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L&D Manual Turn Lane Storage Validation/Update

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L&D Manual Turn Lane Storage Validation/Update

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for the
Ohio Department of Transportation
Office of Research and Development

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16. Abstract

Queuing occurs at intersections mostly due to overflow or inadequacy of turn bays. The ODOT L&D Manual Volume 1 has storage requirements for both signalized and unsignalized intersections. Figures 401-9E and 401-10E of the L&D Manual provide the required turn lane storage lengths which should be compared with the real world conditions to check for adequacy of these lengths as a measure of ensuring that accesses to the left turn lanes are not blocked. In addition to the projected turn lane volume, ODOT's methodology incorporates both deceleration (based on the speed of the roadway) and potential blockage from the adjacent through lane. Currently, however, there are no records whether these storage lengths computed by the methodology put forth in this manual are valid and accurately represent the actual conditions at intersections in Ohio. This study used real world traffic and queue storage data at some intersections and analyzed these data to validate the model ODOT is currently using. This study used the observed field data to evaluate the ODOT's model of storage length at intersections. In addition, the queue storage lengths observed from field data were compared with the prediction results of HCS and SYNCHRO computer packages. The model evaluation task evaluated the level of precision of each of the three models (ODOT, HCS, and SYNCHRO) with respect to the field data observation. L&D Manual lead the way by accurately predicting the observed queues by about 81.6% and closely followed by HCS, which also had a 79.2% prediction accuracy. SYNCHRO was by far the lowest with a 46.0% prediction accuracy.

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L&D Manual Turn Lane Storage Validation/Update

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Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

Disclaimer

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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1. INTRODUCTION

As intersections are critical in affecting the capacity of a transportation system, addressing queuing at intersections by providing enough storage lengths for vehicles in turning lanes is critical for both to-be-designed (new) intersections and modifying existing intersections with queuing problems. This may have an added benefit of reducing some type of traffic crashes which are typical of turning vehicle-related problems notably rear-end and same direction side-swipe crashes.

The formation of queues on a highway facility is a sign of the presence of operationally inefficient sections of the facility. Queuing occurs at intersections mostly due to overflow or inadequacy of turn bays, capacity and poor signal progression. The ODOT Location and Design (L&D) Manual Volume 1 has storage requirements for both signalized and unsignalized intersections. Figures 401-9E and 401-10E of the L&D Manual provide the required turn lane storage lengths which should be compared with the real world conditions to check for adequacy of these lengths as a measure of ensuring that accesses to the turn lanes are not blocked. In addition to the projected turn lane volume, ODOT's methodology incorporates both deceleration (based on the speed of the roadway) and potential blockage from the adjacent through lane. Currently, however, there are no records whether these storage lengths computed by the methodology put forth in this manual are valid and accurately represent the actual conditions at intersections in Ohio. Consequently, collecting real world traffic and queue storage data at some intersections and analyzing these data is valuable for validating and/or updating the model ODOT is currently using. Accordingly, the purpose of this research was to collect traffic and queue storage data at some intersections in Ohio and use the collected data to validate and/or update the model in ODOT's L&D Manual.

2. OBJECTIVES OF THE STUDY

The objective of this research study included the following: (1) to use traffic, signal and geometry data collected from some signalized intersections to validate and/or update the current ODOT's model used for turn lane storage length calculations, and (2) to compare queue storage length calculations by other models available such as the McTrans' Highway Capacity Software (HCS) and SYNCHRO using the same datasets.

3. LITERATURE REVIEW

A method of determining the storage length at unsignalized intersection developed by Harmelink (1967) has been highly cited as many other recent procedures developed have their basis linked to this classical study (e.g., ITE, 1981; AASHTO, 2004). An extensive research study was conducted by Parsons Brinckeroff Quade and Douglas Inc. for PennDOT (Babusci, 2005) in order to recommend the queue length storage method for left-turn and right-turn lanes to be used at unsignalized and signalized intersections in the state of Pennsylvania. According to Babusci (2005), three methods: Gard Method (Gard, 2001), the AASHTO (2004) (two minute arrival method) and the Ohio DOT (2009) methods were established to be the best three methods in calculating queue lengths for left turn lanes at unsignalized intersections. That study recommended the AASHTO method for use in this regard because it was noted that the Ohio DOT method was essentially a variant of the AASHTO method and the Gard method was a bit awkward to use and required additional input data. The same study recommended the Ohio DOT method to be the best method out of seventeen methods it analyzed for calculating left turn queue storage lengths at signalized intersections. Another research conducted by the Virginia Transportation Research Council (Demetsky and Miller, 1991) is related to the proposed study. A survey conducted as part of this study on the types of queuing problems of most interest to the Virginia DOT (VDOT) personnel responsible in analyzing queue problems found that 80% of queuing problems were left turn storage lane requirements. A study conducted by Texas Southern University (Yu et al., 2007) found that the recommended queue storage estimation model by the Texas Department of Transportation (TxDOT) roadway manual overestimates left turn queue lengths. Analyses by three models (SYNCHRO, SimTraffic, and VISSIM) were also used to estimate left-turn lane queue storage length requirement and found that SimTraffic performed better by accurately modeling the storage length. Other notable publications that discuss the issue of turn lane storage length include (Neuman, 1985), Oregon DOT (1996), and Bonneson and Fotaine (2001).

4. SURVEY OF DEPARTMENTS OF TRANSPORTATION

A survey was conducted seeking the experiences of other state departments of transportation (DOTs) in modeling turn lane storage lengths. A questionnaire was prepared to solicit information from state DOT design engineers around the nation. The questionnaire developed and used in this study is included in the Appendix A. Also, included Appendix B is a table of names and contact information of the persons contacted for each state department of transportation. The questionnaire was sent electronically to all state DOTs excluding Ohio. Two reminder emails were also sent at the interval of approximately three weeks of each other to remind those state design engineers who did not respond to the previous request at each time.

Only fourteen state departments of transportation responded to our request corresponding to about 29.2% response rate. These include Arizona, Colorado, Delaware, Florida, Georgia, Idaho, Louisiana, Michigan, North Dakota, Pennsylvania, South Carolina, South Dakota, Virginia, and West Virginia.

5. METHODOLOGY

5.1 Source of Data

Data collection was one of the most important components for this study. ODOT personnel were responsible for the data collection task. ODOT video-taped traffic movements at three different signalized intersections in the Columbus area, which resulted into sixteen hours of recording. Table 1 shows the intersection locations, dates and time of data collection.

Table 1. Intersections Studied Located in Columbus Area

Intersection	Date Studied	Time Studied	Direction Studied	Existing	
				Lane Length* (ft)	Taper* (ft)
Bethel Road & Olentangy River Road	1/12/2012 1/11/2012	8-10 AM 3- 5 PM	Eastbound Eastbound	240	65
US 33 & Grandview Avenue	11/29/2011 11/28/2011	8-10 AM 3- 5 PM	Northbound Northbound		
US 33 & Fishinger Road	12/7/2011 12/7/211	8-10 AM 3- 5 PM	Southbound Southbound	335	45
	2/9/2012 2/8/2012	8-10 AM 3- 5 PM	Northbound Northbound	235	95

*One can't demarcate between the deceleration length and the storage length. See Figure 1 for clarification.

The length measured in this study and called “lane length” and taper as shown in Table 1 and depicted in Figure 1 differ somewhat from ODOT’s definition (See Figure 2). The length measured in this study and called “lane length” (refer to Table 1 and Figure 1) is actually made up of storage and deceleration lengths, therefore, we were not able to determine which portion of it is a storage length and which one is a deceleration length.

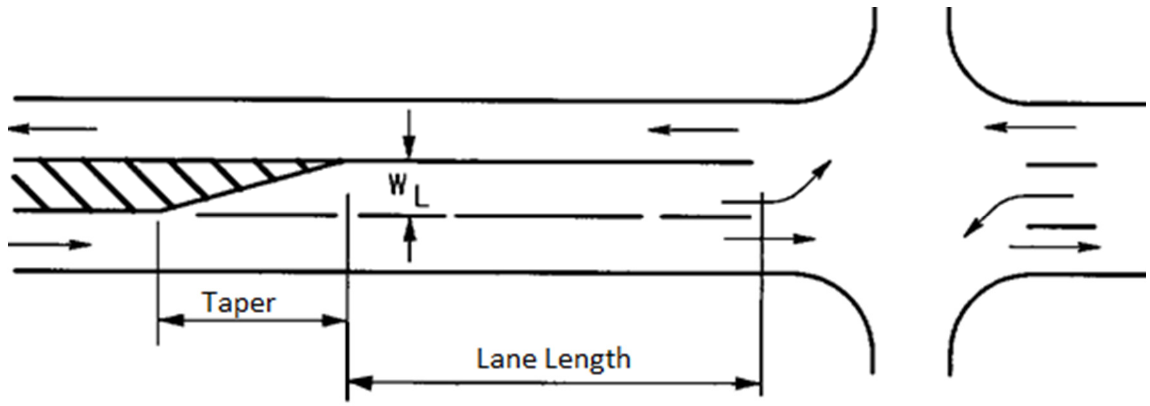

Figure 1. Clarification of Lengths Measured for Turn Lanes

5.2 Data Extraction

The recorded video data were manually counted in 15-minute intervals, by turning movements in our Transportation Engineering Lab. For the left turn lane in the subject approach (i.e. the approach which is the target of the video camera), the number of vehicles in a queue was counted cycle by cycle. The cycle lengths, the green and yellow indications were observed including counting the number of cycles in each hour. Table 2 shows the results of turning traffic counts for all intersections and time periods extracted from the video data.

Table 2. Hourly Traffic Volume Counts

Intersection	Date	Time	Eastbound			Westbound			Northbound			Southbound		
			Left	Thru	Right	Left	Thru	Right	Left	Thru	Right	Left	Thru	Right
US 33 & Fishinger Rd	2/8/12	3-4 PM	171	294	254	194	301	255	306	458	58	53	445	154
US 33 & Fishinger Rd	2/8/12	4-5 PM	181	294	282	179	311	293	399	615	47	74	554	213
US 33 & Fishinger Rd	2/9/12	8-9 AM	199	469	723	116	489	102	300	569	41	109	669	153
US 33 & Fishinger Rd	2/9/12	9-10 AM	126	358	376	70	368	66	241	378	50	78	416	127
US 33 & Fishinger Rd	12/7/11	8-9 AM	99	300	558	168	291	527	256	512	39	80	608	124
US 33 & Fishinger Rd	12/7/11	9-10 AM	39	318	425	183	322	305	226	406	46	84	120	573
US 33 & Fishinger Rd	12/7/11	3-4 PM	218	550	316	71	601	69	369	597	67	103	459	236
US 33 & Fishinger Rd	12/7/11	4-5 PM	265	689	376	72	709	99	489	744	61	95	550	214
US 33 & Grandview Ave	11/28/11	3-4 PM	73	248	114	91	267	133	87	271	21	102	296	38
US 33 & Grandview Ave	11/28/11	4-5 PM	87	379	141	105	391	164	95	352	41	114	391	56
US 33 & Grandview Ave	11/29/11	8-9 AM	114	1109	66	131	1056	90	222	360	76	250	382	92
US 33 & Grandview Ave	11/29/11	9-10 AM	83	471	83	107	582	80	147	260	55	170	316	80
Bethel Rd & Olentangy River Rd	1/12/12	8-9 AM	74	1115	154	90	981	169	145	413	176	142	408	157
Bethel Rd & Olentangy River Rd	1/12/12	9-10 AM	82	978	122	101	986	147	116	287	114	120	146	96
Bethel Rd & Olentangy River Rd	1/11/12	3-4 PM	164	991	132	162	895	150	72	142	106	67	119	92
Bethel Rd & Olentangy River Rd	1/11/12	4-5 PM	169	1033	147	196	999	160	104	153	119	90	136	107

5.3. Model Evaluation and Validation

This task of the study used the observed field data to evaluate the ODOT's model of storage length at intersections. To evaluate the ODOT model of storage length at intersections, the ODOT model calculated queue storage lengths of the study intersections was compared with actual queue lengths observed in the field, with the collected data. The ODOT method computes the storage length at intersections in terms of feet (meters). The ODOT method of computing turn lane lengths is described in L&D Manual Volume 1 (Refer to Section 401.6.1, Section 401.6.3, Figure 401-9E and Figure 401-10E of the L&D Manual, Volume 1). Figure 2 shows the definition of the turn lane as per L&D Manual and how the taper length (T_L), deceleration length (D_L), and storage length (S_L) are related to the turn lane length (L).

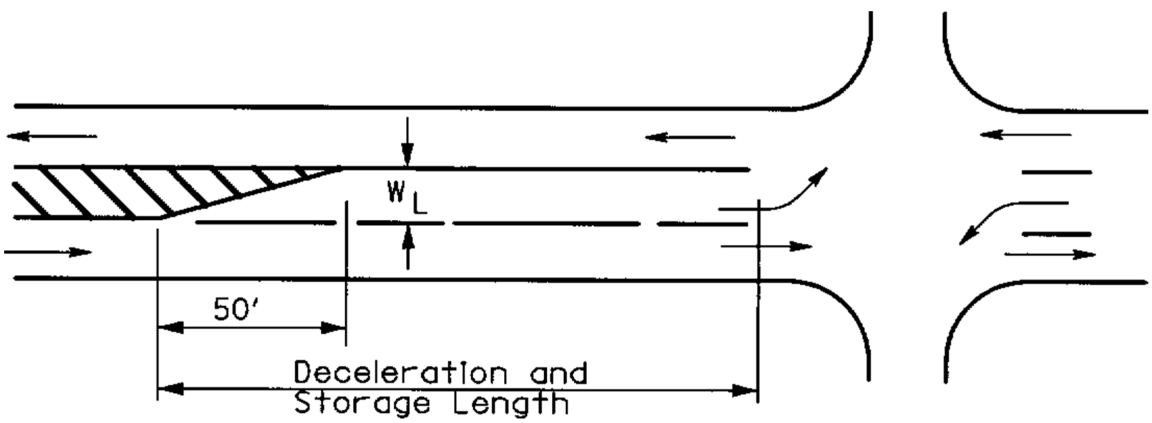

Figure 2. ODOT L&D Manual's Definition of Turn Lane and its Components

Figure 401-9E of L&D Manual provides three conditions when computing the length of turn lanes. These conditions are based on design speed of the approach roadway (30-35, 40-45, and 50-60 mph), turn demand (low or high, low being 10% or less of the approach traffic), and type of traffic control (signalized, unsignalized stopped crossroad, and unsignalized through road). The turn lanes based on these conditions are given as follows:

1. Condition A: this computes storage length only. It is mainly used for low design speed roadways (30-35mph) with any type of traffic control and for unsignalized stopped crossroads only. The turn lane is the sum of diverging taper (50') plus storage length (Based on L&D Manual's Figure 401-10E).

2. Condition B: for this condition, the procedure computes the high speed deceleration length only. The value computed is a function of design speed (for 40 mph or higher) and turn demand volume. The computed turn lane length includes a 50' taper length.
3. Condition C: this computes a turn lane length made up of moderate speed deceleration length (obtained from L&D Manual's Figure 401-09E) based on design speed and storage length (based on Figure 401-10E). This condition also applies for higher design speed roadways (40+ mph). Where Conditions B and C are both applicable, the manual recommends computing both turn lanes and pick the larger of the two values.

The concepts of computing turn lane and storage lengths for Conditions A, B, and C as defined in the L&D Manual are depicted in Figures 3 through 5, respectively. The storage length values in the L&D Manual's Figure 401-10E are based on the turn lane design hourly volumes (DHV) and number of cycles per hour. In this study, it is the computed storage length which is needed for checking against the storage length required to accommodate the number of vehicles observed queued at studied intersections. For Conditions A and C, the storage lengths computed from L&D Manual's Figure 401-10E are used as they are while for Condition B, the storage length is obtained by subtracting 50 feet (taper length) from the turn lane length computed in the L&D Manual's Figure 401-9E.

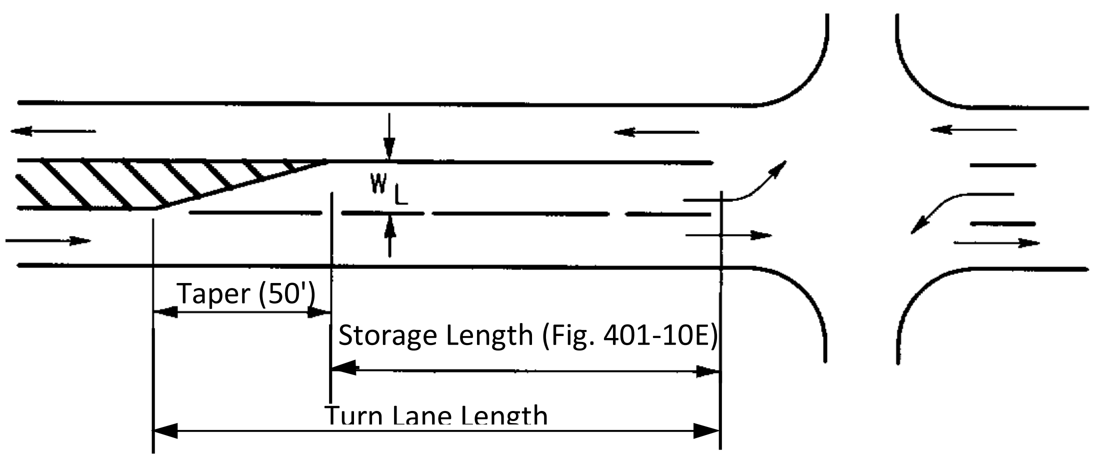

Figure 3. L&D Manual's Definition of Condition A Turning Lane

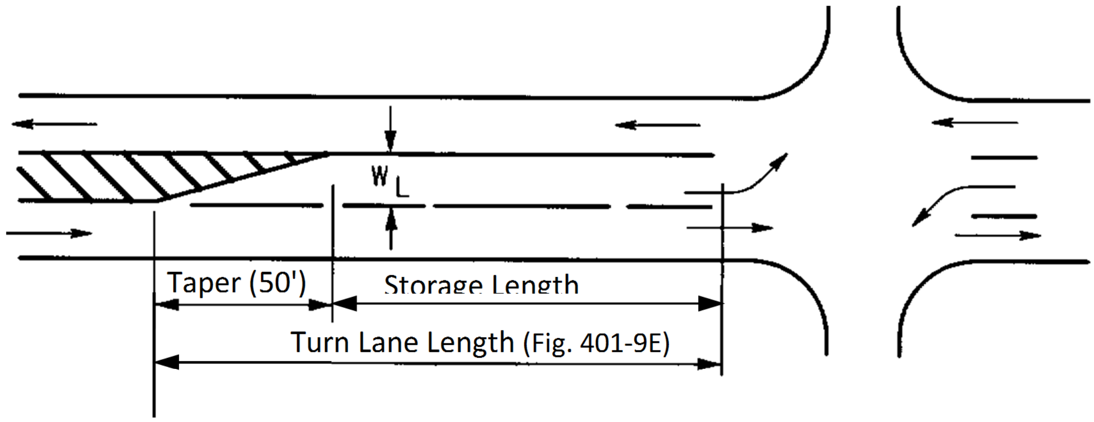

Figure 4. L&D Manual's Definition of Condition B Turning Lane

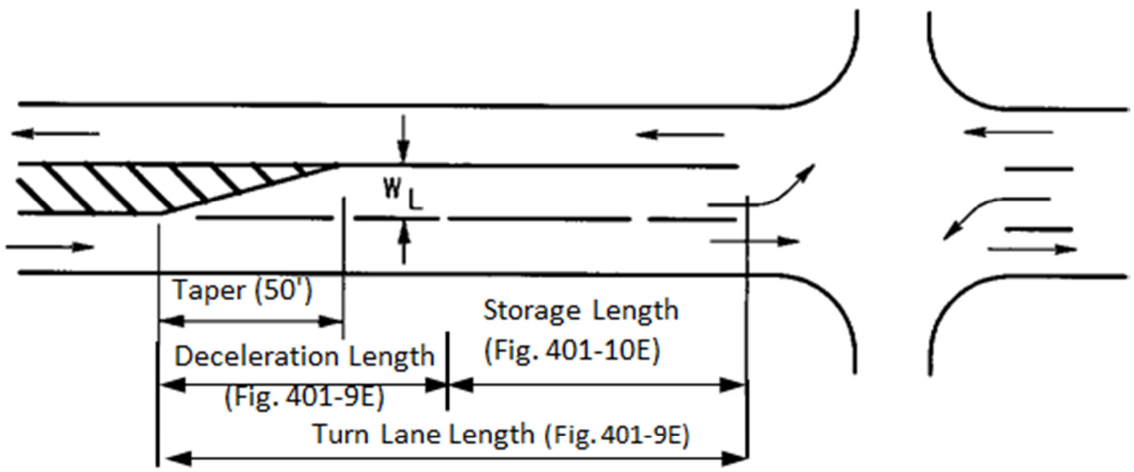

Figure 5. L&D Manual's Definition of Condition C Turning Lane

In addition, the traffic queue lengths observed from field data were also compared with the outputs of the Highway Capacity Software (HCS Version 5.3) and SYNCHRO (Version 7) computer packages as these are some of the widely used software packages. These computer model software packages compute the maximum percentile queues, which represent maximum back distance where vehicles stop during a cycle. HCS Version 5.3 software calculates the back of queue in terms of the number of vehicles that are queued at the intersection's specific lane and it predicts average back of queue (50^{th}), 70^{th}, 85^{th}, 90^{th}, 95^{th}, and 98^{th} percentile backs of queue. On the other hand, SYNCHRO software calculates the 50^{th} and 95^{th} percentile queues in terms of the distance in feet required to store the entire queue length of the vehicles in the specific lane at the intersection. Originally, the 95th percentile queue lengths reported by HCS and SYNCHRO were supposed to be taken as the baseline for comparison because most procedures design storage bays to accommodate the 95th percentile queue length. However, the 98th percentile queues computed by HCS were nearer to the maximum observed queues than the 95th queues, therefore, for HCS, the 98th queues were eventually utilized in this study.

The model evaluation step also included the evaluation of the level of precision of each of the three models (ODOT, HCS, and SYNCHRO) with respect to the field data observation. The performance of the three models was compared based on two criteria. The first performance evaluation criterion was based on the number of times a particular model's predictions are closest to the actual field observed values. A score value of "1" was given to the model with the best value and a "0" value for the other two. Then a value called "SCORE" was determined for each model by adding together its score values. The second performance evaluation criterion was based on the accuracy level of the prediction, i.e., how close the model predicted queue is to the field-based observed queue length. The value called "%ACC" was computed as shown in Equation 1. Based on these formulated evaluation criteria, the higher the SCORE and %ACC values, the better the model in predicting the length of the storage lane.

$$\%ACC = \left[1 - \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\left|L_{pred,i} - L_{obs,i}\right|}{L_{obs,i}}\right)\right] \times 100\% \qquad (1)$$

Where:

$L_{pred,i}$ = Predicted queue length by the model to replicate observed field data *i*

$L_{obs,i}$ = Observed queue length for field data *i*

N = Number of field observation data used in model evaluation

It should also be noted that a method that consistently predicted maximum queues that are equal or higher than the field observed queues should be more preferred than the one that consistently predicted lower queues.

5.4 Conversion between Units Used in Queue Length Computations

As described above, the field observed vehicle queues were measured in terms of counted vehicles in the queue stopped at each intersection waiting for the signal to turn green. The queue length computed by the ODOT method is given in terms of distance in feet required to store the number of queued vehicle. Likewise, SYNCHRO predicts the queue length in terms of distance in feet while HCS reports this prediction in terms of number of vehicles. In order to equitably compare all these results, there was a need to use a common unit of measurement. Since the field observed data were in terms of the number of vehicles, then it was decided to convert all predictions and computations into that unit of measurement. To determine the distance covered per vehicle when queued at the intersection, the "distance calculator" tool in the Microsoft's Bing Map software (website) was used. In this case, the map was zoomed into various major intersections in Columbus and Dayton areas to an extent that a number of vehicles that were obviously stopped waiting for the green light were observed. Values obtained from several intersection sites were used to determine the average distance occupied by a typical vehicle. The calculator tool was used to measure the distance from the stop bar at the intersection to the end of the last vehicle in the queue as shown in Figure 6 and the tool returns the straight line measured distance in feet.

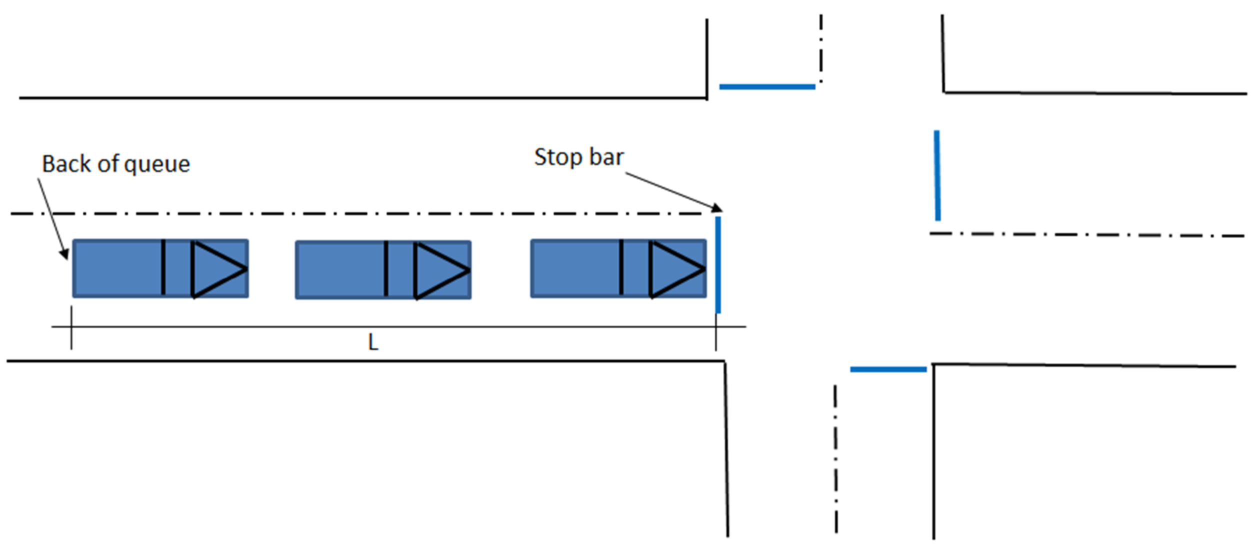

Figure 6. Measuring Length of Queue on Bing Maps by Using the Distance Calculator Tool

The average length occupied by a vehicle was determined by dividing the measured distance to the number of vehicles counted in the queue as depicted in the simple formula in Equation 2:

$$l = \frac{L}{N} \qquad (2)$$

Where:

l = average distance occupied by a queued vehicle at an intersection approach (feet/vehicle)

L = distance measured from the stop bar to the back of queue at the intersection (feet)

N = number of vehicles counted in the queue (number of vehicle)

It is noteworthy to mention that the above calculated average length occupied by a typical stopped vehicle at an intersection assumes all vehicles are passenger cars. If there is a notable number of trucks in the queue will obvious affect the calculated average length of the stopped vehicle since a large truck requires more space than a typical passenger car and also their drivers tend to keep larger distances between themselves and the preceding vehicles. In all queues observed there were negligible number of trucks in the subject left turns at all studied intersections. There were a few numbers of single unit delivery trucks and school buses that quickly cleared the intersections and thus were rarely counted in the largest observed queues in any given hour of study. Likewise, in the Microsoft Bing maps efforts were taken to zoom around a number of intersections in Columbus and Dayton areas but the pictures of intersection's queued vehicles that included trucks were hardly observed. The average distance/length occupied by a stopped vehicle at the intersection was determined to be 25 feet. It is worth mentioning here that coincidently both HCS 5.3 and SYNCHRO 7 use the same value when computing the lengths of stopped vehicles. This happened to be plausible due to increased consistency when comparing the results.

The distance tool calculator in Microsoft Bing map was also used to measure the existing lengths of turn lanes at each intersection in the manner described above. The approach tapers were also measured. The only thing that could not be determined in this exercise was the possibility of breaking down the turn length into the deceleration length and storage length.

6. RESULTS

6.1 Survey Results of State Departments of Transportation

As mentioned earlier, only fourteen state departments of transportation responded to our survey. Most of those responding sent back completed questionnaires, some provided sections of their design manuals that deal with turn lane designs, and some provided both, the completed questionnaires and design manuals. Under this section we are including a summary of information we received from the state engineers.

6.1.1 Arizona

Arizona Department of Transportation (ADOT) responded to our survey by sending us two sections from ADOT Traffic Engineering Policies, Guidelines, and Procedures (PGP) Manual of May 2010. Section 245 deals with turn lane warrants and Section 430 deals with turn lane design. The ADOT turn lane comprises three parts namely, the taper, gap, and storage.

The taper length (ft) is a function of the width of the turn lane (ft) and posted or design speed (mph) as shown in Equation 3.

$$\begin{aligned} T &= WS \quad \text{for } S \geq 45 \text{ mph} \\ T &= \frac{WS^2}{60} \text{ for } S < 45 \text{ mph} \end{aligned} \tag{3}$$

Where:

T = length of taper, ft

W = width of the added lane, ft

S = posted speed for existing roadways, or design speed for new or reconstructed roadways

The gap length (ft) is given as a function posted speed limit or design speed (mph) categorized as < 40, 40-50, and > 50 mph. The manual states that the storage length (ft) is the function of braking distance and queue length depending on the anticipated traffic control type and turning traffic demand. The manual provides a table for gap length as a function of speed but not procedure for determining the queue length but simply states "a traffic analysis may be needed to determine arrival rates and queue lengths."

6.1.2 Colorado

Colorado Department of Transportation (CDOT) responded by sending us a completed survey questionnaire. They stated that all the requirements are generally laid out in the publication called "State Highway Access Code", Volume 2 Code of Colorado Regulations 601-1 of March 2002. The engineer responding to the survey stated that they often use a traffic model to analyze queuing and base storage requirements on 95th percentile queue lengths. Deceleration and taper lengths are based on AASHTO, CDOT and/or MUTCD standards.

6.1.3 Delaware

Delaware Department of Transportation (DelDOT) responded by returning a completed survey. They sent a link to the chapter of their Road Design Manual, Chapter 7 Intersections, which deal with designing turn lanes. Their method is generally based on the 2004 AASHTO Green Book and MUTCD. The storage length is determined by using a formula depicted in Equation 4.

$$SL = (N/C) \times VL \pm 1.5 \qquad (4)$$

Where:

SL = storage length, ft

N = number of left-turn vehicles in peak hour

C = number of cycles per hour

VL = vehicle length, ft (recommended to use 20 ft)

6.1.4 Florida

Florida Department of Transportation (FDOT) responded by returning back a completed survey questionnaire. The completed questionnaire revealed that FDOT's deceleration length is determined using FDOT design standard table based on the following configurations: (1) informed driver, (2) design speed to stop condition (with or without stop control), (3) wet pavement, (4) reaction preceding entry point, (5) minimum braking distance for urban conditions,

(6) 75' minimum for brake to stop distance, (7) use of comfortable deceleration rates for urban conditions (11.2 ft/sec^2) based on 2001 AASHTO's Green Book.

The FDOT's storage length (queue length) is based on a traffic study. Important factors include: (1) the design year volume for the peak hour, (2) an estimate for the number of cycles per hour (NOTE: if the cycle length increases, the length of the storage for the same traffic also increases, (3) the signal phasing and timing.

6.1.5 Georgia

Georgia Department of Transportation (GDOT) responded by sending back a completed survey questionnaire. GDOT personnel mentioned that the length of a turn lane consists of three components: entering taper, deceleration length, and storage length. Where practical, the total length of turn lane should be determined based on the design speed and the storage requirement for the turn lane and adjacent through-lane queue. Their procedure is stipulated in the GDOT's Design Policy Manual, Chapter 7, At-Grade-Intersections for the design of arterial and collector roadways. At a minimum, for design speeds < 45 mph, taper and deceleration lengths should be designed in accordance with the GDOT Regulations for Driveway and Encroachment Control.

At a minimum, for design speeds ⩾ 45 mph, taper and deceleration lengths should be designed in accordance with Georgia Construction Detail M-3. GDOT states that for further design guidance relating to the design of turn lanes, refer to the AASHTO Green Book, Chapter 9, Auxiliary Lanes.

6.1.6 Idaho

Idaho Department of Transportation (IDOT) responded to our survey by an engineer summarizing his responses in an email. The IDOT personnel stated that in Idaho they do not have a published manual on turn lane warrants. He mentioned that their traffic engineers use the AASHTO book "A Policy on Geometric Design of Highways and Streets" as a basis for the initial design and then based on site specific criteria such as crashes, traffic volumes and vehicle types they use their engineering judgment to arrive at the proper design for the turn lanes. Their concerns are points of conflict within the roadway and the safety and operation of the highway and thus turn lanes should be designed to allow turning traffic to complete their turns without interfering with the traffic in the thru lanes.

6.1.7 Louisiana

Louisiana Department of Transportation and Development (DOTD) responded by sending back a completed survey questionnaire. The engineer who completed the survey stated that for urban signalized intersections the deceleration length is based upon the mainline design speed minus 10 mph and for rural intersections, desirably, the deceleration length is based upon the mainline design speed.

The storage length is based upon 1.5 multiplied by the average design year queue. Provision should be made to store a minimum of two vehicles. For design of turn lane they generally use the 2004 AASHTO's Green Book publication. It is their department's policy to provide a minimum storage length of 150 feet.

6.1.8 Michigan

Michigan Department of Transportation (MDOT) responded by returning a completed survey questionnaire. MDOT stated that in their procedure, designing of the taper length is based on posted speed and the storage length is generally provided as 250 ft long and they simulate the intersection to make sure it is long enough. They generally use the AASHTO's Green Book as a guide.

6.19 North Dakota

North Dakota Department of Transportation (NDDOT) currently has a guidance described in Section III-03 of the NDDOT Design Manual for the left and right turn lane deceleration lengths. The deceleration length is based on speed. The deceleration through the taper should be considered to be a max of 10 mph. Therefore it will be assumed that the driver will be able to reduce his or her speed by this amount before leaving the path of the through lane. The storage length is determined using the Highway Capacity Manual.

6.1.10 Pennsylvania

Pennsylvania Department of Transportation (PennDOT) responded by returning back a completed survey questionnaire. The engineer who completed the questionnaire simply stated that designing turn lanes at signalized intersections, they follow guidance stipulated in Publication No. 46, “Traffic Engineering Manual”, Chapter 11.17 “Turn Lane Guidelines” and Chapter 12 “Traffic Engineering Software”

6.1.11 South Carolina

South Carolina Department of Transportation (SCDOT) responded to our survey by sending us Chapter 15 Intersections of their Highway Design Manual of Many 2003 and a completed survey questionnaire. Subsection 15.5.2.2 is the one that deals with design of turn lane lengths. The SCDOT procedure determines two components, the entrance taper and turn lane. The entrance taper into a turn lane can be designed either as a straight or a reverse curve taper. The taper length (ft) is obtained from a table as a function of design speed (mph), the turn lane width (ft), and the radius (ft) for the reverse curve tapers only.

The turn lane length (ft) is also obtainable from a table and is determined as a function of turning volume (vph) and the percentage of trucks in turning volume. The manual recommends that the minimum length of 150 ft and 200 ft should be used for urban and rural areas, respectively

6.1.12 South Dakota

South Dakota Department of Transportation (SDDOT) returned back a completed survey questionnaire. The SDDOT personnel stated that deceleration length is calculated using decelerations rates from the AASHTO Green Book. It is also assumed that some deceleration will take place prior to the vehicle entering the left turn. They determine queue lengths by using methods from the Highway Capacity Manual. The 95^{th} percentile of the back of queue is used for the 20 year projected traffic volumes. This guidance is provided in Chapter 12 of SDDOT‘s Road Design Manual.

6.1.13 Virginia

Virginia Department of Transportation (VDOT) responded by completing a survey questionnaire. They stated that for urban conditions, storage lengths for left and right turn lanes are determined by the appropriate capacity analysis. The engineer responding to the survey stated that they do not use the deceleration lengths shown on page 714 of the 2004 AASHTO Green Book, because in most situations it is impractical. They use the VDOT's Road Design Manual, Appendix "F", pages 49-74, which deal with designing intersection turn lanes.

6.1.14 West Virginia

West Virginia Department of Transportation (WVDOT) responded to our survey by sending us a 4-page document extracted from their Intersections on Rural Divided Highways Guide of February 2006. The document simply states for left-turn lanes where design hourly volume (DHV) for the turn from the through roadway is equal to to greater than 30, a taper, a deceleration lane, and a storage bay (minimum 100 ft long) shall be provided. The guide states that all references, tables, and exhibits contained in the guide are based on "A Policy on Geometric Design of Highways and Streets, 2004" (Green Book) published by AASHTO.

6.2 Model Evaluation Results

Table 3 and Figure 2 show the results of computed storages lengths by L&D Manual, SYNCHRO software, and HCS software versus field observed maximum queued traffic volumes for each hour observed. Appendix C shows an example of how to compute the queue length and storage length using the L&D Manual. The results show that the L&D Manual computation of storage lengths predicted better expected queue lengths when compared to the results of the two software packages. However, HCS's predictions are almost equally better with SYNCHRO consistently predicting much lower queues as expected. Signal timing data for the US 33 & Grandview Avenue were not available and the cycle data could not be estimated from the video DVD due to bad weather and poor visibility when the video were taken. As a result, data from this intersection were not used in the evaluation of SYNCHRO and HCS models.

Table 3. Computed and Observed Queue Lengths

SN	Date	Time	Location	Dir.	Cycle Length (s)	Max. Observed Queue (Veh)	L&D Method			Synchro Model			HCS Model	
							Storage Length, ft	Queue Length (Veh)	Diff. (Veh)	Storage Length, ft	95th Queue Length (Veh)	Diff. (Veh)	98th Queue Length (Veh)	Diff. (Veh)
1	1/12/12	8-9 AM	Bethel-Olentangy	EB	133	6	207.0	8.3	2.3	63	2.5	-3.5	4.2	-1.8
2	1/12/12	9-10 AM	Bethel-Olentangy	EB	109	7	195.5	7.8	0.8	67	2.7	-4.3	4.6	-2.4
3	12/7/11	8-9 AM	US33-Fishinger	SB	150	8	175.0	7.0	0.0	57	2.3	-4.7	5.1	-1.9
4	12/7/11	9-10 AM	US33-Fishinger	SB	113	7	175.0	7.0	-1.0	63	2.5	-5.5	5.5	-2.5
5	12/7/11	4-5 PM	US33-Fishinger	SB	138	9	175.0	7.0	-1.0	133	5.3	-2.7	7.3	-0.7
6	1/11/12	3-4 PM	Bethel-Olentangy	EB	116	11	175.0	7.0	-2.0	73	2.9	-6.1	6.7	-2.3
7	1/11/12	4-5 PM	Bethel-Olentangy	EB	129	10	311.0	12.4	2.4	98	3.9	-6.1	9.9	-0.1
8	12/7/11	3-4 PM	US33-Fishinger	SB	133	8	274.3	11.0	0.0	92	3.7	-7.3	9.4	-1.6
9	2/9/12	9-10 AM	US33-Fishinger	NB	120	14	282.8	11.3	-2.7	148	5.9	-8.1	11.0	-3.0
10	2/8/12	3-4 PM	US33-Fishinger	NB	124	15	348.3	13.9	-1.1	204	8.2	-6.8	16.5	1.5
11	2/9/12	8-9 AM	US33-Fishinger	NB	129	15	355.5	14.2	-0.8	283	11.3	-3.7	16.7	1.7
12	2/8/12	4-5 PM	US33-Fishinger	NB	138	22	509.5	20.4	-1.6	334	13.4	-8.6	24.1	2.1
13	11/29/11	4-5 PM	US33-Grandview	NB	120	9	215.3	8.6	-0.4	N/A	N/A	-	N/A	-
14	11/29/11	3-4 PM	US33-Grandview	NB	138	10	216.5	8.7	-1.3	N/A	N/A	-	N/A	-
15	11/29/11	9-10 AM	US33-Grandview	NB	113	12	247.3	9.9	-2.1	N/A	N/A	-	N/A	-
16	11/29/11	8-9 AM	US33-Grandview	NB	100	14	311.0	12.4	-1.6	N/A	N/A	-	N/A	-

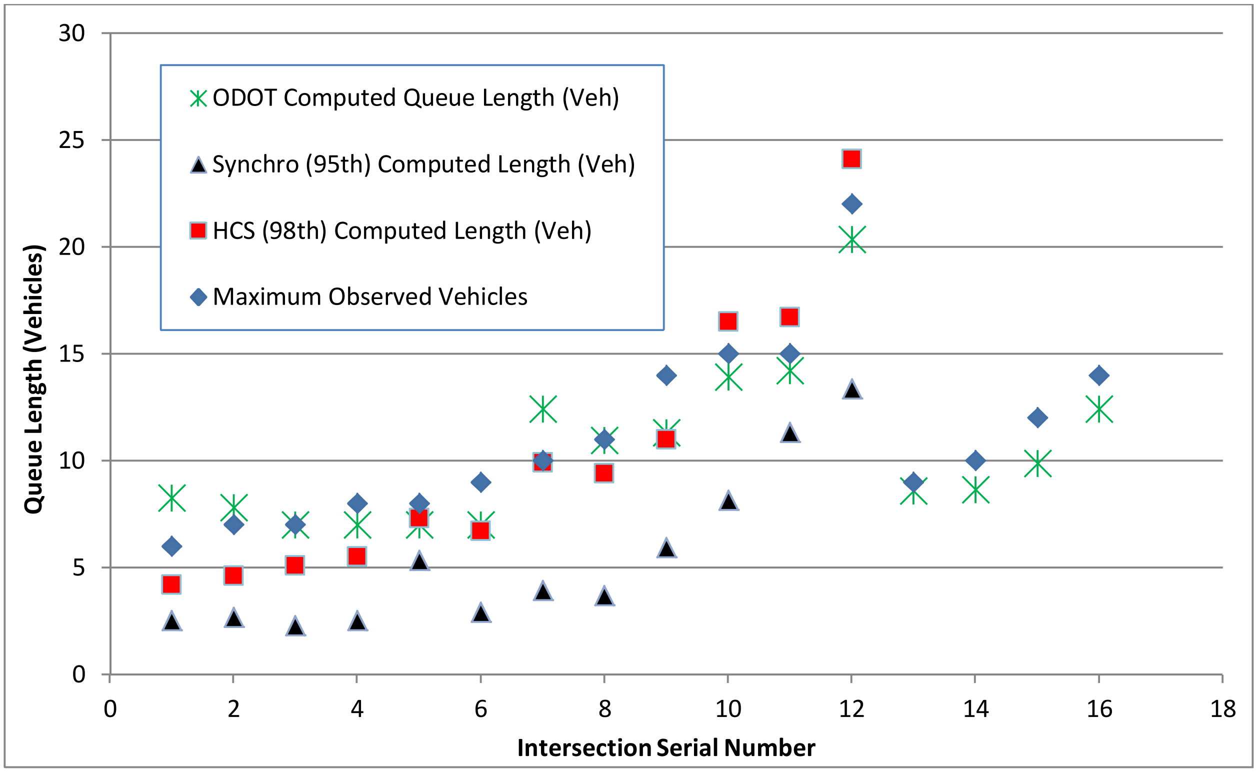

Figure 7. Computed and Observed Queue Lengths

Table 4 shows the results of the model performance comparison criteria in terms of SCORE (having the most predictions closest to the observed field results) and %ACC (relative accuracy in predicting storage lengths). The evaluation criteria are computed as described in Section 5.3. The results show that the L&D Manual model has 8 predictions out of 12 that were closest to the field observed queues when compared to the other two models. Likewise, HCS has a total of 4 predictions out of 12 that were closest to the observed field queues when compared to the other two models. On the other hand, SYNCHRO consistently predicted queues that were much lower than the field observations. The SCORE results are completely supplemented and supported by the accuracy (%ACC) results, which show that L&D Manual lead the way by accurately predicting the observed queues by about 81.6% and closely followed by HCS, which also had a 79.2% prediction accuracy. SYNCHRO was by far the lowest with a 46.0% prediction accuracy. With the combination of higher accuracy, relatively uncomplicated procedure, and less data requirement, the L&D Manual method seem to be a more preferred model than the other two evaluated in this study. A larger study with the ability to collect much more data from different locations and spanning far more varied locations is recommended to validate the results of this study. The setup of this study coupled with a small dataset used, these results can be taken as a preliminary effort that point to a need of conducting a more robust study capable of more reliably validating the L&D Manual model of designing turn lanes that will include dual left turn lanes, right turn lanes, etc.

Table 4. Results of Model Performance Comparison

SN	Date	Time	Location	Score			Accuracy (%)		
				L&D	Synchro	HCS	L&D	Synchro	HCS
1	1/12/12	8-9 AM	Bethel-Olentangy	0	0	1	0.4	0.6	0.3
2	1/12/12	9-10 AM	Bethel-Olentangy	1	0	0	0.1	0.6	0.3
3	12/7/11	8-9 AM	US33-Fishinger	1	0	0	0.1	0.7	0.4
4	12/7/11	9-10 AM	US33-Fishinger	1	0	0	0.0	0.6	0.2
5	12/7/11	4-5 PM	US33-Fishinger	0	0	1	0.2	0.4	0.2
6	1/11/12	3-4 PM	Bethel-Olentangy	1	0	0	0.4	0.7	0.4
7	1/11/12	4-5 PM	Bethel-Olentangy	0	0	1	0.2	0.6	0.0
8	12/7/11	3-4 PM	US33-Fishinger	1	0	0	0.4	0.5	0.2
9	2/9/12	9-10 AM	US33-Fishinger	1	0	0	0.2	0.6	0.2
10	2/8/12	3-4 PM	US33-Fishinger	1	0	0	0.1	0.5	0.1
11	2/9/12	8-9 AM	US33-Fishinger	1	0	0	0.1	0.2	0.1
12	2/8/12	4-5 PM	US33-Fishinger	0	0	1	0.1	0.4	0.1
13	11/29/11	4-5 PM	US33-Grandview						
14	11/29/11	3-4 PM	US33-Grandview						
15	11/29/11	9-10 AM	US33-Grandview						
16	11/29/11	8-9 AM	US33-Grandview						
			TOTAL	**8**	**0**	**4**	**81.6**	**46.0**	**79.2**

7. IMPLEMENTATION PLAN

The results from this study are used in suggesting the implementation plan. Although this study was limited in terms of resources and data, the results implicate that the L&D Manual's method of determining storage lengths is valid and reliable. Therefore, it is recommended that this method should continue to be used by all highway design engineers in Ohio who are involved with design projects. However, it is also recommended for ODOT to perform a larger study with the ability to collect much more data from different locations and spanning far more varied traffic levels to validate the results of this study. It is critical to pay special attention during data collection because quality data is a key in such kind of studies especially video queue capturing and reliable traffic signal timings. The choice of intersections to be studied, the approaches to target, and the positioning of the camera are equally important during pre-data collection planning efforts.

There are no potential foreseen risks and costs involved of using the results of this study because it is recommending of continuing using the procedure that has been widely used by engineers at state, local, and consulting firms in Ohio. The benefits are that, engineers will continue using the method they know confidently by getting an assurance that their methodology has been tested and proved to be reliable and valid. The main advantage of the L&D Manual's procedure is that it is relatively simple and straight-forward procedure when compared with most others available and requires less input data.

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APPENDIX A

SURVEY QUESTIONNAIRE

Dear traffic/highway design engineer,

We need your help in the completion of a very important project on "Turn Lane Storage Length Validation." The University of Dayton is conducting a research project for the Ohio Department of Transportation (ODOT) to examine the validity of the methodology used by ODOT in designing turning lane lengths in the ODOT's Location and Design (L&D) Manual. In this study we are seeking experiences of other state departments of transportations (DOTs) in modeling queue storage lengths.

To achieve the research objectives, this survey is designed to seek your state of practice in designing turn storage lengths from which ODOT may benefit when evaluating and validating/updating their own methodology. Please respond to all questions. Please e-mail your responses to deo.eustace@udayton.edu or fax to (937)-229-3491 before July 6th 2011. If you have any question, you can contact Dr. Deogratias Eustace by telephone 937-229-2984 or by email at deo.eustace@udayton.edu. We kindly appreciate your participation in this survey.

Part I: General Questions on Left-Turn and Right-Turn Lane Design

Left-Turn Lanes

1. In your agency, what is the existing practice in determining the deceleration and storage length requirements?

Signalized Intersection:

____

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Unsignalized Intersection:

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____

2. Briefly, can you mention the existing warrants for multiple left turn lanes in your agency?

Signalized Intersection:

____

____

Unsignalized Intersection:

____

____

3. Upon your experience, could you specify any good experiences/methods on the determination of lane deceleration and storage length requirements of a left turn lane?

Signalized Intersection:

Unsignalized Intersection:

4. Upon your experience, could you specify any good experiences/methods on developing the warrants for multiple left turn lanes?

Signalized Intersection:

Unsignalized Intersection:

5. In your point of view, which factors are the most critical issues in the design and operation of left turn lanes?

Signalized Intersection:

Unsignalized Intersection:

6. In evaluating the design of a left turn lane, what are the most important criteria to be considered?

Signalized Intersection:

Unsignalized Intersection:

7. In your opinion, do the guidelines that your agency uses provide efficient left turn lane lengths at all intersections? (Please Explain)

Signalized Intersection:

Unsignalized Intersection:

Right Turn Lanes:

1. In your agency, what is the existing practice in determining the deceleration and storage length requirements?

Signalized Intersection:

Unsignalized Intersection:

2. Briefly, can you mention the existing warrants for multiple right turn lanes in your agency?

Signalized Intersection:

Unsignalized Intersection:

3. Upon your experience, could you specify any good experiences/methods on the determination of lane deceleration and storage length requirements of a right turn lane?

Signalized Intersection:

Unsignalized Intersection:

4. Upon your experience, could you specify any good experiences/methods on developing the warrants for multiple right turn lanes?

Signalized Intersection:

Unsignalized Intersection:

5. In your point of view, which factors are the most critical issues in the design and operation of right turn lanes?

Signalized Intersection:

Unsignalized Intersection:

6. In evaluating the design of a right turn lane, what are the most important criteria to be considered?

Signalized Intersection:

Unsignalized Intersection:

7. In your opinion, do the guidelines that your agency uses provide efficient right turn lane lengths at all intersections? (Please Explain)

Signalized Intersection:

Unsignalized Intersection:

Part II: Your Storage Length Design Manual

Please send us the design manual your agency uses in designing storage lengths. If the manual is available on line, please provide us with a link.

Part III: Acknowledgement

We appreciate for your participation in this survey. Please provide the following contact details:

Name of the person who filled this survey:

Job Title:

Name of the Organization:

Telephone:

E-mail:

Website:

APPDENDIX B

NAMES AND CONTACT INFORMATION OF ENGINEERS CONTACTED

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APPENDIX C

EXAMPLE OF COMPUTING QUEUE AND STORAGE LENGTH BY L&D METHOD

Example of US 33 & Fishinger Road Intersection for February 2012 Data

Time Period:	8:00-9:00 AM
Traffic Volume:	300 veh/h
Design Speed:	50 mi/h
Total No. of Cycles:	27
Average length occupied by a vehicle:	25 ft
Average No. of Vehicles/Cycle:	300/27 = 11.111 vehicles/cycle

From L&D Manual Figure 401-9E, length of turn lanes have to be computed for Conditions A and B:

Note: Use the greater of the two calculated values and each of them includes a 50 ft of diverging taper.

From L&D Manual Figure 401-10E:

Average No.of Vehs/Cycle		Required Length	
X_1	11	Y_1	400
X_2	11.111	Y_2	?
X_3	12	Y_3	450

By interpolation, Y_2 = 405.5 ft

Method (Condition) B: High Speed Deceleration Only
From L&D Manual Figure 401-9E: Turn lane Length = 225 ft

Method (Condition) C: Moderate Speed Deceleration And Storage
From L&D Manual Figure 401-9E: Turn Lane Length = 143 + 405.5 = 548.5 ft

From Methods B & C: Use the greater value for storage length = 405.5 ft
For Method C, 143 ft is for deceleration length and 405.5 ft is for storage.

Final storage length, L_S = Calculated storage length - diverging taper

L_S = 405.5 - 50 = 355.5 ft.

L_S = 355.5/25 = 14.2 vehicles

Please note that for the whole turn lane, L = 548.5 ft

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