Research Report

Research Project T9903, Task 50
Intersection Improvement

METHOD FOR PRIORITIZING INTERSECTION IMPROVEMENTS

by

Larry Larson
Transportation Engineer

Fred L. Mannering
Professor of Civil Engineering
University of Washington

Washington State Transportation Center (TRAC)
University of Washington, 354802
University District Building
1107 N.E. 45th St., Suite 535
Seattle, Washington 98105

Washington State Department of Transportation
Technical Monitor
Lester Rubstello
Traffic Operations Engineer

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

January 1997

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 413.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Method for Prioritizing Intersection Improvements		5. REPORT DATE January 1997 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Larry Larson and Fred L. Mannering		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) University of Washington, 354802 University District Building; 1107 NE 45th Street, Suite 535 Seattle, Washington 98105-4631		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. Agreement T9903, Task 50
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Transportation Building, MS 7370 Olympia, Washington 98504-7370		13. TYPE OF REPORT AND PERIOD COVERED Research Report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

The most common type of intersection improvement considered by many state DOTs is signalization. The Washington State Department of Transportation (WSDOT) uses a system called the Intersection Priority Array, which was originally developed by Ching. This system provides a tool for objectively considering numerous intersections. Although the system is useful, it only addresses the need for and relative priority of a signal. It does not address other actions that may improve the safety and efficiency of the intersection. The goal of this research project was to develop a system for analyzing the need for left- and/or right-turn lane improvements to an intersection and prioritizing the severity of that need.

Development of the system was based on two questions it would have to answer about the intersection:

1. Is a left- or right-turn lane recommended for a particular intersection? This question is answered on the basis of traffic conditions and accident history. Threshold values for volume and accident history are determined from published engineering studies.

2. How severe is the need for a turn lane compared to other intersections being considered? To answer this question, the system assigns dollar values to delay conditions and accident history specific to the intersection. Dollar values are assigned to accidents over the worst 12-month period in a 3-year accident history. The system then calculates the reduction in delay that would result from installing the left- or right-turn lanes by using regression equations from published engineering studies or standards such as the Highway Capacity Manual.

The scaled sum of the accident and delay costs is the severity score for the specific intersection improvement.

The benefits of this system are that it is an objective method of ranking intersections against others and it is easy to use. It requires data that are easily obtainable from resources available at most traffic offices.

17. KEY WORDS Key words: channelization, left-turn lanes, right-turn lanes, prioritization	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES	22. PRICE

DISCLAIMER

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The most common type of intersection improvement considered by many state DOTs is signalization. The Washington State Department of Transportation (WSDOT) uses a system called the Intersection Priority Array, which was originally developed by Ching (Ching, 1979). This system provides a tool for objectively considering numerous intersections. Although the system is useful, it only addresses the need for and relative priority of a signal. It does not address other actions that may improve the safety and efficiency of the intersection.

The goal of this research project was to develop a system for analyzing the need for left- and/or right-turn lane improvements to an intersection and prioritizing the severity of that need. To be effective the system needed to be

- based on engineering studies
- objective and logical
- easy to use
- able to use easily obtainable data
- able to adapt to changing standards
- accepted by operation engineers, management, and planners.

RESEARCH APPROACH

To accomplish the objectives an extensive literature search was undertaken. A survey was also sent to each state department of transportation in the United States. From these sources, methods of analysis were chosen that could be programmed into a computer database program. A database program was developed to accomplish the goals listed above.

The results of the original project were implemented by WSDOT's Northwest Region. After a six-month implementation and testing period, the performance of the system was reviewed, and some changes were made to the methodology.

PRIORITIZATION STRATEGY

Development of the system was based on two questions it would have to answer about the intersection:

1. *Is a left- or right-turn lane recommended for a particular intersection?*
2. *How severe is the need for a turn lane compared to other intersections being considered?*

The first question is answered on the basis of traffic conditions and accident history. Threshold values for volume and accident history are determined from published engineering studies. The volume threshold for left-turn lanes is based on a modified AASHTO table (Kikuchi and Chakroborty 1991). The accident threshold for left-turn lanes is four preventable accidents in a 12-month period (Agent 1983). The volume threshold for right-turn lanes is based on warrant graphs developed by Cottrell (Cottrell 1981). The accident guideline for right-turn lanes is five preventable accidents in a 12-month period. This number is a based on other warrant guidelines for traffic control devices and has no statistical basis.

To answer the second question, the system assigns dollar values to delay conditions and accident history specific to the intersection. Dollar values are assigned to accidents over the worst 12-month period in a 3-year accident history. The dollar values are taken from the Federal Highway Administration (FHWA 1991) and WSDOT (Wessels and Limotti 1992) guidelines for the Most Severe Injury (MSVJ) of an accident. The system then calculates the reduction in delay that would result from installing the left- or right-turn lanes by using regression equations from published engineering studies or standards such as the Highway Capacity Manual (HCM).

The scaled sum of the accident and delay costs is the severity score for the specific intersection improvement.

NEED FOR A LEFT-TURN LANE

Left-Turn Lane Accident Guideline

The left-turn accident guideline is the threshold number of accidents that would justify installation of a left-turn lane. Agent's proposal (Agent 1983) of four preventable accidents during a 12-month period was originally adopted for this guideline. As implemented, the 12-month period was taken from a three-year history. A preventable accident is assumed to be any accident

that would have been prevented or less likely to occur as a result of the installation of a left-turn lane. After implementation and review, this threshold number was modified.

Left-Turn Lane Volume Guideline

The left-turn volume guideline is used to determine when volume levels reach the point that a left-turn lane is needed or recommended. There are two primary situations for consideration: two-lane highways and four-lane highways. For the two-lane highway situation, Kikuchi and Chakroborty's modified Harmelink (AASHTO) model was chosen as the source for guideline threshold values for left-turn lanes. The four-lane highway equations are from Harmelink's original study (Harmelink 1967).

LEFT-TURN LANE SEVERITY SCORE

After the program has determined whether a left-turn lane is justified, the intersection approach has to be ranked among other candidate intersections. A severity score is used to determine this ranking. The left-turn lane severity score is the sum of the costs related to accident history and delay.

Accident Severity Score

The accident score was originally found by summing the costs of preventable accidents over a 12-month period. The cost factors below are used by WSDOT and were adopted for this system (Wessels and Limotti 1992):

Per Fatal or Disabling Injury Collision	$700,000
Per Evident Injury Collision	$57,000
Per Possible Injury Collision	$30,000
Per Property Damage Only Collision	$5,300

Implementation of the original program revealed that this methodology did not necessarily reflect actual conditions or reliably predict future conditions. As mentioned above, WSDOT figures the cost of fatality and disabling-injury accidents at $700,000 (FHWA values are even higher). An evident-injury accident is listed at $57,000. Using these values as a severity score would mean that an intersection with one disabling accident would be considered more serious than

an intersection with 12 evident-injury accidents. This method failed to recognize that many variables determine the severity of an injury. Factors such as seat belt usage, tire condition, type and size of automobile, alcohol involvement, physical condition of vehicle occupants, and others could mean the difference between a possible injury accident and a fatality.

Although the seriousness of a disabling or fatal accident must not be diminished, the system needed to be based on data that more reliably conveyed accident conditions and likelihood.

WSDOT's accident database was searched for all accidents that occurred for through-movements with no stop or signal control at urban and rural locations. The search was conducted on data from WSDOT's Northwest region and included five years of data. Out of these, accidents that could have been prevented by a left- or right-turn lane were used for analysis. The most prevalent types were rear-end, sideswipe, and opposite direction. The percentages of the five accident severity classifications were then found for each type of accident.

For example, on rural highways .3 percent of sideswipe accidents are fatal, 4.1 percent are disabling injury, 15.4 percent are evident injury, 22 percent are possible injury, and 58.1 produce no injury. By applying the societal costs already used by WSDOT to these percentages, the average societal cost was found for each type of accident.

Accident Analysis Period Modifications

In the performance review, concerns were raised that the "worst 12 months in a three-year period" criterion used for accident data analysis might give too much emphasis to problems that may no longer exist. Examples of this include problems due to construction projects or weather, and problems fixed by new projects.

WSDOT decided to instead use the annual average of a three-year accident history. This approach spreads out data spikes and better identifies ongoing problems.

Accident Threshold Modifications

The accident threshold was also based on the worst 12 months in a three-year history. Although this did not necessarily need to change, leaving it the same would force the engineer to analyze an accident record twice, once for the worst 12 months and once for the annual average. To maintain consistency among and clarity for many database users, a threshold was needed for

the annual average. Using 58 accident records in the database the mean and standard deviation of the average number of accidents per intersection approach were determined. There were .86 accidents per year, with a standard deviation of .60. Reviewers decided that approaches with an average of more than one standard deviation above the mean (1.46 accidents per year) would justify a left-turn lane. Eight (14 percent) of the intersections were above this range. A critical accident rate based on more in-depth analysis is needed.

Delay Severity Score

The system calculates the delay severity score for left-turn lanes with equations from chapter 10 of the Highway Capacity Manual (HCM) (TRB 1994).

The basic procedure is to first assume that a left-turn lane has already been installed and then to figure the delay for that movement. Next, subtract the left-turn traffic delay (from the assumed condition) from the delay in the existing condition (shared lane use). This is the estimated delay reduction that would result from the installation of a left-turn lane. The delay reduction is then annualized and assigned a cost based on truck and passenger vehicle volumes. Cost factors for these volumes are $50 per hour for trucks and $10 per hour for automobiles.

NEED FOR A RIGHT-TURN LANE

Right-Turn Lane Accident Guideline

The Literature Review found no published studies that recommend a threshold value for the number of accidents that would justify a right-turn lane. This is primarily because of the lack of sufficient data for statistical analysis.

After six months of operation, the database for right-turn lane prioritization had accumulated 22 entries. Similarly to the left-turn threshold, these 22 entries were analyzed. The mean accident rate was .54 accidents per year, the standard deviation was .28. Intersections with average accident rates of greater than one standard deviation above the mean (.82 accidents per year) are said to need a right-turn lane. Research is needed to determine the critical accident rate that would justify a right-turn lane.

Right-Turn Lane Volume Guideline

Cottrell's guidelines for right-turn lanes (Cottrell 1981) were chosen for this system. Included in Cottrell's study are guidelines to determine whether right-turn lanes or tapers are recommended. In this system only right-turn lanes are included in the priority ranking.

RIGHT-TURN LANE SEVERITY SCORE

The Right-Turn Lane Severity Score is calculated by summing costs associated with delay and accident history.

Accident Severity Score

The right-turn lane accident severity score is figured in the same manner as the left-turn lane accident severity score.

Delay Severity Score

The regression equations proposed by McCoy et al. (McCoy 1993) were chosen to determine the reduction in delay caused by the installation of a right-turn lane.

CONCLUSIONS

Along with signalization, other improvements should be considered that will increase the safety and efficiency of an intersection. Left- and right-turn lanes can significantly improve the operations of an intersection. This project developed a computer program based on published standards and engineering studies that enables the engineer to maintain a prioritized list of intersections being considered for such improvements.

The benefits of this system are that it is an objective method of ranking intersections against others and it is easy to use. It requires data that are easily obtainable from resources available at most traffic offices.

CHAPTER ONE
INTRODUCTION

PROBLEM

The most common type of intersection improvement considered by many state DOTs is signalization. The Washington State Department of Transportation (WSDOT) uses a system called the Intersection Priority Array, which was originally developed by Ching (Ching, 1979). This system provides a tool for objectively considering numerous intersections. Although the system is useful, it only addresses the need for and relative priority of a signal. It does not address other actions that may improve the safety and efficiency of the intersection.

Other potential improvements include left-turn lanes, right-turn lanes, acceleration tapers, illumination, and sight-distance improvements. If these improvements are considered in conjunction with a signal warrant analysis, the intersection may be analyzed more comprehensively. Many times, implementing one of the other improvements will increase safety and efficiency to such a degree that the intersection will no longer warrant signalization. Currently, WSDOT lacks a program or system similar to the Signal Priority Array for other intersection improvements. The most significant need is for a system that will rank unsignalized intersections being considered for left- and right-turn lanes.

Left- and right-turn lanes can significantly improve operations and safety at many intersections. Left-turning vehicles conflict with opposing through-traffic, crossing traffic, and advancing through-traffic. Accidents at an intersection are reduced an estimated 35 percent by the installation of a left-turn lane at an unsignalized intersection (TRB 1985). Right-turning vehicles conflict with fewer movements but can still reduce the overall operation of an intersection.

One benefit of a system that determines the need for left- and right-turn lanes and compares and prioritizes that need among intersections is objectivity. Sometimes decisions about whether to improve a highway are influenced by politics or public outcry. A system based on engineering factors such as delay and safety would help alleviate this problem.

Another benefit of such a system is that it would provide a mechanism for planners to allocate public monies in a more diversified manner. The specific needs of an intersection would be met more easily when additional options were considered.

OBJECTIVES

The goal of this research project was to develop a system for analyzing the need for left- and/or right-turn lane improvements to an intersection and prioritizing the severity of that need. To be effective the system needed to be

- based on engineering studies
- objective and logical
- easy to use
- able to use easily obtainable data
- able to adapt to changing standards
- accepted by operation engineers, management, and planners.

To accomplish these objectives an extensive literature search was undertaken. A survey was also sent to each state department of transportation in the United States. From these sources, methods of analysis were chosen that could be programmed into a computer database program. A database program was developed that accomplishes the goals listed above. Although this database is described herein, the purpose of the report is to present the methodology selected. Any standard database structure could be used with standard programming techniques.

The results of the original project were implemented by WSDOT's Northwest Region. After a six-month implementation and testing period, the performance of the system was reviewed. This report describes the results of the original research, as well as changes that were made to the methodology.

DEVELOPMENT STRATEGY

Development of the system was based on two questions it would have to answer about the intersection:

1. *Is a left- or right-turn lane recommended for a particular intersection?*

2. *How severe is the need for a turn lane compared to other intersections being considered?*

The basic strategy for answering these questions is described below and then in detail in the appropriate sections.

The first question is answered on the basis of traffic conditions and accident history. Threshold values for volume and accident history are determined from published engineering studies (described in Chapter 2).

To answer the second question, the system assigns dollar values to delay conditions and accident history specific to the intersection. Dollar values are assigned to accidents over the worst 12-month period in a 3-year accident history. The dollar values are taken from the Federal Highway Administration (FHWA 1991) and WSDOT (Wessels and Limotti 1992) guidelines for the Most Severe Injury (MSVJ) of an accident. The system then calculates the reduction in delay that would result from installing the left- or right-turn lanes by using regression equations from published engineering studies or standards such as the Highway Capacity Manual (HCM).

The scaled sum of the accident and delay costs is the severity score for the specific intersection improvement.

Notes on Development Strategy

This report and the software developed are intended to be used as a planning tool, not a design tool. They provide a starting point and an aid for analyzing intersections being considered for left- or right-turn lanes. Although the warrant guidelines, cost of delay, and cost of accidents are based on current engineering studies and practices, they are also intended to be simplified so that engineers can use the system with readily available data. If a particular intersection is chosen for further development, it should be subjected to the normal process of design and thorough cost-benefit analysis. Furthermore, this project is not intended to provide warrants for left-turn lanes or right-turn lanes. Instead, it provides guidelines and/or recommendations for left- and right-turn lanes.

Each intersection is considered for individual improvements specific to its movement and approach. For example, the northbound and southbound approaches of a given intersection would

be considered separately for left-turn lanes and could be ranked against each other. In reality, a left-turn lane would probably be added to both approaches because of alignment reasons, even if only one approach warranted the improvement.

CHAPTER TWO
STATE OF THE ART

LITERATURE REVIEW

An extensive literature review was conducted using the Transportation Research Information Service database. Studies were needed to provide threshold values for volume and delay in the following nonsignalized intersection scenarios:

- left-turn lanes for two-lane highways
- left-turn lanes for four-lane highways
- right-turn lanes for two-lane highways
- right-turn lanes for four-lane highways.

All relevant studies found are described below. The equations and values chosen from these articles are described in Chapter 3.

Left-Turn Lanes

Intersections on two-lane roads are most often considered for left-turn lanes. The first parameter considered in determining the need for a left-turn lane is based on volume. In 1967, Harmelink proposed a model for determining volume warrants for left-turn lanes at unsignalized intersections (Harmelink 1967). The report states that left-turning vehicles blocking through-lane traffic are the main cause of safety and efficiency breakdowns at unsignalized intersections. Harmelink proposed a set of maximum probabilities for this occurrence as warrants for left-turn lanes. This methodology was adopted by the American Association of State Highway And Transportation Officials (AASHTO) (AASHTO 1964) and subsequently by many departments of transportation across the nation. The National Cooperative Highway Research Program (NCHRP) Report #279 also recommends Harmelink's model (TRB 1985).

In 1991, Kikuchi and Chakroborty published a comparative analysis of level-of-service (LOS), delay, and the Harmelink models (Kikuchi and Chakroborty 1991). Included in the article was a critical analysis of the Harmelink model that revealed some errors in the model's application of queuing theory. Kikuchi and Chakroborty modified the model to use queuing theory correctly.

A comparison of the three methods revealed that if conditions warranted a left-turn lane in the modified Harmelink model, it was also warranted in the LOS model and most of the delay model. Only when traffic volumes were high did the delay model warrant a left-turn lane before the Harmelink model.

Harmelink's original report also introduced a model for left-turn lanes on four-lane highways, which was also based on the probability of a queue being formed behind a left-turning vehicle (Harmelink 1967). The model uses different values for divided four-lane highways and undivided highways, but the rationale is the same. No table of values was available in the original study. Rather, a graph is offered with left-turning volume and opposing volume on the x-axis and y-axis, respectively. When conditions plotted on the graph are above a threshold line, the left-turn lane is warranted.

Interestingly, AASHTO never adopted this model. In fact, AASHTO does not mention warrants or guidelines for left-turn lanes on four-lane highways. WSDOT makes the same omission in its Design Manual, except that it does reference Harmelink's original work if left-turn warrants are sought for four-lane highways. This is probably because left-turning traffic on four-lane highways is less of a safety and operational problem than on two-lane highways.

Harmelink's four-lane model has not been critically analyzed in the same manner as the two-lane model. However, the queuing problems of the two-lane model were related to its inability to clear queues waiting for a left-turning vehicle, and thus a steady state was never achieved. This problem would not be as prevalent on a four-lane highway (in normal conditions) because traffic waiting for left-turning vehicles can move into the outside lane. The NCHRP Report #279 also recommends Harmelink's model for left-turn lanes on four-lane highways (TRB 1985).

The other parameter for determining the need for a left-turn lane is based on accident history. Only one source contained accident guidelines for left-turn lanes (Agent 1983). This article proposes that the warranting number of preventable accidents be four in a 12-month period. This criterion is the result of an "average critical accident rate" formula developed for the Kentucky

Department of Transportation. This guideline is recommended by the ITE Committee 4A-22 article *Guidelines for Left-Turn Lanes* (ITE 1990).

Once the need has been established for a particular intersection approach, a severity score is necessary to rank the approach. The first part of the severity score is based on delay. The 1994 HCM, Chapter 10, equations for capacity, shared-lane capacity, and delay are used to figure the reduction in delay that would be produced by the installation of a left-turn lane (TRB 1994). Delay is first figured for the approach by assuming that a left-turn lane has already been installed. Overall delay is then figured using the shared lane equation. The difference between the two is the reduction in delay.

The second part of the severity score is found by assigning dollar values to the accident history. The Federal Highway Administration published a report that lists costs per crash for accidents that occurred across the United States in 1988 (FHWA 1991). The results are shown in Table 2.1.

Table 2.1 FHWA Collision Cost Factors

Severity	Per Crash
Fatal	$2,722,548
Incapacitating	$228,568
Non-incapacitating	$48,333
Possible Injury	$25,228
Property Damage Only	$4,489

WSDOT used these cost factors to establish its standards for priority selection. However, WSDOT traffic safety personnel recommend that a weighted average for fatal and disabling (incapacitating) injuries be used. They recognize that the margin between a disabling and a fatal injury accident is often very small (Wessels and Limotti 1992). WSDOT cost factors are shown in Table 2.2.

Table 2.2 WSDOT Collision Cost Factors

Severity	Per Crash
Fatal & Disabling	$700,000
Non-incapacitating	$57,000
Possible Injury	$30000
Property Damage Only	$5,300

Right-Turn Lanes

In a manner similar to the left-turn lane analysis, the first parameter for determining the need for a right-turn lane is based on volumes. Little research has been conducted on volume guidelines for installing right-turn lanes. However, NCHRP Report #279 (TRB 1985) recommends guidelines for right-turn lanes on two- and four-lane highways that were developed by Cottrell (Cottrell 1981). Cottrell's recommendations reflect guidelines from Iowa and Idaho that are adjusted to match traffic conditions in Virginia. A distinction is made between right-turn lanes and right-turn tapers. WSDOT has adopted these guidelines in its Design Manual.

McCoy, et al. (McCoy 1993) developed guidelines for right-turn lanes based on a more comprehensive approach than other methods. They proposed basing right-turn lane guidelines on benefit-cost analysis over a wide range of factors. Benefits in operations and accident reduction are figured, along with cost savings in delay and fuel consumption. These are compared with typical construction costs in Nebraska.

The second parameter for determining the need for right-turn lanes is based on accident history. Several attempts have been made to develop a threshold recommendation for the critical number of preventable accidents to warrant a right-turn lane. However no recommendation has been found, primarily because of the lack of sufficient accident data for statistical analysis (Cottrell 1981, McCoy 1993).

The severity score for right-turn lanes is also based on delay and accident history. The HCM assumes that right-turning traffic experiences no delay, and for this reason it proposes no delay reduction equations (TRB 1994). However, McCoy et al.(McCoy 1993) used the TRAF-NETSIM software to generate data that were used in multiple regression analysis to determine delay on two- and four-lane highways. Included in the regression results was a variable for

intersections with right-turn lanes already installed. Using this variable and its coefficient, the reduction in delay for a right-turn lane is easily found.

DOT SURVEY

In an effort to determine the state of the art and other standards for left- and right-turn lanes, a survey was sent to state traffic engineers across the United States (including Puerto Rico). Out of 51 surveys sent, 29 were returned. The results of the surveys are shown in tables 2.3 and 2.4. A copy of the survey is in Appendix 1.

Of the 25 states that responded, none maintain priority lists for right-turn lanes exclusively. Michigan maintains a priority list of "high accident intersections" being considered for future improvements. Fifty-five percent (16 of 29) of the responding states use no set standard or guideline for right-turn lanes. Rather, they apply engineering judgment and/or a delay or capacity analysis. Fourteen percent (4 of 29) use the NCHRP report #279/Cottrell model to warrant a right-turn lane.

The remaining states use standards that are relatively unique to their DOTs. Georgia uses a rule of thumb guideline that recommends right-turn lanes when side road volume is greater than 300 vpd, mainline right-turn volume is greater than 30 vph, and mainline volume exceeds 6000 vpd on multi-lane highways or 2000 vpd on two-lane highways.

Idaho's DOT uses a standard that is similar to the NCHRP report #279/Cottrell standard. However Idaho's standard is more conservative from a safety standpoint (warranting conditions are much lower than the NCHRP standard). For instance, the NCHRP report would not warrant a right-turn lane when the right-turn volume is below 40 vph. Idaho's standard will warrant a right-turn lane for right-turning volumes as low as 5 vph, depending on other conditions.

Kansas provides right-turn lanes when the right-turn volume exceeds 40 vph. Tennessee uses the HCM recommendation for right-turn lanes at signalized intersections for unsignalized intersections. This recommendation states that right-turn lanes should be considered when the through-volume of an approach exceeds 300 vehicles per hour per lane (vphpl), and the right-turning volume exceeds 300 vehicles per hour (vph).

Similarly to the right-turn results, no states maintain a database for intersections being considered for left-turn lanes exclusively. Fifty-two percent (15 of 29) of responding states use the AASHTO/Harmelink standard for their left-turn warrants. Thirty-one percent (9 of 29) use no set standard but install left-turn lanes as a result of engineering judgment, accident analysis, delay analysis, and/or political pressure.

The remaining states use unique standards. For example, Georgia attempts to install left-turn lanes at all divided highway median openings. Idaho uses a warrant curve similar to its right-turn guideline. In this model, a left-turn lane is recommended when the left-turning volume is as low as 12 vph, and the through-volume is 100 vph. By contrast, the AASHTO model would only recommend a left-turn lane with a left-turning volume of 12 when the through volume is 230 vph.

TABLE 2.3 Right-Turn Lane Survey Results

State	Priority List?	Published Standard		Engineering Judgment	Capacity or Delay Analysis	Rule of Thumb	Standard used/Comments
		NCHRP	Unique state policy				
California	no		X				Caltrans Design Manual
Delaware	no			X			
Georgia	no		X				Minimum volume and R/W cost criteria
Hawaii	no					X	
Idaho	no		X				State policy based on approach volume and right-turn volume.
Iowa	no		X	X			State policy & Engineering judgment
Kansas	no		X				State policy. Lane provided when right-turn volume exceeds 40 vph.
Maine	no	X					Maine Hwy Design Guide, based on NCHRP Rpt 279/Cottrell Table
Massachusetts	no			X	X		
Michigan	yes	X					Department Policy based on NCHRP/Cottrell Guidelines.
Minnesota	no		X	X			Minnesota Design Manual
Mississippi	no		X				MDOT Design Manual
Nebraska	no	X		X	X		HCM and NCHRP Rpt 279/Cottrell
Nevada	no			X	X		
New Hampshire	no			X			
New York	no			X	X		Evaluate safety & capacity benefits
North Dakota	no			X	X		

TABLE 2.3 Right-Turn Lane Survey Results (continued)

State	Priority List?	Published Standard		Engineering Judgment	Capacity, or Delay Analysis	Rule of Thumb	Standard used/Comments
		NCHRP	Unique state policy				
Ohio	no			X			
Pennsylvania	no			X	X		
Puerto Rico	no				X		
Rhode Island	no			X	X		
S. Carolina	no			X			
Tennessee	no		X				TDOT Roadway Design Guide references HCM Ch 9 App1--right-turn volume exceeds 300 vph and thru volume exceeds 300 vphpl. (For signalized intersections.)
Texas	no			X	X		
Utah	no				X		
Vermont	no		X				AASHTO*
Virginia	no		X	X			AASHTO* And at steep, long downgrades.
Washington	no	X					State Design Manual based on NCHRP/Cottrell
W. Virginia	no			X	X		
Wisconsin	no					X	Standard under development.
Wyoming	no				X		

* The author could find no warrant information for right-turn lanes. However, design information is provided.

TABLE 2.4 Left-Turn Lane Survey Results

State	Priority List?	Published Standard		Engineering Judgment	Capacity, Delay Analysis	Rule of Thumb	Standard used/Comments
		AASHTO	Unique state policy				
California	no	X					Design Publication based on AASHTO
Delaware	no			X			
Georgia	no		X		X		Ltls installed at all divided highway median openings, and at accident/congestion problems
Hawaii	no			X			
Idaho	no		X				State Traffic Manual--Warrant curve and when PHV left turns exceed 12
Iowa	no	X		X			AASHTO
Kansas	no	X					AASHTO
Maine	no	X					Maine Hwy Design Guide/AASHTO
Massachusetts	no			X	X		
Michigan	yes	X					Prioritized-list of high accident intersections is maintained.
Minnesota	no	X		X			Minnesota Design Manual/AASHTO
Mississippi	no		X				Political solution and to relieve congestion.
Nebraska	no	X		X	X		HCM and NCHRP Report 279
Nevada	no			X	X		

TABLE 2.4 Left-Turn Lane Survey Results (continued)

State	Priority List?	Published Standard		Engineering Judgment	Capacity, Delay Analysis	Rule of Thumb	Standard used/Comments
		AASHTO	Unique state policy				
N. Hampshire	no	X					AASHTO
New York	no			X	X		Emphasis on reduction of rear-end accidents.
N. Dakota	no			X	X		
Ohio	no			X			
Pennsylvania	no			X	X		Base on Accident Experience
Puerto Rico	no	X					
Rhode Island	no	X		X	X		
S. Carolina	no			X			
Tennessee	no	X					TDOT Roadway Design Guide uses AASHTO.
Texas	no			X	X		
Utah	no				X		Usually considered during design phase.
Vermont	no	X					AASHTO/Harmelink
Virginia	no		X	X			VDOT manual, accident problems, volumes.
Washington	no	X					State Design Manual based on AASHTO
W. Virginia	no	X			X		AASHTO
Wisconsin	no		X			X	Standard under development.
Wyoming	no	X		X			AASHTO

CHAPTER THREE
RESULTS

METHODOLOGY

Microsoft Access was chosen for ease of integration with WSDOT's signal priority list, which uses the same package. The program is written using standard database techniques. There are four primary sections to the database: tables, forms, queries, and reports. The left- and right-turn priority lists are derived from two master data tables, one for each list. All the data about a particular intersection is stored in the master table.

The data in the master tables are entered into forms. There are two types of forms for each priority list. The first form is the "add" form. With this form new intersection approaches are entered for consideration of either a left- or right-turn lane. The other form is the "edit" form. The edit form is used to change or update data in the master table about an intersection approach.

The query section uses the equations that are described below to determine which data it needs to "query" from the master table. When the correct data have been queried, the equations are then applied to the data to produce the proper recommendation and/or severity score.

The report section is used to view and print reports about the priority list. Two types of reports are available. The first is the "individual intersection" report. The engineer is able to examine all the information about individual intersections from this report. The other report is the list report. With this report the engineer is able to examine the entire priority list with just the relevant ranking information. This report can be sorted by highway number and milepost, or by priority ranking. Examples of forms and reports are shown in Figures 3.1 and 3.2.

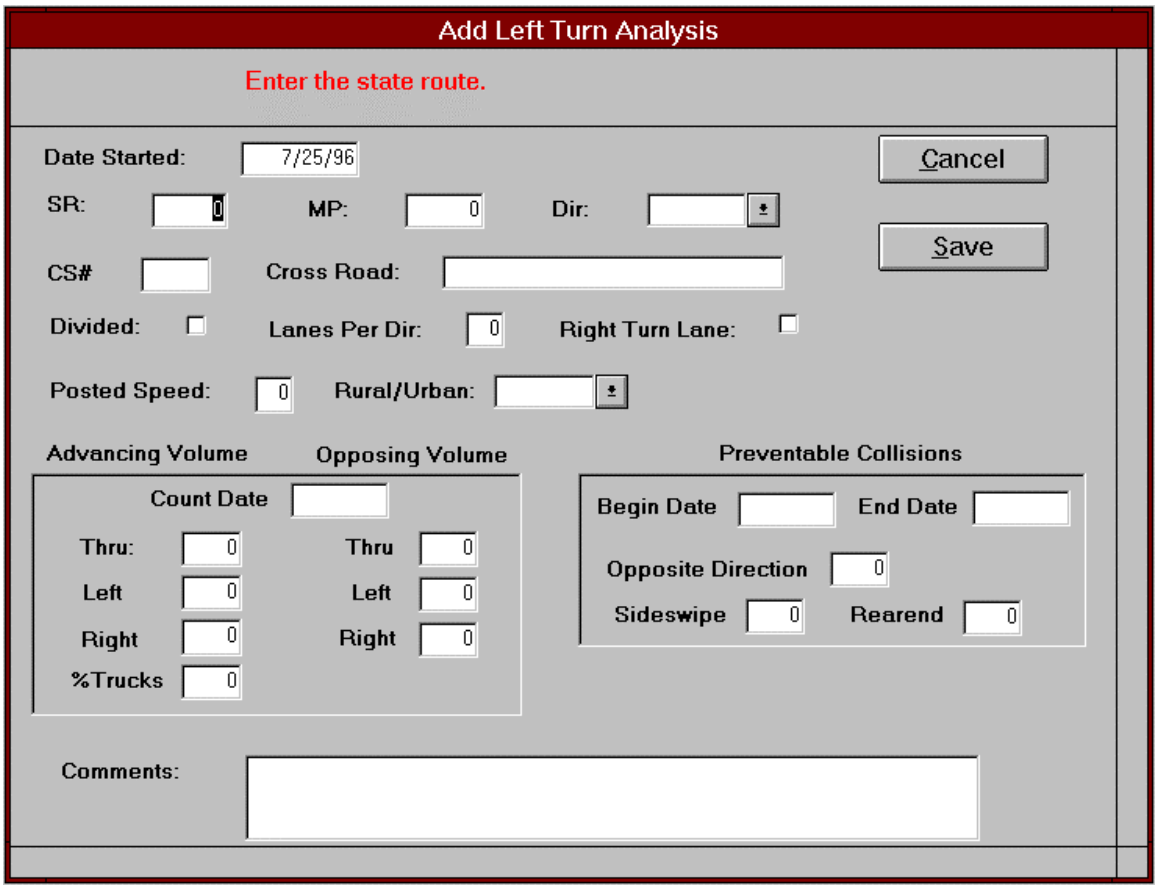
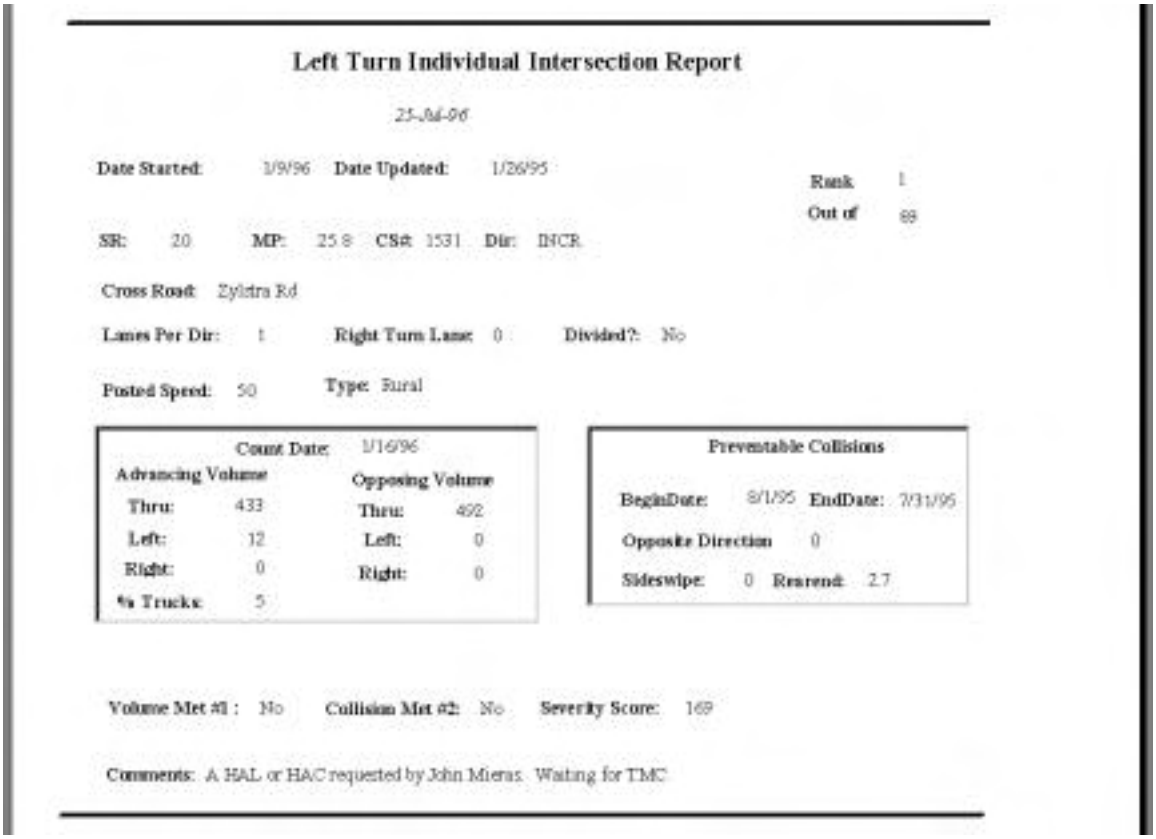


Figure 3.1 Edit Form



Left Turn Individual Intersection Report

25-Jul-96

Date Started: 1/9/96 Date Updated: 1/26/95

Rank 1
Out of 69

SR: 20 MP: 25.8 CS#: 1531 Dir: INCR

Cross Road: Zylstra Rd

Lanes Per Dir: 1 Right Turn Lane: 0 Divided?: No

Posted Speed: 50 Type: Rural

Count Date: 1/16/96

Advancing Volume		Opposing Volume	
Thru:	433	Thru:	492
Left:	12	Left:	0
Right:	0	Right:	0
% Trucks:	5		

Preventable Collisions

BeginDate: 8/1/95 EndDate: 7/31/95

Opposite Direction 0

Sideswipe: 0 Rearend: 2.7

Volume Met #1 : No Collision Met #2: No Severity Score: 169

Comments: A HAL or HAC requested by John Mieras. Waiting for TMC

Figure 3.2 Left-Turn Individual Intersection Report

LEFT-TURN LANE ACCIDENT GUIDELINE

The left-turn accident guideline is the threshold number of accidents that would justify installation of a left-turn lane. Agent's proposal (Agent 1983) of four preventable accidents during a 12-month period was originally adopted for this guideline. As implemented, the 12-month period was taken from a three-year history. A preventable accident is assumed to be any accident that would have been prevented or less likely to occur as a result of the installation of a left-turn lane. After implementation and review, this threshold number was modified. This modification is described in a later section.

LEFT-TURN LANE VOLUME GUIDELINE

The left-turn volume guideline is used to determine when volume levels reach the point that a left-turn lane is needed or recommended. There are two primary situations for consideration: two-lane highways and four-lane highways. The four-lane situation can be further categorized into divided and undivided highways.

Two-Lane Highways

For the two-lane highway situation, Kikuchi and Chakroborty's modified Harmelink (AASHTO) model was chosen as the source for guideline threshold values for left-turn lanes. Table 3.1 and Table 3.2 show the original Harmelink Model and the Modified Harmelink model, respectively. As can be seen, the modified Harmelink model is a less conservative model; i.e., it will recommend the installation of left-turn lanes for higher volumes than the original Harmelink model. For example, in a situation where the left-turning volume was 10 percent of the approach volume, the speed limit was 40 mph, and the opposing volume was 400 vph, the AASHTO model (original Harmelink model) would warrant a left-turn lane when the approach volumes reached 380 vph. In the modified Harmelink model, a left-turn would be warranted when the approach volumes reached 472 vph.

For ease in programming, an equation was needed that would yield the same values as the table. The computer program Statistical Software Tool (SST) (California Institute of Technology) was used to perform a regression analysis on the modified Harmelink model. The following equation was estimated:

$$AV = \exp(6.9017 - .001151OpVol + 0.81007PLTF + .45384PLTT + 0.13858PLTW - .01816SP) \qquad \textbf{Eq. 3.1}$$

where:

AV	=	Advancing volume to warrant a left-turn lane (includes left- and right-turning vehicles)
OpVol	=	Total opposing volume in opposite direction lanes
SP	=	Operating speed. This value is assumed to be the posted speed limit or 85th percentile speed (if available)

PLTF = 1 when the percentage of left-turning traffic is rounded up to 5 percent, otherwise equal to zero.

PLTT = 1 when the percentage of left-turning traffic is rounded up to 10 percent, otherwise equal to zero.

PLTW = 1 when the percentage of left-turning traffic is rounded up to 20 percent, otherwise equal to zero.

Table 3.1 Harmelink/AASHTO Left-Turn Warrants

	Approach Volume			
Opposing Volume	5% Left	10% Left	20% Left	30% Left
	40-mph Operating Speed			
800	330	240	180	160
600	410	305	225	200
400	510	380	275	245
200	640	470	350	305
100	720	575	390	340
	50-mph Operating Speed			
800	280	210	165	135
600	350	260	195	170
400	430	320	240	210
200	550	400	300	270
100	615	445	335	295
	60-mph Operating Speed			
800	230	170	125	115
600	290	210	160	140
400	365	270	200	175
200	450	330	250	215
100	505	370	275	240

Table 3.2 Modified Harmelink/AASHTO Left-Turn Warrants

	Approach Volume			
Opposing Volume	5% Left	10% Left	20% Left	30% Left
	40-mph Operating Speed			
800	434	300	219	189
600	542	375	272	234
400	682	472	343	293
200	863	600	435	375
100	946	679	493	424
	50-mph Operating Speed			
800	366	257	185	162
600	460	320	234	202
400	577	403	294	255
200	735	513	373	324
100	830	576	424	365
	60-mph Operating Speed			
800	294	207	154	146
600	365	259	187	165
400	461	324	238	206
200	586	414	303	263
100	663	468	344	297

Performance characteristics for Equation. 3.1 are shown in Table 3.3.

Table 3.3 Equation 3.1 Performance Characteristics

Independent Variable	Estimated Coefficient	Standard Error	t- Statistic
One	6.90170	1.88e -2	366.28
OpVol	-1.15e -3	1.11e -5	-103.99
PLTF	0.81007	8.02e -3	101.04
PLTT	0.45384	8.02e -3	56.61
PLTW	0.13858	8.02e -3	17.29
SP	-1.82e -2	3.47e -4	-52.31
Corrected R-squared = 99.7%			

Equation 3.1 required the left-turn percentage to be rounded up to the nearest 5 percent. To make it easier to use, a regression analysis was performed on the left-turn coefficients only. This yielded the following equation estimate and the corresponding performance characteristics in Table 3.4:

$$LtCoef = .383 - .118lt\% \qquad \textbf{Eq. 3.2}$$

where lt% is the percentage of left-turning traffic.

Table 3.4 Equation 3.2 Performance Characteristics

Independent	Estimated	Standard	t- Statistic
One	.38251	.009	42.42
lt%	-.118	.0007	-172.90
Corrected R^2 = 99%			

Substituting Equation 3.1 into Equation 3.2 yields the following final equation for left-turn lanes at two-lane nonsignalized intersections:

$$AV = \exp(6.9017 - .001151OpVol + (\exp(.383 - .118lt\%) - .01816SP)) \qquad \textbf{Eq. 3.3}$$

An example problem using this equation is shown below:

Example 3.1

Assume the following peak-hour conditions exist on an intersection approach to a two-lane highway:

Total Advancing Volume	=	1321
Advancing Left-Turning Volume	=	111
Opposing Volume	=	533
Operating Speed	=	45 mph

Determine whether a left-turn lane is recommended using the equation for the modified Harmelink model.

Solution:

lt% = (111/1321)100 = 8.403 Eq. 3.2

AV = exp(6.9017 - .001151*533 + (exp(.382 - .118*8.403) - .01816*45)) Eq. 3.3

= 409

Because the advancing volume at this location is greater than 409 cars, a left-turn lane is recommended.

Four-Lane Highways

The four-lane highway equations are from Harmelink's original study (Harmelink 1967). The plotted line described earlier on Harmelink's curves represents threshold values for left-turn warrants on four-lane highways. For the four-lane divided highway, the curve was best fit by doing a regression on three segments of the curve. Points on the curve were tabulated with their corresponding coordinate values (left-turning volume, opposing volume). MINITAB for Windows was used to estimate the following regression equations for the three curve segments:

- For Opposing Volume $\leq$ 800 veh/hour

  LtVol = exp(4.3 - .00116 OpVol) **Eq. 3.4**

  where:

  LtVol = Threshold value for peak-hour left-turn volume

  OpVol = Opposing peak-hour volume

Table 3.5 Equation 3.4 Performance Characteristics

Independent	Estimated	Standard	t- Statistic
One	4.3	.014	297.57
OpVol	-.00116	.00002	-49.26
Corrected R^2 = 99.7%			

- For 800 < Opposing Volume $\leq$ 1400 veh/hour

  LtVol = exp(4.86 - .00182OpVol) **Eq. 3.5**

Table 3.6 Equation 3.5 Performance Characteristics

Independent	Estimated	Standard	t- Statistic
One	4.86	.068	71.92
OpVol	-.00182	.00006	-31.08
Corrected R^2 = 98.9%			

- For Opposing Volume > 1400 veh/hour

  LtVol = exp(9.42 - .0049OpVol) **Eq. 3.6**

Table 3.7 Equation 3.6 Performance Characteristics

Independent	Estimated	Standard	t- Statistic
One	9.42	.74	12.73
OpVol	-.0049	.0005	-10.61
Corrected R^2 = 98.2%			

The equations in most cases fit with less than 5 percent error. The exceptions were roads with higher opposing volumes, where only a few left-turning vehicles were needed to warrant a lane. The equations are applicable to opposing volumes from 100 to 1800 veh/hour. When opposing volumes are greater than 1800 veh/hour, a left-turn lane is warranted on the basis of Harmelink's curves.

Harmelink's model for undivided four-lane highways is similar to the divided four-lane highway model. The parameters are the same; the only difference is in the shape of the curve (Harmelink 1967). MINITAB was used to regress points taken along the curve, which yielded the

equation estimate below (Equation 3.7). This equation estimates the undivided curve for all volumes (as opposed to the divided curve, which needed three equation estimates).

$$LtVol = \exp(3.51 - .00132OpVol) \qquad \textbf{Eq. 3.7}$$

where:

LtVol = Threshold value for peak-hour left-turn volume

OpVol = Opposing peak-hour volume

Table 3.8 Equation 3.7 Performance Characteristics

Independent	Estimated	Standard	t- Statistic
One	3.51	.045	78.22
OpVol	-.00132	.00005	-26.15
Corrected R^2 = 98.8%			

Examples of the volume guidelines for divided and undivided four-lane highways are shown below:

Example 3.2

Assume the following peak-hour conditions exist on an approach to an intersection on a four-lane divided highway:

Total Advancing Volume = 700 veh/hour
Advancing Left-Turning Volume = 19 veh/hour
Opposing Volume = 450 veh/hour

Determine the threshold volume of left-turning traffic that would justify a left-turn lane.

Solution:

$$LtVol = \exp(4.3 - .00116 * 450) \qquad \text{Eq. 3.4}$$

$$= 44$$

Because the left-turning volume at this location is less than 44 vehicles, a left-turn lane is not warranted.

Example 3.3

Assume the same conditions as in Example 3.2 for an undivided four-lane highway. Determine the threshold value of left-turning volume to justify a left-turn lane.

Solution:

$$LtVol = \exp(3.51 - .00132 * 450) \qquad \text{Eq. 3.7}$$

$$= 18$$

Because the left-turning volume at this location is greater than 18, a left-turn lane is warranted.

LEFT-TURN LANE SEVERITY SCORE

After the program has determined whether a left-turn lane is justified, the intersection approach has to be ranked among other candidate intersections. A severity score is used to determine this ranking. The left-turn lane severity score is the sum of the costs related to accident history and delay.

Accident Severity Score

The accident score was originally found by summing the costs of preventable accidents over a 12-month period. The cost factors below are used by WSDOT and were adopted for this system (Wessels and Limotti 1992):

Per Fatal or Disabling Injury Collision	$700,000
Per Evident Injury Collision	$57,000
Per Possible Injury Collision	$30,000
Per Property Damage Only Collision	$5,300

The 12-month period was taken from a three-year accident record if possible. Severity codes for accidents are readily available from the WSDOT accident database. Preventable accidents are defined as any accident that would have been prevented or less likely to occur as direct result of the installation of a left-turn lane. Accidents are classified by the most severe injury. For example, one accident may involve two disabling injuries but would only be classified as a disabling injury accident; costs for other injuries would not be factored.

Implementation of the original program revealed that this methodology did not necessarily reflect actual conditions or reliably predict future conditions. As mentioned above, WSDOT figures the cost of fatality and disabling-injury accidents at $700,000 (FHWA values are even higher). An evident-injury accident is listed at $57,000. Using these values as a severity score would mean that an intersection with one disabling accident would be considered more serious than an intersection with 12 evident-injury accidents. This method failed to recognize that many variables determine the severity of an injury. Factors such as seat belt usage, tire condition, type and size of automobile, alcohol involvement, physical condition of vehicle occupants, and others could mean the difference between a possible injury accident and a fatality.

Another problem is the subjective nature of accident severity classifications. The classifications are taken from accident records filled out by state patrol officers on the scene. An officer might interpret the precautionary actions taken by a paramedic (such as taking a passenger to the hospital for observation) as evidence of an injury when in actuality no injury had occurred.

Although the seriousness of a disabling or fatal accident must not be diminished, the system needed to be based on data that more reliably conveyed accident conditions and likelihood. WSDOT engineers examined a variety of possible solutions to this problem. Below is a description of the proposed (and currently adopted) solution.

WSDOT's accident database was searched for all accidents that occurred for through-movements with no stop or signal control at urban and rural locations. The search was conducted on data from WSDOT's Northwest region and included five years of data. Out of these, accidents that could have been prevented by a left- or right-turn lane were used for analysis. The most prevalent types were rear-end, sideswipe, and opposite direction. The percentages of the five accident severity classifications were then found for each type of accident. For example, on rural highways .3 percent of sideswipe accidents are fatal, 4.1 percent are disabling injury, 15.4 percent are evident injury, 22 percent are possible injury, and 58.1 produce no injury. By applying the societal costs already used by WSDOT to these percentages, the average societal cost is found for each type of accident. Tables 3.9 and 3.10 show the severity percentages for each type of the three types of accidents, as well as the average societal costs.

Table 3.9 Severity Percentages for Rural Accidents

Rural	Fatal $700,000	Disabling Injury $700,000	Evident Injury $57,000	Possible Injury $30.000	No Injury $5,300	Societal Cost
All Accidents N=8,692	1.1%	7.0%	19.8%	22.7%	49.5%	$77,420
Sideswipes N=1,295	0.3%	4.1%	15.4%	22.0%	58.1%	$49,257
Rear-ends N=1,833	0.2%	5.4%	18.3%	35.7%	40.2%	$62,472
Opp. Direction N=934	1.4%	9.9%	23.8%	19.4%	45.6%	$100,903

Table 3.10 Severity Percentages for Urban Accidents

Urban	Fatal $700,000	Disabling Injury $700,000	Evident Injury $57,000	Possible Injury $30.000	No Injury $5,300	Societal Cost
All Accidents N=16,763	0.2%	3.8%	13.6%	25.5%	56.8%	$46,412
Sideswipes N=2,482	0.0%	1.4%	5.9%	15.7%	77.0%	$21,954
Rear-ends N=4,472	0.0%	2.4%	12.3%	38.6%	46.6%	$37,861
Opp. Direction N=1,781	0.2%	6.5%	19.3%	24.4%	49.6%	$67,850

By applying the societal costs of accident to the injury classification percentages, the priority ranking does not diminish the value of a fatality or disabling injury accident but more accurately reflects the types of accidents and costs.

Accident Analysis Period Modifications

In the performance review, concerns were raised that the "worst 12 months in a three-year period" criterion used for accident data analysis might give too much emphasis to problems that may no longer exist. Examples of this include problems due to construction projects or weather, and problems fixed by new projects.

WSDOT decided to instead use the annual average of a three-year accident history. This approach spreads out data spikes and better identifies ongoing problems.

Accident Threshold Modifications

The accident threshold as also based on the worst 12 months in a three-year history. Although this did not necessarily need to change, leaving it the same would force the engineer to analyze an accident record twice, once for the worst 12 months and once for the annual average. To maintain consistency among and clarity for many database users, a threshold was needed for the annual average. Using 58 accident records in the database, a Microsoft Excel-Data Analysis Pack run was used to determine the mean and standard deviation of the average number of accidents per intersection approach. There were .86 accidents per year, with a standard deviation of .60. Reviewers decided that approaches with an average of more than one standard deviation above the mean (1.46 accidents per year) would justify a left-turn lane. Eight (14 percent) of the intersections were above this range. A critical accident rate based on more in-depth analysis is needed and is discussed in later in this report.

Delay Severity Score

The system calculates the delay severity score for left-turn lanes with equations from chapter 10 of the Highway Capacity Manual (HCM) (TRB 1994). The equations can be used for both two- and four-lane highways. A few assumptions must be made to use the equations. They are as follows:

- Through-traffic is split 50/50 between the two through-lanes on four-lane highways.
- On four-lane highways, only the inside lane is affected by a left-turn queue. (The outside lane is neglected in the analysis.)
- Right-turning traffic is added to the through-lane traffic on two-lane highways if no right-turn lane has been installed. On four-lane highways the right-turning traffic is added to the outside though-lane (and therefore neglected).

The basic procedure is to first assume that a left-turn lane has already been installed and then to figure the delay for that movement. Next, subtract the left-turn traffic delay (from the assumed condition) from the delay in the existing condition (shared lane use). This is the estimated

delay reduction that would result from the installation of a left-turn lane. The delay reduction is then annualized and assigned a cost based on truck and passenger vehicle volumes. Cost factors for these volumes are $50 per hour for trucks and $10 per hour for automobiles. This is described in more detail below.

Some of the HCM equations are cumbersome and have been reduced and simplified if possible. Some basic nomenclature and equations are as follows:

LtVol = left-turn volume
ThVol = through volume + Right-turn volume (if no right-turn lane)
OpRtVol = Opposing right turns
OpThru = Opposing through-volume

OpVol = (OpRtVol + OpThru) **Eq. 3.8**

The first step is to assume that a left-turn lane has already been installed and then to determine the delay that would occur to left turners in the "build" condition. It is assumed that the through-traffic experiences no delay when the left-turn lane is separated. The capacity for the left-turn lane is needed to determine the delay;, this is figured with Equation 3.9:

$$Cap_{lt} = 1714 \exp\left(-\frac{OpVol(t_g - 1.05)}{3600}\right) \qquad \textbf{Eq. 3.9}$$

T_g is equal to 5.0 for two-lane highways and 5.5 for four-lane highways.

Left-turn delay is figured using Equation. 3.10.

$$D_{lt} = \frac{3600}{Cap_{lt}} + 900\left[\frac{LtVol}{Cap_{lt}} - 1 + \sqrt{\left(\frac{LtVol}{Cap_{lt}} - 1\right)^2 + \frac{\left(\frac{3600}{Cap_{lt}}\right)\left(\frac{LtVol}{Cap_{lt}}\right)}{450}}\right] \qquad \textbf{Eq. 3.10}$$

D_{lt} is the delay in sec/veh for the left-turn lane traffic. Cap_{lt} is the capacity for the left-turn lane traffic.

Next, delay is converted to peak hour delay (PHD) by multiplying left-turn sec/veh by left-turn volume divided by 3600, as shown in Equation 3.11:

$$PHD = D(Vol/3600) \qquad \textbf{Eq. 3.11}$$

The next step is to determine the delay to vehicles in the current condition. Capacity for the current condition is found with Equation 3.12, which is the shared lane capacity equation from the HCM (TRB 1994).

$$Cap_{sh} = \frac{ltVol + thVol}{\left[\frac{ltVol}{Cap_{lt}}\right] + \left[\frac{thVol}{Cap_{th}}\right]} \qquad \textbf{Eq. 3.12}$$

The through-lane capacity is assumed to be 1400 vph and 2200 vph for two-lane and four-lane highways, respectively. The shared-lane capacity in this form assumes that there are no impediments from left-turning traffic. It needs to be adjusted by the probability of a queue-free state at the intersections. This is found with Equation 3.13, which is a compilation of equations 10-3 and 10-10 in the HCM (TRB 1994).

$$p = 1 - \frac{\frac{ltVol}{Cap_{lt}}}{1 - \frac{thVol + rtVol}{1800}} \qquad \textbf{Eq. 3.13}$$

The denominator in this equation is 1 minus the left-turn volume divided by 1800, which is the assumed saturation flow rate. The shared-lane capacity is multiplied by the probability of a queue-free state to get the adjusted shared-lane capacity. This adjusted shared-lane capacity is used to determine the left-turn delay in the shared condition by plugging the left-turn volume into Equation 3.14, which is similar to Equation 3.10.

$$D_{LtVol} = \frac{3600}{Cap_{adj}} + 900\left[\frac{LtVol}{Cap_{adj}} - 1 + \sqrt{\left(\frac{LtVol}{Cap_{adj}} - 1\right)^2 + \frac{\left(\frac{3600}{Cap_{adj}}\right)\left(\frac{LtVol}{Cap_{adj}}\right)}{450}}\right] \qquad \textbf{Eq. 3.14}$$

The delay results for the left-turns in the shared condition are now used to determine the delay to the through-movement in the shared condition. They are plugged into Equation 3.15a for multi-lane highways and Equation 3.15b for single-lane highways. These equations are not included in the 1994 HCM. However, they are expected to be included in the 1997 HCM supplement (Kittelson & Associates 1997).

$$D_{thru} = \frac{(1-p)*(ltDelay)*\left(\frac{ThVol}{\#ofLanes}\right)}{ThVol} \qquad \text{(Two or more lanes)} \qquad \textbf{Eq. 3.15a}$$

$$D_{thru} = (1-p)*(ltDelay) \qquad \text{(One lane)} \qquad \textbf{Eq. 3.15b}$$

The results of Equations 3.14 and 3.15 (a or b) are summed and plugged into Equation 3.11 to determine the shared peak-hour delay. This is total delay for the shared lane or existing condition. The difference of the shared peak-hour-delay and the left-turn delay is the delay reduction (RD), as shown in Equation 3.16.

$$RD = PHD_{sh} - PHD_{lt} \qquad \textbf{Eq. 3.16}$$

The annual delay reduction (ADR) is then computed by multiplying the RD by 260, which is the assumed number of work days per year.

$$ADR = (RD)260 \qquad \textbf{Eq. 3.17}$$

The final step is to assign dollar values to the ADR to determine the Delay Severity Score (DSS). Two classifications are used for this program: trucks and automobiles. The hourly rate of delay is $50 for trucks and $10 per passenger for automobiles. In Washington the calculated Passenger Rate (PR) per vehicle is 1.1 in rural areas and 1.3 in urban areas (Technical Advisory Committee 1994). Equation 3.17 shows this breakdown and also scales the amount by $1000 for easier computation.

$$DSS = [(AD)(\%Truck)(\$50) + (AD)(1 - \%Truck)(\$10)(PR)]/\$1000 \qquad \textbf{Eq. 3.18}$$

"%Truck" is the percentage of trucks in highway traffic and is expressed in decimal form. These equations and methodology are programmed into the database. An example of this methodology is shown below:

Example 3.4

Assume the following conditions exist at an intersection approach on a rural two-lane highway:

Advancing through-volume	=	1210	
Advancing right-turning volume	=	46	
Advancing left-turning volume	=	111	
Opposing through-volume	=	487	
Opposing right-turn volume	=	50	
Average number of preventable accidents in a three-year period	=	.67/year	Rear-ends
		.67/year	Sideswipes
Percentage of trucks		11%	

Determine the Total Severity Score for the conditions listed.

Solution:

The accident severity score is found by applying the accident cost factors.

Accident Cost Rates (from Table 3.1):

.67 X $62,472	=	$41,856
.67 X $49,257	=	$33,002
Total		$74,858/$1000 = 74.9 (Accident Severity Score)

Now the Delay Severity Score is figured. The first step is to assume that a left-turn lane has already been installed and then to figure out the capacity and delay for the separate movements. Equation 3.8 is used to calculate the correct opposing volume, which is then plugged into the capacity Equation 3.9.

$$\begin{aligned} OpVol &= OpRtVol + OpThru \qquad \text{Eq. 3.8} \\ &= 50 + 487 \\ &= 537 \text{ vph} \end{aligned}$$

$$\text{Cap} = 1714\exp\left(-\frac{537(5.0-1.05)}{3600}\right) = 951 \text{ vph} \qquad \text{Eq. 3.9}$$

The left-turn capacity is then entered into Equation 3.10 to determine the delay in the left-turn lane.

$$D_{lt} = \frac{3600}{951} + 900\left[\frac{111}{951} - 1 + \sqrt{\left(\frac{111}{951} - 1\right)^2 + \frac{\left(\frac{3600}{951}\right)\left(\frac{111}{951}\right)}{450}}\right] = 4.3 \text{ sec/veh} \qquad \text{Eq. 3.10}$$

Equation 3.11 is used to determine peak-hour delay (PHD) by multiplying by the left-turning volume and dividing by 3600.

$$\text{PHD}_{lt} = 4.3 * 111/3600 \qquad \text{Eq. 3.11}$$

$$= .13 \text{ hours}$$

Now the delay for the existing conditions is figured using the shared-lane capacity formula, Equation 3.12.

$$\text{Cap}_{sh} = \frac{111 + 1210 + 46}{\left[\frac{111}{951}\right] + \left[\frac{1210 + 46}{1400}\right]} = 1348 \text{ Veh/hour} \qquad \text{Eq. 3.12}$$

Now the probability of a queue-free state is found with Equation 3.13

$$p = 1 - \frac{\frac{111}{1348}}{1 - \frac{1210 + 46}{1800}} = .73 \qquad \text{Eq. 3.13}$$

The shared-lane capacity is multiplied by the probability of a queue free state to obtain the adjusted shared-lane capacity.

.73 X 1348 = 981 Veh/hour

Delay for the left-turn movement is found by entering the volume and adjusted capacity into Equation 3.14.

$$D_{LtVol} = \frac{3600}{981} + 900\left[\frac{111}{981} - 1 + \sqrt{\left(\frac{111}{981} - 1\right)^2 + \frac{\left(\frac{3600}{981}\right)\left(\frac{111}{981}\right)}{450}}\right] = 4.14 \text{ sec/veh} \qquad \text{Eq. 3.14}$$

The next step is to determine the delay to the through-traffic delayed by the left-turning vehicles with Equation 3.15a.

D_{thru} = (1-.73) * 4.14) = 1.1 sec/veh Eq. 3.15a

The peak-hour delay (PHD), delay reduction (RD), and annual delay reduction (ADR) are found by applying equations 3.11, 3.16 and 3.17, respectively.

PHD_{lt} = 4.14(111)/3600 Eq. 3.11
= .13 hours

PHD_{thru} = 1.1(1210)/3600
= .37 hours

Total PHD_{sh} = . 13 + .37 = .50 hours

RD = PHD_{sh} - PHD_{lt} Eq. 3.16
= .50 - .13
= .37 hours

ADR = RD(260) Eq. 3.17
= .37(260)
= 96.2 hours

Now the Delay Severity Score can be found using Equation 3.18.

Delay Severity Score = ADR(%Truck)($50) + ADR(1 - %Truck)($10)(PR) Eq. 3.18
= [96.2(.11)($50) + 96.2(1-.11)($10)(1.1)]/1000
= 1.5

The Total Severity Score can now be found by summing the Delay Severity Score and the Accident Severity Score.

Total Severity Score = 1.5 + 74.9
= 76.4

RIGHT-TURN LANE ACCIDENT GUIDELINE

As mentioned in the Literature Review, no published studies have recommended a threshold value for the number of accidents that would justify a right-turn lane. This is primarily because of the lack of sufficient data for statistical analysis.

As an example of the lack of sufficient data, in WSDOT's Northwest Region, where there are approximately 4,325 intersections, the average right-turn accident rate for all 4,325 intersections is only 244 per year.

After six months of operation, the database for right-turn lane prioritization had accumulated 22 entries. Similarly to the left-turn threshold, these 22 entries were analyzed with Microsoft Excels Analysis Pack. The mean accident rate was .54 accidents per year, the standard deviation was .28. Intersections with average accident rates of greater than one standard deviation above the mean (.82 accidents per year) are said to need a right-turn lane. Research is needed to determine the critical accident rate that would justify a right-turn lane. (See Future Research.)

RIGHT-TURN LANE VOLUME GUIDELINE

Cottrell's guidelines for right-turn lanes (Cottrell 1981) were chosen for this system. Included in Cottrell's study are guidelines to determine whether right-turn lanes or tapers are recommended. In this system only right-turn lanes are included in the priority ranking. However, the report section of the program includes a recommendation for tapers for informational purposes. Line equations for Cottrell's graphs were derived algebraically by the author.

Right-turn lanes are recommended on two-lane highways when the advancing volume exceeds the result of Equation 3.18 and the speed limit is equal to or greater than 45 mph.

$$V_A = 600 - \frac{V_{RT} - 40}{0.1333} \qquad \textbf{Eq. 3.19}$$

where V_A is the advancing volume, which includes all advancing peak-hour flow, including left- and right-turning vehicles. V_{RT} is the peak-hour right-turning volume. The upper and lower bounds of this equation are 120 and 40 vph turning right. If the right-turning volume is higher than 120 vph, the right-turn lane is always recommended. If the right-turning volume is lower than 40, a right-turn lane is not recommended and right-turn taper criteria should be checked. Depending on the conditions, Equation 3.19 and all of the other right-turn lane and taper equations could yield a negative result. In this case, the right-turn lane (or taper) is still recommended.

An adjustment factor is used in Cottrell's guidelines when the speed limit is less than 45 mph. In this case, if the right-turning volume is greater than 40 vph, and if the advancing volume is less than 300 vph, Equation 3.20 is used.

$$V_A = 600 - \frac{V_{RT} - 60}{0.1333} \qquad \textbf{Eq. 3.20}$$

If the results for a right-turn lane are not met, the taper criteria should be checked. Equation 3.21 is used to determine whether a right-turn taper is warranted when the speed limit is 45 mph or greater.

$$V_A = 500 - \frac{V_{RT} - 20}{0.1} \qquad \textbf{Eq. 3.21}$$

The upper and lower bounds of Equation 3.21 are 70 and 20 vph vehicles turning right. If the right-turning volume is greater than 70, the taper is always recommended. If the right-turning volume is less than 20, the taper is never recommended.

An adjustment factor is also applied to Equation 3.21 when the speed limit is less than 45 mph. In this case, if the right-turning volume is greater than 40 vph, and the advancing volume is less than 300 vph, Equation 3.22 is used.

$$V_A = 500 - \frac{V_{RT} - 40}{0.1} \qquad \textbf{Eq. 3.22}$$

Right-turn lanes on four-lane highways are recommended when the advancing volume exceeds the result of Equation 3.23.

$$V_A = 1200 - \frac{V_{RT} - 40}{0.0714} \qquad \textbf{Eq. 3.23}$$

The upper and lower bounds for this equation are 90 and 40 vph of right-turning vehicles. If the right-turning volume is greater than 90 vph, a right-turn lane is always recommended. If the right-turning volume is less than 40 vph, the lane is not recommended and right-turn taper criteria should be checked. There is no speed adjustment to the right-turn lane or taper recommendations on four-lane highways.

The right-turn taper is recommended when the advancing volume exceeds the result of Equation 3.24.

$$V_A = 1000 - \frac{V_{RT} - 10}{0.03} \qquad \textbf{Eq. 3.24}$$

All of the right-turn lane and taper equations are programmed into the priority database. An example of their application is given below.

Example 3.5

Assume the following conditions exist on an intersection approach on a two-lane highway:

Through Volume	=	210 vph
Right-Turn Volume	=	35 vph
Total Advancing	=	245 vph
Speed limit	=	45 mph

Determine whether a right-turn lane is recommended.

Solution:

Using Equation 3.19 yields the threshold advancing volume for the approach.

$$V_A = 600 - \frac{V_{RT} - 40}{0.1333} = 638 \text{ vph} \qquad \text{Eq. 3.19}$$

Because the total advancing is less than 638 veh/hour, a right-turn lane is not recommended, and the taper criteria should be checked.

RIGHT-TURN LANE SEVERITY SCORE

The Right-Turn Lane Severity Score is calculated by summing costs associated with delay and accident history.

Accident Severity Score

The right-turn lane accident severity score is figured in the same manner as the left-turn lane accident severity score.

Delay Severity Score

The regression equations proposed by McCoy et al.(McCoy 1993) were chosen to determine the reduction in delay caused by the installation of a right-turn lane. Equation 3.25 is used to determine the delay in reduction caused by the installation of a right-turn lane on a two-lane highway. The delay in reduction caused by the installation of right-turn lane on a four-lane highway is found by using Equation 3.26.

$$(DR_{2l}) = 0.1552 * V_{rt} \qquad \textbf{Eq. 3.25}$$

$$(DR_{4l}) = 0.0800 * V_{rt} \qquad \textbf{Eq. 3.26}$$

V_{rt} is the peak-hour right-turn volume, and the units are in seconds per through vehicle.

The peak-hour delay reduction (PHDR) is found by using Equation 3.27.

$$PHDR = DR(AdVol + RtVol)/3600 \qquad \textbf{Eq. 3.27}$$

AdVol is the peak-hour advancing volume. PHDR is then plugged into Equation 3.28 to determine the annual delay reduction.

$$ADR = PHDR(260) \qquad \textbf{Eq. 3.28}$$

Just as with the left-turn delay severity score, Equation 3.18 is used to find the delay severity score for right-turn lanes. An example determination of a right-turn lane severity score is shown below.

Example 3.6

Assume the following peak-hour conditions below are at an intersection approach on an urban two-lane highway. Determine the right-turn lane severity score.

Through-lane volume	=	242 veh/hour
Right-turn volume	=	40 veh/hour
Percentage of trucks	=	29%
Average number of preventable accidents in a three-year period	=	1.33/year Rear-ends

Solution:

Accident Cost Rates:

Per Rear-end Accident = $37,861

1.33 X $37,861 = $50,481/1000 = 50.5 (Accident Severity Score)

Now the reduction in delay is found with Equation 3.25. The peak-hour delay reduction and the annual delay reduction are found with equations. 3.27 and 3.28, respectively.

(DR_{21}) = 0.1552 * 40 Eq. 3.25
= 6.2 sec/through veh

PHDR = 6.2(282)/3600 Eq. 3.27
= .49 hours

ADR = .49(260) Eq. 3.28
= 127 hours

Finally, Equation 3.18 is used to determine the Delay Severity Score.

DSS = [(127)(.29)(50) + (127)(1-.29)(10)(1.3)]/1000 Eq. 3.18
= 3.0

The total severity score is the sum of the accident severity score and the delay severity score:

50.5 + 3.0 = 53.5

CHAPTER FOUR
DATA COMPILATION AND FIELD STUDIES

The data needed for this program are easily obtained by ordering turning movement counts and accident records. However, the engineer should make every effort to visit the site in question to determine other factors that might affect the decision to install a turn lane. For example, sight distance limitations, vertical curves, and horizontal curves could significantly affect the decision to install a turn-lane.

Included in the field study should be a discussion with local residents and officials who might be able to offer information on conditions that are not readily apparent. The engineer should be aware of conditions under which the installation of a left- or right-turn lane might cause the intersection to be more dangerous. For example, adding a left-turn lane significantly increases the width of a roadway and therefore increases the required gap time needed to cross or enter the roadway. If the gap time available during the peak hour is short or marginal, the additional gap time could create a more dangerous situation, as well as increase sidestreet delay. Additionally, the sidestreet traffic's sight distance could be reduced by the widening necessary to install a left- or right-turn lane. These conditions can be addressed in preliminary analysis and should be addressed if the intersection is chosen for a left- or right-turn lane installation.

Another issue to be considered is access control. It is entirely possible that the presence of left-turning traffic, whether in through-lanes or left-turn lanes hinders, operations to such a degree that the movement should be prevented by access control. For example, if two intersections are very close together, the queue from left-turning traffic at one (whether in the through-lane or left-turn lane) could hinder operations at the other. In this situation, the engineer should consider restricting the movement through access control.

The software program developed includes a comment section where these considerations and field study information may be addressed. Below is a list of the data required and/or recommended for the database program:

LOCATIONAL AND CHARACTERISTIC INFORMATION

- Highway number
- Mile post
- Cross road name
- Approach direction (increasing or decreasing milepost)
- Control section number
- Divided or undivided
- Number of lanes
- Existing right turn
- Speed limit

PEAK HOUR VOLUME INFORMATION

- Advancing turning movement counts

  Through-volume

  Left-turning volume

  Right-turning volume
- Opposing turning movement counts

  Through-volume

  Left-turning volume

  Right-turning volume

ACCIDENT INFORMATION

Number of preventable:

- Fatality accidents
- Disabling accidents
- Evident injury accidents
- Possible injury accidents
- Property damage only accidents

RELEVANT INFORMATION

This information is not required for the priority array to function; however, if the items are relevant to the installation of a left- or right-turn lane, they should be addressed by the engineer in the comments section of the database entry form.

- Horizontal and vertical curves
- Grade information
- Intersection skew angles
- Sight distance
- Roadway width
- Possible obstructions to widening
- Community comments

CHAPTER FIVE
RECOMMENDATIONS AND CONCLUSIONS

FUTURE RESEARCH NEEDED

Harmelink's original model for left-turn lanes was based on the probability of a queue waiting for a left-turning vehicle. The maximum probabilities allowable before a left-turn lane is recommended are based in part on the opinions of a panel of transportation engineers assembled in the late 1960s. Although the model has been effective, changing conditions and technologies could warrant a study on the appropriateness of the maximum probabilities chosen. Methods derived from risk analysis studies may be used to derive more accurate and objective probabilities based on the geometrics of the intersection (Poch and Mannering).

Only one study recommended a threshold value of accidents for left-turn lane installation. No studies provided a threshold value of accidents to justify a right-turn lane. It is appropriate to question the value of a warrant or guideline based solely on accident history. Although accident history can certainly alert the engineer to existing trouble spots, this approach is reactive. Recent risk analysis studies are attempting to allow the engineer to pro-actively address potential problems (Poch and Mannering). Unfortunately, no research has been done that would apply to the individual intersection with regard to left- and right-turn lanes.

A risk analysis based on intersection conditions such as roadway width, vertical and horizontal curves, sight distance, and volumes, used in conjunction with an accident history, may be the most appropriate method of "warranting" left- and right-turn lanes.

CONCLUSIONS

Along with signalization, other improvements should be considered that will increase the safety and efficiency of an intersection. Left- and right-turn lanes can significantly improve the operations of an intersection. This project developed a computer

program based on published standards and engineering studies that enables the engineer to maintain a prioritized list of intersections being considered for such improvements.

Each intersection is analyzed by first determining whether a left- or right-turn lane is recommended. This is done with threshold values for traffic volumes and accident history. The volume threshold for left-turn lanes is based on a modified AASHTO table (Kikuchi and Chakroborty 1991). The accident threshold for left-turn lanes is four preventable accidents in a 12-month period (Agent 1983).

The volume threshold for right-turn lanes is based on warrant graphs developed by Cottrell (Cottrell 1981). The accident guideline for right-turn lanes is five preventable accidents in a 12-month period. This number is a based on other warrant guidelines for traffic control devices and has no statistical basis.

Once it has been determined that a left- or right-turn lane is recommended, the intersection has to be ranked among other intersections being considered. This is done by assigning dollar values to delay analysis and accident history reports.

The benefits of this system are that it is an objective method of ranking intersections against others and it is easy to use. It requires data that are easily obtainable from resources available at most traffic offices.

The system and methodology presented in this report are not considered warrants; rather, they serve as logical starting points for left- and right-turn lane guidelines. The system and methodology's primary function is to serve as an analysis and planning tool for operation engineers. As intersection operation problems become evident through public outcry, analysis, and other means, the engineer is able to analyze the intersection and compare it to others objectively.