles processed for all demand traffic on the northbound and southbound approaches in this case study when using the existing signal settings. The number of vehicles processed through the diamond interchange was consistently less when the separate u-turn lanes were removed from the simulated interchange. On the northbound approach these values were 630, 770, and 930 veh/hr, while the specified traffic demands for the simulation were 929, 1301 and 1858 veh/h for the low, medium, and high traffic demand levels, respectively. That is, only about 68 to 50 percent of the various simulated demand traffic volumes on this approach was processed by the TEXAS Model when free u-turn lanes were not provided and the observed signal settings (for existing free u-turn lanes) were used. The u-turn percentage processed through the two diamond interchange intersections from the northbound approach was noticeably less than the observed u-turn demand of 27 percent. Though not shown in this figure, the u-turn demands processed through both intersections of the diamond interchange were 16, 14, and 11 percent, respectively, for the low, medium, and high levels of demand traffic approach volume. All these values are less than the observed demand percentage, when free u-turn lanes were not in place. However, the percentage of u-turn demand processed when free u-turn lanes were provided was higher than without them for the three simulated traffic volume levels.

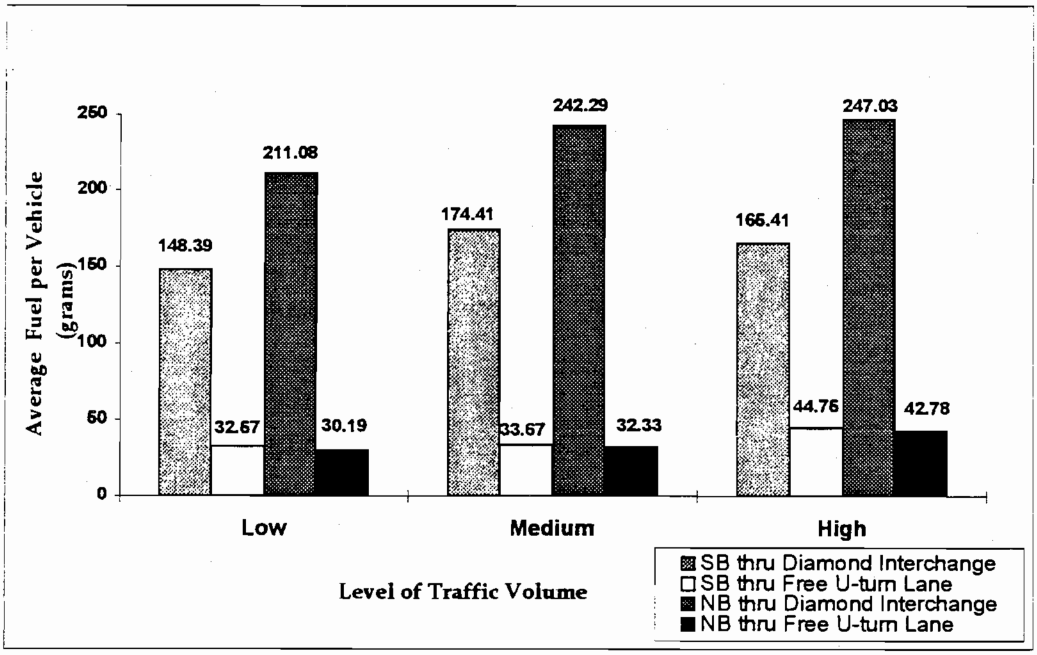

Figure 3.19 Average fuel per u-turning vehicle vs. volume for Ben White at IH-35

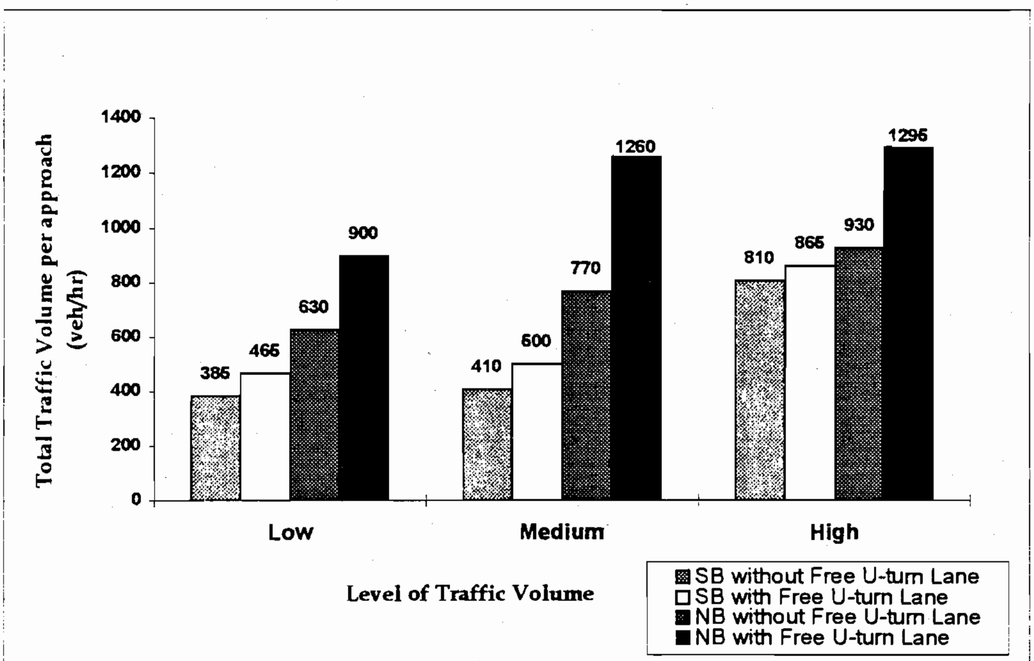

Figure 3.20 Total traffic volume processed per approach vs. volume for Ben White at IH-35

Figures 3.21 and 3.22 show the average total delay and average travel time for the u-turning vehicles under three traffic volumes at the Ben White interchange. The simulation results indicate that u-turning vehicles experienced very small delay when they used the free u-turn lane to perform the maneuver. An exception was the average total delay for the southbound approach at the high-traffic volume level. In this case the total delay when using the free u-turn lane was 146 seconds, more than 2 minutes of delay. The total travel time was 234 seconds, more than 3 minutes. This indicates that at the high-traffic volume level the southbound approach experienced the formation of long queues. However, this delay was still appreciably less than u-turning vehicles reversing direction through the diamond interchange two intersections. The average total delay for u-turning vehicles in this case was 451 seconds, more than 7 minutes of delay, with a total travel time of 542 seconds, more than 8 minutes. U-turning vehicles saved about 2 minutes of travel time and total delay when using the free u-turn lane. Comparable values for the northbound approach show appreciably high total delay for u-turning vehicles using the two diamond interchange intersections, about 10 minutes of delay and more than 11 minutes of travel time, for the high-traffic volume level. However, u-turning vehicles experienced small delay and travel time using the free u-turn lane, 63 (about 1 minute) and 142 seconds (more than 2 minutes), respectively. This indicates that on this approach the high u-turn demand caused considerably higher delay to the approach, when the free u-turn lane was not provided.

3.3.2 Effect of U-turn Demand

Figure 3.23 shows the effect of various u-turn demand percentages on the average fuel consumption of u-turning vehicles when the Ben White interchange operated under a high traffic volume level. Fuel consumed by u-turning vehicles going through the diamond interchange increased as the u-turn demand increased. For instance, the fuel consumption by u-turning vehicles through this path on the northbound approach was 169, 187, and 198 grams/veh for the 10, 20, and 30 percent u-turn demands, respectively. Meanwhile, comparable values for the u-turning vehicles using the free u-turn lane were 36, 31, 34 grams/veh, respectively. This indicates potential fuel savings of 78, 84, and 83 percent, correspondingly. Trends for the southbound approach were similar. Higher u-turn demand increased the average amount of fuel consumed by u-turning vehicles going through the diamond; however, the average fuel consumed by u-turning vehicles using a free u-turn lane did not change appreciably with u-turn traffic demand.

Figure 3.24 the number of vehicles processed for traffic on the northbound and southbound approaches for the three u-turn demand levels. The simulation results indicate that

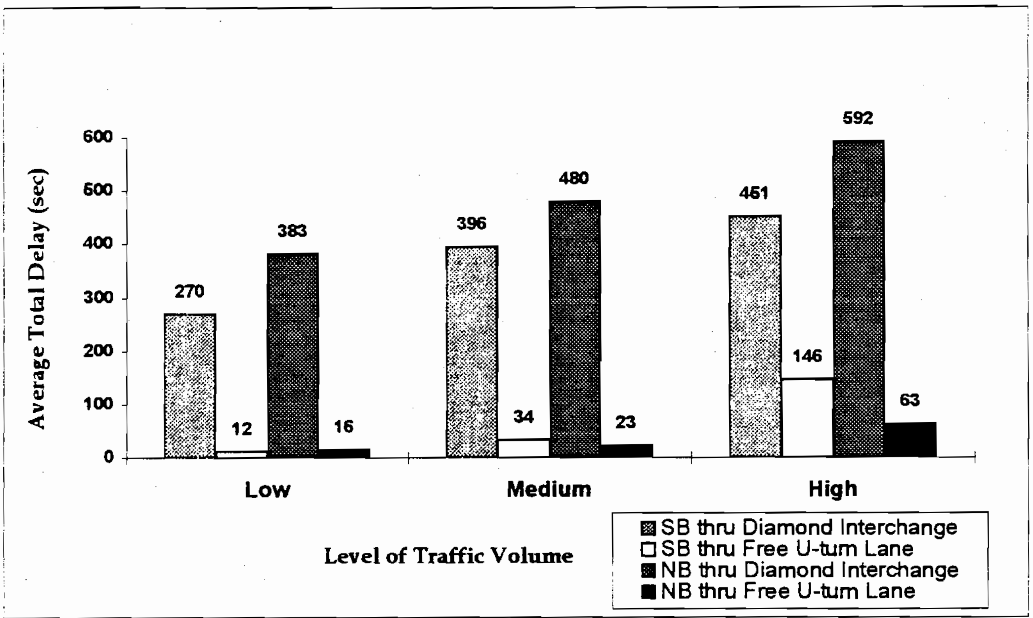

Figure 3.21 Average total delay per u-turning vehicle vs. volume for Ben White at IH-35

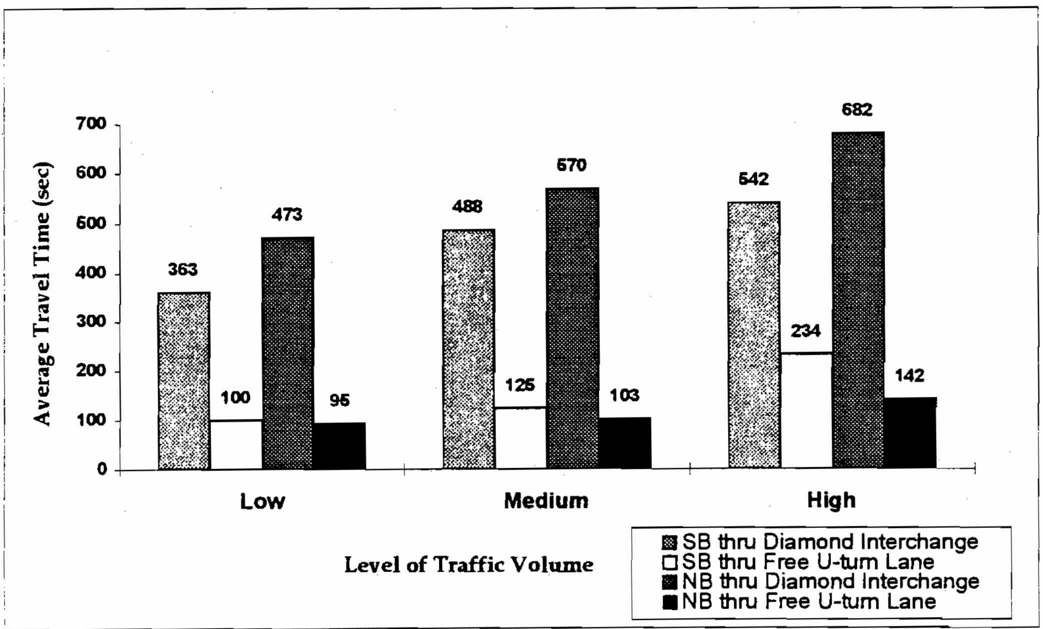

Figure 3.22 Average travel time per u-turning vehicle vs. volume for Ben White at IH-35

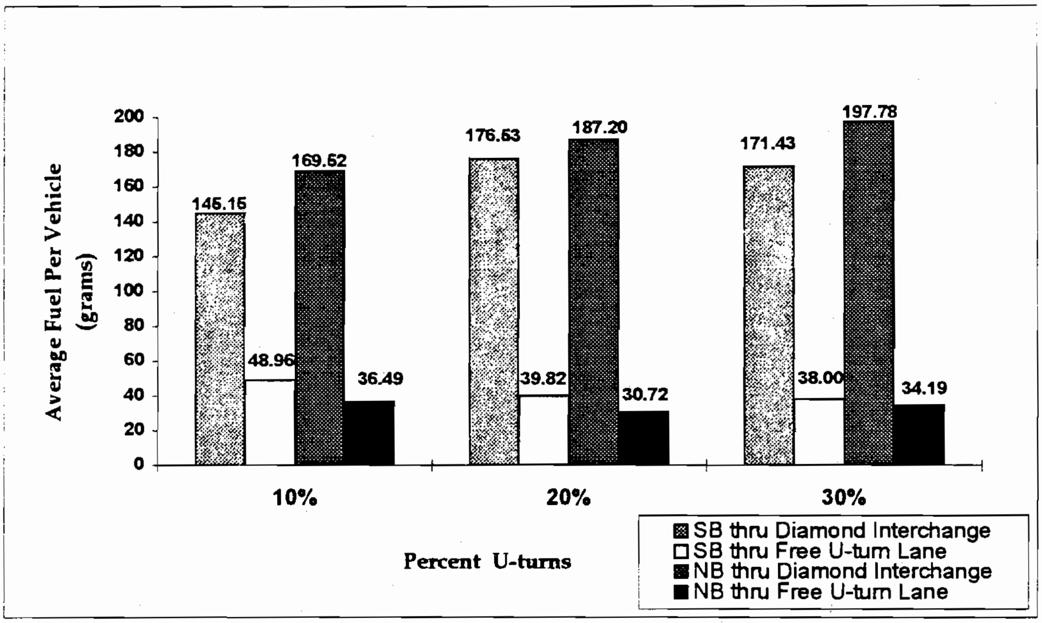

Figure 3.23 Average fuel per u-turing vehicle vs. percent u-turns for Ben White at IH-35

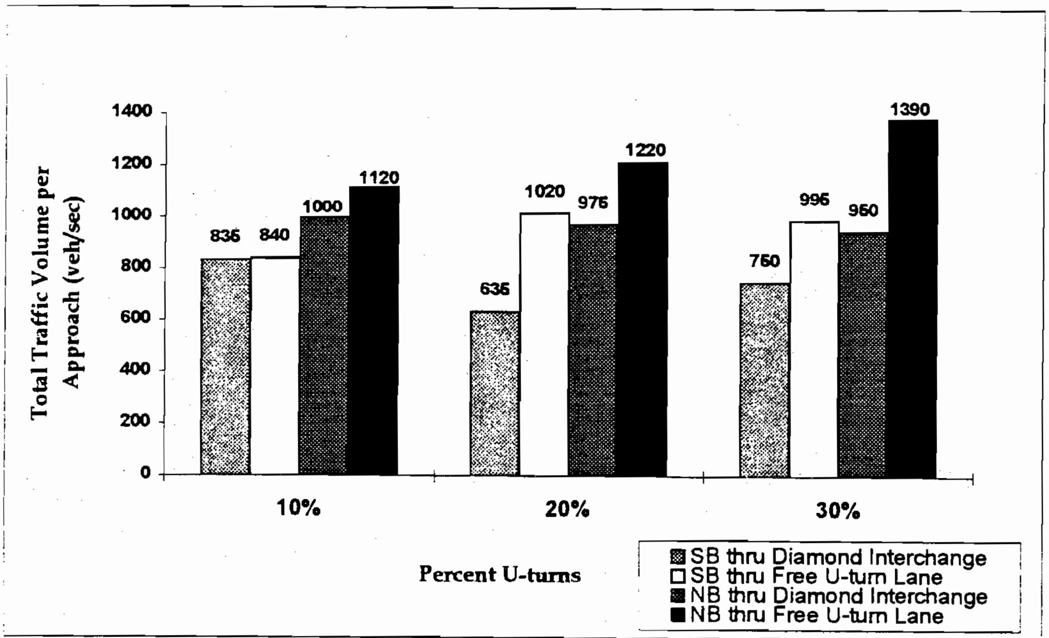

Figure 3.24 Total traffic volume processed per approach vs. percent u-turns for Ben White at IH-35

the number of vehicles processed on the approaches when free u-turn lanes were not provided was appreciably less than the actual traffic volume demand. Furthermore, the percentage of u-turn vehicles processed through the two intersections of the diamond interchange was less than the specified u-turn demand for the simulation, see Table C.6 in Appendix C. For instance, on the northbound approach these values were 5, 9, and 11 percent for the 10, 20 and 30 percent u-turn demand levels, respectively. Comparable values on the southbound approach were 6, 15, and 15 percent, respectively. However, the number of u-turning vehicles processed through the free u-turn lane was more than the specified u-turn demand for the simulation. The addition of free u-turn lanes increased the number of u-turning vehicles processed at this diamond interchange.

Figures 3.25 and 3.26 show the average total delay and average travel time for the u-turning vehicles under three u-turn demand traffic percentages at the Ben White interchange. The simulation results indicate that u-turning vehicles using the free u-turn lanes on the northbound approach experienced noticeably less delay than when traveling through the intersections. This delay decreased as the u-turn demand increased, indicating that the northbound approach experienced the formation of long queues. The highest total delay on the northbound approach for u-turning vehicles using both intersections of the diamond interchange was 559 seconds, more than 9 minutes of delay. The average travel time in this case was 649 seconds, more than 10 minutes. These values were for the 30 percent condition. Meanwhile, the maximum total delay for u-tuning vehicles using the free u-turn lane was 176 seconds, nearly 3 minutes of delay, with a total travel time of 255 seconds, more than 4 minutes. These values corresponded to the 10 percent condition.

As described previously in the case of St. Johns, for the u-turn demand experiment the percentages of the other traffic movements on the inbound approach were decreased as the u-turn demand increased, while the total traffic volume of the approach were kept constant. These means that there was a high number of vehicles on the inbound lanes forming long approach queues. Therefore, u-turning vehicles experienced significant delay on the inbound approach, which increased their overall total delay. As the percentages of the other traffic movements decreased the queue length decreased, thereby the total delay of u-turning vehicles using the separate u-turn lane decreased.

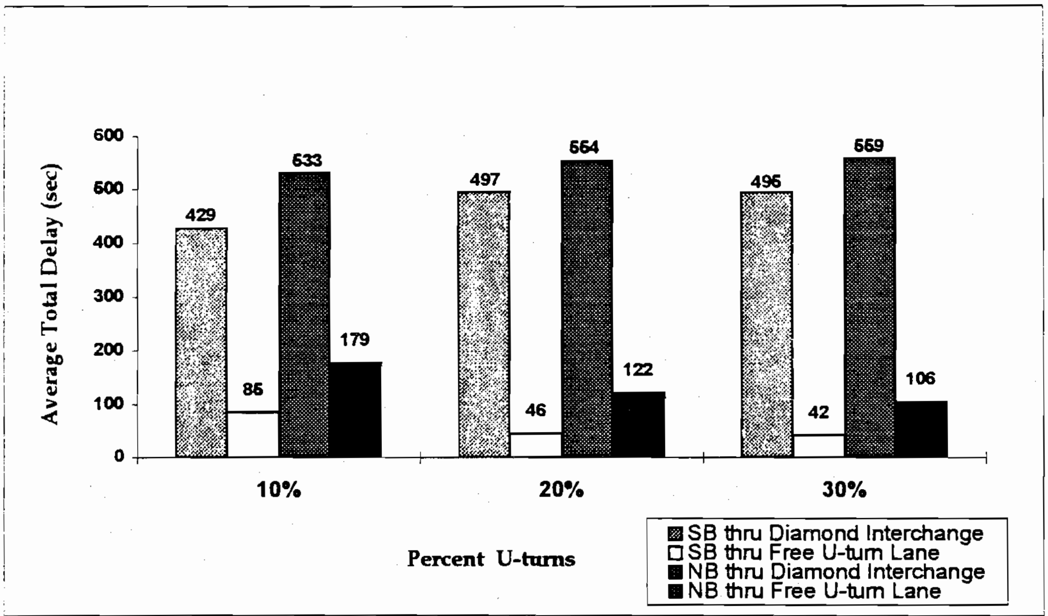

Figure 3.25 Average total delay per u-turing vehicle vs. percent u-turns for Ben White at IH-35

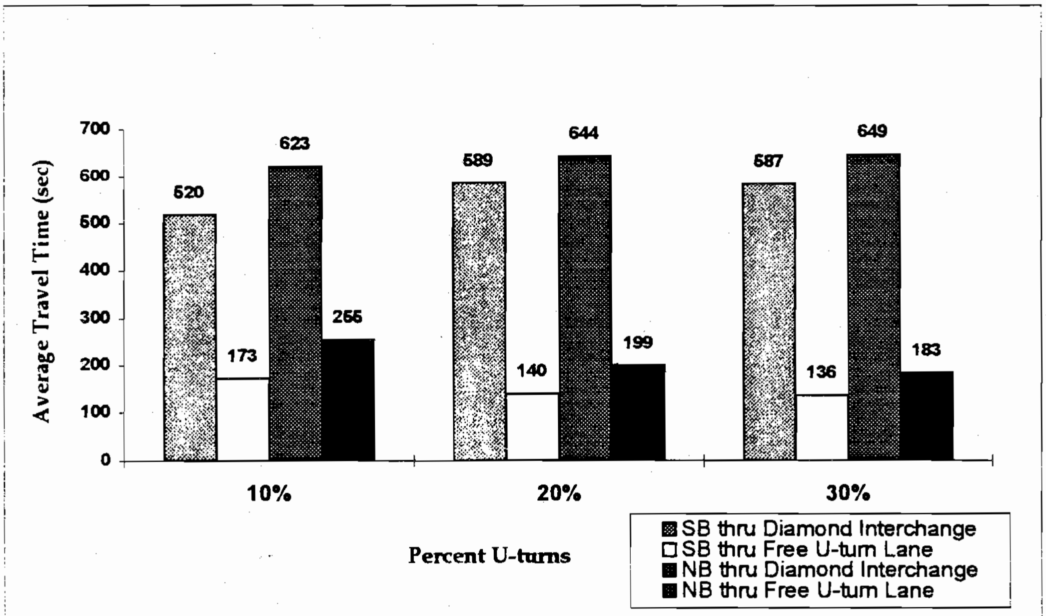

Figure 3.26 Average travel time per u-turning vehicle vs. percent u-turns for Ben White at IH-35

3.4 CASE STUDY 4 -- MLK AT 183

As described in Chapter 2, MLK is a special case for this study. The total traffic volume observed was very low, about 404 veh/hr on the northbound approach and 560 veh/hr on the southbound approach. Furthermore, its u-turn demand was less than 1% of the total approach traffic volume for both approaches. However, its geometric configuration was interesting. For instance, the diamond interior lanes were about 400 ft long, the largest diamond interchange configuration among the case studies. The cycle length of the traffic signal used for the simulation was 100 seconds. Approximately, 26 seconds of green time were allocated for the traffic movement on the southbound approach, and 12 seconds were allocated for the northbound approach.

3.4.1 Effect of Demand Traffic Volume

Free u-turn lanes were not simulated in the traffic volume experiment since the u-turn demand for MLK was less than 1 percent. Figure 3.27 shows the results for average fuel consumption along a u-turn path through the two diamond interchange intersections under the three traffic volume conditions. The simulation results show that average fuel consumption through this path was 88 grams/veh for the observed low-traffic flow level, for both approaches. This value increased significantly for the simulated medium- and high-traffic volume conditions. For instance, on the northbound approaches the fuel consumed on this u-turn path was 192 and 330 grams/veh, for the medium- and high-traffic volume conditions, respectively. The trend for the southbound approaches was similar. Higher traffic volume increased significantly the fuel consumption on the u-turn path.

The number of vehicles processed for all traffic demands on the northbound and southbound approaches at the MLK interchange during the TEXAS Model simulation is shown in Figure 3.28. The simulation results show that the maximum total traffic volume processed across the diamond interchange was less than the specified traffic volume demand for the simulation at the medium- and high-traffic volume levels. The high-traffic volume demands were 808 and 1118 veh/hr for the northbound and southbound approach, respectively. These indicate that 92 and 56 percent of the specified approach traffic volume, respectively, were simulated by the TEXAS Model in this experiment. This indicates that the observed traffic signal control used for the simulation did not provide adequate progression for these traffic volume conditions. This resulted in excessive fuel consumption and total delay.

Figures 3.29 and 3.30 show the average total delay and average travel time for the u-turning vehicles under three demand traffic volumes at the MLK interchange. The results show

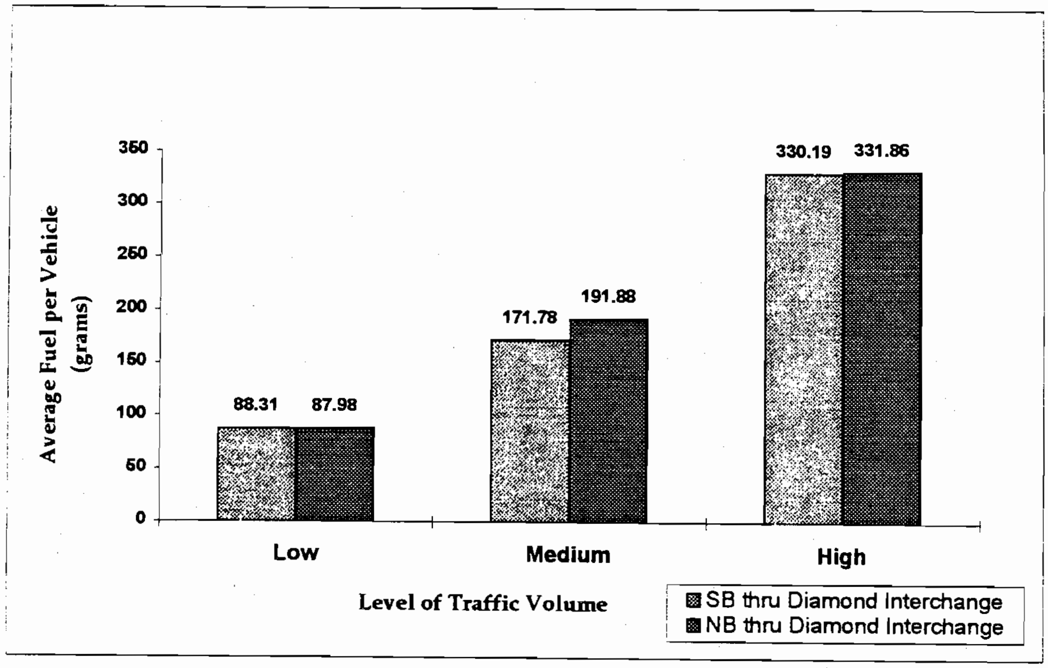

Figure 3.27 Average fuel per u-turning vehicle vs. volume for MLK at US-183

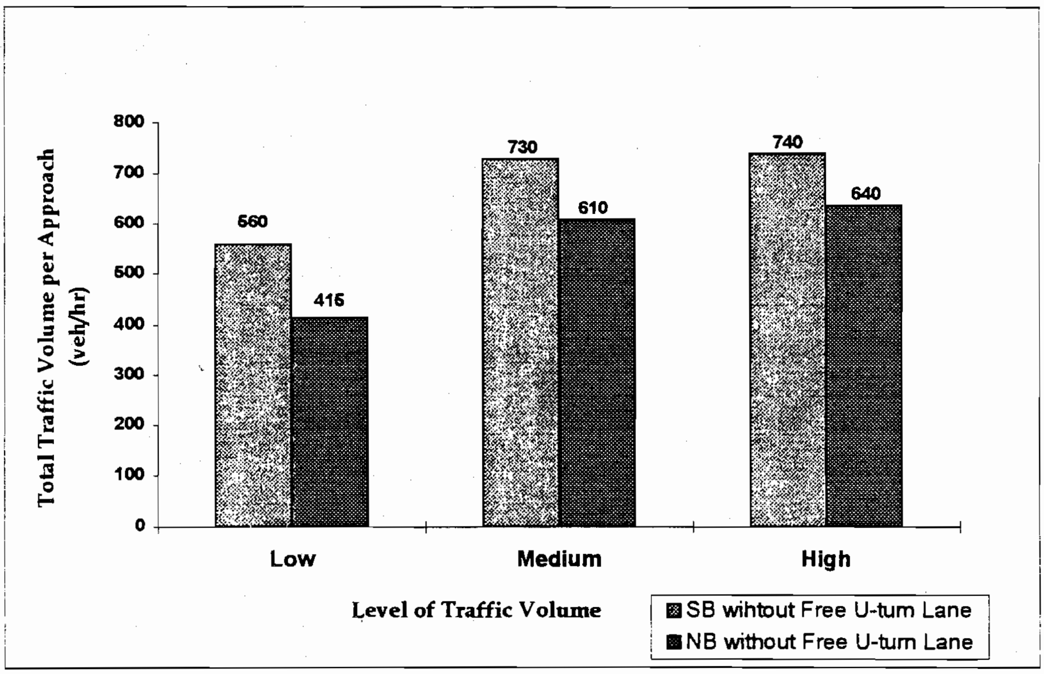

Figure 3.28. Total traffic volume processed per approach vs. volume for MLK at US-183

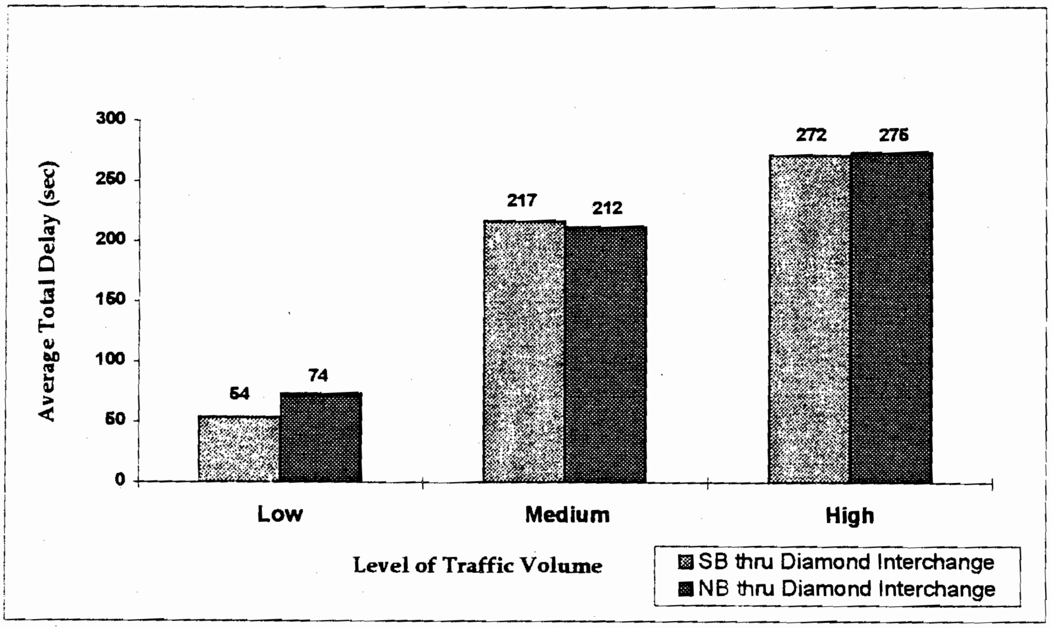

Figure 3.29 Average total delay per u-turning vehicle vs. volume for MLK at US-183

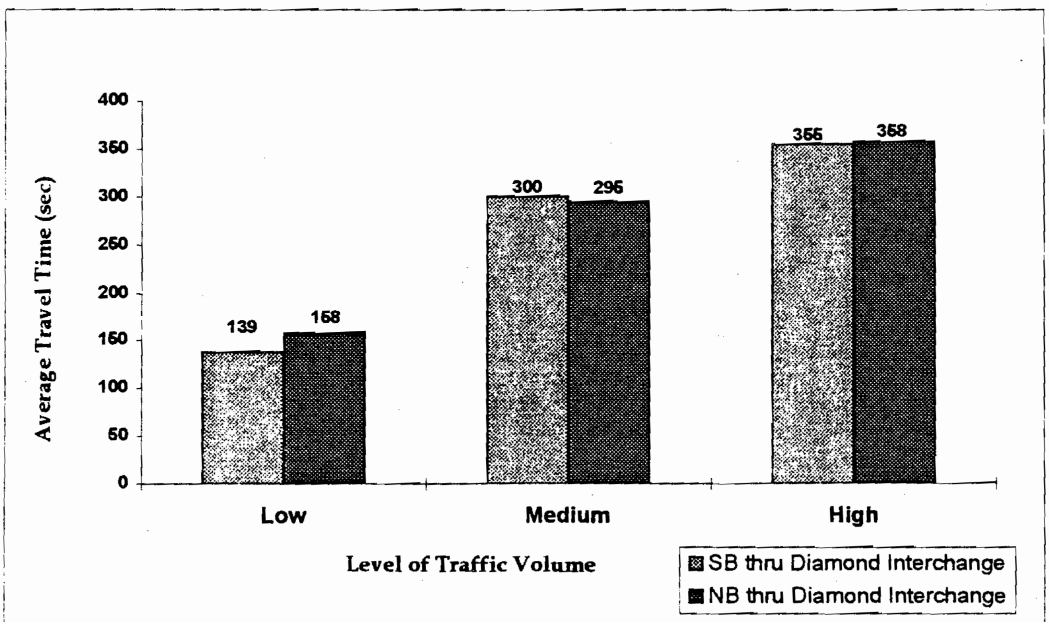

Figure 3.30 Average travel time per u-turning vehicle vs. volume for MLK at US-183

that significant total delay and travel time were experienced by vehicles traveling along the u-turn path through the diamond interchange, and these values increase with increasing traffic volume. The total delay was 74, 212, and 275 seconds on the northbound approach for the low, medium, and high traffic flow conditions, respectively. Travel time was 158, 295, and 358 seconds, respectively. These trends were similar for the southbound approach. As the traffic volume increased the total delay and travel time also increased; thereby, the fuel consumption by vehicles on this path also increased. These results show that the fuel consumption, total delay and travel time are affected by the operational control of the diamond interchange. In this case the traffic signal control used for the simulation was a pre-timed signal set up for low-traffic volume conditions. There was a significant increase in all these values when the traffic volume increased.

3.4.2 Effect of U-turn Demand

Figure 3.31 shows the effect of various u-turn traffic demands on average fuel consumption for u-turning vehicles when the MLK interchange operated under a high traffic volume level. The maximum fuel consumption on the free u-turn lane was 42 grams/veh, and the minimum value was 32 grams/veh for this diamond interchange. These values resulted from the 30 percent u-turn demand on the northbound approach and 10 percent u-turn demand on the southbound approach, respectively. The fuel consumed by u-turning vehicles on the free u-turn lane varied from 32 to 35 grams/veh on the northbound approach, and it varied from 35 to 42 grams/veh on the southbound approach. Meanwhile, the fuel consumed by u-turning vehicles going through the two intersections of the diamond interchange was within the same range of values. For instance, on the northbound approach the average fuel consumption on this path was 173, 180, and 176 grams/veh for the 10, 20, and 30 percent u-turn demands, respectively. The trends for the southbound approach were similar. The average amount of fuel consumed by a u-turning vehicle going through the diamond interchange did not change appreciably with u-turn traffic demand. This indicates that the traffic signal control influenced significantly the fuel consumed by u-turning vehicles going through the diamond interchange. Furthermore, the fuel consumption by u-turning vehicles for this diamond interchange was higher than in other cases, i.e. Braker Lane or St. Johns, because the size of this interchange was larger.

Figure 3.32 shows the number of vehicles processed for traffic on the northbound and southbound approaches for three u-turn demand levels. On the northbound approach, the percentages of u-turn demands processed without the free u-turn lane were 10, 18, and 23 percent for the 10, 20, and 30 percent, respectively. When free u-turn lanes were provided at the interchange, all the specified u-turn demands were processed without difficulty. See Appendix

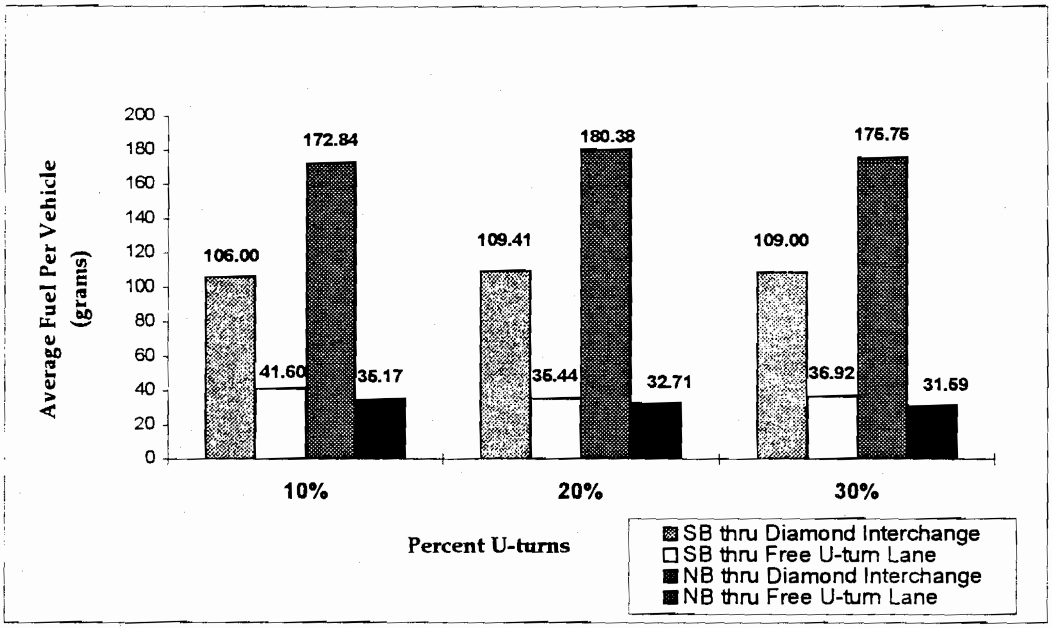

Figure 3.31 Average fuel per u-turning vehicle vs. percent u-turns for MLK at US-183

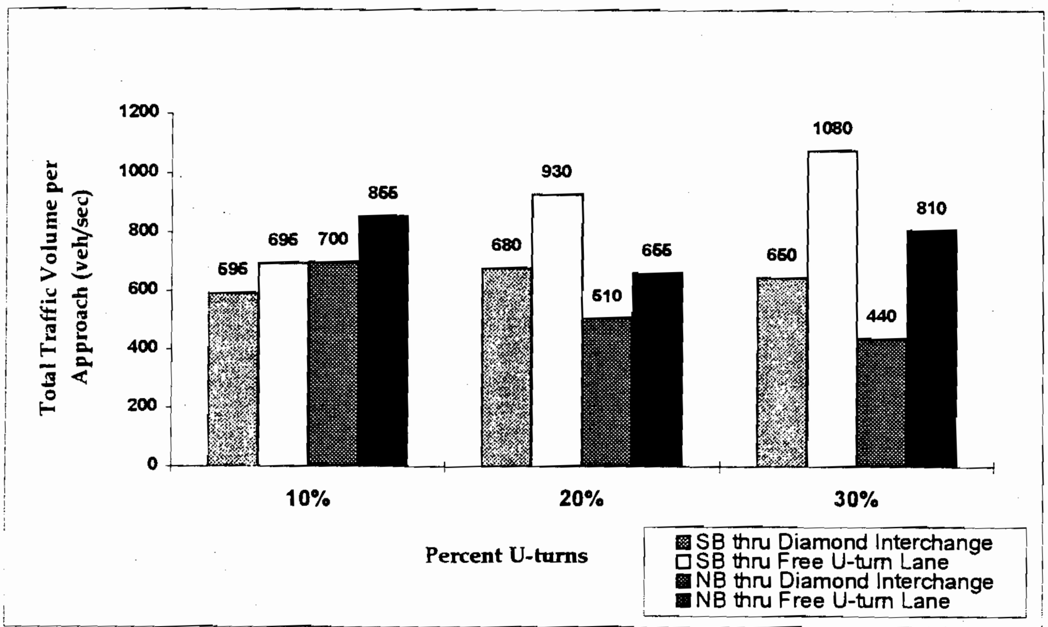

Figure 3.32 Total traffic volume processed per approach vs. percent u-turns for MLK at US-183

C, MLK simulation results for details. Furthermore, the number of vehicles processed through the approaches increased when free u-turn lanes were provided at the diamond interchange.

Figures 3.33 and 3.34 show the total delay and travel time for u-turning vehicles at three levels of u-turn demand. The simulation results indicate that high total delays and travel times were experienced by u-turning vehicles going through the two intersection of the diamond interchange. Meanwhile, these values were reduced when free u-turn lanes were added to the interchange. On the southbound approach, u-turning vehicles using the free u-turn lane experienced significant delay caused by the formation of long approach queues. The total delay of u-turning vehicles on the free u-turn lane decreased as the u-turn demand increased, on the southbound approach.. As described in previous case studies, for the u-turn demand experiment the percentages of u-turn demand increased as the other traffic volume demand decreased. Therefore, at a low u-turn demand level, u-turning vehicles experienced significant delay caused by the formation of long queues by the other traffic volume on the approach. As the traffic volume of other movements on the approach decreased the queue length on the approach decreased, therefore reducing the overall total delay of u-turning vehicles using a free u-turn lane.

3.5 CASE STUDY 5 -- MCRAE

The existing geometric configuration of McRae does not include separate u-turn lanes on any of its approaches. The total traffic volume observed on the eastbound approach was 2000 veh/hr, a saturated traffic flow condition. Its u-turn demand was only 6 percent of the total traffic volume. On the westbound approach the total traffic volume was 1228 veh/hr, with 5 percent observed u-turn demand. The observed traffic signal cycle length for this diamond interchange was 140 seconds. Approximately, 40 seconds of green time were allocated for the traffic movement of the eastbound approach, and 30 seconds for the westbound approach. Tables C.9 and C.10 in Appendix C summarizes the simulation results of the TEXAS Model for this diamond interchanges. The results are described here.

3.5.1 Effect of Demand Traffic Volume

Figure 3.35 shows the simulation results for average fuel consumption by u-turning vehicles at McRae interchange under three traffic volume conditions, with and without (existing geometry) free u-turn lanes. These results indicate that the maximum average fuel consumption on the free u-turn lane was 16 grams/veh, and the minimum was 11 grams/veh. Both values resulted from the simulated medium-traffic volume conditions on the eastbound and westbound approaches, respectively. For the low and high-traffic volume levels, average fuel consumption

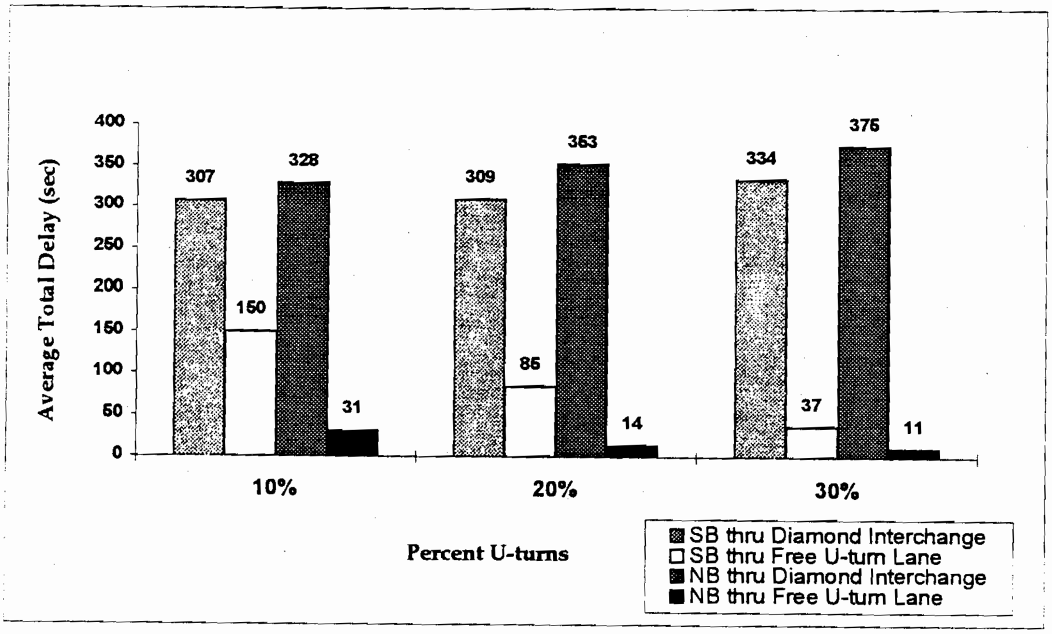

Figure 3.33 Average total delay per u-turning vehicle vs. percent u-turns for MLK at US-183

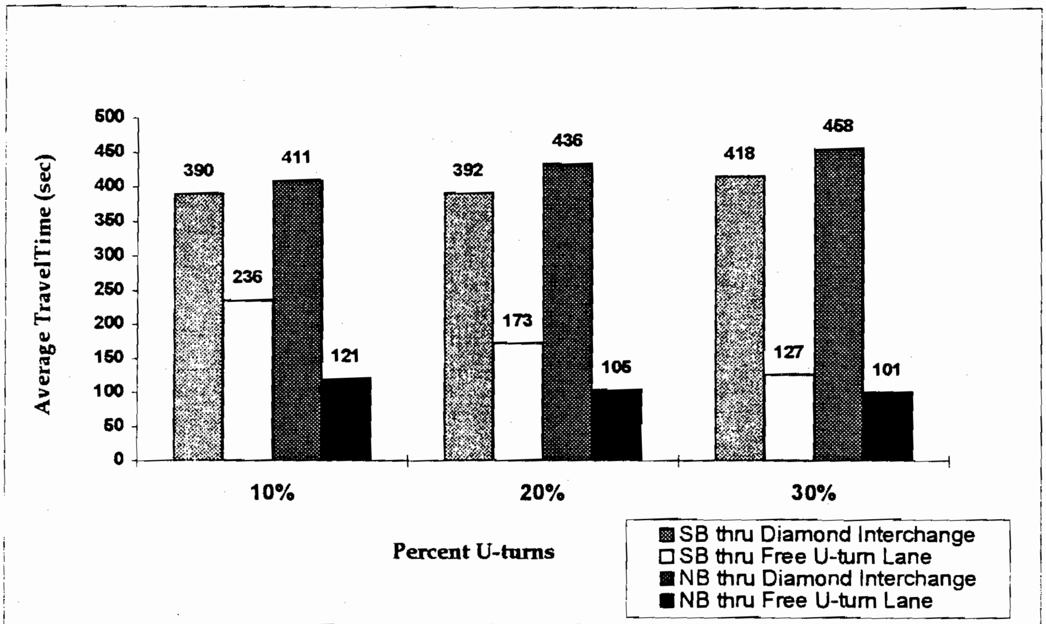

Figure 3.34 Average travel time per u-turning vehicle vs. percent u-turns for MLK at US-183

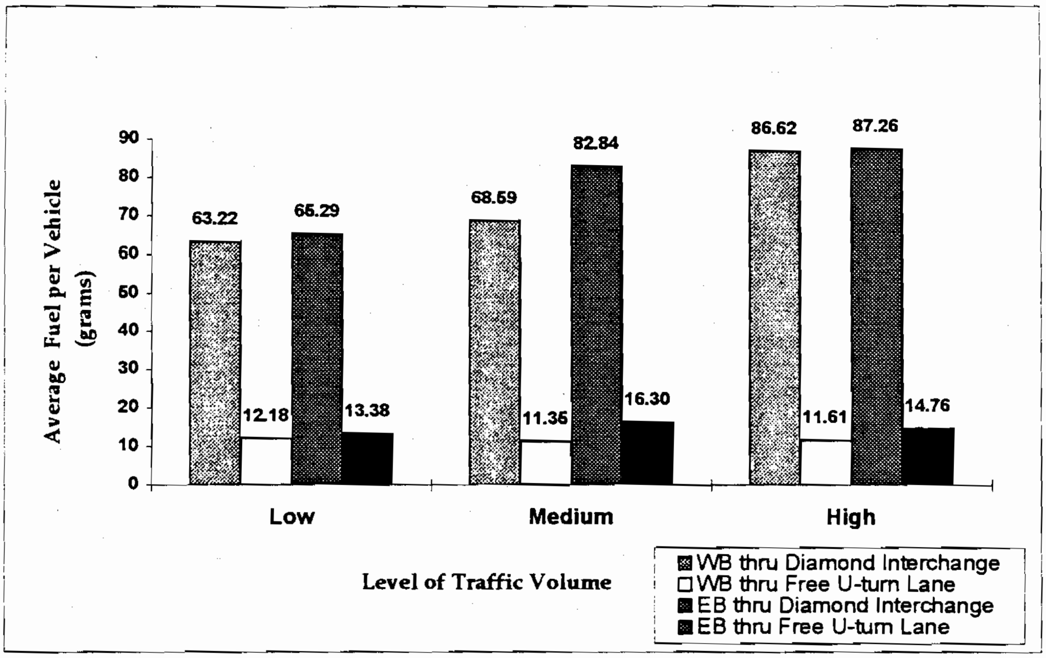

Figure 3.35 Average fuel per u-turning vehicle vs. volume for McRae at IH-10

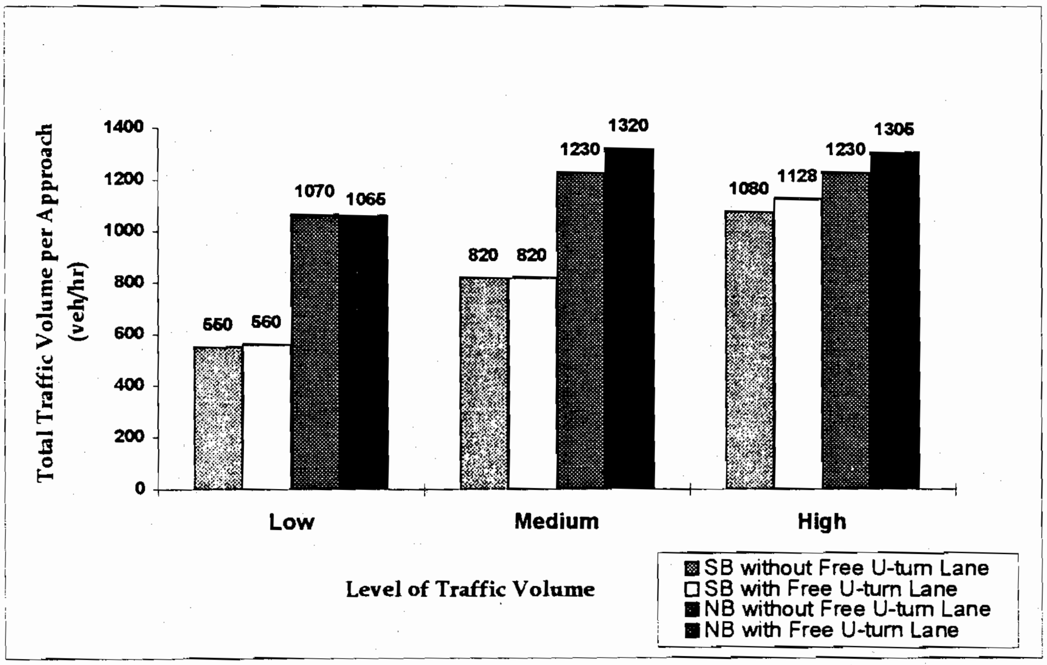

Figure 3.36 Total traffic volume processed per approach vs. volume for McRae at IH-10

on the free u-turn lanes varied from 17 to 20 grams/veh. Meanwhile, the simulation results show that the maximum fuel consumption by u-turning vehicles using the two intersections to reverse direction was 87 grams/veh, and the minimum value was 63 grams/veh. Thus, use of free u-turn lanes represented savings in fuel of 83 and 81 percent, respectively, as compared to making u-turns through the two intersections. Comparison of the data in Figure 3.35 shows that the fuel consumed by vehicles using the free u-turn lane was noticeably less than the fuel consumed by u-turning vehicles going through the two diamond interchange intersections. Change in demand volume did not affect fuel consumption appreciably on either free u-turn lane for this case study. However, the fuel consumed by u-turning vehicles going though the two intersections of the diamond interchange increased as the traffic volume level increased.

The number of vehicles processed for all traffic demand levels on the eastbound and westbound approaches at the McRae interchange during the TEXAS Model simulation is shown in Figure 3.36. The number processed on the westbound approach did not change significantly with the addition of free u-turn lanes to the diamond interchange; the height of each bar in the pair is about the same. Comparable values on the eastbound approach showed an appreciable increase when a free u-turn lane was provided for the simulated medium- and high-traffic volume conditions. However, the number of vehicles processed by the model during the 15 minutes of simulation time was considerably less than the observed total traffic volume of 2000 veh/hr. This resulted from the formation of long queues on the approaches during simulation. Queue length exceed the 800-ft length of the simulated inbound approach. As discussed in previous case studies, the results show that the TEXAS Model has problems simulating high traffic demand using the default model simulation parameters, see Chapter 2 for details. This situation would be improved by adjusting the simulation parameters to the observed traffic conditions, which is out of the scope of this study. Default values were used in all simulation, however, model simulation parameters such as approach speed, car following equation parameters, headway distribution, type of vehicles, and driver specifications among others can be modify as needed in the TEXAS Model.

Figures 3.37 and 3.38 show the average total delay and average travel time for the u-turning vehicles under three demand traffic volumes at the McRae interchange. The u-turning vehicles experienced very small delay when they used the free u-turn lane to perform the maneuver. An exception was the average total delay on the eastbound approach for the simulated medium- and high-traffic volume conditions. In these cases total delay for u-turning vehicles using the free u-turn lane was 56 and 187 seconds, respectively; about 1 and 3 minutes of delays. The total travel time was 130 and 260 seconds, about 2 and 4 minutes,

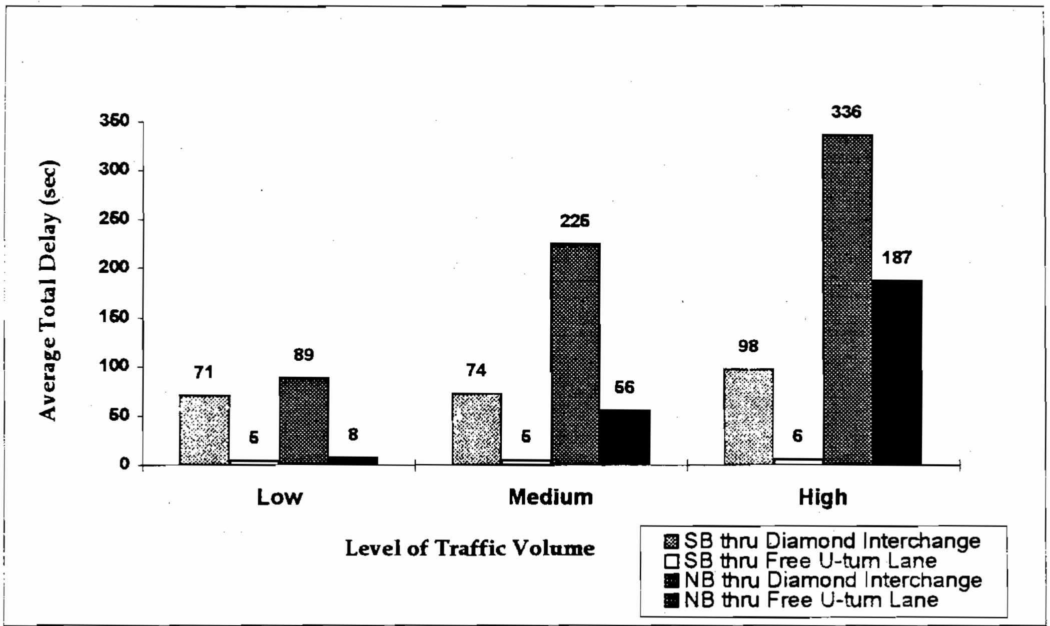

Figure 3.37 Average total delay per u-turning vehicle vs. volume for McRae at IH-10

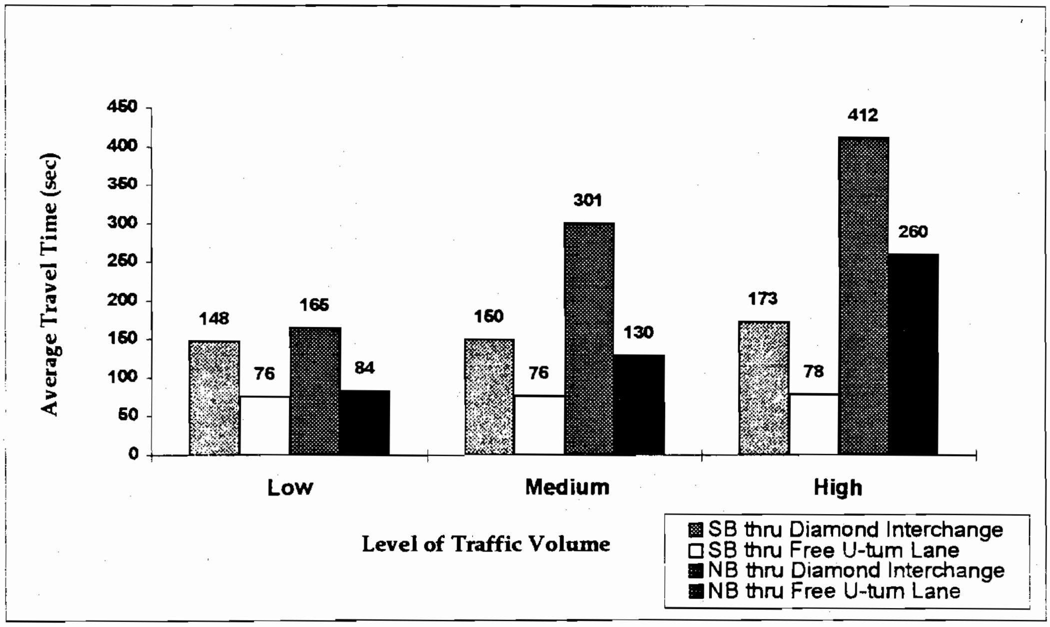

Figure 3.38 Average travel time per u-turning vehicle vs. volume for McRae at IH-10

correspondingly. This indicates that under these traffic volume conditions the eastbound approach experienced long queues, causing significant delays to u- turning vehicles on the inbound approach. However, these delays were still noticeably less than u-turning vehicles reversing direction through the two diamond interchange intersections. The average total delay for u-turning vehicles through this path was 225 and 336 seconds, more than 3 and 5 minutes of delays, with travel times of 301 and 412 seconds, about 5 and 7 minutes. U-turning vehicles saved about 2 minutes of delay, and about 3 minutes of travel time when using the free u-turn lane.

3.5.2 Effect of U-turn Demand

Figure 3.39 shows the effect of various u-turn traffic demands on average fuel consumption for u-turning vehicles when McRae interchange operated under a high traffic volume level and the observed traffic signal control. The simulation results show that the average fuel consumed by u-turning vehicles going through the diamond interchange increased as the u-turn demand increased. For instance, on the westbound approach the average fuel consumption by u-turning vehicles on this path was 99, 108, 124 grams/veh for the 10, 20, and 30 percent u-turn demands, respectively. Meanwhile, comparable values for u-turning vehicles using the free u-turn lane were 16, 16, and 17 grams/veh. This indicates potential fuel savings of 84, 85, and 86 percent, correspondingly, as compared to making u-turns through the two intersections. The trends for the eastbound approach were similar. The average fuel consumption by u-turning vehicles going through the diamond interchange increased at higher u-turn demand levels; however, the fuel consumed by u-turning vehicles using the separate u-turn lane did not change noticeably with u-turn traffic demand.

Table C.10 in Appendix C shows that the maximum percentage of u-turning vehicles processed through the two intersections of the diamond interchange was 21 percent, for the 30 percent u-turn demand conditions at McRae interchange, using the observed traffic signal control. However, when free u-turn lanes were simulated this high u-turn demand was processed without a problem. The use of free u-turn lanes increased the capacity of the diamond interchange to handle high u-turn demand without affecting normal diamond interchange operation. Figure 3.40 shows the number of vehicles processed for traffic on the eastbound and westbound approaches for three u-turn demand levels. Without free u-turn lanes the number of vehicles processed through the two diamond interchange intersections decreased as the u-turn demand increased. Conversely, the number of vehicles processed on these approaches increased as the u-turn demand increased, when free u-turn lanes were provided. Figures

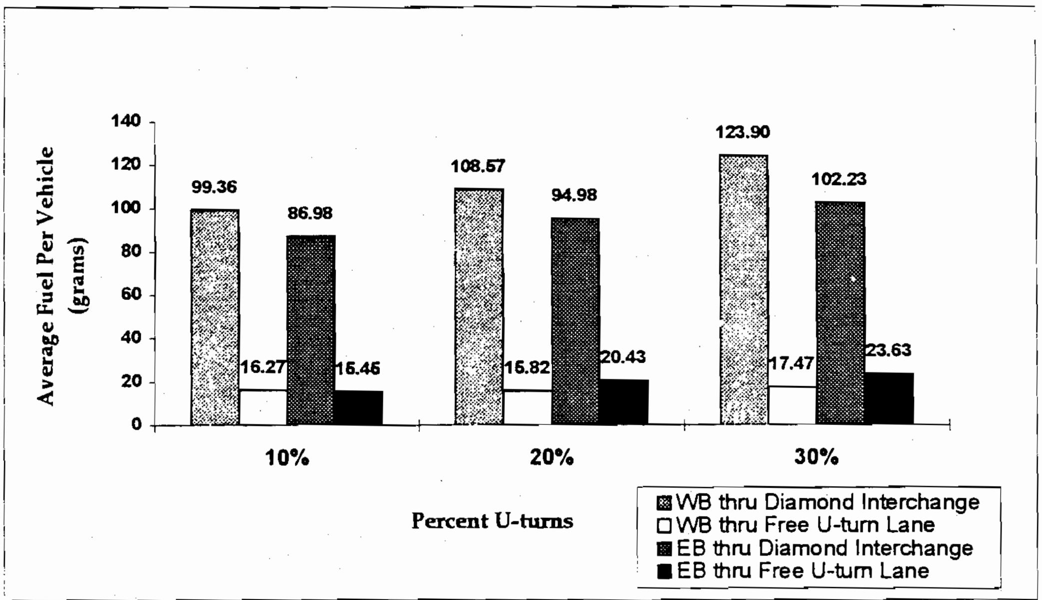

Figure 3.39 Average fuel per u-turning vehicle vs. percent u-turns for McRae at IH-10

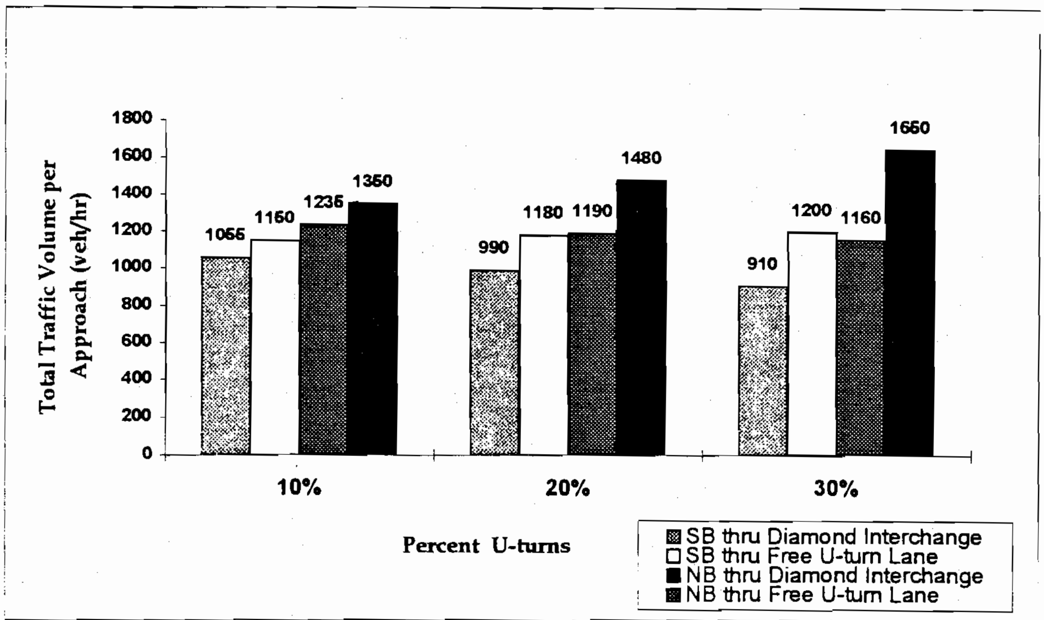

Figure 3.40 Total traffic volume processed per approach vs. percent u-turns for McRae at IH-10

3.41 and 3.42 show the results of the simulation for average total delay and average travel time for u-turning vehicles at three levels of u-turn demand. The maximum total delay through the diamond interchange was 392, more than 6 minutes, for the 30 percent u-turn demand level. Correspondingly, the average travel time was 468 seconds, more than 7 minutes. Meanwhile, the average total delay to u-turning vehicle on the eastbound approach decreased significantly as the u-turn demand increased for u-turning vehicles using the free u-turn lane. Those delays were 150, 115, and 87 seconds for the 10, 20, and 30 u- turn demand levels, respectively. This correspond to an average travel time of 222, 187, and 161 seconds. These results indicate that the traffic signal control and other traffic caused significant delay to u-turn traffic. Also, it demonstrates that free u-turn lanes significantly reduced delay to u-turning vehicles.

3.6 Case Study 6 -- Lee Trevino

The geometric configuration of Lee Trevino does not include free u-turn lanes on any of its approaches. The total traffic volume observed on the eastbound approach was 1776 veh/hr, during peak hour, and u-turn demand was 4 % . The total traffic volume of the westbound approach was 864 veh/hr, with u-turn demand of 5 %. The existing cycle length of the traffic signal was 140 seconds. Approximately, 40 seconds of green time were allocated for the traffic movement on the eastbound approach, and 25 seconds were allocated for the westbound approach. Tables C.11 and C.12 summarize the results of the TEXAS Model simulations for this case study. These results are described below.

3.6.1 Effect of Demand Traffic Volume

Figure 3.43 shows the simulation results for average fuel consumption by u-turning vehicles at Lee Trevino under three traffic volume conditions, with and without (existing geometry) separate free u-turn lanes. These indicate that the maximum average fuel consumption on a free u-turn lane was 29 grams/veh, and the minimum value was 14 grams/veh for this diamond interchange. These values correspond to the simulated low and medium conditions on the eastbound and westbound approaches, respectively. For the westbound approach, average fuel consumption on the free u-turn lanes varied from 14 to 17 grams/veh, and it varied from 26 to 29 grams/veh on the eastbound approach. Meanwhile, the simulation results show that the maximum average fuel consumption by u-turning vehicles using the two intersections to reverse direction was 94 grams/veh, and the minimum value was 60 grams/veh. Thus, use of free u-turn lanes represented savings in fuel of 72, and 71 percent, respectively, as compared to making u-turns through the two intersections. Comparison of the data in Figure 3.43

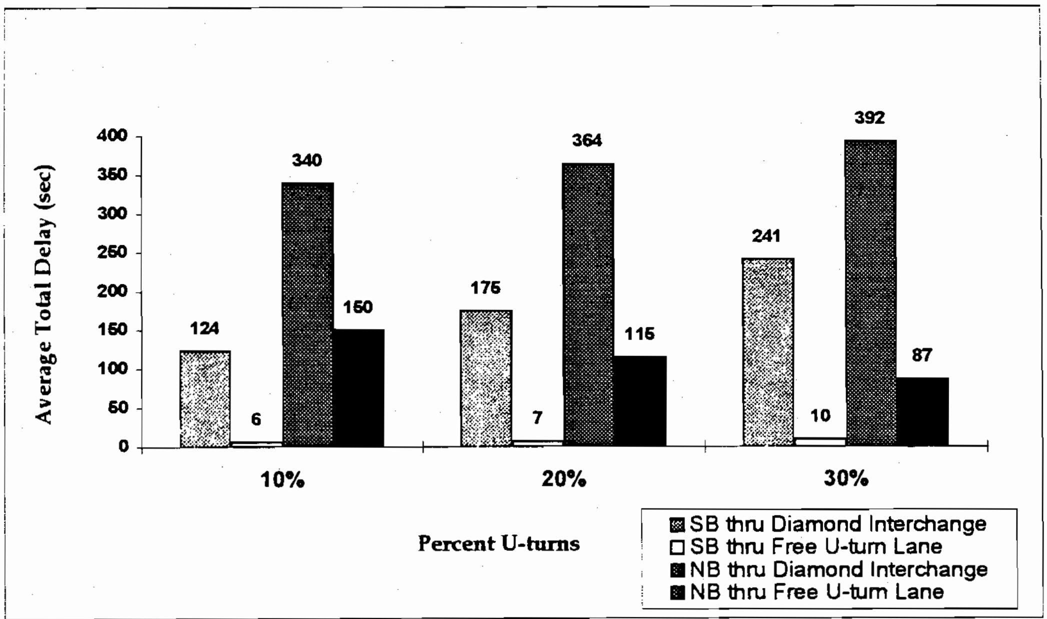

Figure 3.41 Average total delay per u-turning vehicle vs. percent u-turns for McRae at IH-10

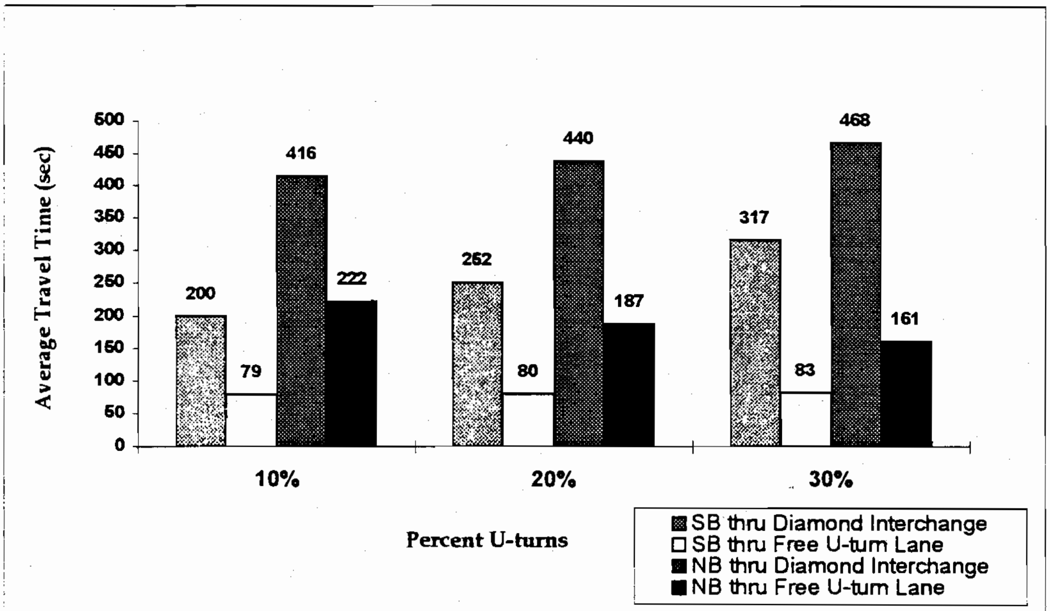

Figure 3.42 Average travel time per u-turning vehicle vs. percent u-turns for McRae at IH-10

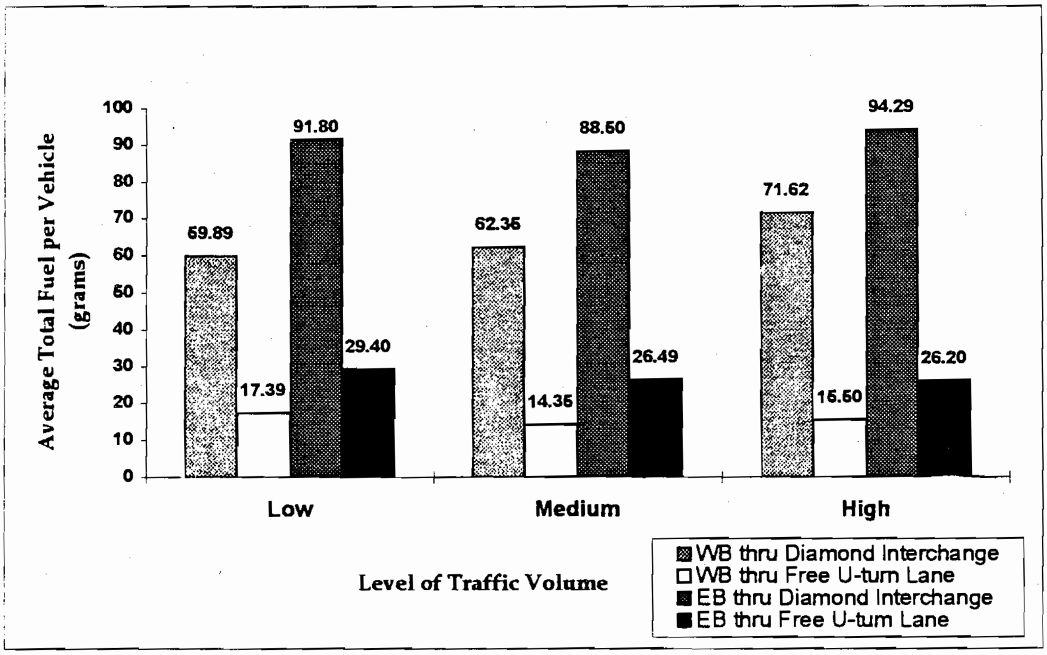

Figure 3.43 Average fuel per u-turning vehicles vs volume for Trevino at IH-10

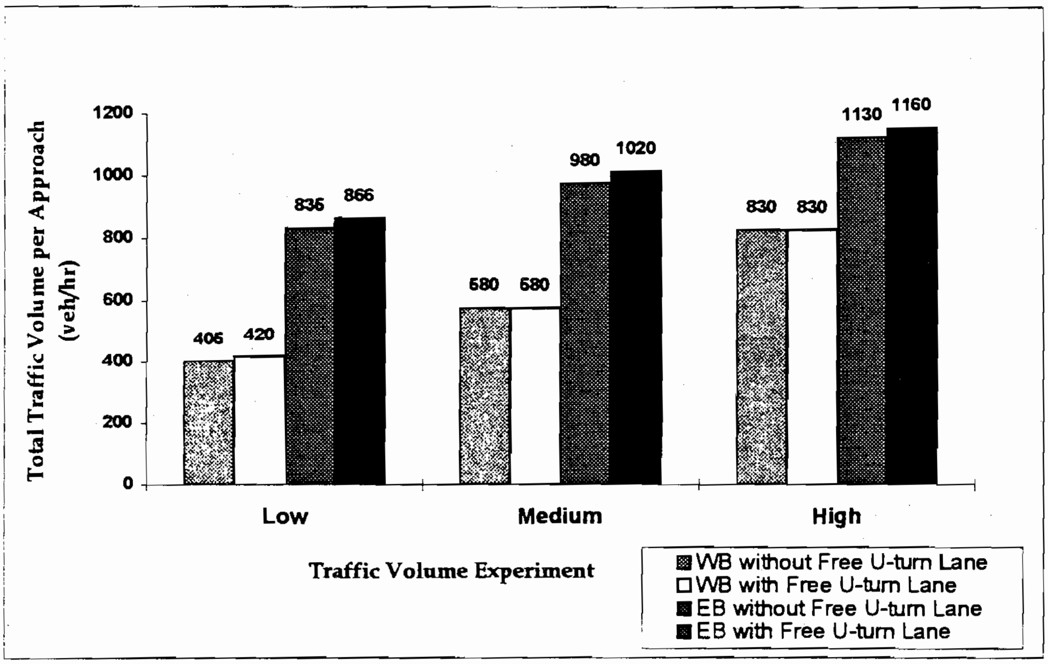

Figure 3.44 Total traffic volume processed per approach vs. volume for Trevino at IH-10

shows that the fuel consumed by u-turning vehicles using the free u-turn lane was noticeably less than the fuel consumed by vehicles going through the two intersections of the diamond interchange. Change in demand volume did not affect the fuel consumption appreciably on either free u-turn lane for this case study. However, the fuel consumption for u-turning vehicles using the two intersections of the diamond interchange on the westbound approach increased as the traffic volume level increased.

Figure 3.44 shows the number of vehicles processed for all traffic demand levels on the eastbound and westbound approaches at the Lee Trevino interchange. On both approaches the number of vehicles processed did not change significantly with the addition of free u-turn lanes to the diamond interchange; the height of each bar in the pair is about the same. This resulted from the small u-turn demand on the approaches in proportion to a high-traffic volume demand, specially the eastbound. The maximum number of vehicles processed on the eastbound approach was 1160 veh/hr, less than the observed traffic volume demand, 1776 veh/hr. This indicates that traffic signal control caused the formation of queues longer than the 800-ft length of the simulated approach lane. As a consequence, vehicles waiting at the back of the queue to enter into the simulation scheme were discarded by the model, thereby reducing the number of vehicles processed during the simulation.

Figures 3.45 and 3.46 show the average total delay and average travel time for u-turning vehicles under the three traffic demand levels. On the westbound approach, u-turning vehicles experienced very little delay when they used the free u-turn lane. Conversely, on the eastbound approach, u-turning vehicles experienced significant delay with and without free u-turn lanes. This was caused by the long approach queues. However, the average total delay for u-turning vehicles using the free u-turn lane was significantly less than the delay for u- turning vehicles through the two intersections of the diamond interchange. For instance, at the high-traffic volume level, the average total delay for u-turning vehicles through the interchange was 402 seconds, more than 6 minutes, and average travel time of 478 seconds, about 8 minutes. Meanwhile, on the free u-turn lane these values were 237 seconds, about 4 minutes of delay, and 402 seconds (more than 6 minutes) of travel time. This represents savings of greater than 2 minutes. Similar savings can be observed from the other simulated low and medium-traffic volume conditions.

3.6.2 Effect of U-turn Demand

Figure 3.47 shows the effect of various u-turn demand traffic volume on the average fuel consumption for u-turning vehicles when the Lee Trevino interchange operated under a high traffic volume level using the existing traffic signal control. The simulation results indicate that the

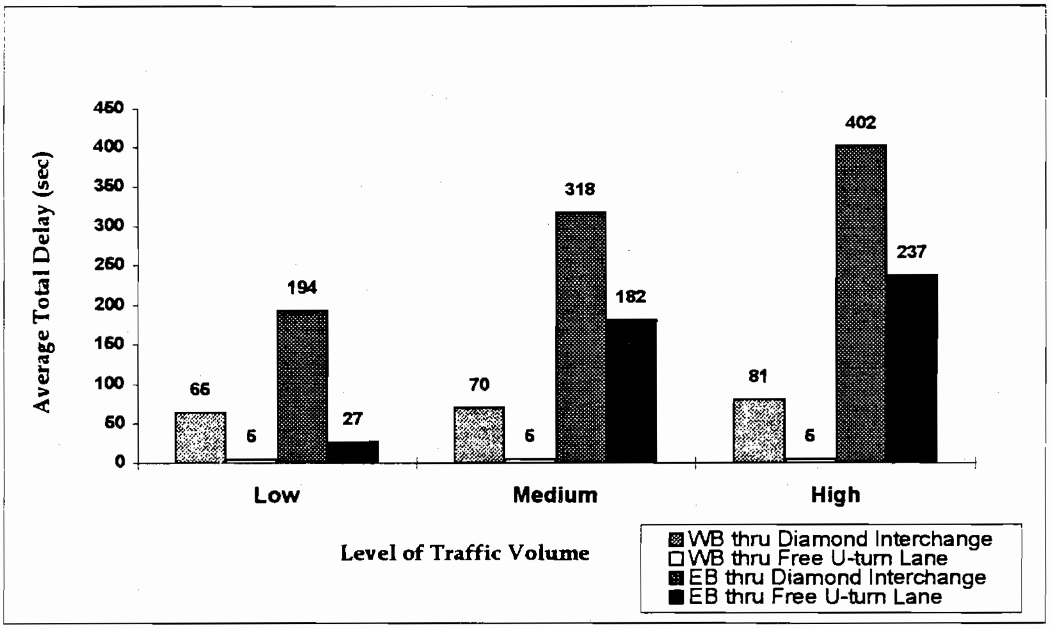

Figure 3.45 Average total delay per u-turning vehicle vs. volume for Trevino at IH-10

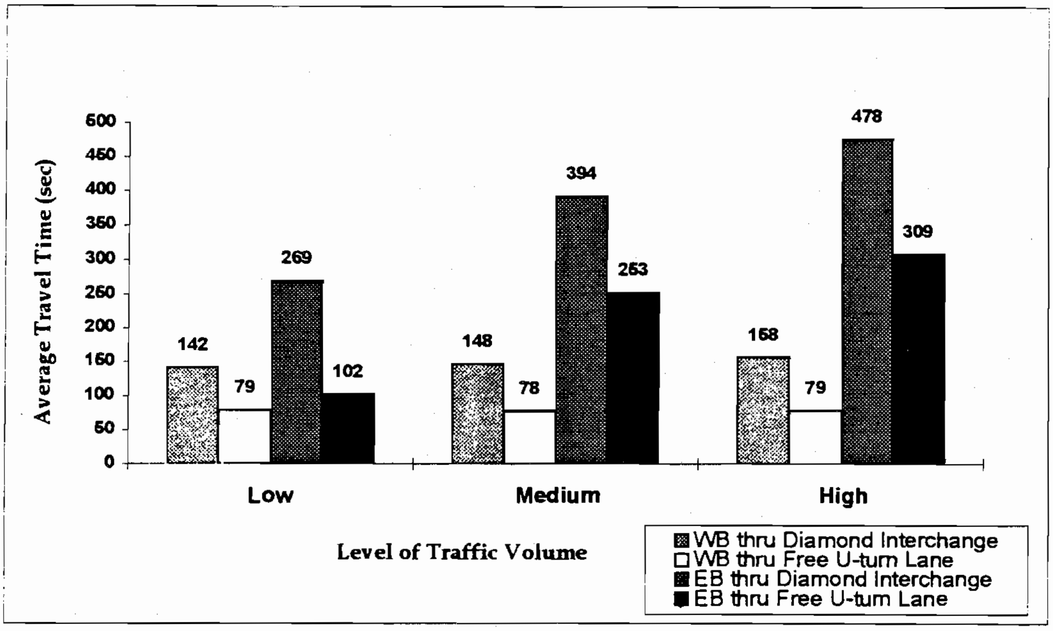

Figure 3.46 Average travel time per u-turning vehicle vs. volume for Trevino at IH-10

average fuel consumption through the two diamond interchange intersections on the eastbound approach did not change appreciably with change in u-turn demand volume. The average fuel consumption on this path was about was 82 grams/veh. On the westbound approach this value was 68, 81, and 86 grams/veh for the 10, 20, and 30 percent levels. These results show a slight change in average fuel consumption by u-turning vehicles going through the two intersections for the simulated 20 and 30 percent u-turn demand conditions. Comparable values of average fuel consumed by u-turning vehicles on a free u-turn lane was not affected by change in u-turn demand. The average fuel consumption on the free u-turn lanes was between 16, 17, and 18 grams/veh on the westbound approach, and 24, 27, and 25 grams/veh on the eastbound approach for the three simulated u-turn demand, respectively.

Table C.12 in Appendix C shows the percentages of u-turn demand processed during the 15 minutes of simulation time using the existing traffic signal control. The results show that the westbound approach, total traffic volume of about 860 veh/hr, handled three u-turn demands without difficulties with and without free u-turn lanes. However, on the eastbound approach (total traffic volume of 1776 veh/hr) the results show that the maximum percentages of u-turn demand processed during the simulation were 15 and 21 percent without the free u-turn lane, and 17 and 22 percent with free u-turn lane for the 20 and 30 percent conditions. This indicates the formation of queues longer than the 800-ft length of the inbound approach lanes, causing a significant amount of u-turn vehicles were discarded by the model. Figure 3.48 shows the number of vehicles processed for traffic on the eastbound and southbound approaches for three u-turn demand levels. Without free u-turn lanes the number of vehicles processed decreased as the u-turn demand increased. On the other hand, the number of vehicles processed on the approaches increased as the u-turn demand increased, when free u-turn lanes were provided. This increment is appreciably larger on the eastbound approach. This indicates that use of free u-turn lanes improve the capacity of the diamond interchange, specially when the u-turn demand is high.

Figures 3.49 and 3.50 show the simulation results for the average total delay and average travel time for u-turning vehicles at the three u-turn demand levels. The average total delay through the diamond interchange on the eastbound approach was about 400 seconds, almost 7 minutes. This corresponds to an average travel time of about 475 seconds, almost 8 minutes. These values were about the same for the three simulated u-turn demand conditions. As mentioned, the simulated traffic flow conditions were similar for the three levels of u-turn demand. These results indicate that the traffic signal control and the other traffic affected significantly the operation of u-turning vehicles through this diamond interchange.

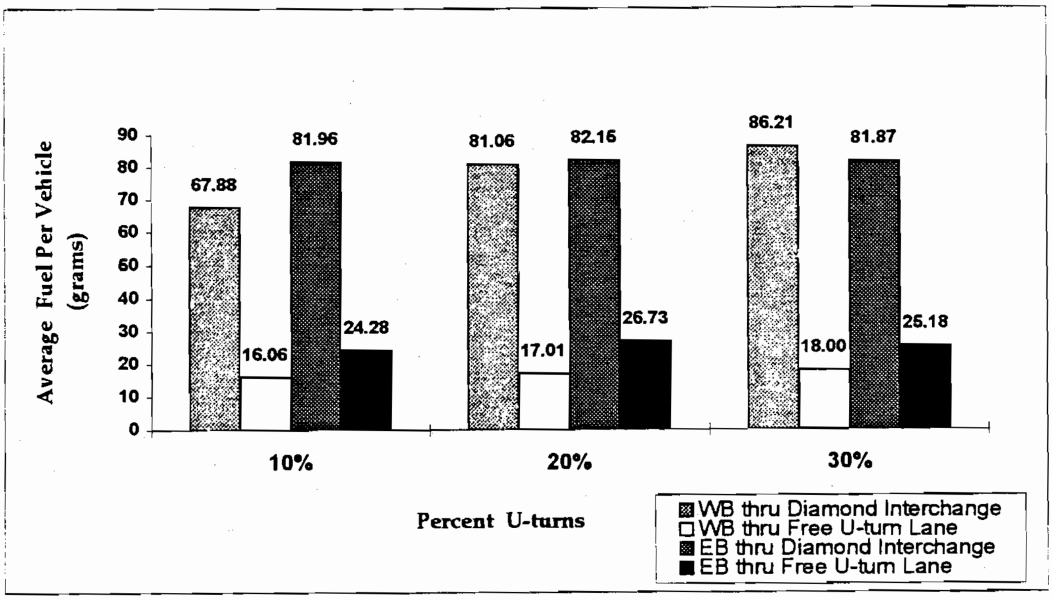

Figure 3.47 Average fuel per u-turning vehicle vs. percents u-turn for Trevino at IH-10

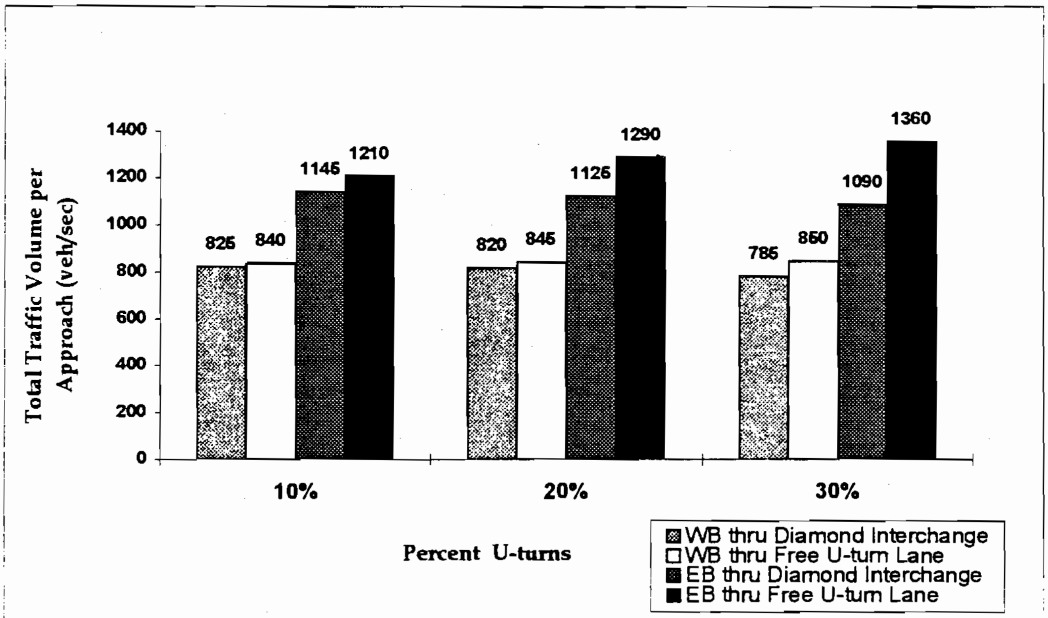

Figure 3.48 Total traffic volume processed per approach vs. percent u-turns for Trevino at IH-10

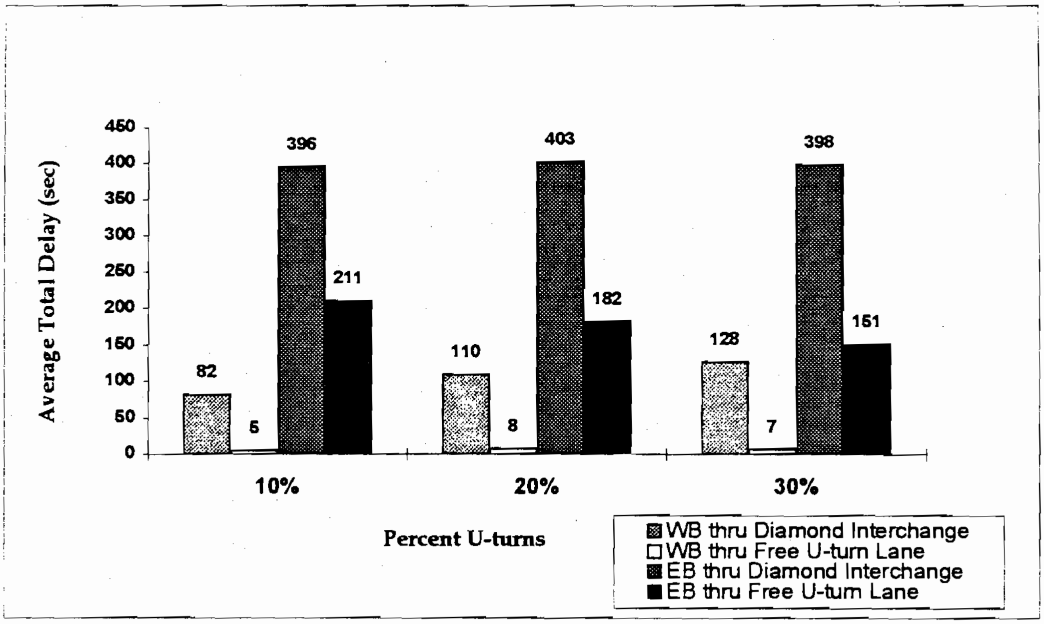

Figure 3.49 Average total delay per u-turning vehicle vs. percent u-turns for Trevino at IH-10

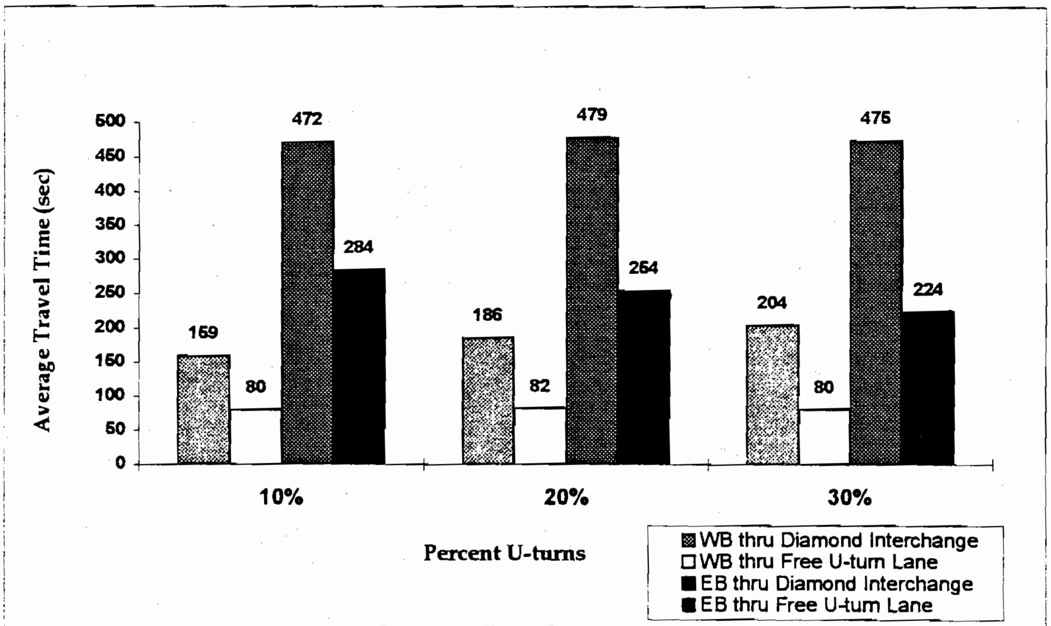

Figure 3.50 Average travel time per u-turning vehicle vs. percent u-turns for Trevino at IH-10

CHAPTER 4. SUMMARY, CONCLUSION AND RECOMMENDATIONS

4.1 SUMMARY

Six diamond interchanges, with and without free u-turn lanes, were selected as case studies for this research. Field surveys were made to gather information about the existing geometry, traffic volumes, and signal timing at each site. Traffic volume data were collected between 4 and 6 P.M.. The observed signal timing at each diamond interchange was used throughout a series of more than 2000 runs of the TEXAS Model for Intersection Traffic, Version 3.2. The emissions processor, EMPRO, was used to examine fuel consumption by mixed combinations of vehicles in two experiments.

In one experiment, three levels of traffic demand volume on each external approach were used: high (observed level of traffic volume for the majority of the case studies), medium (70% of the observed traffic volume), and low (50% of the observed traffic volume). The u-turn demand volume was simulated as a percentage of the respective approach volume, and was held constant at the percentage observed in the field on each external approach during peak-hour traffic. For the other experiment, the high traffic volume (observed) was used for each external approach, and three levels of u-turn demand were simulated: low (10%), medium (20%), and high (30%). The case studies were simulated with and without free u-turn lanes. When free u-turn lanes were simulated, all u-turning vehicles were forced to perform the u-turn movement using the free u-turn lane.

4.1.1 Traffic Volume Experiment

The objective of the *traffic volume experiment* was to estimate the average fuel consumption of u-turning vehicles at a diamond interchange under three traffic volume levels with other variables held constant. The results of this experiment showed that the average fuel consumed by a u-turning vehicle going through the two diamond interchange intersections was within the range of 70 to 120 grams/veh in three of the four cases where free u-turn lanes were not provided. Average fuel consumption values for the low traffic volume level were within the lower limit of the range, and those for the high traffic volume level were within the upper limit. An exception was MLK, where estimated average fuel consumption for both the medium and high traffic volume levels exceeded the above range.

MLK was a special case study in this research. The observed u-turn demand was less than 1 % of the approach traffic volume, and the total traffic volume at the interchange was rather low during the field survey. The observed signal settings, which were used for all traffic volume levels in the simulation experiment, had been chosen for these conditions. The fuel consumed along a u-turn path through the two intersections of this diamond interchange was relatively high with these signal settings. It was 88, 172, and 330 grams/veh for the southbound approach, and 88, 192, and 332 grams/veh for the northbound approach for the respective low, medium, and high traffic volume levels. For the low-volume experiment, the value was within the general range discussed previously for the other case studies without free u-turn lanes. However, values for the medium- and high-volume levels were higher than this range. The higher fuel use resulted from the operational parameters used for the simulation. The traffic signal timing used throughout the simulation had been set up for the low traffic volume conditions that existed at the time the field survey was made. Therefore, the signal green times were not adequate for the simulated medium and high traffic levels. This resulted in higher travel time, total delay, and fuel consumption.

The estimated fuel consumption values for the case study at St. Johns were within the general range mentioned above even though this diamond interchange included a free u-turn lane only on its northbound approach, where a high u-turn demand was seen in the field survey. The observed green signal times for the northbound and the southbound approach were the same, despite the fact that the northbound approach had a higher total traffic volume demand. However, after subtracting the u-turn demand that would be handled by the free u-turn lane from the total demand volume on the northbound approach, the remaining demand on both intersection approaches was almost the same. Therefore, it was appropriate that both approaches had the same green times. Fuel consumption by simulated u-turning vehicles on both approaches at St. Johns, was similar for all three traffic demand levels. Generally, the results of the other case studies showed different fuel consumption for each approach at the three traffic levels and different green signal times. By contrasting it with other case studies, the case at St. Johns indicates that the traffic signal settings directly influence the fuel consumption of vehicles as they travel through the intersections of a diamond interchange.

In the Ben White case study, estimated fuel consumption at the three traffic volume levels exceeded the general range previously discussed. U-turning vehicles going through this diamond interchange consumed between 150 and 250 grams of fuel per vehicle, on average. Values between 200 and 250 grams/veh were for u-turning vehicles on the northbound approach, where u-turn demand volume was very high. The lower values from 150 to 200 gm/veh were for u-turning vehicles on the southbound approach, where the traffic demand was lower than on the northbound approach. Higher fuel consumption was expected in this case study since this diamond interchange was large, its traffic volume demand was very high, and its existing geometric configuration included two free u-turn lanes. Therefore, the existing traffic signal settings, which were for traffic other than u-turning vehicles, did not provide adequate progression for the simulated high u-turn demand through the diamond interchange intersections.

In general, the results of the simulation indicated that the average fuel consumption of a vehicle going through the two diamond interchange intersections, was within the range of 70 to 120 grams/veh when the operational conditions at the interchange were favorable for the progression of u-turning vehicles through the intersections. However, the average fuel consumption for u-turning vehicles ranged up to more than 300 grams/veh, when conditions were not appropriate for progression of the u-turn movement. The conditions which showed significant influence on the fuel consumption of u-turning vehicles traveling through the diamond interchange were: the signal phasing and timing, approach traffic volume, percent of u-turn demand, and the size of the diamond interchange.

When free u-turn lanes were added to the diamond interchange, the result of the traffic volume experiment showed that u-turning vehicles consumed significantly less fuel. Fuel consumption along the free u-turn lanes was variable, with average values from 10 to 45 grams/veh for most case studies. Higher values were calculated at large diamond interchanges such as Ben White, where the average fuel consumption was about 30 to 45 grams/veh for all demand traffic levels. Lower values occurred at smaller diamond interchanges such as McRae, where the average fuel consumption for a u-turning vehicle was about 11 to 16 grams/veh. For all the conditions simulated in this experiment the average amount of fuel saved by a u-turning vehicle using a free u-turn lane rather than going through the two intersections of a diamond interchange was usually at least 60 percent.

The average fuel consumption of a vehicle using the free u-turn lane was not significantly affected by a change in traffic volume, but it was affected by the length or the size of the free u-turn lane and the type of vehicles. The fuel consumed along the free u-turn lane itself was not affected by interaction with other turning vehicles or by traffic signal control, but there was some effect from movements on the entrance and exit lanes at each end. Table 4.1 summarizes the average fuel consumption estimated from the TEXAS Model simulation of the existing conditions at the case study sites at the time of data collection.

TABLE 4.1 SUMMARY OF THE RESULTS OF SIMULATING THE OBSERVED FIELD CONDITIONS

		Fuel Consumption (grams/veh)	
Case Study	Approach	Using Free U-turn Lane	Using Two Intersections
	NB	19	102
Braker Lane	SB	20	105
	* NB	24	118
St. Johns	SB	19	120
	* NB	43	247
Ben White	* SB	45	165
	NB	–	88
MLK **	SB	–	88
	WB	12	87
McRae	EB	15	87
	WB	16	94
Trevino	EB	26	72

* Indicates that the existing geometric configuration of the diamond interchange had a free u-turn lane on the marked approach.

** These results correspond to the low traffic volume experiment, which represent the existing conditions of the diamond interchange at the time of data collection.

4.1.2 U-turn Demand Experiment

The objective of the *u-turn demand experiment* was to evaluate the operational efficiency of diamond interchanges with and without free u-turn lanes and estimate the relative average fuel consumption of u-turning vehicles at three percentage levels of the approach volume, with all other parameters held constant. For this experiment, a high level of traffic demand on the external approaches was used throughout, while the u-turn demand was varied from 10 to 30 percent. The non u-turning volume on the external approaches was proportioned among the other intersection movements according to the observed field data. The operational traffic signal control, and geometry of the interchange were kept constant throughout the experiment.

The results of this experiment showed that the fuel consumed by a u-turning vehicle going through the two intersections of a diamond interchange increased considerably as the u-turn demand increased. On the contrary, average fuel consumption by a u-turning vehicle using a free u-turn lane did not increase significantly with an increase in u-turn demand. Fuel consumption along the free u-turn lane showed only a small increase as the u-turn demand percentage increased.

It was interesting to evaluate the capacity of the diamond interchange to process high u-turn demand through the two intersections. For the traffic signal settings used, all the case studies did not show noticeable difficulties processing u-turn demands of 10 or 20 percent through the two intersections of the diamond interchange. However, in most cases, the TEXAS Model was unable to process a 30 percent u-turn demand through the two intersections. Conversely, when free u-turn lanes were provided it was feasible to process 30 percent or more u-turn demand on the free u-turn lanes. This indicates that the capacity of a diamond interchange to process high u-turn demands through the two intersections is limited by the geometry, and especially by the traffic signal settings. The availability of a free u-turn lane can improve the capacity of a diamond interchange to process high u-turn demand without significantly affecting the operational characteristics of the interchange itself.

The principal limitation of the simulated diamond interchanges to process high u-turn demand was a consequence of the traffic signal settings. Two important characteristics influenced the operation of the u-turning vehicles as they traveled through the two intersections; the signal phasing pattern and the green phase timing. The traffic signal phasing for all the case studies was a four-phase pattern. This phasing pattern allows progression of u-turning vehicles through the two intersections of the diamond interchange.

The results of the u-turn demand experiment showed that for most case-study interchanges the simulation model was able to process a maximum u-turn demand of about 20 to

23 percent of the approach volume through the two intersections when using the existing signal phasing and timing plan. However, it is important to remember that in this simulation experiment the demand volume of the other traffic movements on the external approaches was reduced proportionally as the u-turn demand was increased. If the demand volume of the other movements had been kept constant while 10 to 30 percent u-turn demand was added to the approach traffic volume, there is a high probability that the number of u-turning vehicles processed through the two intersections would have been considerably less than the u-turn demand. The simulation results showed that to accommodate various levels of u-turn demand, optimization of the signal timing is necessary. On the contrary, free u-turn lanes are able to process various levels of u-turn demand without affecting the capacity of the diamond interchange intersections.

Another observation from the experiment was that the traffic signal timing that existed at the interchanges without free u-turn lanes was usually set to allow the progression of u-turning vehicles, but in cases such as Ben White, which includes two free u-turn lanes in its geometric configuration, the timing gave priority to the other movements and only limited time for progression of u-turn traffic through the intersections. In the simulation studies of Ben White, the maximum u-turn demand that could be processed was about 10 % of the total traffic volume on the northbound approach, 1858 veh/hr. This indicates that where free u-turn lanes were provided, the traffic signal control had been set to handle the progression of other traffic movements efficiently through the interchange while the u-turn vehicles are expected to use the free u-turn lane.

Besides the fuel savings resulting from the use of free u-turn lanes, u-turning vehicles on these lanes also experienced significant reductions in total delay and travel time. The simulation results showed that u-turning vehicles had much less delay when they used the free u-turn lanes. Furthermore, the results showed that when there was no a queue on the approach lane, the u-turning vehicles were able to reverse direction at or near their desired speed. This was possible mainly under low and medium traffic demand conditions. Under high traffic demand, u-turning vehicles usually experienced significant total delay caused by queues on the external approach lanes. Even, under these conditions, however, the average total delay for u-turning vehicles using the free u-turn lane was less than the total delay that would have been experienced if they traveled through the two intersections of the diamond interchange.

The amount of total delay and travel time varied among the case studies. The highest total delays for u-turning vehicles were between 5 and 7 minutes. These usually occurred when free u-turn lanes were not provided. Generally, the highest total delay to u-turning vehicles using a free u-turn lane was between 3 and 4 minutes under critical conditions of traffic flow. An exceptional case was Ben White where the highest total delay to u-turning vehicles was more than 10 minutes through the two intersections of the diamond interchange. This was a consequence of using the existing traffic signal settings for simulation; these did not provide adequately for progression of u-turning vehicles through the intersections. The simulated travel time of u-turning vehicles through the two intersections at Ben White was more than 11 minutes, while the travel time of u-turning vehicles using the free u-turn lane was about 4 minutes in the worst scenario. The average travel time for the other case studies was between 7 and 8 minutes under high traffic volume conditions. Typically, travel time using a free u-turn lane was about 4 minutes less than that needed to go through the two intersections under high traffic volume conditions.

It is important to point out that high total delays to u-turning vehicles using a free u-turn lane were usually a result of queued vehicles on the approach waiting to make other traffic movements. The results of the u-turn demand experiment showed that as u-turn demand increased, the average total delay decreased when free u-turn lanes were available. This is because the demand for other traffic movements from the approach was reduced, and queues were not as long.

Furthermore, results of the simulation showed that the addition of free u-turn lanes increased the capacity of the diamond interchange, especially under high traffic volume conditions. This is because free u-turn lanes removed a considerable number of vehicles from the intersection demand, allowing the interchange to process other traffic movements more effectively. The traffic volume experiment showed that when free u-turn lanes were added to the diamond interchange a higher traffic volume was processed by the simulation model for the external approaches. This increase in traffic volume processed was particularly noticeable under high traffic volume conditions. In the u-turn demand experiment, the total traffic volume processed decreased significantly as the u-turn demand increased, when free u-turn lanes were not provided. Conversely, higher total traffic volumes were processed as the demand for u-turns increased when a free u-turn lane was in place.

4.2 CONCLUSION

The results of studying six diamond interchanges via a microscopic traffic simulation program called the TEXAS Model showed that the amount of fuel consumed by u-turning vehicles using a free u-turn lane is significantly less than that by turning vehicles going through the two intersections of a diamond interchange. When u-turning vehicles use a free u-turn lane, they typically consume about 60 to 80 percent less fuel, on average, than when traveling through the two intersections. This is partially due to the fact that vehicle drivers using a free u-turn lane can travel near their desired speed without incurring deceleration, idling, and acceleration caused by traffic signal control and by interaction with other vehicles.

The estimated average fuel consumption of u-turning vehicles was found generally to be between about 70 and 120 grams/veh when going through the two intersections of a diamond interchange, depending upon the traffic flow conditions. However, such fuel consumption ranged up to more than 300 grams/veh for a situation in which adequate progression for u-turning vehicles through the two diamond interchange intersections was not provided by the signal settings. The estimated average fuel consumption of u-turning vehicles using a free u-turn was between 10 to 30 grams/veh. This value mainly depends on the length of the free u-turn lane. In cases where the size of the diamond interchange was very large, e.g. Ben White and MLK at US 183, the estimated average fuel consumption was up to 45 grams/veh.

The case studies showed that fuel consumed by u-turning vehicles going through the two intersections of a diamond interchange increased significantly as the total traffic demand increased. Similarly, the fuel consumed by u-turning vehicles through the two intersections increased as the u-turn demand increased. Traffic signal settings had a definite influence in these situations.

Conversely, the average amount of fuel consumed by u-turning vehicles using a free u-turn lane was not affected markedly by changes in the overall traffic volume demand conditions, the percentages of u-turn demand, or by the traffic signal settings. However, the simulation results showed that fuel consumed by vehicles on a free u-turn lane varied among the different case studies, depending mostly upon length of the free u-turn lane.

In addition to the fuel savings that can be realized from providing free u-turn lanes at a diamond interchange, overall operational conditions can be improved. The results of the simulation studies showed that when free u-turn lanes were added, the total traffic volume processed on the inbound approach was higher. Another advantage of free u-turn lanes was the reduction of total delay and travel time for u-turning vehicles.

The capacity of a diamond interchange to process high u-turn demand through the two intersections is limited significantly by the traffic signal control. Signal settings must be adjusted to accommodate changes in u-turn demand. This is usually impractical to implement in a timely way. But, free u-turn lanes can handle large fluctuations in u-turn demand without affecting the normal operation of the two diamond interchange intersections. Free u-turn lanes are an attractive feature for diamond interchanges in some cases. The TEXAS Model for Intersection Traffic, Version 3.2 provided an effective tool for evaluating the relative effectiveness of specific alternative designs in terms of traffic performance as well as fuel consumption and vehicle emissions.

4.3 RECOMMENDATIONS

The estimates of fuel consumption reported herein resulted from computer simulation by the TEXAS Model when traffic signal control operated in a pretimed mode for all case studies. The signal phasing and timing used in all the simulation runs was that which was observed at each case-study site during the afternoon peak hour. Also, a random time for one specified mix of vehicle and driver types was used throughout the study. The following research is suggested for future studies:

- Simulate various traffic signal control scenarios to determine the traffic signal timing that will minimize total vehicular delay for peak demand traffic at each particular diamond interchange when free u-turn lanes are provided.
- Use representative percentages of the various vehicle types at each interchange to determine the potential fuel savings that can be realized from the provision of free u-turn lanes.
- Analyze the simulation output data to estimate the vehicle emission savings that can be realized from the provision of free u-turn lanes.

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APPENDIX A

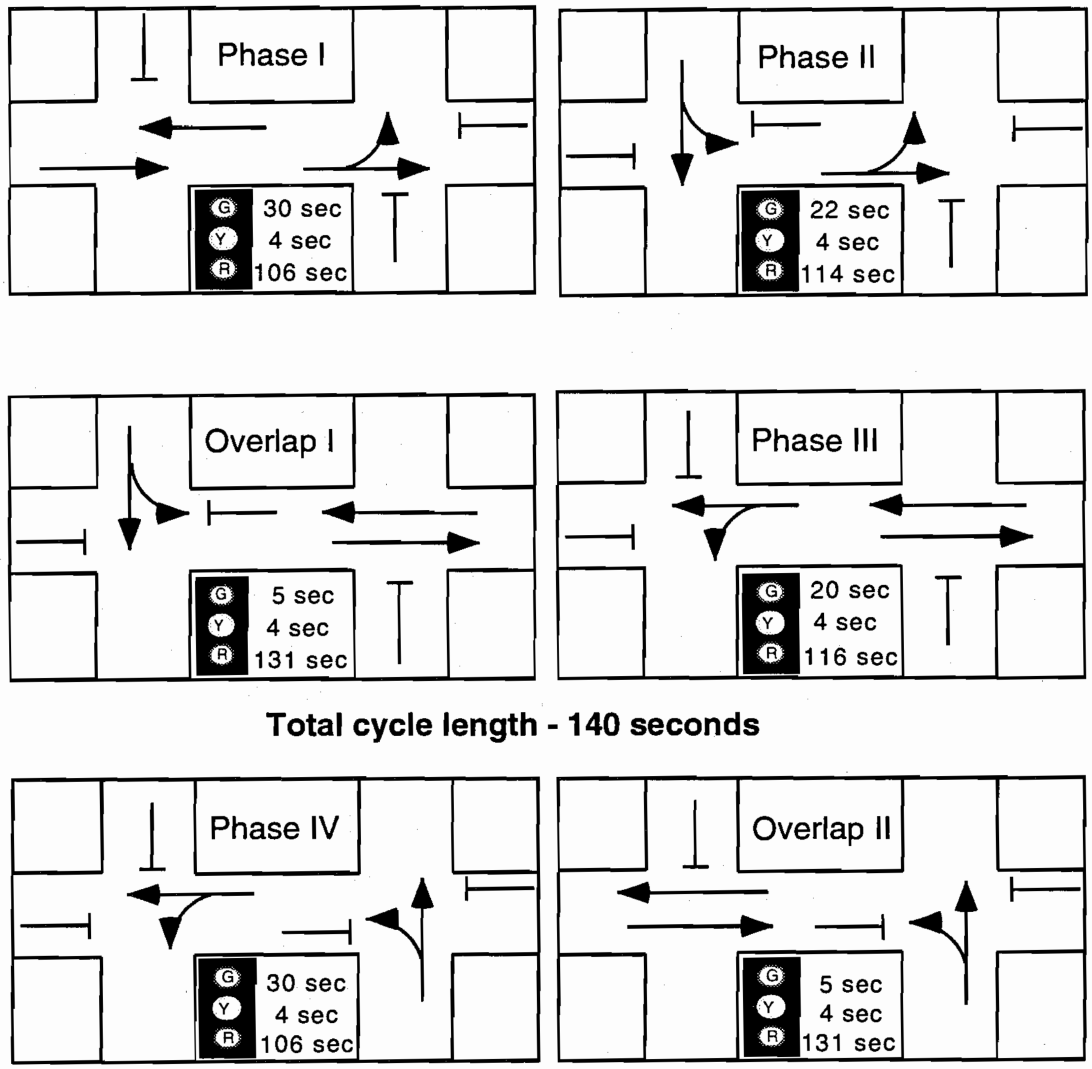

Figure A.1 Traffic signal timing for Braker Lane at IH-35

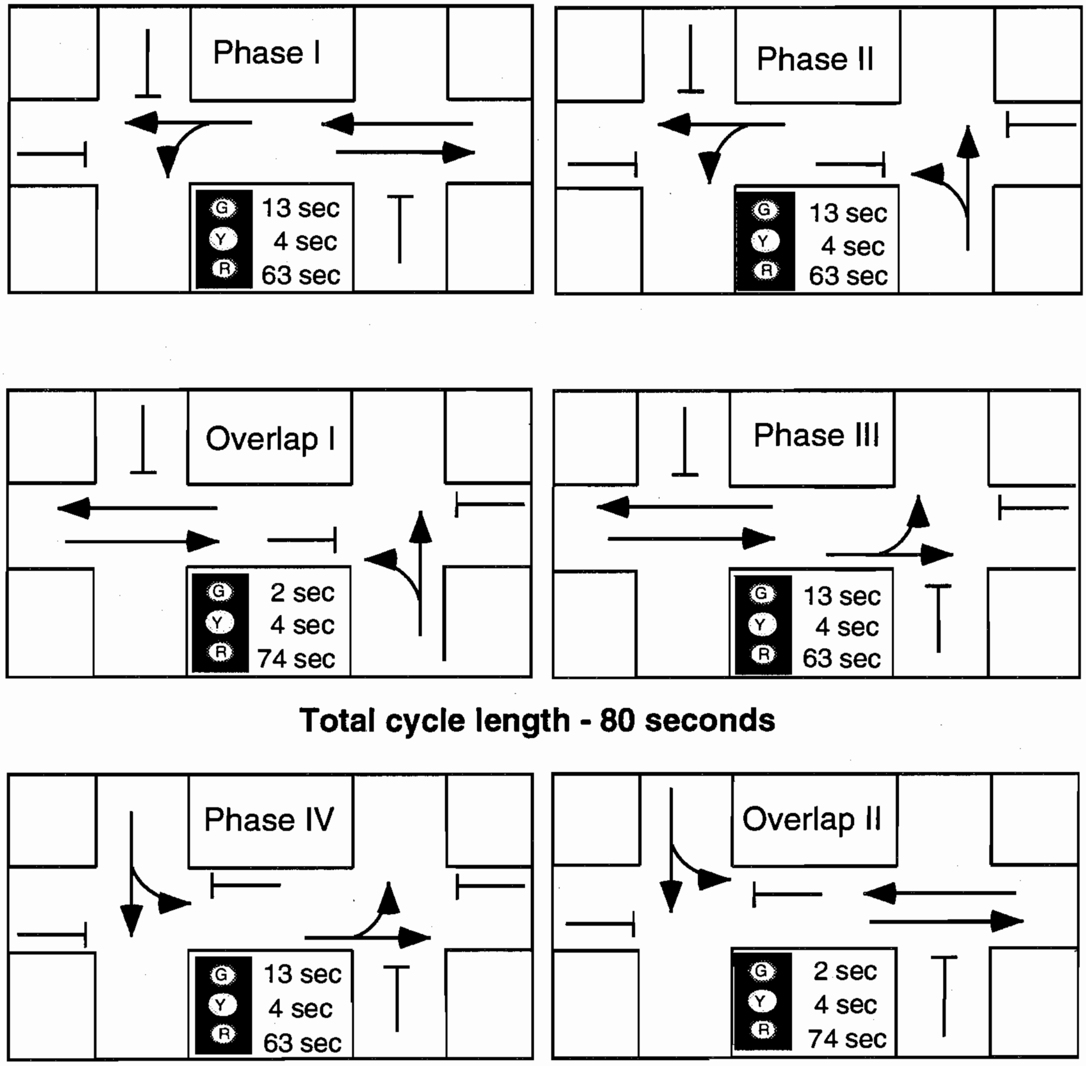

Figure A.2 Traffic signal timing for St. Johns at IH-35

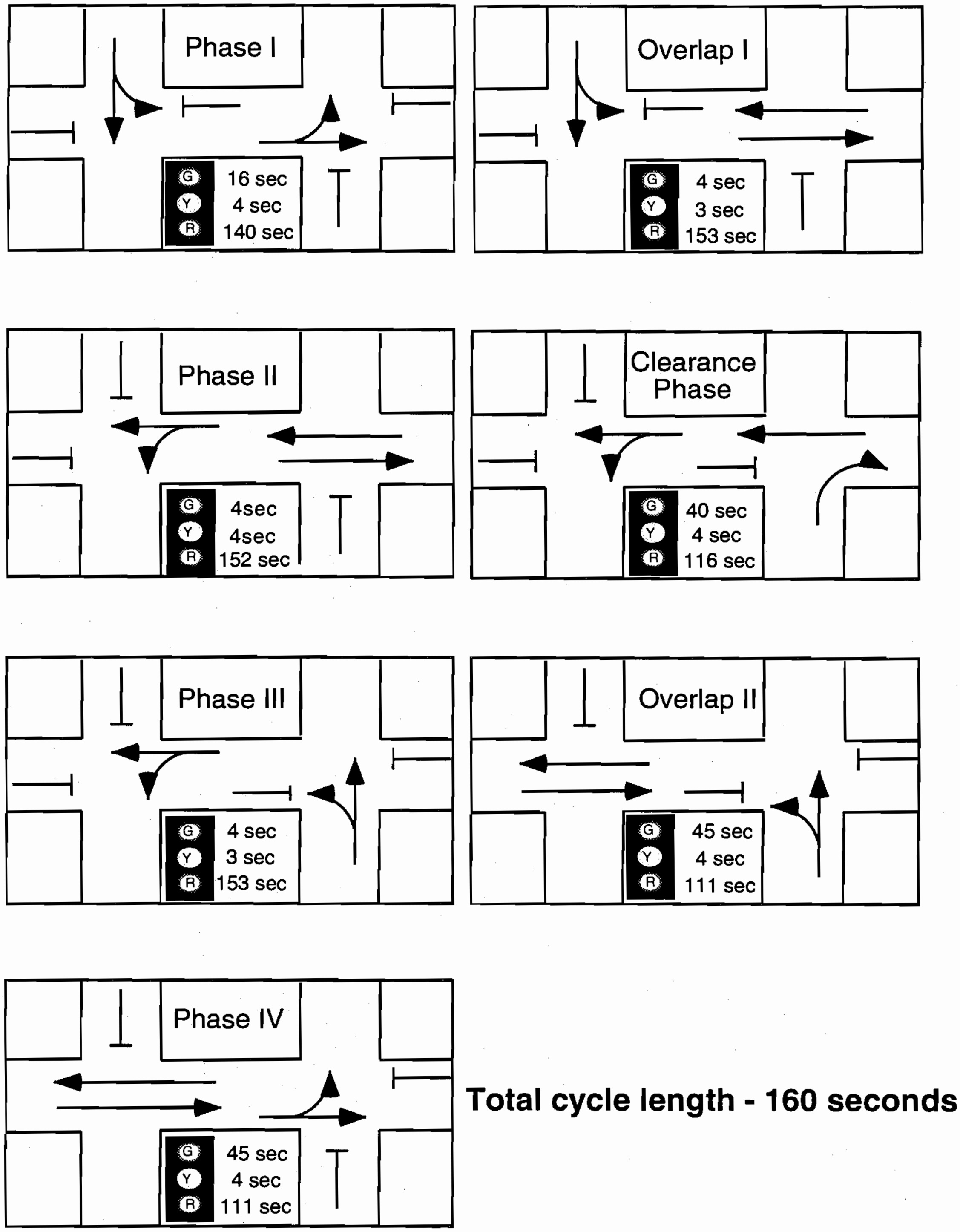

Figure A.3 Traffic signal timing for Ben White at IH-35

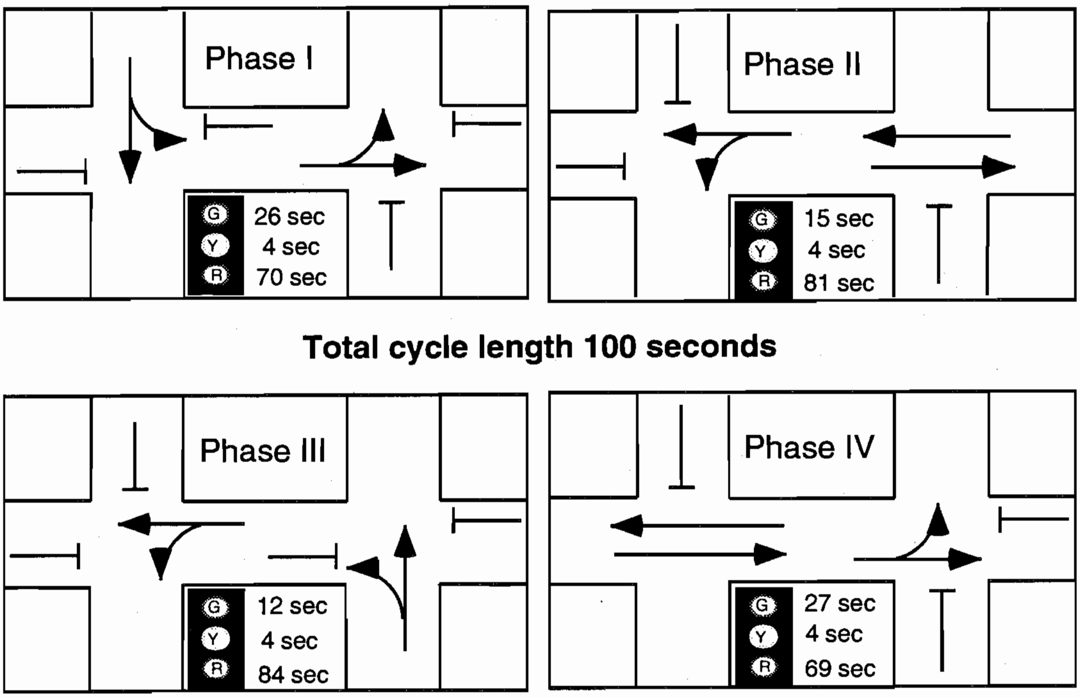

Figure A.4 Traffic signal timing for MLK at US-183

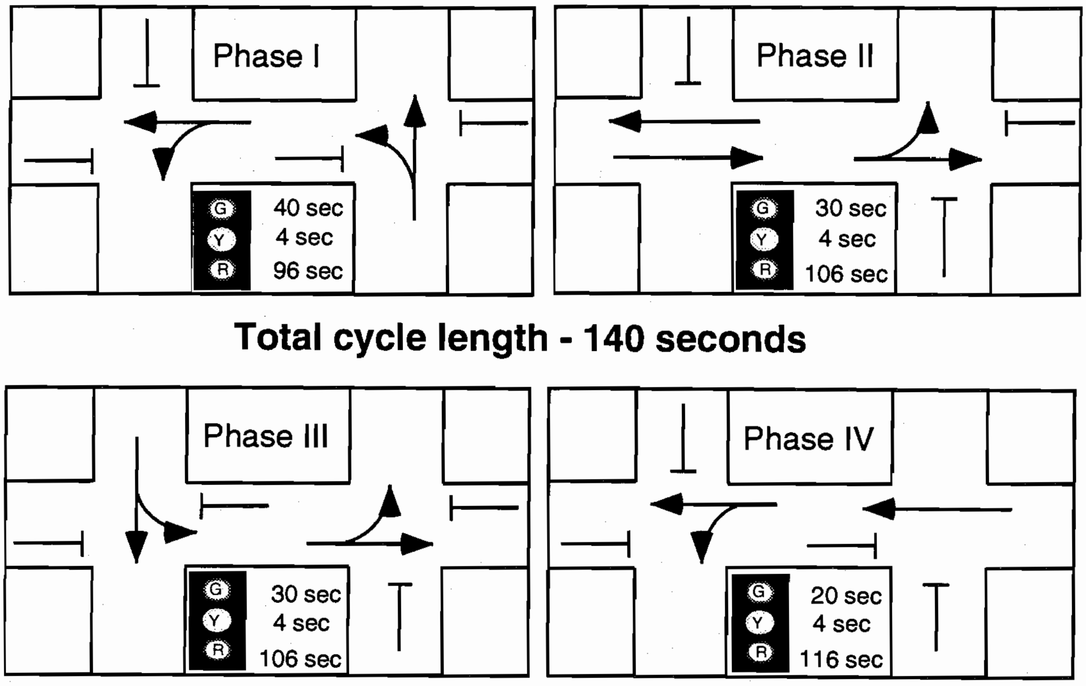

Figure A.5 Traffic signal timing for McRae at IH-10 in El Paso

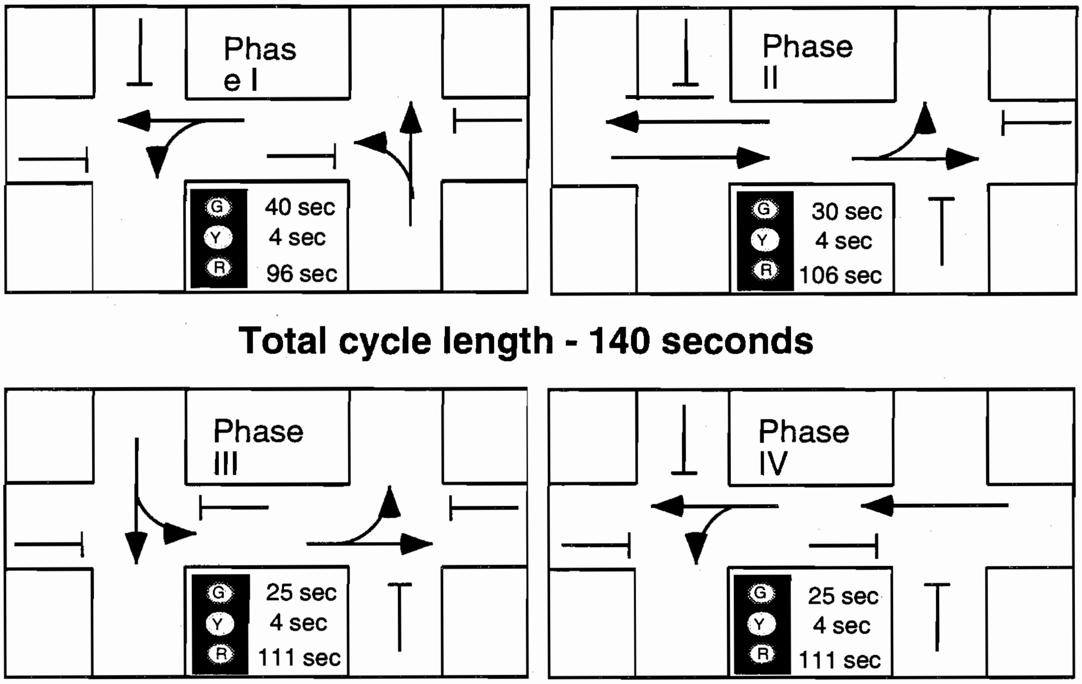

Figure A.6 Traffic signal timing for Lee Trevino at IH-10 in El Paso

APPENDIX B

TABLE B.1 SIMULATION DATA FOR THE TRAFFIC VOLUME EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
Braker Lane	NB	1200	High	10	54	8	28
		840	Medium				
		600	Low				
	SB	906	High	19	20	35	26
		634	Medium				
		453	Low				
	EB	809	High	*	22	40	38
		566	Medium				
		405	Low				
	WB	880	High	*	24	50	26
		616	Medium				
		440	Low				

TABLE B.2 SIMULATION DATA FOR THE U-TURN DEMAND EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
Braker Lane	NB	1200	High	10	54	8	28
				20	48	7	25
				30	42	6	22
	SB	906	High	10	22	40	28
				20	20	35	25
				30	17	31	22

TABLE B.3 SIMULATION DATA FOR THE TRAFFIC VOLUME EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
St. Johns	NB	1537	High	27	30	33	10
		1076	Medium				
		769	Low				
	SB	943	High	13	23	39	25
		660	Medium				
		472	Low				
	EB	678	High	*	43	32	25
		475	Medium				
		339	Low				
	WB	613	High	*	41	50	9
		429	Medium				
		307	Low				

TABLE B.4 SIMULATION DATA FOR THE U-TURN DEMAND EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
St. Johns	NB	1537	High	10	36	41	13
				20	32	37	11
				30	29	32	9
	SB	943	High	10	24	40	26
				20	21	36	23
				30	19	30	21

TABLE B.5 SIMULATION DATA FOR THE TRAFFIC VOLUME EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
Ben White	NB	1858	High	34	18	25	23
		1300	Medium				
		929	Low				
	SB	1188	High	12	25	31	32
		832	Medium				
		594	Low				
	EB	1963	High	*	33	46	21
		1374	Medium				
		982	Low				
	WB	2071	High	*	31	45	24
		1550	Medium				
		1036	Low				

TABLE B.6 SIMULATION DATA FOR THE U-TURN DEMAND EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
Ben White	NB	1858	High	10	25	34	31
				20	22	30	28
				30	19	26	25
	SB	1188	High	10	25	32	33
				20	23	28	29
				30	20	25	25

TABLE B.7 SIMULATION DATA FOR THE TRAFFIC VOLUME EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
MLK	NB	808	High	1	44	1	54
		687	Medium				
		404	Low				
	SB	1118	High	1	70	1	28
		950	Medium				
		559	Low				
	EB	1238	High	*	20	69	11
		1052	Medium				
		619	Low				
	WB	1050	High	*	25	44	31
		893	Medium				
		525	Low				

TABLE B.8 SIMULATION DATA FOR THE U-TURN DEMAND EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
MLK	NB	808	High	10	40	1	49
				20	36	1	43
				30	32	1	37
	SB	1118	High	10	64	1	25
				20	57	1	22
				30	49	1	20

TABLE B.9 SIMULATION DATA FOR THE TRAFFIC VOLUME EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
McRae	EB	2000	High	6	38	47	9
		1400	Medium				
		1000	Low				
	WB	1228	High	5	11	63	21
		860	Medium				
		614	Low				
	SB	1032	High	*	29	32	39
		723	Medium				
		516	Low				
	NB	444	High	*	45	48	7
		310	Medium				
		222	Low				

TABLE B.10 SIMULATION DATA FOR THE U-TURN DEMAND EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
McRae	EB	2000	High	10	36	45	9
				20	33	40	7
				30	29	35	6
	WB	1228	High	10	10	60	20
				20	9	54	17
				30	8	47	15

TABLE B.11 SIMULATION DATA FOR THE TRAFFIC VOLUME EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
Lee Trevino	EB	1776	High	4	66	16	14
		1243	Medium				
		888	Low				
	WB	864	High	5	21	38	36
		605	Medium				
		432	Low				
	SB	1700	High	*	19	31	50
		1190	Medium				
		850	Low				
	NB	824	High	*	35	52	13
		577	Medium				
		412	Low				

TABLE B.12 SIMULATION DATA FOR THE U-TURN DEMAND EXPERIMENT

Case Study	Approach	Total Traffic Volume (veh/hr)		Distribution of Turning Movements (%)			
				U-turn	Left	Straight	Right
Lee Trevino	EB	1776	High	10	61	15	14
				20	54	14	12
				30	47	12	11
	WB	864	High	10	21	36	33
				20	19	31	30
				30	16	28	26

APPENDIX C

TABLE C.1 SIMULATION RESULTS OF THE TRAFFIC VOLUME EXPERIMENT FOR BRAKER LANE

Fuel Consumption (grams/veh)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	70	69	105	72	91	102
Through Free U-turn Lane	22	17	20	12	20	19
Percentage of Fuel Savings	69	75	81	83	78	82
Average Total Delay (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	85	124	167	88	158	323
Through Free U-turn Lane	12	11	15	14	22	184
Average Travel Time (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	160	177	241	163	232	396
Through Free U-turn Lane	82	82	86	85	93	254
Total Number of Vehicles Processed (veh/hr)	*Southound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Traffic Volume Data	453	634	906	600	840	1200
Without Free U-turn Lane	475	640	820	585	795	834
With Free U-turn Lane	480	640	920	590	795	900
U-Turn Demand Processed (%)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
U-turn Demand Data		19%			10%	
Without Free U-turn Lane	21	19	20	13	13	11
With Free U-turn Lane	14	17	20	12	14	13

TABLE C.2 SIMULATION RESULTS OF THE U-TURN DEMAND EXPERIMENT FOR BRAKER LANE

Fuel Consumption (grams/veh)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	85	106	125	100	108	123
Through Free U-turn Lane	15	17	17	25	24	24
Percentage of Fuel Savings	83	84	86	75	78	80

Average Total Delay (seconds)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	130	169	171	316	340	356
Through Free U-turn Lane	7	8	10	117	55	29

Average Travel Time (seconds)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	204	242	245	390	414	430
Through Free U-turn Lane	77	78	80	188	127	101

Total Number of Vehicles Processed (veh/hr)	*Southound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Traffic Volume Data	906			1200		
Without Free U-turn Lane	865	830	795	845	820	790
With Free U-turn Lane	920	910	940	920	1044	1120

U-Turn Demand Processed (%)	*Southbound*			*Northbound*		
U-turn Demand Data	*10%*	*20%*	*30%*	*10%*	*20%*	*30%*
Without Free U-turn Lane	11	20	26	11	17	22
With Free U-turn Lane	10	20	29	10	22	30

TABLE C.3 SIMULATION RESULTS OF THE TRAFFIC VOLUME EXPERIMENT FOR ST. JOHNS

Fuel Consumption (grams/veh)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	88	101	120	91	106	118
Through Free U-turn Lane	14	20	19	25	21	19
Percentage of Fuel Savings	84	80	85	73	80	80
Average Total Delay (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	62	114	291	76	194	369
Through Free U-turn Lane	10	17	49	18	21	95
Average Travel Time (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	139	190	367	154	271	445
Through Free U-turn Lane	82	88	122	89	93	166
Total Number of Vehicles Processed (veh/hr)	*Southound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Traffic Volume Data	472	660	943	769	1076	1537
Without Free U-turn Lane	467	626	845	775	898	833
With Free U-turn Lane	467	646	925	745	1075	1204
U-Turn Demand Processed (%)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
U-turn Demand Data	13%			27%		
Without Free U-turn Lane	12	13	11	26	24	20
With Free U-turn Lane	14	13	11	26	27	24

TABLE C.4 SIMULATION RESULT OF THE U-TURN DEMAND EXPERIMENT FOR ST. JOHN

Fuel Consumption (grams/veh)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	124	127	131	109	116	141
Through Free U-turn Lane	23	20	21	29	26	24
Percentage of Fuel Savings	82	84	84	73	78	83
Average Total Delay (seconds)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	278	303	379	350	358	380
Through Free U-turn Lane	13	9	12	169	95	55
Average Travel Time (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	354	379	454	425	434	456
Through Free U-turn Lane	85	82	85	239	166	126
Total Number of Vehicles Processed (veh/hr)	*Southound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Traffic Volume Data	943			1537		
Without Free U-turn Lane	845	810	770	895	855	835
With Free U-turn Lane	930	945	955	995	1130	1355
U-Turn Demand Processed (%)	*Southbound*			*Northbound*		
U-turn Demand Data	*10%*	*20%*	*30%*	*10%*	*20%*	*30%*
Without Free U-turn Lane	9	14	19	8	16	22
With Free U-turn Lane	11	20	30	7	19	31

TABLE C.5 SIMULATION RESULTS OF THE TRAFFIC VOLUME EXPERIMENT FOR BEN WHITE

Fuel Consumption (grams/veh)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	148	174	165	211	242	247
Through Free U-turn Lane	33	34	45	30	32	43
Percentage of Fuel Savings	78	81	73	86	87	83

Average Total Delay (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	270	396	451	383	480	592
Through Free U-turn Lane	12	34	146	16	23	63

Average Travel Time (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	363	488	542	473	570	682
Through Free U-turn Lane	100	125	234	95	103	142

Total Number of Vehicles Processed (veh/hr)	*Southound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Traffic Volume Data	594	832	1188	929	1300	1858
Without Free U-turn Lane	385	410	810	630	770	930
With Free U-turn Lane	465	500	865	900	1260	1295

U-Turn Demand Processed (%)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
U-turn Demand Data		12%			34%	
Without Free U-turn Lane	15	15	7	16	14	11
With Free U-turn Lane	14	19	10	35	36	41

TABLE C.6 SIMULATION RESULTS OF THE U-TURN DEMAND EXPERIMENT FOR BEN WHITE

Fuel Consumption (grams/veh)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	145	177	171	170	187	198
Through Free U-turn Lane	49	40	38	36	31	34
Percentage of Fuel Savings	66	77	78	78	84	83
Average Total Delay (seconds)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	429	497	495	533	554	559
Through Free U-turn Lane	85	46	0	179	122	106
Average Travel Time (seconds)	*Southbound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	520	589	587	623	644	649
Through Free U-turn Lane	173	140	0	255	199	183
Total Number of Vehicles Processed (veh/hr)	*Southound*			*Northbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Traffic Volume Data	1188			1858		
Without Free U-turn Lane	835	635	750	1000	975	950
With Free U-turn Lane	840	1020	995	1120	1220	1390
U-Turn Demand Processed (%)	*Southbound*			*Northbound*		
U-turn Demand Data	*10%*	*20%*	*30%*	*10%*	*20%*	*30%*
Without Free U-turn Lane	6	15	15	5	9	11
With Free U-turn Lane	12	23	33	10	17	29

TABLE C.7 SIMULATION RESULTS OF THE TRAFFIC VOLUME EXPERIMENT FOR MLK

Fuel Consumption (grams/veh)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	88	172	330	88	192	332
Average Total Delay (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	54	217	272	74	212	275
Average Travel Time (seconds)	*Southbound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	139	300	355	158	295	358
Total Number of Vehicles Processed (veh/hr)	*Southound*			*Northbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Traffic Volume Data	559	950	1118	404	687	808
Without Free U-turn Lane	560	730	740	415	610	640

TABLE C.8 SIMULATION RESULTS OF THE U-TURN DEMAND EXPERIMENT FOR MLK

Fuel Consumption (grams/veh)	Southbound			Northbound		
	10%	20%	30%	10%	20%	30%
Through Diamond Interchange	106	109	109	173	180	176
Through Free U-turn Lane	42	35	37	35	33	32
Percentage of Fuel Savings	61	68	66	80	82	82

Average Total Delay (seconds)	Southbound			Northbound		
	10%	20%	30%	10%	20%	30%
Through Diamond Interchange	307	309	334	328	353	375
Through Free U-turn Lane	150	85	37	31	14	11

Average Travel Time (seconds)	Southbound			Northbound		
	10%	20%	30%	10%	20%	30%
Through Diamond Interchange	390	392	418	411	436	458
Through Free U-turn Lane	236	173	127	121	105	101

Total Number of Vehicles Processed (veh/hr)	Southound			Northbound		
	10%	20%	30%	10%	20%	30%
Traffic Volume Data	1188			808		
Without Free U-turn Lane	595	680	650	700	510	440
With Free U-turn Lane	695	930	1080	855	665	810

U-Turn Demand Processed (%)	Southbound			Northbound		
U-turn Demand Data	10%	20%	30%	10%	20%	30%
Without Free U-turn Lane	9	18	26	7	18	22
With Free U-turn Lane	9	20	31	10	22	30

TABLE C.9 SIMULATION RESULTS OF THE TRAFFIC VOLUME EXPERIMENT FOR MCRAE

Fuel Consumption (grams/veh)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	63	69	87	65	83	87
Through Free U-turn Lane	12	11	12	13	16	15
Percentage of Fuel Savings	81	83	86	80	80	83
Average Total Delay (seconds)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	71	74	98	89	225	336
Through Free U-turn Lane	5	5	6	8	56	187
Average Travel Time (seconds)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	148	150	173	165	301	412
Through Free U-turn Lane	76	76	78	84	130	260
Total Number of Vehicles Processed (veh/hr)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Traffic Volume Data	614	860	1228	1000	1400	2000
Without Free U-turn Lane	550	820	1080	1070	1230	1230
With Free U-turn Lane	560	820	1128	1065	1320	1350
U-Turn Demand Processed (%)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
U-turn Demand Data	*5%*			*6%*		
Without Free U-turn Lane	6	6	6	10	9	8
With Free U-turn Lane	6	6	6	10	10	7

TABLE C.10 SIMULATION RESULTS OF THE U-TURN DEMAND EXPERIMENT

Fuel Consumption (grams/veh)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	99	109	124	87	95	102
Through Free U-turn Lane	16	16	17	15	16	24
Percentage of Fuel Savings	84	85	86	82	78	77

Average Total Delay (seconds)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	124	175	241	340	364	392
Through Free U-turn Lane	150	115	87	6	7	10

Average Travel Time (seconds)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	200	252	317	416	440	468
Through Free U-turn Lane	222	187	161	79	80	83

Total Number of Vehicles Processed (veh/hr)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Traffic Volume Data	1228			2000		
Without Free U-turn Lane	1055	990	910	1235	1190	1160
With Free U-turn Lane	1150	1180	1200	1350	1480	1650

U-Turn Demand Processed (%)	*Westbound*			*Eastbound*		
U-turn Demand Data	*10%*	*20%*	*30%*	*10%*	*20%*	*30%*
Without Free U-turn Lane	11	16	21	10	15	21
With Free U-turn Lane	11	21	32	10	20	29

TABLE C.11 SIMULATION RESULTS OF THE TRAFFIC VOLUME EXPERIMENT FOR TREVINO

Fuel Consumption (grams/veh)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	60	69	72	92	91	94
Through Free U-turn Lane	17	14	16	29	26	26
Percentage of Fuel Savings	71	79	78	68	71	72

Average Total Delay (seconds)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	65	78	81	194	329	402
Through Free U-turn Lane	5	5	5	27	182	237

Average Travel Time (seconds)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Through Diamond Interchange	142	155	158	269	405	478
Through Free U-turn Lane	79	78	79	102	253	309

Total Number of Vehicles Processed (veh/hr)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Traffic Volume Data	432	605	864	888	1243	1776
Without Free U-turn Lane	405	820	830	835	980	1130
With Free U-turn Lane	420	580	830	866	1020	1160

U-Turn Demand Processed (%)	*Westbound*			*Eastbound*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
U-turn Demand Data	5%			4%		
Without Free U-turn Lane	5	6	6	10	8	7
With Free U-turn Lane	6	6	6	13	11	7

TABLE C.12 SIMULATION RESULTS OF THE U-TURN DEMAND EXPERIMENT FOR TREVINO

Fuel Consumption (grams/veh)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	68	81	86	82	82	82
Through Free U-turn Lane	16	17	18	24	27	25
Percentage of Fuel Savings	76	79	79	70	67	69
Average Total Delay (seconds)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	82	110	128	396	403	398
Through Free U-turn Lane	5	8	7	211	182	151
Average Travel Time (seconds)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Through Diamond Interchange	159	186	204	472	479	475
Through Free U-turn Lane	80	82	80	284	254	224
Total Number of Vehicles Processed (veh/hr)	*Westbound*			*Eastbound*		
	10%	*20%*	*30%*	*10%*	*20%*	*30%*
Traffic Volume Data	864			1776		
Without Free U-turn Lane	825	820	785	1145	1125	1090
With Free U-turn Lane	840	845	850	1210	1290	1360
U-Turn Demand Processed (%)	*Westbound*			*Eastbound*		
U-turn Demand Data	*10%*	*20%*	*30%*	*10%*	*20%*	*30%*
Without Free U-turn Lane	11	21	30	10	15	21
With Free U-turn Lane	11	22	31	10	17	22