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OPERATIONAL EFFECTS OF NON-TRAVERSABLE MEDIANS AND TWO-WAY LEFT-TURN LANES: ACOMPARISON

A Thesis

Presented for the

Master of Science

Degree

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Mohan Muralidhar Venigalla

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DEDICATION

To my heavenly parents, whose love and concern for me have always been the source of my motivation to succeed.

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ABSTRACT

This research attempted to compare an arterial roadway with a two-way left-turn lane (TWLTL) with one with a non-traversable median (NTM, raised or depressed) with respect to operational efficiency reflected through delay examined by traffic under a variety of traffic and development situations. A three-way factorial design of experiment was developed, and the microscopic NETwork SIMulation software, NETSIM was used to generate information for the experiment. The expected differences in traffic delay and fuel consumption between TWLTL and NTM were quantified with the help of NETSIM.

It was concluded that driveway density, traffic volume on the arterial, and the type of design (TWLTL or NTM) have significant effect on the performance measures such as networkwide delay, fuel consumption, and delay to left-turning traffic and through traffic on the arterial. At low driveway density and low traffic volume, the difference in networkwide delay between the two designs is not found to be significant. At higher driveway densities no significant difference in delay to left-turning traffic on the arterial can be expected between TWLTL and NTM. However, TWLTL design was found to cause less delay to through traffic and be more fuel efficient at all levels of driveway density and traffic volume.

The study did not examine the safety aspects of TWLTL and an NTM, which should be considered for complete evaluation. This study developed estimates of the reduction in traffic

delay and fuel consumption when a TWLTL is used instead of an NTM. These estimates would be useful for a benefit-cost analysis of alternative design features.

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CHAPTER 1

INTRODUCTION

Operational problems on urban or suburban two-way arterial highways, especially those with commercial strip development are mainly caused by the conflicts between the through traffic and the left turning traffic into and from driveways. The magnitude of the problem is related to the type of access provided to adjacent land uses. In this respect, two-way left turn lanes (TWLTL) offer unrestricted or only partially restricted access to left-turning vehicles along a given section of roadway. On the other hand, a cross-section with a non-traversable (raised or depressed) median (NTM) would, in general, limit the left turn maneuvers to the places where a median cut is provided and this cross-section may discourage strip commercial development. The choice between these two alternative designs is often controversial and presents a challenge to highway and traffic engineers.

The important issues to be addressed when choosing between the two alternative designs include the following:

- 0 Which design is safer at a given traffic volume level and land use intensity?
- 0 Which design offers less congestion and more capacity under the same operating and other physical characteristics?

0 Considering safety and operational efficiencies, which one of the two designs is more cost-effective?

In order to develop a set of guidelines for choosing and recommending one of the two designs, an in-depth study is needed on accident and operating experiences. The purpose of this study is to examine the operational effects of the two median designs, TWLTL and NTM, in terms of delay, operating speed, congestion and fuel consumption. It is hoped that the findings of this study would be used in formulating guidelines to choose between the two designs of interest as well as in economic evaluation of the design alternatives.

Functions of an Arterial Highway

Since the designs of interest are mainly applicable to arterial highways, it is appropriate to discuss the functions of an areterial. The two basic functions of any road are access to developments and movement that integrates different developments. The American Association of State Highway Officials' (AASHTO) (1990) functional classification of roads includes local streets, collectors, minor arterials and major arterials. Different sub-classifications can exist within the above mentioned basic types. At one extreme, the freeway (major arterial) provides no access to the abutting land except through controlled access interchanges and frontage roads giving top priority to the movement function. At the other extreme is the cul-de-sac, which is a dead-end local street with a turnaround at the end. Through movements are nonexistent, as every vehicle on a cul-de-sac has an origin or destination there giving top priority to the access function.

Arterials fall between these two extremes. Typically arterials provide both local access and movement function to some extent. In urban and suburban environments, commercial and other developments along the arterials are common. The demand for access and the frequency of access to these developments causes capacity and safety concerns on the arterial.

Operation of TWLTL Arterials

TWLTLs have been used increasingly as the median of choice. TWLTL provides separate storage to the left-turn vehicles at intersections or driveways of the adjacent land uses. Several before and after studies have proved that TWLTLs reduce the number of rear-end and angled collisions. Some studies indicated that the business sector and the motoring public prefer the TWLTL to NTM.

On the other hand, some traffic engineers and highway designers believe that there is a point at which traffic volumes, especially left turns, exceed the capacity of a TWLTL. It is argued that there may be a volume at which a TWLTL breaks down in operation, no longer providing the capacity and/or safety that could perhaps be obtained from an alternative median treatment (Parsonson,1990).

Operation of NTM Arterials

As an alternative design to TWLTL, NTM median restricts the left-turns to those sections of the arterial where a median opening is provided. However, most or some of the left-turning traffic would experience longer travel time, forced U-turns and/or traversal around the block to reach the desired destination. Also, concentration of left turns at a median opening is high for NTM design. At the same time, there are fewer locations permitting left-turn maneuvers than in the case of a cross-section with TWLTL.

General Characteristics of the Two Designs

Nemeth (1975) and others have listed the advantages and disadvantages of the two median designs over each other which can be summarized as follows:

Advantages of TWLTL over NTM

- 0 Removal of left-turning vehicles from through traffic while still providing maximum left-turning access.
- 0 Reduction of delay to the left-turning vehicles.
- 0 Direct access to the adjoining property.

- O Flexibility in roadway use, as for a detour lane, a path for emergency vehicles, refuge for disabled vehicles etc.

<u>Disadvantages of TWLTL Compared With NTM</u>

- O No refuge area for pedestrians crossing wide arterial.
- O Unsafe operation where sight distance is inadequate.
- O Visibility problem of painted median on rainy nights.
- O More traffic conflict points, especially at driveways.
- O Burden of instructing the public in proper use of these lanes.

<u>Advantages of NTM Over TWLTL</u>

- O Reduced conflicts and accidents in mid-block area.
- O Reduced conflict points, especially at driveways.
- O Encouragement of access road and parallel street development.
- O Service as pedestrian refuge.
- O Service as a location for signals and signs.

<u>Disadvantages of NTM Compared With TWLTL</u>

- O Over-concentration of turns, including U-turns, at median openings and intersections.
- O Increased congestion at signalized intersections because of the presence of drivers desiring to turn

left where median openings are not provided.

- 0 Increased travel time due to circuity of route for drivers desiring to turn left where median openings are not provided.
- 0 Restriction of direct access to the adjoining property.
- 0 Higher initial costs.

Objective and Scope of the Study

Although some of the above stated properties seem obvious, many are intuitive and are not based on any scientific studies. There is a need to study the operational differences of these two designs in a thorough manner. Such a study would help engineers and planners know when a particular cross-section would be suitable and cost-effective for a given condition. Thus, the primary objective of this study is to examine the differences in key performance indicators such as delay, queuing and/or stops, operating speed and capacity between the NTM and TWLTL cross-sections. The approach of the study is theoretical and limited to studying the differences by modeling a half-a-mile section of arterial using the NETwork SIMulation (NETSIM) package under a number of scenarios with varying driveway density and "through volume."

Disclaimer

The study <u>was not</u> aimed at an all-out comparison between the two designs. Only the operational differences were quantified. Other issues such as safety and land development are outside the scope of the study.

Thesis Outline

Chapter 2 of this thesis focusses on some of the earlier related studies. Chapter 3 presents an outline of NETSIM logic and discusses its applicability to the current research problem. The methodology for this study is described in Chapter 4. In Chapter 5, results of the simulation are summarized and the conclusions of the study are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

Several studies have been done contrasting the safety related issues of the two cross-sections. Some research was exclusively aimed at studying the advantages of TWLTL cross-sections. Additionally, a limited number of studies focussed on the operational differences between TWLTL and NTM. In the following sections of this chapter some of these related studies are discussed.

National Practice

<u>AASHTO's Recommendations</u>

AASHTO's (1990) recommendations on medians advocate a judicial use of the two cross-sections. The guidelines set-up by AASHTO are highly subjective and the users can interpret them in many different ways. The following are some of the recommendations mentioned in "A Policy on Geometric Design of Highways and Streets" (1990, page 528-529, 826).

> *A street with an odd number of lanes, perhaps three or five, may be used to advantage in providing a storage lane for left-turning vehicles. This lane is one form of utilizing a paved, flush median. Left turn bays are marked in advance of the intersections. The length of lane between left-turn bays may be used for storage of vehicles making midblock left turns if this usage does not adversely affect traffic flow and safety on the arterial; otherwise, midblock left turns may be prohibited. Under some conditions it is better to permit midblock turns than to require that vehicles make U-turns at intersections or travel around a block to reach a destination. . . .*

Where an arterial must pass through a developed area having numerous street and driveway intersections, and where it is impractical to limit left turns, the continuous left-turn median lane is often the only practical solution. Because all left turns are thus protected, the interference to through traffic lanes is minimized. Successful operation of a continuous left-turn lane requires adequate lane marking.

A raised median with barrier-type curbing may be used on low and intermediate speed arterial streets. This type is desirable where it is necessary to prevent midblock turns. On streets serving low-speed traffic this type will prevent midblock turns. . . .

. . . .

In general, continuous left-turn lanes should be used only in an urban setting where operating speeds are relatively low and where there are no more than two through lanes in each direction. The operational characteristics of left-turn lanes with more than two through lanes in each direction is the subject of ongoing research and caution is recommended at this time when considering more than five lane cross section.

NCHRP Recommendations

National Cooperative Highway Research and Program (NCHRP) Study Report 282 (Harwood, 1986) deals with safety, operational and cost characteristics of selected multilane design alternatives for suburban highways. Operational characteristics studied in this report included capacity, level of service and accessibility and safety characteristics included the frequency, severity and type of accidents.

The report draws distinctions among several cross-sectional designs such as four-lane undivided, four lane divided, TWLTL with three, five and seven lane cross-sections etc. Some of the general recommendations of this report are listed below.

- 0 A four lane undivided cross-section is most appropriate for residential and light commercial areas on suburban highways classified as collectors and minor arterials.
- 0 Four lane divided cross-section and five lane cross-section with a center TWLTL, if physically feasible, would be more desirable than the four lane undivided design alternative on arterials that have dense commercial development and heavy left-turn volumes.
- 0 The four lane divided design alternative is best suited for use on major arterials with volumes higher than 1000 vph in one direction and less than 45 driveways per mile.
- 0 The four lane divided alternative is not well suited to highways with strip commercial development and can be used to discourage such development from occurring.
- 0 A five lane TWLTL design alternative is more appropriate for suburban highways with commercial development, driveway densities greater than 45 driveways per mile, low-to-moderate volumes of through traffic, high left-turn volumes and/or high rates of rear-end and angle accidents associated with left-turn maneuvers.

The report emphasizes the need for further research in this field as follows:

> *It should be recognized that the quantitative operational results presented in this report are based on a traffic simulation model that is in need of further development and validation....... Further research is needed on the traffic operational effects of raised medians, two-way left-turn lanes, and suburban development.*

Safety Effects

In an FHWA report, Azzeh et. al., (1975) compared the effectiveness of different median and TWLTL treatments in reducing the number of accidents on a road section. Referring to an analysis by Glennon, the report indicates that TWLTLs are "inferior to raised median", where frequent driveways are in combination with high arterial road volumes. It was also stated that TWLTLs are more effective in accident reduction at lower levels of roadside development and traffic volumes, as shown in Tables 2.1 and 2.2. At all values of average daily traffic (ADT), the annual accident reduction rate is more for a TWLTL up to a maximum of 60 driveways per mile. However, just as the number of driveways per mile exceeds 60, the accident reduction capability becomes more for a raised median treatment than for a selection with a TWLTL (Azzeh et. al., 1975).

Table 2.1 Estimated Annual Accident Reduction (per mile) by Installing Raised Median Divider With Left-Turn Deceleration Lanes.

Level of Development (Driveways per Mile)		Highway ADT (vpd) Low (<5,000)	Medium (5-15,0000)	High (>15,000)
Low	(<30)	2.2	4.1	6.3
Medium	(30-60)	5.8	11.2	17.2
High	(>60)	10.7	20.7	31.2

Source: Azzeh, et. al., FHWA Report No. FHWA-RD-76-85

Table 2.2 Estimated Annual Accident Reduction (per mile) by Installing TWLTL or Continuous Left Turn Lanes (for Each Direction of Traffic).

Level of Development (Driveways per Mile)		Highway ADT (vpd) Low (<5,000)	Medium (5-15,0000)	High (>15,000)
Low	(<30)	4.4	8.8	13.3
Medium	(30-60)	7.1	13.9	20.9
High	(>60)	9.7	19.0	28.6

Source: Azzeh, et. al., FHWA Report No. FHWA-RD-76-85

Parsonson (1990) studied the accident experiences on 32 raised median cross-sections with a total length of almost 48 miles and TWLTL sections totalling about 75 miles on the Georgia state highway system. He concluded that with 78 percent confidence raised-median designs experience fewer total accidents than do TWLTL designs. Six-lane raised median designs are safer than TWLTLs with a confidence level of 95 per cent.

NCHRP Report 282 suggests that three lane design alternatives can be expected to reduce accident rates, on the average, by 11 to 35 percent below the accident rate for a two-lane undivided facility, with even grater reduction possible for highly congested two-lane undivided facilities. The report also states that in some situations with high left turn volumes and relatively low through volumes, re-striping of a four lane undivided facility as a two lane road with center TWLTL may promote safety without sacrificing operational efficiency.

Operational Issues

In NCHRP report 282 Harwood concludes that a two-lane road with a center TWLTL will provide a substantial reduction in delay to through vehicles caused by left-turning vehicles, especially for flow rates above 500 to 600 vph in one direction. Also, he concludes that a four-lane cross section with a center TWLTL provides traffic operational benefits, relative to four lane undivided and four-lane divided design alternatives. However, Harwood did not quantify the operational differences between TWLTL and NTM (or raised median).

McCoy et. al., (1982) developed a simulation model to quantify the effects of a TWLTL on the efficiency of traffic flow on urban streets. By using this model, McCoy et. al., and Ballard et. al., (1983) studied the operational differences between TWLTL and undivided cross-sections. They concluded that the installation of a TWLTL on two-way, four-lane streets and two-way two-lane streets would improve the efficiency of traffic operations over a wide range of traffic volumes, left-turn volumes and driveway densities.

Heikal et. al., (1985) also studied potential benefits from TWLTLs by using a simulation program developed by Heikal. The recommendations of their study include a suggested procedure to determine potential benefits from the introduction of a TWLTL on an arterial section. The procedure uses the average number of stops per vehicle in the inside lane as a measure of the potential benefits.

Referring to a study by Hibbard, Parsonson points out that field studies indicated that at sites with TWLTL average delay per left-turning vehicles increased dramatically when the two-way through volume reached 2800 vph. He also adds (page 14):

> *The maximum delay to left-turning vehicles ever observed in Hibbard's study was greater at the TWLTL site than at the raised median site. This occurred despite the fact that the raised median site carried higher through volumes, and had a higher percentage turning left, than did the TWLTL site.*

Another field study coupled with simulation by Celniker was referred by Parsonson in his report. Celniker concluded that, at the study site where a TWLTL exists, a raised median would increase delay primarily because of the lack of interconnection of the driveways and parking lots.

According to a study conducted by ITE Technical Committee 5b-4 (1985), TWLTLs were reported to have a broad range of applications with AADT (Average Annual Daily Traffic) volumes ranging from 5,000 to 45,000. On the average, AADT increased by substantial amounts after the installation of TWLTLs. The normalized decrease in accidents per unit of traffic was approximately 36 per cent. ITE Technical Committee concluded that ADTs of 43,000 vpd, and up to 5,000 vehicles in peak hour can be handled successfully with a road having a TWLTL.

In a recent master's thesis, Mukherjee (1990) concluded that accurate guidelines are difficult to formulate based on accident and delay criteria only. He identified land use as a significant parameter in determining the choice of a cross-section. He also developed a stepwise procedure to assist highway engineers in making a choice between a TWLTL and an NTM.

CHAPTER 3

APPLICABILITY OF NETSIM TO THE STUDY

As mentioned in Chapter I, NETSIM simulation program was chosen as the analytical tool to address the issues of this study. Therefore, it is appropriate to provide a brief overview of NETSIM and discuss its applicability to the present case. Also, in the following sections, the stochastic nature of the model is discussed because of its importance in designing a statistical experiment for the study.

NETSIM Overview

NETSIM is a microscopic and stochastic NETwork SIMulation program that simulates traffic on a given network and keeps a historical record of individual vehicles and their paths in the system. NETSIM also models saturated conditions and intersection overflows (spill-backs). NETSIM was developed for the Federal Highway Administration (FHWA) in the early 1960's, and it has been continuously updated since that time. NETSIM is now one of the component models of the integrated traffic simulation system, TRAF, and therefore it is referred to as TRAF-NETSIM. FHWA is responsible for development and distribution of TRAF. TRAF-NETSIM can simulate the effects of traffic controls ranging from a simple 'stop' sign controlled intersection to a dynamic real-time control system along an arterial.

Inputs to NETSIM

Inputs to NETSIM include a road network and its lane geometry, traffic volumes, turn movements, intersection details such as type of control (sign or signal, pretimed or actuated signals, etc.), signal intervals, posted speed, headway, etc. The physical environment is represented in TRAF-NETSIM as a network comprised of links and nodes. Generally, the nodes of the network represent intersections and links represent urban street segments with one direction traffic flow. Up to 19 different time periods in a day can be simulated in a single run of NETSIM. Several card types which contain different traffic and network characteristics data define the input to the model. For example, card type 11 inputs the network geometric features like a link (defined in terms of an upstream node and a downstream node) and its length, number of lanes, lane usage, receiving links for the turn volumes, posted speed, start-up lost time, etc.

NETSIM Logic

NETSIM enters traffic into the coded network through a number of user defined entry links and moves the traffic stream every second according to the car-following logic while responding to traffic control devices, pedestrians, buses, and other conditions which influence driver behavior. When the simulation run is started, the network will be empty and NETSIM allows some initialization or fill time for attaining system equilibrium based on the run control directions specified by the user. System equilibrium is achieved when the traffic volume levels on the network generated by the model are nearly the same as the volumes that were input. Once equilibrium is attained, the model generates traffic in the network at a uniform rate proportional to the input volume. Each vehicle in the system is assigned a lane depending on whether it is a right or left turning or through going vehicle. Default or user specified acceleration and deceleration rates for the vehicles are adopted by the NETSIM logic.

The program models automobile, truck, bus and car pool vehicles using similar logic. However, within each class of vehicle, driver behavior is varied randomly. Ten types of drivers with a set of speeding, start-up lost time and headway acceptance characteristics (default or user specified) are chosen to represent the driver population. Each of these ten drivers would drive at a free flow speed which is some percentage (varying from 75% for driver type 1 to 127% for driver type 10 as default) of the posted speed on a given link. Likewise, each of these drivers is associated with a unique start-up lost time (218% for driver 1 to 23 % for driver 10 as default) and a headway (170% for driver 1 to 50% for driver 10 as default) specified as a percentage of the input lost time and headway on a given link. Each vehicle in the system would be assigned one of these ten driver types at random.

At signalized and sign controlled intersections, and at stopped vehicles in the system the program models the traffic close to reality. For example, when a vehicle approaches a signalized intersection and if the signal is red, a deceleration rate of 1 ft/sec would be applied until the vehicle speed has dropped by 10 percent. Then a deceleration rate of 7 ft/sec is applied until the vehicle halts at the stop line or behind a stopped vehicle. If the signal turns yellow, and if the vehicle position is at a distance closer than the safe stopping distance from the stop line, the vehicle will proceed without stopping. If the safe stopping distance is available, the vehicle would stop at the stop line and the following vehicles would also be stopped.

Wong (1990) describes the logic adopted in NETSIM in a detailed manner and the reader is advised to refer this article for further information on NETSIM and its logic.

NETSIM Output

NETSIM generates link specific delay, move time, total time, queue time, average speeds and other measures of effectiveness (MOE). The user may optionally output movement specific statistics for different links as well as the intermediate statistics. Intermediate statistics would help the user to study the system characteristics at a given time into simulation.

TRAF-NETSIM is currently available with a post-processor graphics package called GTRAF. The static graphics display package of GTRAF, SNETG, allows the user to view link specific output graphically. The animated graphics display package, ANETG, animates the simulated network to enable the user check the correctness of the input data.

Application of NETSIM to the Present Case Study

The basic approach to the comparison of TWLTL designs to NTM was to design hypothetical cases and hold all basic inputs to NETSIM constant while varying only the network geometry to represent either a TWLTL or a median. Hence it is appropriate to discuss how effectively NETSIM can model these cross-sections.

Network coding for median design fits perfectly within the NETSIM logic. On the other hand, since TRAF-NETSIM logic is based on an intersection-approach basis, the actual representation of TWLTL operation is not possible. However, Rathi et. al., (1990) indicate that this operation can be simulated by adding several "dummy" nodes between the street blocks. That means, the model can be tricked to represent two-way left turn lanes as a series of left-turn pockets leading the left turning traffic into the respective drive ways or cross-streets.

In a typical NETSIM application a link is defined as the road segment between two important adjacent intersections and the minimum length of a link allowed by NETSIM is 50 ft. All minor intersections or driveways along this link would be represented as a source and/or a sink node(s) with no specific parametric measures available at these nodes. Due to the microscopic nature of this study, each driveway is represented as a link and each arterial-driveway intersection as a node.

This representation helps examine the delay, queuing and other details at the driveways. Thus, in each case there are two sets of links one the arterial links and the other driveway links.

As identity of driveways was maintained as individual links, the turning traffic generated at the driveways was put into the system through entry and/or exit links connected to the respective driveways. Through traffic on the arterial street was also put into the system by entry/exit links connected to the arterial.

Stochastic Nature of NETSIM

NETSIM employs Monte Carlo simulation technique and uses a number of stochastic processes which are random sampling from discrete and continuous distributions to adequately represent real world behavior. Each one of these processes is assigned a different random number which is generated as explained below.

To start with, the user inputs two random number seeds to the model which are used as the bases for all the stochastic processes in the model. In a typical run, NETSIM recursively generates a sequence of pseudo random numbers by always calculating the next random number from the number generated in the preceding step. In particular, (n+1)st random number X_{n+1} is calculated from the (n)th random number X_n which is between k+1 and m-1 by using the recursive relation

$$X_{n+1} = [\ a*X_n + \mathrm{mod}(X_n,k)*k]\ (\mathrm{mod}\ m)$$

where a, k, and m are positive integers (Rathi et. al., 1990).

Due to this, the user has no control over the traffic stream and its operational and behavioral performance from one run to the next. The simulation model produces an entirely different vehicle stream as well as its performance if the user alters the sequence of random number seeds from one run to the next. In simple terms, the variation in the results of two such different runs can best be compared to the differences in traffic stream characteristics of one weekday morning to that of another. The traffic streams in such replications are called identical traffic streams.

Rathi et. al., (1990, page 6-7) discussed the problem associated with use of only one random number seed in TRAF-NETSIM as:

> *... This problem relates to the statistical behavior of the system and consequently the efficiency in simulation experimentation. By using one random number streams for all stochastic processes, the random behavior generated by the simulation model cannot be characterized or controlled in any way. That is, one cannot determine the source of variance in the simulation output and the controlled aspects of simulation experiments cannot be realized. By using a single source of random numbers throughout the simulation process, the model is not amenable to many of the commonly employed variance reduction techniques (e.g., common random numbers, antithetic variates, etc.) for stochastic models. Therefore, the simulation experiments where the analyst assumed to be comparing alternatives, cannot be effectively performed.*
>
> *Also, by limiting to one sequence of random numbers, some degree of interdependency is implied for all stochastic processes in the simulation. For example, in simulating urban traffic flow, one would expect the turn movement decision at an entry link to be independent of the desired speed of the vehicle. However, such independence cannot be accomplished if only one random number stream is sequentially used for all stochastic decisions.*

Simulation Experiments Using NETSIM

The limitation of single random number seed identified above opens the door for a simulation experiment with identical traffic stream generations. This feature of the model can conveniently be used to setup experiments to compare system alternatives by studying the random behavior of identical traffic streams for each of the alternatives. In this context, the presence of a high variance of the response variables (or measures of effectiveness) is highly undesirable. To counter the problem of large variance, the model must be run for longer simulation time or replicated many times to achieve a desired precision level.

For example, if the user wishes to know if the delay at an intersection would be lower if the phasing and signal timings are changed, it is possible to setup an experiment as follows. The user may prepare two input data sets containing 'before' and 'after' signal strategies. By changing the random number seeds, a number of runs may be made on each data set to obtain the delay. A simple t-test on the output would explain if there is a real variation in delay before and after implementing the new strategy. Thus the analyst can interpret the variation in delay, if any, by attributing it to either random variation or real variation between the two control strategies tested.

Simulation Time

Most important aspect of a simulation experiment using NETSIM is the dilemma associated with obtaining a mean and sources of variance for the measurement or dependent variables. Grafarian et. al., (1986) recommend the following two methods of performing simulation experiments.

Method 1: Running the simulation model for a long duration and using observations generated in this single, continuous and long run to estimate the parameters of interest and to obtain a measure of accuracy of estimate; and,

Method 2: Repeated runs of the model are performed in such a way that the output of the model in each run is independent of the others by using a different random number generator seed in each run.

The main disadvantage of the first method is that developing a confidence interval for the measurement variables is extremely complex and involves auto-correlations and cross-correlations of the variables within the model which are used to compute the parameter estimates. This requires an extremely long run to get reliable estimates of all the needed correlations, as well as to reduce the inherent bias present in the estimate of process parameters.

In the second method, difficulty of getting reliable estimates of all the auto-correlations and cross-correlations between successive observations (at 1 sec intervals which is the duration at which data is recorded in NETSIM) within the model is circumvented. Grafarian et. al., recommend that this method may be applied to the estimation of parameters and assessment of accuracy of the estimates from field data, to the analysis of traffic simulation outputs and to the comparison of field data with simulated data for validation studies. However, this method has the disadvantage of requiring a warm-up time (initialization period) for each replication during which no data may be collected.

By taking advantage of this stochastic nature of NETSIM, a three factor-factorial experiment with cross-section design, driveway density and arterial volume as the three independent variables was set up for the present study. Measurement of response variables was done through a series of simulation runs. The experiment is discussed in detail in the following chapter.

CHAPTER 4

STUDY DESIGN

The inputs to NETSIM are extensive and it is possible to study a wide range of variationes in input parameters. However, a study design varying all possible inputs will be very complicated and not feasible. Hence it was necessary to assume some constant inputs to the model and vary only a manageable number of parameters. Also, the study design was subjected to the limitations and capabilities of TRAF-NETSIM. In this chapter, the input values of parameters adopted in the study and the development of a three-way factorial experiment within the framework of NETSIM are discussed.

Input Values of Parameters

Number of Lanes

Since the most common type of application of TWLTL and NTM is on two-way four lane roads, only four lane arterials were studied for both the alternative designs. Driveways were assumed to be two-way and to have only one lane in each direction.

Length of the Study Section

One of the important considerations for the study is the length of the study section. If the length is not sufficient, the results may not be realistic. Aly et. al. (1985) referred to an ITE report that recommended an arterial spacing of 0.25 to 0.5 miles in designing an urban arterial street network. Complying with this recommendation, a half-a-mile long study section was chosen for the present study. Half mile sections keep the number of links (including the driveway links) within the allowable maximum for the IBM/PC version of TRAF-NETSIM. It was decided that there would be no cross-streets within this section. A traffic signal would make the operational characteristics very complex or complicated, and hence it was decided not to incorporate signals in the coded network. To avoid the influence of entry links at each end of the arterial, a 500 ft long section without any driveway or cross-street connections was inserted between the entry links and the study section. All driveways were coded as links of 100 feet length.

Driveway Density

Typically driveways along an urban or suburban arterial have an irregular pattern with varied spacing and other characteristics. Some developments have a pair of one-way driveways for entry and exit respectively, traffic whereas some developments have driveways with bi-directional traffic. Since adopting every possible driveway configuration into the study is practically impossible, two average driveway densities were adopted to represent low and medium/high density of development as follows:

0 Low Density Development: 32 driveways per mile, i.e., driveways on both sides of the arterial at

every 330 feet.

0 Medium/high Density Development: 64 driveways per mile, i.e., driveway on both sides of the arterial at every 165 feet.

Representing a section at a higher level of development than 64 driveways per mile was found to be infeasible as the number of one-way links, including the entry links, would exceed 150 which is the allowable maximum for the PC version of TRAF-NETSIM. One feasible solution to this problem would be to reduce the length of the section. However, a length of section shorter than one-half mile was not considered desirable/appropriate for this simulation analysis.

Another important assumption that should be pointed out is that no off-set was considered for driveway locations. In other words, driveways were assumed to be located on both sides of the arterial directly across from each other. Figure 4.1 illustrates a typical study section.

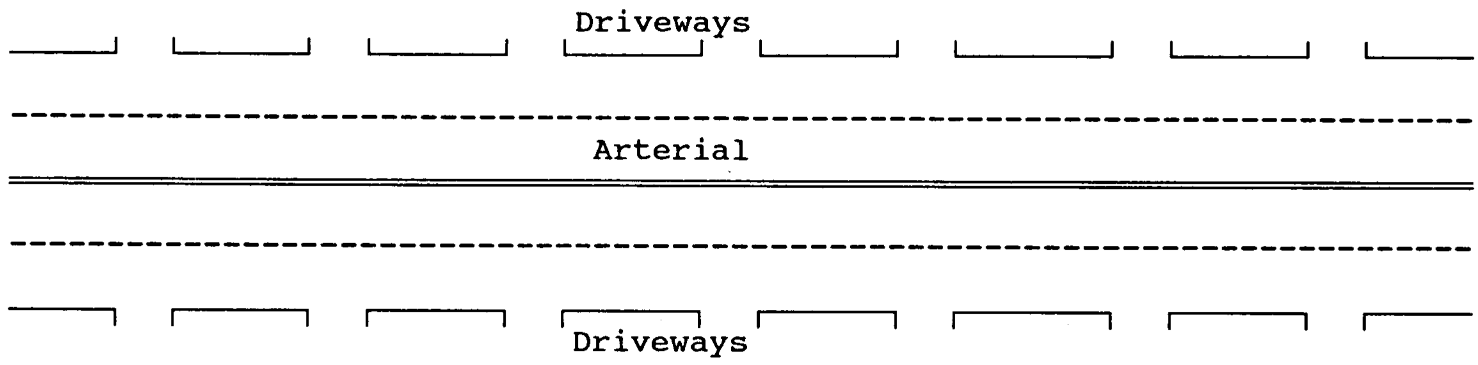


Fig 4.1 Typical Arterial-Driveway Configuration

Turn Demand and Distribution of Traffic at Driveways

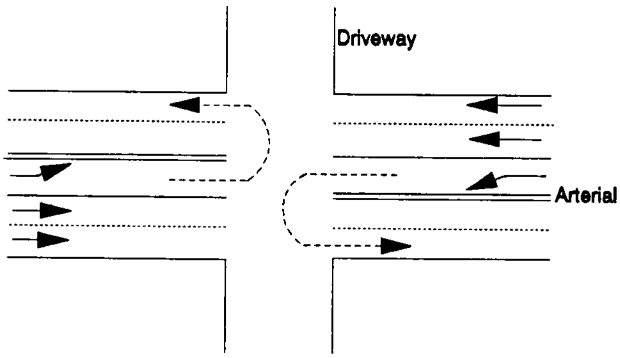
In practice, there will be a considerable variation in turn demand at driveways which is sensitive to many factors such as the size and type of land use, direction of flow, through traffic volume etc. However, as in the case of driveway spacing, studying all possible combinations of turn demand at driveways is an impossible task. Harwood (1986) identified three levels of left-turn demand for arterial traffic for comparing alternative designs which are 7.5, 10.0 and 12.5 percent of the through traffic. However, for simplicity, it was assumed for this study that 3 per cent of the through arterial traffic would be turning at each pair of opposite driveways. Of this 3 percent, half would turn left and the other half would turn right in to the driveways. These figures are equivalent to a total left-turn demand of approximately 10 percent in a 1000 ft. long section. For the simulated hour, entry and exit volumes at driveways were assumed to be the same. Exit traffic from the driveways was also assumed to have a 50-50 percent split in both directions of the arterial.

Since left turns are prevented at most of the driveways in the case of a raised median design, the assignment in this case is more complex. In this case, the prevented left turns into driveways were treated as follows:

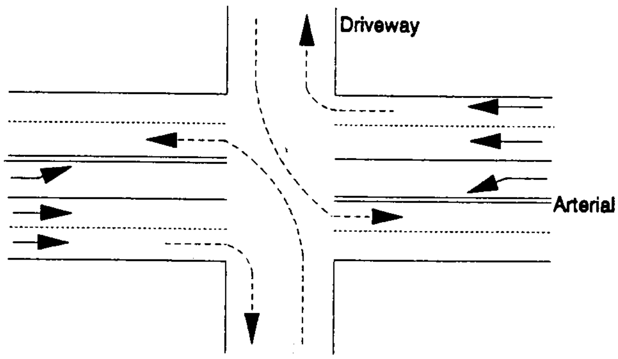
Traffic intending to take a left turn at a particular driveway would traverse the segment further ahead till it reaches a median opening. At the median opening, three actions are possible for this traffic as illustrated in Figure 4.2. First, a U-turn may be executed followed by travel in the opposite direction until the desired driveway is reached where a right turn is executed to reach the destination (action 1). Second, when a U-turn is not possible, these vehicles may take a right turn into the driveway at the median cut and from there a left turn is made on to the arterial to head towards the desired direction (action 2). Third, a left-turn may be executed into the driveway at the median cut which would be followed by a right turn on to the arterial leading toward the desired driveway (action 3).

In the same fashion, traffic prevented to make a left turn from a driveway due to the raised median would take a right turn on to the arterial, travel further until a median cut is reached and then either one or a combination of the above mentioned maneuvers would be performed to travel in the desired direction.

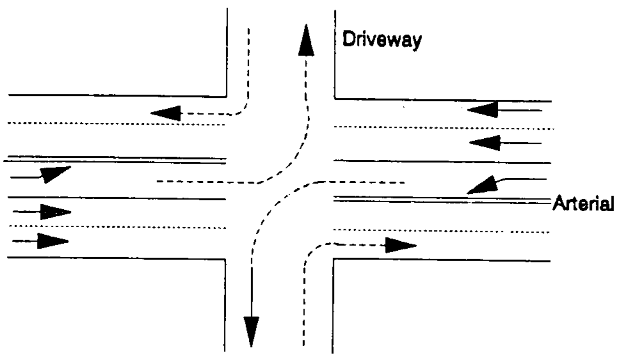
In practice all three actions illustrated in Figure 4.2 are possible with U-turns being most likely at low volumes, and one or both of actions 2 and 3 being possible at high volumes. Since NETSIM cannot model U-turns, it was assumed that the other two actions would adequately represent the demand for U-turns at median openings.



Action 1: Simple U-Turn



Action 2: Right-Turns Followed by Left-Turns



Action 3: Left-Turns Followed by Right-Turns

Figure 4.2 Reverse Traversal at Median Openings

Following the logic in actions 2 and 3, and adopting the turn demand at each driveway (3% of the arterial traffic), turn percentages were computed for each case with NTM design and were input to NETSIM. Computation of turn percentages is straight forward in case of TWLTL design since there is no restriction in access to the driveways.

Turn volumes were coded in such a way that the traffic turning into a particular driveway, either by left-turn or by right-turn (for both action 2 and action 3), was absorbed and immediately generated on the exit and entry links at that driveway, respectively. It is assumed that the time lapsed between the exit and re-generation of a vehicle trip coupled with the gap required for both left-turns and immediate right-turns or vice versa would represent for the U-turn gap acceptance at low levels of through volume. Since at higher through volumes actions 2 or 3 are more likely to be executed by a motorist, this representation is valid for medium and high through volume levels.

Arterial Volume

Through volume is an important variable that affect the performance of the alternative designs. Through volume was chosen as one of the three factor levels of the three-way factorial experiment. The following three levels of through volume on the arterial were studied for both TWLTL and raised median.

0 Low Volume: 600 vehicles per hour in each direction.

0 Medium Volume: 900 vehicles per hour in each direction.

0 High Volume: 1200 vehicles per hour in each direction.

Median Spacing

Median spacing has a significant influence on left-turn concentrations at median openings. Lesser the spacing lower will be the degree of left-turn concentrations. In practice, as in the case of driveway spacing and location, median spacing varies from case to case. Most of the highway agencies have different standards for different types of development pattern - urban, suburban and rural. For the purpose of this study, a median opening is provided at every 660 ft (1/8th of a mile) in the NTM case. This spacing is commonly used for suburban locations.

Other Input Data

Posted speed limits on the arterial and the driveways were held constant at 40 mph and 25 mph, respectively. In the raised median case, left-turn pockets of 250 ft length were providedat median openings. A stop sign was provided at each driveway link entering the arterial. Other input parameters of the model were set to NETSIM default values.

Factorial Experiment

Before the discussion of the factorial experiment set-up for this study, it is appropriate to mention some of the important definitions associated with factorial experiments.

Definitions

A Factorial experiment is an experiment in which the response variable Y is observed at all factor-level combinations of the independent variables (Ott, 1988, page 682). Factorial experiments are useful for examining the effects of two or more factors (or independent variables) whether or not interaction exists among factors.

A factor is an independent variable characterized by different levels at which measurements are obtained. Generally in factorial experiments, factors are categorical variables.

The term main effect refers to the influence of a factor on the response variable(s) individually. Should there be a significant influence of a factor on the response variable, its main effect is said to be significant.

Two factors A and B are said to interact if the difference in the mean responses for any two levels of one factor is not constant across the different levels of the second factor (Ott, 1988, page 686). Similarly, three-way interaction is said to exist when the difference in mean responses for any two levels of one factor is not constant across the levels of the other two factors.

The Experiment

Due to inherent advantages of performing simulation experiments with multiple replications of identical traffic streams as discussed in Chapter 3, it was decided to use this method for this study. As discussed in earlier sections, the three factors (categorical variables) of the experiment are:

Factor 1: Driveway density (two levels - low and medium/high)

Factor 2: Traffic volume on the arterial (three levels - low, medium and high), and

Factor 3: Two alternative designs (TWLTL and NTM).

The experimental design is shown in Figure 4.3. The measurement of response variables at different levels of the three factors is discussed in the followinig section. Figure 4.4 illustrates the interrelation among the factors and different variables. The response variables are network-wide delay, delay to left-turning and through traffic on the arterial street, and network-wide fuel consumption which are obtained from NETSIM output. It may be noted that the experimental design created 12 "cells" of a matrix, each cell representing a particular combination of the three factors.

Driveway Density (driways/mile)	Arterial Traffic Volume (vph)	Median Design TWLTL	NTM
Low (32)	Low (600)	y_i	y_i
Low (32)	Medium (900)	y_i	y_i
Low (32)	High (1200)	y_i	y_i
Medium (64)	Low (600)	y_i	y_i
Medium (64)	Medium (900)	y_i	y_i
Medium (64)	High (1200)	y_i	y_i

y_i refers to the i th measured value of response variable at the given factor level
where i = 1 to n (n = sample size)

Figure 4.3 Factotial Experiment Design

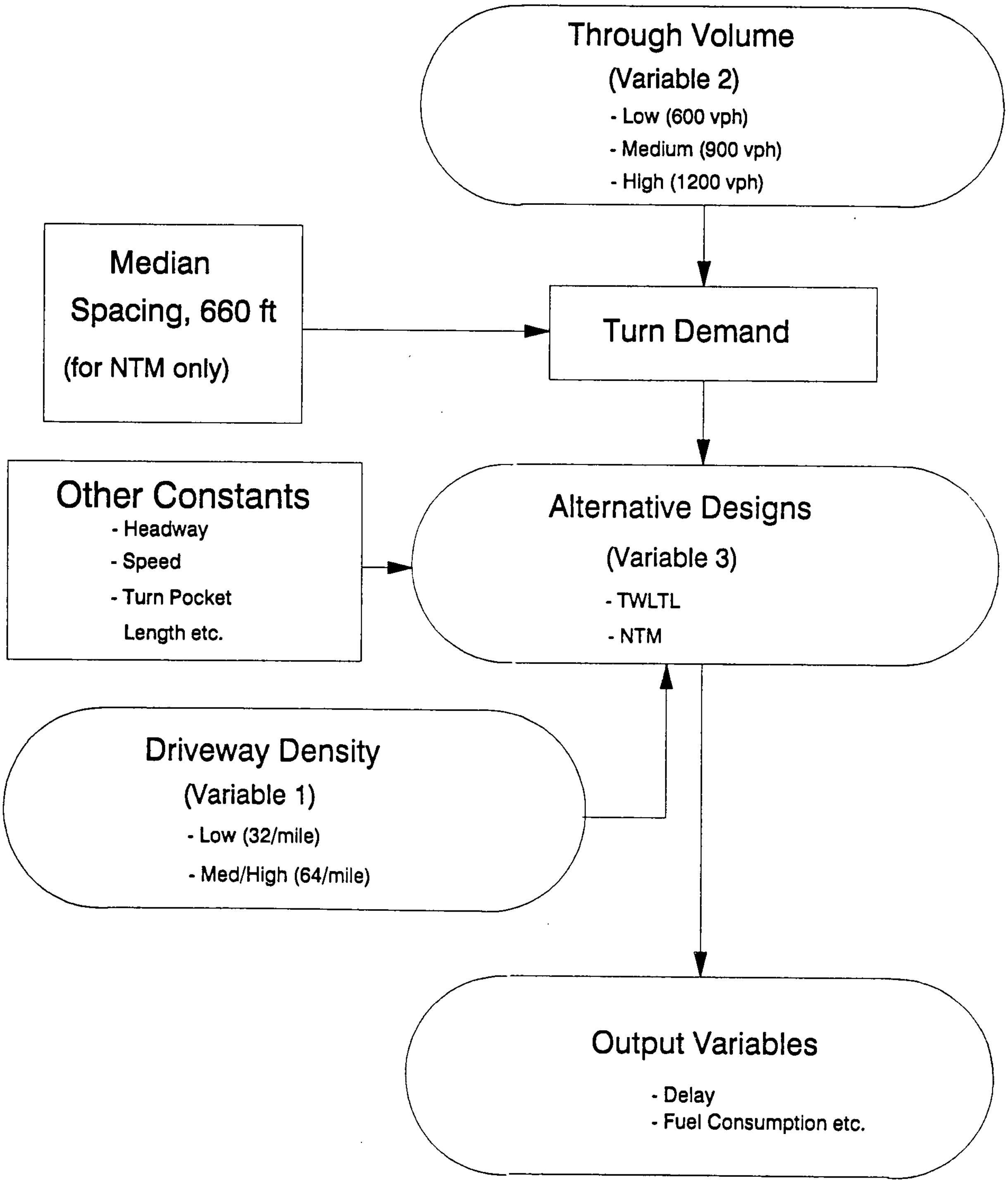


Figure 4.4 Relationships Among Input Variables

Network Coding and Simulation Runs

Network coding for NETSIM is a time consuming and laborious process. NETSIM does extensive error checking before executing simulation of input data. Error messages generated by NETSIM help the user to identify coding mistakes. However, error-free data sets are not necessarily correct in terms of intended network representation. In order to ensure accuracy of representation, two networks were first coded as TWLTL designs for each of the two driveway densities with low through volume. These two networks were copied into two different files and were modified to represent NTM with no left-turns at driveways without median opening. Thus, there were four different "base" networks for TWLTL and NTM with low and medium driveway densities. The "base" network files were subjected to a thorough testing for accuracy of coding by visualizing the effectiveness of coding through ANETG, which is an animation display package for NETSIM output. Any coding errors identified in this process were rectified.

Subsequently each of these base network files were copied into two other files to provide medium and high through volume inputs. Therefore, for generating one replication of the factorial design (analysis data sets), there are 12 different input files requiring 12 different runs of NETSIM, each run representing one cell of the matrix.

As discussed earlier, for generating multiple data replications of the factorial experiment, the sequence of random numbers in each input file was varied. Of course, the random number sequence was the same for all 12 input files for any particular replication. It was decided to generate four replications of each cell sets to conduct an analysis of variance on the measurement variables, and hence four different sequences of random numbers were used.

Figure 4.5 is a schematic representation of the sequence of operations in network coding and multiple runs made for the study. Node and link representation of a typical coded network is shown in Figure 4.6.

The study required 48 (12 x 4) individual NETSIM runs which produced 48 different NETSIM output files. A typical NETSIM run lasted for about 30 to 35 minutes on an IBM compatible 386 machine with 20 Mhz clock speed and a math co-processor.

Since NETSIM is a microscopic simulation model, its output has extensive information much of which was redundant for this study. The huge size of the output files necessitated the development of a post-processor computer program to extract the information needed for this study. This program was written in BASIC programming language and was custom made for this study only. This post processor program outputs only those sections of NETSIM output which are of interest to this study in a format readily appropriate for by the statistical analysis system, SAS.

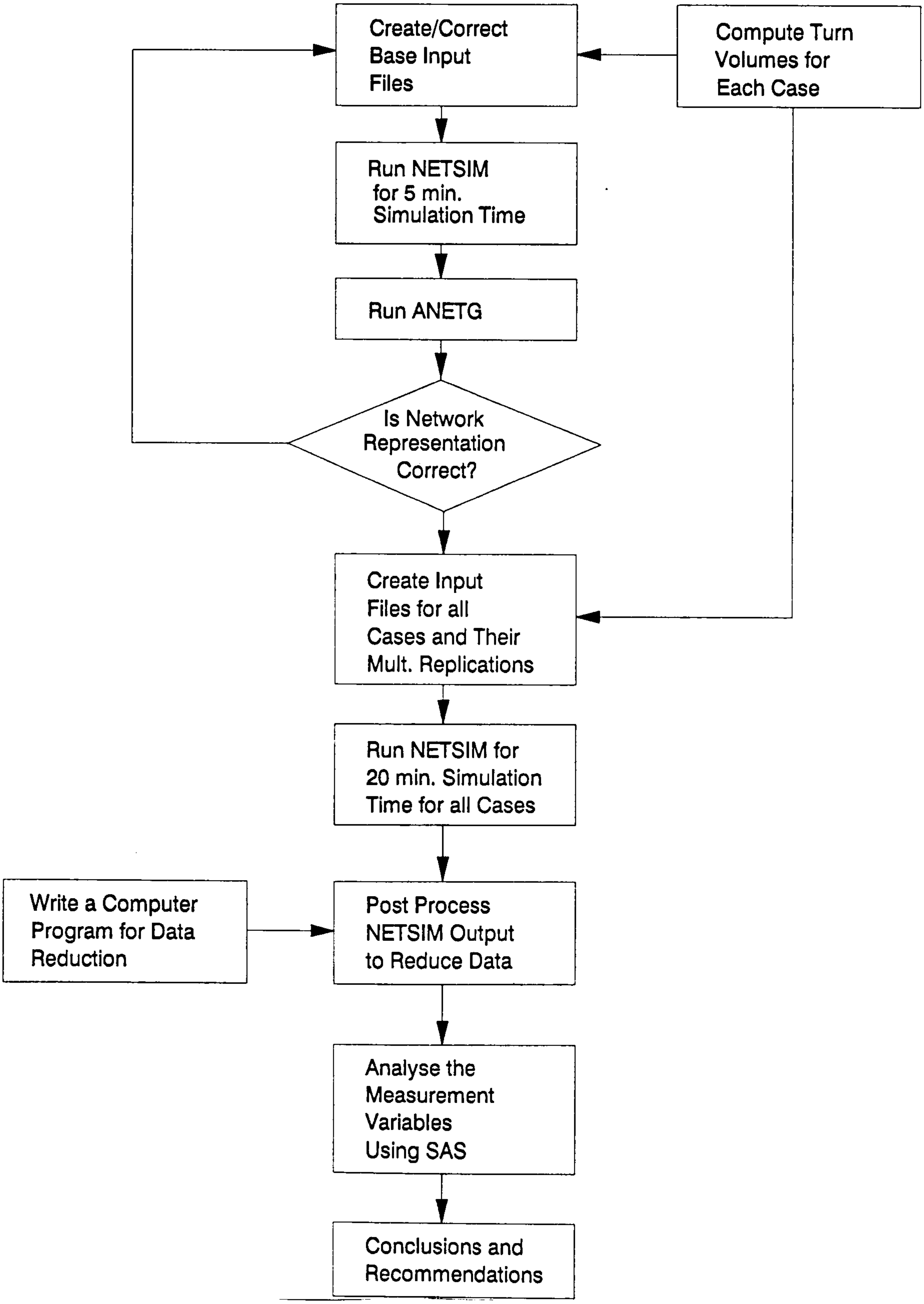


Figure 4.5 Schematic Representation of Steps Involved in NETSIM Runs

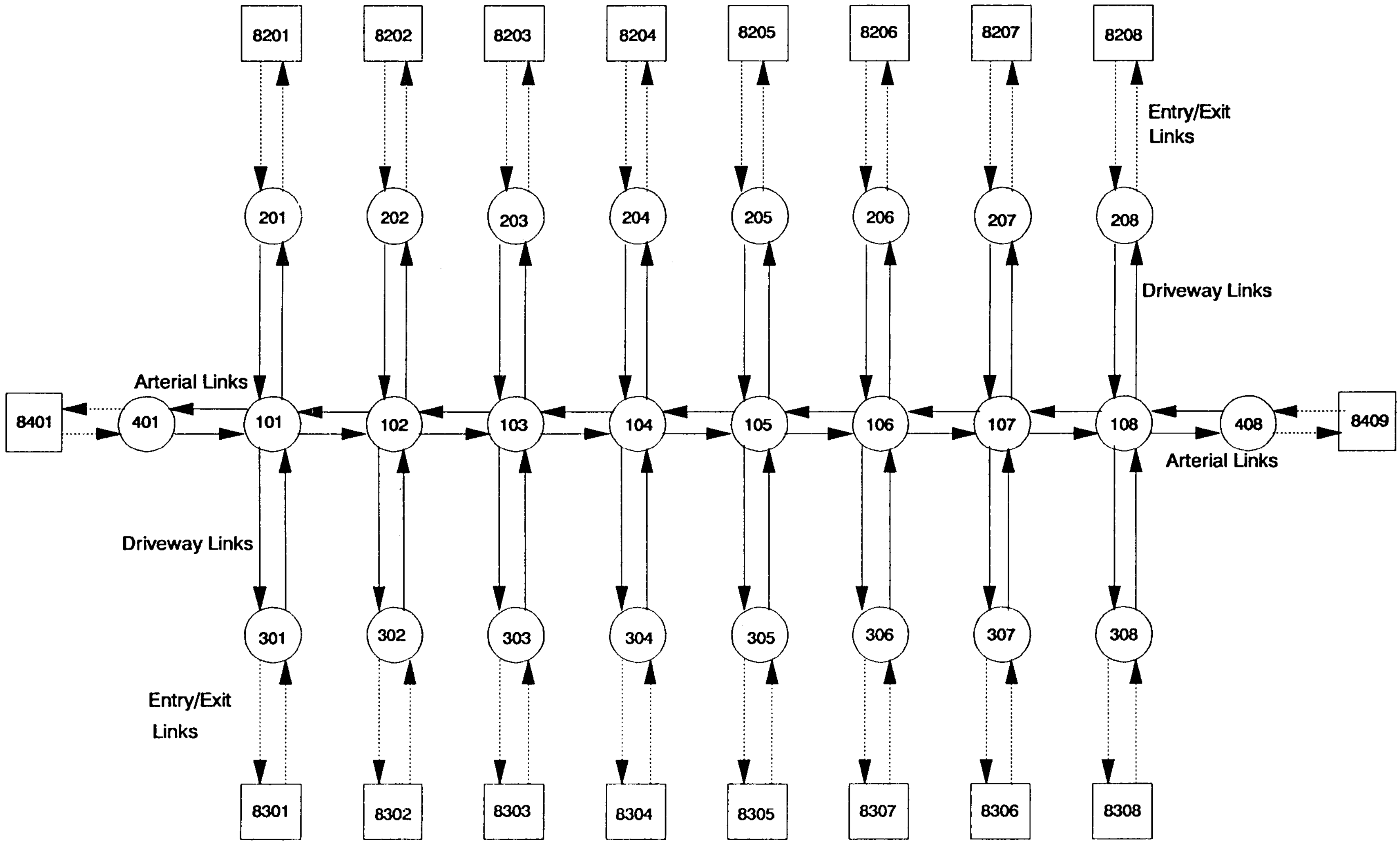


Figure 4.6 Node-Link Representation of Low Driveway Density Case

CHAPTER 5

ANALYSIS OF NETSIM OUTPUT

The differences in the performance of response variables were analyzed using the analysis of variance (ANOVA) technique. The Statistical Analysis System (SAS) sytem installed on the VAX cluster at the University of Tennessee was used to perform ANOVA for this study. This chapter presents a discussion on the analysis and the results.

Selection of Response Variables

The operational differences of the two cross section designs are characterized by different parameters/variables such as delay, average speed, stop time, queue discharge, fuel consumption, exhaust emissions, etc. However, most of these variables are interrelated, and hence it is not appropriate to use all these variables for analysis. Variation in delay is sensitive to stop time, and time spent in queueing. Therefore, delay estimates would adequately represent system performance. On the other hand, fuel consumption statistics are important from vehicle operating cost considerations. Estimates of average delay and fuel consumption are very important for economic evaluation of alternatives. Due to this, the analysis was focussed on these two variables only.

Intuitively, since "through traffic" on arterials has uninterrupted right-of-way within the test section, significant differences in delay to the through traffic are not expected. However, the delay to left-turning traffic from the arterial is expected to be significantly different between the two designs. To test this hypothesis, delay data specific to through and left-turning volume respectively were extracted from NETSIM output in addition to combined delay to all vehicles.

Analysis Focus

Average values of networkwide delay, delay to left-turning arterial traffic, delay to through traffic and networkwide fuel consumption were computed. These average values were plotted for visualizing any obvious trends. Then, each of these response variables were subjected to a series of statistical tests which are explained below.

Tests of Significance for Main Effects and Interaction Effects

The purpose of this analysis was to verify whether or not the three factors affect the response variables individually (main effects) and/or collectively (interaction). For this purpose, the general linear model procedure (PROC GLM in SAS) was used. The three null (H_0) and alternate (H_1) hypotheses sets tested for the main effects are listed below:

1. H_0: Driveway density has no effect on the response variable considered.

   H_1: Driveway density influences the response variable considered.

2. H_0: Traffic volume on the arterial has no effect on the response variable considered.

   H_1: Traffic volume influences the response variable considered.

3. H_0: Type of median design has no effect on the response variable considered.

   H_1: Median design has significant influence on the response variable considered.

The four null (H_0) and alternate (H_1) hypotheses sets tested for the interaction effects were:

1. H_0: There is no interaction between driveway density and traffic volume.

   H_1: The interaction between driveway density and traffic volume is significant.

2. H_0: There is no interaction between driveway density and type of median design.

   H_1: The interaction between driveway density and median design is significant.

3. H_0: There is no interaction between traffic volume and median design.

   H_1: The interaction between traffic volume and median design is significant.

4. H_0: There is no threeway interaction among driveway density, traffic volume and median design.

   H_1: The threeway interaction among driveway density traffic volume and median design is significant.

<u>Contrasts and Estimates</u>

Tests of significance for the differences in the performance of the two roadway designs at all levels of driveway density and traffic volumes will indicate the levels at which the two designs are significantly different from each other. These tests are called contrasts. The "cell address" model was used to do contrast analysis. In this approach, every individual level at which measurements were recorded was given a unique identification called 'cell address' as shown in Table 5.1.

Each digit in a cell address refers to a factor level. For example, cell 212 refers to the observations at medium driveway density, low-volume and NTM design. Using these unique cell addresses, the differences in the performance of the two designs were contrasted at all levels of driveway density and traffic volumes.

Table 5.1 Cell Address Information for Contrast/Estimate Analysis of Response Variables

Driveway Density	Arterial Traffic Volume Volume	Median Design	
		TWLTL	NTM
Low	Low	111	112
Low	Medium	121	122
Low	High	131	132
Medium	Low	211	212
Medium	Medium	221	222
Medium	High	231	232

The hypotheses tested for the significance of the differences in performance variables at a given level of driveway density and traffic volume are:

H_0: The specified difference is not significant, and

H_1: The difference is significant.

In addition to the above proposed analysis, if the difference in the mean response (networkwide delay and/or fuel consumption) is found to be significant for a combination of driveway density and volume level, estimates of these differences were also obtained by using the general linear models procedure. Estimates of differences between the two designs were also computed by using the 'cell address' model. However, no attempt was made to estimate the differences in delay to left-turning traffic and through traffic on the arterial.

Acceptance Criteria

Significance tests on main effects, interaction effects and the differences were done at $\alpha = 0.05$. All null hypotheses were rejected at probability levels less than 0.05; (i.e., at probability levels greater than 0.05 no strong evidence was assumed against the null hypothesis. In other words, a 5 percent significance level was adopted for all the conclusions derived from this study.

Networkwide Average Delay

From Table 5.2, it can be seen that the average delay for NTM cross-sections is consistently more than that for TWLTL cross-sections. This trend is illustrated in Figure 5.1. The difference in delay appears to increase at higher level of driveway density and traffic volumes. The difference in rates of increase observed in the figure indicates that there may be some interaction among the three study variables - driveway density, through volume and median design.

SAS output from the general linear model for tests of significance on main effects and the interactions is shown in Fig 5.2. The results of hypotheses tests indicate the following:

- 0 driveway density, through volume and the type of median have significant effect on delay (main effects are significant), and
- 0 pairwise interactions of the three variables and three-way interaction also have significant effect on delay.

By contrasting the difference in delay between the two designs within each driveway density and each through volume levels (Fig. 5.3) it was observed that the two designs differ from each other at all possible combinations of driveway density and volume levels except at low driveway density with low arterial volume.

Table 5.2 Average Networkwide Delay (min/veh-trip)

Driveway Density	Arterial Traffic Volume Volume	Median Design TWLTL	NTM
Low	Low	0.2175	0.2400
Low	Medium	0.2625	0.3000
Low	High	0.3700	0.4975
Medium	Low	0.2400	0.2700
Medium	Medium	0.2725	0.4025
Medium	High	0.3800	0.6475

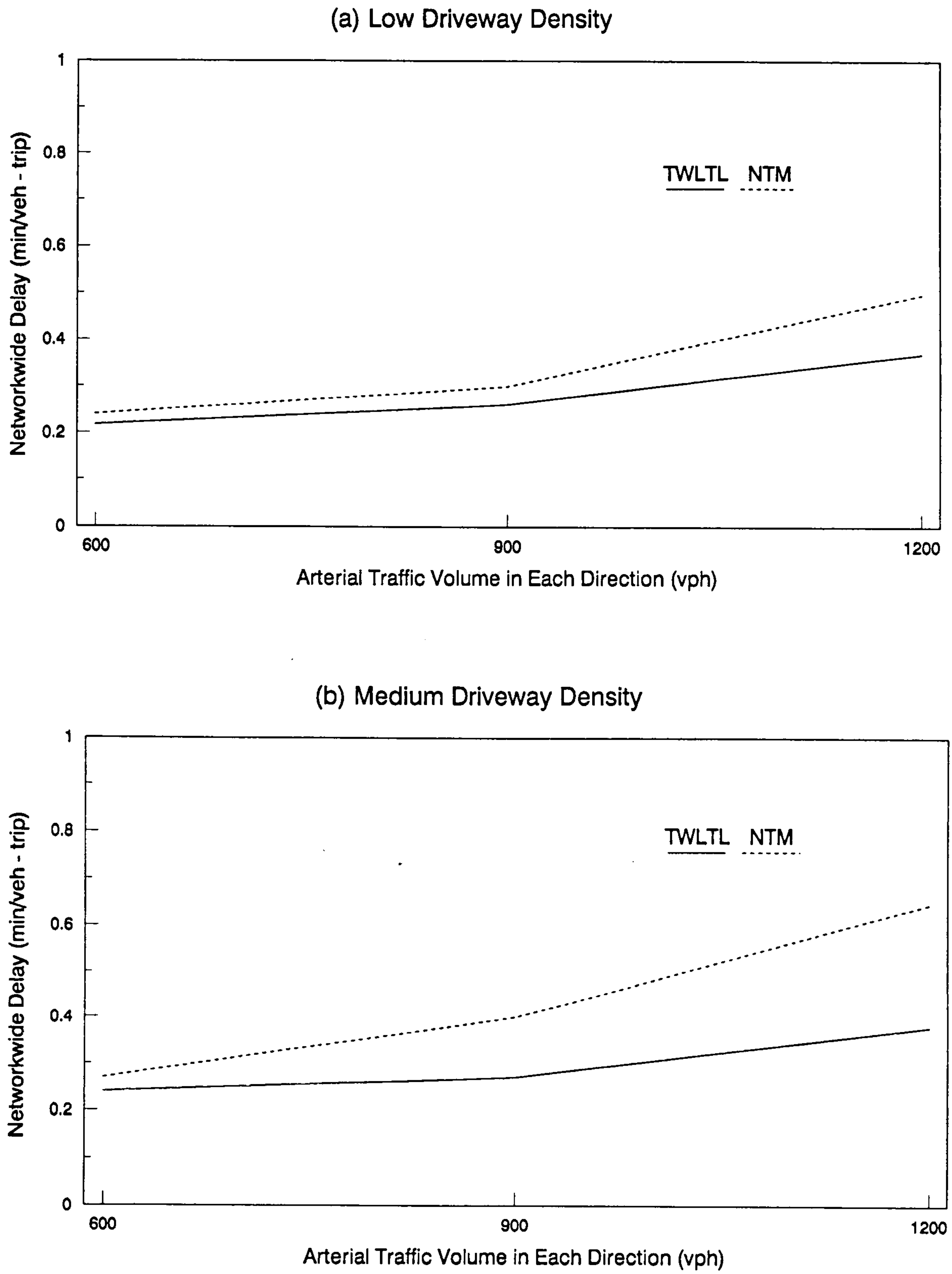


Figure 5.1 Networkwide Delay for the Two Designs

General Linear Models Procedure

Dependent Variable: DELAY

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.7112167	0.0646561	178.36	0.0001
Error	36	0.0130500	0.0003625		
Corrected Total	47	0.7242667			

R-Square	C.V.	Root MSE	DELAY Mean
0.981982	5.572517	0.0190	0.3417

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DENS	1	0.0352083	0.0352083	97.13	0.0001
VOLUME	2	0.4551542	0.2275771	627.80	0.0001
MEDIAN	1	0.1260750	0.1260750	347.79	0.0001
DENS*VOLUME	2	0.0058042	0.0029021	8.01	0.0013
VOLUME*MEDIAN	2	0.0607625	0.0303812	83.81	0.0001
DENS*MEDIAN	1	0.0192000	0.0192000	52.97	0.0001
DENS*VOLUME*MEDIAN	2	0.0090125	0.0045062	12.43	0.0001

Figure 5.2 SAS Output for Analysis of Variance in Networkwide Delay

General Linear Models Procedure

Dependent Variable: DELAY

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.7112167	0.0646561	178.36	0.0001
Error	36	0.0130500	0.0003625		
Corrected Total	47	0.7242667			

R-Square	C.V.	Root MSE	DELAY Mean
0.981982	5.572517	0.0190	0.3417

Source	DF	Type III SS	Mean Square	F Value	Pr > F
CELL	11	0.7112167	0.0646561	178.36	0.0001

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
LD, LV	1	0.0010125	0.0010125	2.79	0.1033
LD, MV	1	0.0028125	0.0028125	7.76	0.0085
LD, HV	1	0.0325125	0.0325125	89.69	0.0001
MD, LV	1	0.0018000	0.0018000	4.97	0.0322
MD, MV	1	0.0338000	0.0338000	93.24	0.0001
MD, HV	1	0.1431125	0.1431125	394.79	0.0001

LD - Low Density and MD - Medium Density
LV - Low Volume, MV - Medium Volume and HV - High Volume

Figure 5.3 Contrasts of Networkwide Delay Between the Two Designs

In other words, there is no significant evidence to conclude that TWLTL experiences lesser delay than NTM at low driveway density with low level of through volume on the arterial.

Reduction in networkwide delay if a TWLTL is used instead of an NTM was estimated using the general linear models procedure. These estimates are listed in Table 5.3 along with their 95 percent confidence intervals. These figures can be of immense help in economic evaluation of the two alternative designs.

Left-Turn Delay to Arterial Traffic

Estimates of average delay are listed in Table 5.4. In this case also, TWLTL design shows the potential for lesser delay than NTM design at all levels of other variables. Figure 5.4 illustrates the trend in variation of this delay component.

SAS output for analysis of main effects and interaction is presented in Fig 5.5. It may be concluded from the analysis that left turn delay is dependent on the level of roadside development (or driveway density), arterial traffic volume and the type of median (TWLTL or NTM). Also, it can be seen

Table 5.3 Estimated Reduction in Networkwide Delay for TWLTL over NTM Design

Driveway Density (driveways/ mile)	Volume (vph)	Difference* in Delay (min/veh-trip)	95% Confidence Interval	
			Lower	Upper
Low (32)	Low (600)	Not significant		
	Medium (900)	0.0375	0.0111	0.0639
	High (1200)	0.1275	0.1011	0.1539
Med/High (64)	Low (600)	0.0300	0.0036	0.0564
	Medium (900)	0.1300	0.1036	0.1564
	High (1200)	0.2675	0.2411	0.2939

*These reductions would be attained if a TWLTL is used instead of an NTM

Table 5.4 Delay to Left-Turning Vehicles (sec/veh)

Driveway Density	Arterial Traffic Volume Volume	Median Design	
		TWLTL	NTM
Low	Low	1.5600	1.7075
Low	Medium	1.7700	2.0250
Low	High	1.8025	2.0925
Medium	Low	3.0950	3.2725
Medium	Medium	3.2325	3.3300
Medium	High	3.2525	3.4375

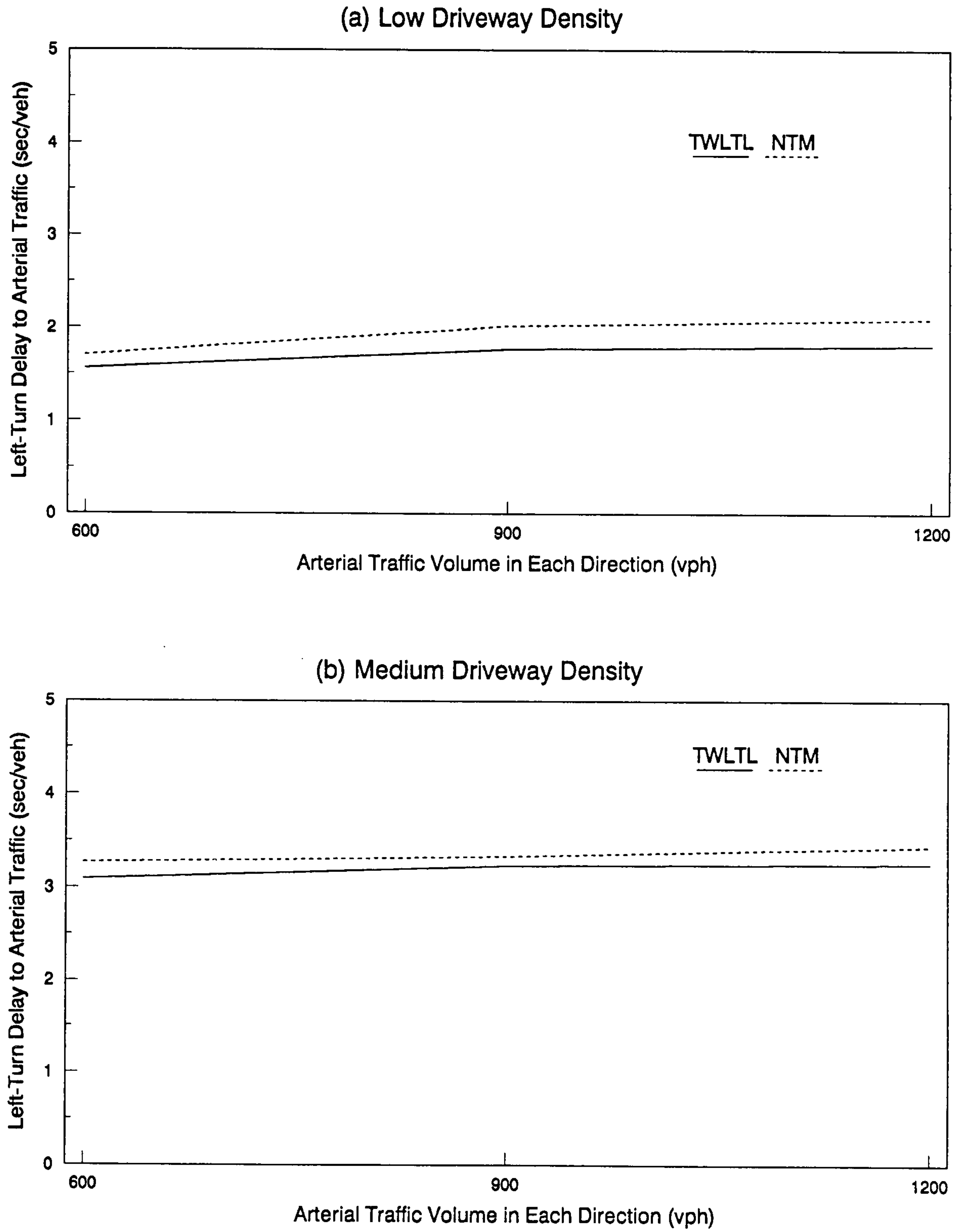


Figure 5.4 Delay for Left-Turning Traffic on Arterial

General Linear Models Procedure

Dependent Variable: LFTDLY

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	26.05631667	2.36875606	256.89	0.0001
Error	36	0.33195000	0.00922083		
Corrected Total	47	26.38826667			

R-Square	C.V.	Root MSE	LFTDLY Mean
0.987421	3.768156	0.0960252	2.5483333

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DENS	1	24.99853333	24.99853333	2711.09	0.0001
VOLUME	2	0.49405417	0.24702708	26.79	0.0001
MEDIAN	1	0.44467500	0.44467500	48.23	0.0001
DENS*VOLUME	2	0.06857917	0.03428958	3.72	0.0340
DENS*MEDIAN	1	0.01840833	0.01840833	2.00	0.1663
VOLUME*MEDIAN	2	0.01321250	0.00660625	0.72	0.4953
DENS*VOLUME*MEDIAN	2	0.01885417	0.00942708	1.02	0.3699

Figure 5.5 SAS Output for Analysis of Variance in Left-Turn Delay

from this output that, unlike the case of networkwide delay, there is no conclusive evidence to support the hypotheses that the following interactions are significant:

- interaction between driveway density and median design (prob[H_0 being true]=0.1663),
- interaction between traffic volume and median design (prob[H_0] = 0.4953), and
- three-way interaction among the three factors (prob[H_0] = 0.3699)

However, the interaction between driveway density and traffic volume on the arterial is significant.

Contrast analysis results on the difference in left-turn delay between the two designs within each factor level are shown in Fig 5.6. These results indicate that at low driveway density the differences are significant for all volume levels. However, at medium driveway density the differences were found to be significant only at the low volume level. There is no statistical evidence to conclude that the two designs significantly differ from each other in left-turn delay at the following two levels:

o medium driveway density with medium traffic volume on the arterial, and

o medium driveway density with high traffic volume on the arterial

General Linear Models Procedure

Dependent Variable: LFTDLY

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	26.05631667	2.36875606	256.89	0.0001
Error	36	0.33195000	0.00922083		
Corrected Total	47	26.38826667			

R-Square	C.V.	Root MSE	LFTDLY Mean
0.987421	3.768156	0.0960252	2.5483333

Source	DF	Type III SS	Mean Square	F Value	Pr > F
CELL	11	26.05631667	2.36875606	256.89	0.0001

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
LD, LV	1	0.04351250	0.04351250	4.72	0.0365
LD, MV	1	0.13005000	0.13005000	14.10	0.0006
LD, HV	1	0.17111250	0.17111250	18.56	0.0001
MD, LV	1	0.06301250	0.06301250	6.83	0.0130
MD, MV	1	0.01901250	0.01901250	2.06	0.1597
MD, HV	1	0.02332519	0.02332519	2.53	0.0934

LD - Low Density and MD - Medium Density
LV - Low Volume, MV - Medium Volume and HV - High Volume

Figure 5.6 Contrasts of Left-Turn Delay Between the Two Designs

In other words, delay reduction to left-turning traffic from the arterial by employing TWLTL design in preference to NTM design is not possible for cases with medium to high driveway density that carry moderate to high traffic volumes.

Delay to Through Traffic

Average delay to the through traffic on arterial is listed in Table 5.5. In this measure also, TWLTL cross-section appears to experience lesser delay than NTM cross-section at all levels. Figure 5.7 illustrates this trend.

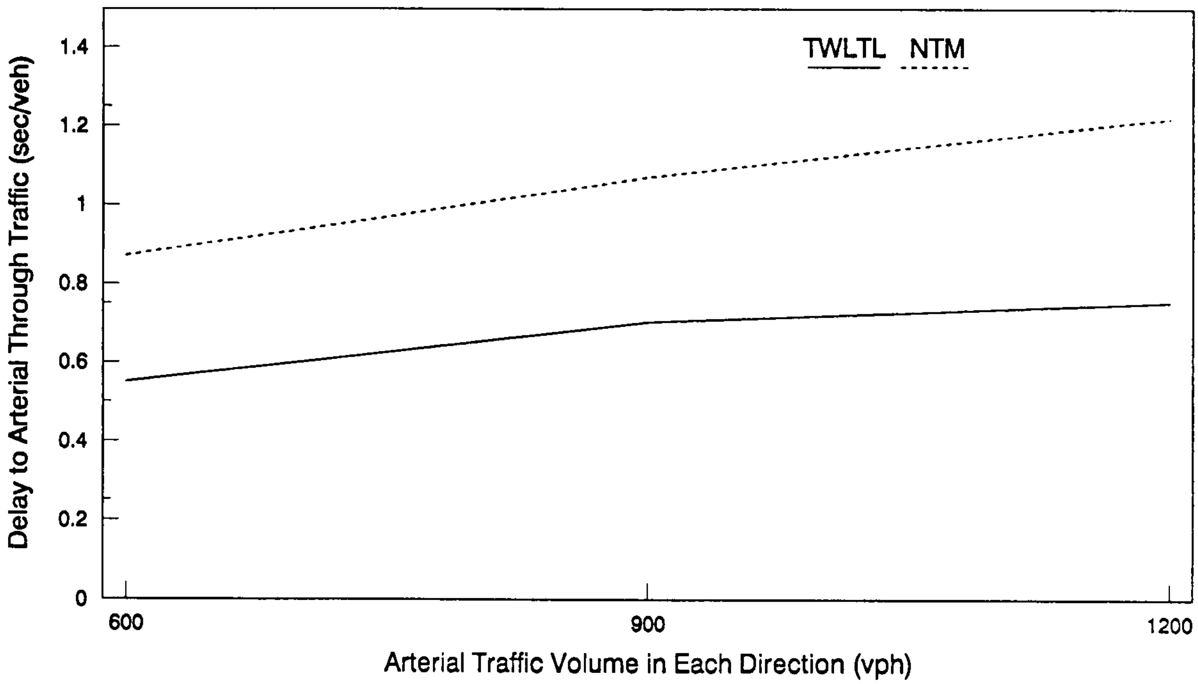
SAS general linear model output used for significance tests on main effects and interaction effects is shown in Figure 5.8. The results indicate that the delay to through traffic on arterial are dependent on the three variables individually as well as their pairwise interactions. In other words, the main effects and the mutual interaction are significant. However, there is not much evidence to conclude that three-way interaction among the factors exists.

Results of contrast analysis on the differences in delay to through traffic between the two designs are shown in Fig 5.9. These results indicate that the TWLTL experiences significantly lesser delay than NTM for all the driveway density and through traffic levels studied.

Table 5.5 Delay to Through Traffic (sec/veh)

Driveway Density	Arterial Traffic Volume Volume	Median Design TWLTL	NTM
Low	Low	0.5525	0.8725
Low	Medium	0.7025	1.0700
Low	High	0.7550	1.2200
Medium	Low	0.7400	0.9600
Medium	Medium	0.9875	1.1975
Medium	High	1.1500	1.4025

(a) Low Driveway Density



(b) Medium Driveway Density

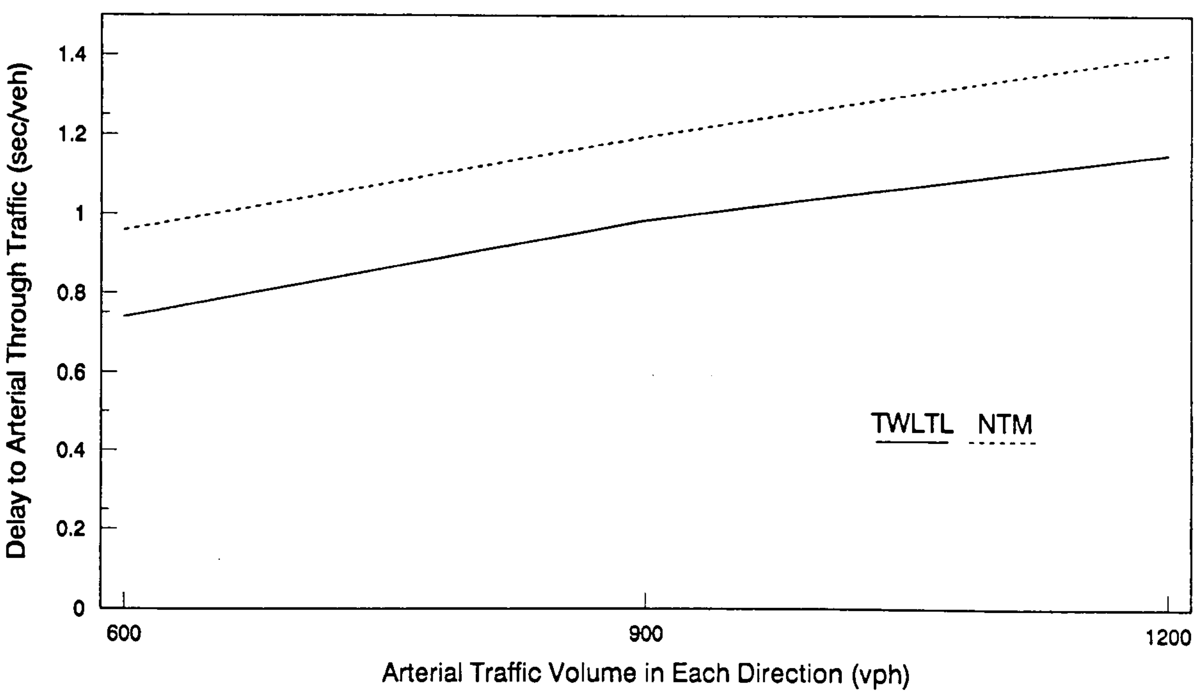


Figure 5.7 Delay for Through Traffic on Arterial

General Linear Models Procedure

Dependent Variable: THRDLY

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	2.79415000	0.25401364	203.44	0.0001
Error	36	0.04495000	0.00124861		
Corrected Total	47	2.83910000			

R-Square	C.V.	Root MSE	THRDLY Mean
0.984168	3.652268	0.0353357	0.9675000

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DENS	1	0.53340833	0.53340833	427.20	0.0001
VOLUME	2	0.99498750	0.49749375	398.44	0.0001
MEDIAN	1	1.12240833	1.12240833	898.93	0.0001
DENS*VOLUME	2	0.04587917	0.02293958	18.37	0.0001
VOLUME*MEDIAN	2	0.01750417	0.00875208	7.01	0.0027
DENS*MEDIAN	1	0.07363333	0.07363333	58.97	0.0001
DENS*VOLUME*MEDIAN	2	0.00632917	0.00316458	2.53	0.0934

Figure 5.8 SAS Output for Analysis of Variance in Delay to Through Traffic

General Linear Models Procedure

Dependent Variable: THRDLY

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	2.79415000	0.25401364	203.44	0.0001
Error	36	0.04495000	0.00124861		
Corrected Total	47	2.83910000			

R-Square	C.V.	Root MSE	THRDLY Mean
0.984168	3.652268	0.0353357	0.9675000

Source	DF	Type III SS	Mean Square	F Value	Pr > F
CELL	11	2.79415000	0.25401364	203.44	0.0001

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
LD, LV	1	0.20480000	0.20480000	164.02	0.0001
LD, MV	1	0.27011250	0.27011250	216.33	0.0001
LD, HV	1	0.43245000	0.43245000	346.34	0.0001
MD, LV	1	0.09680000	0.09680000	77.53	0.0001
MD, MV	1	0.08820000	0.08820000	70.64	0.0001
MD, HV	1	0.12751250	0.12751250	102.12	0.0001

LD - Low Density and MD - Medium Density
LV - Low Volume, MV - Medium Volume and HV - High Volume

Figure 5.9 Contrasts of Delay to Through Traffic Between the Two Designs

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Fuel Consumption

NETSIM recognizes different types of vehicles and their differences in fuel consumption. It also recognizes the influence of speed and delay on fuel consumption. However, for this study, a vehicle stream comprising of only automobiles was assumed. NETSIM estimates fuel consumption in gallons for the entire network during the simulation time period. These values were weighted with the corresponding vehicle miles of travel in the network to obtain more accurate unit of fuel consumption in gallons per 100 vehicle trips. Average fuel consumption estimates are given in Table 5.6. The figures indicate that overall fuel consumption on cross-sections with TWLTL is lesser than that of designs with NTM cross-sections. This trend is illustrated in Figure 5.10.

SAS output for the siginificance tests on the main effects and interaction effects is shown in Figure 5.11. These results indicate that the main effects, mutual interactions and three-way interactions are all significant at $\alpha = 0.05$.

Contrast analysis results on the differences in fuel consumption between TWLTL and NTM are shown in Figure 5.12. The results indicate that NTM designs are significantly higher in fuel consumption rate than TWLTL designs at all levels of study. Table 5.7 provides estimates of differences in fuel consumption levels between TWLTL and NTM at different driveway

Table 5.6 Average Fuel Consumption (gal/100 veh-miles) in the Network

Driveway Density	Arterial Traffic Volume	Median Design TWLTL	Median Design NTM
Low	Low	6.3938	7.1786
Low	Medium	6.9380	7.5148
Low	High	7.1796	8.0912
Medium	Low	7.1872	8.9487
Medium	Medium	7.9747	9.6782
Medium	High	8.0276	10.4814

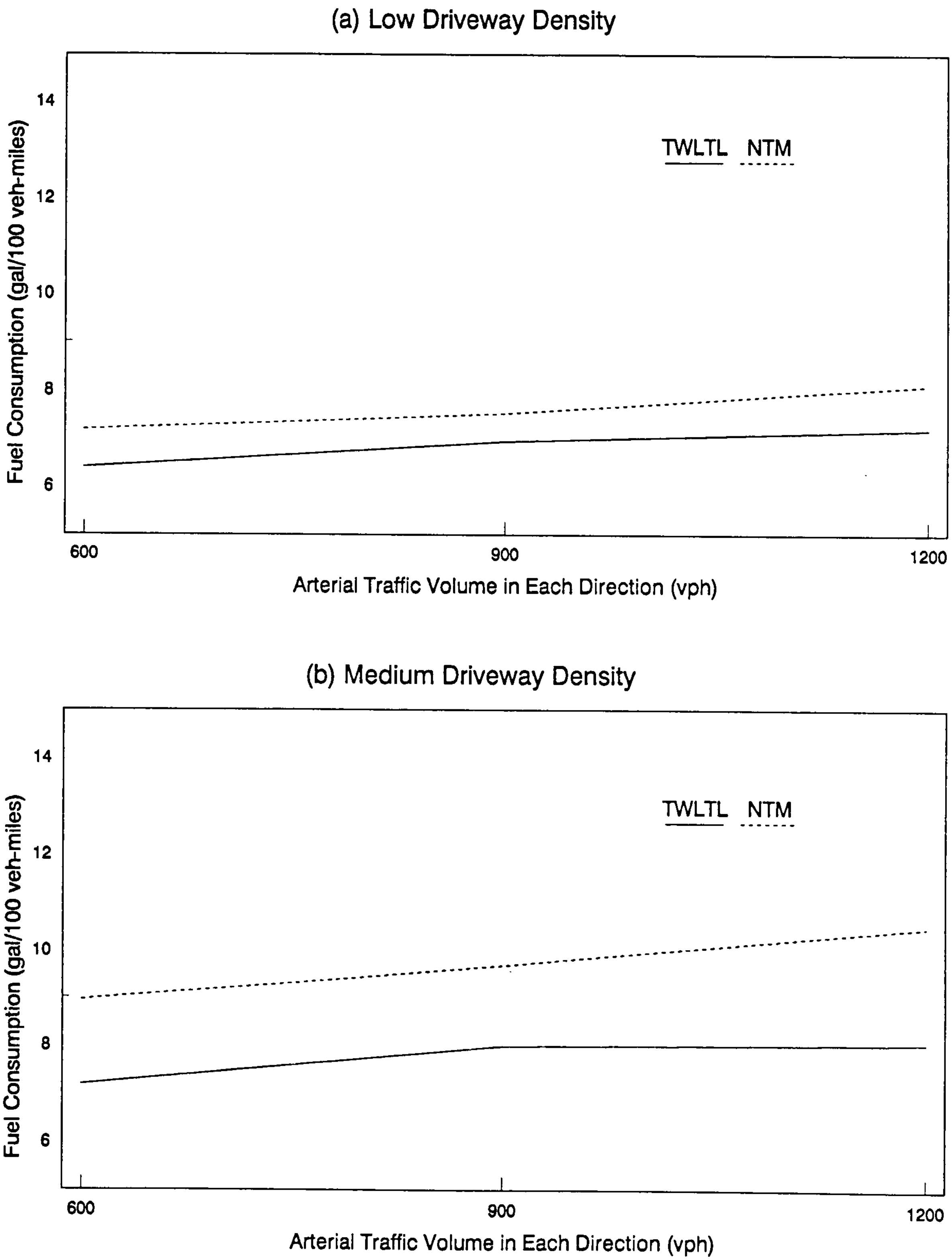

Figure 5.10 Fuel Consumption in the Network

General Linear Models Procedure

Dependent Variable: FUELCONS

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	63.284156	5.753105	1488.87	0.0001
Error	36	0.139107	0.003864		
Corrected Total	47	63.423263			

R-Square	C.V.	Root MSE	FUELCONS Mean
0.997807	0.780321	0.0622	7.9662

Source	DF	Type III SS	Mean Square	F Value	Pr > F
DENS	1	27.009115	27.009115	6989.78	0.0001
VOLUME	2	8.375595	4.187798	1083.77	0.0001
MEDIAN	1	22.370437	22.370437	5789.32	0.0001
DENS*VOLUME	2	0.287289	0.143644	37.17	0.0001
VOLUME*MEDIAN	2	0.639841	0.319920	82.79	0.0001
DENS*MEDIAN	1	4.430231	4.430231	1146.51	0.0001
DENS*VOLUME*MEDIAN	2	0.171648	0.085824	22.21	0.0001

Figure 5.11 SAS Output for Analysis of Variance in Fuel Consumption.

General Linear Models Procedure

Dependent Variable: FUELCONS

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	63.284156	5.753105	1488.87	0.0001
Error	36	0.139107	0.003864		
Corrected Total	47	63.423263			

R-Square	C.V.	Root MSE	FUELCONS Mean
0.997807	0.780321	0.0622	7.9662

Source	DF	Type III SS	Mean Square	F Value	Pr > F
CELL	11	63.284156	5.753105	1488.87	0.0001

Contrast	DF	Contrast SS	Mean Square	F Value	Pr > F
LD, LV	1	1.231817	1.231817	318.79	0.0001
LD, MV	1	0.665426	0.665426	172.21	0.0001
LD, HV	1	1.662188	1.662188	430.16	0.0001
MD, LV	1	6.206017	6.206017	1606.08	0.0001
MD, MV	1	5.803740	5.803740	1501.97	0.0001
MD, HV	1	12.042970	12.042970	3116.64	0.0001

LD - Low Density and MD - Medium Density
LV - Low Volume, MV - Medium Volume and HV - High Volume

Figure 5.12 Contrast Analysis For Difference in Fuel Consumption Between the Two Designs

Table 5.7 Estimated Reduction in Fuel Consumption for TWLTL over NTM Design

Driveway Density (driveways/ mile)	Volume (vph)	Difference in Fuel Consumption (gal/100 veh miles)	95% Confidence Interval	
			Lower	Upper
Low (32)	Low (600)	0.7848	0.6986	0.8709
	Medium (900)	0.5768	0.4906	0.6629
	High (1200)	0.9116	0.8254	0.9977
Med/High (64)	Low (600)	1.7615	1.6753	1.8476
	Medium (900)	1.7035	1.6173	1.7896
	High (1200)	2.4538	2.3676	2.5399

density and through volume levels. This table can have a practical use in estimating the changes in vehicle operating costs that occur if one design has to renovated as the other.

Summary of Statistical Tests

Tables 5.8 summarizes the probabilities of the null hypotheses, H_0, being true (prob[H_0]) resulted from the tests of significance on main effects and interaction effects. Table 5.9 summarizes the probabilities of the differences in the performance variables between the TWLTL and NTM not being significant. As mentioned earlier, a null hypothesis was rejected in favor of the alternative hypothesis if prob[H_0] is less than the specified α (5 percent or 0.05). It may be noted that lesser the value of prob[H_0], stonger the support in favour of the alternative hypothesis. For example, a prob[H_0] of 0.0001 for the H_0 that the effect of driveway density on networkwide delay is not significant indicates that the altenative hypothesis H_1 (that driveway density significantly influences the delay) is highly significant. In such situations, stating that H_1 is significant at $\alpha = 0.05$ is an understatement of the strong evidence in favor of H_1. However, a 5 percent significant level was used as a bench mark for acceptance criteria and the reader is advised to be aware of this phenomenon.

Table 5.8 Summary of Statistical Tests for Main Effects and Interaction Effects (the figures indicate probablity of H_0 being true)

Variable	Dependent Variable			
	Network Delay	Left-Turn Delay	Through Delay	Fuel Consumption
<u>Main Effects</u>				
Drv. Dens.	0.0001	0.0001	0.0001	0.0001
Volume	0.0001	0.0001	0.0001	0.0001
Median	0.0001	0.0001	0.0001	0.0001
<u>Interactions</u>				
Dens-Volume	0.0013	0.0340	0.0001	0.0001
Vol-Median	0.0001	0.1663*	0.0027	0.0001
Dens-Median	0.0001	0.4953*	0.0001	0.0001
Density-Volume-Median	0.0001	0.3699*	0.0934*	0.0001

'*' Indicates that the effect is <u>not</u> significant at $\alpha = 0.05$

Table 5.9 Summary of Contrast Tests on the Difference Between TWLTL and NTM (the figures indicate probablity of H_0 being true)

Driveway Density	Volume Level	Dependent Variable			
		Network Delay	Left-Turn Delay	Through Delay	Fuel Consumption
Low	Low	0.1033*	0.0365	0.0001	0.0001
Low	Medium	0.0085	0.0006	0.0001	0.0001
Low	High	0.0001	0.0001	0.0001	0.0001
Medium	Low	0.0322	0.0130	0.0001	0.0001
Medium	Medium	0.0001	0.1591*	0.0001	0.0001
Medium	High	0.0001	0.0934*	0.0001	0.0001

'*' Indicates that the difference is <u>not</u> significant at $\alpha = 0.05$

Computation of Operational Benefits of TWLTL Design Over NTM

The purpose of this section is to demonstrate the use of the estimated operational differences between TWLTL and NTM listed in Tables 5.3 and 5.7. The application assumes a proposal for replacing an existing TWLTL cross-section with an NTM. However, no attempt was made to compute the differences in safety related costs between the two designs. The reader is cautioned that the values obtained from the calculations shown below can only help in estimating the operational benefits of TWLTL over NTM and this is not a complete cost-benefit analysis.

Data and Assumptions

Medium Driveway Density

Arterial Volume (ADT) - 24,000

Peak Hour Factor = 0.10

Directional Split = 50% -50%

Section Length = 0.5 miles

Average Off-Peak Hour Volume = 600 vph

Savings in Delay with TWLTL Design Using Table 5.3

Peak-Hour (High Volume) = 0.2675 min/veh

= 0.2675 x 2 (peaks) x 2 (directions) x 1200

= 1284 min/day or 21.4 hrs/day

Off-Peak Hour (Low Volume) = 0.03 min/veh

= 0.03 x 19,200 (vehicles)

= 576 min/day or 9.6 hrs/day

Total = 31 hrs/day or 9,300 hrs/year*

Savings in Fuel Consumption with TWLTL Design Using Table 5.7

Peak-Hour (High Volume) = 2.4538 gal/100 v-miles

= 2.4538/100 x 2 (peaks) x 2 (directions) x 0.5 (miles) x 1200

= 58.8 gal/day

Off-Peak (Low Volume) = 1.7615 gal/100 v-miles

= 1.7615/100 x 0.5 (miles) x 19,200 (volume)

= 169.1 gal/day

Total = 227.9 gal/day or 68,370 gal/year*

* based on 300 working days/year

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The study attempted to identify the differences in the operational characteristics of two alternative roadway designs, viz., continuous two-way left turn lanes and discontinuous non-traversable medians, by using a simulation technique. Important findings of the study are summarized below.

Figure 6.1 summarizes the results of tests of significance for the effects of driveway density, traffic volume and median design as well as their pairwise and threeway interactions on the delay and fuel consumption. Driveway density, traffic volume and median design have significant influence on networkwide delay, delay to left-turning traffic and through traffic on the arterial, and fuel consumption in the road network. For left-turn delay, there is no convincing evidence in support of significant pairwise and threeway interaction effects of median design with driveway density and traffic volume. For delay to through traffic on the arterial, the pairwise interactions were found to be significant and there is not much evidence in support of the existence of a three-way interaction. For networkwide delay and fuel consumption, the pairwise and three-way interactions were found to be significant.

Variable	Dependent Variable			
	Network Delay	Left-Turn Delay	Through Delay	Fuel Consumption
<u>Main Effects</u>				
Drv. Dens.	*	*	*	*
Volume	*	*	*	*
Median	*	*	*	*
<u>Interactions</u>				
Dens-Volume	*	*	*	*
Volume-Median	*	NS	*	*
Dens-Median	*	NS	*	*
Density-Volume-Median	*	NS	NS	*

Note: '*' Indicates that the effect is significant and 'NS' indicates that the effect is <u>not</u> significant at $\alpha = 0.05$

Figure 6.1 Summary of Analysis for Main Effects and Interaction Effects Analysis

Figure 6.2 summerizes the results of contrast analyses between TWLTL and NTM median designs. Average networkwide delay for NTM cross-sections is observed to be consistently more than that for TWLTL cross-sections. The difference is greater at higher levels of driveway density and through volumes. However, the difference is found to be statistically significant at all levels.

Delay to left-turning traffic on the arterial is less for TWLTL than NTM design at low driveway density with low, medium and high traffic volumes, and at medium driveway density with low traffic volume. However, the potential for delay reduction to left-turning traffic by employing TWLTL design in preference to NTM design is not significant for cases with medium to high driveway density that carry moderate to high traffic volumes.

Through traffic on the arterial is also observed to have more delay with NTM design than TWLTL design even though the logic in coding the network assigned an un-interrupted right-of-way to this traffic. This can be attributed to the fact that there are more vehicle miles of travel in NTM design than in the case of TWLTL because of the added travel due to U-turns.

Average fuel consumption for NTM cross-sections is also observed to be consistently more than that for TWLTL cross-sections. The difference is found to be statistically significant at all levels.

Driveway Density	Volume Level	Dependent Variable			
		Network Delay	Left-Turn Delay	Through Delay	Fuel Consumption
Low	Low	NS	*	*	*
Low	Medium	*	*	*	*
Low	High	*	*	*	*
Medium	Low	*	*	*	*
Medium	Medium	*	NS	*	*
Medium	High	*	NS	*	*

Note: 1. '*' Indicates that the difference is significant and 'NS' indicates that the difference is <u>not</u> significant at $\alpha = 0.05$

2. Significance in differences suggest that the two designs perform significantly different from each other at the indicated level.

Figure 6.2 Summary of Significant Differences in Performance Measures of TWLTL and NTM

It is recommended that tables 5.3 and 5.7 be used for estimating additional delay and excess fuel consumption for arterials with NTM design over arterials with TWLTL designs. These estimated differences would be useful for cost-benefit analysis, should there be a need for such analysis to choose between the two designs. An example application of these tables is given in chapter 5.

It is to be emphasized that this study does not conclude that TWLTL designs are better than NTM designs in all respects. Other important criteria such as accident experience should also be studied in depth before a complete evaluation be made. The user should be cautious in applying the results because of the theoretical nature of the study with little or no field data inputs.

Scope for Further Research

The study used constant values for several input parameters such as spacing of median openings, left-turn demand, and posted speed limit on the arterial in order to keep the number of cases within a manageable limit. The values for most of these parameters vary in practice. Further research can focuss on studying the operational differences between the two designs by varying speed, left-turn demand and spacing of median openings in the NTM case along with varying driveway density and traffic volumes.

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