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16. Abstract

At least six different median design combinations can be utilized to serve the traffic demands of suburban streets and highways. These range from raised to flush medians with or without left-turn bays, continuous left-turn lanes, or no left-turn geometric treatment. Virtually all of these are commonly used by the aggregate of geometric designers in the United States; however, there is less than complete agreement regarding the conditions under which each is most appropriate.

This research study developed guidelines for median design based upon dual considerations of accident experience and operational considerations. Operational criteria address two, sometimes conflicting, design objectives which are maximization of flow and minimization of traffic delay. Key variables employed in the criteria include the magnitudes of straight through and left-turn traffic demands, types of development adjacent to the street section, and operating speeds.

The quality of traffic service provided by a street or highway is usually heavily influenced by the performance and number of intersections along the section. Streets that have intermittent curb cuts or driveways and a traffic demand for left-turns into these driveways might be viewed as having pseudo intersections at all locations where left-turns are permitted across the median into driveways. Median designs were found to have a strong impact upon the operations of most real and pseudo intersections and therefore, upon most street sections.

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CRITERIA FOR THE SELECTION OF A LEFT-TURN MEDIAN DESIGN

by

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Research Report Number 1138-1F

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Medians with Continuous and Intermittent Permitted Left-Turn Movements

conducted for

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There was no invention or discovery conceived or first actuallly reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

Urban arterial streets and highways provide highway users with access to property and opportunities for connection with other streets or highways. In many cases, property access and route changes are accomplished through left-turn maneuvers. The efficiency and safety with which left-turns can be accomplished is heavily dependent upon the type of median incorporated into the street or highway. Although a variety of median concepts have been used, many questions regarding the relative desirability of median types remain unanswered. This study has attempted to provide answers to, at least, some of these questions.

ABSTRACT

At least six different median design combinations can be utilized to serve the traffic demands of suburban streets and highways. These range from raised to flush medians with or without left-turn bays, continuous left-turn lanes, or no left-turn geometric treatment. Virtually all of these are commonly used by the aggregate of geometric designers in the United States; however, there is less than complete agreement regarding the conditions under which each is most appropriate.

This research study developed guidelines for median design based upon dual considerations of accident experience and operational considerations. Operational criteria address two, sometimes conflicting, design objectives which are maximization of flow and minimization of traffic delay. Key variables employed in the criteria include the magnitudes of straight-through and left-turn traffic demands, types of development adjacent to the street section, and operating speeds.

The quality of traffic service provided by a street or highway is usually heavily influenced by the performance and number of intersections along the section. Streets that have intermittent curb cuts or driveways and a traffic demand for left-turns into these driveways might be viewed as having pseudo intersections at all locations where left-turns are permitted across the median into driveways. Median designs were found to have a strong impact upon the operations of most real and pseudo intersections and, therefore, upon most street sections.

SUMMARY

A wide variety of median design concepts are employed along arterial streets. These range from raised medians (with curbs or barriers) which can concentrate or totally prohibit all left-turns, to flush medians with continuous left-turn lanes. The quality of traffic service along an urban arterial may be heavily influenced by the choice of median design concepts. The engineer's choice among these is usually, and appropriately, based upon operational and safety issues.

The choice of median designs has been investigated through many excellent research efforts. Several of those that deal with operational aspects of the design choice are briefly described in Chapter 2. A sampling of those dealing more specifically with safety issues are described in Chapter 6. A comparative operational analysis of the various median designs is presented from the standpoint of a single street intersection, an intersection formed by a street and driveway openings, and an extended arterial street section containing both of the previous intersection forms. Based upon these data and analyses, general guidelines for use of arterial street median designs are developed as follows:

1) Left-turn lanes may be used as recommended by Tables 6.1 and 6.2 as long as the speed of traffic on the arterial is less than 45 mph. For higher speeds, raised median treatments should be used if a left-turn treatment is recommended in the tables.
2) On arterial streets with significant numbers of driveways, the left-turn lane treatment is operationally better than the raised median treatment; however, the accident rates also increase as there is more weaving in the traffic stream. It is better to provide a raised median treatment and concentrate the left-turns if the driveways are spaced less than 100 feet apart. On streets with driveways very far apart, i.e, greater than 400 feet apart, raised median and left-turn lane treatments would be operationally similar. However, infrequent driveways would not provide the usual justification for continuous left-turn lanes.
3) From the safety standpoint, the sections with the left-turn treatment are always better than the sections with no treatment. So in sections with disproportionately large number of accidents, left-turn treatments can be used even though not warranted due to the operational criteria.
4) For very high left-turn volumes the left-turn lane treatment is recommended as it provides a storage area for all the left-turners and is safer than the other treatments.

IMPLEMENTATION STATEMENT

The guidelines for use of median designs contained within this report will provide a rational basis upon which median types can be selected. Since the guidelines are based upon operational as well as safety criteria, their implementation offers the potential of improved traffic operational efficiency without an inherent cost in safety.

TABLE OF CONTENTS

PREFACE iii

ABSTRACT iii

SUMMARY iv

IMPLEMENTATION STATEMENT iv

CHAPTER 1. INTRODUCTION 1

CHAPTER 2. LITERATURE REVIEW
- Operational Aspects of Median Treatments 2
- Safety Aspects of Median Treatments 3
- Warrants for Median Treatments 5

CHAPTER 3. OPERATIONAL EFFECTS OF MEDIAN TREATMENTS ON TRAFFIC AT NON-INTERSECTION LOCATIONS
- Introduction 8
- Data Collection 8
- Description of the Experiment 9
- Analysis of the Data 9
- Conclusion 12

CHAPTER 4. OPERATIONAL EFFECTS OF MEDIAN TREATMENTS ON AN ARTERIAL NETWORK
- Introduction 13
- Procedure for Conduct of Experiment 14
- Analysis of the Data 14
- Experiments on Other Geometries 16
- Addition of a Lane in Each Direction 17
- Experiments on Networks with Left Turns Occurring on Both Sides of the Street 20
- Network with Driveways Opposite Each Other 20
- Network with Driveways Offset on Alternate Sides of the Arterial 22
- Conclusions 24

CHAPTER 5. LEFT-TURN CAPACITY ANALYSIS FOR THE VARIOUS LEFT-TURN TREATMENTS
- Introduction 26
- Theoretical Background 26
- Application to the Present Problem 27
- Conclusion 27

CHAPTER 1. INTRODUCTION

Many urban arterials face serious operational and safety difficulties due to a combination of high traffic volumes and large traffic demands for access to many driveways. These arterials frequently have a large number of left-turn movements occurring at midblock locations. Traffic engineers have long recognized the efficacy of median treatments in alleviating left-turn-related operational and safety difficulties. Left-turning vehicles are often a major cause of accidents and delay along these arterials. Median treatments alleviate the problem by separating the left-turning vehicles from the through traffic.

Two median treatments which are commonly used are (1) raised medians with intermittent openings and left-turn pockets or (2) continuous left-turn lanes which may either be one-way or two-way. These two treatments have different operational characteristics and accident experiences. There has been considerable concern among traffic engineers about the safety aspects of median treatments, especially the continuous two-way left-turn lane. A number of before-after field studies have been conducted to investigate this problem, and they have resolved the issue in favor of the left-turn lane. Very few studies dealing with the operational aspects of the problem have been conducted; therefore, this study is intended to develop guidelines for the use of the two left-turn treatments described above, based upon the operational characteristics as well as accident experience.

Within this study, the operational characteristics of street sections with various median types were compared to each other and to a base case consisting of a section with no median treatment. Through computer simulation several measures of effectiveness were generated and compared. The traffic on the sections was simulated using the TEXAS Model for Intersection Traffic and the NETSIM simulation models. Details of the simulation are explained in the Chapters 3 and 4.

Accident experience associated with different types of median treatments was gathered through a review of the literature. As was mentioned before a number of studies have been conducted to study the safety aspects of median treatments. Data from these studies were used to characterize probable accident experience. Operational characteristics and probable accident experience are used together in this study to propose guidelines for the use of left-turn median treatments.

CHAPTER 2. LITERATURE REVIEW

Traffic engineers responsible for arterial streets have long recognized the significance of median treatments. These treatments have been in use for nearly 40 years, but concerns still exist among engineers about their efficacy, particularly safety. A number of median-treatment studies have been conducted which can be classified into three broad categories: (1) studies about the operational aspects of the treatments, (2) studies about the safety aspects, and (3) studies directed toward developing warrants based on either the safety or the operational aspect. This chapter is divided into three parts based on these three different categories.

OPERATIONAL ASPECTS OF MEDIAN TREATMENTS

Since the early 1950's engineers have been mainly concerned with safety aspects of median treatments with the result that only a few studies have been conducted concerning operational considerations. Most of the operational work has dealt with the effects of the continuous two-way left-turn lane (CTWLTL), while relatively little work has been done on the operational aspects of the other kinds of median treatments.

Most of the early operational work on median treatments consisted of before-and-after field studies. The problem with this kind of study is that the conclusions in most cases are specific to the field site. It was also impossible to isolate the effects of different geometries on traffic flow explicitly. This problem was rectified in later studies by using simulation of the median treatment, particularly simulation of the CTWLTL.

The earliest major work done in this area is the study conducted by Sawhill and Neuzil (Ref 1) in the early 60's. They made their operational study in terms of travel distance within the CTWLTL prior to turning, use of turn signals prior to turning and general observations on user behavior. Several of their observations were

1) People who don't understand the CTWLTL tend to stop or slow down prior to the left-turn maneuver.
2) Seventeen percent of out-of-town drivers tend to make no use of the CTWLTL prior to turning left.
3) Most drivers completed their left-turn maneuver into the left-turn lane within 40 to 50 feet of the beginning of their destination.
4) The average travel distance within the CTWLTL is 200 feet for a local driver and 140 feet for an out-of-town driver.
5) Travel distance within the left-turn lane is longer during rush hour than during non-rush hour for a local driver and relatively consistent for an out-of-town driver.
6) Drivers decelerate in the through lane prior to entering the left-turn lane.
7) Automobiles entering the roadway from driveways make little use of CTWLTL as an acceleration lane; however, truckers make use of it for their left-turn movement.
8) Few drivers use it as a passing lane.
9) Approximately 80% of the drivers use their turn indicators prior to making the turn into a driveway and only 40% use it when turning from driveways to the roadway.

Nemeth (Ref 2) conducted 'before and after' operational studies on two CTWLTL sites in Ohio. His major parameters were traffic conflicts, travel time, left and right turning volumes and volume on each lane. Traffic conflict is defined by Nemeth as "any instance in which a vehicle must swerve or brake to avoid an accident." He further classified the conflicts into cross conflict, opposing conflict, rear-end conflict and weaving. The first site involved conversion of a four-lane arterial into a three-lane arterial with a CTWLTL. The second site included conversion of a four-lane arterial into a five-lane arterial with a CTWLTL. His conclusions about the first site were that the conversion resulted in increased travel times, increased weaving, and some observed reduction in conflicts. He concluded that the beneficial effects of the CTWLTL are offset by elimination of one through lane in each direction. Nemeth's conclusions about the second site were that, though changes in volumes were noted, the change in speeds were statistically insignificant. There was considerable variation in the conflicts attributable to confusion over markings.

A number of other studies have been conducted following a similar methodology including studies by Hoffman (Ref 3), Ray (Ref 4), etc. Their conclusions were that CTWLTLs are generally effective in reducing delay to traffic as well as in reducing accidents.

There has been little work done on the operational aspects of other median treatments such as the raised median with intermittent openings, and continuous one-way left-turn median lane, etc. Walton (Ref 5) et al did operational studies on three types of median treatment sections: the continuous one-way left-turn lane (COWLTL), the continuous two-way left-turn lane, and a transition from the former to the latter. They conducted the study on twenty sites of which six were CTWLTL, four were transitions from CTWLTL to COWLTL, and the rest were either raised or flush COWLTL. They collected data about the entrance distance, maneuvering distance, lateral distance, traffic volume, and conflicts. The entrance distance parameter applied only to the CTWLTL since the COWLTL has specific openings for left-turn entry. This distance is measured from the intersection to where the vehicle enters the turn lane before making the left-turn maneuver. The maneuvering distance is the distance required for the left-turn vehicle to fully enter the left-turn lane. Lateral placement is the lateral position of the vehicle in the left-turn lane. These data were analyzed by analysis of variance techniques to determine the effects of different lane widths, different delineation systems, and different types of left-turn facilities. Their conclusions were:

1) Lane widths between 11 to 12.4 ft had no adverse effect on the traffic, but wider lanes (e.g., 15 ft) created confusion among the drivers.
2) Smaller lane widths of 8.5 ft to 11 ft caused a significant variation in the traffic stream.
3) Traffic volume, especially the left-turning and the adjacent through-lane traffic, has a significant effect on the entrance distance.
4) Entrance distances to left-turns at midblock and at intersection approaches are different.
5) The type of lane delineation has a significant effect on entrance distance.
6) There is a wide range of entrance distances on CTWLTLs. The majority of drivers entered the left-turn lane 135-225 ft from the intersection while very few drivers entered the lane less than 100 ft from the intersection.
7) A large number of drivers completed the left-turn entry within 50 ft.
8) Traffic volumes and numbers of through lanes were found to influence the maneuvering distance.
9) Maneuvering distances were shorter at midblock than at intersection approaches.

In recent times simulation models have become popular for looking at the operational effects of median treatments because they are relatively inexpensive to use and it is possible to compare different geometries under exactly the same traffic. The model developed by Ballard, McCoy, and Wijaya (Ref 6) is specially used to determine the operational effect of the CTWLTL. This model has been validated and can be used to compare the operational effectiveness of the treatment with that of the same section under similar conditions without any treatment. The required input for the model is given below:

(a) Number of through lanes,
(b) Presence or absence of CTWLTL,
(c) Length of the simulated section,
(d) Location of individual driveways,
(e) Entering traffic volume by lane in each direction,
(f) Arrival distribution of the traffic,
(g) Percentage of vehicles turning left at individual driveways,
(h) Percentage of vehicles turning right at individual driveways,
(i) Travel speed in each direction, and
(j) Random number seed.

The output data is

(a) The number of vehicles entering and leaving the section,
(b) Number of left turns attempted or completed,
(c) Number of stops,
(d) Travel time in the segment, and
(e) Stopped time delay.

The travel time, stops, and delay totals are output separately for through-vehicles, left-turning vehicles, and all vehicles.

They ran simulation for different input volumes and driveway densities. The driveways were spaced evenly along the section on opposite sides of the road. All the simulated driveways had the same turning volume. The travel speed was assumed to be 40 mph for flow rates of 400 and 650 vph and 35 mph for flow rates of 900 and 1000 vph. The results of their simulation are shown in Figs 2.1 and 2.2.

SAFETY ASPECTS OF MEDIAN TREATMENTS

The safety aspects of median treatments can be studied in two ways, (1) before-after studies at the same site and (2) comparison of accident rates at similar sites with different design alternatives. The former method suffers from the lack of a control group to ensure that a general, unrelated trend in the accidents is not mistaken for the effect of the treatment. The latter method suffers from the fact that highway sections with different design alternatives may also differ in many other respects such as adjacent land use.

An early study concerning the safety aspects of CTWLTLs was a before-and-after study by Sawhill and Neuzil (Ref 1) at three locations. The sites were chosen based on the following criteria:

1) There was minimal change in the traffic volume before and after the installation of the median treatment.
2) Accident data were available for several years before and after the installation of the CTWLTL.
3) The CTWLTL should be of sufficient length.

Accident data collected at the sections were analyzed and the following conclusions were drawn.

1) There was a reduction in the total number of accidents for CTWLTLs as compared to the accident rate for the city as a whole.
2) There was a dramatic decrease in the occurrence of rear-end collisions. There was a decrease in the number of other types of accidents though not as much as in the number of rear-end collisions.
3) The severity of accidents was also reduced with the introduction of CTWLTLs.

Flow Rate[a] (vph)	Driveway Density[b] (driveways/mile)	Left-Turn Volume[a] in 1,000-ft Section: % of Through Volume	Left-Turn Volume[a] in 1,000-ft Section: Turns/ Hour	Average Delay Reduction (veh-sec) for Through Vehicles: Per Hour[a]	Average Delay Reduction (veh-sec) for Through Vehicles: Per Left-Turn Vehicle	Average Reduction in Number of Stops by Through Vehicles: Per Hour[a]	Average Reduction in Number of Stops by Through Vehicles: Per Left-Turn Vehicle	Waiting Time (veh-sec) for Left-Turn Vehicles: Per Hour[a]	Waiting Time (veh-sec) for Left-Turn Vehicles: Per Left-Turn Vehicle
650	30	7.5	49	480	9.80	120	2.45	342	6.99
		10.0	65	715	11.00	111	1.71	461	7.10
		12.5	81	795	9.82	131	1.62	475	5.87
	60	7.5	49	372	7.59	89	1.82	284	5.80
		10.0	65	507	7.80	122	1.88	312	4.80
		12.5	81	780	9.63	122	1.51	338	4.17
	90	7.5	49	359	7.34	80	1.63	199	4.06
		10.0	65	648	9.97	110	1.69	301	4.64
		12.5	81	530	6.55	112	1.38	311	3.85
900	30	5.0	45	1,977	43.94	297	6.60	613	13.63
		7.5	68	4,800	70.58	423	6.22	970	14.26
		10.0	90	6,084	67.60	488	5.42	1,183	13.15
	60	5.0	45	713	15.84	206	4.58	529	11.76
		7.5	68	4,569	67.19	668	9.82	918	13.50
		10.0	90	5,407	60.08	459	5.10	1,090	12.11
	90	5.0	45	765	17.00	198	4.40	325	7.23
		7.5	68	1,779	26.17	264	3.88	536	7.88
		10.0	90	6,072	67.47	489	5.43	960	10.66
1,100	30	2.5	28	25,895	924.80	938	33.50	1,057	37.74
		5.0	55	45,245	822.63	1,165	21.18	1,675	30.47
		7.5	83	59,278	714.19	1,143	13.77	2,614	31.50
	60	2.5	28	16,631	593.95	855	30.54	1,345	48.04
		5.0	55	42,640	775.26	1,337	24.31	1,505	27.36
		7.5	83	52,465	632.10	1,208	14.55	2,261	27.24
	90	2.5	28	22,184	792.30	928	33.14	680	24.29
		5.0	55	30,236	549.75	1,157	21.04	1,176	21.38
		7.5	83	40,607	489.25	1,072	12.92	2,131	25.67

[a] In each direction of travel
[b] Driveways per mile including driveways on both sides of highway

Fig 2.1. Comparison of five-lane TWLTL section with a four-lane section with no treatment.

4) Some of the accidents were caused by out-of-town drivers unfamiliar with the median treatment.

A number of other before-and-after studies have come to more or less the same conclusions. A study conducted by Nemeth (Ref 2) found that brake applications increased at two of the three sites studied and weavings decreased at two of the three sites. The results of this before-and-after study was not very conclusive about the effectiveness of the CTWLTL.

Another approach used to study the safety of median treatments is the comparative study of different median treatments. Usually the end result of a comparative study is a regression equation relating the accident rate to some independent variables. One study of this kind by Walton et al (Ref 5) produced a set of equations relating various dependent variables such as the number of accidents per mile, the total number of accidents, and the number of accidents per million vehicle-miles, with independent variables such as weekday ADT, number of signals, number of driveways, and city size. There was little data about treatments other than the CTWLTL, so the regression equations were mainly for the CTWLTL. When the regression equations developed for the CTWLTL were used to predict accident rates for the COWLTL and for the reversible lane, there was a consistent over-estimating of the accident rates. Their conclusions were:

1) The general accident statistics for the raised COWLTL and the CTWLTL reveal similar patterns by hour-of-day, number-of-vehicles involved, and severity.
2) Raised COWLTL have a greater proportion of intersection and intersection-related accidents than CTWLTL sites. The CTWLTL have a greater proportion of driveway and driveway-related accidents.
3) The most frequently noted factors contributing to accidents on all sites were unsafe speed and failure to yield right-of-way.

Flow Rate[a] (vph)	Driveway Density[b] (driveways/mile)	Left-Turn Volume[a] in 1,000-ft Section: % of Through Volume	Left-Turn Volume[a] in 1,000-ft Section: Turns/ Hour	Average Delay Reduction (veh-sec) for Through Vehicles: Per Hour[a]	Average Delay Reduction (veh-sec) for Through Vehicles: Per Left-Turn Vehicle	Average Reduction in Number of Stops by Through Vehicles: Per Hour[a]	Average Reduction in Number of Stops by Through Vehicles: Per Left-Turn Vehicle	Waiting Time (veh-sec) for Left-Turn Vehicles: Per Hour[a]	Waiting Time (veh-sec) for Left-Turn Vehicles: Per Left-Turn Vehicle
400	30	15	60	1,073	17.88	232	337	337	5.67
		20	80	1,370	17.13	250	368	368	4.61
		25	100	2,203	22.03	287	460	460	4.60
	60	15	60	535	8.92	140	218	218	3.63
		20	80	967	12.09	208	267	267	3.34
		25	100	1,042	10.42	207	288	288	2.88
	90	15	60	741	12.35	169	184	184	3.06
		20	80	1,030	12.87	216	264	264	3.30
		25	100	1,841	18.41	249	301	301	3.01
650	30	10	65	22,551	346.94	780	1,853	1,853	28.51
		15	98	39,905	407.20	799	2,517	2,517	25.68
		20	130	45,819	352.45	705	2,899	2,899	22.30
	60	10	65	33,492	515.27	866	1,070	1,070	16.46
		15	98	35,857	365.89	907	1,854	1,854	18.92
		20	130	41,224	317.11	881	1,937	1,937	14.90
	90	10	65	25,337	389.81	785	741	741	11.40
		15	98	23,911	243.99	879	996	996	10.16
		20	130	32,566	250.21	872	1,873	1,873	14.41
900	30	5	45	62,426	1,387.26	188	18,866	18,866	419.24

[a] In each direction of travel

[b] Driveways per mile including driveways on both sides of highway

Fig 2.2. Comparison of three-lane TWLTL section with a two-lane section with no treatment.

A similar methodology applied by Squires and Parsonson (Ref 8) to compare the raised median with the CTWLTL revealed that for a four-lane section the raised medians were safer but that the sample had a higher statistical error. For a six-lane section, the raised median was safer than the CTWLTL in most cases except where there were a high number of driveways per mile, low number of signals per mile, and low number of approaches per mile.

Another major study by Harwood (Ref 9) compared the safety of a two-lane road with no treatment, a three-lane road with CTWLTL, a four-lane road with no treatment, a four-lane road divided with a raised median, and a five-lane road with CTWLTL. He grouped the sections based on whether they were in commercial or residential areas and grouped the accidents into intersection and non-intersection accidents. The results of this study indicate that sections with residential development have a lower rate than sections with commercial development. The three-lane CTWLTL has a lower accident rate than the two-lane road with no treatment, and the five-lane CTWLTL sections have a lower accident rate than either the four-lane road with no treatment or the the four-lane section with a raised median. The reason that this result is contrary to what was stated above might be due to inadequate sizes of sample data sets and related sampling problems.

WARRANTS FOR MEDIAN TREATMENTS

From the beginning of the use of median treatments, engineers have been interested in warrants for their use. Most of the earlier warrants were based on the experience of engineers using various types of median sections. One of the warrants of this kind was developed by Z. A. Nemeth (Ref 2). He lays out a stepwise procedure for the implementation of the CTWLTL. The steps are given below.

1) Document the existing conditions so that the problem can be defined. The objective of the review of existing conditions is to establish that a conflict exists between the left-turn and the through traffic and that the solution offered by the CTWLTL is feasible and desirable. Information is needed in three areas—the existing physical conditions, existing traffic conditions, and accident histories.
2) Establish the appropriateness of the CTWLTL. Nemeth gives a number of guidelines in order to do

this. The guidelines are once again divided into three areas—the physical conditions, the existing traffic conditions, and the accident histories. The guidelines include details about the driveway spacing, type of land use, ease of alternate access, distance between intersections, number of lanes, and width of pavement.

A later study by Harwood (Ref 9) also lays out a stepwise procedure for selecting among different median treatments. Guidelines for use of median treatments are given in Table 2.1, which has two parts—operational and safety factors. Selection of a median treatment involves the use of Table 2.2 and the following steps:

1) Determine existing conditions.
2) Determine projected future conditions.
3) Identify constraints which limit the feasibility of a particular design alternative or make a particular alternative more attractive.
4) Identify the land use, community development and the highway agency priorities which affect the choice of the median treatment.
5) Determine the basic number of through lanes to serve the present and the future traffic needs.
6) Examine the possible geometric variations in the design alternatives.
7) Determine benefits and disadvantages of feasible alternatives.
8) Select the ultimate design alternative for the site.

Another approach which is used for the selection of a section for median treatment is to find the cost and the benefits of a particular treatment. A study of this type was done by Ballard et al (Ref 6) to provide guidelines for the use of CTWLTL on four-lane roadways. They came up with regression equations for savings in stop delay and travel time and savings due to reduction in accidents for various cases. The data for the reduction in delay was collected from simulation of the CTWLTL using the simulation program described above, and the accident data were provided by the Nebraska D.O.T.

TABLE 2.1. GUIDELINES FOR USE OF MEDIAN TREATMENTS

Operational Factors
1. Minimize or eliminate delay to through vehicles by left-turning vehicles.
2. Minimize delay to through vehicles by right-turning vehicles.
3. Allow provision of turning lanes at intersections and high volume driveways.
4. Ease the movement of emergency vehicles.
5. Provide for storage of disabled vehicles.
6. Compatible with use of frontage roads.
7. Facilitate U-turns.
8. Shadow vehicles making crossing maneuvers at unsignalized intersections (eliminate blocking of one direction while waiting for gap in the other direction).
9. Facilitate pedestrian crossings.
10. Encourage access development on side streets off of the arterial.
11. Minimize high volume of left-turn and U-turn movements at intersections.

Safety Factors
1. Minimize rear-end conflicts between left-turning and through vehicles and allow left-turn drivers time to evaluate opposing gaps.
2. Minimize high concentration of driveways and overlapping conflict patterns.
3. Control conflicts between left turns into and out of driveways.
4. Minimize or eliminate conflicts between opposing left-turn off of the arterial.
5. Minimize or eliminate conflicts caused by encroachment on opposing lanes of vehicles turning right into and out of driveways.
6. Minimize or eliminate conflicts caused by encroachment on adjacent lanes of vehicles turning right into and out of driveways.
7. Minimize or elimate conflicts in opposing lanes of vehicles turning left off of the arterial.
8. Minimize time during which left-turn conflicts with opposing traffic can occur.
9. Provide protected position in median for crossing vehicles.
10. Provide protected position in median for crossing pedestrians.
11. Minimize conflicts between bicycles and motor vehicles.
12. Increase width of roadside clear recovery area.

TABLE 2.2. RELATIVE RATINGS OF OPERATIONAL AND SAFETY FACTORS FOR DESIGN ALTERNATIVES

Design Alternative	Description of Geometrics	Total Available Width (ft)	Operational Factors											Safety Factors												
			1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13
Two-Lane Undivided (2U)	Narrow Lanes	20 - 22	--	--	--	--	--	--	--	+	+	--	+	--	--	--	--	--	--	0	--	+	--	--	--	--
	Wide Lanes	24 - 26	--	--	--	--	--	--	--	+	+	--	+	--	--	--	--	--	-	0	+	+	--	--	-	--
	Narrow Shoulder	28 - 36	-	-	--	+	+	--	-	+	+	--	+	--	--	--	--	-	+	0	+	+	--	--	+	-
	Full Shoulder	38 - 40	+	++	+	++	++	--	-	+	+	--	+	--	--	--	--	-	++	0	++	+	--	--	++	+
Three-Lane with TWLTL (3T)	Narrow Lanes	30 - 32	+	--	--	+	--	--	--	--	+	--	+	+	--	-	-	-	++	--	--	+	--	--	--	--
	Wide Lanes	34 - 40	++	--	--	+	--	--	-	-	-	--	+	++	--	-	-	+	++	+	+	+	-	--	-	--
	Narrow Shoulder	42 - 48	++	+	--	++	+	--	-	-	-	--	+	++	--	-	-	+	++	++	+	+	-	--	+	-
	Full Shoulder	50 - 56	++	++	+	++	++	-	-	-	-	--	+	++	--	-	-	++	++	++	++	+	-	--	++	+
Four-Lane Undivided (4U)	Narrow Lanes	40 - 42	-	-	--	-	--	--	-	--	--	--	+	--	--	--	--	++	++	--	-	-	--	--	--	--
	Wide Lanes	44 - 52	-	-	--	-	--	--	-	--	--	--	+	--	--	--	--	++	++	+	+	-	--	--	-	--
	Narrow Shoulder	54 - 58	-	+	--	+	+	--	-	--	--	--	+	--	--	--	--	++	++	++	++	-	--	--	+	-
	Full Shoulder	60 - 64	-	++	+	++	++	--	-	--	--	--	+	--	--	--	--	++	++	++	++	-	--	--	++	+
Four-Lane Divided with raised Median (4D)	Narrow Lanes	48 - 54	+	-	--	-	--	++	-	--	+	++	-	+	++	++	++	++	++	--	-	-	--	++	--	--
	Wide Lanes	56 - 64	++	-	--	-	--	++	+	-	++	++	-	++	++	++	++	++	++	+	++	-	-	++	-	--
	Narrow Shoulder	66 - 70	++	+	--	+	+	+	++	-	++	++	-	++	++	++	++	++	++	++	++	-	-	++	+	-
	Full Shoulder	72 - 80	++	++	+	++	++	+	++	-	++	++	-	++	++	++	++	++	++	++	++	-	-	++	++	+
	Wide Median	72 - 94	++	-	--	++	++	+	++	++	++	+	-	++	++	++	++	++	++	+	++	-	++	++	-	--
Five-Lane with TWLTL (5T)	Narrow Lanes	50 - 54	+	-	--	+	--	--	-	--	--	--	+	+	--	-	-	++	++	--	--	-	--	--	--	--
	Wide Lanes	56 - 64	++	-	--	+	--	--	+	-	--	--	+	++	--	-	-	++	++	+	++	-	-	--	-	--
	Narrow Shoulder	66 - 68	++	+	--	+	+	--	++	-	--	--	+	++	--	-	-	++	++	++	++	-	-	--	+	-
	Full Shoulder	70 - 80	++	++	+	++	++	--	++	-	--	--	+	++	--	-	-	++	++	++	++	-	-	--	++	+

Scale of Operational and Safety Ratings:

++ Most desirable ↓
+
0
—
-- Least desirable

CHAPTER 3. OPERATIONAL EFFECTS OF MEDIAN TREATMENTS ON TRAFFIC AT NON-INTERSECTION LOCATIONS

INTRODUCTION

The behavior of traffic on an arterial which has curb cuts or driveways and adjacent median openings can be studied by considering the driveway-median opening locations as pseudo-intersections. The pseudo-intersections behave like real intersections except that they are often uncontrolled and usually have very little traffic crossing the arterial. In order to study pseudo-intersections, a simulation model which permits study of the effects of different geometric features under various traffic conditions was used. The different sections studied are shown in Figs 3.1, 3.2, and 3.3. Two of the sections represent a continuous one-way left-turn lane (COWLTL) and a raised median with left-turn pockets. There is also a section with no median treatment which represents a comparative base case.

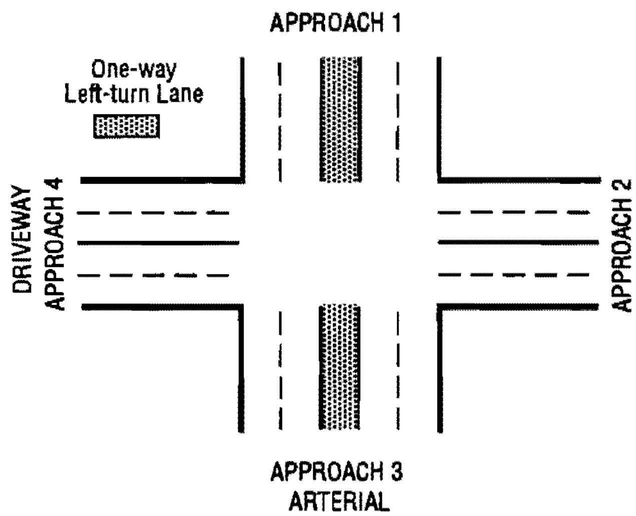


Fig 3.1. Geometrics of a pseudo-intersection continuous one-way left-turn lane on the arterial.

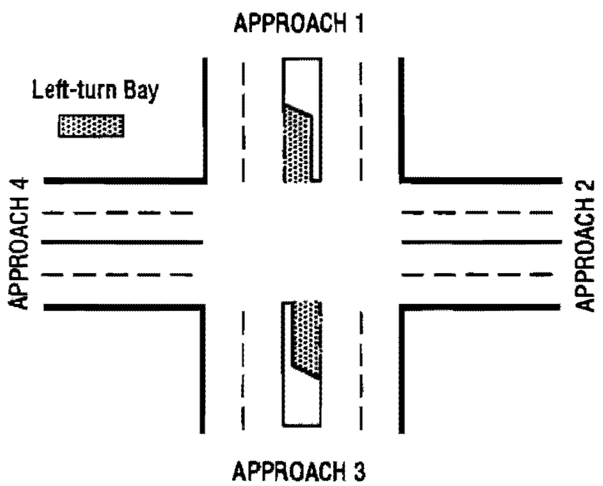


Fig 3.2. Geometrics of a pseudo-intersection for a raised median with turn bays on the arterial.

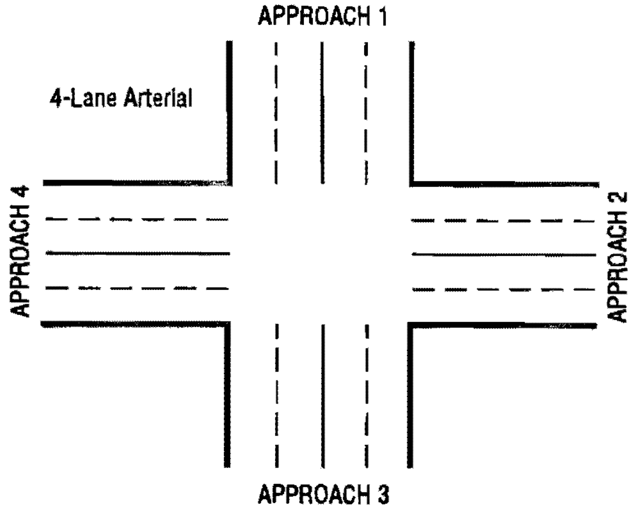


Fig 3.3. Geometrics of a pseudo-intersection for base-case with no median treatment on arterial.

DATA COLLECTION

Most of the previous studies were based upon field observations, which suffer from the fact that it is very difficult to find sites with different geometries but similar in every other aspect. It is also difficult to study the sites under different selected volumes and traffic control features. These difficulties can be overcome by using simulation. Hence, in this study computer simulation was chosen as a primary data collection tool. Simulation provided the means for examining the different selected combinations of geometries and traffic demand. The TEXAS Model for Intersection Traffic (Ref 9) was used as the tool, as it provides highly-detailed traffic operations information by allowing each driver-vehicle unit to react with the intersection geometry, traffic-control features, and other driver-vehicle units.

The model is essentially composed of four component parts normally called processors. The driver-vehicle and geometry processors generate traffic streams and vehicle paths in conformance with user specifications regarding proportions of three driver classes, twelve vehicle classes and basic intersection geometry. The simulation processor does the work of "moving" the vehicles through the intersection geometry and allowing each vehicle to react to traffic-control features as well as to other vehicles and to driver decisions. The emissions processors uses the speed-time history of each vehicle and acceleration to produce estimates of vehicular emissions and fuel consumption.

DESCRIPTION OF THE EXPERIMENT

The sections which were used in the conduct of the experiment are shown in Figs 3.1-3.3. The sections which were tested were a four-lane arterial with a raised median and intermittent openings, a four-lane arterial with the continuous left-turn lane on each approach, and a four-lane arterial with no median treatment. The continuous two-way left-turn median lane was not simulated in this experiment, even though its use is widespread, as in most cases the operation of the one-way left-turn median lane is similar. The experiment was conducted with low, medium, and high volumes of left-turn, straight-through, and opposing traffic as shown in Table 3.1.

TABLE 3.1 SELECTED EXPERIMENTAL TRAFFIC VOLUMES

Volume	Left-Turn Volume	S.T. Volume	Opposing Volume
Low	200	300	400
Medium	400	600	800
High	600	900	1200

The experiment was conducted twice with different random-number seeds. In all, 198 runs were performed. Data collected were the different types of delay values generated by the TEXAS Model. The delays chosen for examination and analysis were:

1) Total delay: This is defined as the difference in time actually required to traverse the intersection compared to the time required to traverse the intersection under ideal conditions.
2) Queue delay: This is defined as the delay incurred by a vehicle while in a queue i.e, when there are minimum headways and the vehicles move less than 3 mph.
3) Stopped delay: This is the delay incurred by a vehicle moving less than 2 mph.

ANALYSIS OF THE DATA

Total delay was considered for the purpose of this analysis as the most applicable definition of delay. An analysis of variance was conducted to determine whether there was any difference in the delay on the arterial streets due to the various median treatments in the sections and to study the effect of the volume change on the delay. The results of the Analysis of Variance (ANOVA) are given in Table 3.2.

It can be seen that the model with the above variables explains most of the delay associated with the arterial. The F value (15.56) associated with the treatment is greater than the critical value, so the null hypothesis that there is no difference between the treatments can be rejected. The left-turn volume (F-value of 80.89) has the greatest effect on delay, so in order to make judgements about the use of a particular type of section, the left-turn volume will be used as an indicator of relative effectiveness. A pairwise comparison of the various treatments was conducted to identify any differences between pairs of sections. The results of this comparison are given below in Tables 3.3 to 3.5.

Values shown in these tables indicate that a clear difference exists between the two channelized sections compared to the section with no treatment; however, the difference between the two individual treatments is not significant. The magnitude of the variation in delay due to volumes is greater than that due to the treatments, but the combined effect of the treatment and the volume is significant; hence a graphical analysis was developed using the left-turn volume as the independent variable and the average delay on the approach as the dependent variable.

In Figs 3.4 through 3.12 the left-turn volume on an approach is plotted against the average total delay on that approach. The straight-through and opposing traffic volumes are constants and the left-turn volumes are varied in these plots to demonstrate the effects of left-turners and the treatments themselves on the delay. In Figs 3.4 through 3.6, low straight-through volumes produce little difference among delays for the treatments over the range of opposing and left-turn volume concerned.

In Figs 3.7 through 3.9, the straight-through volumes are constant at their medium values and the opposing traffic and the left-turn volumes are varied. There is little difference among the three median treatments until left-turn demands reach the high level (600 vph). With high left-turn demand, and medium straight-through traffic (600 vph on two lanes), both channelization sections performed better than the no-treatment case. However, differences between the continuous turn lane and raised median are not practically significant.

In Figs 3.10 through 3.12, the straight-through volumes are high, and the opposing traffic and the left-turn volumes are varied. As before, there is no difference among the left-turn treatments at low left-turn volumes. At high values of all traffic volumes, the channelized sections again perform better than no treatment. However, raised-median sections appear to produce lower delay than the left-turn-lane section. This is likely due to an undesirable feature in the simulation model which maintains long left-turn queues in the continuous-turn lane, but for the raised median, after filling the bay, shunts much of the left-turn traffic to a straight destination. In reality, the effect of the full bay would be to stack left-turners on the through lanes and produce much higher delay than the continuous-turn-lane case.

CONCLUSION

Intersections of an arterial with driveways are very important components of an urban arterial network. A "pseudo intersection" was studied in great detail using a microscopic simulation model, the TEXAS Model. Three sections were studied, the left-turn lane, the raised median, and an approach with no left-turn treatment. Delay data were collected from the simulation runs and were analyzed graphically and using the analysis of variance techniques. The three candidate treatments produce little difference in traffic delay unless the combination of left-turn and opposing volume produces large queues of waiting left-turn vehicles. If large left-turn queues are present, the continuous-left-turn lane produces least delay, but raised median-turn bay is far better than no channelization.

The conclusions from the study are:

1) The left-turn treatments always reduce the delay on a section except in a case of very low volumes.
2) At low and medium left-turn volumes there is no difference between the left-turn treatments.
3) At high left-turn volumes there is a difference between the left-turn treatments which is dependent on the opposing traffic volumes.

TABLE 3.2. COMPARISON OF THE EFFECTS OF THE THREE SECTION TYPES

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	5225556411	80.89	0.0001
Straight-ThroughVolume	2	35655517909	55.19	0.0001
Opposing Volume	3	199350804.47	2.06	0.1075
Treatment	2	1005515445	15.56	0.0001
Error	184	5943586446	—	—
Total	193	15939527017	—	—

R Square = 0.627117

TABLE 3.3. COMPARISON BETWEEN LEFT-TURN LANE AND NO-TREATMENT SECTIONS

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	4045535930	49.18	0.0001
Straight-ThroughVolume	2	3085939916	37.51	0.0001
Opposing Volume	3	132288581	1.07	0.3637
Treatment	1	757789834	18.42	0.0001
Error	120	4935645969	—	—
Total	128	12957200230	—	—

R Square = 0.619081

TABLE 3.4. COMPARISON BETWEEN LEFT-TURN LANE AND RAISED MEDIAN

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	2466564603	93.29	0.0001
Straight-ThroughVolume	2	1169782449	44.25	0.0001
Opposing Volume	3	178634513	4.50	0.0049
Treatment	1	243275	0.02	0.8923
Error	121	1599533904	—	—
Total	129	5414758746	—	—

R Square = 0.704597

TABLE 3.5. COMPARISON BETWEEN LEFT-TURN LANE AND NO TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	4063390299	50.53	0.0001
Straight-ThroughVolume	2	3191635313	39.69	0.0001
Opposing Volume	3	122273572	1.01	0.3892
Treatment	1	775260460	19.28	0.0001
Error	120	4824746091	—	—
Total	128	12977305735	—	—

R Square = 0.628217

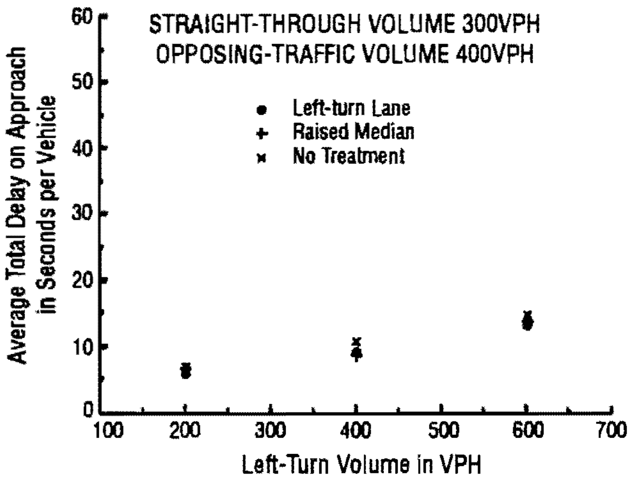


Fig 3.4. Left-turn volume on approach vs average total delay for 400 vph opposing traffic volume.

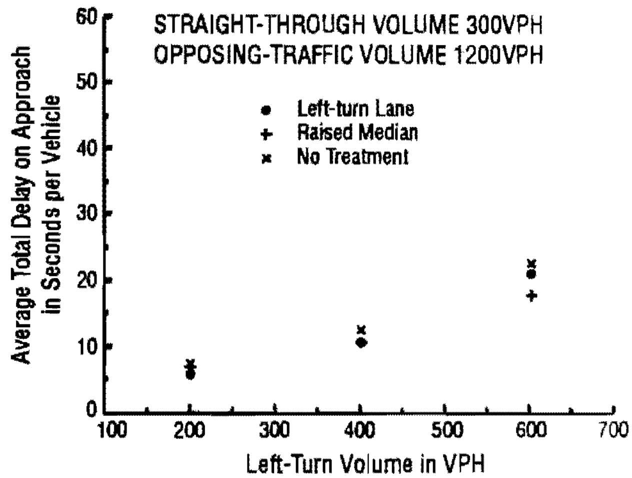


Fig 3.6. Left-turn volume on approach vs average total delay for 1200 vph opposing traffic volume.

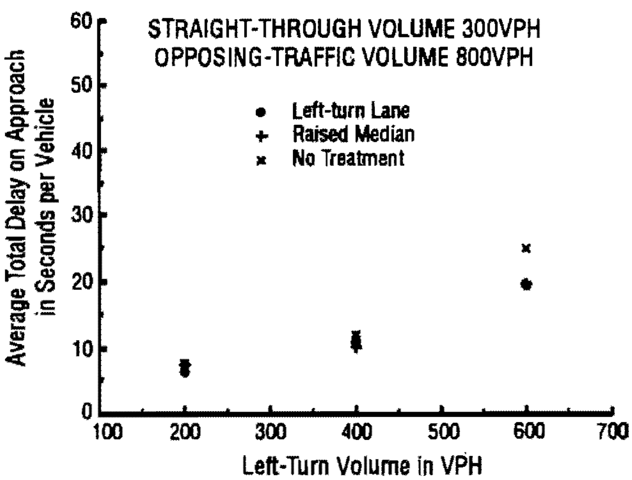


Fig 3.5. Left-turn volume on approach vs average total delay for 800 vph opposing traffic volume.

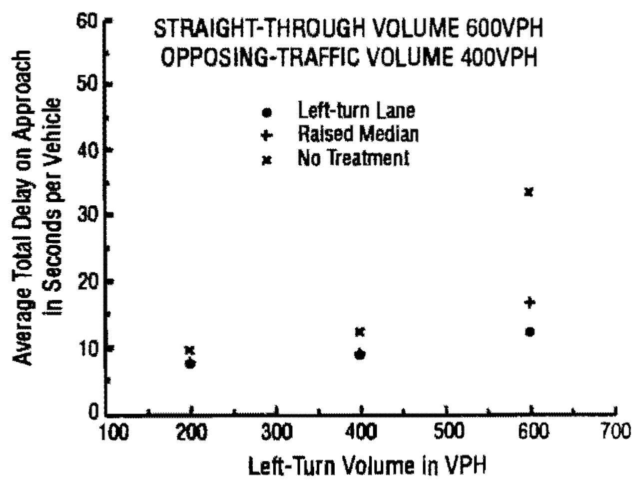


Fig 3.7. Left-turn volume on approach vs average total delay for 400 vph opposing traffic volume.

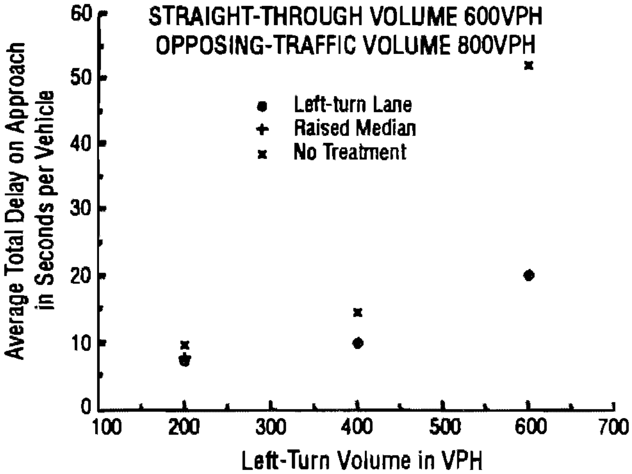


Fig 3.8. Left-turn volume on approach vs average total delay for 800 vph opposing traffic volume.

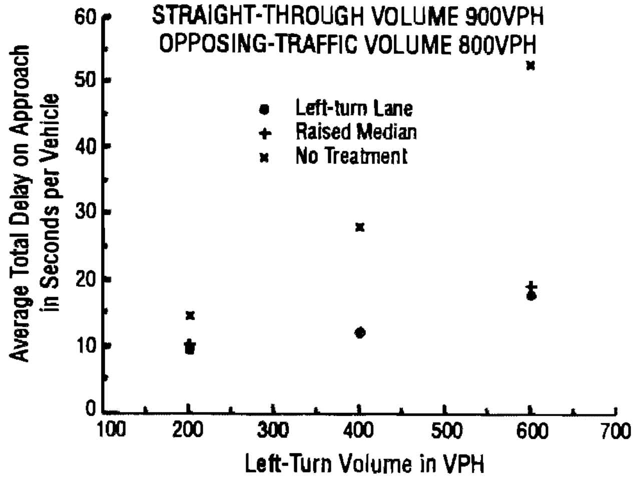


Fig 3.11. Left-turn volume on approach vs average total delay for 800 vph opposing traffic volume.

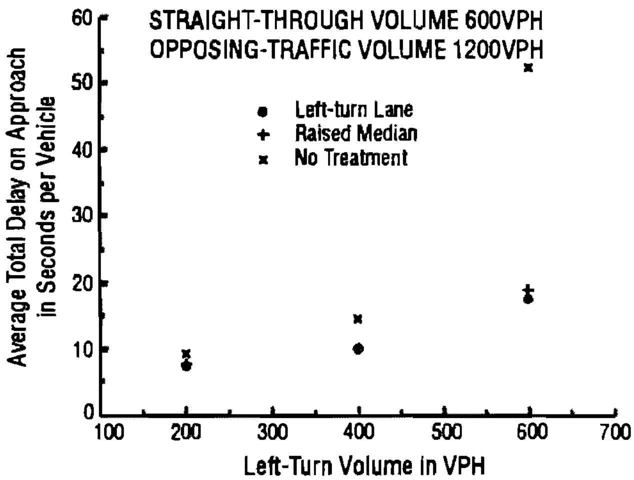


Fig 3.9. Left-turn volume on approach vs average total delay for 1200 vph opposing traffic volume.

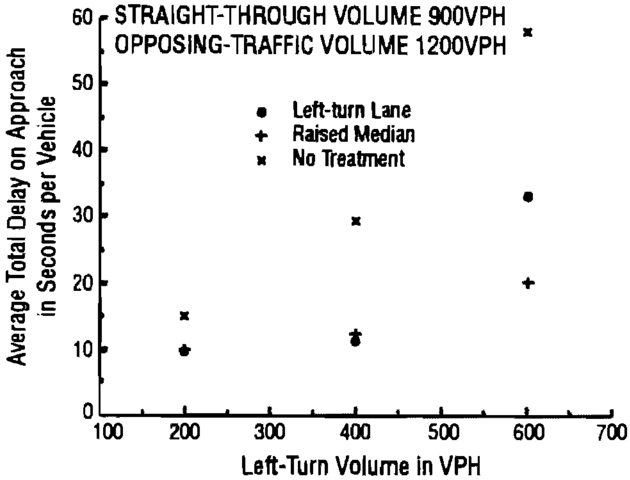


Fig 3.12. Left-turn volume on approach vs average total delay for 1200 vph opposing traffic volume.

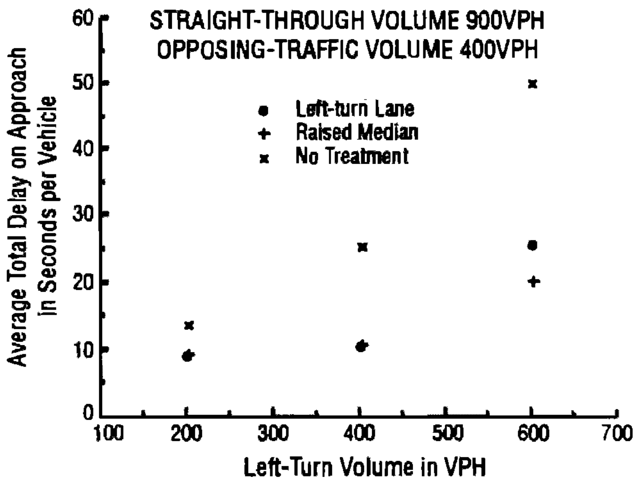


Fig 3.10. Left-turn volume on approach vs average total delay for 400 vph opposing traffic volume.

CHAPTER 4. OPERATIONAL EFFECTS OF MEDIAN TREATMENTS ON AN ARTERIAL NETWORK

INTRODUCTION

In the previous chapter, the operational effects of three different median treatments on a single, unsignalized pseudo-intersection formed by a driveway and an arterial were studied. This idealized intersection was assumed to be far enough from any street intersections so that the traffic headway distribution would be essentially random. In this chapter, a study of an arterial street network with a number of pseudo-intersections is presented. Simulation of the network is done using the NETSIM traffic simulation model. The effect of changes in geometry upon delay due to the median treatments is also studied.

The NETSIM model is a microscopic simulation model which describes the street network in terms of interconnected links and nodes, along which traffic is processed in discrete time steps subject to imposition of varying forms of traffic control. There are three major components of the model:

The NETSIM pre-processor — This module is designed to simplify the preparing and checking of data inputs. This includes a comprehensive set of diagnostic checks which are performed on all data inputs.

The NETSIM simulator — This module contains the main simulation program. It contains 60 separate routines which may be linked together in a variety of configurations depending on the user's needs.

The NETSIM post-processor — This module consists of a set of standard data manipulation and evaluation routines designed to operate on the output of the simulation program. It also has routines which perform standard statistical analyses on the data set generated.

The simulation requires that the urban street network be described as a set of unidirectional links and nodes. Mid-block changes in geometry are accommodated by breaking a single block into two or more successive links with dummy nodes. Provision is also made for mid-block sources and sinks to describe features such as entrances to parking lots, etc.

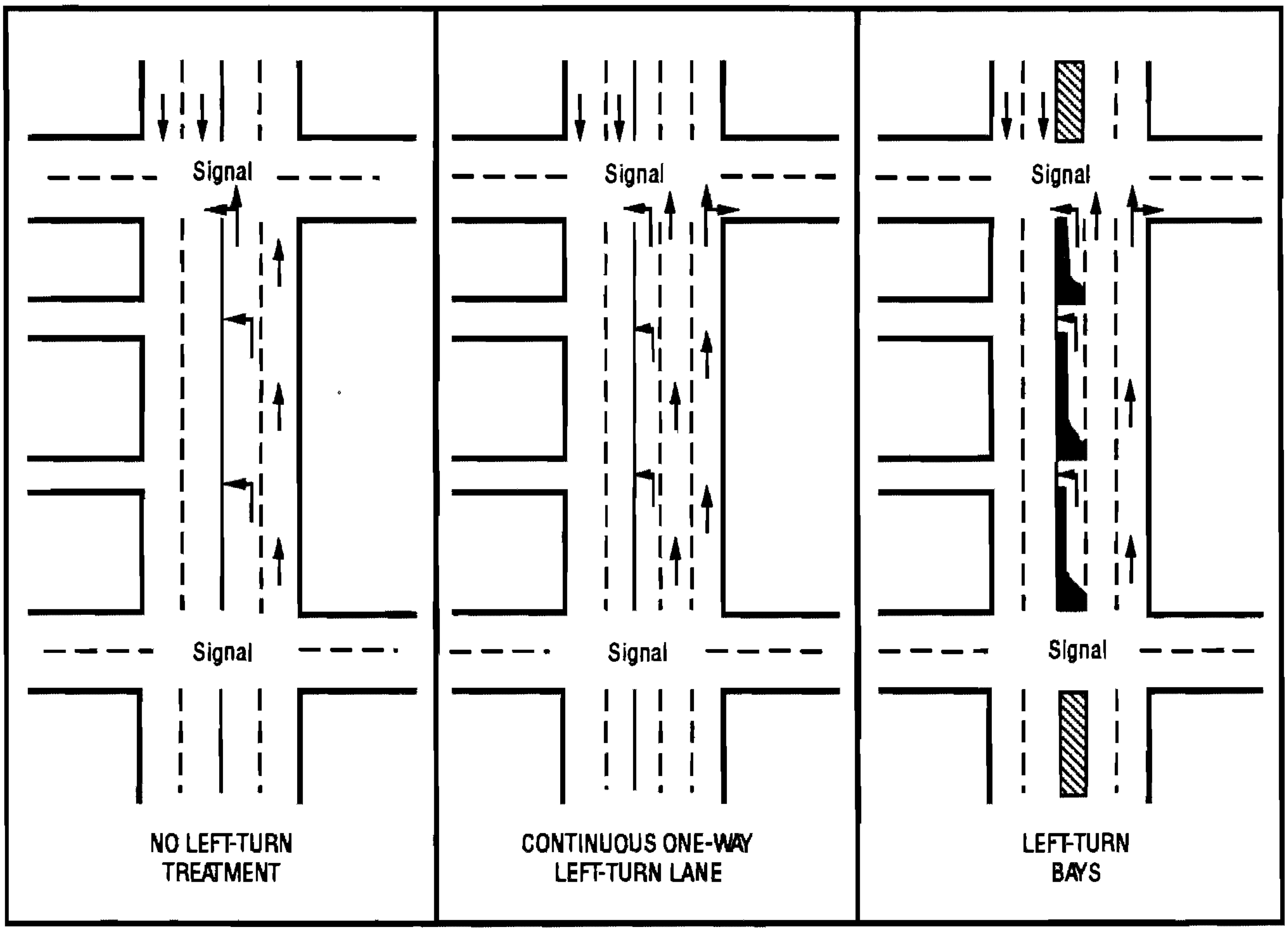


Fig 4.1. Schematic arterial street network.

PROCEDURE FOR CONDUCT OF EXPERIMENT

The three simulated test sections are depicted in Fig 4.1.

The experiment was conducted with low, medium and high volumes of left-turn, straight-through, and opposing traffic whose values are shown in Table 4.1. The left-turn volume shown in the table is the total left-turn volume over the network, i.e, the stated left-turn volumes are divided among the driveways along the simulated arterial.

TABLE 4.1. INPUT TRAFFIC VOLUMES USED IN THE EXPERIMENT

Volume	Left-Turn Volume	S.T. Volume	Opposing Volume
Low	200	300	400
Medium	400	600	800
High	600	900	1200

The assumptions which were made in the conduct of the experiment are:

1) The left turns occur only from one lane as shown in the figures.
2) There is no traffic emanating from the driveways which are the destination of the left- turners.
3) The signal cycle length was assumed to be 60 seconds and the green time was varied depending on the critical-lane volume. The signals were coordinated so as to have the maximum green band.
4) The driveways were assumed to be 200 feet apart.
5) At the intersections with signals, the cross traffic was 400 straight-through vehicles per hour.

The experiment was conducted thrice with different random-number seeds. In all, 243 runs were made. The data collected was the delay time per vehicle on the links from which the left turns occur red. This value was then averaged over all the links along the arterial between the signalized intersections.

ANALYSIS OF THE DATA

The data were first analyzed using the Analysis of Variance, ANOVA, procedure. Then plots of the delay values vs the left-turn volumes were used to draw conclusions about the effect of the treatments on the delay caused by particular median treatments. Results from the analysis of variance are shown in Tables 4.2 through 4.5 and plots are shown in Figures 4.4 through 4.6.

The fourth row of Table 4.2 presents values which indicate the statistical significance of variations in delay due to the three different geometric median treatments. Variations in delay due to the treatments is significant at greater than the 95 percent level, indicating that the treatments probably produce real differences in traffic delay. The relatively low R square value suggests that there are variables other than those included in the experiment which affect delay. The effect of left-turn volume is significant at the 95% confidence level. hence it will be used as an independent variable in the graphical analysis. Pairwise comparisons of the different treatments using ANOVA are presented in the Tables 4.3, 4.4, and 4.5.

Values shown in these tables indicate a statistically significant difference among the treatments at more than the 90 percent confidence level. In order to further distinguish among the performance of the sections it was decided to use plots of the left-turn volume vs average delay.

Each plotted delay value is the mean for all vehicles for all links in the network with the simulation replicated three times. The data thus collected were organized in such a manner that the effect of left-turn volume on the delay could be studied in detail.

Initially, the straight-through volume was kept constant at its low value. Figure 4.2 is representative of a series of plots with low straight-through volume. There is no difference between the average delay values for the sections with left-turn treatments at low and moderate left-turn volumes for all values of opposing-traffic volume. At the higher left-turn volumes the differences between average delay to traffic on the sections with left-turn-lane treatment and the section with left-turn bay treatment becomes manifest and the section with the left-turn lane exhibits less delay.

Figure 4.3 is representative of a series of plots with the straight-through volume at the moderate level. In this series of plots, at low left-turn volumes, there is virtually no difference in the average delay to the traffic between the sections with different treatments; however, at higher opposing-traffic volumes the differences in the average delay become more prominent. As before the traffic on the left-turn-lane section has a slightly smaller average delay than that on the left-turn-bay section.

Figure 4.4 represents the plots where the straight-through volume is high. As before, there is no difference in the delay values between different treatments for low values of the left-turn volume. At higher left-turn volumes the differences in the average delay values became significant.

For a four-lane arterial with two lanes in either direction, it has been shown that a section with a left-turn treatment is operationally better than a section with no left-turn treatment for all combinations of left-turn, straight-through, and opposing-traffic volumes. At low left-turn volumes in most cases there is very little difference operationally between the left-turn treatments, however at higher left-turn volumes the differences become manifest. The section with a left-turn lane treatment is slightly better than a section with a raised median treatment for higher left-turn volumes and all values of straight-through and opposing-traffic volumes.

TABLE 4.2. ANOVA FOR ALL THE DELAY DATA COLLECTED

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	22192.225	4.14	0.0177
Straight-ThroughVolume	2	9616.17232	1.79	0.1696
Opposing Volume	2	1763.334	0.33	0.72
Treatment	2	20432.4784	3.81	0.024
Error	230	570370.0727	—	—
Total	238	624374.2827	—	—

R Square = 0.322009

TABLE 4.3. COMPARISON OF RAISED-MEDIAN SECTION AND SECTION WITH NO TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	34499.077	4.24	0.0177
Straight-ThroughVolume	2	14849.0598	1.82	0.166
Opposing Volume	2	2559.1328	0.31	0.7309
Treatment	1	14545.654	3.57	0.0615
Error	150	552022.36	—	—
Total	157	618475.28	—	—

R Square = 0.6313

TABLE 4.4. COMPARISON OF RAISED-MEDIAN AND LEFT-TURN-LANE SECTIONS

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	12349.081	3.48	0.0345
Straight-Through Volume	2	6370.898	1.79	0.11714
Opposing Volume	2	553.818	0.16	0.856
Treatment	1	6086.6115	3.43	0.0267
Error	150	244985.75	—	—
Total	157	270946.16	—	—

R Square = 0.6313

TABLE 4.5. COMPARISON OF LEFT-TURN LANE SECTIONS AND SECTION WITH NO TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	19.533	500.13	0.0001
Straight-Through Volume	2	0.4475	11.46	0.0001
Opposing Volume	2	23.435425	0600.04	0.0001
Treatment	1	16.952	868.1	0.0001
Error	154	13.009	—	—
Total	161	73.3787	—	—

R Square = 0.322

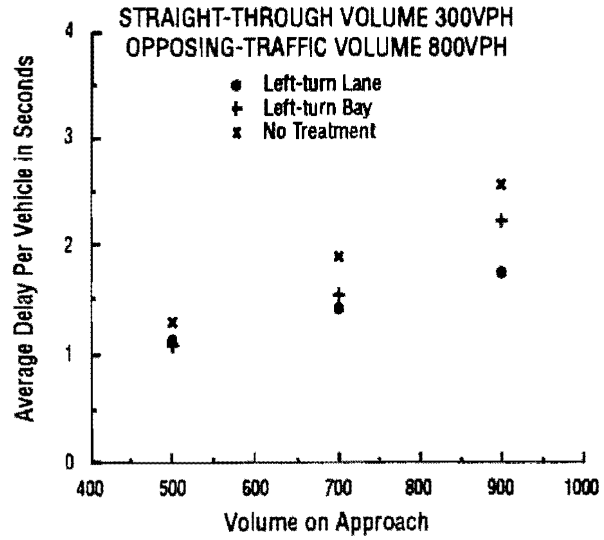


Fig 4.2. Volume vs delay for low straight-through volumes.

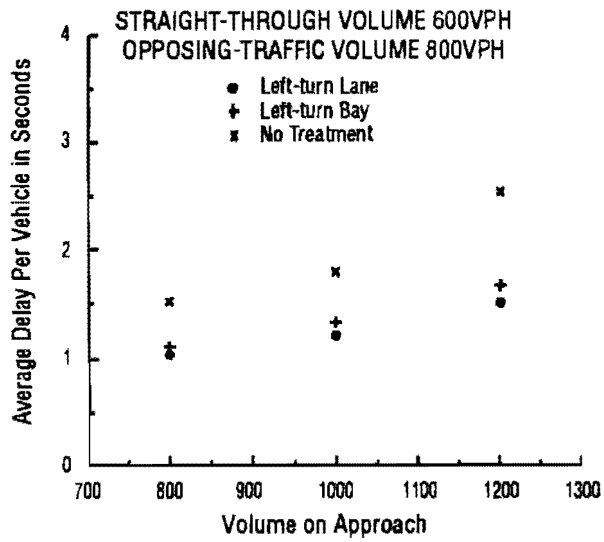


Fig 4.3. Volume vs delay for moderate straight-through volumes.

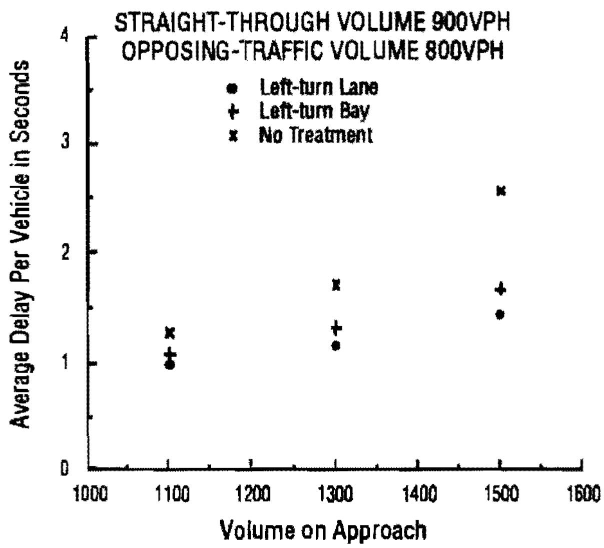


Fig 4.4. Volume vs delay for high straight-through volumes.

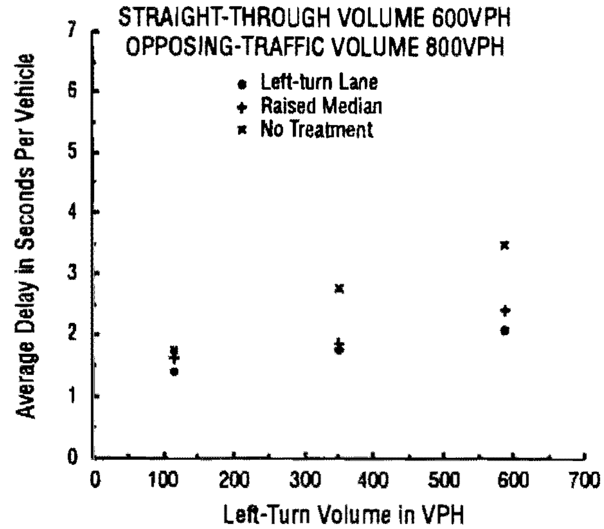


Fig 4.5. Left-turn volume vs delay for moderate straight-through volumes when driveways are 400 feet apart.

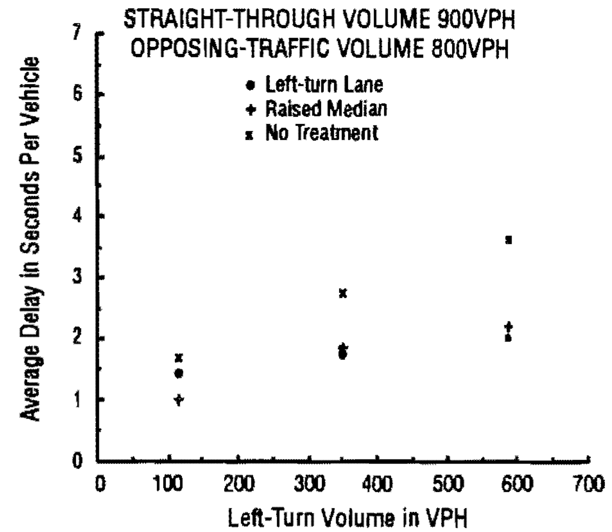


Fig 4.6. Left-turn volume vs delay for high straight-through volumes when the distance between driveways is 400 feet.

EXPERIMENTS ON OTHER GEOMETRIES

It was assumed in the previous experiment that the driveway spacing was 200 feet, which is realistic in most cases and has been used in other simulation experiments such as that by Ballard and McCoy (Ref 6). It was decided to study the operational difference between the median treatments when the driveway spacing is 400 feet versus 200 feet. This larger value represents the normal spacing between city blocks and can occur if there there are a few large commercial developments adjacent to each other.

The procedure for conducting this experiment was the same as that used before. There were 162 runs of the NETSIM model with each volume combination being repeated twice. As before, the data were analyzed first using Analysis of Variance procedures. The results of this analysis are given in the Tables 4.6 through 4.9. Later, graphs were drawn of the volume versus the average delay over the network to determine the probable effect of using a particular median treatment over the selected volume range.

The results of the analysis of variance for the network data are given in Table 4.6. It can be seen that all the different volumes considered affect delay significantly and that left-turn volume and opposing-traffic volume have the greatest effect on the average delay to traffic. The left-turn treatments also have a rather significant effect on delay. Most of the delay is explained by these variables (R square = 0.768), hence the model is a reasonable one. The F-value associated with the treatments is significant; therefore, the hypothesis that there is no difference in the effect of the treatments on delay can be rejected.

A pairwise comparison of the different treatments was conducted in order to see whether any significant difference exists between the treatments. The results of these comparisons are shown in Tables 4.7 through 4.9. The treatment effects are all significant at the 95% confidence level, indicating that pairs of median treatments are significantly different from each other.

Figure 4.5 represents a series of graphs drawn with moderate straight-through volume. There is no significant difference in the delay values for the left-turn treatments for the low and moderate values of left-turn volume and the opposing-traffic volume; however, at higher left-turn and opposing-traffic volumes the difference becomes apparent. The section with the left-turn lane treatment will probably perform better operationally than the section with a raised median and left-turn bays.

One may note that the average delay per vehicle statistics presented in this and following series of charts (Figs 4.2-4.15) have smaller magnitude that similar statistics present in Chapter 3. Statistics in Chapter 3 figures have as ordinates average total delay for vehicles that experienced delay. Those of Chapter 4 are average delay for all vehicles traversing the link. That is, the denominators of the averages for Chapter 3 are smaller than those of Chapter 4.

Figure 4.6 is one of a series of graphs drawn with high straight-through volume. As before, there is no significant difference in delay between the left-turn treatments for low left-turn and opposing-traffic volumes. The difference only becomes manifest at higher values of left-turn and opposing-traffic volumes.

The conclusions that may be drawn from this experiment are similar to those drawn previously. For low to moderate volumes of left turns, all left-turn treatments produce about the same delay as long as the opposing-traffic volume is not very large. In all cases, a section with a left-turn treatment performs better operationally than a section without any treatment. At higher values of left-turn and opposing-traffic volumes the section with the left-turn-lane treatment causes less delay than a section with a raised-median with turn-bay treatment.

ADDITION OF A LANE IN EACH DIRECTION

Six-lane arterial streets are quite common. A number of operational studies of six-lane streets have been conducted; these have consisted primarily of direct field observation. For the study described here, a six-lane arterial street section was simulated using NETSIM with a procedure similar to that described before. There were 162 runs of the NETSIM model with each case replicated twice. The data collected were again analyzed using Analysis of Variance procedures. The results are given in the Tables 4.10 through 4.13. Graphs of left-turn volume versus average delay over the links were also drawn to determine the likely results of using a particular median treatment under different volume conditions.

In Table 4.10 the results of the Analysis of Variance conducted on the entire data set are shown. All the variables considered affect delay significantly, and the opposing-traffic volume seems to have the greatest impact on the average delay values. With the addition of an extra lane, the usable gaps in the opposing-traffic stream are smaller; so the opposing-traffic flow has the greatest impact on delay.

The AVOVA for comparison of the two median-treatment schemes to no treatment are presented in Tables 4.12 and 4.13. Both schemes produce significantly different delays compared to no treatment.

Figures 4.7, 4.8, and 4.9 with the left-turn volume as the abscissa and the average delay as the ordinate were prepared. The first series of graphs are drawn with the straight-through volume at its low value and various left-turn and the opposing-traffic volumes. Figure 4.7 is typical of these. In all the different volume combinations for this case, the section with the left-turn lane exhibited least delay.

Another series of graphs were drawn by keeping the straight-through volume at its medium value, and Fig 4.8 is representative of these. Generally, the sections with the left- turn treatments show less delay than the section with no treatment; however, traffic on the left-turn-lane section experienced the least delay compared to the other sections in most of the volume combinations.

Figure 4.9 is representative of the graphs drawn keeping the straight-through volume at its highest value. The traffic on the sections with the left-turn treatments experienced less delay than that on the section with no treatment, and once again, the section with the left-turn lane has the least delay among all the sections considered.

TABLE 4.6. ANOVA FOR ALL SECTIONS TAKEN TOGETHER

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	43.4189	86.82	0.0001
Straight-Through Volume	2	2.97737	15.95	0.00032
Opposing Volume	2	53.2287	106.44	0.0001
Treatment	2	30.6548	61.80	0.0001
Error	157	39.25675	—	—
Total	165	169.53665	—	—

R Square = 0.768

TABLE 4.7. ANOVA FOR COMPARISON OF SECTION WITH A RAISED MEDIAN AND A SECTION WITH NO TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	41.1964	72.17	0.0001
Straight-Through Volume	2	1.0773	1.89	0.01567
Opposing Volume	2	41.7856	73.20	0.0001
Treatment	1	20.1872	70.73	0.0001
Error	103	29.398	—	—
Total	110	133.645	—	—

R Square = 0.631

TABLE 4.8. ANOVA FOR COMPARISON OF SECTIONS WITH A RAISED MEDIAN VERSUS A LEFT-TURN LANE

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	13.1298	82.38	0.0001
Straight-Through Volume	2	3.2878	19.71	0.0001
Opposing Volume	2	421.7626	130.50	0.0001
Treatment	1	0.34106	4.09	0.0457
Error	103	8.588	—	—
Total	110	47.7183	—	—

R Square = 0.820

TABLE 4.9. ANOVA FOR COMPARISON OF SECTIONS WITH A LEFT-TURN LANE VS NO TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	36.8905	57.90	0.0001
Straight-Through Volume	2	1.9121	3.00	0.0541
Opposing Volume	2	45.6337	171.63	0.0001
Treatment	1	25.5460	80.21	0.0001
Error	102	32.492	—	—
Total	109	142.4742	—	—

R Square = 0.772

TABLE 4.10. ANOVA AFOR THE DATA FOR ALL SECTIONS TAKEN TOGETHER

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	4.06914	34.98	0.0001
Straight-Through Volume	2	2.4652	21.19	0.0001
Opposing Volume	2	7.8339	67.35	0.0001
Treatment	2	1.4706	12.64	0.0001
Error	72	4.1874	—	—
Total	80	20.0264	—	—

R Square = 0.791

TABLE 4.11. ANOVA FOR COMPARISON BETWEEN A SECTION WITH A LEFT-TURN LANE AND A SECTION WITH A RAISED MEDIAN

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	2.447	24.25	0.0001
Straight-Through Volume	2	1.836	18.20	0.0001
Opposing Volume	2	3.9117	38.77	0.0001
Treatment	1	0.2831	5.61	0.0221
Error	46	2.3208	—	—
Total	53	10.7992	—	—

R Square = 0.788

TABLE 4.12.. ANOVA FOR COMPARISON BETWEEN A SECTION WITH A LEFT-TURN LANE AND A SECTION WITH NO TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	3.3787	23.33	0.0001
Straight-Through Volume	2	2.0910	14.44	0.0001
Opposing Volume	2	6.4685	44.67	0.0001
Treatment	1	0.4592	6.34	0.0153
Error	46	3.3305	—	—
Total	53	15.7282	—	—

R Square = 0.788

TABLE 4.13. ANOVA FOR COMPARISON BETWEEN A SECTION WITH A RAISED MEDIAN AND A SECTION WITH NO TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	2.413	23.54	0.0001
Straight-Through Volume	2	1.101	10.74	0.0001
Opposing Volume	2	5.4545	53.21	0.0001
Treatment	1	1.4535	28.55	0.0001
Error	46	2.357	—	—
Total	53	12.7901	—	—

R Square = 0.816

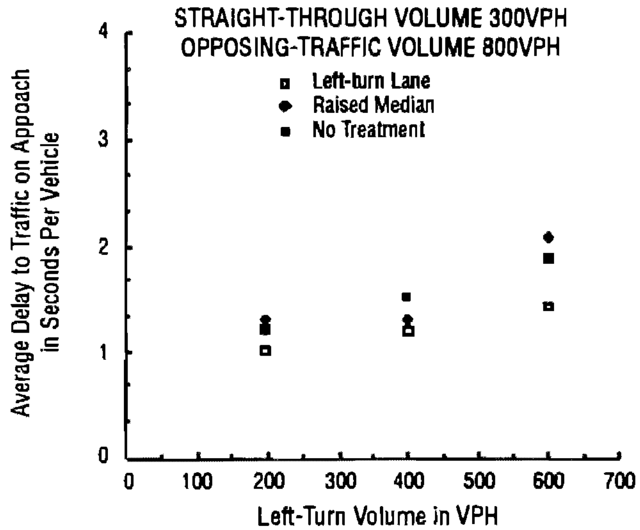


Fig 4.7. Left-turn volume vs average delay for low straight-through volumes.

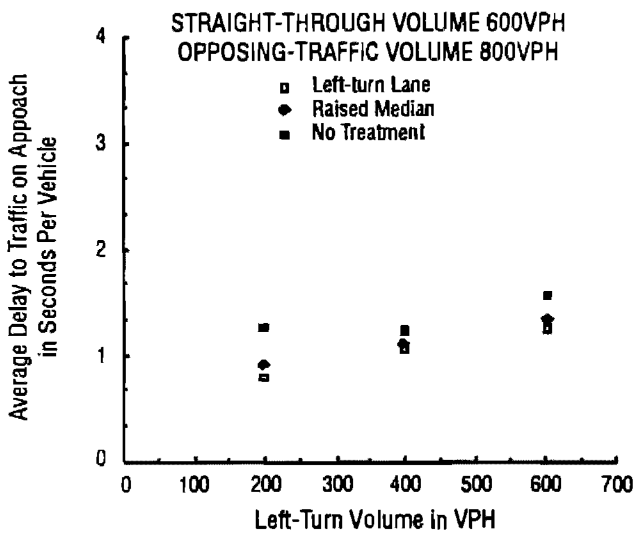


Fig 4.8. Left-turn volume vs average delay for moderate straight-through volumes.

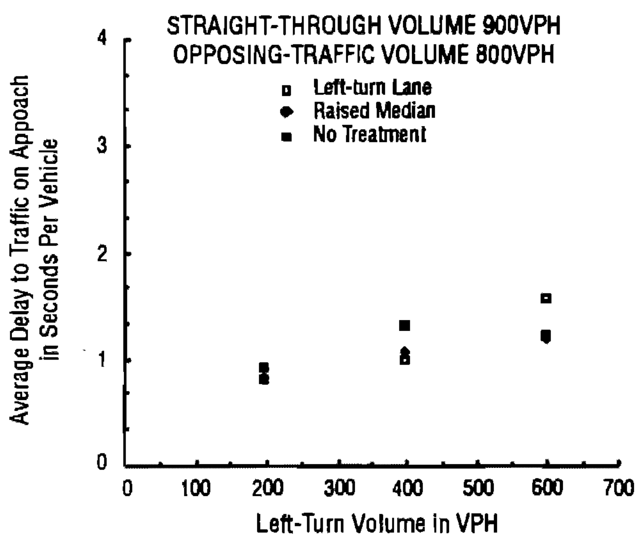


Fig 4.9. Left-turn volume vs average delay for high straight-through volumes.

EXPERIMENTS ON NETWORKS WITH LEFT TURNS OCCURRING ON BOTH SIDES OF THE STREET

In the previously described experiments, left turns were assumed to occur from only one approach, i.e, the north-bound approach on the arterial. In the series of experiments described below, left turns are assumed to occur on both north-bound and south-bound arterial street approaches, and left-turn treatments are provided appropriately. This is perhaps a more realistic representation of a "real" network. Two different network configurations were examined, one in which the driveways on the two sides of the street were directly opposite each other, and another in which the driveways were offset from each other.

The networks were simulated as a series of nodes and links using NETSIM. The traffic volumes used were similar to those of previously described experiments and were selected such that the network would not get saturated. The dependent variable was the link delay averaged over all arterial links with unsignalized nodes. The average link delay for the northbound traffic was compared with that from previous studies. The data were analyzed using the Analysis of Variance techniques and plotted to differentiate between the treatments.

NETWORK WITH DRIVEWAYS OPPOSITE EACH OTHER

The assumptions used in the simulation of this network are similar to those used before except that left turns occur on the arterial from both directions. The traffic volume on the network was the same as before as was the analysis procedure. The results of the ANOVA are shown in the Tables 4.14 through 4.17.

All the variables considered in the model have a significant effect on delay at the 95% confidence level as depicted in Table 4.14. As seen in almost all the previous studies, the left-turn volume seems to have the greatest effect on average delay values. The left-turn volumes will therefore be used in making judgements about the efficacy of the various median treatments. The F-value associated with the geometric treatment variable is significant indicating that there is a difference between the various sections.

Tables 4.15, 4.16, and 4.17 show the ANOVA for the reduced data set when only two treatments are considered at a time. This helps to identify the differences between the sections if they exist. Table 4.15 shows the ANOVA for a data set comparing a left-turn-lane section with a raised-median section. The F-value associated with the treatments indicates a significant difference between left-turn lane and raised median. In Table 4.16 the section with no treatment and a section with a raised median are compared. The F-value associated with the treatment is not significant at the 95% confidence level but is so at

TABLE 4.14. ANOVA FOR ALL SECTIONS TAKEN TOGETHER

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	19.1797	28.44	0.0001
Straight-Through Volume	2	5.3814	7.98	0.0010
Treatment	2	6.56901	9.74	0.0003
Error	47	15.846881	—	—
Total	53	46.97717	—	—

R Square = 0.663

TABLE 4.15. ANOVA FOR THE SECTION WITH A LEFT-TURN TREATMENT VERSUS A RAISED MEDIAN

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	7.2630	28.44	0.0001
Straight-Through Volume	2	0.84937	7.98	0.0010
Treatment	1	0.28090	9.74	0.0003
Error	30	14.2502	—	—
Total	35	9.1393	—	—

R Square = 0.91832

TABLE 4.16. ANOVA FOR THE SECTION WITH NO TREATMENT VERSUS A RAISED MEDIAN

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	16.1402	16.98	0.0001
Straight-Through Volume	2	5.3952	5.68	0.0081
Treatment	1	3.6353	7.65	0.0096
Error	30	14.2502	—	—
Total	35	39.4300	—	—

R Square = 0.638

TABLE 4.17. ANOVA FOR THE SECTION WITH NO TREATMENT VERSUS A LEFT-TURN LANE

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	16.129	17.22	0.0001
Straight-Through Volume	2	5.9818	6.39	0.0049
Treatment	1	5.9373	12.68	0.0013
Error	30	14.2502	—	—
Total	35	42.1003	—	—

R Square = 0.666

the 90% level. This indicates that the raised-median section and the section with no treatment are somewhat similar. This will be investigated further in the graphs.

Table 4.17 shows the ANOVA for comparison of the left-turn-lane and the no-treatment section. The F-value for treatment indicates that there is a statistically significant difference between the two sections.

Graphs were drawn with the left-turn volume as the abscissa and the average delay time per vehicle as the ordinate with straight-through volume constant and left-turn volume taking on three different values. Figure 4.10 shows the plot when the straight-through volume is low. At all left-turn volumes, the section with the left-turn lane has least delay. The raised-median treatment has a delay value almost equal to that of the no-treatment section at low left-turn volumes.

Figure 4.11 was drawn with the straight-through volume at its middle value, and once again, the left-turn-lane section has the least delay at all the considered left-turn volumes. The differences in delay between the sections increases with increases in the left-turn volume.

For conditions shown in Fig 4.12 the straight-through volume is high, and it is again seen that the left-turn-lane section seems to have the least delay. Traffic on the section with the raised-median treatment has an average delay only slightly greater than that of the section with the left-turn lane. For the run of the section with no treatment the network was saturated. The delay value represented here is for only one run. It is seen that delay increased, exponentially with increase in the left-turn volume for a section with no left-turn treatment. With the introduction of the treatment the average delay for the vehicles on the network was dramatically reduced. This clearly proves the efficacy of left-turn treatments in providing operational improvements for the conditions being considered in this portion of the study.

NETWORK WITH DRIVEWAYS OFFSET ON ALTERNATE SIDES OF THE ARTERIAL

The network consists of driveways placed 200 feet apart along each side of the arterial but offset 100 feet relative to the ones on the opposite side of the arterial street. A series of three-leg pseudo-intersections is created. This configuration is an idealized one which is useful for studying the traffic operational effects of the displacement of the driveways. The various left-turn treatments were provided as before and the effects on delay were studied.

The network was simulated using NETSIM with the volume combinations which were used in the previous experiments. The ANOVA are shown in the Tables 4.18 through 4.21 and graphs of the left-turn volume vs average delay to north-bound vehicles appear in Figs 4.13 through 4.15.

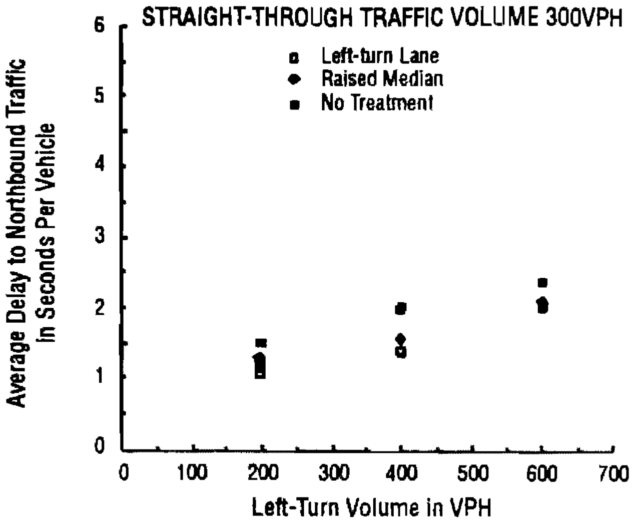


Fig 4.10. Left-turn volume vs delay when the straight-through volume is low.

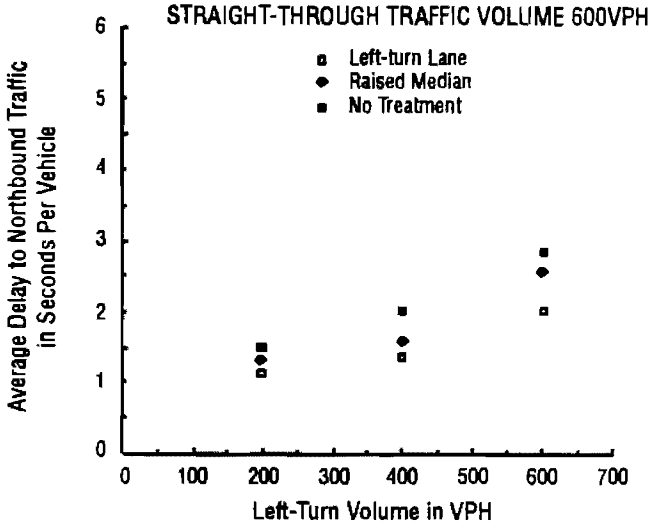


Fig 4.11. Left-turn volume vs delay when the straight-through volume is moderate.

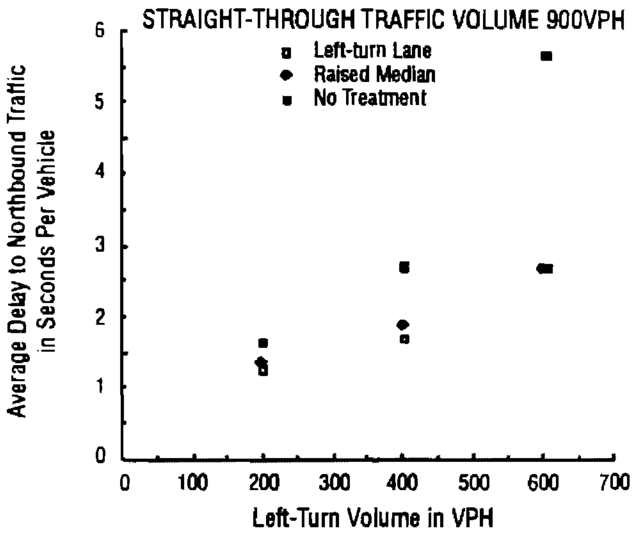


Fig 4.12. Left-turn volume vs delay when the straight-through volume is high.

TABLE 4.18. ANOVA FOR ALL SECTIONS TAKEN TOGETHER

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	0.69601	54.50	0.0001
Straight-Through Volume	2	0.33281	26.06	0.0001
Treatment	2	0.64233	50.30	0.0001
Error	47	0.30009	—	—
Total	53	1.97125	—	—

R Square = 0.848

TABLE 4.19. ANOVA FOR THE SECTION WITH A LEFT-TURN-LANE TREATMENT AND A SECTION WITH A RAISED MEDIAN TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	0.279616	48.86	0.0001
Straight-Through Volume	2	0.100850	20.88	0.0001
Treatment	1	0.018225	56.78	0.0001
Error	30	0.075958	—	—
Total	35	0.47465	—	—

R Square = 0.834

TABLE 4.20. ANOVA FOR THE SECTION WITH NO TREATMENT AND A SECTION WITH A RAISED-MEDIAN TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	0.65448	48.86	0.0001
Straight-Through Volume	2	0.279605	20.88	0.0001
Treatment	1	0.380277	56.78	0.0001
Error	30	0.2009	—	—
Total	35	1.51528	—	—

R Square = 0.867

TABLE 4.21. ANOVA FOR THE SECTION WITH NO TREATMENT AND A SECTION WITH LEFT-TURN-LANE TREATMENT

Source of Variation	Degrees of Freedom	Sum of Squares	F Value	Prob > F
Left-Turn Volume	2	0.505338	32.34	0.0001
Straight-Through Volume	2	0.326705	20.91	0.0001
Treatment	1	0.565002	72.33	0.0001
Error	30	0.234358	—	—
Total	35	1.631405	—	—

R Square = 0.856

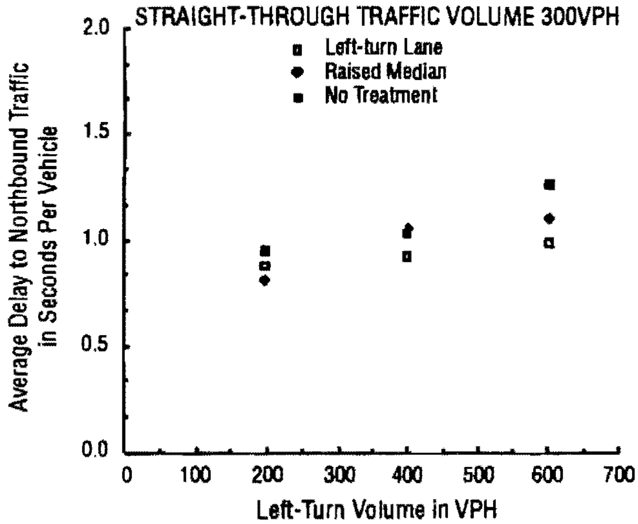


Fig 4.13. Average link delay versus left-turn volume for offset driveways case (low straight-through traffic volume).

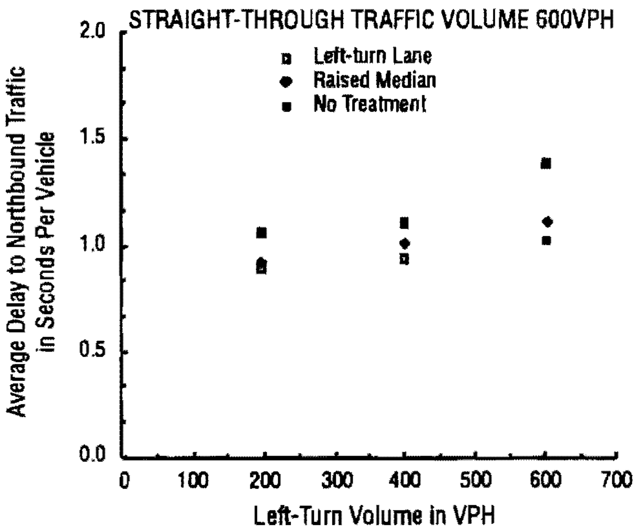


Fig 4.14. Average link delay versus left-turn volume for offset driveways case (moderate straight-through traffic volume).

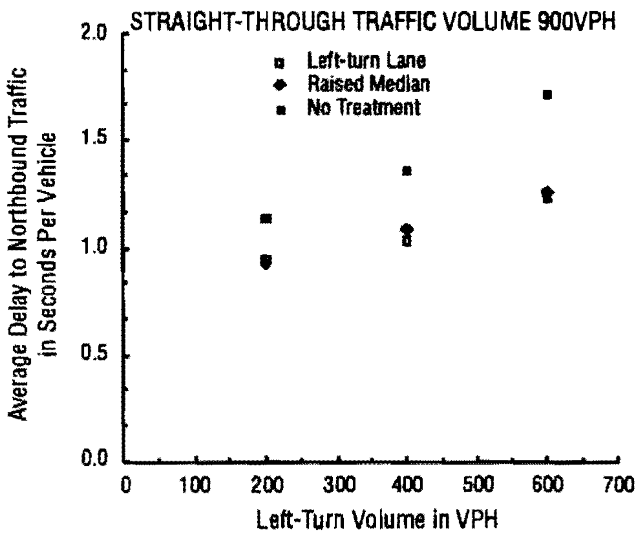


Fig 4.15. Average link delay versus left-turn volume for offset driveways case (high straight-through traffic volume).

From the values shown in Table 4.18 it may be seen that all variables are significant at the 95% confidence level and that the geometric treatments seem to have the greatest effect on average delay . The F-value associated with treatment indicates that a significant difference exists among the different options. The R-square value of 0.867 is quite high indicating that the chosen variables explain much of the delay variation. Tables 4.19, 4.20, and 4.21 show the pairwise comparison of the various options considered.

The F-value associated with treatments is significant at the 95% confidence level indicating that the three section types produce different delays. Tables 4.20 and 4.21 show the ANOVA for the comparison between sections with a left-turn treatment and no treatment. The geometries seem to have the greatest effect on the average delay and as before the F-values are statistically significant.

Graphs of left-turn volume versus average delay to northbound traffic are shown in Figs 4.13, 4.14, and 4.15 with straight-through volumes held constant and the left-turn volume taking on different values. In Fig 4.13, when the straight-through volume is low, average delay on the the section with the left-turn lane is low compared to the other sections. The sections with left-turn treatments generally have less delay than those with no treatment. This trend is repeated for the higher straight-through volumes as can be seen in Figs 4.14 and 4.15. The average delay to traffic flowing on this network configuration is lower than that flowing through the one considered earlier. The impact of not having the left turns interact with each other at a four-leg pseudo-intersection results in considerable savings in average delay. The two cases of pseudo-intersection leg arrangements that have been considered are rather idealized; however, on real networks it can be expected that driveway spacing along the arterial street might fall somewhere between the two extremes.

CONCLUSIONS

The operational characteristics of the traffic flowing on an arterial street network with different median treatments have been studied. The network was simulated using the NETSIM software. Data collected from the simulation runs were analyzed using the Analysis of Variance procedures, and graphs of left-turn volume vs average link delay were drawn. Delay to traffic on the arterial street was used as the measure of effectiveness to compare three different median treatments.

Initially basic networks shown in Fig 4.1 were simulated using certain assumptions about the signal timing and the geometric configuration of the network. Then, other assumptions regarding driveway spacing, numbers of through lanes, and the presence of left turn from both directions along the arterial were introduced. The conclusions drawn from these studies are:

1) Sections with left-turn median treatments produce less delay than sections with no treatments.
2) In most cases for low left-turn volumes, there is little difference in delay resulting from either type of median treatment.
3) At higher left-turn volumes, the sections with the left-turn-lane treatment cause less delay than those sections with a raised median and left-turn bays.
4) At very high left-turn, straight-through, and opposing-traffic volumes, a section with no treatment tends to saturate and average delay tends to increase exponentially. Either type of median treatment can alleviate this condition.

In the study described in this chapter, only some the factors which affect traffic operations on an arterial street with various median treatments have been considered. It is prohibitive both in terms of cost and time to investigate all possible factors and combinations. Studies described in the literature consider other factors and develop explanatory models. The variables used in these models to explain traffic behavior along an arterial street section with various geometric, traffic, and traffic-control configurations are generally the same as those chosen for use in this study.

CHAPTER 5. LEFT-TURN CAPACITY ANALYSIS FOR THE VARIOUS LEFT-TURN TREATMENTS

INTRODUCTION

In previous chapters, the traffic operational effects of various left-turn median treatments were examined through computer simulation. The operational effectiveness was assessed in terms of delay. One of the most important considerations in the operation of any road network is its capacity. In this chapter the left-turn capacity of the network described in the previous chapters is investigated using general methods developed by Lin, Machemehl, Lee, and Herman (Ref 10). The methods were developed for a single, signalized intersection using empirical results from the TEXAS Model for Intersection Traffic. An intersection of a driveway and an arterial is considered to be a pseudo-intersection and the left-turn capacity of this pseudo-intersection is investigated. Left-turn capacity will be used to identify the need for a left-turn median treatment.

THEORETICAL BACKGROUND

A number of mathematical models have been developed for calculating left-turn capacity; however, these models make simplifying assumptions in order to make them mathematically tractable. This might make their use unrealistic in certain domains. In order to solve this problem, simulation models are frequently utilized. In developing a general method for studying left-turn capacity Lin et al (Ref 9) used the TEXAS model for simulating a single intersection.

These researchers used the concept of transparency in order to explain the left-turn capacity conceptually. Transparency is a term introduced by Herman and Weiss to explain the problem of highway crossing. It is defined as the ratio of the total unblocked time to the total time gap. A gap is unblocked if it can be used by drivers; otherwise it is not. Transparency indicates the impedance of the opposing traffic and signalization to left turns. In order to study left-turn capacity, the approach lane for left-turn traffic was oversaturated so that there was always a left-turn demand.

The cycle split was found to be a major factor influencing transparency, and transparency was found to decrease with increases in opposing traffic volume. Transparency changes linearly as opposing volume increases. Transparency is used to find the average left-turn capacity. The average left-turn processing time, t, is the total time available for left turns in one hour divided by the left-turn capacity.

$$t = (3600T)/Q_L$$

where

t = average left-turn processing time
T = Transparency
Q_L = Left-turn capacity

The left-turn processing time is approximately constant, so the left-turn capacity can be determined once the transparency is known. The analysis of left-turn operations is simplified by the fact that the average left-turn capacity is approximately constant. The left-turn capacity was determined empirically by TEXAS Model simulation. The average value of left-turn capacity was approximated by a piecewise linear function, the general form of which is

$$1)\ Q_L = Q_C(G/C) - e_O Q_O$$

$$2)\ Q_L + e_O Q_O = Q_C(G/C)$$

where

Q_L = left-turn capacity
e_O = equivalence factor of the opposing to the left-turn traffic
Q_O = opposing traffic volume
Q_C = effective capacity of the conflict area
G/C = green time per cycle

The left-hand side of equation 1 is the sum of the total conflicting flows in terms of the left-turn traffic. This is produced by converting the opposing traffic to left-turn traffic by using an equivalence factor. The right-hand side of equation 2 is the maximum volume of the total conflicting flows that can be processed through the intersection and can be regarded as capacity of the conflict area.

In order to preclude critical conditions of left-turn operations the left-turn demand should not be near capacity. Let Q_W be the critical left-turn volume at signalized intersections having an adequate length of bay without a separate left-turn phase. Let fc be the allowable utilization factor of the conflict area and be defined as

$$fc = (Q_W + e_O Q_O)/Q_C(G/C)$$

hence for any left-turn volume $Q_W < Q_L$ there exists an allowable utilization factor of the conflict area $fc < 1$ such that the following holds.

$$Q_W + e_O Q_O = fc\ Q_C(G/C)$$

$$Q_W = fc\ Q_C(G/C) - e_O Q_O$$

As Q_W approaches Q_L, fc tends to 1. If the values of e_O, Q_O and fc are known for the various traffic conditions and geometric configurations then the critical left-turn volume can be determined from the above equation.

The relation between the left-turn capacity and the critical left-turn volume can be obtained as follows

$$Q_W = fc\ Q_C(G/C) - e_O Q_O$$
$$= (Q_C(G/C) - e_O Q_O) - (Q_C(G/C) - fc\ Q_C(G/C))$$
$$= Q_L - (1-fc)\ Q_C(G/C)$$

If $M = (1-fc)\ Q_C(G/C)$ then the above equation becomes

$$Q_W = Q_L - M$$

The critical left-turn volume is M vehicles less than the left-turn capacity Q_L. This implies that a threshold exists at M vehicles less than the left-turn capacity, and once the left- turn demand reaches this threshold, the left-turn operations become critical. The value of M depends on the geometric configuration , signal timing, and the opposing-traffic volume.

The above equations were developed considering that a left-turn bay is present. The researchers involved in developing the above criteria also developed criteria to find out when a left-turn treatment is required based on the above approach. In order to simplify the process, at first no left turns in the opposite direction are considered, and later they were considered.

The left-turn capacity for no-left-turn treatments (no separate signal phase or geometric treatment) when there are no left turns in the opposite direction is given by

$$Q_L = Q_C(G/C) - e_O Q_O$$

The warrants for the left-turn treatment can be expressed as

$$Q_W = Q_L - (1-fc)\ Q_C(G/C)$$

When there are left turns in the opposing flow and there are V_{OL} and Q_O left-turning and through vehicles, respectively, then

$$\mathbb{Q}_L = Q_L - a\ Q_O$$

where

$\mathbb{Q}_L$ = left-turn capacity with no bay when there are V_{OL} left-turn vehicles in the opposing flows

Q_L = left-turn capacity with no bay when there are no left turns in the opposing flows

a = correction factor given by 0.317 (P_C - 1/N) Q_O. P_C is the percentage of the total op posing traffic that is carried on the lane with heaviest opposing volume and N is the number of opposing lanes.

The warrant for the left-turn treatment can be obtained as follows:

$$\mathbb{Q}_W = Q_W - a\ Q_O$$

APPLICATION TO THE PRESENT PROBLEM

Initially a single intersection with no signalization was considered with three opposing- flow levels. The G/C ratio in this case is 1 and the values of the left-turn capacity and the warranted left-turn capacity are given in Table 5.1. Figure 5.1 shows a decision chart for this case.

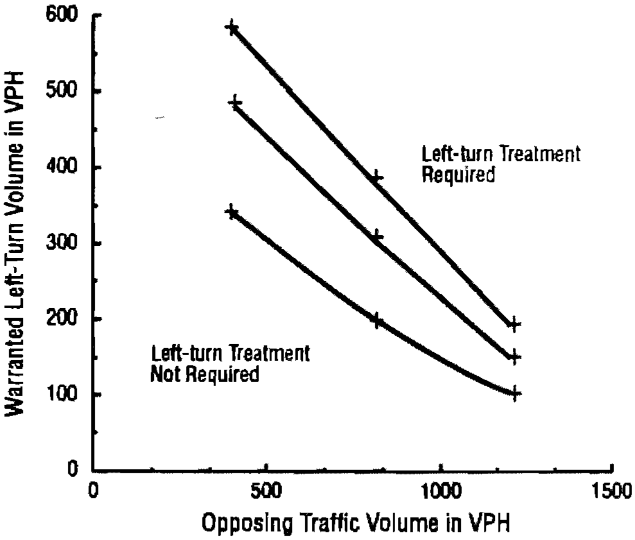


Fig 5.1. Decision chart for the use of left-turn treatment.

It can be seen that as the opposing traffic volume increases, the warranted left-turn capacity decreases. This is because of the reduction in the number of gaps in the opposing- traffic stream. The decision chart helps in making a decision as to the use of a left-turn treatment. In the next chapter, results given by this decision chart are compared with results of the previous chapters.

In Table 5.2 the values of the warranted left-turn capacity as calculated by the above formulas are given for a network with pseudo intersections. In a network with pseudo intersections there is only one pseudo intersection which is critical, i.e the first intersection from the signal as it receives the maximum through traffic. The warranted left-turn capacity is calculated for this intersection and Fig 5.2 is a decision chart for this case. The warranted left-turn volume as calculated from the above formulas is very dependent on the green time per cycle so the decision chart can be used only when the green time per cycle ratio varies from 0.47 to 0.63. Similar methodology can be used to find the warranted left-turn volumes for other cases.

CONCLUSION

In this chapter the left-turn capacity of a single intersection and a single pseudo-intersection in a network is examined. The method used in finding the left-turn capacity is general and does not depend on any assumptions

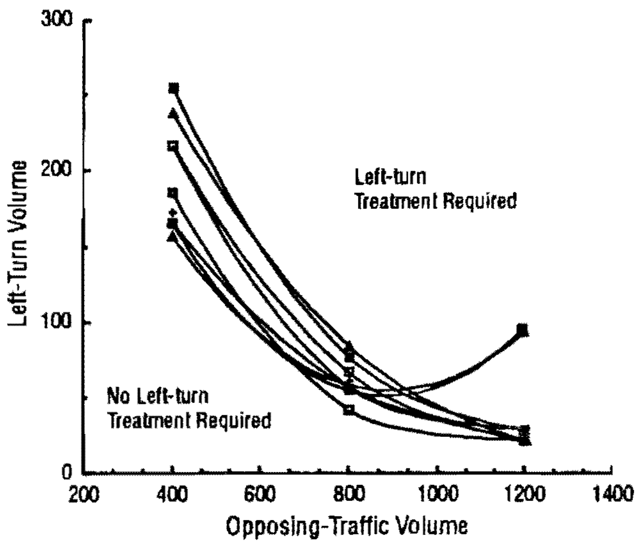


Fig 5.2. Decision chart for the use of a left-turn treatment in the case of a network.

about the gaps in the opposing traffic stream. The left-turn capacity is mainly dependent on the capacity of the conflict area between the left-turn-traffic and the opposing-traffic streams. The warranted left-turn capacity is a certain number of vehicles less than the left-turn capacity. A left-turn treatment should be provided if the number of left turns in the intersection exceeds the warranted left-turn capacity.

The conclusions which may be drawn from the discussion presented in this chapter are:

1) Left-turn capacity decreases with an increase in the opposing-traffic volume.
2) The left-turn demand which seems to justify a left-turn storage area (bay or lane), at an intersection, varies from 100 to 600 vehicles per hour depending on opposing traffic demand. For a pseudo-intersection (driveway opening), the corresponding left-turn demands range from about 50 to 250 vehicles per hour.
3) As opposing traffic volume increases, there is a greater likelihood of needing a left-turn treatment.

TABLE 5.1. LEFT-TURN VOLUME REQUIRING GEOMETRIC TREATMENT, ISOLATED INTERSECTION (UNSIGNALIZED, NO GEOMETRIC TREATMENT, TWO LANES PER DIRECTION)

Opposing Traffic Volume	Straight Through Volume	Left-Turn Volume	e_L	e_O	Q_C	fc	G/C	C/G	Q_L	Q_W
400	150	200	2.05	0.50	875	0.89	1	1	677	581
400	400	200	2.05	0.50	875	0.89	1	1	677	581
400		600	2.05	0.50	875	0.89	1	1	677	581
400	300	200	2.30	0.43	740	0.89	1	1	563	481
400		400	2.30	0.44	740	0.89	1	1	563	481
400		600	2.30	0.44	740	0.89	1	1	563	481
400	450	200	2.95	0.34	535	0.89	1	1	398	339
400		400	2.95	0.34	535	0.89	1	1	398	339
400		600	2.95	0.34	535	0.89	1	1	398	339
800	150	200	2.05	0.50	875	0.89	1	1	479	383
800		400	2.05	0.50	875	0.89	1	1	479	383
800		600	2.05	0.50	875	0.89	1	1	479	383
800	300	200	2.30	0.44	740	0.89	1	1	386	304
800		400	2.30	0.44	740	0.89	1	1	386	304
800		600	2.30	0.44	740	0.89	1	1	386	304
800	450	200	2.95	0.34	535	0.89	1	1	261	202
800		400	2.95	0.34	535	0.89	1	1	261	202
800		600	2.95	0.34	535	0.89	1	1	261	202
1200	150	200	2.80	0.36	732	0.85	1	1	306	193
1200		400	2.80	0.36	732	0.85	1	1	306	193
1200		600	2.80	0.36	732	0.85	1	1	306	193
1200	300	200	3.40	0.29	590	0.85	1	1	242	151
1200		400	3.40	0.29	590	0.85	1	1	242	151
1200		600	3.40	0.29	590	0.85	1	1	242	151
1200	450	200	4.85	0.21	415	0.85	1	1	164	100
1200		400	4.85	0.21	415	0.85	1	1	164	100
1200		600	4.85	0.21	415	0.85	1	1	164	100

TABLE 5.2. LEFT-TURN VOLUME REQUIRING GEOMETRIC TREATMENT, NON-ISOLATED INTERSECTION (UNSIGNALIZED, NO GEOMETRIC TREATMENT, TWO LANES PER DIRECTION

Opposing Traffic Volume	Straight Through Volume	Left-Turn Volume	G/C	C/G	QoC/G	EL	Eo	Qc	Fc	QL	Qw
400	150	200	0.47	2.14	857	2.05	0.50	875	0.89	210	165
400		400	0.53	1.88	750	2.05	0.50	875	0.89	269	217
400		600	0.58	1.71	686	2.05	0.50	875	0.89	312	256
400	300	200	0.55	1.82	727	2.30	0.44	740	0.89	230	185
400		400	0.60	1.67	667	2.30	0.44	740	0.89	267	218
400		600	0.63	1.58	632	2.30	0.44	740	0.89	291	240
400	450	200	0.62	1.62	649	2.95	0.34	535	0.89	193	157
400		400	0.63	1.58	632	2.95	0.34	535	0.89	202	165
400		600	0.65	1.54	615	2.95	0.34	535	0.89	211	172
800	150	200	0.55	1.82	1455	2.80	0.36	733	0.85	119	57
800		400	0.55	1.82	1455	2.80	0.36	733	0.85	119	57
800		600	0.58	1.71	1371	2.80	0.36	733	0.85	144	77
800	300	200	0.55	1.82	1455	3.40	0.29	590	0.85	93	42
800		400	0.60	1.67	1333	3.40	0.29	590	0.85	122	67
800		600	0.63	1.58	1263	3.40	0.29	590	0.85	142	84
800	450	200	0.62	1.62	1297	4.85	0.21	415	0.85	89	49
800		400	0.63	1.58	1263	4.85	0.21	415	0.85	96	55
800		600	0.65	1.54	1231	4.85	0.21	415	0.85	103	61
1200	150	200	0.63	1.58	1895	6.70	0.15	405	0.82	77	29
1200		400	0.63	1.58	1895	6.70	0.15	405	0.82	77	29
1200		600	0.63	1.58	1895	6.70	0.15	405	0.82	77	29
1200	300	200	0.63	1.58	1895	8.70	0.12	310	0.82	58	22
1200		400	0.63	1.58	1895	8.70	0.12	310	0.82	58	22
1200		600	0.63	1.58	1895	8.70	0.12	310	0.82	58	22

CHAPTER 6. DEVELOPMENT OF WARRANTS FOR USE OF LEFT-TURN TREATMENTS

INTRODUCTION

In the previous chapters the operational effects of left-turn treatments on the traffic stream flowing through a single intersection and an arterial network were discussed. The operational study included the effect of the left-turn treatments on the average delay incurred by each vehicle and an investigation of the capacity of a single-intersection/pseudo-intersection.

In this chapter the operational effects are studied in detail in order to propose guidelines for the use of left-turn treatments. Another important aspect of the use of median treatments is potential safety impact. In Chapter 2 some of the references which dealt with this aspect were mentioned, and based on these readings from the literature, guidelines are proposed for the use of left-turn treatments. Finally, the two kinds of proposed guidelines are put together in order to produce a guideline which optimizes the use of a left-turn treatment with respect to both safety and operations.

WARRANTS BASED ON OPERATIONAL EFFECTS OF THE MEDIAN TREATMENTS

WARRANTS FOR A SINGLE ISOLATED INTERSECTION

The description and the results of the experiments on the operational effects of the left-turn median treatments are described in Chapter 3. Figures 3.4 through 3.6 provide indications of the efficacy of a particular median treatment for a particular volume combination.

The left-turn treatments do not exhibit any differences as far as the effect on the traffic stream is concerned for low and medium straight-through and left-turn volumes. As the left- turn volumes increase the treatments start to exhibit some difference operationally. The left- turn-lane treatment is better operationally than the raised-median-turn-bay treatment for most of the higher left-turn volumes. At the higher left-turn volumes the limited left-turn storage area under the median-turn-bay scheme may cause greater traffic stream friction and delay. However, for over-saturated conditions (left-turn demand significantly exceeding capacity), a continuous-median-turn lane may store more vehicles than a bay, and left-turn delay may exceed that for the bay due to more waiting stored vehicles. Here, one must consider the tradeoff between having all the vehicles suffer delay or having only the left-turn vehicles suffer delay.

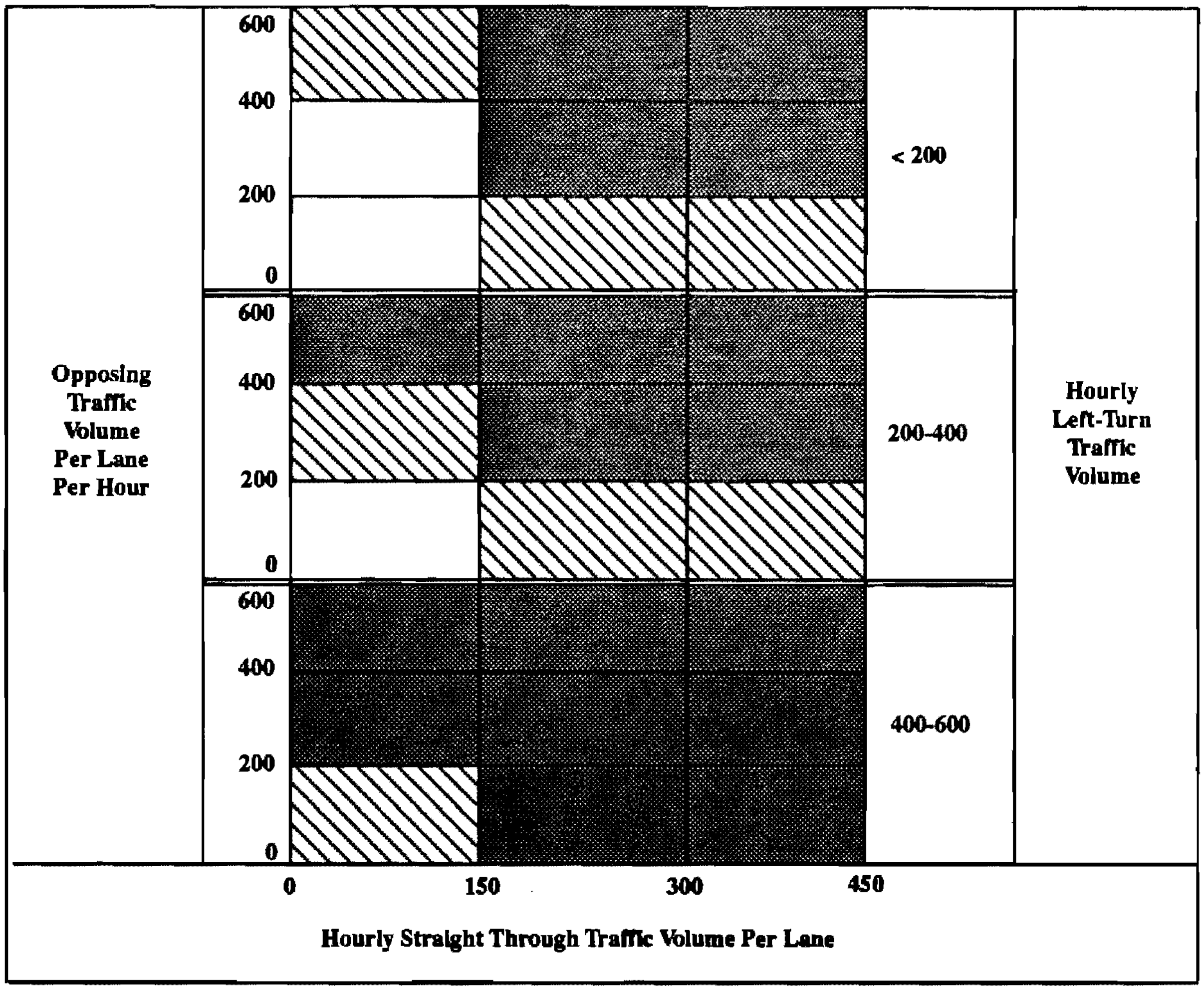
The opposing traffic volume has an important effect on the delay caused to left turners and the entire traffic stream. Gaps in the opposing traffic control the left-turn movements, thus in the case of very high opposing traffic volumes, gaps may disappear completely.

Left-turn capacity is an important element of the operational aspect of a left-turn treatment. For an unsignalized intersection the opposing-traffic volume determines the left-turn capacity. The higher the opposing traffic volume the lower the left-turn capacity. Consequently, the possibility of using a left-turn treatment in order to provide a storage area for the left turners is higher. From the study described in the previous chapter the warranted left-turn capacity varied from about 600 to 100 vph for the volume conditions considered. In conjunction with the delay values presented in Chapter 3, guidelines for the use of a left-turn treatment at a single isolated intersection can be developed.

A general set of such guidelines is presented in Table 6.1, which indicates that for low opposing and low and medium volumes of straight-through traffic, a left-turn treatment is required only when the left-turn volume is high. For high straight-through volumes the left-turn treatment is also needed for moderate left-turn volumes. The difference in the average delay values between the section with no left-turn treatment and that with a treatment becomes apparent even at low values of left-turn volume when the straight-through volume is moderate to high. So, it is better to provide the left-turn treatments even though the left-turn capacity warrant does not require it. There is little difference operationally between a section with a left-turn lane and one with a raised median for all values of left-turn volume when the opposing traffic has low to moderate volumes; however, at high opposing-traffic volumes the left-turn lane treatment is better operationally in most cases for the reasons discussed before.

For moderate values of the opposing traffic and low to moderate values of straight- through volume a left-turn treatment is needed when the left-turn volumes exceed the lowest value as seen from Table 6.1. From the graphics of previous chapters it can be inferred that only in the case of low straight-through and moderate opposing-traffic volume, no left-turn treatment is required to process low to moderate values of the left-turns. For all other volume combinations a left-turn treatment is indicated. There is little difference operationally between the left-turn treatments even for high left-turn volumes, however, since the left-turn storage capacity is a concern, a left-turn lane is preferable in high demand situations.

TABLE 6.1. GUIDELINES FOR LEFT-TURN TREATMENT BASED ON OPERATIONAL CHARACTERISTICS FOR A SINGLE ISOLATED INTERSECTION



Legend:

Guidelines for Left-Turn Treatment

■ Left-turn treatment desirable provided treatment can be accommodated within available right of way and pavement width.

a. Left-turn lane preferable if midblock turns are operationally and safely allowable.

b. Raised medians may be considered if adequate storage capacity is available.

▨ Optional left-turn treatment may be considered. Left-turn lane or raised median satisfactory based on individual site considerations.

□ Left-turn treatment not required based on operational or safety considerations.

GUIDELINES FOR A SINGLE PSEUDO-INTERSECTION IN A NETWORK

The operational effects of the left-turn treatments on an arterial street with a number of unsignalized intersections was described in the Chapter 4. The left-turn capacity of a single arterial intersection was investigated in Chapter 5.

Recommendations for use of geometric treatments at intersections formed by adjacent driveway openings (pseudo-intersections) are presented in Table 6.2. For low values of opposing traffic volume the left-turn treatment is not needed for any volume combination considered. The plots of left-turn volume versus average delay indicate that at low straight-through and left-turn volumes, no left-turn treatment is required, however at higher volumes of left-turn and straight-through volumes left-turn treatment is required. There is a substantial difference in average delay in the case of a section with no treatment compared with a section with a left-turn treatment. The section with the left-turn lane section is better operationally than the section with the raised median in all the cases. It is recommended that a left-turn treatment be provided in all cases except for low left-turn and straight-through volumes.

At moderate values of the opposing traffic the left-turn treatment should be provided for all volume combinations except in the case of low straight-through and left-turn volumes. Once again a section with a left-turn lane performs better than a section with a raised median.

At high opposing traffic volumes a left-turn treatment should be provided for all the different volume combinations. The graphics of the previous chapters indicate that the sections with continuous left-turn lanes performs better operationally than turn bays, therefore this is reflected in the recommendations of Table 6.2.

WARRANTS BASED ON SAFETY CRITERIA

Most of the previously published warrants for the use of left-turn median treatments were based on safety criteria. These warrants were developed by empirical means, i.e from before and after studies. In this section some of the papers described in the literature review are discussed and results of those papers are presented. Most of the studies have been concerned with the continuous two-way left-turn median lanes (CTWLTML) exclusively, however the studies described in this section deal with the other kinds of median treatments as well.

A study conducted by Walton et al developed warrants for the use of the left-turn lanes using regression equations for the prediction of the accident rates on sections with CTWLTML and continuous one-way left-turn median lane (COWLTML). The significant variables in the regression equation are weekday ADT, number of signals per mile, number of driveways per mile and city size. The R squared for the equation is 0.75 and the form of the equation is given below.

Accidents/mile = – 43.5 + 0.00203 (ADT) + 0.000175 (City Population) + 0.491 (Number of driveways/mile) + 9.20 (number of signals/mile)

Data used in the study included driveways placed at 60, 105 and 232 feet apart while in this study driveway spacings are 200 feet. The authors warn about using the equation for the prediction of accidents for the sections with the COWLTML since it consistently over-estimates COWLTL accident rates.

A similar study by Squires and Parsonson (Ref 8) compares the safety of sections treated with the raised median to that with the CTWLTML. They also developed a regression equation for the prediction of the accident rate on arterials with four and six lanes. The data set used in developing the equations was collected for the states of Georgia and California over a period of two to three years. The data was analyzed first by testing the hypothesis that the means of the accident rates for sections with the raised median are less than those of sections with CTWLTLs. The results of the hypothesis tests are given in terms of the alpha errors and are reproduced in Table 6.3. Raised medians are safer in terms of midblock conflicts because they shift accidents to the intersections. A better means of comparison is total accidents which in the table show no significant difference at the 95% confidence level. However, there is difference at the 90% confidence level in most cases.

Later the authors develop regression equations for the prediction of accidents on the four and six lane arterials. They further subdivided the data by the total and midblock accidents and accidents per million vehicle miles and accidents per mile per year. The best set of variables for the regression were chosen on basis of Mellow's C_p statistic. Then a stepwise regression procedure was used to get a smaller data set and alternate variable lists were compared to get the equations with the best combination for R square and F ratio values. The equations are given below.

TWLTL 6 Lane Acc/MVM = 3.087 SIG – 0.086 DR + 0.448 APP + 7.532

TWLTL 4 Lane Acc/MVM = 2.291SIG + 4.018

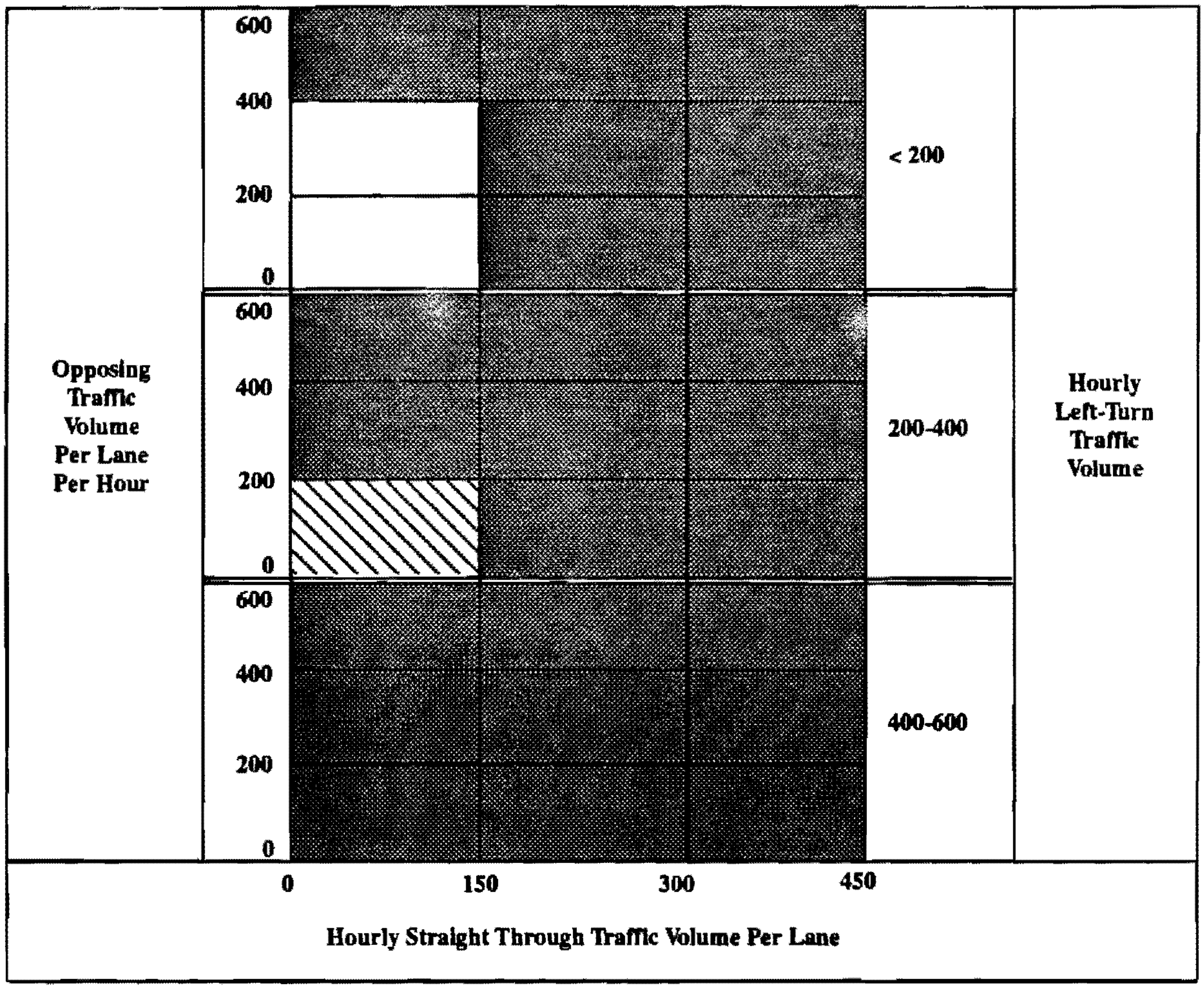
Raised median 6 Lane
Acc/MVM = 1.962 SIG + 3.856

Raised median 4 Lane
Acc/MVM = 2.721 SIG +1.918

where

Acc/MVM = Total accidents per million vehicle miles
SIG= Signals per mile
DR= Driveways per mile
APP= Approaches per mile

TABLE 6.2. GUIDELINES FOR LEFT-TURN TREATMENT BASED ON OPERATIONAL CHARACTERISTICS FOR A SINGLE PSEUDO-INTERSECTION



Legend:

Guidelines for Left-Turn Treatment

Left-turn treatment desirable provided treatment can be accommodated within available right of way and pavement width.

a. Left-turn lane preferable if midblock turns are operationally and safely allowable.

b. Raised medians may be considered if adequate storage capacity is available.

Optional left-turn treatment may be considered. Left-turn lane or raised median satisfactory based on individual site considerations.

Left-turn treatment not required based on operational or safety considerations.

The expected values of the accidents were calculated using the above equations and they support the conclusions of Table 6.2. The conclusions of the authors were that the raised median treatments were better at higher ADT's. For four-lane sections the raised medians were always safer than the TWLTL. The difference in the accident rates was found to decrease with increasing number of signals per mile. For six-lane sections the raised medians were found to be safer except when there were many driveways per mile, low numbers of signals per mile, and low numbers of approaches per mile.

A study by Harwood (Ref 9) developed warrants for the use of the various median treatments based on operational and the safety criteria. The data for developing the safety criteria was collected from various sites in California and Michigan over a period of five years. The key measure of effectiveness for the study was the accident rate per million vehicle miles. Independent variables used in the analysis were the average daily traffic, truck percentage, type of development, left-turn demand, lane width, shoulder width, speed, driveways per mile, and unsignalized intersections per mile. The results of the accident rates analysis are summarized in Table 6.4. These tables give the average or expected values of the accident rates and indicate that the suburban highways with residential development have a lower accident rate than the highways with commercial development. The five-lane TWLTL sections have lower accident rates than either the four-lane treatment with raised medians or four-lane sections with no treatment. The conclusions of this study are opposite to the conclusions of the study mentioned above. This is due to the fact that accidents are rare events and any sample collected over a period of 2 or 5 years is still very small and hence may not be representative. The results of the above studies will be used to develop a warrant for the use of a particular section.

TABLE 6.3. SIGNIFICANT DIFFERENCE OF ACCIDENT RATES BETWEEN TWLTL AND RAISED MEDIANS

Total Accidents

Section Type	Accident Type	Alpha-Error at Point of Significant Difference	Significant Difference = 0.10	Significant Difference =0.05
4-Lane sections	Acc/MVM	0.2168	No	No
	Acc/mile/yr	0.0980	Yes	No
6-Lane sections	Acc/MVM	0.0549	Yes	No
	Acc/mile/yr	0.0883	Yes	No

Midblock Accidents

Section Type	Accident Type	Alpha-Error at Point of Significant Difference	Significant Difference = 0.10	Significant Difference =0.05
4-Lane sections	Acc/MVM	0.0009	Yes	Yes
	Acc/mile/yr	0.0128	Yes	Yes
6-Lane sections	Acc/MVM	< 0.0005	Yes	Yes
	Acc/mile/yr	0.0224	Yes	Yes

Source: Ref. 7

GUIDELINES BASED ON OPERATIONAL AND SAFETY CRITERIA

One of the biggest problems with developing warrants for the use of the left-turn treatments is the conflict of objectives of reducing delay and increasing safety. An acceptable warrant would satisfy both objectives. As was seen in Tables 6.1 and 6.2 the left-turn lane treatment is operationally better than all the other treatments, however it is unsafe at higher speeds. The guidelines for the use of the sections are given below.

1) Left-turn lanes may be used as recommended by Tables 6.1 and 6.2 as long as the speed of traffic on the arterial is less than 45 mph. For higher speeds, raised median treatments should be used if a left-turn treatment is recommended.

2) On arterial streets with significant numbers of driveways the left-turn lane treatment is operationally better than the raised median treatment, however, the accident rates also increase as there is more weaving in the traffic stream. It is better to provide a raised median treatment and concentrate the left turns if the driveways are spaced less than 100 feet apart. On streets with driveways very far apart, i.e., greater than 400 feet, raised medians and continuous left-turn lanes are operationally equal. However, large driveway spacings essentially make a continuous turn lane necessary.

3) From the safety standpoint the sections with the left-turn treatment are always better than the sections with no treatment. So in sections with disproportionately large number of accidents left-turn treatments can be used even though not warranted due to the operational criteria.

4) For very high left-turn volumes the left-turn lane treatment is recommended as it provides a storage area for all the left turners and is safer than the other treatments.

TABLE 6.4. OBSERVED ACCIDENT RATES

Non-Intersection Accidents on Suburban Arterial Highways

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	2.39	1.56	2.85	2.90	2.69
Residential	1.88	1.64	0.97	1.39	1.39

Adjustment Factors			
	Under 30	30-60	Over 60
Driveways per mile	-0.41	-0.03	+0.35
	Under 5%	5-10%	Over 10%
Truck percentage	+0.18	-0.07	-0.33

Note: Accident rates should be decreased by 5% for highway sections with full shoulders and increased by 5% for highway sections with no shoulders.

Suburban Arterial Highways (Including Non-Intersection and Unsignalized Intersection Accidents)

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	4.50	3.99	7.62	7.61	5.80
Residential	4.76	3.55	4.00	4.10	3.24

Adjustment Factors			
	Under 30	30-60	Over 60
Driveways per mile	-0.41	-0.03	+0.35
	Under 5%	5-10%	Over 10%
Intersections per mile	+0.99	+0.28	+1.55
	Under 5%	5-10%	Over 10%
Truck percentage	+0.40	-0.15	-0.71

Unsignalized Intersection Accidents on Suburban Arterial Highways

Type of Development	Design Alternative 2U	3T	4U	4D	5T
Commercial	2.11	2.43	4.77	4.71	3.11
Residential	2.88	1.91	3.03	2.71	1.85

Adjustment Factors			
	Under 5%	5-10%	Over 10%
Intersections per mile	-0.99	+0.28	+1.55
	Under 5%	5-10%	Over 10%
Truck percentage	+0.22	-0.08	-0.38

2U = Two lane undivided
3T = Three lane with TWLTL
4U = Four lane undivided
4D = Four lane divided with raised median and one-way LTL's at intersections
5T = Five lane with TWLTL

Source: Ref. 9

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