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TRANSPORTATION
INSTITUTE

STATE DEPARTMENT
OF HIGHWAYS AND
PUBLIC TRANSPORTATION

COOPERATIVE
RESEARCH

ALTERNATIVE ANALYSIS OF X-RAMP AND DIAMOND RAMP DESIGNS

in cooperation with the
Department of Transportation
Federal Highway Administration

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STUDY 2-8-84-335
RAMP DESIGN ANALYSIS

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As congestion increases on Texas urban freeways during periods of peak traffic demand, State Department of Highways and Public Transportation (SDHPT) highway design engineers are considering different methods of improving freeway operations. One problem encountered includes when and where to use an x-ramp pattern as opposed to the more conventional diamond ramp design for freeway interchanges. This report presents the results of a research study conducted by the Texas Transportation Institute (TTI) using the combined results of a field study, aerial photographic survey, and an extensive simulation analysis to evaluate the operational trade-offs of both ramp designs.

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ALTERNATIVE ANALYSIS OF X-RAMP AND DIAMOND RAMP DESIGNS

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Research Report Number 335-1F
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Alternative Analysis of X-Ramp and Diamond Ramp Design

Sponsored by

Texas State Department of Highways and Public Transportation

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Federal Highway Administration

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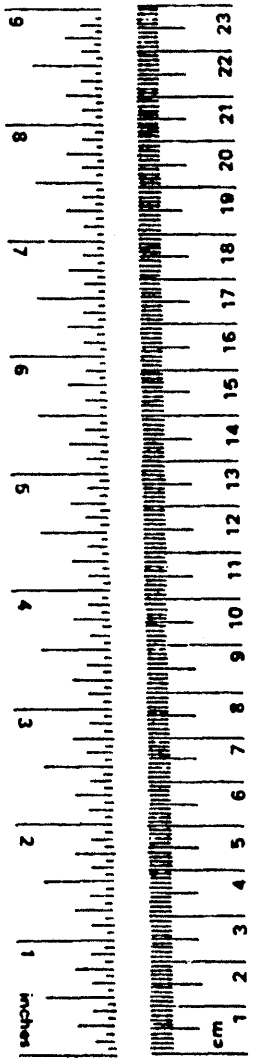
October 1986

METRIC CONVERSION FACTORS

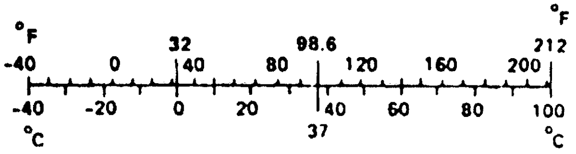
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ABSTRACT

As congestion increases on Texas urban freeways during periods of peak traffic demand, State Department of Highways and Public Transportation (SDHPT) highway design engineers are considering different methods of improving freeway operations. One problem encountered includes when and where to use an x-ramp pattern as opposed to the more conventional diamond ramp design for freeway interchanges. This report presents the results of a research study conducted by the Texas Transportation Institute (TTI) using the combined results of a field study, aerial photographic survey, and an extensive simulation analysis to evaluate the operational trade-offs of both ramp designs.

KEY WORDS:

Freeway, Signalization
Progression, Diamond Interchange
Frontage Road

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SUMMARY

As congestion increases on Texas urban freeways during periods of peak traffic demand, State Department of Highways and Public Transportation (SDHPT) highway design engineers are considering different methods of improving freeway operations. One problem encountered includes when and where to use an x-ramp pattern as opposed to the more conventional diamond ramp design for freeway interchanges. This report presents the results of a research study conducted by the Texas Transportation Institute (TTI) using the combined results of a field study, aerial photographic survey, and an extensive simulation analysis to evaluate the operational trade-offs of both designs.

IMPLEMENTATION

This report provides the procedure developed to analyze x-ramps and diamond ramp designs by using both simulation studies and field data validation. It is intended to provide analytical methodology for solving the increasing traffic demands in most urban areas of Texas. This study provides a study procedure for analyzing traffic operational effects of different types of ramp designs as influenced by various land use types, access methods, traffic volume levels, and internal and external ramp spacings between interchanges. Evaluation procedures and quantified delay-based evaluations were developed to identify conditions where each ramp configuration may be beneficial. These study methods can assist in designing beneficial freeway operations and providing better utilization of both the freeway system and the fiscal resources for more efficient highway operations.

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

As congestion increases on Texas urban freeways during periods of peak traffic demand, State Department of Highways and Public Transportation (SDHPT) highway design engineers are considering different methods of improving freeway operations. One problem encountered includes when and where to use an x-ramp pattern as opposed to the more conventional diamond ramp design for freeway interchanges. This report presents the results of a research study conducted by the Texas Transportation Institute (TTI) using the combined results of a field study, aerial photographic survey, and an extensive simulation analysis to evaluate the operational trade-offs of both designs.

PROBLEM DEFINITION

Several urban areas in Texas are faced with increasing traffic congestion on urban freeways. In these cases, SDHPT highway design engineers are considering major design modifications or minor ramp re-configurations to improve traffic operations. Cases may exist where it may be more beneficial to the motoring public to use an x-ramp pattern as opposed to the more conventional diamond ramp design.

An x-ramp design, as shown in Figure 1, is seen, in many cases, as a configuration with a continuous auxiliary lane between successive ramp pairs. This auxiliary lane may be used for motorists to avoid the signalized intersection as well as providing weaving distance for both entering and exiting traffic. Several continuous pairs of ramps with auxiliary lanes may be used by motorists to provide for an "extra lane" during peak periods in which the freeway mainlanes may be heavily congested. However, this "sling-shooting" maneuver will increase frontage road volumes and may cause delays to "normal" frontage road traffic due to yielding. This type of traffic pattern is not operationally appropriate and should not be encouraged. It should be noted that such operation is a disbenefit of the x-ramp design.

The diamond ramp design, as shown in Figure 2, is the more popular of the two designs. It is implemented based upon the philosophy to keep the motorists on the freeway as long as possible before allowing them to exit. Such a configuration results in a geometric design placing the ramp junctions with the adjacent frontage roads close to the signalized intersection.

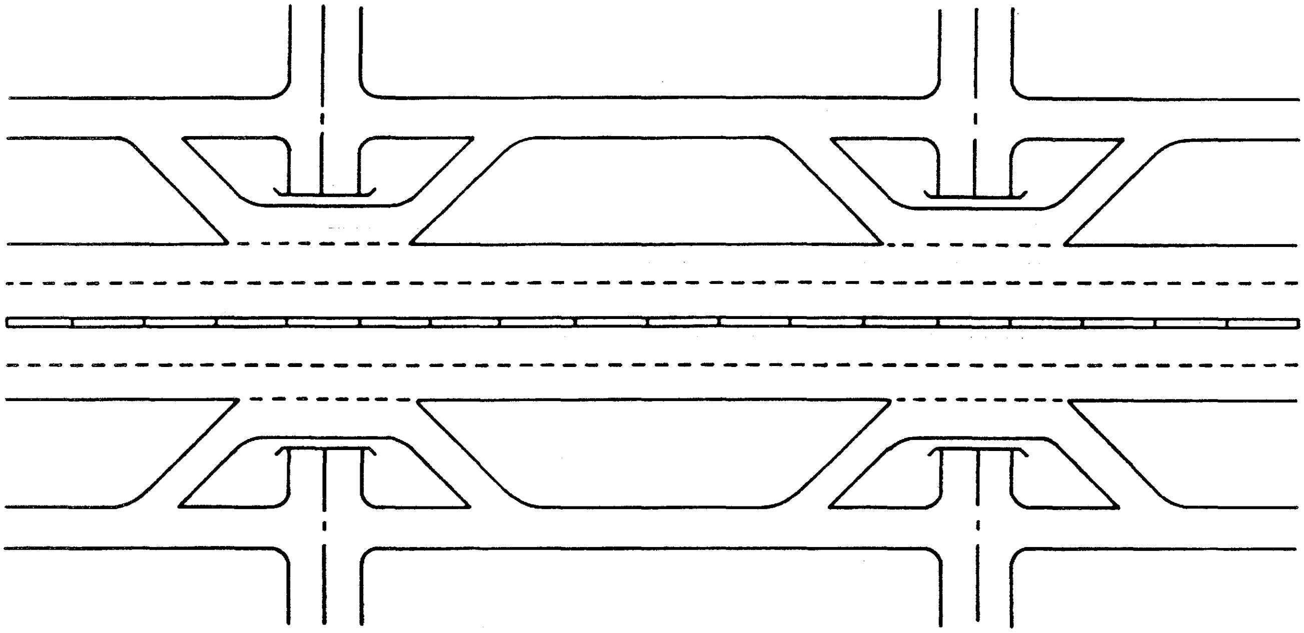


Figure 1. X-Ramp Design with Auxiliary Lane.

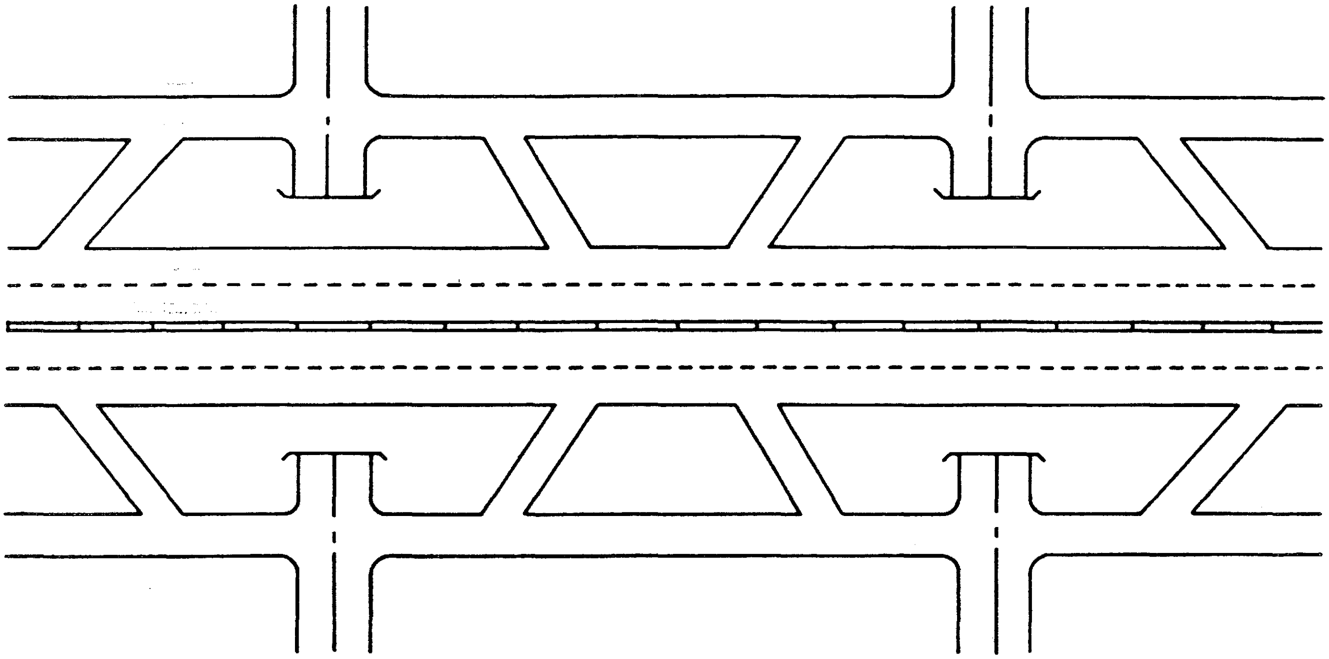


Figure 2. Diamond Ramp Design.

Operational problems may be encountered if queues caused by the traffic signal back into the entrance ramp and onto the freeway mainlanes. In cases where high volume entrance ramps are metered, operational problems may result in ramp queues backing into the signalized intersection. This may be caused by a high ramp volume with inadequate metering rates, lack of frontage road diversion, or limited spacing between the ramp and the intersection. However, in most instances the queuing may be limited through proper adjustment of ramp control strategies.

LITERATURE REVIEW

A fairly extensive literature review was carried out to identify previous research findings which would aid in the selection of the appropriate freeway ramp design. It was conducted primarily through the use of HRIS and TRIS document files. A large portion of the major research work concerned only the operation of the traffic signal at the intersection of the freeway and the frontage road. Comparatively little research was found to evaluate operations of the various ramp designs.

Previous research conducted by Tipton and Pinnell (1) investigated the performance of three ramp designs: stacked ramps, diamond ramps, and x-ramps. This research investigated the desired movement of both entering and exiting traffic, the effect of each design on the amount of acceptable gap time available to those vehicles entering the freeway, and the practicality of each of the interchange layouts. The results of the investigation of the drivers' desires illustrated that standard interchange designs could not always accommodate the desired movement of traffic. Therefore, individual consideration would be necessary at each interchange to satisfy the drivers' desires. A comparison of the effect of freeway ramp geometry on the amount of acceptable gap time available to enter the freeway concluded that a configuration with an off-ramp upstream of an on-ramp offers considerable capacity advantages. The study also concluded that an interchange layout which has an off-ramp located upstream of an on-ramp both upstream and downstream of the arterial street (x-ramp design) is most desirable. However, a diamond configuration should be considered in cases where the freeway mainlane capacity is reduced as the freeway crosses the arterial street.

Wattleworth and Ingram (2) developed a cost-effectiveness methodology for the analysis and comparison of alternative interchange configurations. Seventeen different alternatives were analyzed for a particular case study at one interchange in Orlando, Florida. The authors determined that the linear programming model of the interchange capacity and the cost-effectiveness analysis provides highway design engineers with a powerful tool to use when selecting interchange configurations. The model gives the designer the option of considering many configurations for analysis as well as upgrading each in terms of sequential improvements.

An important point noted in the design of interchanges is the selection of the spacings between the ramps. It has been shown (3) that insufficient ramp spacings may result in signal queues at interchange that block merge areas of exit ramps and the frontage roads and may back into freeway mainlanes. Ramp-metering queues may cause operational problems if they back into cross-street intersections. All freeway ramp pairs should be designed with adequate capacity to avoid these potentially dangerous situations.

The Texas Transportation Institute recently completed research evaluating selected case studies of changes in the geometric layouts of ramps along urban freeways (4). The benefits and disbenefits of a ramp reversal were addressed as well as the development of a method to determine the cost effectiveness of a ramp reversal project. The study concluded that a ramp reversal should not occur without sufficient analysis to determine if the resulting benefits outweigh the accompanying disbenefits and cost.

STUDY DESIGN

The methodology for this study explored several aspects of both ramp designs in a most detailed manner. The research was broken down into three separate but interrelated tasks:

1. Field studies of existing configurations;
2. Aerial photographic survey; and
3. Detailed simulation analysis.

Each of these major tasks addressed different aspects of both the x-ramp and diamond ramp designs as follows. The field studies were conducted to analyze actual traffic operations at selected sites on urban freeways in Texas. An aerial photographic survey of several sites of both designs served to investigate characteristics of the ramps not obvious from ground observations and to analyze the impact of each design on adjacent land-use patterns. The extensive simulation analysis served as a primary means of evaluating the operational trade-offs of both designs under varying volume levels and freeway ramp spacings of the two different types of ramp designs.

OPERATIONAL FIELD STUDIES

Field studies were conducted on freeways in Texas urban areas to provide a data base for analyzing both designs under actual geometric configurations and existing volume levels. The data collected were the basis for constructing simulation models and for model validation.

Selection of Study Sites

The first major step involved in the field study task was the selection of the appropriate sites to conduct the field studies. It was originally proposed that TTI conduct such studies at three sites of each design with ramp spacings of approximately 800, 1600, and 2400 feet. After much consideration, it was determined that a much better representation could be obtained by selecting sites with ramp spacings throughout the desired range. The disadvantage of this arrangement was that the data for each site would be limited to one peak period and one off-peak period of data collection at each site as opposed to multiple days at each of the six sites as originally proposed. This resulted in field data being collected at seven diamond ramp design sites and eight x-ramp design sites. The selection of these additional sites provided for a somewhat better representation of the spacing distribution which actually exists in Texas. Figure 3 shows the distribution of the specific study sites which were used in the field study compared with the proposed ramp spacings.

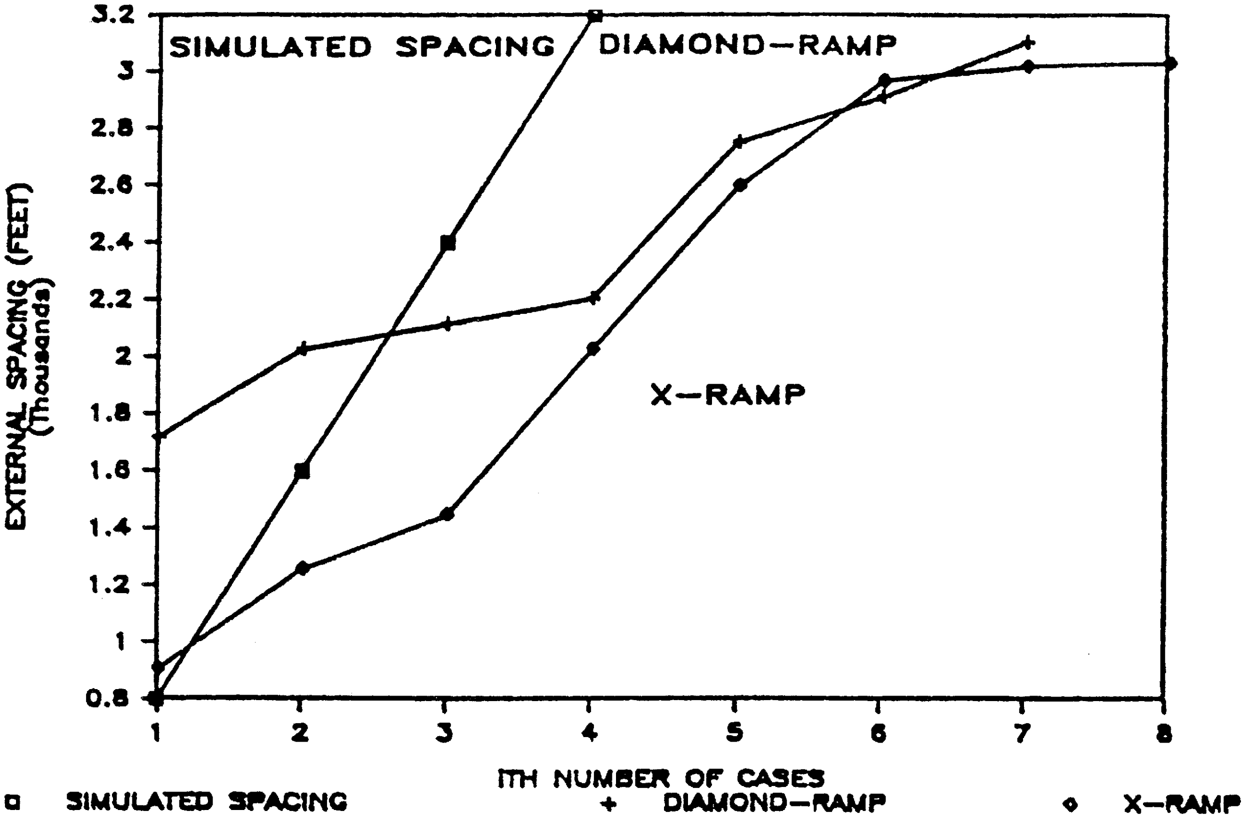
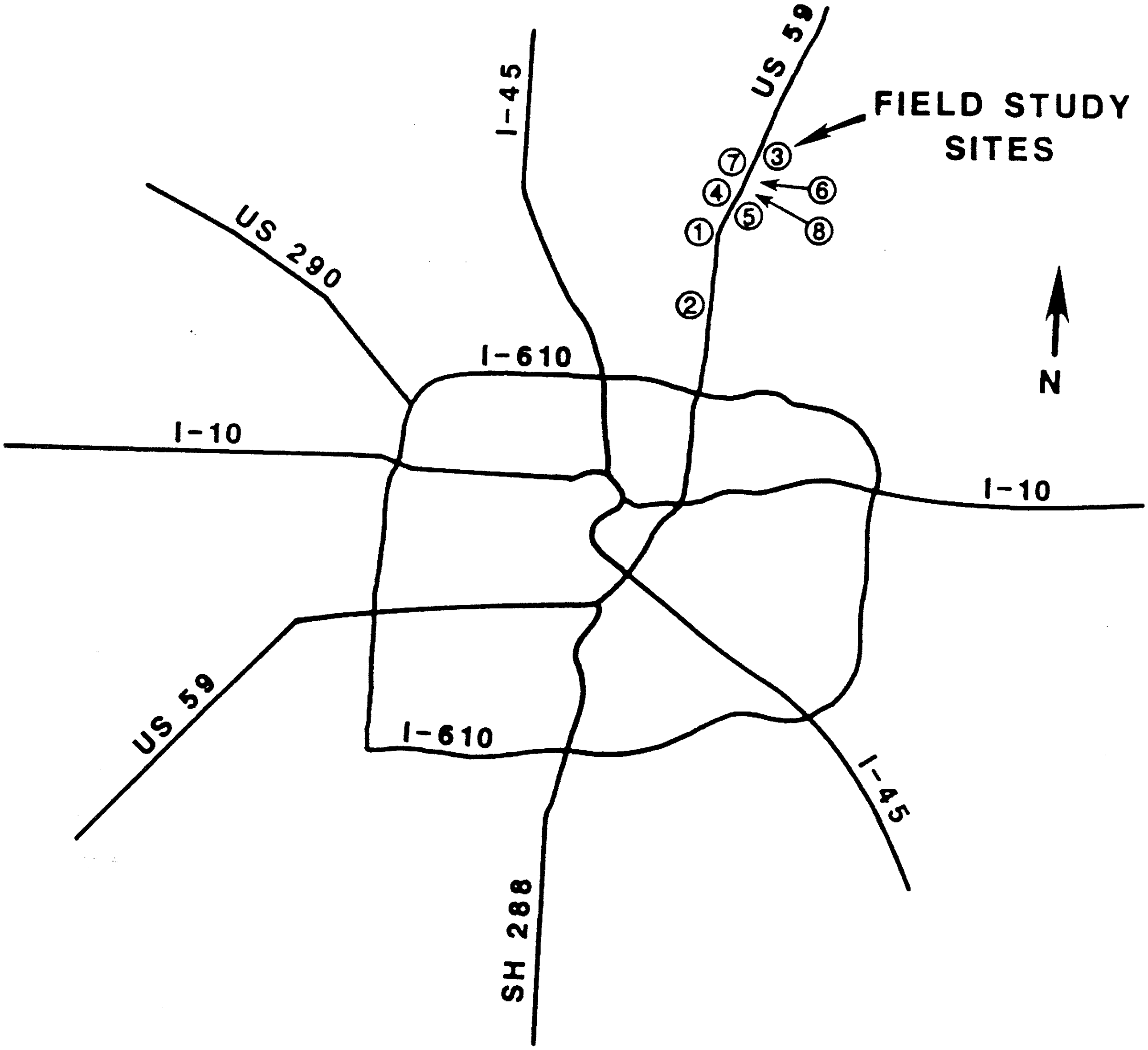


Figure 3. Distribution of External Ramp Spacings of Field Study Sites.

All sites of the x-ramp design were located on U. S. 59 North (Eastex Freeway) in Houston, Texas as shown in Figure 4. This particular freeway serves as a major commuter route to the central business district (CBD) from areas north of the city. Throughout the majority of its length outside I-610 (North Loop), the basic cross-section consists of four freeway mainlanes with a continuous auxiliary lane between successive entrance and exit ramp pairs. Frontage roads adjacent to the freeway are continuous throughout the study sections and are two-lane one-way facilities. Sections with non-continuous frontage roads do exist on this freeway but are not in the immediate area in which this study was conducted. Ramp geometrics are not to be considered acceptable to today's high design standards. This freeway was designed in the 1950's and most sections remain unchanged even today. There are severe capacity problems during peak traffic periods and slow travel speeds and queuing result. Modifications to the freeway to provide added capacity has not kept up with the recent increases in demand. Table 1 lists each of the sites selected for study as well as their respective ramp spacings. It must be noted that the ramp spacing was determined by measuring the spacing between the ramp junctions with the frontage road, thereby defining the weaving area available on the frontage road. This distance was measured in the populated suburban areas located north of the Dallas central business district.

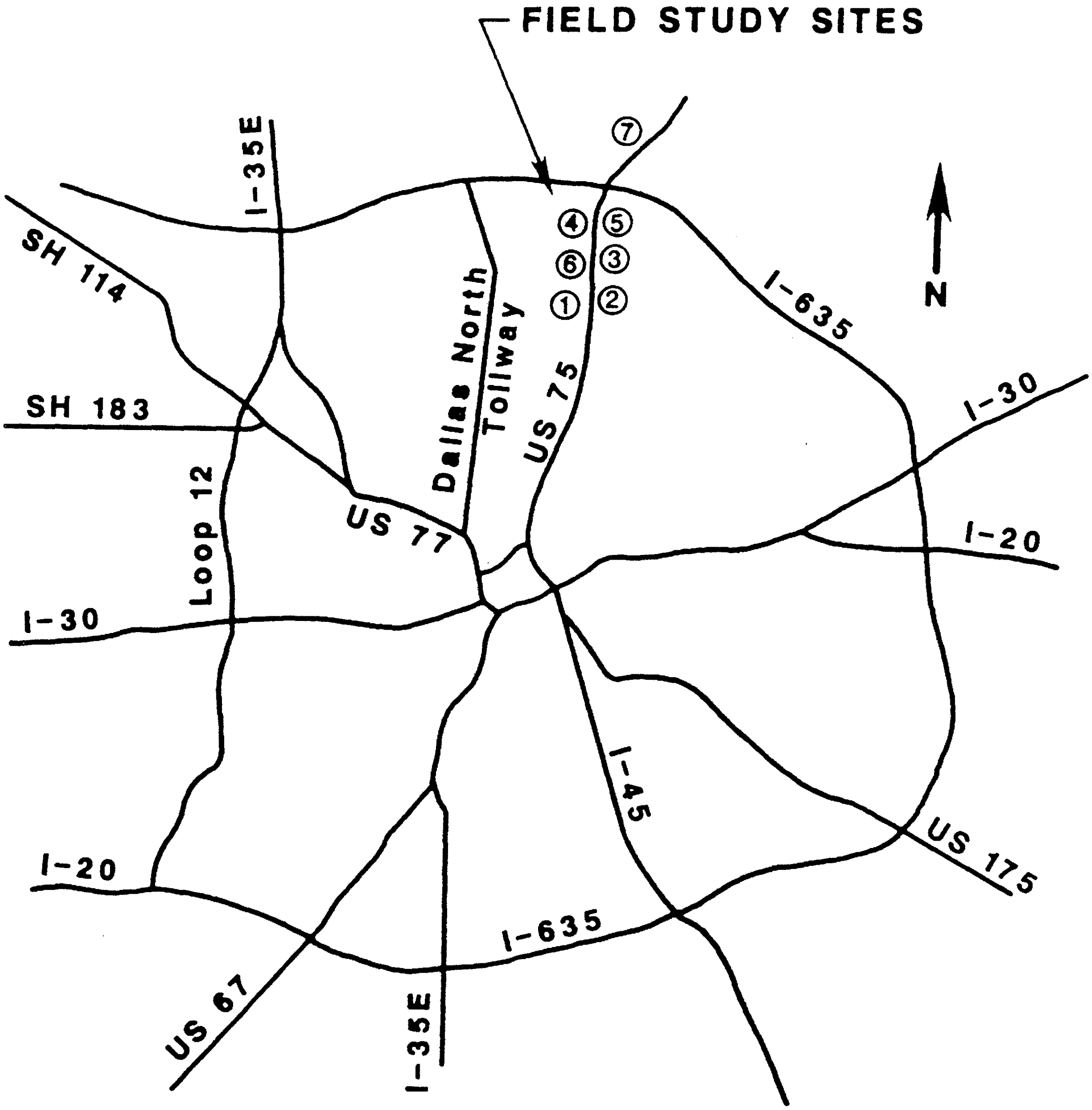
Each of the eight x-ramp design sites is characterized by a continuous auxiliary lane on the freeway between entrance and exit ramp pairs. This configuration was selected for study because it is the kind most likely to be used in field applications. However, pairs of this x-ramp configuration without auxiliary lanes do exist in Texas. Of particular note are those on I-45 North (North Freeway) in Houston. The lack of auxiliary lanes between ramp pairs and the ongoing freeway and transitway construction made field studies along this freeway undesirable. In addition to delays, the construction would cause traffic patterns not directly related to the design of the different ramp types.

Field studies for the diamond ramp designs were conducted on U.S. 75 North (North Central Expressway) in Dallas, Texas as shown in Figure 5. This corridor serves the heavily populated suburban areas located north of the Dallas central business district. The basic geometrics of the freeway consist of four freeway mainlanes with entrance and exit ramp pairs configured in a diamond ramp pattern. No auxiliary lanes between ramps were



Note: Numbers represent approximate study site locations indicated by Table 1.

Figure 4. Location of Field Studies - U. S. 59 North, Houston, Texas.



Note: Numbers represent approximate study site locations indicated by Table 2.

Figure 5. Location of Field Studies - U. S. 75 North, Dallas, Texas.

Table 1. X-Ramp Design Field Study Sites -- U. S. 59 North (Eastex Freeway) Houston, Texas.

Study Site Designation			Direction	Ramp Spacing (feet)
Site No.	Exit	Entrance		
1	Saunders/Jensen	Little York	Southbound	980
2	Laura Koppe	Tidwell	Southbound	1260
3	Lauder Road	Aldine Mail	Northbound	1450
4	Little York	Hopper	Southbound	2035
5	Hopper	Little York	Northbound	2115
6	Aldine Mail	Mt. Houston	Northbound	3060
7	Hopper	Mt. Houston	Southbound	3090
8	Mt. Houston	Hopper	Northbound	3100

located within any study site. Two-lane one-way frontage roads exist adjacent to the freeway and are continuous throughout the study sections. Traffic flow at several entrance ramps was controlled during peak periods through the use of ramp metering. However, minimum compliance of vehicles stopping at the ramp meter reduced the effect of the meters on the study results. Heavy flows resulted in slow speeds and the presence of mainlane queuing during peak periods. Table 2 lists each of the sites selected for study as well as their respective ramp spacings. As with that for the x-ramp design sites, the actual ramp spacings were measured in the field.

It should be noted that similarities exist in the design and operations of the freeways selected for the field studies. Both facilities are of similar cross-section and are not designed to modern interstate standards. Peak period traffic demands exceeding available capacity inflict delays to commuters. These similarities provide a good basis for the validity of the comparison of the results based on these field studies. The varied ramp spacings should provide for a good comparison to evaluate both designs under actual operating conditions. It would have been desirable to have selected sites of both designs with near exact ramp spacings and volume patterns. However, the lack of duplicate pairs in the field resulted in the selection of the best field configurations available. Considering this constraint, it is felt that the number, traffic operations, and ramp spacings of the field sites selected are sufficient for operational effectiveness comparisons.

Data Collection

Data was collected at each of the fifteen study sites during both peak and off-peak periods. Each site was studied only once during peak volume conditions. This arrangement resulted in the collection of data at each site in the direction of peak flow only. The data collection in this manner allowed for the collection at an additional number of sites as opposed to the number originally proposed.

The data was collected during the following three time periods: AM peak (6:30 AM to 9:00 AM), off peak (11:00 AM to 1:00 PM), and PM peak (3:30 PM to 6:00 PM). Volume counts were conducted in 5-minute intervals throughout each study period at each site for the following movements:

Table 2. Diamond Ramp Design Field Study Sites -- U. S. 75 North (North Central Expressway) Dallas, Texas

Study Site Designation			Direction	Ramp Spacing (feet)
Site No.	Entrance	Exit		
1	Meadow Road	Walnut Hill	Southbound	1718
2	Walnut Hill	Meadow Road	Northbound	2030
3	Meadow Road	Royal Lane	Northbound	2119
4	Forest Lane	Royal Lane	Southbound	2208
5	Royal Lane	Forest Lane	Northbound	2755
6	Royal Lane	Meadow Road	Southbound	2915
7	Beltline	Spring Valley	Southbound	3110

- Freeway mainlane throughout;
- Entrance ramp volume;
- Exit ramp volume;
- Frontage road volume at ramp junctions; and
- Intersection turning movements.

Queue counts were also collected at the approaches to the intersection of the frontage road and the arterial. The number of vehicles queued at each of the two major approaches to both sides of the interchange area was recorded every 15-seconds throughout the study period. These were recorded from the frontage road and arterial street approaches only. The signal timing patterns, in most cases, minimized the queuing of the arterial traffic as it proceeded "under the freeway" and therefore queues were not measured there. Exceptions to this included vehicles making U-turn maneuvers where signal patterns were not arranged to provide this particular traffic movement.

In addition to the volume and queuing data, various types of physical data were also collected. Ramp spacings and other geometric data, such as the number of lanes, were initially obtained from construction plan sheets. Actual field measurements were used to verify the field conditions. Detailed intersection diagrams were constructed for later use in the development of the simulation models. Intersection signal timing patterns were obtained from the appropriate agency and were confirmed in the field.

TIMELAPSE cameras were also used to record specific events for each of the two designs. A camera was mounted to record the merging maneuver of vehicles entering the freeway for each of the diamond ramp design sites. In the case of the x-ramp design, a camera was located to view the critical point of merge conflict between exiting vehicles and those already on the frontage road. The photography was conducted for approximately a two-hour period in conjunction with the operational field studies. Each site was filmed using a 1-second time interval on the TIMELAPSE camera.

The field studies were conducted so as to concentrate an entire week on one type of design. Sites of the diamond ramp design were studied in Dallas between July 31, 1984 and August 3, 1984. The studies of the x-ramp design sites were conducted between August 13 and August 17, 1984 in Houston. In order to assure "normal" traffic flow representative of actual flow patterns, no data was collected on either a Monday morning or a Friday afternoon.

AERIAL PHOTOGRAPHIC SURVEY

An aerial photographic survey was conducted to investigate characteristics of both the x-ramp and diamond ramp designs which may not be apparent from on-ground observations. Its secondary purpose involved analyzing the impact of each design on the adjacent land-use patterns.

The survey was collected on August 14, 1984 by surveying sites in both the Houston and Dallas areas. A private plane was rented and several slides were taken using a 35-mm camera utilizing both wide-angle and telephoto lenses. Several pairs of freeway ramps were photographed:

1. U. S. 75 North (North Central Expressway) - Dallas
2. IH 635 (LBJ Freeway) - Dallas
3. U. S. 59 North (Eastex Freeway) - Houston
4. IH 610 South (South Loop Freeway) - Houston

Over 1000 slides were taken during this aerial photographic survey. This included sites of both designs during peak and off-peak volume conditions. It should be noted that additional sites over those selected for the field studies were examined throughout the survey. This provided for a larger data base of more sites than would have been available if the observations were limited to the sites where the operational field studies were to be conducted.

SIMULATION ANALYSIS

The detailed simulation analysis proved to be the most time-consuming effort during the study. The study results were used primarily to serve as the basis for establishing quantifiable delay-based guidelines to aid in the selection of the more appropriate design between the x-ramp and diamond ramp designs. The simulation analysis took a two-stage process in that it included the use of both the Progression Analysis Signal System Evaluation Routine (PASSER III) and NETSIM models (5,6). The PASSER III analysis provides optimized traffic signal control under a set of geometric, traffic volume, ramp spacing conditions. The NETSIM analysis could then be used to study the detailed operational effects on two types of ramp designs after excluding the traffic signal timing effects.

PASSER III Usage

Various volume levels and ramp spacing patterns were initially coded into the proper format for use with the PASSER III diamond interchange simulation model of the Texas State Department of Highway and Public Transportation (5). This simulation geometric design includes the basic variations in the internal interchange spacing between the two paired intersections and the external interchange spacings between the two on-ramp and off-ramp pair. The results of this analysis were used to provide optimum signal timing patterns for use with the NETSIM model. To provide for some degree of consistency in comparing the simulation study results, a cycle length of 80-seconds was selected for use with the analysis of both the x-ramp and diamond ramp designs.

NETSIM Usage

The NETSIM network simulation model was used as the primary means of comparing the operational trade-offs of both designs (6). A matrix of forty-eight scenarios was developed for each design. Each scenario was evaluated using the model and the results were tabulated. The matrix was developed using three internal interchange spacings, three external ramp spacings and three volume levels. Ramp spacings used were 800, 1600, and 2400 feet. Volume levels of 200, 300, and 400 vehicles per hour per lane were used as the various volume levels throughout the simulation. Internal interchange spacing was also varied at 67, 200 and 376 feet. The varied internal interchange spacings provided for interior travel times inside the interchange area were the 6, 10, and 14 seconds respectively, a critical consideration to be used in the PASSER III model.

Being a microscopic traffic simulation model, NETSIM is very sensitive to the way in which the network geometrics for each scenario are constructed. Two basic link-node diagrams were constructed for both the x-ramp and diamond ramp designs as indicated by Figures 6 and 7, respectively. The diagrams shown here are the actual NETSIM link-node diagrams coded in the simulations of x-ramp and diamond ramp designs. In these link-node diagrams, the arrows represent the direction of flow of vehicles for each individual traffic movement to be analyzed in the NETSIM simulation analysis. The distances of

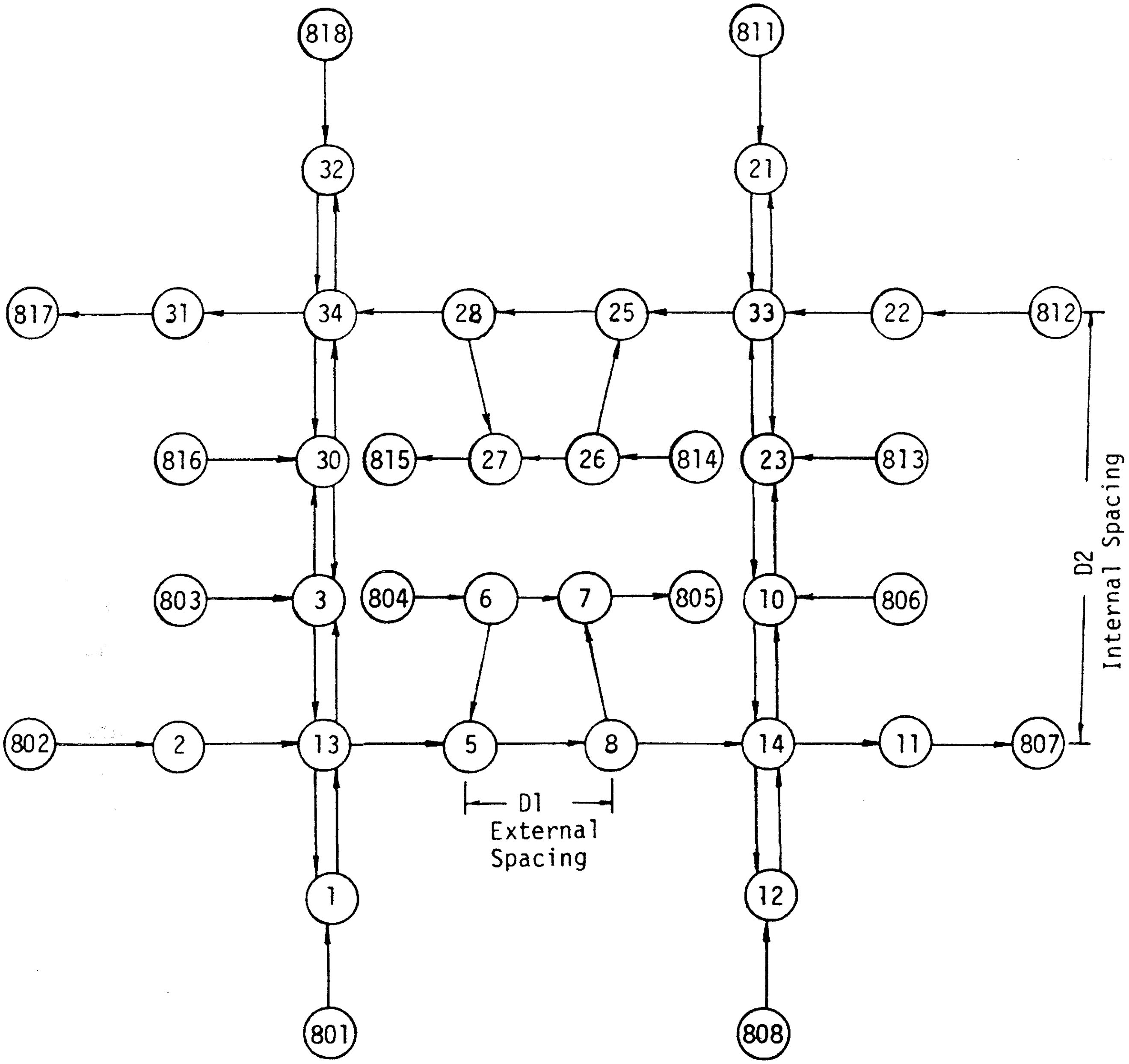


Figure 6. Link-Node Diagram for X-Ramp Design.

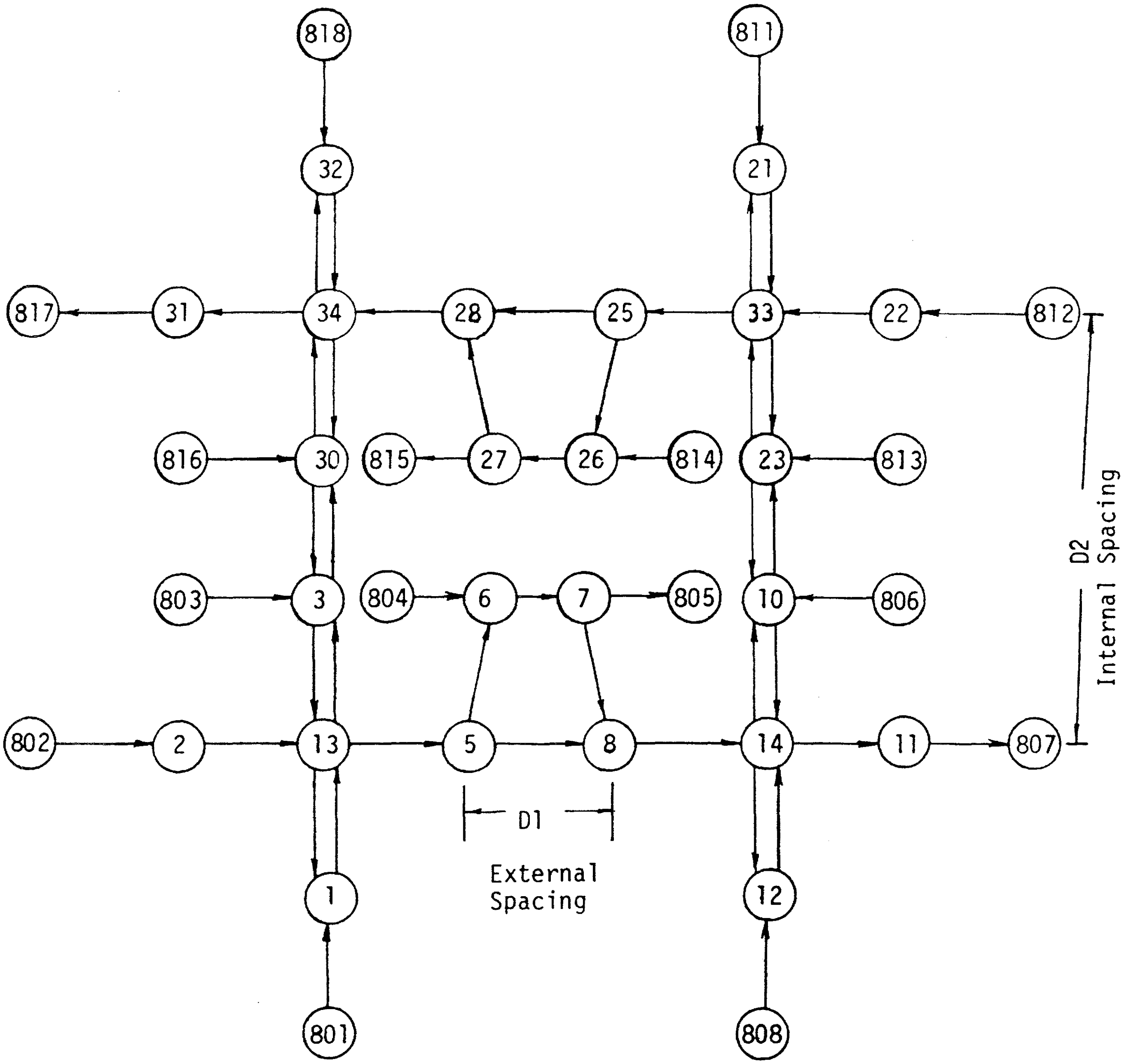


Figure 7. Link-Node Diagram for Diamond Ramp Design.

the internal spacing (D_1) and the external interchange spacings (D_2) were varied throughout the simulation analysis to provide for the different ramp spacings which were analyzed. It should be noted that the only difference between the two different ramp designs is the reverse direction of the link connectors representing the different sequence of on-ramp and off-ramp respective to the interchange in the x-ramp and diamond ramp designs.

It was designed that the desired study geometrics would contain a "mirror-image" type NETSIM simulation model on the opposite side of the freeway. Essentially, the exact same geometric layout was designed and coded on the other side of the two freeway interchange pairs to form a complete self-contained closed system. It was engineered so that the traffic flows in this system could better reach the equilibrium stage in the microscopic traffic simulation environment. This particular geometric setup would then indicate the most desirable configuration for the simulation analysis as well as that which would most likely exist in the field. This basic traffic model would then be used to provide further variations of geometric and traffic flow conditions which could not be easily created in actual urban freeway conditions.

A NETSIM numbering scheme was then developed to facilitate the conversions of the study results obtained from each test scenario in the simulation model to provide useable study results. It involved using a matrix based on the ramp type, volume level, external spacing, and internal interchange spacing. This scheme was used to avoid possible mix-ups in linking the results of an individual simulation model with its corresponding geometric and traffic volume test scenarios.

STUDY RESULTS

The study was performed and structured into three separate tasks: operational field studies, aerial photographic survey and simulation analysis. They were studied to provide results based on each task as well as to provide for methods of combining the overall study results. This was to allow for a detailed analysis of each task without delaying work on any subsequent task.

Results of Operational Field Studies

As previously indicated, the major purpose of the field studies was to provide a data base for later use in the simulation analysis task of this study. A secondary purpose involved reviewing the field study results to determine any operational differences that might exist between the two types of ramp designs. The operational field studies included the collection of field data, TIMELAPSE photography, and visual observations.

The TIMELAPSE photography was used to record the more critical merge points of each design. These critical merge areas are different for the diamond and x-ramp designs. In the case of the diamond ramp design, the merge of the entrance ramp traffic with that of the freeway mainlanes was considered to be more critical. Review of all the TIMELAPSE recordings did not reveal any special problems associated with merging during the period of the observations for both peak and off-peak periods. For the x-ramp design, the merge area of the exit ramp with the frontage road traffic was recorded by the camera. No particular problems were noted concerning the operation of the merge area. The photography did indicate an apparent, more smooth yielding of the frontage road traffic to exiting traffic in the x-ramp design than to that in the diamond ramp design. However, this was most likely the result of the exiting traffic being less able to see the frontage road traffic. The proximity of the ramp junction to the arterial traffic signal provided for noticeably slower speeds at the conflict area, which contributed to smoother merging. During peak periods, a large proportion of the exiting traffic re-enters the freeway at the downstream entrance ramp at the x-ramp design sites located on U. S. 59 North in Houston. This particular traffic pattern of using a section of the freeway mainlanes, exiting to the frontage road, using the frontage road until the next entrance ramp, and re-entering the freeway is referred to as "sling-shooting." Motorists perform this maneuver as they use the combination of the freeway, frontage road, and the auxiliary lane on the freeway to avoid mainline queues and traffic signals along the frontage road during peak traffic periods. It should be noted that those executing this maneuver cause minimal interference to the existing frontage road traffic as they tend to stay in the left lane of the two-lane frontage road. This does provide for additional throughput during peak periods. However, due to possible increased safety hazards associated with the additional ramp volumes and the concern that it is not operationally appropriate, this type of operation should not be encouraged. It may be effectively controlled through the use of a well managed ramp metering system combined with police enforcement to control violations.

Visual observations also provided for useful results from the study. Several of the diamond ramp design sites were operating under ramp meter control. However, as much as 80% of the vehicles using the metered ramp violated the ramp control. In no case did the ramp queue extend into the arterial intersection due to the high metering rates and numerous violations. The ramp meter violations could be effectively controlled through the use of a television surveillance system and police enforcement. Therefore, the effect of ramp metering on the operation of the ramp design cannot be measured. However, it can be concluded that the freeway itself operated less efficiently due to the lack of metering control compliance. The visual observations also served to view operations at the intersection of the arterial and the frontage roads. Such operations at sites of both designs indicated fairly efficient signal operations. In most cases, the signal provided sufficient green time to clear resulting queues on all approaches except for brief intervals during peak periods.

An analysis was also conducted on the raw operational data which was collected in the field. However, this analysis is limited due to the design of the data collection process. The data was collected considering its use in the simulation analysis. Turning movement volumes were useful for the coding of the PASSER III and NETSIM simulation models. Queue counts could only be used for evaluating vehicular delay at the interchange only. However, a comparison can be made of the traffic patterns at the junction of ramp and frontage roads for sites of both designs.

A gross comparison of the relative volume levels of each ramp junction would be inconclusive. However, a comparison of the traffic patterns does provide for meaningful results. Of particular interest in this study is the relationship between the percentage of ramp volumes versus frontage road volumes. These were compared for both peak periods as well as for the off-peak traffic periods.

Table 3 presents these comparisons for all three study periods for the study sites of the diamond ramp design. The table contains the percentage of vehicles making the indicated movement at both ramp/frontage road junctions for each of the diamond ramp design study sites located in Dallas. An overall average for each study period is also included. The results of the AM peak data indicate an almost even split in traffic patterns at the frontage road/entrance ramp junction. However, a close check of the individual site averages over the peak period indicates no distinct pattern among all the study sites. Frontage road volume splits range from a low of 18.7 percent to a high of 76.6 percent. No movement, either that of the frontage road or the entrance ramp, provided for a clear domination over the other. Traffic patterns during the AM peak period would tend to be skewed toward a higher percentage of use of the entrance ramp due to work trips terminating in the CBD. The domination of the exit ramp during the morning peak period is due to the commercial and retail development along the arterial and the destination of work trips along the intersecting arterials. The study results indicate that at the frontage road/entrance ramp junction, the frontage road traffic dominates by approximate ratios of 2.8:1 and 2.6:1 for the off peak and PM peak periods, respectively. This is logical as motorists bypass the entrance ramp to access businesses which are located along the frontage road. Exit ramp traffic also dominates over the frontage volumes during both the off peak and PM peak periods by magnitudes of 3.6 and 2.1, respectively. This is again due to the effects of commuter work trips. Similar results for x-ramp design sites are presented in Table 4. They indicate the effects on the volume distributions along the frontage road which are caused by the "sling-shooting" maneuver performed by motorists during the AM and PM peak periods. In all cases the entrance and exit ramp traffic dominates the frontage road traffic by overall average ratios ranging from approximately 1.4:1 to 3.7:1.

The lowest ratio results at the junction of the frontage road and the exit ramp during the PM peak, primarily due to arterial traffic desiring to access the freeway. Traffic from the arterials must bypass the exit ramp/frontage road junction as it proceeds downstream to the entrance ramp. The entrance ramp dominates its intersecting frontage road by a 3.7:1 ratio during the PM peak period. During off peak periods, the frontage road volume is slightly higher than the exiting volume. However, the entrance ramp traffic again dominates over that of the frontage road during this time period by an approximate 2.4:1 ratio.

Table 3. Comparison of Traffic Patterns at Ramp Junctions--Diamond Ramp Design.

Period	Movement at Ramp Junction	Individual Site Study Period Average (Percent)				Overall Average (Percent)	Ratio
AM Peak (6:30 am to 9:00 am)	Frontage Road	48.4	76.6	18.7	65.6	47.7	---
	Entrance Ramp	51.6	23.4	81.3	34.4	52.3	1.1
	Frontage Road	31.8	23.8	19.7	27.2	27.6	---
	Exit Ramp	60.2	76.2	80.3	72.8	72.4	2.6
Off Peak (11:00 am to 1:00 pm)	Frontage Road	59.2	73.8	79.9	68.4	74.0	2.8
	Entrance Ramp	40.2	26.2	20.1	31.6	26.0	---
	Frontage Road	21.7	22.2	17.3	25.7	21.8	---
	Exit Ramp	78.3	77.8	82.7	74.3	78.2	3.6
PM Peak (3:30 pm to 6:00 pm)	Frontage Road	74.8	71.3	71.2		72.4	2.6
	Entrance Ramp	25.2	28.7	28.8		27.6	---
	Frontage Road	30.1	34.4	33.2		32.6	---
	Exit Ramp	69.9	65.6	66.8		67.4	2.1

Table 4. Comparison of Traffic Patterns at Ramp Junctions--X-Ramp Designs.

Period	Movement at Ramp Junction	Individual Site Study Period Average (Percent)				Overall Average (Percent)	Ratio
AM Peak (6:30 am to 9:00 am)	Frontage Road	34.9	14.8	11.2	36.0	24.2	---
	Entrance Ramp	65.1	85.2	88.3	64.0	75.8	3.1
	Frontage Road	21.3	30.2	22.4	14.7	22.2	---
	Exit Ramp	78.7	69.8	77.6	85.3	77.8	3.5
Off Peak (11:00 am to 1:00 pm)	Frontage Road	42.5	23.9	24.7	26.2	29.3	---
	Entrance Ramp	57.5	76.1	75.3	73.8	70.7	2.4
	Frontage Road	50.7	50.2	57.9	55.0	53.4	1.1
	Exit Ramp	49.3	49.8	42.1	45.0	46.6	---
PM Peak (3:30 pm to 6:00 pm)	Frontage Road	21.4	16.8	19.9	27.3	21.4	---
	Entrance Ramp	78.6	83.2	80.1	72.7	78.6	3.7
	Frontage Road	38.5	39.7	46.2	40.1	41.1	---
	Exit Ramp	61.5	60.3	53.8	59.9	58.9	1.4

This analysis considers the resulting traffic patterns which were observed at the previously mentioned field study sites only. The data for both the AM and PM peak periods were collected in the peak direction of flow. The results indicate possible traffic patterns due to the ramp designs coupled with the resulting land-use pattern.

Aerial Photographic Survey Results

The results of the aerial photographic survey provided for a means to observe characteristics of both designs that would have been more difficult from on-ground observations. The results of this survey were compiled from a review of all the slides which were taken during the actual survey as well as from notes taken by the observer. The observer's notes were extremely helpful in analyzing the slides and conforming those to the actual field conditions. In many cases, the slides would possess little or no meaning without the availability of the observer's notes. The observer served a two-fold purpose in that he also performed the photography. This insured that more emphasis would be placed on photographing the critical elements of both designs.

The results of the aerial photographic survey based upon the observer's notes and the review of the slides could be summarized as follows:

1. Auxiliary lanes on the freeway between the entrance and exit ramp pairs on the x-ramp design provide a bypass around the signalized intersection.
2. A continuous freeway section with several pairs of ramps in the x-ramp design and having auxiliary lanes will provide added throughput capacity during peak traffic periods. Motorists driving in a "sling-shot" pattern can avoid delay, but this type of operation should not be encouraged due to increased yielding conflicts and potential delay to frontage road traffic.
3. Land-use patterns vary significantly for each of the two designs. Both designs exhibit significant commercial development at the intersection of the freeway frontage roads and the arterial street. However, the majority of the sites of diamond ramp design which were observed had sufficient development along the arterial street. Sites

of the x-ramp design were noted to possess extensive development along the frontage road between the arterial streets. The majority of the development was commercial in nature concentrating on strip type shopping centers or closely spaced, unattached structures.

4. The law states that the frontage road traffic must yield to those on-ramp vehicles desiring to exit the freeway. The aerial survey observations noted that this is less of a problem at the x-ramp design sites. Most likely, the conflict is reduced because of the relatively slower speed of vehicles after departing the signalized intersection as opposed to vehicles which have been travelling on the frontage road for some distance without any merge hindrance. Drivers appeared to exhibit more caution in yielding at x-ramp design sites due to the lack of visibility of the exit ramp as it merged with the frontage road. This was especially obvious at sites observed along U. S. 59 North in Houston. It was apparent that the geometrics of the freeway and the frontage road had an affect on the degree of caution used by the yielding frontage road traffic.

Simulation Analysis Results

An extensive simulation analysis was performed as a two-step process to provide a comparison of the traffic operational effects of both ramp designs from the standpoint of a highway design engineer. The first step utilized the PASSER III simulation model to select an optimum signal timing pattern. This involved conducting several simulation runs with varying volume levels and cycle lengths to determine the optimum green times for each movement. These resulting optimum green times at the 80-second signal cycle were then used to code up each of the networks for the NETSIM analysis.

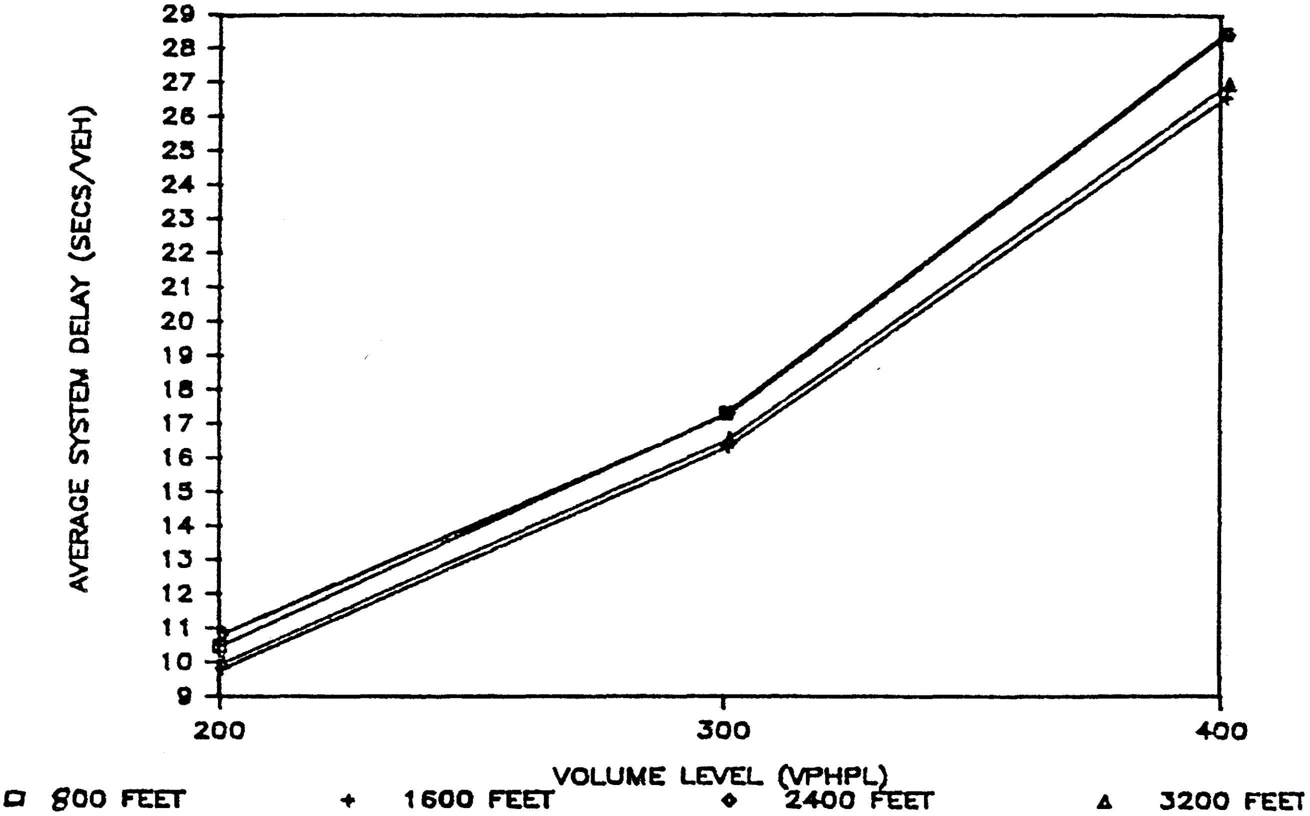
The NETSIM analysis was used to provide the primary means of comparing the operational trade-offs of both the x-ramp and diamond ramp designs. Minor difficulties were encountered in coding up each of the two networks (i.e., x-ramp and diamond ramp designs). These difficulties resulted from the development of a resultant "mirror-image" type basic simulation model of each design on the opposite side of the freeway as shown in Figures 6 and 7. Several models of each design were constructed with variations in the volume levels, internal intersection separations, and the external ramp spacings.

PASSER III Analysis

The PASSER III analysis provided the key results which were useful for investigating the traffic operational effects of both ramp designs. As previously mentioned, its major purpose was to select an optimum cycle length for use in the detailed NETSIM analysis. A portion of the output from the NETSIM model was obtained to evaluate the field operational performance. It should be understood that this study will only reflect the various operational factors at the interchange operation. No conclusions were drawn from the PASSER III analysis alone concerning the operations of the two different ramp designs. This was because there is no explicit method to provide means to simulate a pair x-ramp interchange using the PASSER II model. As a result, the outputs for both the x-ramp and diamond ramp designs are similar except for volume level differences. The volume levels, particularly the frontage road approach volumes, will differ for each ramp design due to the different traffic patterns of each design as indicated in the field study.

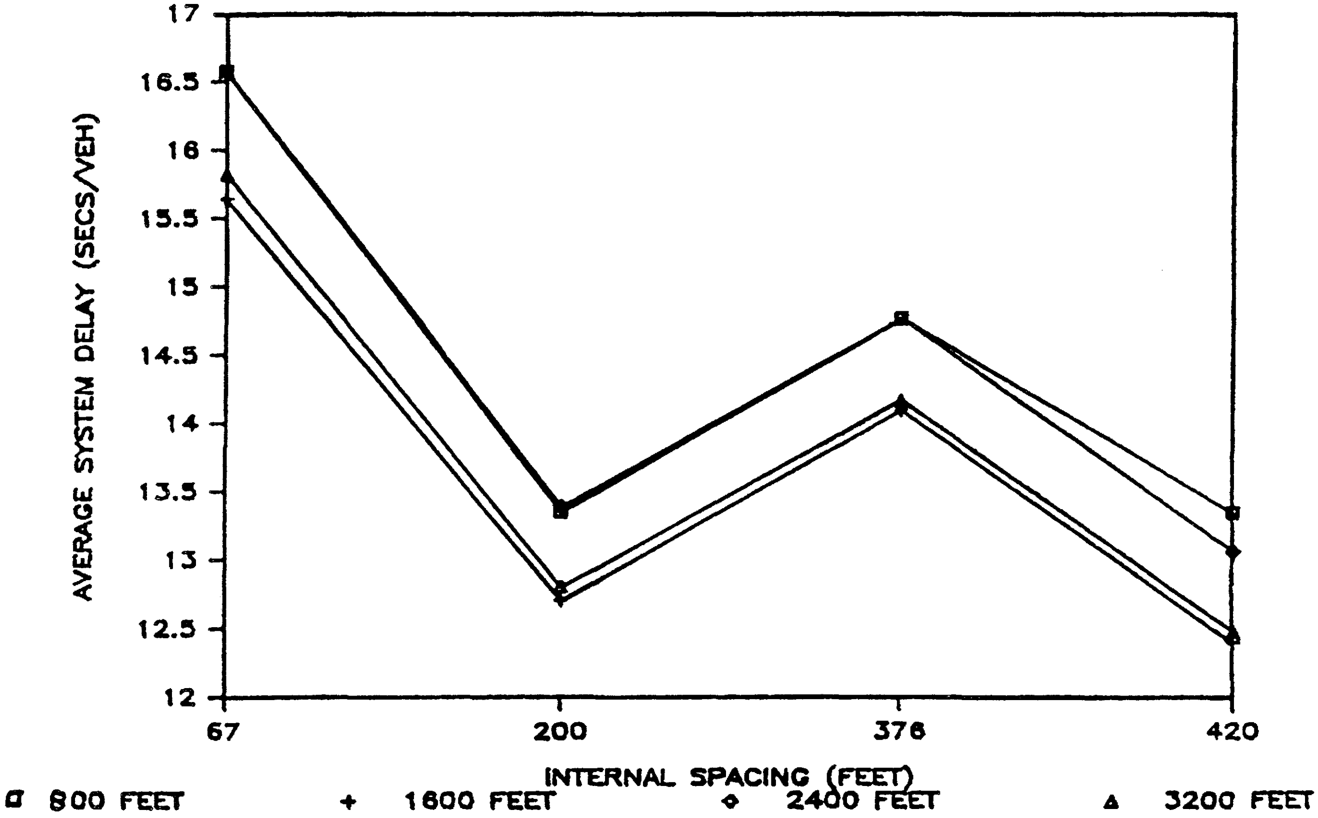
Figure 8 indicates the effect that increasing flow rates have on the operation of a diamond interchange. As expected, increasing volume levels will increase total intersection delay, assuming the same cycle length and optimum traffic signal timing. It also indicates that there is no apparent effect of external ramp spacings at the same flow rates. Curves of similar shape indicating increasing delay with increasing volume resulted from the PASSER III analysis for the sites of the x-ramp design configuration.

One of the model inputs which has a pronounced effect on the resulting total intersection delay is the internal interchange spacing. This distance may be defined as the spacing between the pair of traffic signals at the intersection of the arterial with each frontage road associated with each interchange. Figure 9 indicates that the total delay significantly decreases as the internal spacing increases from approximately 67 to 200 feet. This is due to the optimum signal timing patterns as selected by the model throughout its optimization process assuming an 80-second cycle length. An increase in the internal interchange spacing results in a greater travel time from one intersection to the other. This increased time will allow a larger overlap in the signal timing between the two signals. As a result, more vehicular movements will be permitted at the same time and not result in conflicting movements. Therefore, the interchange delay is significantly decreased.



Note: Based on the analysis of 80 second cycle length.

Figure 8. Effects of Approach Volume on Average System Delay for Diamond Ramp Design Based on PASSER III Evaluation.



Note: Based on the analysis of 80 second cycle length.

Figure 9. Effects of Internal Spacings on Average System Delay for Diamond Ramp Design Based on PASSER III Evaluation.

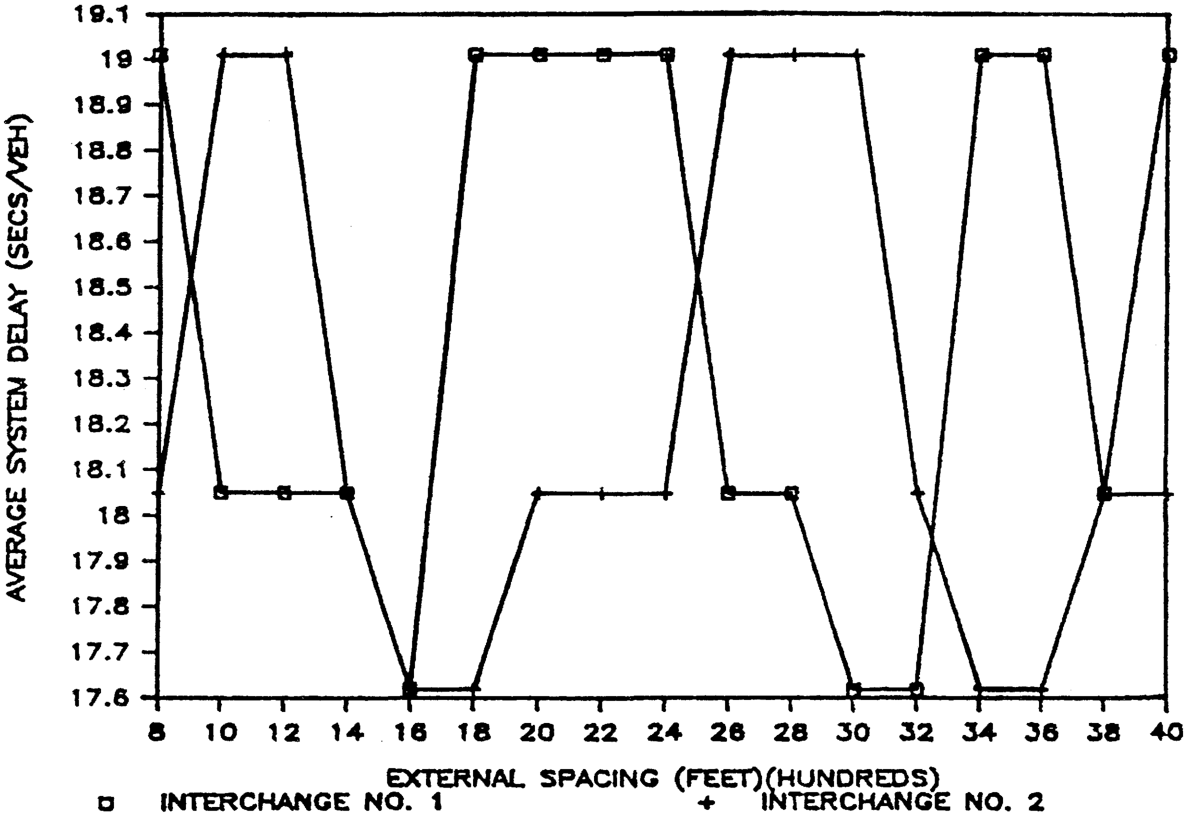
PASSER III models were also constructed to evaluate the effect of external interchange spacing on total interchange delay. This external spacing is of major importance where frontage road progression is desirable. This particular analysis was conducted by comparing the results of seventeen (17) PASSER III test scenarios with the same turning movement volumes, internal spacings, and cycle lengths. The external spacings were varied in 200 feet increments from 800 to 4000 feet. Figures 10 and 11 indicate the relationships of external spacing between interchange to total interchange delay based on PASSER III Evaluation.

Delay 1 and Delay 2 in Figure 10, illustrate the average interchange delay for the two (2) individual interchanges of the two-interchange system. As indicated, the average interchange delay varies when the external spacings between the two interchanges are increased. The proper signal timing setting suitable for one interchange depends on the external spacings between the two interchanges which are analyzed.

On the other hand, the total system delay or the average value of the average delay for the two-interchange system can be calculated from the average of the two average delay measures of the two individual interchanges. As illustrated in Figures 11 and 12, a circular delay pattern exists while the external spacings increase between the two interchanges.

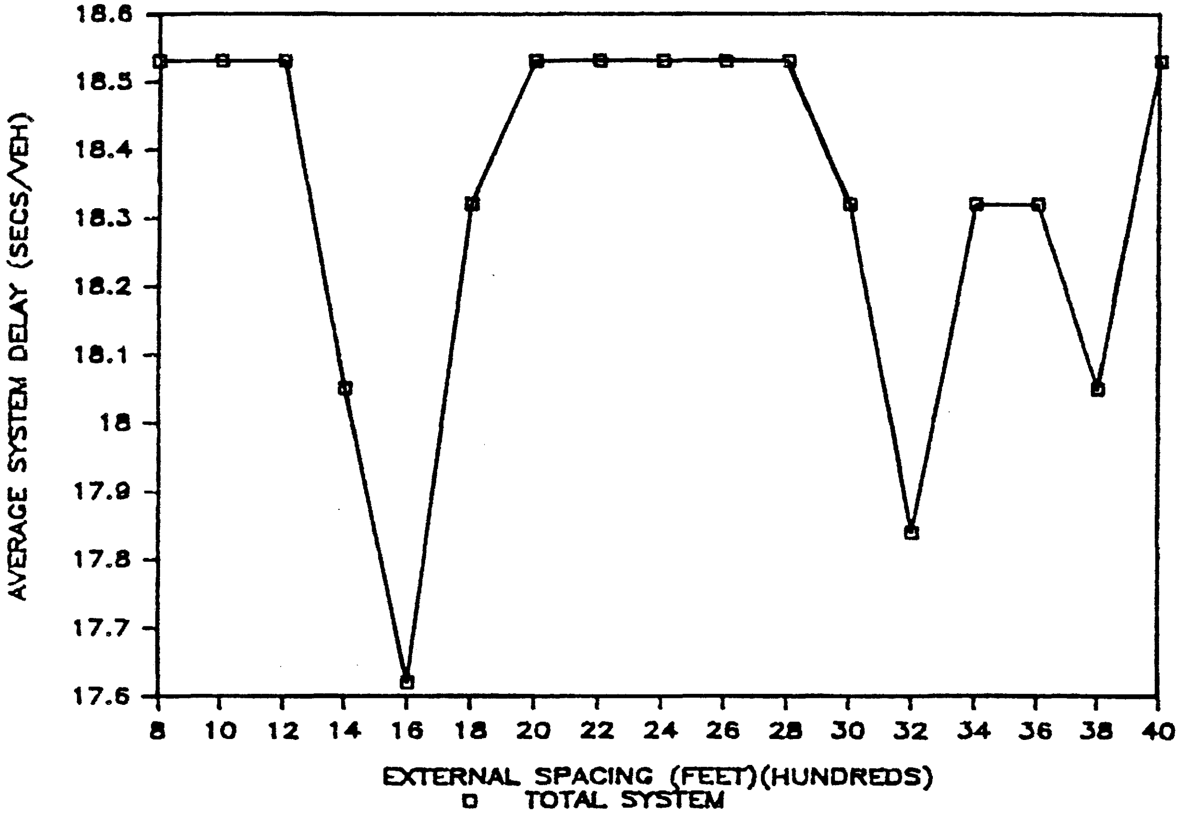
NETSIM Analysis

As previously indicated, the results of the NETSIM analysis could provide meaningful comparisons of the operations of both designs. Such a comparison would be based upon total system delay of each ramp design under similar volume levels and geometric configuration (i.e., spacing). A total number of fifty-four (54) test scenarios were constructed with three ramp or external spacings, three internal interchange spacings and three volume levels. This matrix was simplified with the development of a coding system to eliminate the potential for confusion when comparing the analysis results. Each of the scenarios was denoted by the following basic format:



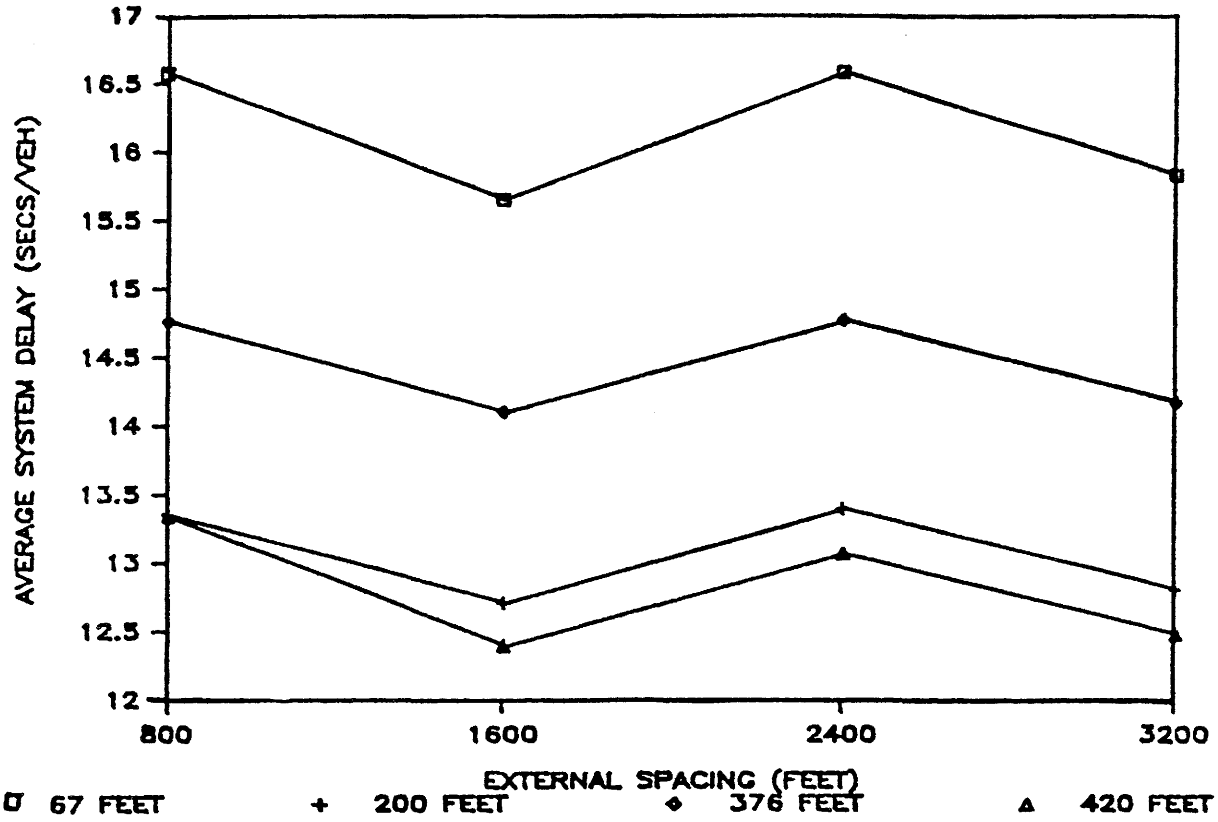
Note: Based on the analysis of 80 second analysis length.

Figure 10. Effect of External Spacings on Average Delay on Individual Diamond Interchange Based on PASSER III Evaluation.



Note: Based on the analysis of 80 second cycle length.

Figure 11. Effect of External Spacings on Total System Delay for Diamond Ramp Design Based on PASSER III Evaluation.



Note: Based on the analysis of 80 second cycle length.

Figure 12. Effects of External Spacings on the Total System Delay for Diamond Ramp Design Based on PASSER III Evaluation.

TEIV

where: T = Type of Ramp
X - X-Ramp
D - D-Ramp

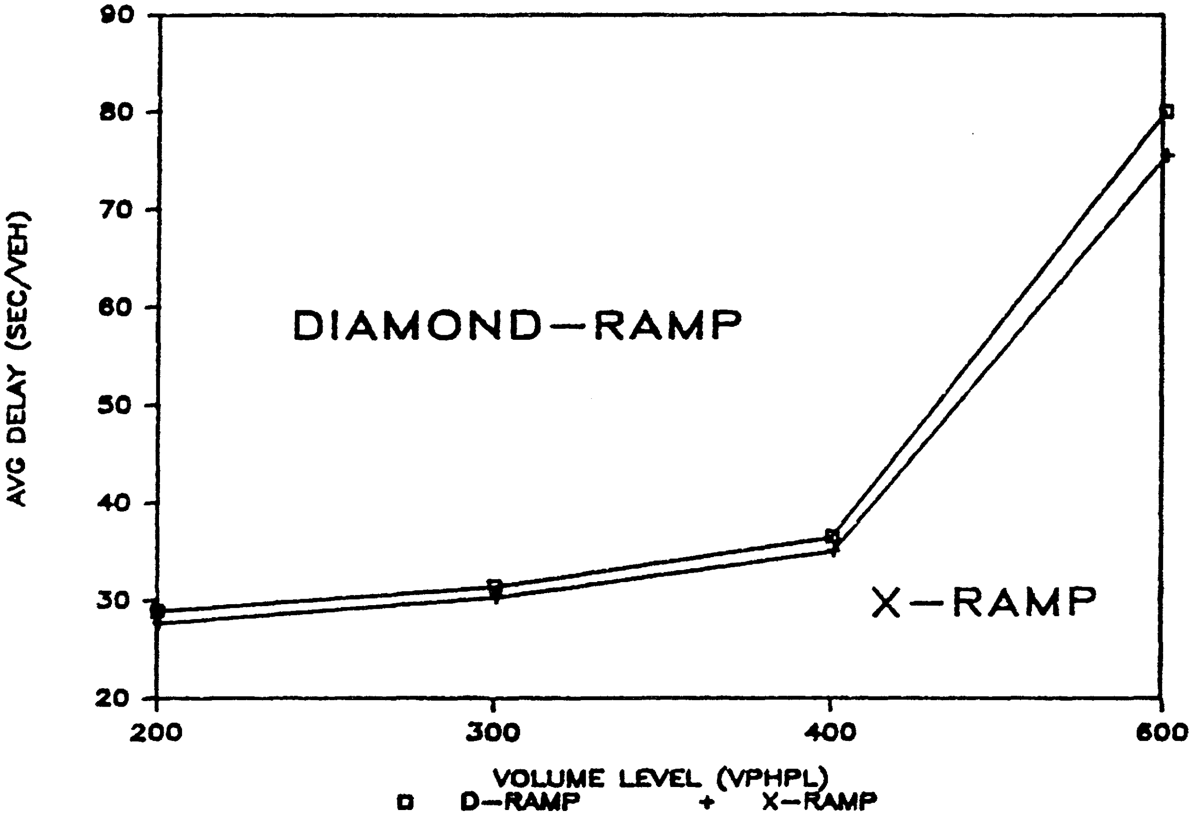
E = External Spacing
1 - 800 feet
2 - 1600 feet
3 - 2400 feet

I = Internal Spacing
1 - 67 feet
2 - 200 feet
3 - 376 feet

V = Volume Level
1 - 200 vehicles/hour
2 - 300 vehicles/hour
3 - 400 vehicles/hour

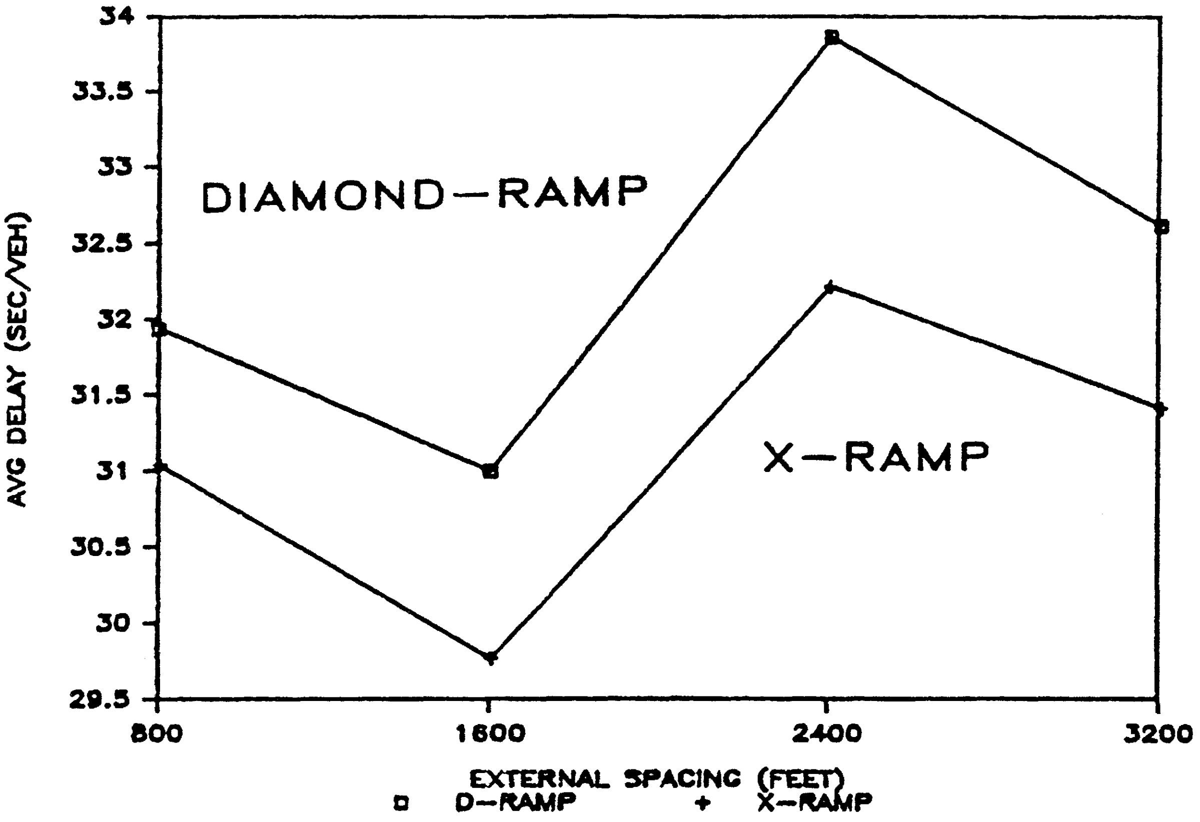
The resulting scenarios were individually coded up in the proper format and the results were generated by the NETSIM model. Appendix A contains the study results of the simulation analysis as performed for each test scenario. The entire output of systemwide measures of effectiveness and delay are provided by NETSIM for each individual case.

Figures 13 and 14 summarize the major study findings based on the NETSIM simulation analysis for both the x-ramp and diamond ramp designs. Figure 13 illustrates the close resemblance of the increasing delay characteristics of both the x-ramp and diamond ramp designs as the total volume (expressed in vehicles per hour per lane) increases. However, there was no statistically significant difference found between the two different ramp designs using a SAS (7) analysis of the data obtained from the NETSIM evaluations.



Note: Based on the analysis of 80 second cycle length.

Figure 13. Effects of Volume Levels to Average System Delay for X-Ramp and Diamond Ramp Designs Based on NETSIM Evaluation.



Note: Based on the analysis of 80 second cycle length.

Figure 14. Effects of External Spacings to Average System Delay for X-Ramp and Diamond Ramp Designs Based on NETSIM Evaluation.

Figure 14 demonstrates the effects of external spacings on average system delay for both the x-ramp and diamond ramp designs based on the NETSIM results of the test scenarios. Similar to those in the PASSER III analysis, a circular delay to spacings relationship exists between the two freeway ramp designs. A constant difference (3-5%) in average system delay is observed between the two ramp designs as the external spacing between the two interchanges is increased. This phenomenon primarily resulted from the additional signal delay due to differences in the frontage road traffic in the NETSIM test scenarios.

CONCLUSIONS AND RECOMMENDATIONS

This study documented the operational characteristics of both x-ramp and diamond ramp interchanges as indicated by the results of this study. The results of the field studies indicated that better yielding occurs at the exit ramp/frontage road junction in the x-ramp design primarily due to limited visibility of exiting traffic and the proximity of the junction to the arterial traffic signal. A continuous series of x-ramps with continuous auxiliary lanes provides for added corridor throughput capacity during peak periods as motorists perform a maneuver referred to as "sling-shooting". However, this type of traffic pattern is operationally inappropriate and should not be encouraged. It may be effectively controlled through the use of a ramp metering system and police enforcement to reduce the number of violations. An examination of traffic patterns at ramp junctions indicated that these patterns vary according to peak period and type of ramp. The aerial photographic survey noted that while commercial development at sites of both designs appeared to be concentrated at the frontage road/arterial intersection, additional development at sites of diamond ramp design concentrated along the arterial, while development along the frontage road was noted where the x-ramp design existed. Simulation analysis revealed that similar study sites consisting of the x-ramp design result in less overall delay than those of the diamond interchange design. However, this difference is not statistically significant nor does it impose the benefits of favoring one particular design versus the other ramp design.

The research provided a documented study methodology for evaluating highway design alternatives based on traffic operational measurements. A set of simulation and field study methods was designed and implemented in this study. Performance measures were made based on the traffic delay approaches. However, delay-based operational results did not indicate which was the more appropriate design. Such selection should be based upon an individual consideration of each location. Access to commercial, retail, and residential development should be the major consideration for ramp design in a particular urbanizing area. New facilities should use the design concept which will provide the needed access capabilities as well as provide for good and continuous freeway operation. The major benefit of the x-ramp design is its capability of removing the traffic load at several upstream locations without requiring motorists to pass through a series of signalized intersections. On the other hand, the diamond interchange design utilizes the adjacent frontage road systems to access the nearby facilities but requires the motorists to pass through signalized intersections. In this manner, the diamond ramp design provides direct access to the intersection of the nearby arterial facilities and keeps the motorist on the freeway mainlanes for a longer distance. In the case of re-designing existing highway and freeway facilities, benefits of improved freeway operations may outweigh the disbenefits of less convenient access due to reversed ramp configuration.

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APPENDIX A

RESULTS OF NETSIM ANALYSIS

TERMINOLOGY USED IN THE SUMMARY OF THE NETSIM SIMULATION TEST CASES

CASE - NETSIM SIMULATION TEST CASE.
VEH-MILE - TOTAL VEHICLE-MILES OF TRAVEL.
VEH-MIN - TOTAL VEHICLE MINUTES OF TRAVEL TIME.
VEH-TRIP - TOTAL VEHICLE TRIPS OF TRAVEL.
STOPS/VEH - AVERAGE NUMBER OF STOPS PER VEHICLE.
MTTT - RATIO OF MOVING TIME TO TOTAL TRAVEL TIME.
AVG SPEED - AVERAGE TRAFFIC SPEED.
MEAN - TOTAL TRAVEL TIME TO DATE FOR PARTICULAR STUDY LINK.
AVG DLY - AVERAGE DELAY TIME PER VEHICLE.
TOT DLY - TOTAL DELAY TIME. (COMPUTED FROM THE DIFFERENCE BETWEEN THE TOTAL TRAVEL TIME AND "IDEALIZED" TRAVEL TIME FOR EACH LINK BASED ON A DESIGNATED TARGET SPEED)
DLY/VEH-MILE - AVERAGE DELAY TIME PER VEHICLE MILE OF TRAVEL.
TT/VEH-MILE - TOTAL TRAVEL TIME PER VEHICLE MILE OF TRAVEL.
SD% OF TOT DLY - STOPPED DELAY AS PERCENTAGE OF TOTAL DELAY TIME.
FUEL(GAL) - FUEL CONSUMPTION OF EACH VEHICLE TYPE, EXPRESSED AS GALLONS.

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL(GAL)	
													1	2
X111	101.36	550.4	797	1.03	.340	11.05	36.4	27.34	363.2	3.58	5.43	60.0	14.91	0.0
X112	107.33	571.2	798	1.01	.349	11.27	37.8	27.98	372.1	3.47	5.32	59.2	15.51	0.0
X113	118.89	597.3	798	1.01	.373	11.94	39.5	28.14	374.2	3.15	5.02	57.5	16.49	0.0
X121	160.60	616.8	801	0.89	.447	15.62	40.9	25.56	341.2	2.12	3.84	54.8	19.22	0.0
X122	168.84	653.7	800	0.91	.446	15.50	43.3	27.15	362.0	2.14	3.87	55.5	20.09	0.0
X123	180.19	677.9	801	0.97	.465	15.95	45.0	27.17	362.7	2.01	3.76	52.7	21.21	0.0
X131	233.98	746.2	801	0.98	.499	18.81	49.4	28.00	373.8	1.60	3.19	55.7	24.14	0.0
X132	241.02	774.5	800	0.99	.502	18.67	51.3	28.95	385.9	1.60	3.21	55.1	24.89	0.0
X133	252.36	792.7	800	1.03	.514	19.10	52.5	28.90	385.4	1.53	3.14	52.7	25.84	0.0
X141	298.06	817.9	797	0.92	.575	21.86	54.2	26.19	347.9	1.17	2.74	52.0	26.83	0.0
X142	311.59	861.6	801	0.92	.558	21.70	57.0	28.50	380.5	1.22	2.77	52.6	28.05	0.0
X143	321.55	890.7	802	1.03	.570	21.66	59.0	28.65	382.9	1.19	2.77	51.7	28.95	0.0

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL(GAL)	
													1	2
X211	152.10	876.9	1200	1.15	.318	10.41	58.9	29.92	598.3	3.93	5.77	61.5	23.36	0.0
X212	160.67	901.9	1196	1.05	.325	10.69	60.4	30.53	608.5	3.79	5.61	61.6	24.10	0.0
X213	179.86	954.8	1203	1.13	.353	11.30	64.0	30.82	617.9	3.44	5.31	59.5	25.87	0.0
X221	242.68	981.0	1204	1.01	.424	14.84	65.5	28.16	565.1	2.33	4.04	56.2	30.08	0.0
X222	254.51	1017.5	1201	0.98	.426	15.01	67.9	29.19	584.2	2.30	4.00	55.8	31.24	0.0
X223	270.20	1064.9	1203	1.08	.437	15.22	71.1	29.90	599.4	2.22	3.94	54.4	32.95	0.0
X231	347.82	1202.4	1199	1.09	.467	17.36	80.2	32.08	641.1	1.84	3.46	59.4	37.34	0.0
X232	358.98	1193.6	1201	1.03	.484	18.04	79.7	30.73	615.2	1.71	3.33	56.8	37.62	0.0
X233	376.90	1273.9	1200	1.13	.482	17.75	85.0	32.98	659.6	1.75	3.38	56.2	39.76	0.0
X241	452.51	1280.6	1200	1.03	.547	21.20	85.5	29.03	580.5	1.28	2.83	53.2	41.25	0.0
X242	467.27	1332.1	1203	1.01	.545	21.05	88.9	30.23	606.1	1.30	2.85	54.1	42.65	0.0
X243	479.41	1385.5	1199	1.13	.548	20.76	92.4	31.32	625.9	1.31	2.89	63.4	44.30	0.0

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL(GAL) 1	FUEL(GAL) 2
X311	203.44	1267.0	1599	1.28	.292	9.63	83.9	33.66	896.9	4.41	6.23	65.7	32.53	0.0
X312	215.53	1330.4	1599	1.25	.292	9.72	88.1	35.32	941.4	4.37	6.17	65.6	34.34	0.0
X313	239.84	1392.8	1604	1.24	.316	10.33	92.2	35.61	952.0	3.97	5.81	64.0	36.41	0.0
X321	325.15	1434.5	1606	1.19	.377	13.60	95.1	33.38	893.6	2.75	4.41	61.3	42.19	0.0
X322	339.51	1465.6	1604	1.14	.393	13.90	97.1	33.30	890.3	2.62	4.32	59.4	43.29	0.0
X323	359.31	1523.4	1602	1.16	.402	14.15	101.0	34.10	910.6	2.53	4.24	58.8	45.35	0.0
X331	466.55	1688.7	1600	1.27	.438	16.58	111.9	35.57	948.6	2.03	3.62	61.8	51.15	0.0
X332	480.81	1737.4	1602	1.26	.442	16.61	115.1	36.28	968.7	2.01	3.61	60.3	52.74	0.0
X333	500.76	1777.7	1601	1.21	.453	16.90	117.8	36.45	972.6	1.94	3.55	57.4	54.54	0.0
X341	601.16	1837.6	1599	1.22	.498	19.63	121.7	34.64	923.2	1.54	3.06	58.2	57.05	0.0
X342	619.77	1927.3	1602	1.18	.497	19.29	127.8	36.32	969.9	1.56	3.11	58.3	59.24	0.0
X343	641.16	2008.6	1600	1.25	.496	19.15	133.1	37.94	1011.6	1.58	3.13	57.3	61.71	0.0

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL(GAL)	
													1	2
X411	276.16	3555.4	2271	1.43	.133	4.66	235.9	81.48	3084.0	11.17	12.87	86.8	70.57	0.0
X412	299.51	3013.1	2319	1.50	.171	5.96	199.8	64.64	2498.4	8.34	10.06	82.3	64.24	0.0
X413	341.42	2941.0	2320	1.50	.201	6.97	195.2	60.77	2349.8	6.88	8.61	79.7	65.38	0.0
X421	443.96	4370.9	2266	1.28	.164	6.09	290.3	96.72	3652.8	8.23	9.85	87.1	92.72	0.0
X422	476.18	3565.6	2327	1.37	.216	8.01	236.7	72.11	2796.5	5.87	7.49	82.0	82.64	0.0
X423	519.05	3245.9	2336	1.45	.264	9.59	215.4	61.34	2388.2	4.60	6.25	77.2	80.48	0.0
X431	647.00	4794.4	2264	1.32	.208	8.10	318.3	100.66	3798.3	5.87	7.41	87.0	105.82	0.0
X432	676.69	4496.5	2285	1.37	.231	9.03	298.5	90.75	3455.9	5.11	6.64	84.8	103.57	0.0
X433	730.81	3445.9	2356	1.45	.330	12.72	228.7	58.75	2307.1	3.16	4.72	73.5	91.40	0.0
X441	833.40	4424.4	2244	1.28	.279	11.30	293.8	85.24	3188.0	3.83	5.31	83.5	106.01	0.0
X442	876.24	4185.8	2298	1.37	.314	12.56	277.9	74.96	2870.9	3.28	4.78	80.1	104.76	0.0
X443	928.43	3811.4	2330	1.43	.370	14.62	253.0	61.78	2399.3	2.58	4.11	73.7	101.93	0.0

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL (GAL)	
													1	2
D111	102.15	560.7	800	1.07	.341	10.93	37.1	27.72	369.5	3.62	5.49	58.7	15.30	0.0
D112	109.54	584.0	798	1.04	.346	11.25	38.6	28.72	382.0	3.49	5.33	58.3	15.99	0.0
D113	121.89	618.2	799	1.08	.368	11.83	40.9	29.34	390.7	3.21	5.07	57.4	17.17	0.0
D121	164.33	636.0	802	0.95	.428	15.50	42.2	27.22	363.8	2.21	3.87	52.3	20.65	0.0
D122	171.06	657.9	800	1.02	.433	15.60	43.6	27.96	372.8	2.18	3.85	51.3	21.23	0.0
D123	182.66	691.4	802	1.08	.449	15.85	45.8	28.52	381.3	2.09	3.79	50.6	22.43	0.0
D131	232.64	762.1	799	1.03	.473	18.32	50.5	30.14	401.4	1.73	3.28	55.5	25.70	0.0
D132	242.24	789.2	797	1.09	.474	18.42	52.2	31.24	415.0	1.71	3.26	55.1	26.50	0.0
D133	252.44	785.5	799	1.08	.502	19.28	52.0	29.38	391.3	1.55	3.11	50.2	27.10	0.0
D141	304.37	821.7	800	0.95	.548	22.23	54.4	27.88	371.7	1.22	2.70	51.7	28.60	0.0
D142	312.27	862.1	798	1.05	.545	21.73	57.2	29.47	392.0	1.26	2.76	51.4	29.64	0.0
D143	323.83	890.6	800	1.11	.550	21.82	58.9	30.06	400.8	1.24	2.75	51.1	30.65	0.0

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL(GAL) 1	2
D211	153.31	873.1	1201	1.15	.324	10.54	58.6	29.48	590.1	3.85	5.69	60.3	23.55	0.0
D212	162.94	924.5	1200	1.12	.323	10.57	62.0	31.31	626.1	3.84	5.67	61.4	24.85	0.0
D213	181.77	960.2	1203	1.14	.349	11.36	64.4	31.17	625.0	3.44	5.28	58.6	26.41	0.0
D221	246.45	1011.3	1205	1.12	.402	14.62	67.5	30.11	604.7	2.45	4.10	55.2	31.94	0.0
D222	258.78	1036.3	1201	1.04	.424	14.98	69.1	29.84	597.3	2.31	4.00	54.2	32.54	0.0
D223	273.88	1090.6	1202	1.15	.429	15.07	72.7	31.11	623.2	2.28	3.98	53.6	34.48	0.0
D231	352.69	1191.3	1197	1.18	.456	17.76	79.6	32.46	647.6	1.84	3.38	57.3	39.43	0.0
D232	365.12	1240.4	1198	1.17	.454	17.66	82.9	33.91	677.1	1.85	3.40	57.5	40.62	0.
D233	379.69	1260.8	1198	1.18	.468	18.07	84.2	33.58	670.4	1.77	3.32	54.2	42.05	0.
D241	457.47	1264.5	1201	1.07	.529	21.71	84.5	29.72	595.0	1.30	2.76	53.3	43.56	0.0
D242	468.13	1332.5	1201	1.10	.516	21.08	88.9	32.22	645.0	1.38	2.85	54.0	45.31	0.
D243	483.31	1385.0	1200	1.18	.522	20.94	92.5	33.08	661.6	1.37	2.87	53.3	46.89	0.

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL(GAL)	
													1	2
D311	206.41	1308.6	1601	1.36	.283	9.46	86.7	35.16	938.3	4.55	6.34	65.9	33.87	0.0
D312	218.43	1352.4	1598	1.30	.291	9.69	89.5	35.99	958.5	4.39	6.19	65.2	35.21	0.0
D313	243.06	1469.0	1598	1.26	.301	9.93	97.4	38.55	1026.8	4.22	6.04	65.7	37.89	0.0
D321	327.98	1445.4	1606	1.21	.372	13.61	95.8	33.91	907.6	2.77	4.41	59.4	43.79	0.0
D322	343.66	1485.5	1602	1.23	.381	13.88	98.5	34.41	918.8	2.67	4.32	58.6	45.37	0.0
D323	366.00	1570.4	1605	1.21	.388	13.98	104.2	35.92	960.8	2.63	4.29	58.5	47.75	0.0
D331	469.37	1712.0	1598	1.32	.416	16.45	113.5	37.55	1000.1	2.13	3.65	62.0	54.24	0.0
D332	484.09	1739.0	1599	1.30	.428	16.70	115.2	37.33	994.8	2.06	3.59	59.6	55.62	0.0
D333	506.35	1828.2	1600	1.26	.429	16.62	121.2	39.16	1044.1	2.06	3.61	60.3	57.81	0.1
D341	611.95	1832.9	1602	1.27	.485	20.03	121.5	35.33	943.3	1.54	3.00	57.5	60.72	0.0
D342	623.08	1894.5	1598	1.29	.482	19.73	125.7	36.88	982.1	1.58	3.04	58.0	62.39	0.0
D343	646.73	2002.3	1600	1.29	.482	19.38	132.8	38.9	1037.4	1.60	3.10	58.4	64.84	0.0

CASE	VEH-MILE	VEH-MIN	VEH-TRIP	STOPS /VEH	MTTT	AVG SPEED	MEAN	AVG DLY	TOT DLY	DLY /VEH-MILE	TT /VEH-MILE	SD% OF TOT DLY	FUEL(GAL)	
													1	2
D411	273.08	4151.3	2231	1.41	.110	3.95	275.7	99.36	3694.7	13.53	15.20	89.5	79.44	0.0
D412	296.76	3216.6	2267	1.47	.156	5.54	213.6	71.82	2713.8	9.14	10.84	84.2	67.38	0.0
D413	342.02	2969.2	2301	1.53	.198	6.91	197.1	62.10	2381.7	6.96	8.68	79.0	66.76	0.0
D421	452.14	3652.1	2261	1.39	.193	7.43	242.4	78.25	2948.7	6.52	8.08	83.9	84.08	0.0
D422	456.52	4293.8	2220	1.29	.167	6.38	285.2	96.63	3595.4	7.83	9.41	86.9	93.47	0.0
D423	515.26	3335.8	2300	1.47	.246	9.27	221.5	65.57	2513.6	4.88	6.47	78.0	82.83	0.0
D431	631.85	5013.3	2202	1.33	.184	7.56	333.1	111.47	4090.8	6.47	7.93	88.4	111.27	0.0
D432	665.77	3969.3	2260	1.41	.247	10.06	263.5	79.39	2990.3	4.49	5.96	82.5	98.00	0.0
D433	723.97	3595.3	2317	1.50	.300	12.08	238.7	65.12	2514.9	3.47	4.97	76.4	95.70	0.0
D441	834.02	4534.9	2221	1.33	.259	11.03	301.2	90.80	3361.2	4.03	5.44	84.6	111.09	0.0
D442	885.39	4149.6	2296	1.43	.302	12.80	275.6	75.69	2896.5	3.27	4.69	79.6	108.87	0.0
D443	916.76	3836.0	2295	1.47	.346	14.34	254.7	65.62	2509.8	2.74	4.18	75.0	105.97	0.0