FHWA/NJ-84/008
84-008-7709

LEFT TURN TREATMENTS AT SIGNALIZED INTERSECTIONS WITHOUT TURN SLOTS

FINAL REPORT

BY

MARK J. SMITH

BUREAU OF TRANSPORTATION SYSTEMS RESEARCH
DIVISION OF RESEARCH AND DEMONSTRATION
NEW JERSEY DEPARTMENT OF TRANSPORTATION

IN COOPERATION WITH
FEDERAL HIGHWAY ADMINISTRATION
US DEPARTMENT OF TRANSPORTATION

OCTOBER 1983

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/NJ-84/008	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Left Turn Treatments at Signalized Intersections Without Turn Slots	5. Report Date Oct. 1983
	6. Performing Organization Code 84-008-7709
7. Author(s) Mark J. Smith	8. Performing Organization Report No.
9. Performing Organization Name and Address New Jersey Department of Transportation Bureau of Transportation Systems Research 1035 Parkway Avenue Trenton, NJ 08625	10. Work Unit No.
	11. Contract or Grant No. NJ HPR Study 7709
12. Sponsoring Agency Name and Address Federal Highway Administration Washington, DC	13. Type of Report and Period Covered Final Report Oct. 1972 - Oct. 1983
	14. Sponsoring Agency Code

15. Supplementary Notes

Conducted in cooperation with the US Department of Transportation, Federal Highway Administration under the title "Design Warrants for Left Turning Vehicles at Signalized Intersections."

16. Abstract

Guidelines were developed for left turn provisions at signalized intersections with mixed traffic lanes. They consist of: 1) a general left turn provision guideline which determines, on the basis of delay, if a left turn provision should be considered for the intersection approach under study, and 2) a set of guidelines which determine the type of left turn provision to be used.

These guidelines were tested using the results of a series of before and after field studies conducted at intersections where a left turn provision was installed. The results of this testing, along with a procedure for proper application of the guidelines, are included.

17. Key Words Traffic Signal, Left Turns, Signalized Intersections	18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 40	22. Price

Form DOT F 1700.7 (8-69)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE PAGE

ACKNOWLEDGEMENTS

The author thanks John Eicher and Steve Cohen of the Federal Highway Administration for their cooperation and instruction in the use of the NETSIM simulation model, and acknowledges Dr. Cohen for his assistance in making the NETSIM runs used to develop the warrants at FHWA. The author also thanks Richard Hollinger for his technical supervision and help in editing; Arthur Roberts for his assistance in editing; and the staff of the Bureau of Transportation Systems Research for their help in collecting data and preparing this report. Acknowledgement is made for the assistance of the Bureau of Transportation Technology Research in conducting field studies and collecting data. Assistance given by the staffs of the Bureau of Traffic Engineering and the Electrical Bureau in locating sites for the prior and post-installation studies is also appreciated.

SUMMARY

Guidelines have been developed for left turn provisions at signalized intersections with mixed traffic lanes. They consist of: 1) a general left turn provision guideline which decides, on the basis of delay, if a turn provision should be considered on the intersection approach under study, and 2) a set of guidelines which decide the type of left turn provision (i.e., lead green, protected slot, three-phase controller) to be used. The general left turn provision guideline is based on delay curves generated through the use of the NETSIM (formerly UTCS-1) model, complemented by adjustment factor tables. The guidelines, as developed, determine if a left turn provision is needed on an individual approach. effect of the provision on total intersection performance is not specifically considered.

Because of the limitations inherent to field data collection NETSIM model (developed by FHWA) was used to generate the data required for development of these guidelines. The proposed guidelines were tested using the results of a series of before and after field studies conducted at intersections where a left turn provision was installed. The results of this testing indicated that the proposed guidelines were a useful criteria for determining whether an intersection approach should be considered for a left turn provision on the basis of delay.

Along with the guidelines, a procedure for their proper application in the field is also included

INTRODUCTION

One problem which can cause congestion at heavy volume signalized intersections is the blockage caused by left turning vehicles. The increased queuing of vehicles, caused by this blockage, results in an effective reduction in approach capacity. The effects of this loss of capacity can be seen in the extensive use of yellow and all red periods, as well as increased conflicts between left turning vehicles and opposing through traffic.

Various provisions are used to alleviate this situation such as left turn lanes and slots, lead and lag greens, multi-phase cycles and, as more expensive solutions, jughandles and overpasses. However, objective guidelines which tell the traffic engineer when to install these provisions are non-existent. Furthermore, once the decision is made to provide a left turn provision there are no existing objective guidelines to indicate what kind of provision to install. In response to this problem, this report sets forth recommendations for both a general guideline for a left turn provision based on delay and a set of guidelines for specific types of provisions.

STUDY PROCEDURES

I. FIELD MEASUREMENT OF DELAY

Originally, video recorders were tested as a means of compiling the necessary delay data for this study. However, problems encountered when this method was implemented in the field limited its usefulness to this study (see Appendix A). These problems, coupled with the time and expense required to obtain sufficient data by the videotape method, made it necessary to find an alternative data collection method. After review, the NETSIM (formerly UTCS-1) simulation model developed by the FHWA was selected for use as this alternative approach. NETSIM is a microscopic model based on the simulation of individual vehicle trajectories as they move through a street network. Thus, the model can theoretically predict changes in intersection delay and congestion at an individual intersection due to changes in the various traffic parameters (i.e., signal timing, traffic volumes, turning movements, etc.) at the intersection. This ability, coupled with the model's flexibility, was the major factor in its selection for use in developing left turn warrants. The NETSIM model was subsequently used, after validation for traffic conditions in New Jersey (Appendix D), to generate the intersection delay data upon which the developed left turn guidelines were based.

The use of the NETSIM model allowed delay data to be generated for a larger number of traffic conditions than was possible through the use of other data collection methods. It also required less time and expense than the collection methods previously in use.

II. EMPIRICAL DESIGN

A. General Guideline

A high volume of left turning movements on an approach tends to reduce capacity because of extensive queuing on the approach. This loss of capacity usually results in an increasing level of delay on the approach For this reason, the level of delay on the approach was chosen as the primary criteria for the guidelines for left turn provision to be developed. However, as the accurate measurement of delay in the field is an expensive and time consuming process, it is normally not included among the traffic characteristics measured in an intersection survey. Therefore, to make use of the warrants as easy as possible, delay was defined in terms of other more readily obtainable traffic characteristics.

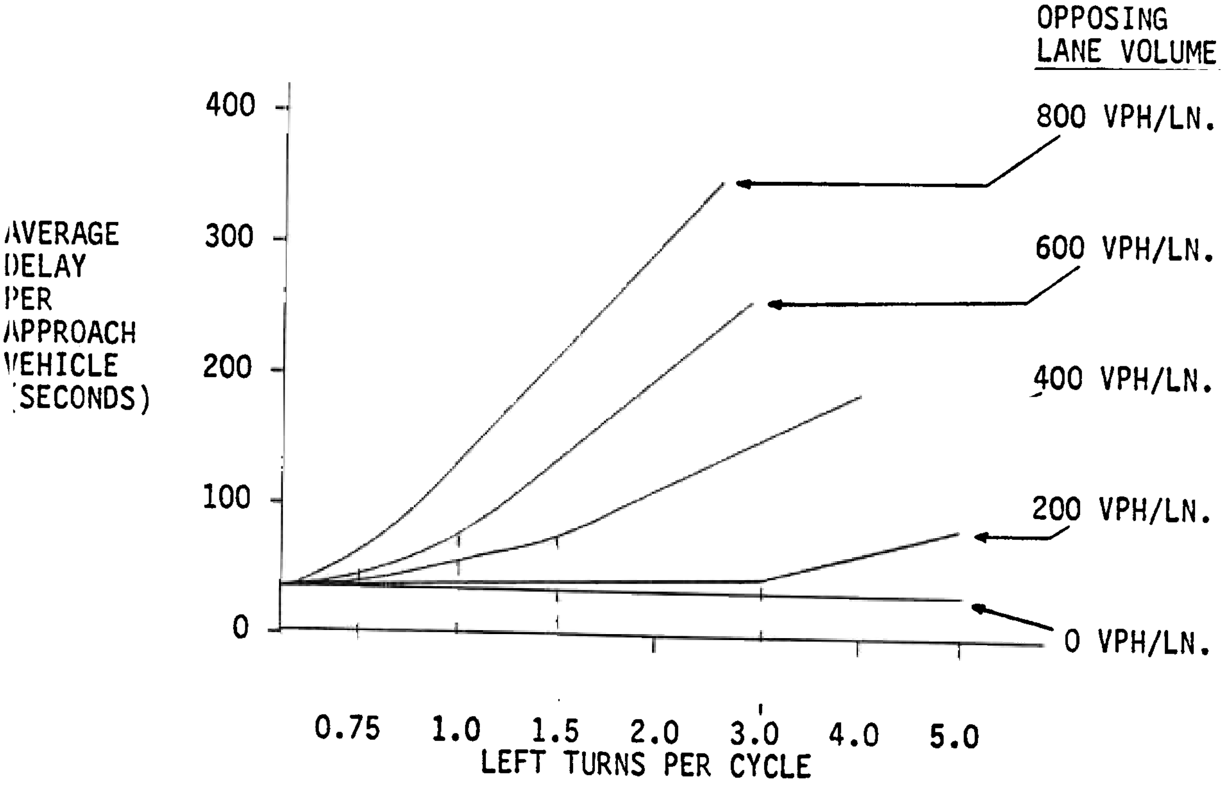
Through the use of delay data generated by the NETSIM model, a series of delay curves were developed for an intersection approach under the following traffic conditions: cycle length = 60 seconds, G/C ratio = 0.50, and approach volume = 600 VPH/Lane (see Figure 1). The values chosen for cycle length and G/C ratio were selected as base conditions on New Jersey roads. The approach volume chosen, which corresponds to a V/C ratio for the NETSIM model of 0.75, was selected with an eye to avoiding the problems which might arise due to the approach running at capacity while still determining delay for a high volume approach. These curves served to define the relationship between average delay per vehicle and average left turn demand per cycle on the approach.

Analysis of the developed curves showed that a point of inflection occurs at that value of left turns per cycle where left turn demand begins

FIGURE 1

AVERAGE DELAY/VEHICLE VS. LEFT TURNS PER CYCLE

C = 60 SECS., G/C = .50, APPROACH VOLUME = 600 VPH/LN



to exceed left turn capacity (see Table 1). Since beyond this point all left turn demand on the approach can no longer be serviced within one cycle, a much more rapid rate of increase in vehicle delay results. For this reason, this point serves as a good warrant point.

Since the high number of runs and excessive cost that would be required rendered it unfeasible to construct a delay curve for every condition possible in the field, it was decided to use the initial curves as the basic set of delay curves. Data taken in the field under conditions other than the basic conditions would be modified for use on the basic curves through the use of adjustment factors.

Three adjustment factor tables, one each for approach volume, cycle length, and G/C ratio, were developed for this purpose (see Tables 2, 3 & 4). Appendix B of this report provides a detailed account of the process by which these tables were developed.

The adjustment factors (A.F. obtained from these tables are used to modify the basic curves to reflect actual street conditions by means of the following equation:

$$V_{LE/C} = V_{L/C} \times F_{C} \times F_{G/C} \times F_{AV}$$

where:

$V_{LE/C}$ = equivalent left turns per cycle

$V_{L/C}$ = average left turns per cycle on the approach

F_{C} = adjustment factor for cycle length (cycle length other than 60 seconds)

TABLE 1

INFLECTION POINTS (FROM CURVES)

OPPOSING VOLUME	LEFT TURNS PER CYCLE
0	
	3.0
	1.5
	1.0
	0.75

TABLE 2

ADJUSTMENT FACTORS FOR CYCLE LENGTH (F_C)

G/C = 0.50, APPROACH VOLUME = 600 VPH/LN.

CYCLE LENGTH (SECONDS)

OPPOSING VOLUME	60	80	90	100	120
0	1.00	1.00	1.01	1.02	1.00
200	1.00	1.03	1.05	1.06	1.11
400	1.00	1.14	1.17	1.20	1.19
600	1.00	1.17	1.18	1.19	1.35
800	1.00	1.33	1.33	1.32	1.48

TABLE 3

ADJUSTMENT FACTORS FOR G/C RATIO (F

C. L. = 60 SECS., APPROACH VOL. = 600 VPH/LN

	G/C RATIO			
OPPOSING VOLUME	0.25	0.50	0.65	0.75
0	1.70	1.00	0.81	0.79
200	1.80	1.00	0.77	
400	1.59	1.00	0.77	
600	1.58	1.00	0.74	0.69
800	1.47	1.00	0.90	

TABLE 4

ADJUSTMENT FACTORS FOR APPROACH VOLUME (F_{AV})

C. L. = 60 SECS., G/C = 0.50
OPPOSING VOLUME = 600 VPH/LN.

APPROACH VPH/LN.	F_{AV}
	0.45
	0.61
	0.71
	0.91
600	1.00
	1.11
	1.33

$F_{G/C}$ adjustment factor for G/C ratio (G/C ratio other than 0.50)

F_{AV} = adjustment factor for approach volume (approach volume other than 600 vehicles per hour

By using the equivalent left turns per cycle and the delay curves, it is now possible to determine if a left turn provision is needed on a particular intersection approach. If the equivalent left turns per cycle is equal to or greater than the value of left turns per cycle at the warrant point, the approach should be considered for a left turn provision. If it is less than the warrant value, no provision is suggested. To simplify use of the general guideline, a curve (Figure 2) was developed by plotting the value of left turns per cycle at the warrant point against opposing volume. This eliminates the need for interpolation among the various delay curves.

B. Specific Provision Guideline

Specific provision guidelines which define the traffic conditions under which each type of left turn provision could be used most effectively have also been developed (Figure 3). These guidelines are used after the general guideline has been met to determine the type of left turn provision which would be most effective on the approach under study.

The lowest form of left turn provision to which these guidelines address themselves is the lead green since the use of unprotected left turn slots is now being discontinued in New Jersey. The criteria for use of a lead green requires that: 1) the general guideline be met, and 2) that there be sufficient capacity in the right lane to handle all through and

FIGURE 2

GENERAL WARRANT CURVE

C = 60 SECS., G/C = 0.50, APP. VOLUME = 600 VPH/LN.

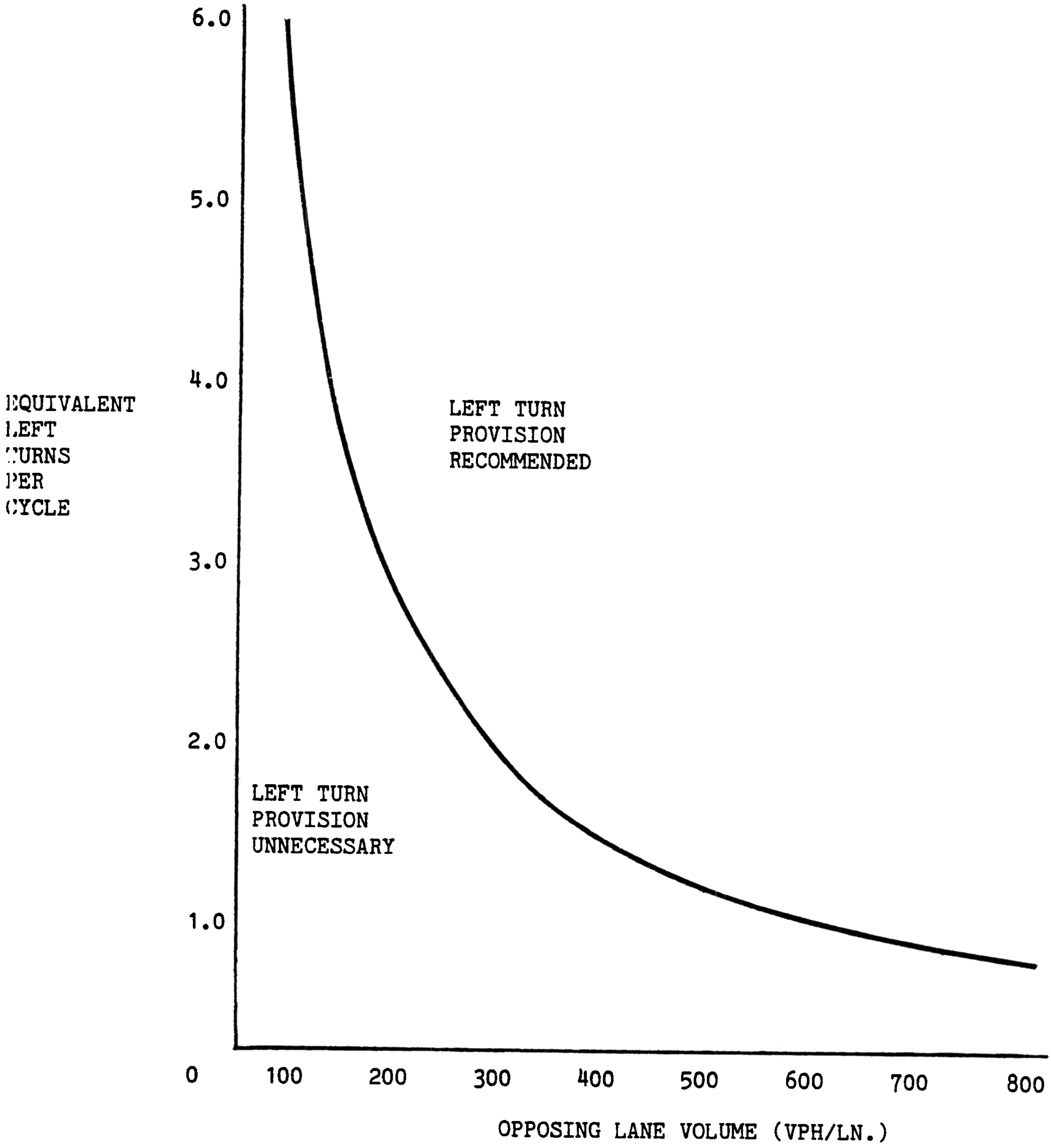


FIGURE 3

SPECIFIC TYPE PROVISION WARRANTS

I. Lead Green

   a) General Guideline Met

   b) Right Lane Capacity > Thru & Right Demand

II. Slot - Not Used Without Protective Phase

   Lead Green and Slot

   a) General Guideline Met

   b) Right Lane Capacity < Thru & Right Demand < 2 x Right Lane Capacity

   Three Phase

   a) General Guideline Met

   b) Opposing Approach Warrants Left Turn Provision Also

V. Three Phase with Slots

   a) General Guidelines met for both approaches.

   b) Specific Guidelines for Lead Green & Slot met for both approaches.

right turn traffic. The second criteria is based on the assumption that a heavy left turning volume will not allow much use of the present left by right and through traffic. Therefore, if there is not sufficient capacity for non-left turning traffic in the right lane, a lead green with an additional left turn slot is recommended.

The criteria for use of a three-phase signal requires the general guideline to be met by both the approach under study and the opposing approach.

Originally, development of criteria, based on delay, for the use of a jughandle as a left turn provision was also considered in the scope of this study. However, in practice, the use of a jughandle is normally based on the roadway characteristics of the arterial rather than the delay and capacity characteristics and, as such, a jughandle can be used in place of any of the provisions listed. For this reason, criteria based on delay could not be developed for jughandles.

An example explaining the process by which both the general and cific provision warrants are applied can be found in Appendix C of this report. These guidelines are meant to help the traffic engineer in determining, first, if a left turn provision should be considered on the basis of delay and, then, what type of provision to use. Since other factors (such as accidents, conflicts, etc.) could influence the final decision, engineering analysis by the traffic engineer is still essential.

FIELD VERIFICATION

The proposed guidelines were tested in the field at six intersections where a left turn provision was installed. Traffic data, including volumes, turning movements, signal timing, and intersection configuration as well as left turn demand and discharge by cycle, was collected on the intersection approach for both prior and post-installation conditions. Concurrent with the traffic study, a delay study was also conducted for both prior and post installation conditions on the study approach. Although during the delay study data was collected for the entire peak hour, only the peak 15 minute period was used to conform with the simulation time of the NETSIM generated data. The results of these studies are presented in Tables 5 & 6

Two of the six intersection approaches studied (Route 202 Southbound and WhiteHorse-Mercerville Road Southbound) met the necessary criteria for a left turn provision to be considered. In both these cases, the post-installation study showed that average vehicle delay had been substantially reduced by the left turn provision.

Of the four intersection approaches which did not meet the criteria three experienced increased delay after installation, and the fourth experienced only a small decrease. However, two of the three intersections where increased delay was noted had a lower G/C ratio after installation which could account for this increase.

An analysis was also made of the difference between left turn demand per cycle and left turn discharge per cycle for both prior and post installation conditions at all six approaches. This analysis consisted of monitoring left turn demand and discharge for all cycles during the peak 15 minute period of the peak hour. The analysis showed three of the six experienced difficulty during this peak period in servicing left turn

TABLE 5

INTERSECTION CHARACTERISTICS

		PRIOR INSTALLATION		POST INSTALLATION			
INTERSECTION	APPROACH	VEHICLES PER HOUR (APPROACH)	VEHICLES PER HOUR (OPPOSING)	VEHICLES PER HOUR (APPROACH)	VEHICLES PER HOUR (OPPOSING)	TYPE OF LEFT TURN PROVISION INSTALLED	LEFT TURN PROVISION WARRANTED? (1)
Rt. 33 & White Horse-Mercerville Road	Rt. 33 WB	L: 134 T: 447 R: 163	L: 17 T: 538 R: 57	L: 154 T: 421 R: 153	L: 17 T: 484 R: 51	Lead Green	No
Rt. 33 & White Horse-Mercerville Road	White Horse-Mercerville Road SB	L: 154 T: 284 R: 19	L: 32 T: 245 R: 167	L: 165 T: 224 R: 32	L: 46 T: 259 R: 131	3-Ø ØA: Rt. 33 ØB: WH-M RD. SB ØC: WH-M RD. NB	Yes
Rt. 35 & Navesink River Road	Navesink River Road WB	L: 144 T: 138 R: 49	L: 152 T: 59 R: 31	L: 234 T: 157 R: 28	L: 178 T: 76 R: 61	3-Ø ØA: Rt. 35 ØB: NR Rd. EB ØC: NR Rd. WB	No
Ewingville Road & Eggerts Crossing Road	Ewingville Road EB	L: 155 T: 349 R: 0	L: 0 T: 536 R: 224	L: 154 T: 372 R: 0	L: 0 T: 621 R: 243	Lag Green	No
Rt. 24 & Cross Street Rosedale Avenue	Rosedale Avenue	L: 143 T: 47 R: 16	L: 19 T: 56 R: 21	L: 141 T: 78 R: 6	L: 36 T: 97 R: 13	Lead Green	No
Rt. 202 & Hanover Avenue	Rt. 202 SB	L: 170 T: 395 R: 48	L: 43 T: 350 R: 169	L: 245 T: 420 R: 57	L 54 T 408 R 193	Lead Green	Yes

(1) Does intersection approach meet proposed general guideline?

TABLE 6

COMPARISON OF PRIOR AND POST INSTALLATION INTERSECTION STUDIES

INTERSECTION	APPROACH	PRIOR DELAY	POST DELAY	LEFT TURNS PER CYCLE NOT DISCHARGED WITHIN ONE CYCLE		PRIOR CYCLE LENGTH & G/C RATIO	POST CYCLE LENGTH & G/C RATIO
				PRIOR (1)	POST (1)		
Rt. 33 & White Horse-Mercerville Road	Rt. 33 WB	18.0 secs./ vehicle	31.4 secs./ vehicle	0.3 L. T. per cycle	0.0 L. T. per cycle	90 secs. G/C = 0.67	90 secs. G/C = 0.43
Rt. 33 & White Horse-Mercerville Road	White Horse-Mercerville Road SB	75.0 secs./ vehicle	39.2 secs./ vehicle	3.0 L. T. per cycle	0.3 L. T. per cycle	90 secs. G/C = 0.22	90 secs. G/C = 0.20
Rt. 35 & Navesink River Road	Navesink River Road WB	25.9 secs./ vehicle	50.9 secs./ vehicle	0.2 L. T. per cycle	1.2 L. T. per cycle	90 secs. G/C = 0.23	90 secs. G/C = 0.14
Ewingville Road & Eggerts Crossing Road	Ewingville Road EB	23.8 secs./ vehicle	16.5 secs./ vehicle	1.0 L. T. per cycle	0.3 L. T. per cycle	60 secs. G/C = 0.50	70 secs. G/C = 0.59
Rt. 24 & Cross Street-Rosedale Avenue	Rosedale Avenue	27.0 secs./ vehicle	32.6 secs./ vehicle	0.1 L. T. per cycle	0.1 L. T. per cycle	90 secs. G/C = 0.24	90 secs. G/C = 0.26
Rt. 202 & Hanover Avenue	Rt. 202 SB	58.1 secs./ vehicle	14.0 secs./ vehicle	4.3 L. T. per cycle	3.2 L. T. per cycle	90 secs. G/C = 0.53	120 secs. G/C = 0.56

(1) Left turns per cycle not discharged within one cycle =
Σ(left turn demand per cycle - left turn discharge per cycle)/# of cycles.
Data represents peak 15 minute period of the peak hour.

demand within one cycle prior to installation of the left turn provision. Two of these (Route 202 Southbound and WhiteHorse-Mercerville Road Southbound) both of which met the criteria, had severe problems in this regard. The problems were reduced at all three intersections by the left turn provision. Although in the case of Route 202 Southbound the data from the post-installation survey still indicates some problem exists in servicing all demand, most of the difference indicated between discharge and demand is made up of left turn vehicles who arrived at the end of the phase rather than left turn vehicles who have been queued at the intersection as was previously the case.

The remaining three intersections included in this study experienced little difficulty during this peak period in servicing left turn demand within one cycle prior to installation. This situation remained the same after installation with one exception (Navesink River Road) which experienced a decay in this ability.

In summary, the results predicted by the proposed guidelines were consistent with the results actually experienced in the field. At the two intersections where the proposed guidelines predicted that a left turn provision would be beneficial in reducing vehicle delay on the approach, the post installation study showed that the left turn provision had substantially improved the situation in terms of both delay and vehicle discharge.

At the four intersections where the proposed guidelines predicted that a left turn provision would not be beneficial, the post installation study showed improvement in the situation in only one case. In the other three cases, the approach experienced increased vehicle delay. These

Latter three cases also showed little improvement in regard to left turn discharge. However, since the three approaches had experienced little difficulty in servicing left turn demand within one cycle prior to installation, not much improvement could be expected.

CONCLUSIONS AND RECOMMENDATIONS

The guidelines presented in this report are meant to help the traffic engineer in determining: 1) if an intersection approach should be considered for a left turn provision on the basis of vehicle delay on the approach, and 2) what type of provision would be most effective. The general provision guideline developed to satisfy the first objective consists of a guideline curve complemented by three adjustment factor tables. Both curves and tables were developed through the use of data generated by the NETSIM model. The specific provision guidelines developed to satisfy the second objective use as criteria for the choice of left turn provision the difference between right lane capacity and the sum of right and through demand. Based on the results of this study, the proposed general and specific guidelines should make for a reasonable criteria in regard to these objectives

It should be noted that the guidelines do not attempt to ascertain the effect of a left turn provision on total intersection delay; but only on delay at the study approach. However, by supplementing the guidelines use of the NETSIM model, the effect of the recommended left turn provision on total intersection delay can be determined. This would be done for those intersections where the guidelines had previously recommended that a left turn provision be considered.

It should also be noted that other factors not included in the scope of this study, such as accidents, traffic conflicts, etc., could warrant installation of a left turn provision where delay does not. For this reason, other engineering analysis is still a necessary part of the decision process.

Several topics are suggested for research in the area of left turn provision warrants. Further investigation should be made into the effect of a left turn provision on accidents and traffic conflicts at an intersection in order to determine a warrant based on these factors. Although, as noted earlier, no guideline for the use of a jughandle could be developed on the basis of delay, further study should be made into the effect of jughandles on accidents and conflicts at an intersection to determine if guideline based on these parameters could be developed.

APPENDIX A

PROBLEMS ASSOCIATED WITH MEASUREMENT OF DELAY IN THE FIELD

This appendix delineates the original methods taken to accurately measure delay in the field and the problems experienced

In the original videotape studies, the cameras were mounted inside a which was parked on the approach at which delay was to be measured. One video camera was aimed upstream of the van and recorded vehicles approaching the intersection. Another camera was aimed downstream of the and recorded vehicles leaving the intersection. A third camera was aimed at the signal head controlling the study approach so as to monitor intersection signal timing. A digital clock was superimposed on each camera to keep track of inbound and outbound times of vehicles, and traffic movements were recorded for periods ranging from 15 minutes to one hour.

From review of recordings made using this approach, it was found that trucks between the camera position and the intersection blocked the view of vehicles exiting the intersection. This led to great difficulty in obtaining vehicle departure times which are necessary to estimate vehicle delay.

In order to gain sufficient height to eliminate this problem, the cameras were next mounted on a lift truck parked on the approach. However the high visibility of the truck had a pronounced "rubbernecking" effect on traffic passing through the intersection. Relocation of the truck to a position across the intersection from the study approach did not reduce this effect

Because of the effect on traffic of the truck's high visibility, it was decided to mount the cameras on the intersection signal pole with associated recording equipment, well away from the approach, connected to cameras by cables. This made the cameras as inconspicuous as possible while still giving adequate height. However, the necessary time expense required made this method prohibitive for any large scale collection effort.

Another problem which could not entirely be eliminated was limited field of view afforded by the cameras. Because of this, a "blind spot" existed between the camera recording inbound vehicles and the one recording outbound vehicles. If a point of access/egress to the approach (for example, a driveway, alley, street, etc.) was located within this "blind spot" a vehicle entering or existing this roadway would be lost or gained. As average travel time is calculated by the formula:

$$\frac{\text{outbound times - inbound times}}{\text{number of vehicles}}$$

Any vehicles lost (recorded inbound, but not outbound) or gained (recorded outbound, but not inbound) would alter one of the variables in the equation resulting in an error in the calculated travel time. To avoid this problem, the total time over which the delay was calculated was broken up into smaller segments of varying length. As the final point in each segment, an easily identifiable vehicle was chosen from the inbound traffic. After the segment of tape had been transcribed, the number of inbound and outbound times were totalled. If the outbound and inbound totals were not equal, the segment in question was reviewed to determine which inbound vehicles were not accounted for on the outbound tape. If for some reason after this review, all of the inbound vehicles could still not be accounted for on the outbound tape, then the excess number of inbound times were randomly discarded

APPENDIX B

DEVELOPMENT OF ADJUSTMENT FACTOR TABLES

Since it would have been a mammoth task to construct delay curves for every set of possible conditions in the field, a basic set of delay curves was developed. Conditions other than the basic conditions would be modified through the use of adjustment factors to render the data into a form comparable with the basic curves. For the purpose of this modification, three tables of adjustment factors were developed.

The difference in approach left turn capacity between the basic conditions and the prevailing field conditions is used as the basis for adjustment factors (Figure 2). Left turn capacity was selected rather than delay because this variable is a better indicator of the actual difference in congestion on the approach for the various sets of traffic conditions simulated. For this study, left turn capacity was defined as the number of left turning movements which can be completed during the time period simulated. Since the number of left turning vehicles discharged is an output of the NETSIM model, the left turn capacities for each of the various sets of traffic conditions simulated can be easily found.

The initial step in the development of the adjustment factor tables was the construction of three matrices of left turn capacities -- one for cycle length, G/C ratio, and approach volume. In the matrices parameter for which the table was to adjust was varied with opposing volume. All other parameters were held constant. In this way, the effect on left turn capacity due to a corresponding change in the individual parameter could be measured.

Left turn capacities were calculated for each set of traffic conditions by averaging the results of ten separate runs of the UTCS-1 model. These capacities were in turn used to calculate the adjustment factors by comparing the capacity for each set of traffic conditions to capacity for the basic conditions. Tables 7, 8 & 9 illustrate the process by which the adjustment factors were calculated.

TABLE 7

EFFECT OF CYCLE LENGTH ON LEFT TURN CAPACITY

<u>LEFT TURN CAPACITY (L.T.C.)</u>

G/C = 0.50, APP. VOLUME = 600 VPH/LN.
(VEHS./15 Mins.)

OPP. VOLUME \ CYCLE LENGTH	60	80	90	100	120
0	234.0	234.8	232.2	229.6	236.8
200	154.1	149.2	147.0	144.8	138.8
400	99.0	86.6	84.8	82.7	83.5
600	71.1	60.9	60.2	59.5	52.5
800	60.2	45.2	45.4	45.5	40.8

$$F_C \text{ of 80, OPPOSING VOLUME OF 200 VPH/LN.} = \frac{\text{L.T.C.}_{60/200}}{\text{L.T.C.}_{80/200}} = \frac{154.1}{149.2} = 1.03$$

TABLE 8

EFFECT OF G/C RATIO ON LEFT TURN CAPACITY

LEFT TURN CAPACITY (L.T.C.)

CYCLE LENGTH = 60 SECS., APPROACH VOLUME = 600 VPH/LN.
(VEHS. / 15 MINS.)

OPP. VOLUME	G/C RATIO .25	.50	.65	.75
0	138.3	234.7	290.5	296.7
200	85.8	154.5	201.2	228.4
400	61.7	98.0	126.2	141.0
600	43.8	69.3	93.5	99.8
800	42.0	61.8	68.9	78.7

F
G/C of ~~.65,~~ OPPOSING VOLUME of 200 VPH/LN. = $\frac{\text{L.T.C.}_{0.5/ 200}}{\text{L.T.C.}_{0.65/200}} = \frac{154.5}{201.2} = 0.77$

TABLE 9

EFFECT OF APPROACH VOLUME ON LEFT TURN CAPACITY

LEFT TURN CAPACITY (L.T.C.)

CYCLE LENGTH = 60 SECS., G/C RATIO = 0.50
OPPOSING VOLUME = 600 VPH/LN.

APPROACH VOLUME	VEHS./15 MINS.
	32.4
	23.9
	20.6
	16.0
	14.6
	13.2
	11.0

$$F_{\text{APPROACH VOLUME of 300 VPH/LN.}} = \frac{\text{L.T.C.}_{600}}{\text{L.T.C.}_{300}} = \frac{14.6}{23.9}$$

$$F_{\text{APPROACH VOLUME of 300 VPH/LN.}} = 0.61$$

APPENDIX C

PROCEDURE FOR USE OF GUIDELINES

This appendix, which includes the procedure for application of the guidelines, is intended to serve as a guide to the use of both the General and Specific Provision Guidelines. As a further aid, an example using the results of one of the field intersection studies is included. Table 10 illustrates how the adjustment factors used in the example were calculated

Procedure for Using the General and Specific Provision Guidelines

1. Obtain traffic counts for the study approach and opposing approach for both the a.m. and p.m. peak hours including: total volume, turning movements, and signal timing.

2. Using the traffic data for the higher peak hour, calculate average left turns per cycle. (Average left turns per cycle = total left turns for the peak hour/number of cycles in peak hour.)

3. Obtain equivalent left turns per cycle by multiplying the average left turns per cycle (calculated previously) by the adjustment factors for cycle length, G/C ratio, and approach volume (see example).

4. Once calculated, check equivalent left turns per cycle for the approach against the curve to determine if a left turn provision should be considered on the approach. Enter the curve using the opposing volume (in vehicles per hour per lane). If the equiva-

lent left turns per cycle is above the curve, a left turn provision should be considered; if below the curve, a left turn provision is not needed.

5. If the general guideline recommends a left turn provision, then compare the approach with the type provision guidelines to determine which provision is appropriate

6. If a new signal timing requiring a major decrease in G/C ratio for any approach is contemplated, the approach should be rechecked using the new signal timing since the decrease in G/C time may necessitate a left turn provision where the original timing did not.

7 The general guideline, as developed, determines if an individual approach should be considered for a left turn provision on the basis of delay on the approach. While the provision will decrease delay on the study approach, it could increase delay on any of the other approaches enough to actually increase total intersection delay. Thus, a check should be made to see if the green time required for the left turn provision is available. This check could be accomplished either through normal traffic analysis procedures or through use of the NETSIM model.

8. Although a left turn provision may not be warranted on the study approach on the basis of delay, other factors (such as accidents and traffic conflicts) may yield a warrant for one.

EXAMPLE

APPLICATION OF GENERAL AND SPECIFIC GUIDELINES TO INTERSECTION APPROACH

A. GENERAL GUIDELINE

Route 202 and Hanover Avenue

	ROUTE 202 - SB	ROUTE 202 - NB
Total	613 VPH	562 VPH
Lefts	170 VPH	43
G/C	0.53	0.53
C	90 secs.	90 secs.

Opposing lane volume = $\frac{562}{2}$ = 281 VPH/LN

Average left turns per cycle = 170/40 = 4.25

Assume 60-40 lane split

Left lane volume = .4 x 613 = 245 VPH

4.25 x 1.1	x 0.95	x 0.52	= 2.3 Equivalent left turns per cycle
Adjustment Factor (Cycle Length)	Adjustment Factor (G/C Ratio)	Adjustment Factor (Approach Volume)	

2.3 > 2.1 @ 281 VPH/LN Opposing

Left Turn Provision Should Be Considered

B. SPECIFIC GUIDELINE

ROUTE 202 - SB

1. General guideline met for Route 202-SB

2. Check if slot needed

Right lane capacity < thru and right demand

R.L.C. = $\underset{G/C}{.53}$ x 1600 VPHG = 848 VPH < 443 VPH

No Slot Necessary

3. Check opposing approach

Route 202 - NB

L.T./Cycle F_C F_{GC} F_{VA} App. Vol.

1.1 x 1.11 x 0.95 x 0.49 = 0.6 L.T./Cycle

0.6 < 2.6 @ 228 VPH/LN Opposing

Three phase not needed

4. Lead Green recommended

C. CHECK OF TOTAL INTERSECTION (Using new timing plan)

ROUTE 202 - NB

2 Lanes x 1600 VPHG x $\overset{G/C}{.49}$ = 1568 VPH Capacity

1568 VPH>562 VPH Demand

Sufficient capacity is available.

HANOVER AVENUE - EB

2 Lanes x 1600 VPHG x $\overset{G/C}{.41}$ = 1312 VPH Capacity

1312>1194 VPH Demand

Sufficient capacity is available.

HANOVER AVENUE - WB

3 Lanes x 1600 VPHG x $\overset{G/C}{.41}$ = 1968 VPH Capacity

1968 VPH>380 VPH Demand

- Sufficient capacity is available

TABLE 10

USE OF ADJUSTMENT FACTOR TABLES

1. ADJUSTMENT FOR CYCLE LENGTH:

CYCLE LENGTH F_C

G/C = 0.50, APP. VOL. = 600 VPH/LN.
CYCLE LENGTH = 90 SECS.

	CYCLE LENGTH OPP. VOLUME	60	80	90	100	
	0	1.00	1.00	1.01	1.02	
	200	1.00	1.03	1.05	1.06	1.11
OPP. VOL. = 281 VPH/LN.	400	1.00	1.14	1.17	1.20	1.19
	600	1 00	1.17	1.18	1.19	1.35
	800	1.00	1.33	1.33	1.32	1.48

ADJUSTMENT FACTOR FOR CYCLE LENGTH $= 1.05 + \frac{81}{200}\ 1.17-1.05) = 1.10$

2. ADJUSTMENT FOR G/C RATIO:

G/C RATIO $F_{G/C}$

C.L. = 60 SECS., APP. VOL. = 600 VPH/LN.
G/C RATIO = 0.53

	G/C RATIO OPP. VOLUME	0.25	0.50	0.65	0.75
	0	1.70	1.00	0.81	0.79
	200	1.80	1.00	0.77	0.68
OPP. VOL. = 281 VPH/LN.	400	1.59	1.00	0.77	0.69
	600	1.58	1.00	0.74	0.69
	800	1.47	1.00	0.90	0.78

ADJUSTMENT FACTOR FOR G/C RATIO $(F_{G/C}) = 0.77 + \frac{.12}{.15}\ 1.00-0.77) = 0.95$

3. ADJUSTMENT FOR APPROACH VOLUME:

<u>APPROACH VOLUME</u> F_{VA}

C.L. = 60 SECS., G/C = 0.50
OPPOSING VOLUME = 600 VPH/LN.

LEFT LANE APPROACH
VOL. = 245 VPH

APP. VOL. (VPH/LN.)	F_{VA}
	0.45
300	0.61
400	0.71
500	0.91
	1.00
	1.11
	1.33

ADJUSTMENT FACTOR FOR APPROACH VOLUME $F_{VA} = 0.45 + \frac{45}{100}(0.61-0.45) = 0.52$

APPENDIX D

VALIDATION OF NETSIM SIMULATION MODEL FOR USE IN NEW JERSEY

Before the UTCS-1 simulation model could be used for this study, it was first necessary to validate the model for traffic conditions in New Jersey. The procedure for this validation consisted of a comparison of data from 10 intersection approach studies performed in the field with data generated by NETSIM model for the same 10 approaches under the same conditions as found in the field. The field data for this comparison was collected by means of the videotape method (see Appendix A). The NETSIM data was compiled by averaging the results of 10 iterations of the model for each approach. The measure of effectiveness for this validation was chosen to be total travel time per vehicle.

Due to the recurrence of the equipment problems explained in Appendix A, field data for one of the approaches proved to be unreliable. For this reason, only nine of the original 10 approaches were included in this comparison; the results of which can be seen in Table 11.

Use of the student-t test on the comparison results showed no signifi- difference existing between the field data and the model data at the 95 per cent confidence level. Since data taken from different sites may be normally distributed, the Wilcoxon signed-ranked test was also applied to the data. This test also showed no significant difference at at a 95% confidence level. However, because of the small number of data points available for comparison these results were viewed with caution.

Although the sample size (9) was too small for complete confidence in the result of the student-t test, it was still felt that the simulated data

TABLE 11

COMPARISON OF FIELD DATA VS. NETSIM

SIMULATED DATA

Intersection	Field Data Total Time (sec./veh.)	Simulated Data Total Time (sec./veh.)	Difference
Route 206 and Route 518	20.1	14.1	+6.0
Scotch Road and Route 546	38.0	35.0	+3.0
Route 29 and Upper Ferry Road	13.2	11.7	+1.5
Delaware Avenue and Route 31	43.4	39.0	+4.4
Route 31 and Delaware Avenue	20.5	22.0	-1.5
Prospect Street and Olden Avenue	37.0	32.4	+4.6
South Broad Street and Trebor Avenue	9.2	12.3	-3.1
Trebor Avenue and South Broad Street	63.6	50.7	+12.9
Harrison Street and Hamilton Avenue	13.2	20.2	-7.0

$X = 2.31$
$S = 5.76$

$$t = \frac{2.31}{1.92} = 1.21$$

$$t_{8,x/2} = 0.025 = 2.306$$

had been found sufficiently accurate under a variety of intersection conditions for the purposes of this study. This, coupled with the good results previously experienced by FHWA elsewhere, led to the decision to forego any further validation testing in favor of generating the necessary data to develop the left turn provision guidelines.

BIBLIOGRAPHY

1. Agent, Kenneth R., Development of Warrants for Left Turn Phasing, Kentucky DOT, August 1976.

2. Behnam, J.,Gap Acceptance as a Criterion for Left Turn Phasing, Traffic Engineering, June 1972.

3. Box, P.C. and Alroth, W.A., Warrants for Traffic Control Signals Traffic Engineering, November and December 1967 and January 1968.

4. Dart, O.K., Development of Factual Warrants for Left-Turn Channelization, Ph.D. Dissertation, Texas A & M University, January 1966.

5. Dart, O., Left-Turn Characteristics at Signalized Intersections on Four-Lane Arterial Streets, Record Number 230, Highway Research Board, 1968.

6. Failmezgar, Ronald W., Relative Warrant for Left Turn Refuge Construction, Traffic Engineering, April 1963, p. 18.

7. Fairfax, B.W., Methods of Signalizing Left-Turn Movements at Channelized Intersections, Traffic Engineering, May 1967.

8. Fellinghauer, Edward and Berry, Donald S., Effects of Opposing Flow on Left Turn Reduction Factors at 2-ϕ Signalized Intersections, Transportation Research Record 489, 1974, p. 13.

9. Gerlough, D.L. and Wagner, F.A., Improved Criteria for Traffic Signals at Individual Intersections, NCHRP Report 32, 1967.

10. Gurnett, G., Intersection Delay and Left Turn Phasing, Traffic Engineering, June 1969.

11. Hammer, Charles J., Jr., Evaluation of Minor Improvements, Highway Research Record 286, 1969, p. 33.

12. Left Turns at Signalized Intersections in Wisconsin, Report for the Wisconsin Section of the Institute of Traffic Engineers.

13. Leisch, J., Capacity Analysis Techniques for Design of Signalized Intersections, Public Roads, Vol. 34, No. 9 and 10, August and October 1967.

14. Manual on Uniform Traffic Control Devices, Federal Highway Administration, 1971.

15. May, Adolph D., Jr. and Hom, Robert E., Intersection Capacity of Exclusive Turning Lanes, Traffic Engineering, March 1968, p. 48.

16. McKay, B.W., Lead and Lag Left Turn Signals, Traffic Engineering, April 1968.

17. Network Flow Simulation for Urban Traffic Control System - Phase II, Federal Highway Administration, March 1974.

18. Plummer, R.W. and King, L.E., Meaning and Application of Color and Arrow Indications for Traffic Signals, Record Number 445, Highway Research Board, 1973.

19. Ray, James C., Two Left Lane Turns Studied at Signalized Intersections, Traffic Engineering, April 1965, p. 17

Reilly, E.F., Hollinger, R.L., and Dommasch, I.N., Design Warrants for Left-Turning Vehicles at Signalized Intersections (Interim Report), New Jersey Department of Transportation, June 1973.

Ring, S.L. and Carstens, R.L., Guidelines for the Inclusion of Left Turn Lanes at Rural Highway Intersections, Highway Research Record 371, 1971, p. 64.

22. Spitz, S., Left-Turn Phases -- Who Needs Them?, Traffic Engineering, December 1974.

Sofokidis, H., Tilles, D.C., and Geiger, D.R., Evaluation of Intersection-Delay Measurement Techniques, Record Number 453, Highway Research Board, 1973.

24. Stover, V.G., Adkins, W.G., and Goodknight, J.C., Guidelines for Medial and Marginal Access Control on Major Roadways, National Cooperative Highway Research Program Report 93, Highway Research Board, 1970.

Traffic Signal Warrants, KLD Associates, KLD TR No. 17, November 1973.