Turn Lane Warrants: Concepts, Standards, Application in Review

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2004 ITE, District 1
Annual Meeting
Burlington, Vermont

Introduction

Turning lanes at intersections reduce accidents (crashes) as crash rate comparisons in the ITE Traffic Engineering Handbook have demonstrated; yet, warrants or guidelines are not clearly established for a sufficiently broad range of conditions. Typically, state transportation departments review crash rates in determining the need for turn lanes and most review roadway volumes. States generally refer to American Association of State Highway Transportation Officials (AASHTO) for guidance on highway design; however, most ITE District 1 states have adopted volume warrants or guidelines at unsignalized intersections that supplement the AASHTO guidance, which is partial for left turn lanes and absent for right turn lanes.

This turn lane warrant review focuses on unsignalized intersections, where there appears to be the greatest need. AASHTO’s left turn guideline for left turns is examined in its effectiveness to convey the results of the 1967 research conducted by Harmelink. Harmelink utilized a probabilistic model to establish left turn lane warrants for two-lane and four-lane highways at unsignalized T- intersections. AASHTO presents a summary table of points on Harmelink’s graphed curves for two-lane highways. Interpretation of the table is difficult and many states have adopted forms of the graphs for two-lanes and remain consistent with AASHTO by excluding Harmelink’s four-lane highway curves.

Volume based right turn lane warrants at unsignalized intersections are included in most state design manuals. The typical form is a graph for use on two-lane highways. Cottrell compiled existing research in 1981 and derived right turn lane design graphs for two-lane and four-lane highways. These graphs delineated warranting thresholds for multiple treatments: full turning lanes, a taper, and a radius. Alternatively, VTrans has developed a right turn lane protocol that is based on the Harmelink probability model.

Several published research efforts and reports exhibit forms of the original Harmelink graphs. These are cited in this review for several reasons: the work is more effective in conveying the warrant information; there is inconsistency with the original graphs (and with AASHTO); or there is contention with the Harmelink model on specific points. Other research (Agent, Kikuchi and Chakroborty) exists that proposes turn lane warrants based on accidents, delay, and level of service as alternate basis for warranting turning lanes; however, this review does not report on these concepts.

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Standards

AASHTO standards are typically applied by most states where they are available. These standards provide minimal guidance on turning lane warrants. There is repetition of Highway Capacity Manual advice at signalized intersections: at hourly volumes of 100 and 300 for left and right turn lanes respectively, auxiliary lanes should be considered. But different criteria apply to unsignalized intersections and AASHTO guidance is limited to left turn lanes on two-lane highways.

AASHTO Exhibit 9-75 (shown as Figure 1) from the 2001 “Greenbook” summarizes left-turn lane warrant information from 16 of Harmelinks original graphs. AASHTO guidance is thereby provided for two-lane roadways with speeds between 40 and 60 mph, left-turn volume percentages between 5 and 30 percent, and total hourly volume in a single direction of 800 vehicles or less. Maximum advancing volume without a left turn lane can be read from the AASHTO summary table given a known left turn percentage and the opposing volume. At 5 percent left turns opposed by 800 vehicles the maximum advancing volume without a left turn lane can be read from the table for three speeds: 330 vehicles per hour at 40 mph, 280 at 50 mph, and 230 at 60 mph. Minimum warranting left turn volumes within the AASHTO table are derived from the 5 percent left turn column. When opposed by 800 vehicles, the minimum suggested left turn volume requiring a left turn lane is: 17 left turns per hour at 40 mph, 14 at 50 mph, and 12 at 60 mph.

<table>
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<th>Opposing volume (veh/h)</th>
<th>Advancing volume (veh/h)</th>
<th>5%</th>
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Figure 1: AASHTO Guide for Left turn Lanes on Two-Lane Highways
Most states provide this information in a graphical form that summarizes Harmelink warrant thresholds by roadway speed. Curves for specific left turn percentages are shown. Each is like that shown for 40 mph in Figure 2.

Figure 2: Typical State Design Manual Graph of Left Turn Lane Warrant Conditions on Two-Lane Highways at 40 mph.
Most states include a graph in their design manuals for determining warranting volumes for right turn lanes at unsignalized intersections (Figure 3). This graph typically relates only to two-lane highways. This graph of right turn volumes and total design hourly volume (DHV) presents a threshold line above which a right turn lane should be considered. The minimum hourly right turn volume where a right turn should be considered is 80 of 300 or 40 of 600 or more approach vehicles. Speed is not a factor except for a correction when posted speeds are below 45 mph (sometimes stated operating speed of 40 mph or design speed of 50 mph), the approach volume is less than 300 and right turns exceed 40. The correction reduces the right turn volume by 20 before entering the chart.

![Figure 3: Typical State Design Manual Guideline for Right-Turn Lanes at Unsignalized Intersections on Two-lane Highways](image)
VTrans has adopted an alternate right turn lane volume warrant, which is based on the Harmelink left turn warrant (Figure 4). A limited probability of a right turn vehicle delaying a through vehicle is set to derive a design chart with curves for speeds of 30-60 mph on two-lane highways and one curve for four-lane highways. When approach volumes are 800 vehicles per hour, the warranting right turn volumes range from 25 vehicles at 60 mph to 90 at 30 mph for two-lane roadways and 60 right turn vehicles on four-lane roadways.

Figure 4: VTrans Right Turn Auxiliary Lanes Traffic Volume Warrants
Concepts

Harmelink’s model for left turn warrants at unsignalized intersections is based on probability theory. A description of some of the parameters and an outline of the concept will provide the understanding needed to interpret the ASSHTO table or the original curves. As shown in Figure 5, the concept is based on the arrival of a vehicle on the advancing approach that queues behind a left turning vehicle that is waiting for a gap in the opposing approach flow.

Figure 5: Harmelink’s Arrival Event on a Two-lane Highway

The arrival event on a two-lane highway involves a compound probability: first the probability of the presence of a left-turn vehicle, and second, the probability of the arrival of one or more through vehicles. The probability of this dual occurrence should not exceed 0.010 for 40 mph and 0.015, and 0.020 for operating speeds of 50, and 60 mph respectively. On a four-lane divided highway, the design condition is probability of no more than one left turn vehicle stored in the median space (P = 0.030). On four-lane undivided highways, the design condition is the probability of a left turn vehicle waiting in the through lane (P = 0.005).

These limiting probabilities and the application of queuing theory enable the determination of the utilization factor, which is the ratio of the arrival rate to the service rate. The ratio must be less than 1 for the theory to apply. The arrival rate is a function of the advancing approach volume, the percentage of left turns, the average wait time (a function of opposing volume and the critical gap), the time for a left turning vehicle to clear the lane on the advancing approach, and median headway of the advancing traffic. Critical gaps of 5.0 and 6.0 seconds were used for two-lane and four-lane highways.
Time to clear the lane is 1.9 sec. The service rate is equal to “unblocked time,” which in general constitutes gaps longer than the critical gap and additional capacity calculated from the remaining unblocked time recognizing the time required to complete a left turn (3.0 seconds for two-lane highways and 4.0 for four-lane highways). It should be noted that Harmelink based his assumptions on field observations and later checked his results with additional field studies.

Harmelink developed 18 graphs for left turn lanes under two-lane conditions and one for four-lane conditions. Each graph related to the same roadway operating and percent left turns and presented a lane-warranting curve and lane storage lengths. The plotted curves reflected a negative exponential form. Harmelink’s four-lane highway graph, which is shown below as Figure 6, presents a curve for the undivided left turn lane warrant roughly defined by 13 vehicles turning left across 800 opposing vehicles and 25 turning left across 200 opposing vehicles. The four-lane divided curve contains points associated with 25 left turns into 900 opposing vehicles and 50 left turns into 300 left turns.

![Figure 6: Harmelink’s Figure 1. Warrant for Left-Turn storage on four-lane highways.](image)

**Figure 6:** Harmelink’s Figure 1. Warrant for Left-Turn storage on four-lane highways.
The Cottrell right turn lane warrant model was prepared around 1981 after surveying state DOTs and determining that volume based warrants was used by the greater number of DOTs that used any consistent criteria. His research involved field data collection and previously established state DOT standards. It may be noted that during this same time period, the Virginia Transportation Research Council documented a similar pair of graphs with plots of thresholds for a full width lane and for taper treatment. These are presented in Figures 7 and 8.

**Figure 7: Cottrell’s Two Lane Right Turn Treatment**
Figure 8: Cottrell’s Four-Lane Right Turn Treatment.

VTrans’ alternative right turn lane volume warrant is based on the Harmelink left turn warrant. All of Harmelink’s speed related probabilities were held for two-lane highways. For four-lane highways, Harmelink’s value of 0.03 for undivided highways was used. The time required to make a right turn maneuver was assumed to be 2.1 seconds which compares with Harmelink’s left turn times of 3.0 for two-lanes and 4.0 for four-lanes. Under four lane conditions the warrant is met when the volume of right turns is greater than 50 and the two-lane warrant is met.

Application

Interpretation is typically required to use the ASSHTO guide for left turn lanes because volume conditions are often off the chart while not clearly exceeding turn lane thresholds. One caution is provided with the ASSHTO table: “For the volumes shown, left turns and right turns from the minor street can be equal to but not greater than, the left turns from the major street.” By the words “for the volumes shown” it can be assumed that a left turn lane could be warranted when lesser volumes are present. This note is not
Several TRB reports including NCHRP Report 279 Intersection Channelization Design Guide\textsuperscript{9}, and Report 348 Access Management Guidelines for Activity Centers\textsuperscript{10}, and Synthesis of Highway Practice 225\textsuperscript{11}, Left-Turn Treatments at Intersections, provide modified versions of the original Harmelink graphs. Two of the three reports also include the AASHTO table derived from Harmelink. It should be noted that only Report 279 provides graphs whose curves present the Harmelink results.

Report 279 provides four graphs, which are similar to those provided in most state design manuals. Three graphs relating to operating speeds of 40, 50 and 60 miles per hour present the left turn lane warrant conditions at unsignalized intersections on two-lane highways. Each graph includes curves for 5, 10, 15, 20 and 40 percent left turns. The Harmelink 30 percent curve is omitted. The fourth graph provided in Report 279 presents the warrant threshold for left turn lanes on four-lane highways. It is presented at a scale, which is significantly easier to read than the original. No distinction is made between four-lane divided and undivided roadways but Harmelink’s note is provided stating that for opposing volume of less than 400 vehicles, a turning lane is not normally provided when left turning volumes are less than 27 vehicles per hour and total advancing volume is less than 400 vehicles per hour. These four graphs are shown in Figure 9.

Report 225 includes the AASHTO two-lane unsignalized left turn lane guidance table (Exhibit 9-75 in 2001) and on the next page four Harmelink-like graphs referenced as ITE guidelines for left turn lanes. Two graphs relate to two-lane highways at 30 and 50 mph operating speeds and a graph for four-lane undivided and divided roadways. The graphs differ from Harmelink’s for several reasons. First, the axes showing advancing volumes and opposing volumes are switched. Second, the graphs are greatly expanded to account for advancing volume of 1,600-2,400 vehicles per hour and opposing volume of 1,300-1,800 vehicles. Third, a curve is provided for 0.5 percent intervals up to 4 percent and 6, 8 and 50 percent curves have been added to the original 5, 10, 15, 20 and 30 percent curves (40 percent is not included). Lastly, these curves indicate threshold left-turn volumes that are significantly lower for corresponding conditions, than those of the original Harmelink curves and the ASSHTO table on the previous page. These graphs developed by Oppenlander and Bianchi\textsuperscript{12} are an extensive effort to expand the range of calculated conditions that would reduce the need for interpretation. No reason is provided for the differences with Harmelink and AASHTO.
Kikuchi and Charborty conducted a notable research work containing a review of the Harmelink model. They cited two specific problems with Harmelink and offered modified turn lane volume thresholds. First, Harmelink’s definitions of arrival rate and service rate relate to arriving through vehicles and left-turn vehicles respectively. They point out that proper application of queuing theory would have the same type vehicle arriving and serviced but note that the Harmelink model would still hold for conditions that would result in only one through vehicle queuing behind a left turn vehicle. Kikuchi and Charborty’s second problem concerned the calculation of the left turn capacity. Harmelink calculated unblocked time and divided that by the time to turn left to determine capacity. In his calculation, gaps greater than the required time to turn are counted. Then, each of these gaps were reduced by one half the critical gap and the time
to turn left; the remaining time in these gaps was aggregated and divided by the time to turn left. Kikuchi and Charoborty’s modified volumes are significantly higher than Harmelink’s.

Findings

1. At unsignalized intersections, AASHTO provides a volume-based guide on thresholds for left turn lanes on two-lane highways where approach volumes are 800 or less and operating speeds are between 40 and 60 mph; AASHTO provides no volume-based guidance for left turn lanes on four-lane highways or for right turn lanes.

2. The AASHTO left turn guidance is based on graphs developed by M. D. Harmelink and published in Highway Research Record 211 in 1967. Harmelink’s model is based on the probability of a through vehicle arriving in a queue behind a waiting left turn vehicle. Harmelink established probability limits for roadway types and roadway speeds and solved for advancing volumes and a specific left turn percentage over a range of opposing vehicles. The graph relating to a specific left turn percentage forms a negative exponential curve.

3. The AASHTO Exhibit 9-75 is a summary table of discrete points from the Harmelink curves. The summary table is more difficult to interpret than the original graphs.

4. ITE District 1 State DOTs typically refer to AASHTO or have adopted graphs that are similar to the Harmelink’s for left turn lanes on two-lane highways, been adopted by ASSHTO or these DOTs.

5. NCHRP Report 279 provides a set of graphed curves for two-lane and four-lane highways that are accurate representations of the warrant thresholds derived by Harmelink and consistent with the AASHTO summary table for two-lane highways.

6. NCHRP Report 348 provides a graph without use restrictions (suggesting two-lane and four lane use) but was developed by Harmelink for only four-lane highways.

7. NCHRP Synthesis of Highway Practice 225 provides expanded graphs (that would significantly extend their utility) using the Harmelink model with substituted values for some factors. These graphs yield lower left turn lane warranting volumes than Harmelink and AASHTO.

8. TRR 1327 offers modified left turn lane warranting volumes that are higher than the Harmelink results and therefore not consistent with AASHTO.
9. ITE District 1 State DOTs use a variety of volume based right turn lane warrants and guidelines.

10. The most common right turn volume-based warranting concept is derived from research presented by Cottrell in TRR 855. The Cottrell research includes graphs for two-lane and four-lane conditions that indicate full width lane warranting thresholds and a lane taper treatment. More often, state design manuals contain only two-lane highway graph for only full width lane treatment.

11. VTrans has developed and uses a right turn lane warrant based on Harmelink probability model for left turn lanes.

12. Although field research is cited in Harmelinks 1967 work, the limiting probabilities used to define turn lane volume thresholds are described as the collective judgment of several people. Recent research of the applicability of these probabilities and other assumptions such as acceptable gap time was not found.

13. Turn lane requirements at unsignalized and signalized intersections are based on different criteria. AASHTO guidelines suggest thresholds for turn lanes at unsignalized intersections are significantly less than at signalized intersections.
References