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TEXAS TRANSPORTATION INSTITUTE

# FACTORS AFFECTING TRAFFIC OPERATIONS ON SEVEN-LANE CROSS SECTIONS

## RESEARCH REPORT 1293-2F

COOPERATIVE RESEARCH PROGRAM

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the
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Texas Department of Transportation

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16. Abstract

Previous research has documented the operational and safety benefits of installing a TWLTLs on two-lane and four-lane arterials. Unfortunately, very little research has been performed to quantify the effects of seven-lane cross sections on traffic operations and safety. The goal of this research was to provide information on the factors that affect traffic operations on seven-lane cross sections in urban and suburban areas.

Field studies were conducted to evaluate the affects of these factors. Acceleration noise, a measure of the relative smoothness of a trip, was used to assess the impacts of these factors on operations. Acceleration noise was collected in each lane in both directions during four periods (A.M. Peak, Off-peak, Noon, and P.M. Peak) at nine sites throughout Texas with different roadway and roadside development characteristics.

From the studies, it was found that the quality of flow on seven-lane cross sections is impacted by such roadway and roadside development factors as the density of the driveways located on each side of the roadway, the average daily traffic carried by a roadway, and the average number of unsignalized intersection approaches along each side of the roadway. Generally, as the density of driveways and the amount of traffic carried on a roadway increase, the ability of the driver to maintain a trip with few changes in speed decreases. Therefore, designers should carefully consider not just the overall type of development and traffic demands on a roadway, but also the specific type of roadway and roadside development characteristics on *each side of the roadway* when considering implementing seven-lane cross sections in urban and suburban arterials.

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# FACTORS AFFECTING TRAFFIC OPERATIONS ON SEVEN-LANE CROSS SECTIONS

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# IMPLEMENTATION STATEMENT

This research is intended to provide transportation designers with insight into the factors that influence the operations and safety of seven-lane cross sections on urban and suburban arterials. The findings are intended to provide design and operations engineers with general direction and insight on the use of seven-lane cross sections in these areas. The findings of the research suggest that driveway density, average daily traffic, and number of unsignalized intersection approaches in each direction of the roadway be considered when evaluating whether to install a seven-lane cross section. Additional research is still needed to identify specific threshold where seven-lane cross sections no longer function as intended.

# DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT), or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineers in charge of the project were Kevin N. Balke, P.E. #66529, and Kay Fitzpatrick, P.E. # PA-037730-E.

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# SUMMARY

Previous research has documented the operational and safety benefits of installing is impacted by such roadway and roadside development factors as the density of driveways located on each side of the roadway, the average daily traffic carried by a roadway, and the average number of unsignalized intersection approaches along each side of the roadway. Generally, as the density of driveways and the amount of traffic carried on a roadway increase, the ability of the driver to maintain a "smooth" trip (i.e., one with few changes in speed) decreases. Therefore, designers should carefully evaluate not just the overall type of development and traffic demands on a roadway, but also the specific type of roadway and roadside development characteristics *on each side of the roadway* when considering whether to implement seven-lane cross sections on urban or suburban arterials.

# 1. INTRODUCTION

The need to provide greater mobility in urban areas has led to the consideration of a network of high-mobility arterials that would operate at a level between that of existing principal arterials and freeways (1). These arterials would provide greater capacity and operating speeds than current principal arterials; however, they would not have the same degree of access control or right-of-way requirements as freeways. Methods of improving mobility on these arterials include strict control of access, restrictions and prohibitions of turning movements, and installation of raised (or depressed) median islands or barriers.

However, access control, turn prohibitions and restrictions, and medians are often highly sensitive issues with the public. Access remains an important concern for those who own properties adjacent to many higher functional class roadways. Property owners often cite reduced property values and potential loss of business as reasons for opposing restrictions on left-turn access. Without strong supporting evidence documenting an improvement in operations or safety, implementing stricter access controls on an arterial can be politically difficult. Once a level of access on a facility has been established, it can become difficult to implement a different type of median improvement that would restrict left turns and medial access.

Since the type of median used in the design of urban and suburban roadway improvements can often become a sensitive issue, existing and future traffic volumes and development activities must be carefully evaluated prior to implementing a median treatment. The long-term implications and desirability of using a particular median treatment must be considered prior to installation. In order to insure that appropriate decisions are made, quantitative measure of the impacts of various median treatments on traffic flow and safety are needed.

This report focuses on the applications of a particular type of cross section commonly used in many urban areas in Texas and the United States: the seven-lane cross section. A seven-lane roadway has three lanes in each direction separated by a two-way, left-turn lane. The intent of this research is to provide quantitative information on the factors that affect operations and safety on seven-lane cross sections in urban and suburban areas.

## BACKGROUND AND PROBLEM STATEMENT

The median area is defined by the American Association of State Highway and Transportation Officials (AASHTO) as that "portion of divided highway separating the traveled way for traffic in opposing directions." (2) Medians serve a number of functions on urban and suburban highways, including the following:

- limiting the amount of interference of opposing traffic,
- providing a recovery area for out-of-control vehicles,
- providing a stopping area in case of emergencies,
- providing for speed changes and storage of left-turning and U-turning vehicles,
- minimizing headlight glare, and
- preserving right-of-way for future roadway expansion.

An additional benefit of medians in urban areas is that they provide an area for landscaping and sign placement (as long as they are of sufficient width).

The two most commonly used median treatments on urban and suburban arterials are two-way, left-turn lanes (TWLTLs) and median islands. TWLTLs are typically employed in areas of moderate or intense roadside development where the demand for mid-block left turns is currently (or expected to be) high. With a TWLTL, left-turn access can be provided at any point along the roadway. For this reason, they are typically used on arterials where there are frequent and randomly organized access points. On the other hand, raised medians present a physical barrier to drivers and, as such, cannot be easily traversed. For this reason, raised medians are often used where it is desirable to prevent mid-block left turns. On roadways with raised medians, left-turn maneuvers are concentrated at established openings in the median or at signalized intersections.

Both of these types of median treatments have advantages and disadvantages in terms of operations and safety. The primary advantage of a raised median is that left-turning traffic can be concentrated at established median openings. This makes it easier to regulate crossing traffic. In addition, raised medians can be used to provide a refuge area for pedestrians crossing the roadway.

The primary disadvantage of a raised median, however, is that it often increases the amount of travel time and delay experienced by some left-turning traffic. Because a raised median forces left-turns to occur at established openings only, some left-turning motorists must travel circuitous routes to reach their destination. This can often lead to undesirable turning movements (e.g., U-turns on roadways of insufficient width) and unwanted travel patterns (e.g., traffic entering neighborhood areas). In addition, the raised median island can pose a potential safety hazard on streets serving high-speed traffic. If accidentally struck, a raised median could cause the driver to lose control of the vehicle. Furthermore, a raised median (particularly a narrow island) may be difficult to see at night unless a fixed lighting source is provided (2).

The main advantage of a TWLTL is that it provides a storage area for left-turning vehicles as they wait for gaps in the opposing traffic stream. This not only improves the operations of through traffic by removing the left-turning vehicle from the traffic stream, but also reduces the potential for rear-end accidents. Since turning traffic is not physically restricted in any way with TWLTLs, drivers can take more direct routes when entering and exiting adjacent properties. For this reason, drivers and adjacent property owners generally prefer TWLTLs over raised medians (2).

Previous research has documented the operational and safety benefits of installing TWLTL on two-lane and four-lane roadways that were previously undivided. Unfortunately, very little research has been performed to quantify the effects of seven-lane cross sections on traffic operations and safety. This research attempts to provide insight to some of the issues surrounding the use of seven-lane cross sections on urban and suburban arterials.

## STUDY OBJECTIVES

The overall goal of this research was to provide information on the factors that influence the operations of traffic traveling on seven-lane cross sections. Safety was not examined in this study because previous studies have documented the safety benefits to be achieved by installing TWLTLs on urban and suburban arterials. The specific objectives of this research study were as follows:

- based on the existing literature, identify the factors that potentially affect the operations and safety of traffic on seven-lane cross sections in Texas,

- conduct field studies to quantify the extent to which the identified factors affected traffic operations, and
- provide general guidelines and insight into situations where seven-lane cross sections can be expected to function safely and efficiently.

## STUDY APPROACH

The general approach of the research was to combine the findings from the literature with data collected from field studies to provide insight into situations where seven-lane cross sections could be expected to operate safely and efficiently. We first performed a critical review of the literature related to the design and evaluation of TWLTLs on three-lane and five-lane cross sections. From this review, we developed a set of critical factors that could potentially affect the operations of seven-lane cross sections. We then conducted field studies to assess how these factors influenced traffic operations on select seven-lane cross sections throughout the State of Texas. Using the results of the literature review and the operational studies, we attempted to develop general guidelines and recommendations on the use of seven-lane cross sections.

It should be noted that the purpose of this research effort was to collect quantitative data on the factors that influence traffic operations on seven-lane cross sections that could be used to assess the desirability and practicality of using seven-lane cross sections in specific situations. This study was not intended to compare the performance of five-lane, six-lane divided, and seven-lane cross sections.

## ORGANIZATION OF REPORT

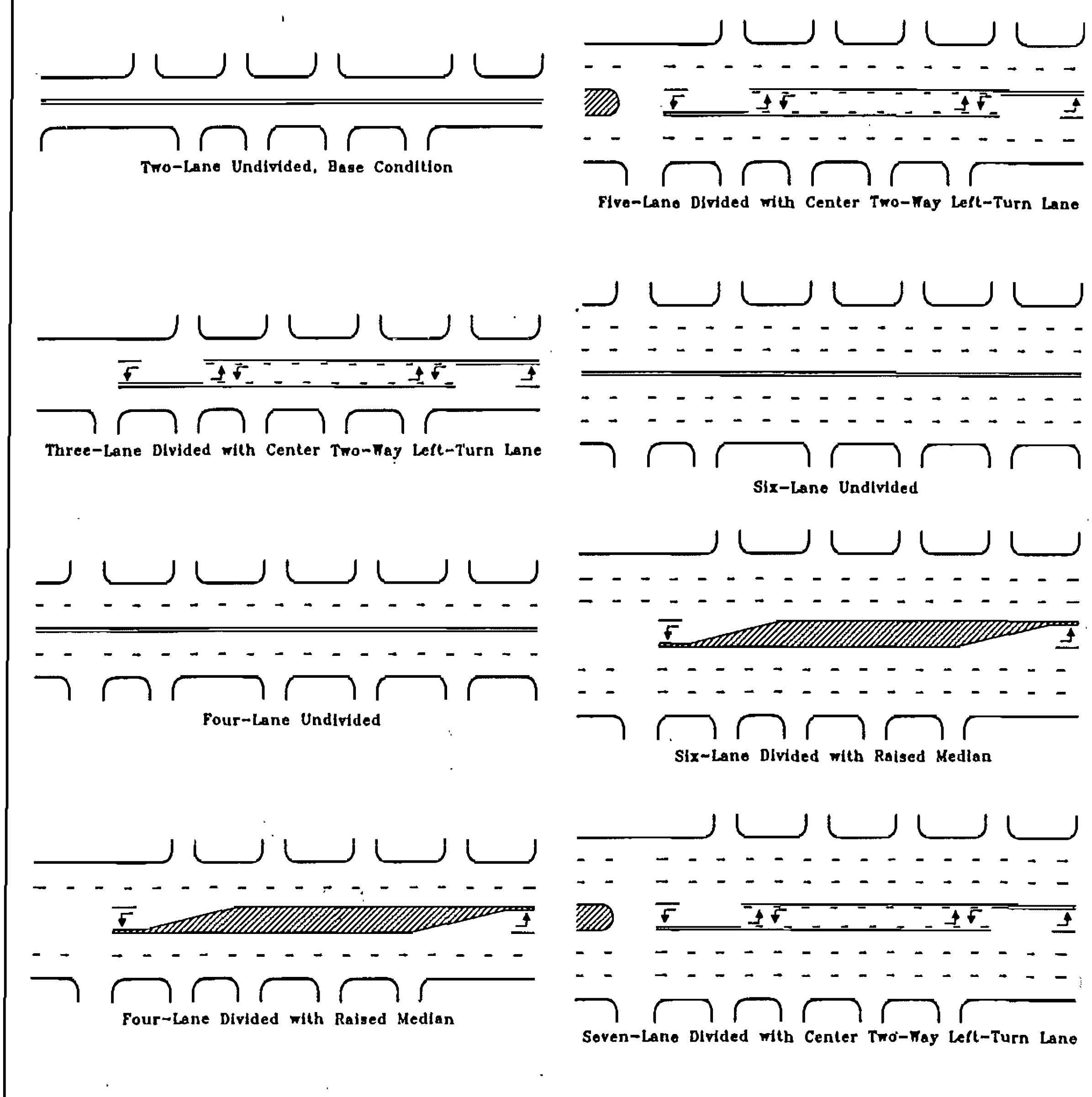
The main body of this report is contained in four additional chapters. Chapter 2 provides a summary of the literature pertaining to the design and operations of TWLTLs and other median treatments on urban and suburban arterials. As part of this chapter, we identify the factors that are believed to affect traffic operations and safety of seven-lane cross sections. A discussion of the methodology used to examine how the factors potentially affect the operations of seven-lane cross sections is provided in Chapter 3. Chapter 4 presents the findings of the field studies and discusses their implications. In the final chapter, Chapter 5, a summary of the findings of the research as well as general guidelines and recommendations on the use of seven-lane cross sections on urban and suburban arterials are provided.

# 2. LITERATURE REVIEW

Commercial development along a roadway often spurs an increase in driveway density. Without a left-turn median treatment, the turning maneuvers of motorists can cause adverse effects on the safety and operational characteristics of the roadway. On an undivided roadway, vehicles wait in a through lane to turn left until an acceptable gap is available through which to complete the left-turning maneuver. This action can cause significant delay to the other through vehicles, as well as, increase the chances of rear-end collisions. In addition, some motorists accept a smaller gap in opposing traffic through which to turn left that they would not have normally taken because of pressure from other vehicles backed up behind them. As a result, left-turning median treatments at mid-blocks have become an attractive alternative. Left-turning median treatments offer refuge for turning vehicles. In turn, this increases the running speeds of through vehicles, decreases delay, decreases the potential for rear-end accidents, and allows motorists to accept more comfortable gaps.

Several types of left-turning median treatments exist on arterial streets as illustrated in Figure 2-1. The two-lane undivided roadway represents, perhaps, the most adverse effects on safety and operational characteristics. Vehicles stopped in the through lane waiting to turn left can cause all other through vehicles to wait (when shoulders are not available). Supplying a raised median with turn bays concentrates left-turning maneuvers at selected locations. Some driveways will not have direct access for opposing traffic, and left-turning motorists will have to travel a more circuitous route before entering the desired driveway. A two-way left-turn lane (TWLTL), however, offers the advantages of potential decreases in delay and rear-end accidents, increases in running speeds, and provides a refuge area for the left-turning vehicles in addition to offering direct access to all driveways along the roadway, not just a select few.

Extensive literature can be found regarding the safety advantages of TWLTLs on all types of roadways. In general, it has been documented that TWLTLs can reduce accident rates, particularly rear-end accidents. However, the operational characteristics of TWLTLs have not received as much attention in the literature, particularly in-field studies. To date, most of the operational studies have been computer simulation studies designed to determine the reduction in delay offered by TWLTLs and the cost effectiveness of TWLTLs.



Two-Lane Undivided, Base Condition

Three-Lane Divided with Center Two-Way Left-Turn Lane

Four-Lane Undivided

Four-Lane Divided with Raised Median

Five-Lane Divided with Center Two-Way Left-Turn Lane

Six-Lane Undivided

Six-Lane Divided with Raised Median

Seven-Lane Divided with Center Two-Way Left-Turn Lane

Figure 2-1. Commonly Used Median Treatments (3).

The following literature review specifically addresses the safety, operations, and cost effectiveness of the TWLTL median treatment. Research approaches have included before-and-after studies, accident analyses, comparative studies, and computer simulation.

## SAFETY

A variety of studies have addressed the safety performance of TWLTLs. These studies can generally be classified as before-and-after studies and comparative studies. Before-and-after studies typically review the number or types of accidents that occurred prior to the installation of TWLTLs and after its installation. Comparative studies use accident information on sites with similar characteristics but with differing median treatments. The difference in number of accidents or the accident rate is compared for the different treatments. Regression analysis is frequently used to determine an equation that will generate accident rates for comparison. These equations are also used to calculate accident rates for different scenarios, such as number of driveways or signal spacing.

### Before-and-After Studies

Harwood in the 1990 NCHRP 330 Report (4) investigated the safety performance of TWLTLs and raised medians using before-and-after evaluations. Emphasis was placed on improvement of highway sections *without increasing the overall width of the roadway*. The results of the analysis indicated no change in the severity of accidents for all conversions investigated. Harwood concluded that conversions of four-lane roads that involve lane width reductions and installation of TWLTLs will reduce both total (44.1 to 52.6 percent) and mid-block (45.0 to 56.6 percent) accident rates.

Harwood's data revealed that the conversion of a five-lane road to a seven-lane road will increase total accidents by 23.7 percent and mid-block accidents by 31.3 percent. Harwood concluded that these higher accident rates are more prevalent on roadways having higher speed limits. The accident data collected on highways where the cross section changed from a six-lane narrow median to a seven-lane TWLTL revealed that total accident rates were reduced by 24.0 percent and mid-block accident rates were reduced by 32.1 percent after the seven-lane cross section was installed.

The study also compiled a distribution of percent changes in accident rates of specific accident types experienced on certain types of median conversion projects (see Table 2-1). Most accident types (angle, sideswipe, and rear-end) were reduced when a TWLTL was installed on four-lane undivided roads. However, an increase in angle and sideswipe mid-block accidents was experienced when a four-lane divided roadway with a narrow median was converted to a five-lane roadway with a TWLTL. Almost all accident types (angle, sideswipe, and rear-end) were increased when a five-lane TWLTL section was converted to a seven-lane section, except for rear-end intersection accidents. A decrease in all accident types was experienced when a six-lane divided roadway with a narrow median was converted to a seven-lane roadway with a TWLTL, except angle mid-block accidents.

**Table 2-1. Percent Change in Specific Accident Types on Four-Lane Roads (4).**

| Median Improvement | Mid-block Accidents | | | Intersection Accidents | | |
|---|---|---|---|---|---|---|
| | Angle | Sideswipe[*] | Rear-end | Angle | Sideswipe[*] | Rear-end |
| Four-lane undivided → five-lane w/TWLTL | -33 | -38 | -60 | 0 | -53 | -68 |
| Four-lane divided w/narrow median → five-lane w/TWLTL | +20 | +120 | -40 | -23 | -52 | -80 |
| Five-lane w/TWLTL → seven-lane w/TWLTL | +15 | +180 | +11 | +65 | +77 | -65 |
| Six-lane divided w/narrow median → seven-lane w/TWLTL | +37 | -28 | -51 | -5 | -17 | -37 |

[*] Sideswipe accidents consist of same-direction accidents only.

In summary, the research found that projects where narrower lanes are used to provide space for installation of a TWLTL generally reduce accidents by 24 to 53 percent. Projects where narrower lanes were installed to provide additional through traffic lanes on an arterial street generally did not affect mid-block accident rates, but did increase accident rates at intersections. None of the projects involving narrower lanes had any effect on the accident severity distribution. The author concluded that lane widths as narrow as 10 feet (3 m) can be used effectively without increasing accident rates and that lane widths as narrow as 9 feet (2.7 m) can be used without increasing accident rates if the project involves the installation of a TWLTL that would not otherwise be feasible. The author also stated that such narrow lanes are not desirable, but can be used where necessary without compromising safety.

In a study conducted in 1984, Thakkar (5) examined accident reports two years prior to the installation of a TWLTL and two years after the installation. Sixteen two-lane and 15 four-lane sections, each a minimum of 0.25 miles (0.4 km) in length, were investigated. Average daily traffic (ADT) on the two-lane roads was between 4,200 and 21,300 vehicles per day (vpd) and the four-lane roads had ADTs in the range of 10,600 to 25,000 vpd. After a statistical analysis, it was found that both the severity (all accidents) and affected severity (rear-end, left-turn, and sideswipe accidents) were significantly reduced after the TWLTL was installed. However, the severity of unaffected accidents (total minus affected) was not significantly reduced. In addition to investigating the severity of accidents at TWLTLs, Thakkar examined total accident rates and total affected accident rates (rear-end, left-turn, and sideswipe) at TWLTLs. Analysis indicated that both the total accident rate and total affected accident rate was significantly reduced after the installation of a TWLTL.

An early 1970s Arizona study (6) also used before-and-after data to evaluate how the installation of a TWLTL would influence accident occurrences. Seven TWLTL sites totaling 12.2 miles (19.6 m) were investigated for a two-year before and after period. The study revealed that an overall 35.9 percent reduction in accidents was experienced at the seven sites. The study also investigated changes in accident rates for specific accident types. As listed in Table 2-2, the study revealed a number of accident rates for several accident types. The reduction in angle and pedestrian/bicyclist accidents was attributed to the fact that parking was prohibited along most of the sites investigated to gain roadway width. In addition, the reduction in side-swipe, same-direction accidents was attributed to the fact that drivers may feel more comfortable with a "buffer" zone (TWLTL) between them and the opposing traffic. Rates increased for two types of accidents only, namely backing accidents, and run-off road accidents. The increase in backing accidents was attributed to driver error, and the increase in run-off road accidents was attributed to the fact that, in most cases, lane widths were narrowed, forcing drivers to drive closer to the edge of the pavement, and increasing the chance to leave the road.

**Table 2-2. Percent Change in Accident Occurrence by Accident Type (6).**

| Accident Type | Percent Change in Accidents | Accident Type | Percent Change in Accidents |
|---|---|---|---|
| Rear-end | -45 | Parking | -79 |
| Left-turn | -20 | Angle | -40 |
| Head-on | -67 | Pedestrian/ Bicyclist | -30 |
| Sideswipe, opp. direction | -100 | Fixed object | -65 |
| Sideswipe, same direction | -52 | Run-off road | +86 |
| | | Backing | +125 |

### Comparative Studies

In NCHRP 282 (3), data were compiled from existing literature and from a five-year accident history on 469 miles (755 km) of suburban highway in California and Michigan. A distribution of accidents involving a fatality or injury was developed for different median design alternatives for non-intersection accidents and unsignalized intersection accidents. The results, shown in Table 2-3, illustrate a lower number of fatality and injury accidents at unsignalized intersections and at mid-blocks for a three-lane section with a TWLTL in a commercial area than at two-lane undivided sections. The data showed no change in accident severity in residential areas. On four-lane roads, TWLTL sections generally experienced fewer numbers of fatal and injury accidents.

**Table 2-3. Accident Severity on Two-Lane and Four-Lane Arterials (3).**

| Design Alternative | Percent of Accidents Involving a Fatality or Injury | | | |
|---|---|---|---|---|
| | Non-Intersection Accidents | | Unsignalized Intersection Accidents | |
| | Commercial | Residential | Commercial | Residential |
| Two-Lane Suburban Arterial Highways | | | | |
| Undivided | 38.4 | 43.6 | 39.0 | 32.9 |
| TWLTL | 29.9 | 43.6 | 32.1 | 32.9 |
| Four-lane Suburban Arterial Highways | | | | |
| Undivided | 38.4 | 38.8 | 32.1 | 32.9 |
| Divided | 33.7 | 43.6 | 26.9 | 45.1 |
| TWLTL | 33.7 | 38.8 | 32.1 | 26.6 |

The study also used the five-year accident data to develop a distribution of the percentage of accidents commonly reduced by the installation of a TWLTL. These accidents include head-on, rear-end, and angle accidents. Harwood concluded that 45.0 and 49.4 percent of the non-intersection accidents on two-lane roads within commercial and residential areas, respectively, could be corrected by installing a TWLTL. Likewise, unsignalized intersection accidents in commercial and residential areas are susceptible to a 65.2 and 56.7 percent reduction, respectively, when a TWLTL is installed. Harwood also concluded that 50.5 and 60.0 percent of the head-on, rear-end, and angle accidents on four-lane roads within commercial and residential areas, respectively, could be corrected. Likewise, a 44.6 and 55.0 percent reduction in unsignalized intersection accidents in commercial and residential areas, respectively, are susceptible to correction, when a TWLTL is installed.

The California and Michigan accident data on suburban highways were also used to develop estimates of accident rates on suburban highways with several different median treatments. Nine different independent variables were considered for use in a function describing accident rates. These variables included ADT, truck percentage, type of development, estimated level of left-turn demand, lane width, shoulder width, speed, driveways per mile, and unsignalized intersections per mile. Although all were considered, only truck percentage, type of development, shoulder width, driveways per mile, and unsignalized intersections per mile were found to significantly affect suburban highway accident rates. The estimated accident rate for two-lane roads by type of development and median alternative for non-intersection accidents, unsignalized intersection accidents, and total accidents is given in Table 2-4. The rates given in this table should be adjusted by adding the adjustment factors given in Table 2-5. Inspection of these tables reveals that (holding all other characteristics constant) an 11 to 35 percent reduction in accident rates on two-lane roads is experienced when a TWLTL is installed. The reduction can be expected in all cases except for unsignalized intersection accident rates in areas with commercial development: a 15 percent increase is experienced in this case.

**Table 2-4. Average Accident Rates on Suburban Arterial Highways (3).**

| Type of Development | Basic Accident Rates (accidents per million vehicle-miles) for Different Design Alternatives | | | | |
|---|---|---|---|---|---|
| | Two-Lane, Undivided | Three-Lane w/TWLTL | Four-Lane, Undivided | Four-Lane, Divided | Five-Lane w/TWLTL |
| Non-Intersection Accident Rates | | | | | |
| Commercial | 2.39 | 1.56 | 2.85 | 2.90 | 2.69 |
| Residential | 1.88 | 1.64 | 0.97 | 1.39 | 1.39 |
| Unsignalized Intersection Accident Rates | | | | | |
| Commercial | 2.11 | 2.43 | 4.77 | 4.71 | 3.11 |
| Residential | 2.88 | 1.91 | 3.03 | 2.71 | 1.85 |
| Total (Combined) Accident Rates | | | | | |
| Commercial | 4.50 | 3.99 | 7.62 | 7.61 | 5.80 |
| Residential | 4.76 | 3.55 | 4.00 | 4.10 | 3.24 |

**Table 2-5. Adjustment Factors for Average Accident Rates on Suburban Arterials (3).**

|  |  | Adjustment Factor |  |  |
|---|---|---|---|---|
|  |  | Under 5% | 5-10% | Over 10% |
| Truck Percentage | Non-Intersection | +0.18 | -0.07 | -0.33 |
|  | Unsignalized Intersection | +0.22 | -0.08 | -0.38 |
|  | Total | +0.40 | -0.15 | -0.71 |
|  |  | Under 30 | 30-60 | Over 60 |
| Driveways per Mile | Non-Intersection | -0.41 | -0.03 | +0.35 |
|  | Total | -0.41 | -0.03 | +0.35 |
|  |  | Under 5 | 5-10 | Over 10 |
| Intersections per Mile | Unsignalized Intersection | -0.99 | +0.28 | +1.55 |
|  | Total | -0.99 | +0.28 | +1.55 |
|  |  | Full | None |  |
| Shoulders | Non-Intersection | -5% | +5% |  |

In 1989, Squires and Parsonson (7) conducted a study that sought to determine accident rates on highways with raised medians and TWLTLs with certain geometric and operational characteristics. In their study, both four-lane sections and six-lane sections with raised medians were found to have lower accident rates than sections with a TWLTL. The authors attributed these results to the range of ADT on the roads investigated. On higher volume roads, they concluded that left-turn movements seem to be safer at concentrated points, such as those provided by raised medians.

In addition, Squires and Parsonson collected the following data at each accident site: number of driveways, signalized intersections, and unsignalized approaches. For raised medians, the number of unsignalized median openings was also collected. Using this data, regression equations were developed to model accident occurrence for each median type. Equations were developed for four-lane and six-lane roads with raised medians or TWLTLs to predict the following: total accidents, mid-block accidents, accidents per mile per year, and accidents per million vehicle miles (MVM). The results from the equations were compared to the collected accident data. For four-lane sections, Squires and Parsonson found that raised medians experienced fewer accidents than TWLTLs; however, the difference in rates was found to decrease with increasing numbers of signals per mile. The regression analysis for the six-lane sections revealed that, except under certain conditions, raised medians again experienced fewer accidents. The conditions where this was not true included when more than 75 driveways per mile (120 driveways per km), fewer than three signals per mile (4.8 signals per km), and fewer than 7 approaches per mile (9.7 approaches per km) were present at the site.

A study conducted in 1978 by Walton et al. (8) used multiple regression techniques to develop an equation to predict accident rates on roads with TWLTLs. The sections averaged approximately 0.45 miles (0.72 km) in length and were analyzed with and without the inclusion of intersection accidents. The most consistently important independent variables were weekday ADT, signal density, driveway density, and city size. Other potential variables investigated were vehicle miles of travel, percentage of commercial land use, existence of curb side parking, speed limit, and lane widths; however, these were not found to be as significant as the others.

## OPERATIONAL EFFECTS

### Computer Simulation Studies

Three related studies were conducted in which a computer simulation model was used to quantify the effects a TWLTL has on the efficiency of traffic flow. A computer simulation model was developed in the first study by McCoy, et al. (9) in 1982 for a two-lane road. The next study, conducted by Ballard and McCoy (10) in 1983, altered the same model for use on a four-lane road. The third study, also by Ballard and McCoy (11) used an improved version of the computer simulation model to simulate more realistic traffic characteristics than the 1983 model for four-lane urban roads. The simulation model was used in each study to model 1000-foot (305 m) sections of road with and without a TWLTL. Initial inputs to the models included volume, average speed in each direction, percentage of traffic volume turning left into each driveway, and the arrival pattern of the traffic entering at each end of the street. Values for these inputs for each study can be found in Table 2-6. Each successive model built on the previous one.

For the 1982 study, all 27 combinations of left-turn volume, through volume, and driveway density, except one, revealed that the undivided two-lane model had more stops and delay than the TWLTL model. In the one case where the undivided two-lane model did not have more stops and delay, no difference in stops and delay was witnessed between the two models (9). The simulation models in the 1983 study and 1988 study demonstrated that the five-lane road with a TWLTL had fewer stops and delays in all tested operational and geometrical combinations than the four-lane undivided roadway (10, 11).

**Table 2-6. Initial Input Values for Computer Simulation Models.**

| Model Inputs | McCoy, et al. (1982) | Ballard & McCoy (1983) | Ballard & McCoy (1988) |
|---|---|---|---|
| Through Volume (each direction) | 350, 700, 1000 vph | 350, 700, 1050, 1400 vph | 100, 300, 500, 650, 900, 1100 vph |
| Left-Turn Volume or Percentage (each direction) | 35, 70, 105 vph | 35, 70, 105 vph | 2.5, 5, 7.5, 10, 12.5% |
| Driveway Density (both directions) | 30, 60, 90 driveways/mile | 30, 60, 90 driveways/mile | 30, 60, 90 driveways/mile |
| Avg. Running Speed (corresponding to each volume, respectively) | 35, 30, 25 mph | 35, 35, 30, 25 mph | 40, 40, 40, 40, 35, 35 mph |
| Right-Turn Percentage from Through Lanes | 0% | 0% | 10% |
| Right-Turn Percentage from Driveways | 0% | 0% | 10% |
| Left-Turn Percentage from Driveways | 0% | 0% | 0% |

The 1988 Ballard and McCoy study (11) also developed regression equations based on the simulation runs to predict the reductions in stops and delays that would result from the installation of a TWLTL on a four-lane undivided roadway. The equations are shown in Table 2-7. The $R^2$ value for all of these equations ranged between 0.975 and 0.996. All independent variables were found to be statistically significant at the 0.05 significance level.

**Table 2-7. Multiple Regression Equations for Reductions in Stops and Delay (9).**

| Reduction in... | Volume Constraints | Regression Equation |
|---|---|---|
| Stops | < 800 vph | $S=\exp(5.79 \times 10^{-3}V_t + 1.17 \times 10^{-3}V_t - 6.78 \times 10^{-3}D_d)$ |
| | ≥ 800 vph | $S=\exp(6.10 \times 10^{-3}V_t + 2.82 \times 10^{-2}V_d)$ |
| Delay | < 800 vph | $D=\exp(8.45 \times 10^{-3}V_t + 3.30 \times 10^{-2}V_l - 5.61 \times 10^{-3}D_d - 3.08 \times 10^{-5}V_d$ |
| | ≥ 800 vph | $D=\exp(8.98 \times 10^{-3}V_t + 6.52 \times 10^{-2}V_d)$ |
| Variable Definitions | | $S$ = reduction in stops per hour per 1000 feet<br>$D$ = reduction in delay (seconds per hour per 1000 feet)<br>$D_d$ = driveway density (driveways per mile)<br>$V_t$ = average traffic volume per direction (vph)<br>$V_l$ = sum of left-turn volumes in both directions (vph)<br>$V_d$ = average left-turn volume per driveway (vph per driveway) |

Through volume is an important consideration in determining the need for a TWLTL on any street. Many studies have suggested minimum values that should be witnessed before a TWLTL is installed. Both the 1982 McCoy et al. study (9) and the 1983 Ballard and McCoy study (10) recommended that the installation of a TWLTL would be most effective in improving the efficiency of traffic operations on two- and four-lane undivided roads when the through volume is above 700 vehicles per hour in each direction.

Turning volume is another important consideration when determining the need for a TWLTL. Without the demand for mid-block left-turning traffic, TWLTLs would not be necessary. Again, both the 1982 (9) and 1983 (10) studies concluded that the installation of a

TWLTL would be best warranted when left-turning volumes on two- and four-lane undivided roads in each direction were in excess of 70 vph per 1000 feet (230 vph per km).

Many reports have claimed that the installation of a TWLTL spurs commercial growth along a roadway. Commercial growth, in turn, results in the increase in driveway density, which again influences the effectiveness of a TWLTL on operational improvements. McCoy et al. (9) concluded that the effect of driveway density on three-lane roads with a TWLTL at each traffic volume investigated was not consistent over the range of left-turn volumes. The reduction in stops and delay increased with driveway density only at the highest levels of both traffic and left-turn volume. Ballard and McCoy (10) concluded that the amount of reductions in stops and delays experienced when a TWLTL was installed on a four-lane road increased within each level of driveway density as the traffic volume was increased. In every case but two, the amount of stop and delay reductions was increased within each level of driveway density as the left-turn volumes were increased.

Machemehl and Modur (13) used simulation models to compare several different median treatments. The objective of the study was to develop a set of guidelines for the use of arterial street median designs. Two models were developed to test the need for mid-block left-turn storage, based on left-turn, through, and opposing traffic demands, and to test the comparative efficiency of continuous TWLTL and left-turn bays. The first model involved a section of four-lane roadway with either no median, with a turn bay, or with a TWLTL. Each section contained one driveway that acted as a left-turning catalyst. Traffic stream gaps were programmed as random occurrences. Left-turn demands were varied from 200-600 vph, and through and opposing volumes were varied from 300-900 vph. The second model also involved a four-lane section of roadway; however, signalized intersections were placed at each end of the section and several driveways were placed at least 200 ft (60 m) apart between the signalized intersections. The model represented sections of road with approximately 25 driveways per mile (40 driveways per km), with demands ranging from 50 to 150 vph. Traffic demands for through and opposing traffic varied from 300-900 vph. Again, models were run with either no median treatment, a left-turn bay, or a TWLTL. Machemehl and Modur concluded that a storage area for left-turns (either a TWLTL or a left-turn bay) on four-lane roads is not justified if through and opposing volumes are less than 450 and 650 vph per lane, respectively. Machemehl and Modur suggested that a left-turn storage area (either a turn bay or TWLTL) should be considered on four-lane roads if left-turn volumes exceed 200 vph. Machemehl and Modur suggested that 25 driveways per mile (40 driveway per km) may be used as a threshold value on which to consider the use of a TWLTL, if each driveway has significant left-turn demands.

TRAF-NETSIM was used by Venigalla et. al. (14) to compare the operational efficiency under identical traffic and development situations of TWLTLs and nontraversable median islands. The results suggested that driveway density, traffic volume on the arterial, and type of design have a significant effect on the total delay, fuel consumption, and delay to left-turning traffic and through traffic on the arterial performance measures. At low driveway density and low traffic volume, the difference in total delay between the two designs was not found to be significant. At higher driveway densities, no significant difference in delay to left-turning traffic on the arterial was found between TWLTLs and nontraversable median islands; however, TWLTLs were found to cause less delay to through traffic and to be more fuel efficient at all levels of driveway density and traffic volume.

## Field Studies

McCormick and Wilson (15) conducted a study in which the operational effects of TWLTLs on two- and four-lane roads were compared with the operational effects of four-lane roads without a median and with a Z-turn pattern median. The study determined under what circumstances particular medians will operate the best from the standpoint of movement efficiency and safety. Variables such as traffic counts, speed surveys, lateral placement, conflicts, accident histories, turning movements, day or night operations, and dry or wet pavement conditions were monitored. Seven study sites were selected for investigation, including three five-lane sites with a TWLTL, two four-lane sites with a Z-pattern median, one three-lane site with a TWLTL, and one four-lane site with no median. Volumes at these sites varied from 750 to 2,200 vph.

Figure 2-2 shows the twelve different types of conflicts observed in this study. The percentage of conflict occurrences by type of conflict is shown in Table 2-8. Statistical tests were used to verify conclusions made from visual inspection of the conflict data. Adjusted mean conflict rates were calculated for each median type with the same number of through lanes. As shown in Table 2-8, the three-lane road with a TWLTL had the second highest adjusted mean conflict rate. McCormick and Wilson concluded that the three-lane road with a TWLTL may be superior to the four-lane section that does not have a median treatment, especially when the width of the four-lane section is limited and left-turns are permitted on arterials that have established strip commercial development. In addition, results indicated that the five-lane TWLTL sites had a substantially lower mean conflict rate than either the four-lane with a Z-pattern median or the four-lane with no median. Adjusted conflict rates for the TWLTL sites were one-half those of the Z-pattern and one-fifth of the site with no median. McCormick and Wilson recommended the five-lane TWLTL alternative over the four-lane, no median alternative when left-turns are permitted on arterials that have strip commercial development (15).

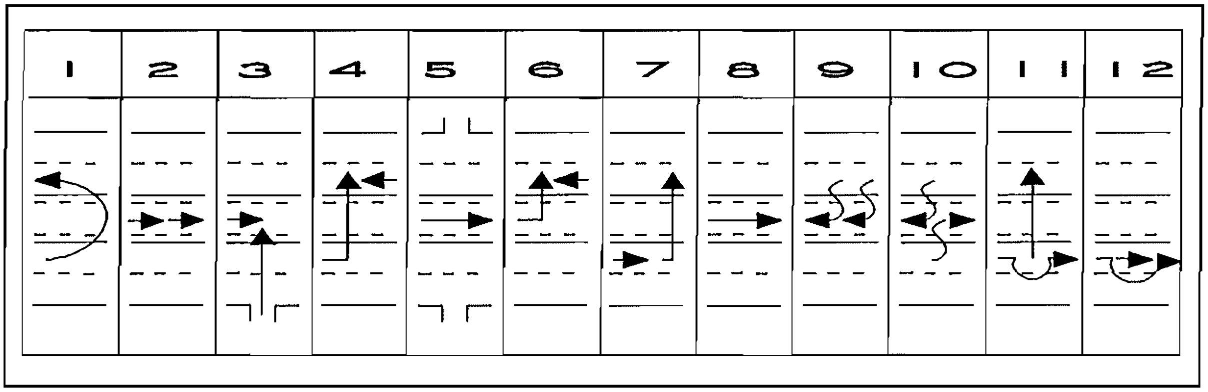


Figure 2-2. Conflict Types (15).

A 1978 study (16) investigated operational characteristics of TWLTLs. The study included a before-and-after analysis of three sites in Ohio in which the only influence on traffic operations at these sites was the installation of a TWLTL. Two of the three sites resulted in a three-lane road with a TWLTL, and the third site involved the installation of a TWLTL on a four-lane road. Traffic conflicts, specifically brake applications and weaving, were collected. In addition, average running speeds were obtained from approximately 40 runs made during 9:00 a.m. and 6:00 p.m. on two weekdays and one Saturday at each site for the before, after, and six months after time periods.

The first site was a four-lane road that was restriped to three-lanes with a TWLTL. Resultant frequencies of conflicts can be seen in Table 2-9. Brake applications decreased from the before period to the after period by 22 percent; however, weavings increased over the same time period by 78 percent. Further analysis of left-turns at this site revealed that approximately 23 percent either protruded from the TWLTL after attempting to enter it or did not use the TWLTL at all. The author cited the incomplete removal of the old lane lines as the source of the improper use of the TWLTL. A decrease in average running speeds was witnessed, leading the author to conclude that the "elimination of one through lane in each direction offsets the beneficial effects of the TWLTL."

**Table 2-8. Percent of Conflicts Observed by Type of Median Treatment (15).**

| Conflict Type* | Conflict Rates by Median Type (%) | | | | Total Observations |
|---|---|---|---|---|---|
| | Five-lane w/ TWLTL | Three-lane w/ TWLTL | Four-Lane w/ Z-Pattern | Four-Lane w/No Median | |
| 1 | 0.8 | 0.0 | 1.9 | 0.2 | 7 |
| 2 | 0.4 | 1.6 | 0.0 | 0.0 | 4 |
| 3 | 3.9 | 2.2 | 0.8 | 3.7 | 30 |
| 4 | 0.8 | 0.0 | 1.9 | 7.2 | 40 |
| 5 | 0.0 | 0.0 | 3.8 | 0.0 | 10 |
| 6 | 18.4 | 6.9 | 3.4 | 0.0 | 66 |
| 7 | 41.0 | 16.5 | 61.8 | 83.6 | 678 |
| 8 | 3.3 | 8.0 | 0.0 | 0.0 | 23 |
| 9 | 2.5 | 4.3 | 7.2 | 0.0 | 33 |
| 10 | 0.0 | 12.8 | 0.0 | 0.0 | 24 |
| 11 | 29.9 | 0.0 | 19.1 | 5.2 | 151 |
| 12 | 0.0 | 47.9 | 0.0 | 0.0 | 90 |
| Adj. Mean Conflict Rate | 4.8 | 17.6 | 9.1 | 22.1 | n/a |

* Conflict types are shown in Figure 2-2.

### Table 2-9. Frequency of Conflicts Observed in Operational Studies of TWLTLs (16).

| Site | Period | Brakings |  | Weavings |  |
|---|---|---|---|---|---|
|  |  | Frequency | Percent Change | Frequency | Percent Change |
| Four-Lane → Three-lane w/TWLTL | Before | 614 | n/a | 105 | n/a |
|  | After | 480 | - 22% | 187 | + 78% |
| Two-Lane → Three-lane w/TWLTL | Before | 1327 | n/a | 245 | n/a |
|  | After | 567 | - 57% | 22 | - 91% |
|  | 6 Months After | 833 | - 37% | 48 | - 80% |
| Four-Lane → Five-lane w/TWLTL | Before | 575 | n/a | 589 | n/a |
|  | After | 685 | + 19% | 530 | - 10% |
|  | 6 Months After | 485 | - 16% | 565 | - 4% |

The second site was a two-lane road that was widened to include a TWLTL. Although the through lanes were reduced from 15 feet (5 m) to 11.5 feet (3.5 m), a significant reduction in conflicts resulted. As can be seen in Table 2-9, brake applications were reduced 57 percent and 37 percent immediately after and 6 months after, respectively, the installation of the TWLTL, and weaving was reduced 91 percent and 80 percent over the same time periods. A small statistically significant increase in running speeds was witnessed, even though lane widths were reduced.

The third site investigated in the study did not involve any pavement widening. The site was just restriped to include a TWLTL. In some areas along the study section, the old center line was not properly removed. Consequently, mixed results were obtained at this site with regard to conflicts. As can be seen in Table 2-9, a small decrease in weaving incidents was witnessed immediately after and 6 months after the installation of the TWLTL; whereas, brakings increased and decreased slightly after and 6 months after the installation, respectively. Further investigation revealed that approximately 36 percent of left-turning vehicles either did not use the TWLTL at all, or protruded from it upon attempting to enter. Nemeth concluded that traffic conditions were already satisfactory at this site, and that the advantages of the TWLTL will not be witnessed until volumes increase.

A 1990 study, conducted by Harwood (4), specifically set out to determine the effect that narrower lanes had at sites where a TWLTL was installed. On-site observations of projects involving the implementation of narrower lanes and a TWLTL, as well as video tapes of traffic were made at seven sites and were later reviewed to determine the frequency of certain conflicts. Four of the seven sites had narrower lanes at tangent sections, two sites had narrower lanes on horizontal curves, and one site had 12-foot (3.6 m) lanes on a tangent section. Three types of conflicts were observed, namely, forced encroachments, unforced encroachments, and traffic conflicts. Encroachments, in general, refer to the movement of a vehicle over a lane line into an adjacent lane, without changing lanes. Forced encroachments occur because of the actions of another vehicle; whereas, unforced encroachments occur for no apparent reason other than "poor vehicle guidance." Traffic conflicts refer to the braking or swerving of one vehicle due to the action of another. For all vehicle types, including large trucks, unforced encroachment rates are higher for sites with narrower lanes than for sites with 12-foot (3.6 m) lanes (four times higher at tangent sections, and 2.5 times higher at horizontal curve sections). Only 0.5 percent of the vehicles in this study experienced a traffic conflict, two of which were caused by unforced encroachments, and another caused by a forced encroachment by a truck. Forced encroachment rates were reasonably comparable at sites with and without narrower lanes. When only large trucks were analyzed, it was discovered that at these sites 57.6 percent of single unit trucks, and 41.7 percent of combination trucks made unforced encroachments. However, only two forced encroachments were observed by large trucks.

## Comparative Studies

Walton et al. (8) in 1978 reported on data that evaluated the operational characteristics of left-turn facilities. Twenty sites with either a TWLTL, a TWLTL with one-way left-turn lanes (OWLTL) at intersections, or raised or flush OWLTLs were used in the analysis. One of the many data collected at these sites was vehicle conflicts. Frequencies for five different types of conflicts were collected:

- head-on conflicts,
- conflicts between vehicles in the TWLTL and left-turning vehicles from a minor road as it enters the TWLTL,
- conflicts between vehicles in the TWLTL and vehicles that start to enter the TWLTL,
- conflicts between left-turning vehicles from the through lane and straight-through vehicles, and
- conflicts between vehicles in the TWLTL and left-turning vehicles from the through lane.

Although no figures were given, Walton et al. concluded from the analysis of these conflicts that "the fear of conflicts and a resultant increase in accidents after implementation is unfounded." The conflicts investigated in this study "rarely occurred" at the sites investigated, and those that were witnessed "were handled with typical driver judgement."

Entrance distance and maneuvering distance data were also collected at the ten sites with TWLTLs. Entrance distance refers to the distance from an intersection/driveway to the point at which the driver decides to enter the TWLTL. Maneuvering distance refers to the distance the driver requires to enter the TWLTL completely. With respect to entrance distance, Walton et al. made the following conclusions:

- Left-turning and adjacent through-lane traffic volumes have a significant effect on entrance distance.
- Entrance distances at mid-block and at intersection approaches are different.
- The type of lane delineation has a significant effect on entrance distance.
- Entrance distance varies with the number of through lanes.
- The majority of drivers maneuvered into the TWLTL 150 feet (45 m) to 250 feet (75 m) prior to the intersection/driveway, while very few drivers entered the lane less than 100 feet (30 m) from the intersection/driveway.

Walton et al. (8) also investigated the width of TWLTLs. The study specifically investigated the lateral placement of vehicles in TWLTLs at 10 sites. Walton et al. concluded that for TWLTLs, widths of 11 feet (3.3 m) and 12 feet (3.6 m) had no significant adverse effects on traffic operations; however, lane widths greater than or equal to approximately 15 feet (5 m) were found to cause some confusion among drivers.

## COST EFFECTIVENESS

Thakkar's 1984 safety analysis study (5) led to some very significant conclusions regarding the safety effectiveness of TWLTLs. Building on his findings, Thakkar continued his study by determining the cost effectiveness of TWLTLs. As mentioned earlier, Thakkar examined accident data two years before and after a TWLTL was installed at sixteen two-lane and fifteen four-lane sections. Significant reductions in total and affected accidents, their rates, and their severity were realized upon analysis of both two- and four-lane roads. A benefit/cost analysis and a cost effectiveness analysis were undertaken in which the only benefits realized were savings in accidents, and the costs involved in construction (both standardized to constant 1977 dollars). A sensitivity analysis was conducted in which the interest rate was varied from 6 to 20 percent, the service life was varied from 10 to 20 years, and the salvage rate was varied from 0 to 20 percent. The result of the analysis indicated that when a two-lane road is improved by the addition of a TWLTL, and only accident reductions are considered as benefits, the improvement is cost effective when interest rates are lower than 12 percent, and service lives are longer than 10 years. The results of the analysis indicated that when a four-lane road is improved by the addition of a TWLTL, and only accident reductions are considered as benefits, the improvement is cost effective for all values of interest rates, service lives, and salvage values investigated.

A 1978 study by Harwood and Glennon (17) employed a benefit/cost comparison of five different median treatments that considered accident reduction, delay reduction, and construction cost. The five median treatments included in the analysis were TWLTLs, continuous one-way left-turn lanes, alternating one-way left-turn lanes, raised median islands with left-turn deceleration lanes, and a median barrier with no direct left-turn access. The analysis was based on findings from other research and "reasonable" assumptions regarding the effectiveness of median treatments. Annual accident frequencies were obtained from other sources (18,19,20). Their corresponding estimated annual number of accident reductions expected for the installation of all median treatments was either based on other research (21,22,23,24,25,26,27) or on assumptions. It was assumed in this study that a typical arterial highway has two signalized intersections per mile (three per km). No data was obtained in the literature regarding the effectiveness of the five median treatments in reducing delay or increasing running speed. Therefore, logical assumptions regarding these variables were also made.

The effectiveness of median treatments were evaluated in relation to three construction options, each of which were evaluated separately. In order of increasing cost, they included 1) no pavement widening necessary, 2) pavement widening necessary, but no additional right-of-way (ROW) required, and 3) both pavement widening and additional ROW required. Unit construction costs were based on data gathered in 1975. Service lives were 20 years, except for pavement striping, which was estimated at 2 years. Harwood and Glennon concluded that median treatments that require pavement widening are warranted only for highways that have traffic volumes >5,000 vpd. Median treatments that require both pavement widening and ROW acquisition are warranted for only two types of sites: 1) highways that have traffic volumes >5,000 vpd and driveway densities >60 per mile (97 per km), and 2) highways that have traffic volumes >15,000 vpd and driveway densities > 30 per mile (48 per km). In every case considered, the TWLTL option is the most desirable median treatment.

Another cost effective study of TWLTLs on four-lane urban roads was conducted by McCoy et al. (28) in 1988. A benefit/cost analysis was used in which the benefits were accident and operational cost savings, and the costs included first time installation and maintenance costs. Operational cost savings were calculated using the regression equations developed in an earlier study (11) predicting the reduction in stops and delay provided by the addition of a TWLTL. The equations used are shown in Table 2-7. Monetary savings related to stopping and delay were provided by a 1975 AASHTO study, adjusted to 1986 values. Accident cost savings were obtained by using a 30 percent accident reduction rate when TWLTLs are installed, accident severity percentages based on the accident histories of four-lane undivided roadways (0.1 percent fatal, 26.5 percent nonfatal injuries, and 73.4 percent property damage only), and by eliminating intersection accidents from the analysis. Costs of a TWLTL used in this analysis included first time construction costs and maintenance costs. The study concluded that, in general, the installation of a TWLTL on four-lane roads is cost effective at lower ADTs when left-turn percentages are high (12.5 percent) and driveways per mile are low (30 driveways per mile [48 driveways per km]). For total cost savings, TWLTLs are cost effective at minimum ADT values between 6,200 and 6,600 vpd, depending on the left-turn percentage (2.5 to 12.5 percent) and driveway density (30 to 90 driveways per mile [48 to 145 driveways per km]). When only operational cost savings are considered, TWLTLs are cost effective when the minimum ADT values are between 10,500 and 16,200 vpd, depending on the left-turn percentage and driveway density. For accident cost savings only, TWLTLs are cost effective at ADTs above 7,100 vpd, no matter what the driveway density or left-turn percentage.

## SUMMARY

The literature clearly shows that TWLTLs can dramatically improve safety and operations of both two-lane and four-lane arterials. Accident rates can be significantly reduced on roadways with either no median treatment (undivided) or very narrow medians (less than 4 feet [1.2 m] in width) by installing a TWLTL. In these situations, accident rates are improved by removing turning vehicles from the traffic stream and giving them a place to store while waiting to make a turn. This reduces the potential for rear-end collisions. Left-turn accident potentials are also decreased because left-turn vehicles do not feel the "pressure" to hurry their maneuvers. Even on roadways where lane widths have been reduced to less than desirable widths, the benefits of installing TWLTLs (in terms of low accident rates) far outweigh the negative effects of the narrower lanes.

In terms of operations, installing TWLTLs on previous undivided highways and highways with narrow medians can result in significant operational benefits as well. Installing TWLTLs in these situations can significantly reduce delays and stops to through vehicles. Installing TWLTLs in these situations can also significantly reduce the number of conflicts between vehicles. Simulation studies have also shown that TWLTLs also reduce total delays and fuel consumption when driveway densities are high.

The benefits of increasing a roadway from a five-lane or six-lane, divided cross section to a seven-lane cross section are still unclear. Accident data collected on highways where the cross section was changed from a six-lane narrow median to a seven-lane cross section revealed a reduction in accident rates. Another suggested that, except on arterials where driveway densities were high with relatively few traffic signals and unsignalized intersection approaches, six-lane divided arterials experience fewer accidents than comparable seven-lane cross sections. No studies were found that specifically evaluated the operational aspects of seven-lane cross sections.

The literature did indicate that several factors affect the operations and safety of roadways with TWLTLs. These factors are summarized in Table 2-10. Several studies indicated that driveway densities, the average number of traffic signals per mile, the traffic volumes, and the density of unsignalized intersection approaches have the greatest impact on TWLTL operations and safety. As a result, these factors were examined in the field studies discussed in the following chapters.

**Table 2-10. Factors Affecting Traffic Operations and Safety of TWLTLs.**

| Affects On | Factors |
|---|---|
| Safety | • Type of Development<br>• ADT<br>• Percent Trucks<br>• Estimated Left-Turn Demand<br>• Through Traffic Demand<br>• Lane Width<br>• Speeds<br>• Driveway Densities<br>• Average Number of Signals per Mile<br>• Average Number of Unsignalized Approaches per Mile<br>• City Population |
| Operations | • Left-Turn Demand<br>• Through Traffic Demand<br>• Driveway Spacings<br>• Driveway Densities<br>• Average Number of Signals per Mile<br>• Average Number of Unsignalized Approaches per Mile |

# 3. DATA COLLECTION METHODOLOGY

Field studies were designed to evaluate how the factors identified through the literature review affected traffic operations on seven-lane cross sections. The purpose of this chapter is to describe the procedures that were used to collect and analyze the data obtained through the field studies.

## MEASURE OF EFFECTIVENESS

We used acceleration noise as the measure of effectiveness to evaluate the operations of seven-lane cross sections. Acceleration noise is a measure of the relative "smoothness" of a vehicle traveling on a section of roadway. It is based on the assumption that drivers traveling on a roadway attempt to maintain a uniform speed (or velocity) (32). Even on limited-access facilities (such as freeways) with low volumes, the speed at which a driver travels fluctuates. These fluctuations become more frequent and pronounced as vehicles interact with one another.

Fluctuations in a driver's speed can be measured by determining the standard deviation of the acceleration about a mean acceleration value. This standard deviation is called *acceleration noise*. It is computed using the following equation:

$$\sigma = \sqrt{\frac{1}{T}\sum [a(t)]^2 \Delta t}$$

where,

$\sigma$ = the acceleration noise,
T = the total time the vehicle is in motion,
a(t) = the acceleration (either positive or negative) at time t,
$\Delta t$ = successive time intervals.

Acceleration noise can be measured by monitoring frequency and magnitude of the speed changes in a vehicle as it travels through a study site. As the vehicle is driven through the study site, the speed of the vehicle is measured at regular intervals. These measurements can then be used to develop a profile of the speed of the vehicle during its trip. The speed profiles were then used to estimate the acceleration noise of the vehicle during the trip through the corridor. In general, a speed profile that is "smooth" (i.e., one that exhibits only minor speed changes) will have a low acceleration noise while a speed profile that is "rough" (i.e., one that exhibits large and frequent undulations) will have a high acceleration noise. Early researchers concluded that an acceleration noise value of 0.7 feet per second squared ($fps^2$)(0.21 $mps^2$) would be considered low while values of 1.5 $fps^2$ (0.21 $mps^2$) would be considered high (33).

Three primary factors affect acceleration noise (32): the driver, the roadway, and the traffic conditions. Typically, more aggressive drivers tend to cause higher acceleration noise because they typically have more frequent and pronounced speed changes than passive drivers. Acceleration noise is also affected by the design of the roadway. Highways that are winding and/or narrow, or highways with a large number of poorly synchronized traffic signals will have higher acceleration noise values than highways that are straight or have good progression. Finally, acceleration noise is greatly impacted by the traffic volumes. Roadways that are typically more congested will have more acceleration noise than highways that carry low traffic volumes.

Jones and Potts were one of the early research teams to use acceleration noise (33). They measured acceleration noise over different roadways with various traffic conditions and driver types. From this research, they found the following about acceleration noise:

- acceleration noise of two drivers driving different speeds below the design speed of a highway is approximately the same,
- acceleration noise increases as traffic volumes increase,
- acceleration noise increases as the amount of side-friction factors (such as parked vehicles, stopping buses, cross traffic, crossing pedestrians, etc.) increases, and
- high values of acceleration noise are indicative of potential hazardous conditions.

Jones and Potts have suggested that acceleration noise may be a better measure of traffic congestion than travel times and stopped time. For these reasons, we selected acceleration noise as the measure of effectiveness for this study.

The hypothesis of this study is that acceleration noise can be used as a means of assessing the impacts of different roadway characteristics (i.e., driveway density, signal spacing, etc.) and traffic conditions on operations and safety of seven-lane cross sections. In this research , we assumed that roadways operate more safely and efficiently when traffic exhibits only minor variations in speed (i.e., with low acceleration noise values). Likewise, we assumed that roadways with high fluctuations in speed (i.e., with high acceleration noise values) operate less efficiently and experience more operational and safety problems.

We conducted field studies to collect acceleration noise data on seven-lane cross sections with different roadway and roadside development characteristics in several major metropolitan areas in Texas. Statistical analyses were then performed to determine which of the roadway and roadside development characteristics had the greatest influence on the measured acceleration noise values.

## STUDY SITES

We first conducted a survey of the individual TxDOT districts to identify potential study sites where field data could be collected. We developed a list of candidate sites using TxDOT's Roadway Inventory Database. Because the Roadway Inventory Database does not specifically identify the type of median on a highway, the following criteria were used to identify potential highways with seven-lane cross sections:

- a functional classification of Principal Arterial,
- six or more travel lanes, and
- a surface width of 70 feet (21 m) or greater.

Only those highways located in urban areas were considered as potential study sites.

Lists of potential seven-lane highways were then sent to various TxDOT Districts. District personnel were asked to provide information on the type (i.e., raised, depressed, flush, or TWLTL) and width of the median for each highway on the list. The Districts were also asked to identify other highways that used a seven-lane cross section that were not included on the list. Using this approach, we identified a total of 30 urban and suburban highways with seven-lane cross sections throughout the State of Texas.

From these 30 sites, nine were selected as data collection sites. We believed that these nine provided a representative cross section of the type of operating conditions where seven-lane cross sections are typically employed in the State of Texas. Table 3-1 summarizes the location of the data collection sites.

With the exception of the sites in Beaumont and in Arlington, the land uses adjacent to most of the sites were retail. The land use adjacent to the site in Beaumont (U.S. 90) was primarily industrial with a few retail and commercial properties interspersed. The site in Arlington (FM 157) was the only site that had a substantial amount of residential land uses abutting the highway.

## DATA COLLECTION

The data collection effort consisted of two elements. The first element consisted of collecting the data needed to compute the acceleration noise for each of the sites. To collect this data, a profile of the speed of an instrumented vehicle as it traveled in each lane in both directions of the study site was obtained. The procedures used to collect the speed profile data were similar to those used to collect travel times on a roadway. A vehicle equipped with an automatic Distance Measuring Instrument (DMI) was driven the length of each of the study sites. An average-car technique (where the vehicle travels according to the driver's judgment of the average speed of the traffic stream) was employed in the data collection effort. An observer in the vehicle used an event button so that the DMI automatically recorded the distance traveled and the speed of the vehicle every two seconds. These data were stored on a portable computer for reduction later in the office.

At most of the sites, speed profile data were collected during four periods:

- AM Peak -- 7:00 am to 8:30 am,
- Noon Peak -- 11:30 am to 1:30 pm,
- PM Peak -- 4:30 pm to 6:30 pm, and
- Off-Peak -- 9:30 am to 11:30 am and 1:30 pm to 4:30 pm.

**Table 3-1. Location of Field Data Collection Sites.**

| Highway | Control Section | Limits | | District Number | City |
|---|---|---|---|---|---|
| | | Beginning | Ending | | |
| SH 174 | 001901 | Renfro | Miles Dr. | 2 | Burleson |
| FM 157 | 074704 | Pleasant Ridge | Park Row | 2 | Arlington |
| FM 1960 (Site 1) | 168501 | Hafer Rd | Kuykendahl | 12 | Houston |
| FM 1960 (Site 2) | 168501 | Kuykendahl | Stubner-Airline | 12 | Houston |
| SH 6 (Site 1) | 168506 | Grisby | West Park | 12 | Houston |
| SH 6 (Site 2) | 168505 | West Little York | Ridge Park | 12 | Houston |
| LOOP 13 (Site 1) | 052102 | I-35 | Mission Rd. | 15 | San Antonio |
| LOOP 13 (Site 2) | 052103 | San Antonio River | I-35 | 15 | San Antonio |
| US 90 | 002807 | Denton | Major | 20 | Beaumont |

A total of nine travel runs (three travel runs in each lane) were made in each direction during these time periods. Whenever possible, all of the data in a period were collected on the same day. Data were collected on weekdays only.

In addition to the speed profile data, an inventory of the characteristics at each site was also performed. The following data were collected as part of the inventory at each site:

- the location and width of each driveway and unsignalized intersection at the study site,
- the posted speed limit of the study site,
- the location and width of all signalized intersections within the study site, and
- the type of development (i.e., residential, commercial, retail, industrial, etc.) served by each driveway or curb cut.

Complete inventories of these characteristics were conducted for each direction at a site. Driveway locations were measured relative to the beginning of the study site using the DMI. Widths of each driveway and intersection were manually measured using a distance measuring wheel. Table 3-2 summarizes the characteristics of each of the nine study sites.

## DATA REDUCTION

A spreadsheet was then used to compute the acceleration noise for each of the speed profile runs. Since the actual acceleration of the vehicle was not measured, the following equation was used to estimate the acceleration noise:

$$\sigma = \sqrt{\frac{1}{T}\sum_{i=1}^{K}\frac{\Delta u^2}{\Delta t_i} - \left(\frac{V_T - V_O}{T}\right)^2}$$

where,

$\sigma$ = the acceleration noise (fps$^2$),
T = the total time the vehicle is in motion,
$\Delta t$ = time interval (sec) for a change in velocity,

# Table 3-2. Characteristics of Field Study Sites.

| Highway | Length (Miles [km]) | Annual Average Daily Traffic (vpd) | Direction | Number of Driveways Openings | Number of Unsignalized Intersections | Number of Signalized Intersections | Total Distance of Driveway Openings (Miles [km]) |
|---|---|---|---|---|---|---|---|
| FM 1960 (Site 1) | 2.4 (3.9) | 35,000 | Eastbound | 33 | 2 | 8 | 0.200 (0.322) |
| | | | Westbound | 68 | 5 | 6 | 0.414 (0.666) |
| FM 1960 (Site 2) | 2.5 (4.0) | 35,000 | Eastbound | 41 | 9 | 5 | 0.265 (0.427) |
| | | | Westbound | 20 | 9 | 5 | 0.159 (0.256) |
| FM 157 | 3.2 (5.2) | 44,000 | Northbound | 91 | 14 | 7 | 0.624 (1.005) |
| | | | Southbound | 106 | 8 | 7 | 0.621 (1.000) |
| US 90 | 3.1 (5.0) | 34,000 | Eastbound | 88 | 12 | 4 | 0.688 (1.108) |
| | | | Westbound | 116 | 7 | 5 | 0.697 (1.122) |
| SH 6 (Site 1) | 4.2 (6.8) | 37,000 | Northbound | 35 | 3 | 7 | 0.277 (0.446) |
| | | | Southbound | 66 | 4 | 6 | 0.387 (0.623) |
| SH 6 (Site 2) | 2.1 (3.3) | 30,000 | Northbound | 20 | 3 | 1 | 0.164 (0.264) |
| | | | Southbound | 5 | 2 | 1 | 0.046 (0.074) |
| Loop 13 (Site 1) | 2.5 (4.0) | 21,000 | Eastbound | 92 | 2 | 7 | 0.600 (0.966) |
| | | | Westbound | 103 | 7 | 7 | 0.584 (0.940) |
| Loop 13 (Site 2) | 3.3 (5.3) | 22,000 | Eastbound | 117 | 12 | 6 | 0.699 (1.125) |
| | | | Westbound | 124 | 13 | 6 | 0.819 (1.319) |
| SH 174 | 1.6 (2.6) | 29,000 | Eastbound | 39 | 3 | 4 | 0.240 (0.386) |
| | | | Westbound | 40 | 5 | 4 | 0.317 (0.510) |

$\Delta u =$ velocity change (mph) that occurred in interval $\Delta t$,
$V_O =$ velocity (mph) at the start of the trip segment,
$V_T =$ velocity (mph) at the end of the trip segment, and
$K =$ the number of segments of uniform acceleration.

Because acceleration noise is present *only when the vehicle is in motion*, the time intervals when the vehicle was stopped (for example, at a traffic signal) have been removed from the acceleration noise calculations (32). The DMI recorded the speed of the vehicle at regular intervals. Therefore, $\Delta u$ was equal to change in speed during the interval $\Delta t$.

A summary of the acceleration noise collected in each lane, direction, period, and site are provided in Appendix A. Although attempts were made to collect data during all periods, problems with the data collection equipment prevent some of the data to be collected at all of the sites. Therefore, we were unable to compute the acceleration noise for certain periods at some sites.

In addition to acceleration noise, a number of parameters were also computed using the data collected during the site inventories. These factors included the following:

- *Driveway Density* -- defined for this study as the total number of driveways on a study site divided by the total length of the study site.
- *Percent Distance of Driveway Openings* -- defined for this study as the portion of the total length of the study site that was traversable by vehicles entering or exiting to the side. It is computed by dividing the total distance of the driveway openings by the total length of the study site.
- *Signal Density* -- defined for this study as the total number of traffic signals in a study site divided by the total length of the study site.
- *Approach Density* -- defined for this study as the total number of unsignalized intersections in a study site divided by the total length of the study site.

Table 3-3 summarizes these factors for each of the study sites.

## Table 3-3. Roadway and Roadside Development Factors of Study Sites.

| Highway | Length (Miles [km]) | Annual Average Daily Traffic (vpd) | Direction | Driveway Density (Drwys/mile [Drwys/km]) | Percent Distance of Driveway Openings | Signal Density (Signals/mile [Signals/km]) | Approach Density (Appr./mile [Appr./km]) |
|---|---|---|---|---|---|---|---|
| FM 1960 (Site 1) | 2.4 (3.9) | 35,000 | Eastbound | 13.65 (21.98) | 8 % | 3.31 (5.33) | 0.83 (1.34) |
| | | | Westbound | 28.13 (45.29) | 17 % | 2.48 (3.99) | 2.07 (3.33) |
| FM 1960 (Site 2) | 2.5 (4.0) | 35,000 | Eastbound | 16.65 (26.81) | 11 % | 2.03 (3.27) | 3.66 (5.89) |
| | | | Westbound | 8.12 (13.07) | 6 % | 2.03 (3.27) | 3.66 (5.89) |
| FM 157 | 3.2 (5.2) | 44,000 | Northbound | 28.28 (45.53) | 19 % | 2.18 (3.51) | 4.35 (7.00) |
| | | | Southbound | 32.94 (53.03) | 19 % | 2.18 (3.51) | 2.49 (4.01) |
| US 90 | 3.1 (5.0) | 34,000 | Eastbound | 28.55 (45.97) | 22 % | 1.30 (2.09) | 3.89 (6.26) |
| | | | Westbound | 37.64 (60.60) | 23 % | 1.62 (2.61) | 2.27 (3.65) |
| SH 6 (Site 1) | 4.2 (6.8) | 37,000 | Northbound | 8.26 (13.30) | 6 % | 1.65 (2.66) | 0.71 (1.14) |
| | | | Southbound | 15.57 (25.07) | 9 % | 1.42 (2.29) | 0.94 (1.51) |
| SH 6 (Site 2) | 2.1 (3.3) | 30,000 | Northbound | 9.65 (15.54) | 8 % | 0.48 (0.77) | 1.45 (2.33) |
| | | | Southbound | 2.41 (3.88) | 2 % | 0.48 (0.77) | 0.96 (1.55) |
| Loop 13 (Site 1) | 2.5 (4.0) | 21,000 | Eastbound | 36.89 (59.39) | 24 % | 2.81 (4.52) | 0.80 (1.29) |
| | | | Westbound | 41.30 (66.49) | 23 % | 2.81 (4.52) | 2.81 (4.52) |
| Loop 13 (Site 2) | 3.3 (5.3) | 22,000 | Eastbound | 35.42 (57.03) | 21 % | 1.82 (2.93) | 3.63 (5.84) |
| | | | Westbound | 37.54 (60.44) | 25 % | 1.65 (2.65) | 3.94 (6.34) |
| SH 174 | 1.6 (2.6) | 29,000 | Eastbound | 24.59 (39.59) | 15 % | 1.62 (2.61) | 1.89 (3.04) |
| | | | Westbound | 25.22 (40.60) | 19 % | 2.52 (4.06) | 3.15 (5.07) |

## DATA ANALYSIS

Two separate analyses were performed on the acceleration noise data. First, the amount of variation in the data were examined. Analysis of Variance (or ANOVA) techniques were used to determine whether the measured acceleration noise data differed statistically depending upon (a) the lane in which the vehicle traveled, (b) the period in which the data were collected (i.e., A.M. Peak, Off-Peak, Noon Peak, or P.M. Peak), and (c) the direction of travel. This analysis was required in order to determine how the acceleration noise data should be correlated with the site factors.

In the second part of the analysis, regression analysis techniques were used to relate the specific characteristics of each site to the measured acceleration noise. A backward elimination technique was used to eliminate factors from an overall regression equation that were statistically insignificant. By using a backward elimination technique, variables are deleted from the regression equation one by one until all the variables remaining in the model produce a statistically significant model. A 0.10 significance level was used to keep a variable in the regression equation.

# 4. RESULTS

We conducted field studies to determine the amount of influence various roadside and roadway development factors had on traffic operations on seven-lane cross sections. Acceleration noise, which measures the relative "smoothness" of a trip, was used as a measure of effectiveness of the impact of select factors on traffic operations. The purpose of this chapter is to summarize the results of the field studies and discuss their implications in terms of operations and design of seven-lane cross sections.

## VARIATION IN ACCELERATION NOISE DATA

The acceleration noise data were first evaluated to determine the amount of variation that was caused by the manner in which the data were collected. We used analysis of variance (ANOVA) techniques to determine if the acceleration noise data varied by lane, direction, site, or data collection period. Since site, direction, and lane were believed to be related variables, we used a nested type of analysis to determine whether these variables were significant. A 0.05 confidence level was used to determine the significance of the variables in the analysis. The results of the analysis are shown in Table 4-1.

**Table 4-1. Results of Analysis of Variance of Acceleration Noise Data.**

| Source of Variation | Degrees of Freedom | F Statistic | Probability > F | Significant ? |
|---|---|---|---|---|
| Period | 3 | 0.45 | 0.7147 | No |
| Site | 7 | 62.39 | 0.0001 | Yes |
| Direction | 7 | 5.23 | 0.0001 | Yes |
| Lane | 9 | 0.40 | 0.9367 | No |

Our original hypothesis was that the lane in which a driver traveled would affect the acceleration noise. For example, we originally thought that the acceleration noise of a vehicle traveling in the inside (or median) lane would be affected more by vehicles entering and exiting the TWLTL than vehicles traveling in the other lanes. Similarly, we thought that the acceleration noise of a vehicle traveling in the outside (curb) lane would be affected more by vehicles turning into and out of driveways than the acceleration noise of vehicles traveling in the other lanes.

However, the ANOVA showed that the acceleration noise within a site did not vary by lane. This implies that the traffic operations in each lane of a roadway are uniformly affected by the amount of side-friction elements (i.e., vehicles turning into and out of the TWLTL and driveways) present on the roadway. Therefore, we concluded that the impact of the various roadway and roadside development factors was not unique to a specific lane, but affected total operations of traffic, regardless of the lane in which the study vehicle travels.

We also thought that the acceleration noise at a site might vary depending upon the period in which it was collected. For example, we originally thought the impact of various roadway and roadside development factors would vary depending upon the time of day. The land uses adjacent to most of the sites were primarily retail and commercial in nature. Because of the typical hours of operations for most retail and commercial land uses, we believed that traffic entering and exiting adjacent properties would be different depending upon the time of day in which the data were collected.

The results of the ANOVA indicated, however, that acceleration noise did not vary statistically by time of day, at a 95% confidence level. Figure 4-1 shows the average acceleration noise collected in each peak of each direction at one of the study sites (FM 1960 [Site 1] in Houston). Similar figures for the remaining sites are contained in Appendix B. These figures show that the average acceleration noise within each direction at each site remains relatively constant regardless of the period in which it was collected. Based on these results, it can be assumed that the impacts of different roadway and roadside development factors would have the same impact on traffic operations (as measured by acceleration noise) for every period in which the data were collected.

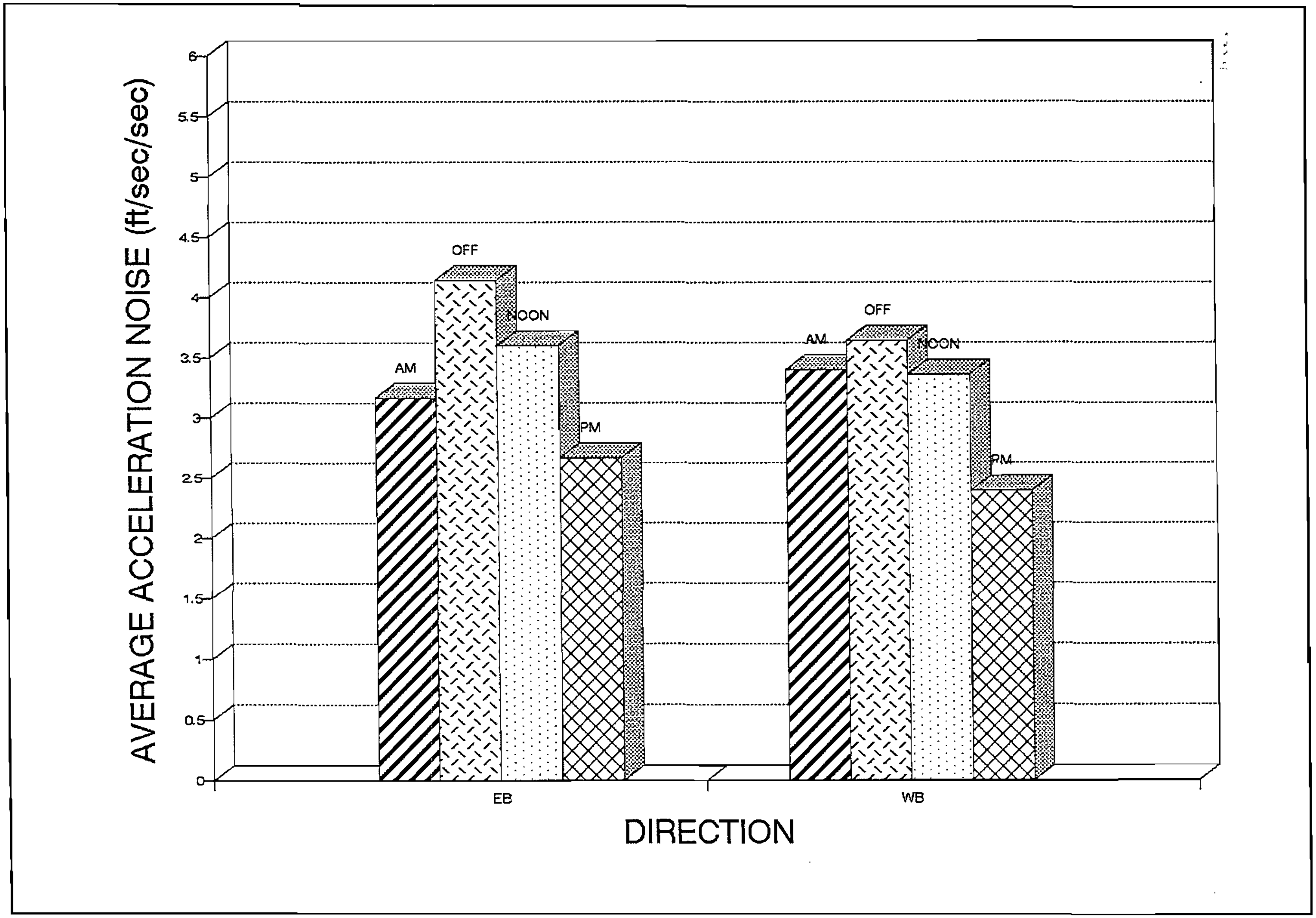


Figure 4-1. Acceleration Noise in Each Lane and Direction for FM 1960 Site 1.

Because the different study sites were believed to have different roadway and roadside development factors, it was expected that the acceleration noise between sites would vary. It was also expected that since most of the study sites had different intensities of development on different sides of the roadway, acceleration noise would vary depending upon the direction of travel. Figure 4-2 shows the acceleration noise averaged across all lanes and periods for each direction at each site. This figure suggests that the acceleration noise did not only depend on the study location, but also on the direction of travel at each study site. The ANOVA showed both of these variables (site and the direction of travel within each site) to be significant.

## FACTORS AFFECTING TRAFFIC OPERATIONS

A regression analysis was performed to relate specific roadway and roadside development factors for a direction of travel to the acceleration measured in that direction at each site. The factors that were evaluated in this study included the following:

- Average Daily Traffic (ADT),
- Driveway Density,
- Signal Density, and
- Approach Density.

The literature has shown that there is a strong relationship between these factors and traffic safety (7).

We used a backward elimination technique to determine the level of significance of each of these factors in predicting acceleration noise. With a backward elimination technique, a regression analysis was performed starting with all four of the variables. Non-significant factors were then eliminated from the regression equation until all of the remaining factors in the equation were significant. A 0.1 significance level was required in order for a factor to remain in the regression model.

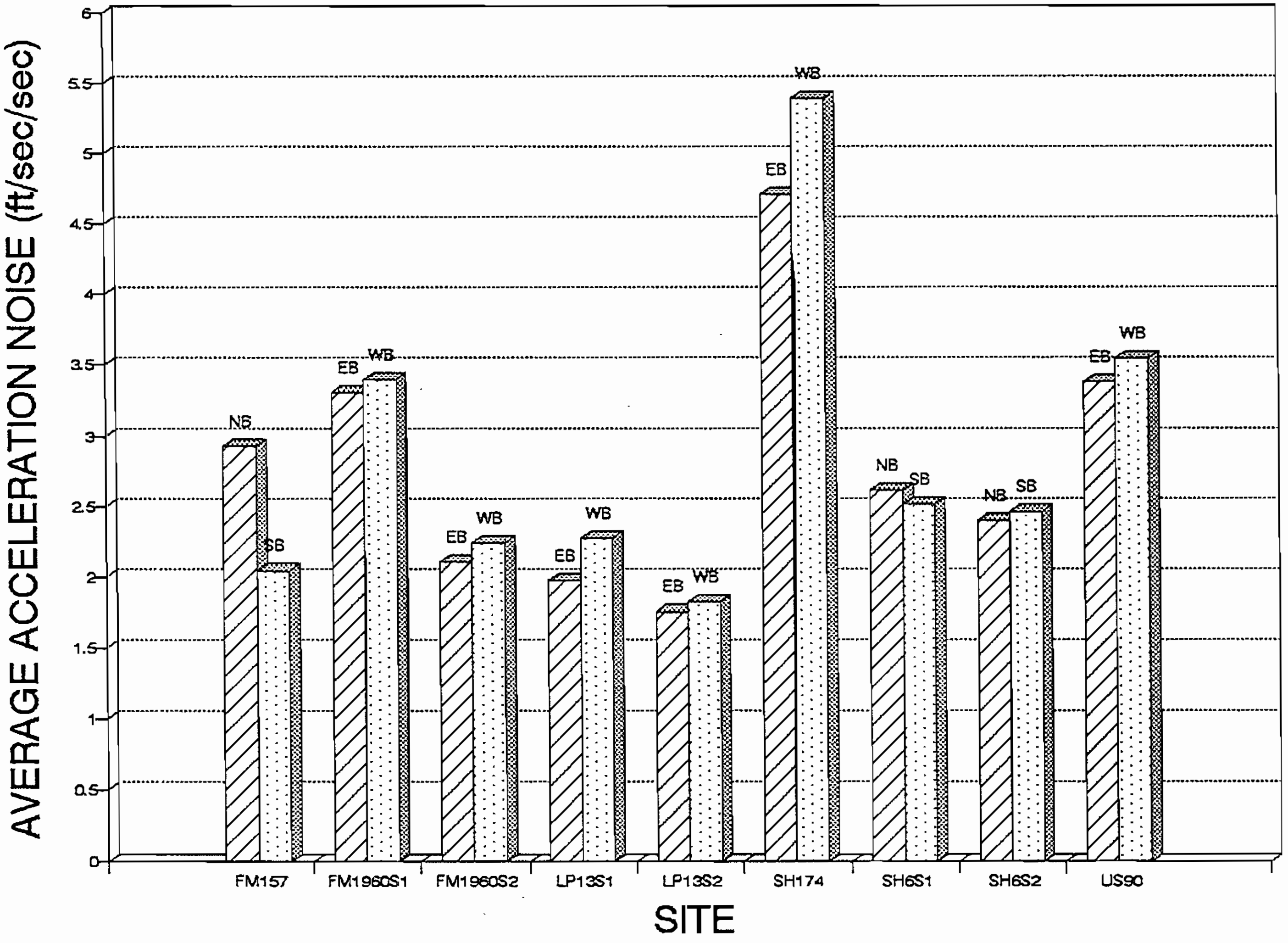


**Figure 4-2. Acceleration Noise in Each Direction for All Sites.**

The results of the regression analysis showed that driveway density, average approach spacing, and ADT were all significant factors affecting the measured acceleration noise at each of the sites. Only average signal spacing was not a significant factor affecting the measured acceleration noise. The equation resulting from the regression analysis was as follows:

$$\sigma = 1.29 + (0.012 * DD) + (0.042 * ADT) - (0.144 * AD)$$

where,

$\sigma$ = Acceleration Noise ($fps^2$)
DD = Driveway Density (driveways per mile),
ADT = Average Daily Traffic (vehicles per day), and
AD = Approach Density (unsignalized intersection approaches per mile).

It should be noted that the correlation coefficient ($R^2$) for the regression equation was relatively low (0.104). Visual inspections of plots of the variables and residuals from the regression analysis confirmed the assumptions of normality and graphical distribution of the error terms were satisfied.

The low correlation coefficient means that only 10 percent of the variation in the measured acceleration noise could be explained by the factors in the regression equation. Acceleration noise is a very stochastic measure of traffic operations and can vary significantly from run to run, depending upon the actual travel conditions and the amount of turning traffic occurring at the time the measurements were made. Factors such as driveway density, approach density, and ADT are very coarse measures of the characteristics of a roadway, and do not account for the dynamic nature of traffic operating on roadways. Therefore, it is not surprising that the regression model was not able to account for much of the variation in the acceleration noise data.

## IMPLICATIONS OF FINDINGS

Based on the results of this analysis, we concluded that traffic operations, as measured by acceleration noise in a particular direction on a roadway, are significantly affected by the density of driveways adjacent to the direction of travel, the average number of unsignalized intersection approaches in that particular direction of travel, and the ADT level on the roadway.

Looking at the regression equation, it can be seen that both ADT and driveway density have an additive effect of acceleration noise. It is logical to expect acceleration noise to increase as both ADT and driveway densities increase. This is because both ADT and driveway density increase the amount of side friction on through traffic. Typically, one would expect the amount of turning traffic on a roadway to be directly related to the overall demand on the roadway. At low levels of demand, one would logically expect low turning volumes. However, as demand levels increase, the frequency of turning traffic also increases.

Likewise, it is also logical to expect acceleration noise to increase as the density of driveways to adjacent properties increase. As the driveway density increases on a roadway, the opportunities for turning traffic to affect through vehicle movements increase. If both driveway density and ADT levels increase, both the potential number of locations for vehicles to turn, as well as the number of turning vehicles will also increase.

The analysis showed, however, that there is an inverse relationship between acceleration noise and the average number of unsignalized approaches intersecting a roadway. This means that as the number of unsignalized approaches increase, acceleration noise actually decreases. One possible explanation for this phenomenon is that turns into and out of adjacent properties become more concentrated as spacing between unsignalized intersections decreases. As the number of unsignalized intersections increase, the amount of land that can be devoted to large retail or commercial land-uses is reduced. This, in effect, reduces the probability that large retail strip centers that generate higher turning movements can be installed between two closely spaced intersection approaches. Unfortunately, specific data to support or refute this conjecture were not collected during this study.

Since it was not possible to cover the entire range of possible site conditions, the relationships presented above are only valid for a particular range of site conditions. Table 4-2 summarizes these conditions. As long as the site conditions are within these ranges, the regression analysis is valid. However, the regression analysis cannot be extrapolated to conditions outside those measured. Additional data are required before conclusions regarding impacts of various roadway and roadside development factors can be made outside the level examined in this study.

**Table 4-2. Limits of Significant Factors from Regression Analysis.**

| Factor | Range |
|---|---|
| ADT | 21,000 - 44,000 vehicles per day |
| Driveway Density (per direction) | 2.41 - 41.40 driveways per mile<br>(3.88 - 66.49 driveways per km) |
| Approach Density (per direction) | 0.71 - 4.35 approaches per mile<br>(1.14 - 7.00 approaches per km) |

# 5. CONCLUSIONS

Previous research has documented the operational and safety benefits of installing TWLTLs on two-lane and four-lane arterials. Very little research has been performed, however, to quantify the effects of seven-lane cross sections on traffic operations and safety. The goal of this research was to provide information on the factors that affect the operations of traffic on seven-lane cross sections in urban and suburban areas.

A review of the existing literature revealed that several factors have been shown to affect operations and safety on three-lane and five-lane cross sections. These factors include the following:

- the type of development present along side the roadway,
- the traffic demands on the roadway (i.e., ADT, through traffic demands, and left-turn traffic demands),
- the densities and spacing of driveways along the roadway,
- the degree of traffic signalization along the roadway,
- the average number of unsignalized intersection approaches per mile along the roadway,
- the widths of both of the TWLTL and the through travel lanes,
- the speeds of traffic on the roadway, and
- the size of the population of the city where the roadway is located.

In this study, we evaluated several roadway and roadside development factors including ADT, driveway density, the average number of traffic signals per mile, and the average number of unsignalized intersection approaches per mile. These factors were selected because they tended to be the factors cited most in the literature as having the greatest impact on traffic safety and operations on three-lane and five-lane arterials.

Field studies were designed to evaluate the effects of these factors on traffic operations on seven-lane cross sections. We used acceleration noise, a measure of the relative smoothness of the speed of a trip, to assess the impacts of these factors on operations. We chose acceleration noise as our measure of effectiveness because it directly measures the amount of speed variations exhibited on a trip through a study section. We collected acceleration noise in each lane in both directions during four periods (A.M. Peak, Off-peak, Noon, and P.M. Peak) at nine sites throughout Texas with different roadway and roadside development characteristics. A regression analysis was used to relate the factors from each individual site to the measured acceleration noise. The findings from these field studies are as follows:

- Acceleration noise did not statistically vary by lane or by time-of-day at any of the study sites. This implies that the impact of various roadway and roadside development factors existing at each site are consistent throughout the site, regardless of the lane or the time in which the acceleration noise data were collected.

- Acceleration noise did vary statistically between sites and between directions within each site. This implies that not only were the traffic operations at each site different, but also the traffic operations in each direction at a site were different. This suggests that the characteristics along each side of the roadway affects operation in that particular direction of travel.

- A positive relationship was found to exist between acceleration noise and both ADT and driveway density. Higher levels of ADT and driveway densities tend to produce higher acceleration noise in through traffic. This is because at higher ADT and driveway densities, the interaction between vehicles, which impacts acceleration noise, increases.

- A negative relationship was found to exist between acceleration noise and the average number of unsignalized intersection approaches per mile. One possible explanation for this phenomenon is that sites with more unsignalized intersection approaches per mile are less likely to have large strip commercial centers which produce high turning movements. This hypothesis, however, was not tested in this research.

- No relationship was found to exist between acceleration noise and the average number of traffic signals per mile along a site. However, this is to be expected since acceleration noise is measured only when a vehicle is in motion. Therefore, stops and delays due to traffic signals are not included in acceleration noise.

## CONCLUSIONS AND RECOMMENDATIONS

This research showed that the quality of flow on seven-lane cross sections is impacted by such roadway and roadside development factors as the density of driveways located on each side of the roadway, the average daily traffic carried by a roadway, and the average number of unsignalized intersection approaches along each side of the roadway. Generally, as the density of driveways and the amount of traffic carried on a roadway increase, the ability of the driver to maintain a "smooth" trip (i.e., one with few changes in speed) decreases. Therefore, designers should carefully consider not just the overall type of development and traffic demands on a roadway, but also the specific type of roadway and roadside development characteristics *on each side of the roadway* when considering implementing seven-lane cross sections in urban and suburban arterials.

Unfortunately, a definitive conclusion as to when and where seven-lane cross sections should be used cannot be made based on the results of this analysis. Additional analyses are needed to assess the safety benefits (or lack there of) of seven-lane cross sections with particular roadway and roadside development characteristics. Additional field studies are needed to compare the operational performance of five-lane, six-lane divided, and seven-lane cross sections with similar levels of traffic demands and roadside development characteristics. Only then can an extensive set of guidelines and recommendations be developed on the use of seven-lane cross sections.

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# APPENDIX A.

## Average Acceleration Noise by Lane for Each Study Site.

Table A-1. Average Acceleration Noise (fps$^2$) by Lane and Directions for SH 6 (Site #1) in Houston, Texas.

| Period | Northbound | | | Southbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | 2.38 | 3.03 | 2.38 | 2.82 | 2.32 | 2.41 |
| NOON | 2.80 | 2.49 | -- | -- | -- | 2.57 |
| OFF | 2.65 | 2.60 | -- | -- | 2.29 | 2.25 |
| PM | 2.51 | 2.53 | 2.55 | 2.70 | 2.86 | 2.52 |

Table A-2. Average Acceleration Noise (fps$^2$) by Lane and Directions for SH 6 (Site #2) in Houston, Texas.

| Period | Northbound | | | Southbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | -- | 2.66 | 2.39 | 2.26 | 2.36 | 2.40 |
| NOON | 2.27 | 1.45 | 2.32 | 2.68 | 2.48 | 2.44 |
| OFF | 2.42 | 2.94 | 2.12 | 2.56 | 2.07 | 2.13 |
| PM | 2.81 | 2.67 | 2.09 | 2.60 | 2.74 | 3.01 |

Table A-3. Average Acceleration Noise (fps$^2$) by Lane and Directions for US 90 in Beaumont, Texas.

| Period | Northbound | | | Southbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | 3.27 | 3.75 | 3.38 | 3.79 | 3.68 | 3.40 |
| NOON | 3.37 | 3.28 | 3.37 | 4.02 | 3.40 | 3.35 |
| OFF | 3.40 | 2.96 | 3.99 | 3.94 | 3.86 | 3.49 |
| PM | 3.30 | 3.54 | 3.00 | 3.47 | 3.30 | 2.80 |

Table A-4. Average Acceleration Noise (fps$^2$) by Lane and Directions for FM 1960 (Site #1) in Houston, Texas.

| Period | Eastbound | | | Westbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | 3.07 | 3.16 | 3.25 | 3.425 | 3.26 | 3.52 |
| NOON | 3.59 | 3.21 | 4.00 | 3.33 | 3.43 | 3.32 |
| OFF | 4.32 | 3.95 | 4.14 | 3.43 | 3.63 | 3.84 |
| PM | 2.77 | 2.84 | 2.73 | 2.22 | 2.73 | 2.88 |

Table A-5. Average Acceleration Noise (fps$^2$) by Lane and Directions for FM 1960 (Site #2) in Houston, Texas.

| Period | Eastbound | | | Westbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | 2.67 | 2.25 | 1.94 | 2.12 | 2.33 | 2.08 |
| NOON | 2.38 | 1.32 | 1.90 | 2.40 | 1.76 | 1.31 |
| OFF | 2.30 | 2.20 | 1.70 | 2.23 | 2.11 | 2.24 |
| PM | 2.62 | 2.28 | 2.59 | 2.22 | 2.06 | 3.06 |

Table A-6. Average Acceleration Noise (fps$^2$) by Lane and Directions for Loop 13 (Site #1) in San Antonio, Texas.

| Period | Eastbound | | | Westbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | 2.20 | -- | 2.29 | 1.86 | 2.23 | 1.74 |
| NOON | 2.36 | -- | -- | 1.99 | 1.68 | 1.86 |
| OFF | -- | 2.39 | 2.08 | 2.08 | 2.07 | 2.40 |
| PM | 2.29 | -- | -- | 2.16 | 2.00 | 1.70 |

Table A-7. Average Acceleration Noise ($fps^2$) by Lane and Directions for Loop 13 (Site #2) in San Antonio, Texas.

| Period | Eastbound | | | Westbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | 1.70 | 1.82 | 1.86 | 1.86 | 2.04 | 1.64 |
| NOON | -- | -- | 1.77 | 1.88 | 1.73 | 2.06 |
| OFF | -- | -- | 1.71 | 1.78 | 1.47 | 1.76 |
| PM | -- | -- | 1.64 | 1.54 | 2.11 | 1.95 |

Table A-8. Average Acceleration Noise ($fps^2$) by Lane and Directions for FM 157 in Arlington, Texas.

| Period | Northbound | | | Southbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | 1.76 | 1.37 | 2.94 | 2.01 | 2.17 | 2.10 |
| NOON | 3.53 | 2.91 | 3.65 | 1.73 | 1.62 | 2.18 |
| OFF | 2.43 | 1.79 | 1.70 | 1.67 | 2.07 | 2.48 |
| PM | 3.88 | 5.12 | 1.37 | 1.76 | 2.28 | 2.39 |

Table A-9. Average Acceleration Noise ($fps^2$) by Lane and Directions for SH 174 in Burleson, Texas.

| Period | Northbound | | | Southbound | | |
|---|---|---|---|---|---|---|
| | Outside | Middle | Inside | Inside | Middle | Outside |
| AM | -- | -- | 4.15 | 5.90 | 4.47 | 5.50 |
| NOON | 3.60 | 3.85 | 5.71 | 5.76 | 5.79 | 6.03 |
| OFF | -- | -- | -- | -- | -- | -- |
| PM | 5.45 | 5.12 | 5.07 | 5.83 | 4.45 | 5.16 |

# APPENDIX B.

## Acceleration Noise for Each Period and Direction at Data Collection Sites.

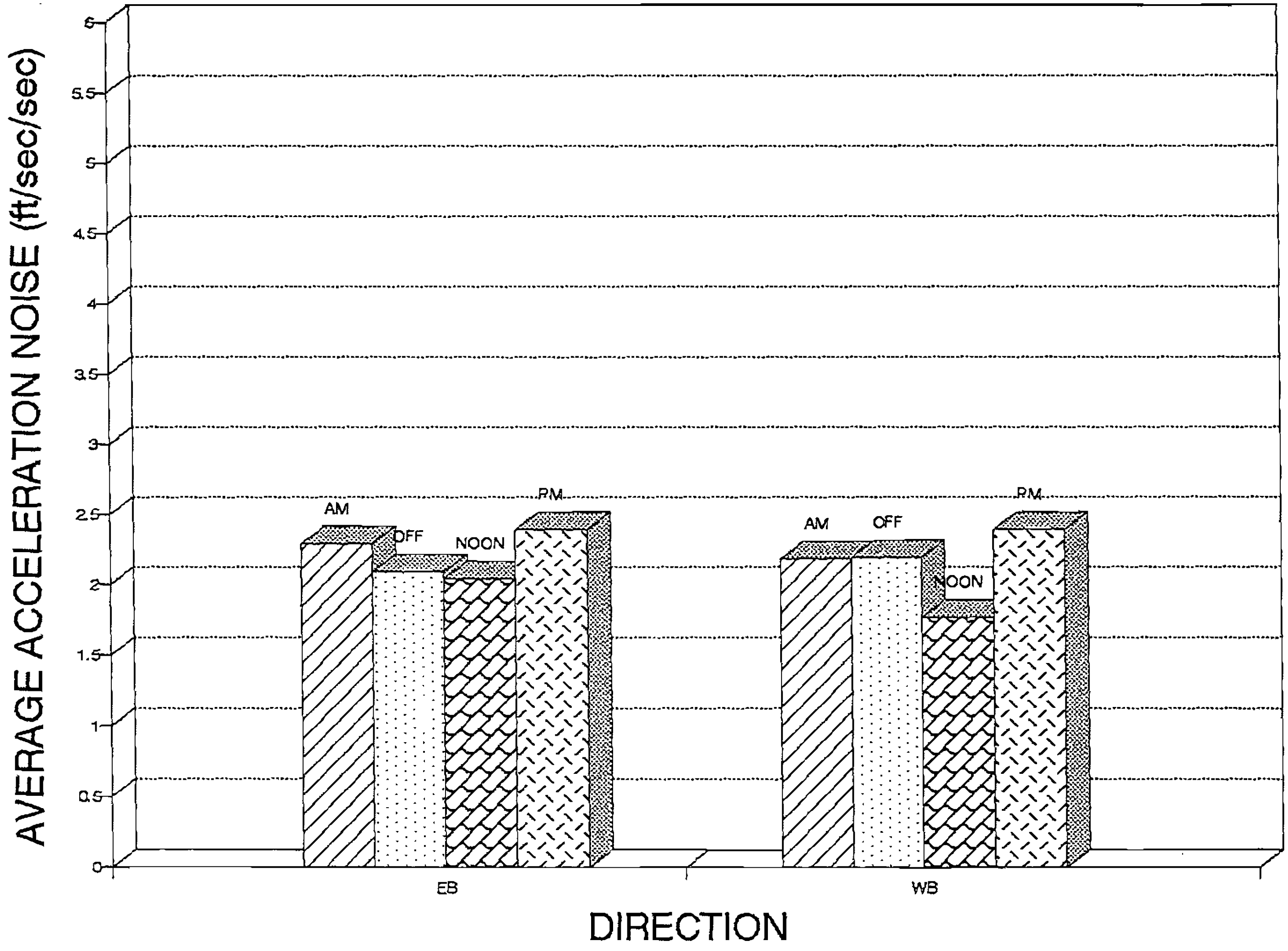

Figure B-1. Acceleration Noise in Each Lane and Direction for FM 1960 Site 2.

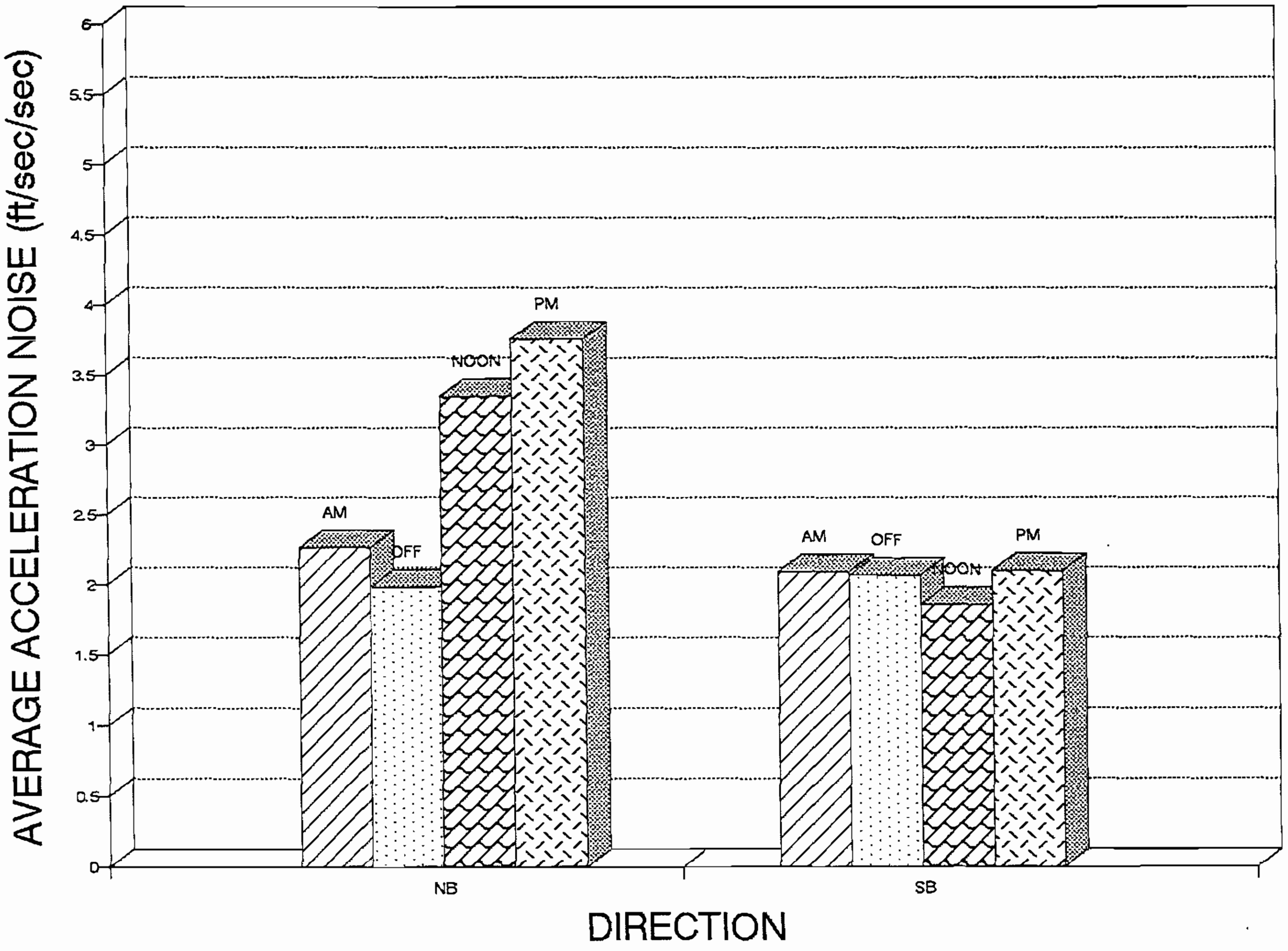

Figure B-2. Acceleration Noise in Each Lane and Direction for FM 157.

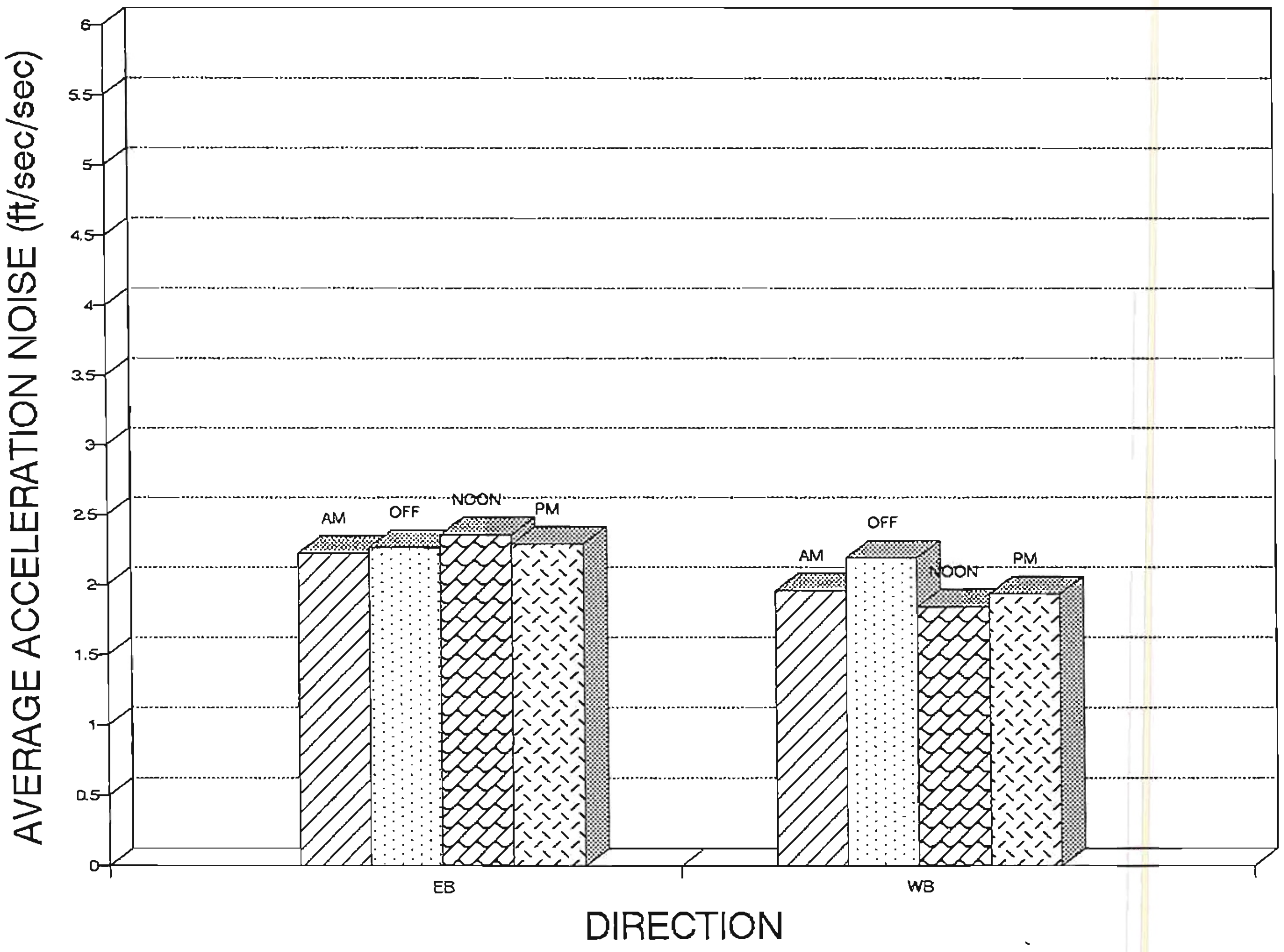

Figure B-3. Acceleration Noise in Each Lane and Direction for Loop 13 Site 1.

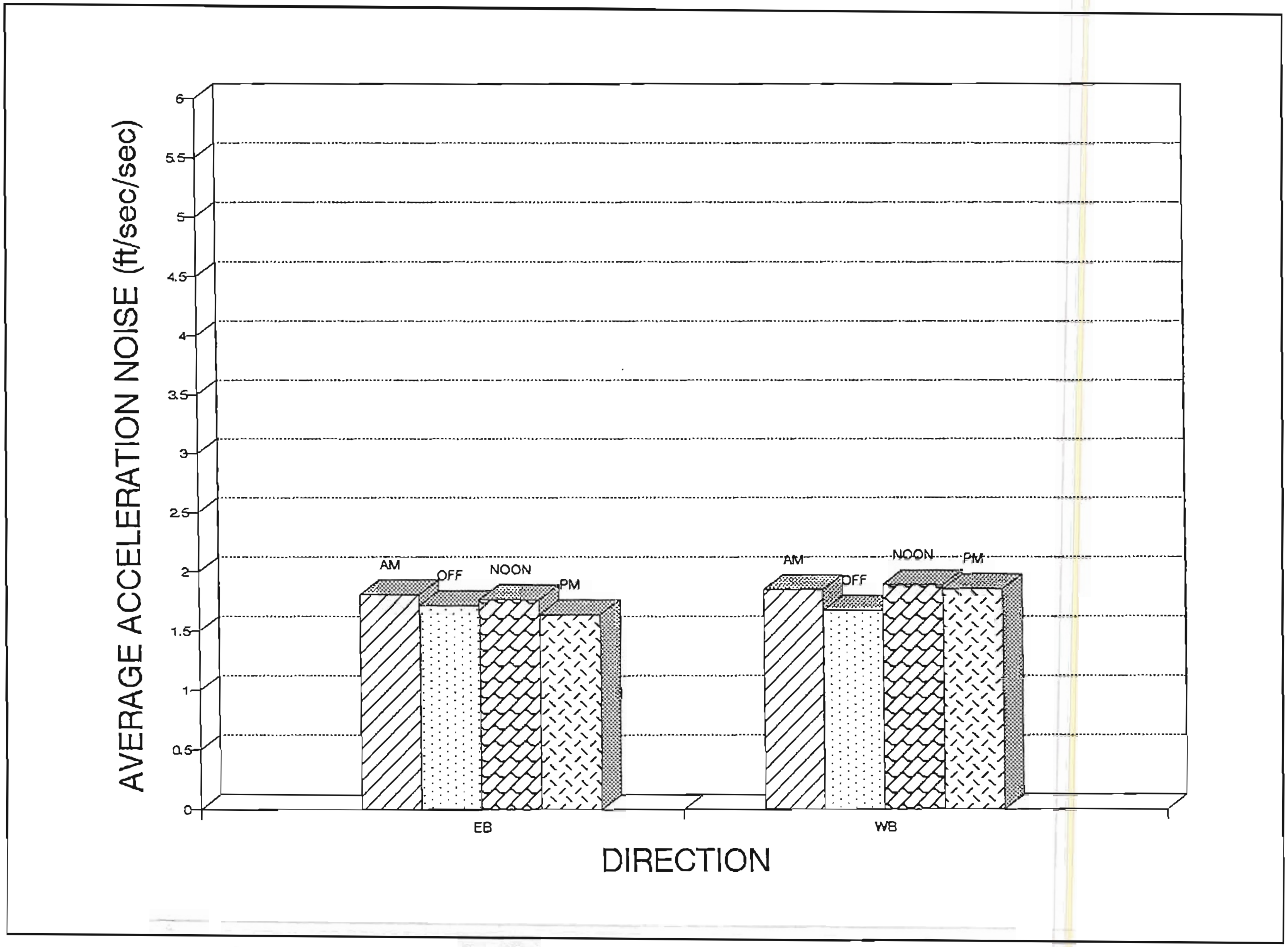

Figure B-4. Acceleration Noise in Each Lane and Direction for Loop 13 Site 2.

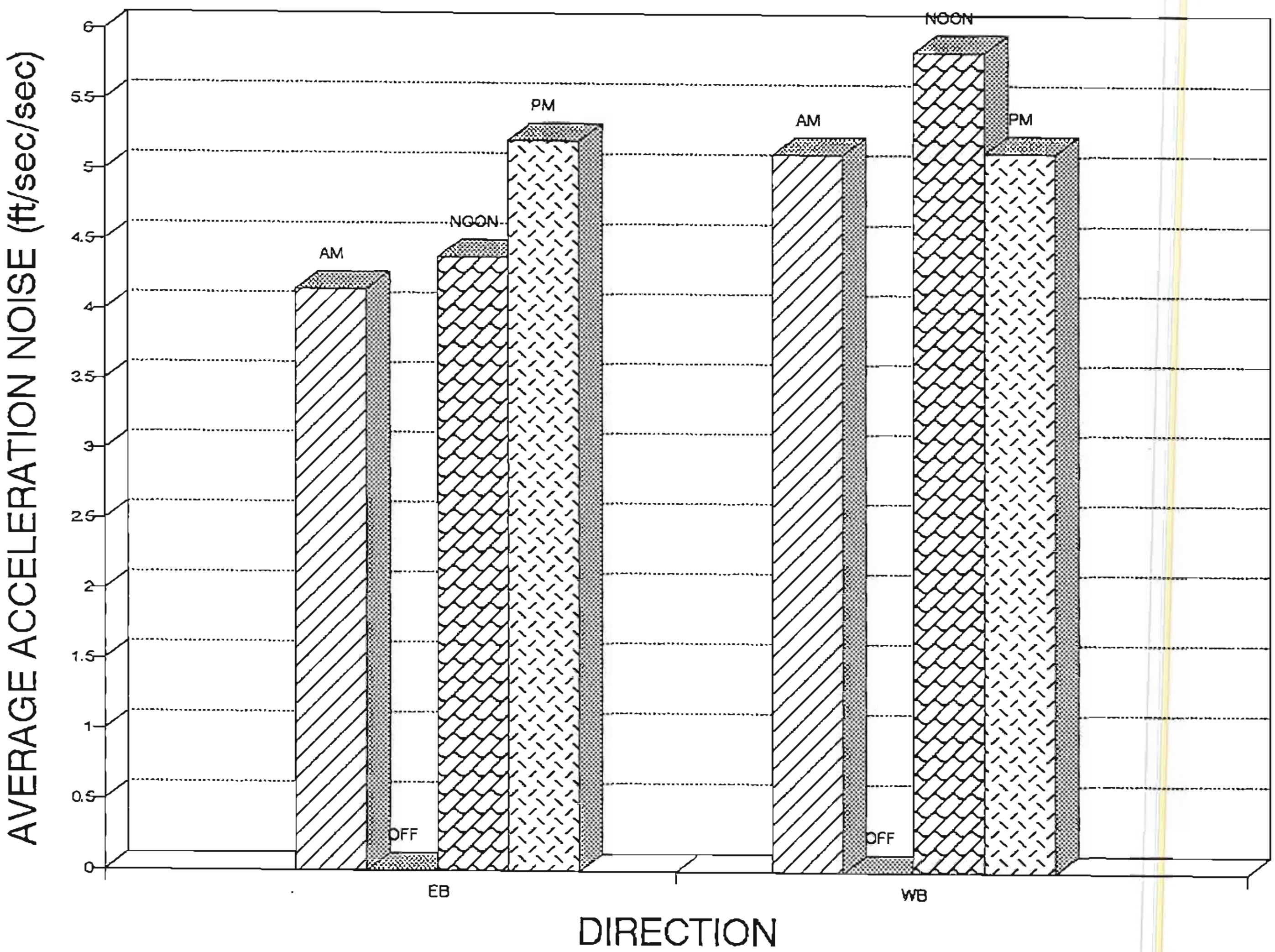

Figure B-5. Acceleration Noise in Each Lane and Direction for SH 174.

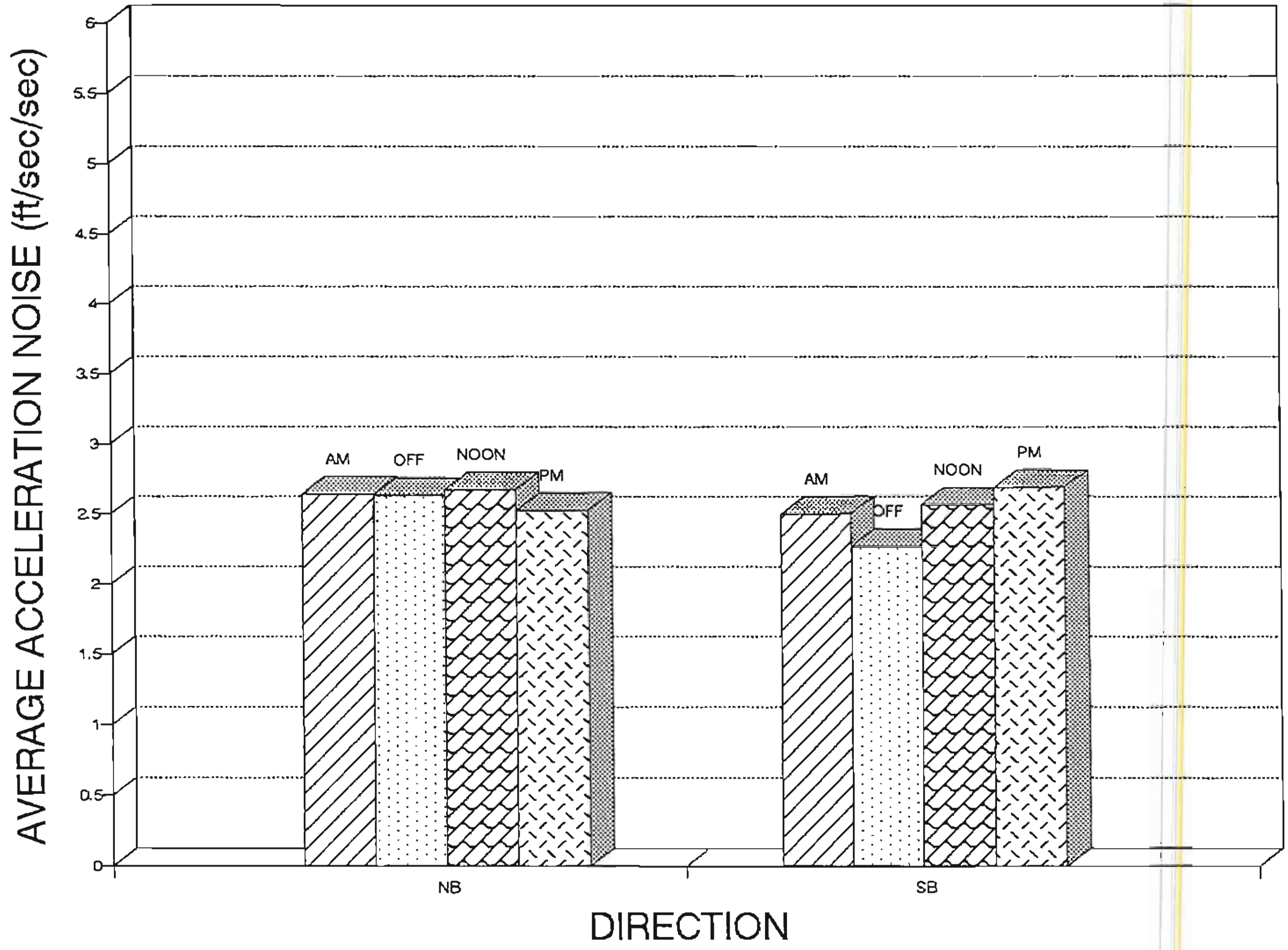

Figure B-6. Acceleration Noise in Each Lane and Direction for SH 6 Site 1.

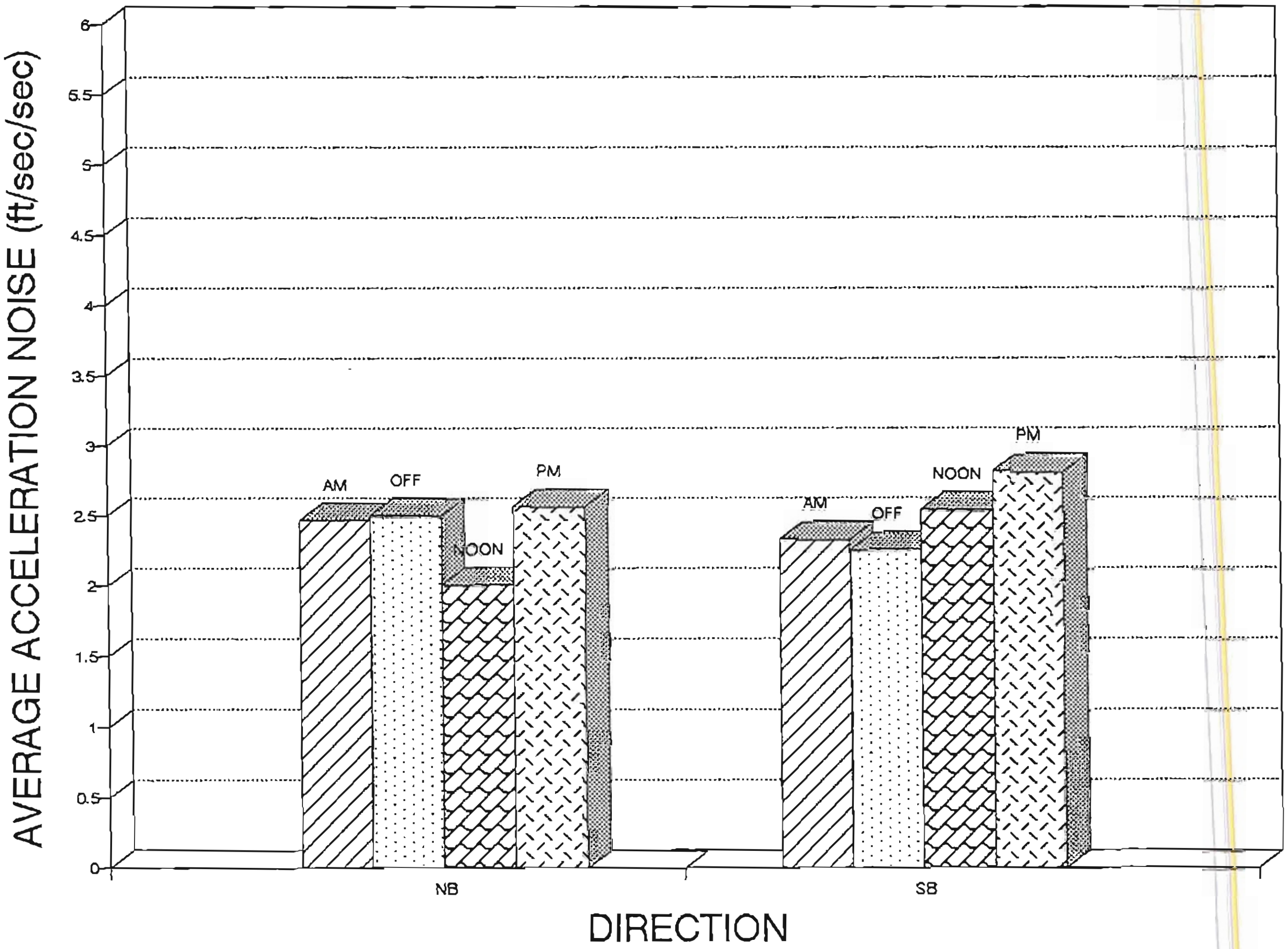

Figure B-7. Acceleration Noise in Each Lane and Direction for SH 6 Site 2.

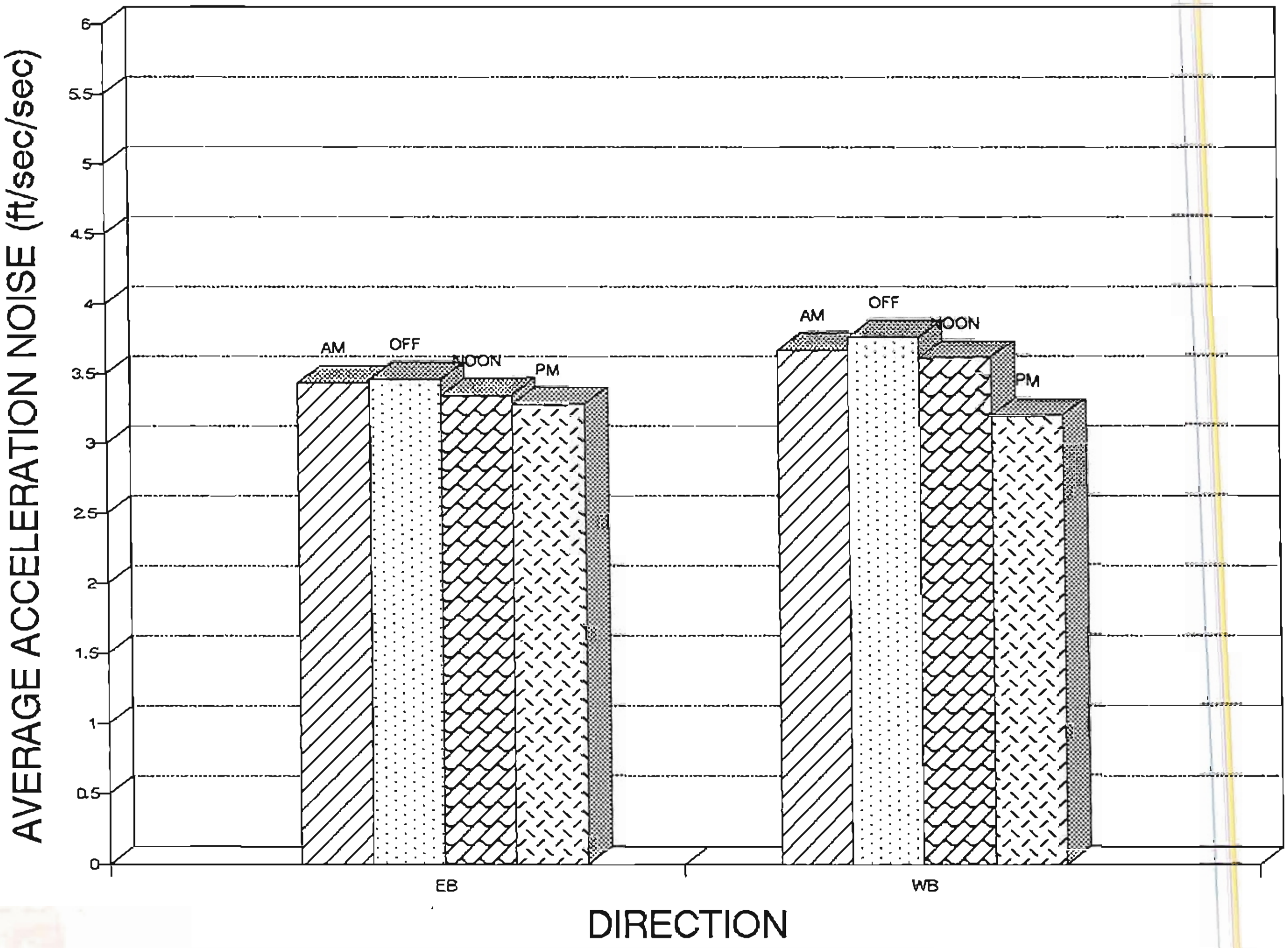

**Figure B-8. Acceleration Noise in Each Lane and Direction for US 90.**