RESEARCH & DEVELOPMENT

Guidelines for Signalization of Intersections with Two or Three Approaches

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This research provides NCDOT with a defensible method for determining the need for considering additional signalization analysis at intersections with fewer than four legs where drivers desire to merge with or cross two lanes of oncoming traffic. This document is intended to provide guidance and support to traffic engineers in their decision making process. Charts are provided to determine the expected 95th percentile queue lengths for left turn, right turn, and U turn movements crossing or merging with two lanes of opposing traffic. This situation is typically present along four lane roadways where a *one way* primary movement opposes either a minor road right turn movement or a left turn movement, or in the case of a median U turn opening. Adjustment factors to the opposing flowrate are also provided to account for the presence of upstream signalized intersections.			
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EXECUTIVE SUMMARY

This research provides NCDOT with a defensible method for determining the need for considering additional signalization analysis at intersections with fewer than four legs where drivers desire to merge with or cross two lanes of oncoming traffic. This document is intended to provide guidance and support to traffic engineers in their decision making process. Charts are provided to determine the expected 95th percentile queue lengths for left turn, right turn, and U turn movements crossing or merging with two lanes of opposing traffic. This situation is typically present along four lane roadways where a *one way* primary movement opposes either a minor road right turn movement or a left turn movement, or in the case of a median U turn opening. Adjustment factors to the opposing flowrate are also provided to account for the presence of upstream signalized intersections.

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1 INTRODUCTION

Traffic engineers are often faced with the decision of whether to signalize intersections, but guidance for making such decisions as applied to intersections with fewer than four legs is lacking. While traffic signal warrants for standard intersections in the 2009 Manual on Uniform Traffic Control Devices (MUTCD)[1] – such as crash experience or coordinated signal systems – can be applied to any intersection geometry, volume specific warrants primarily apply to four-legged intersections with vehicles approaching from each leg. This assumption is not valid to intersections at superstreets (also known as synchronized streets), directional crossovers, or the meeting of two one way streets, where there may not be both departing and receiving lanes on each approach.

This report summarizes the results of an investigation to evaluate North Carolina-specific gap acceptance parameters. This was done in order to develop volume based guidelines for left turns, right turns, and U turns crossing or merging with two lanes of conflicting traffic. These movements are frequently, although not exclusively, found along four lane divided roadways with leftovers, T intersections, and median U turn openings.

Appropriate guidelines for signalization are important to ensuring public funds and time are well managed. The installation of unnecessary traffic signals requires both capital and maintenance funds and could, in some instances, result in additional delay to roadway users. The guidelines laid out in this document are intended to determine if further consideration should be given to the need for signalization but do not in themselves *require* the installation of a traffic signal.

Charts are provided to determine the expected 95% queue length for each of the three movements of interest. Additionally, adjustment factors to the opposing traffic stream flow rates are provided for sites with nearby upstream signalized intersections. Queue length charts are also provided for intersections where both left turns and U turns are mixed in the same turning lane.

[1] National Advisory Committee on Uniform Traffic Control Devices. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways*. US Department of Transportation.

2 LITERATURE REVIEW

A study was conducted to determine how various NCDOT divisions determined signalization needs for intersections with fewer than four legs. No explicit procedure was uncovered, although many engineers appeared to informally use the cross product rule described below. Multiple attempts were made to contact Minnesota DOT as well as Michigan DOT to determine if procedures existed for those states. No response was provided.

NCDOT officials frequently cited the left turn cross product rule of 100,000 for four lane roadways or 50,000 for two lane roadways. These values are the threshold cross products of left turning volume and conflicting volume at signalized intersections. Kenneth Agent developed these thresholds based on observations made at seven Kentucky intersections[2]. The threshold serves as a delay based warrant for protected left turn signalization needs. Although these thresholds were developed for use in determining protected signal phasing, it was observed that these thresholds were often used by NCDOT officials as a proxy for left turn permissive signalization needs.

The MUTCD[1] provides volume based signalization warrants. While there is literature documenting the evolution of the MUTCD[3,4,5], no documentation was found for the original studies that led to the volume based warrants. While some provisions are provided for analysis of non-four leg intersections, it is generally assumed the warrants are to be applied to four leg intersections.

Using gap acceptance parameters such as critical and follow-up headways, various guidelines for signalization have been developed. The MUTCD uses cross product warrants. Agent developed volume based warrants with an underlying delay based methodology[2]. Texas has expanded on the MUTCD warrants, providing volume, safety, and progression based warrants[6]. Additionally, protected movement warrants have also been developed[7]. The literature review in summary did not reveal any existing volume based signalization warrants for intersections with fewer than four legs.

Various researchers have measured region-specific gap acceptance parameters. Parameters for permitted left turn movements are the most-well understood, although no North Carolina specific parameters were discovered.

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[2] Agent, K. R., Stamatiadis, N., & Dyer, B. (1995). Guidelines for the Installation of Left-turn Phasing.
[3] Hawkins, H. G. (1992). Evolution of the MUTCD: Early standards for traffic control devices. *ITE Journal*, *7*, 23-26.
[4] Hawkins, G. (1992). Evolution of the MUTCD: Early Editions of the MUTCD. *ITE Journal, 8*, 17-23.
[5] Hawkins, H. G. (1992). Evolution Of The MUTCD: The MUTCD Since World War II. *ITE Journal, 11*, 17-23.
[6] Hawkins Jr, H. G., & Carlson, P. J. (1998). *Traffic Signal Warrants: Guidelines for Conducting a Traffic Signal Warrant Analysis* (No. FHWA/TX-99/3991-2).
[7] Al-Kaisy, A. F., & Stewart, J. A. (2001). New approach for developing warrants of protected left-turn phase at signalized intersections. *Transportation Research Part A: Policy and Practice*, *35*(6), 561-574.

3 METHODOLOGY

The critical headway for permitted left turn movements is a well-studied metric, so the data collection effort in this study focused on determining the critical headway for right and U turns. Data collection occurred at 11 sites in North Carolina for each turn movement. The sites were concentrated in Wilmington, Raleigh, and Charlotte as well as the surrounding suburbs and towns. A list of sites is provided in Appendix A. Each site was a four lane, un-signalized segment. Data were only collected for turning passenger vehicles. In all cases the major road had a posted speed limit of either 45 or 55 mph.

Data analysis was conducted at each site individually using both the Troutbeck[8] and Ramsey Rutledge[9] critical headway estimation methods. The difference in critical headways between the 45 mph and 55 mph segments was not statistically significant for either turning movement.

An analysis was also conducted for the right turn sites to determine if the distance to a downstream left or u turn pocket impacted the critical headway. This was not found to be the case. When comparing all of the right turn sites, pairwise comparisons were made between sites. Two sites were identified as being statistical outliers. It was hypothesized that at one site an upstream crest curve modified the decision making process of drivers accepting gaps. At the second site, it was hypothesized that there was an error in data collection. Both of these sites were removed from the analysis. All U turn sites were also analyzed using pairwise comparisons, with one site identified as a statistical outlier. It was hypothesized that there was an error in data collection, and that site was removed from the analysis.

Following the removal of the three sites, there were a total of 563 valid headway observations for the right turn movement and 622 observations for the U turn movement. The critical headway was determined using both Troutbeck and Ramsey Rutledge methods. Both methods yielded similar results, as shown in Table 1. The HCM 6th Edition[10] values are also provided for reference. The charts developed in this study used the Troutbeck values because the bias in the method is lower than the Ramsey Routledge method[11]. The pooled data was also used in determining the follow-up headways shown in Table 2.

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[8] Troutbeck, R. J. (1992). *Estimating the critical acceptance gap from traffic movements*. Queensland University of Technology.

[9] Ramsey, J. B. H., & Routledge, I. W. (1973). A new approach to the analysis of gap acceptance times. *Traffic Engineering & Control*, *15*(7).

[10] (2016). Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis. Transportation Research Board. Washington, D.C.

[11] Troutbeck, R. J. (1975). A Review of the Ramsey-Routledge Method for Gap Acceptance Times. *Traffic Engineering and Control*. 16(9)

Table 1. Critical Headway Values by Movement and Source (sec)

	Left Turn	Right Turn	U Turn
Troutbeck	--	6.40	6.56
Ramsey Routledge	--	5.99	6.86
HCM	4.1	--	--

Table 2. Follow-Up Headway Values by Movement (sec)

	Left Turn	Right Turn	U Turn
Field Measured	--	2.98	3.4
HCM	2.8	--	--

From the critical headways and follow-up headways (as well as the HCM 6th Edition reported values for left turns), the permitted movement capacity was determined for each movement type using the isolated intersection capacity model taken from the HCM 6th Edition. Then, assuming random arrivals for both the opposing and opposed movements, and assuming a single turn lane, the 95% queue length was derived as a function of the turning and conflicting volumes. A 25 foot vehicle headway while stopped was assumed.

Another important assumption in this study is that a downstream intersection queue would not spill back onto the intersection of interest. For a superstreet configuration, a downstream intersection operating with two critical phases should not be expected to spill back, with an anticipated green-to-cycle length ratio of 0.7, an 800-foot spacing and a cycle length below 120 seconds. A spacing of less than 800 feet may be acceptable. The queue length for a shorter spacing can be evaluated analytically using the HCM 6th Edition.

4 RESULTS

Three queue length charts were developed for application to isolated intersections. Each chart considers a turning movement across two lanes of traffic: a left turn from the major to the minor road, a right turn from the minor to the major road, and a U turn from one direction of the major road to the other. The queue lengths are plotted along with the 85% capacity and 100% capacity lines.

The developed charts were compared to guidelines or warrants commonly cited for use by NCDOT officials. These include the volume based warrants found in the MUTCD as well as the left turn protected phasing warrants developed by Kenneth Agent. Details of the comparison can be found in Appendix B.

For intersections that are not isolated, conflicting volume adjustment factors (CVAF) have been developed. In this model, the downstream intersection is the intersection being investigated for a signal while the upstream intersection serves as a metering point for conflicting mainline vehicles. Capacity at the (un-signalized) downstream intersection increases as the percent of conflicting vehicles contained within the platoon increases. This is due to the fact that while a larger platoon results in a longer blocked period for downstream vehicles accepting gaps, the resulting gaps outside of the platoon are always larger compared to the isolated case. As the follow-up headway is lower than the critical headway, a conflicting vehicle stream with a higher percentage of large gaps provides greater capacity than a stream with the same number of vehicles but more frequent small gaps.

The platoon dispersion model developed by Rouphail[12] was used to calculate the equivalent flowrate at a point downstream based on the travel time between the intersections, the arrival rate, saturation flowrate, cycle length, and green time for the inbound mainline movement at the upstream intersection. The model does not consider the impact of upstream movements originating on the side street. By calculating the equivalent flowrate at various points downstream, a capacity adjustment factor, CAF, was developed as a function of the travel time of the conflicting vehicles. Equation 3 models the relationship of the capacity adjustment factor.

$$CAF_t = \frac{CAF_{t=0}}{CAF_{t=\infty}} e^{at^n}$$

where:

[12] Rouphail, Nagui. 1983. "Analysis of TRANSYT Platoon-Dispersion Algorithm." (1983) *Transportation Research Record.* Washington, D.C. (905)72 - 79.

t = travel time,
a = adjustment factor, and
n = adjustment factor.

A regression analysis was conducted to determine the values of the adjustment factors. From the capacity adjustment factors, a conflicting volume adjustment factor or CVAF was developed. This process was conducted for a range of cycle lengths (60s to 120s in increments of 10 s), green-to-cycle length ratios (0.3 and 0.7), and arrival flowrates (720 vph to 2350 vph in increments of 180 vph). The saturation flowrate was kept constant at 1800 vph per lane. The resulting CVAFs were then plotted against the travel time to analyze how the CVAF varied with variations in the cycle lengths, g/c, and arrival rates. Variations in CVAF due to cycle length were sufficiently small (< 10% within a travel time) such that it could be considered a constant. This allowed two sets of charts to be created for engineers to use in determining the CVAF.

Six conflicting volume adjustment factor charts were created, two for each turning movement. There is one chart covering the case of an upstream intersection with an inbound g/C of 0.3 (approximately representative of a four critical phase intersection) and one chart for an upstream intersection with inbound g/C of 0.7 (approximately representative of a two critical phase intersection). Each chart plots the CVAF against the travel time from the upstream intersection to the intersection being studied for signalization. Multiple lines are provided on the chart representing varying arrival rates at the upstream intersection. Prior to using the queue lengths charts, one must multiply the opposing flow rate by CVAF, when applicable.

For intersections with multiple movements of interest (i.e. a left turn onto a minor road with a right onto the major road), each movement should be analyzed separately.

Appendix C contains the charts as well as the assumptions and directions for use. Appendix D contains queue length charts for isolated intersections where a mixture of left turns and u turns are expected. CVAFs for a mixed left/U turn lane was not developed, but the adjustment factor charts for the left turn can be used as a conservative estimate.

For the analysis of a superstreet corridor where both the U turn and minor street intersections are considered, it is recommended that the U turn intersection be considered first with the appropriate adjustment factors for any upstream signal. Following the determination of signalization needs for the U turn movement, the left turn/right turn minor street intersection can be considered with appropriate conflicting volume adjustments made for any upstream signalization.

A numerical example of how to use the charts is provided in Appendix E.

5 CONCLUSION

The appropriate and cautious use of signalization at intersections with fewer than four legs is necessary for the preservation of public funds. Unnecessary signalization can result in the misappropriation of both capital and maintenance funding for signal installation and ongoing coordination. While two phase signals can often be coordinated with adjacent signals for efficient progression, the installation of an unnecessary signal may result in increased delay for traffic.

This project provided guidelines for determining initial signalization needs for intersections with fewer than four legs including left turns, right turns, and U turns crossing or merging with two lanes of conflicting traffic. Adjustment factors were provided for intersections of interest that have upstream signalized intersections where some degree of platooning can be expected.

These guidelines should be used in conjunction with the MUTCD warrants 4 – 9 in determining the need for further analysis of signalization.

6 Extensions to the Work

This work could be further enhanced by developing delay-based guidelines. There is a scenario under which users could experience excessive delay even in the case of short queues. Consider a conflicting volume near capacity paired with very low demand for the movement of interest. In this scenario, the few drivers desiring to turn may experience increased delay despite the fact that the queue will be short (due to the low demand). The movement of interest is likely a low priority movement, and NCDOT would need to consider the benefit of reducing delay for a very small proportion of users with the cost of installing a signal.

Additional research should be considered to validate the developed charts. Such research could also include development of guidance on how to proceed if further analysis of a signal is found necessary.

The methodology used in creating the queue length and Conflicting Volume Adjustment factor charts are directly applicable for use in future work. New scenarios that would impact the critical gap and follow-on headway (different number of conflicting lanes, different speed limit, different geographical region) would require a calibration of those variables and regeneration of the charts.

It is not recommended that this work be extended to a movement of interest served by dual turn lanes. The sight distance for the driver of the inside vehicle may be blocked by the presence of a vehicle in the outside turning lane. This could impact the driver’s decision to accept or reject a gap irrespective of the size of the gap. Effort should be taken to understand how the critical gap is impacted under this scenario.

7 APPENDIX A – DATA COLLECTION SITES

Data were collected at the sites listed in Table 1. Blank entries for the critical headway indicate there were an insufficient number of viable observations.

Table A1. Data Collection Locations

City	Major Street	Minor Street	Mvmt	Vehicles	Speed Limit	Dist. to Turn Bay (ft)	Dist to Upstream Signal (ft)	Troutbeck Mean t_c (s)	Troutbeck SD of t_c (s)	Ramsey Mean t_c (s)	Ramsey SD of t_c (s)
Cary	NW Maynard Rd	Wendy's Driveway	R	101	45	121	546	10.628	6.309	8.27	4.75
Charlotte	Sam Furr Rd	Greenfarm Rd	R	20	45	0	1128	8.487	4.300	6.02	2.84
Charlotte	Sam Furr Rd	Sutters Run Ln	R	9	45	733	2018	7.355	5.355	5.98	2.49
Charlotte	WT Harris Blvd	Dunstaff Rd	R	7	55	158	3422	--	--	5.6	1.85
Raeford	Fayetteville Rd	Scull Rd	R	62	55	127	3620	6.222	2.732	--	--
Wake Forest	Louisburg Rd	Pulley Town Dr	R	2	55	173	6969	10.074	5.176	6.78	3.04
Wake Forest	Louisburg Rd	Jonesvile Rd	R	186	55	131	8976	19.792	13.686	8.97	6.43
Wilmington	S College Rd	Jay Bird Circle	R	38	45	0	3393	5.151	2.274	--	--
Wilmington	S College Rd	Prior Dr	R	14	45	0	7392	5.481	1.398	--	--
Wilmington	S College Rd	Still Meadow Dr	R	44	45	0	6388	5.713	1.455	5.5	1.63
Winston	Peters Creek Pkwy	Franciscan Dr	R	29	55	878	2335	5.899	2.174	6.36	2.43
Charlotte	Sam Furr Rd	Cambridge Grove Dr	U	46	45	N/A	2047	6.358	1.691	--	--
Charlotte	Sam Furr Rd	Knoxwood Dr	U	2	45	N/A	1402	--	--	--	--
Charlotte	WT Harris Blvd	Norcroft Dr	U	37	55	N/A	5491	5.565	0.996	5.73	1.59
Charlotte	Sam Furr Rd	Sutters Run Ln	U	5	45	N/A	2018			7.23	0.99
Raeford	US 401	S of Bugle Call Dr	U	23	55	N/A	1389	7.499	3.127		
Wake Forest	Louisburg Rd	Jonesvile Rd	U	37	55	N/A	9662	6.797	1.186	7.07	1.89
Wake Forest	Louisburg Rd	Pulley Town Dr	U	57	45	N/A	1657	6.416	2.003	6.3	2.37
Wilmington	US 74	Dungannon Blvd	U	132	45	N/A	1032	5.881	1.238	7.27	5.87
Wilmington	S College Rd	Jay Bird Circle	U	33	45	N/A	1039	7.351	2.467	10.33	8.33
Wilmington	S College Rd	Greenbriar Rd	U	67	45	N/A	2282	8.623	4.327	6.75	4.35
Wilmington	S College Rd	Hidden Valley Rd	U	14	55	N/A	3229	--	--	11.6	3.71

8 APPENDIX B – COMPARISON TO COMMON WARRANTS

The queue length charts for isolated intersections were compared to the warrants referenced by NCDOT staff as commonly used. This includes the left turn protected phasing warrant developed by Kenneth Agent, the NCDOT Policy on Street and Driveway Access[13] warrant, and the peak hour volume based warrants found in the MUTCD. In most cases, the queue length chart tends to be less conservative than each of the other warrants.

Comparison with each of the three warrants should be conducted cautiously. Both the Agent, and Policy on Street and Driveway warrants are not intended to determine if a traffic signal is warranted. The Policy warrant is queue based, so a direct comparison is possible, but the underlying research is unknown. While the MUTCD warrants are for signalization needs, the underlying research unknown.

The Agent cross product warrant is for protected left turn signalization and not intended for use in determining the need for signalization in general. As is shown in Figure B1, The Agent 100,000 vehicle cross product warrant (used for two lanes of conflicting traffic) is more conservative than the left turn queue length guidance. This is to be expected because, with the Agent warrant, the presence of a signal changes the headways presented to the left turning vehicle. Additionally, when signalized, the left turn has less time in which the turn is permitted (due to the need to yield to minor street movements) compared to the case for an un-signalized intersection where the left turn maintains the right of way over all minor street movements.

Also shown in Figure B1 is the LOS D to E threshold in the HCM for un-signalized delay for a left turn from the major roadway. It can be seen that generally whenever the delay reaches LOS E, the queue based guidelines would recommend further signalization consideration for the movement.

Figure B2 shows the left turn queue length chart with the four hour and peak hour MUTCD warrant volumes for two or more lanes on the major road and one lane on the minor road. The dashed lines indicate the warrant has been modified to consider the traffic is conflicting with only one direction of traffic on the main line. The MUTCD would recommend consideration of a signal with queue lengths generally less than 50 feet and significantly under capacity.

Figure B3 shows the right turn queue length chart with the four hour and peak hour MUTCD warrant volumes for two or more lanes on the major road and one lane on the minor road. The dashed lines indicate the warrant has been modified to consider the traffic is conflicting with only one direction of traffic on the main line. While the peak hour unmodified warrant aligns

[13] (2003). *Policy on Street and Driveway Access to North Carolina Highways*. North Carolina Department of Transportation Division of Highways.

well with the capacity guidance, the modified warrants would recommend consideration of a signal with queue lengths generally less than 100 feet.

Figure B4 shows the U turn queue length chart with the four hour and peak hour MUTCD warrant volumes for two or more lanes on the major road and one lane on the minor road. The dashed lines indicate the warrant has been modified to consider the traffic is conflicting with only one direction of traffic on the main line. The peak hour unmodified warrant suggests a signal would only be warranted when the movement is over capacity. The modified warrants would recommend consideration of a signal with queue lengths generally less than 100 feet.

Figure B5 shows the left turn queue length chart with the guidance from NCDOT's Policy on Street and Driveway Access. This warrant sets required storage lengths for left and right turn bays based on turning demand and conflicting volumes. The blue line on the chart indicates the volumes under which the warrant requires a storage of 100 feet while the purple line highlights the volumes under which the expected 95% queue length is 100 feet. As can be seen, the Policy on Street and Driveway Access is more conservative than the guidance recommended in this report.

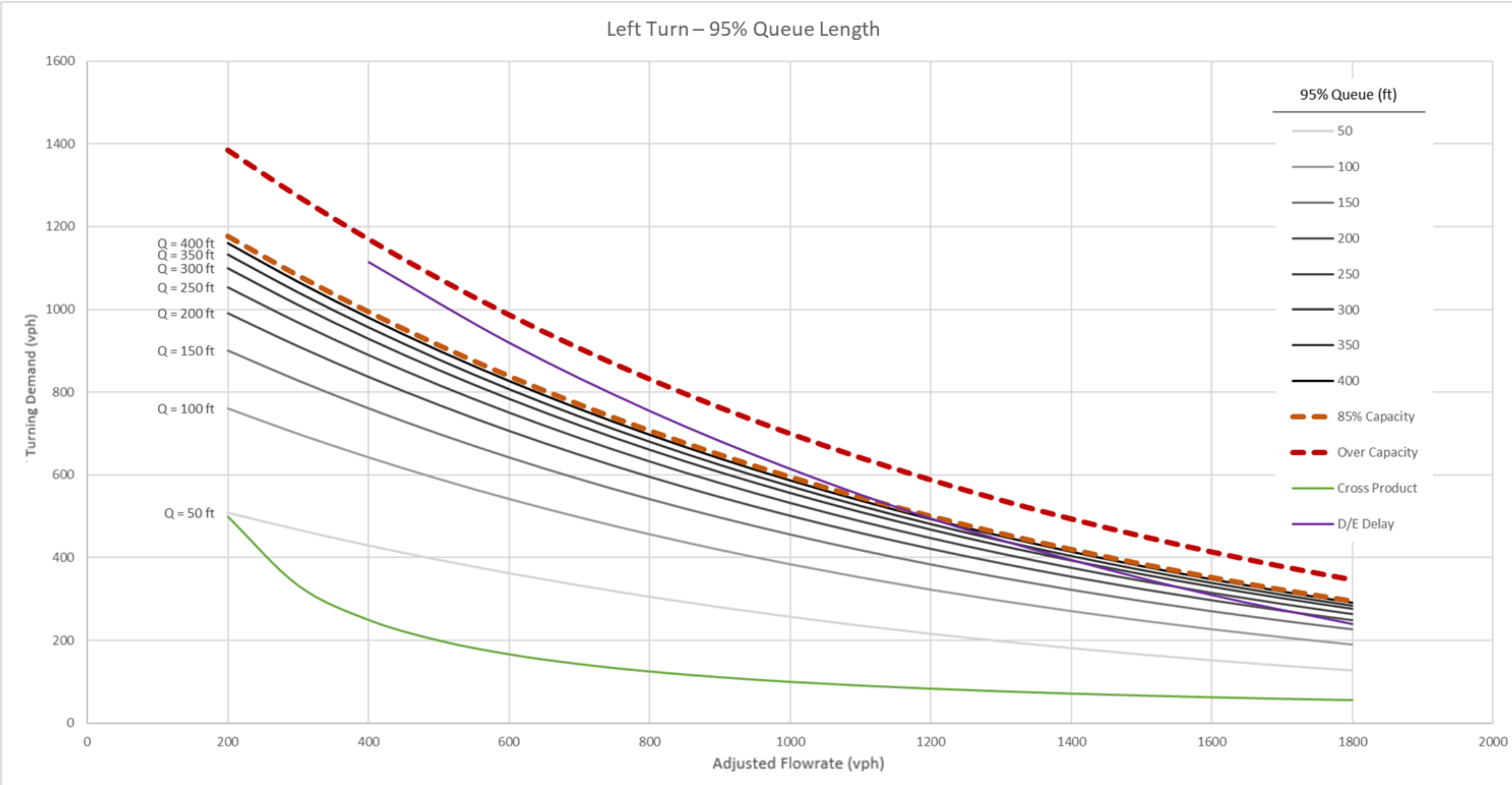


Figure B1. 95% left turn queue length compared to Agent 100,000 vehicle cross product and HCM LOS D/E.

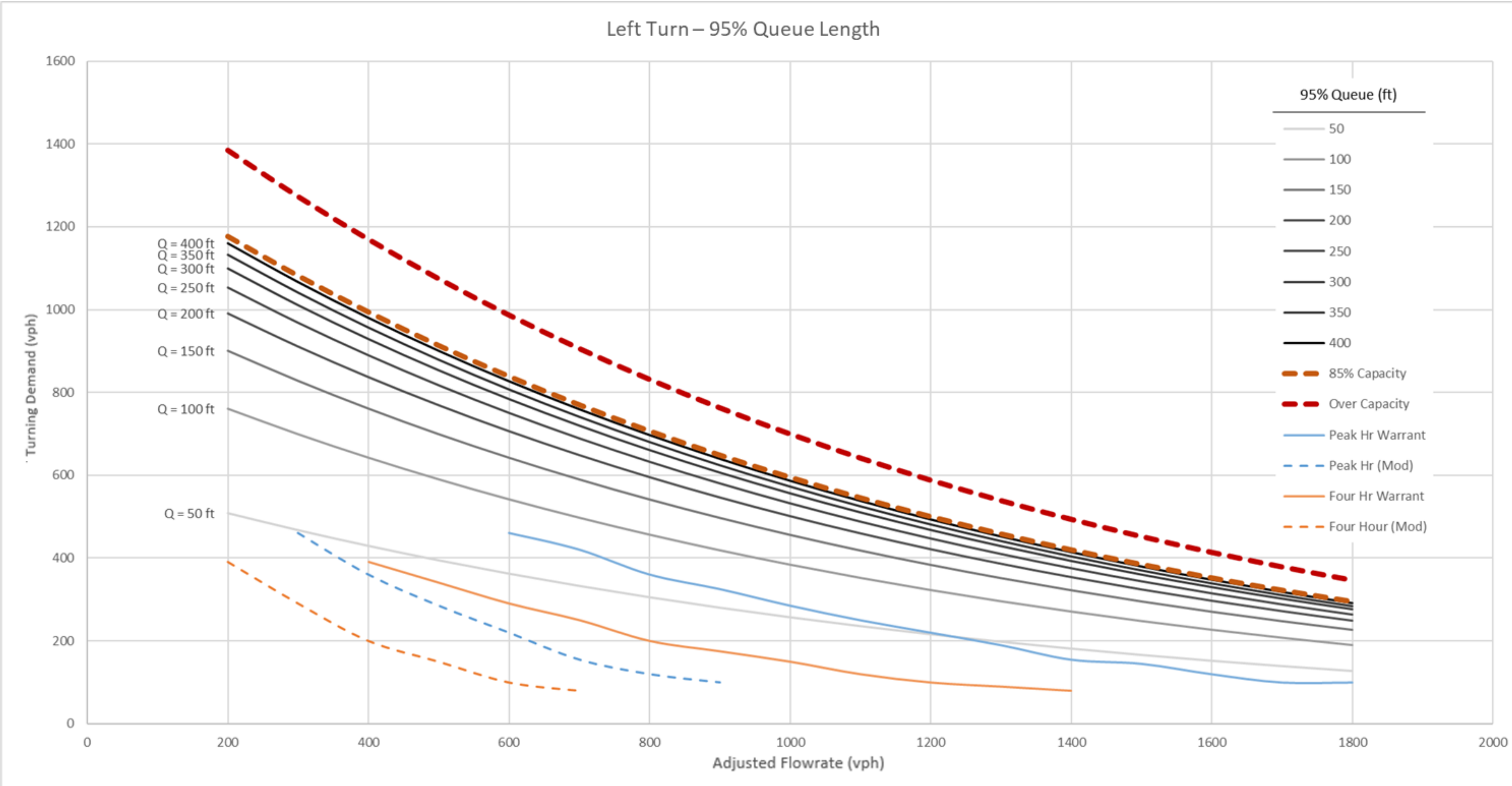


Figure B2. 95% left turn queue length compared to MUTCD peak hour and four hour warrants.

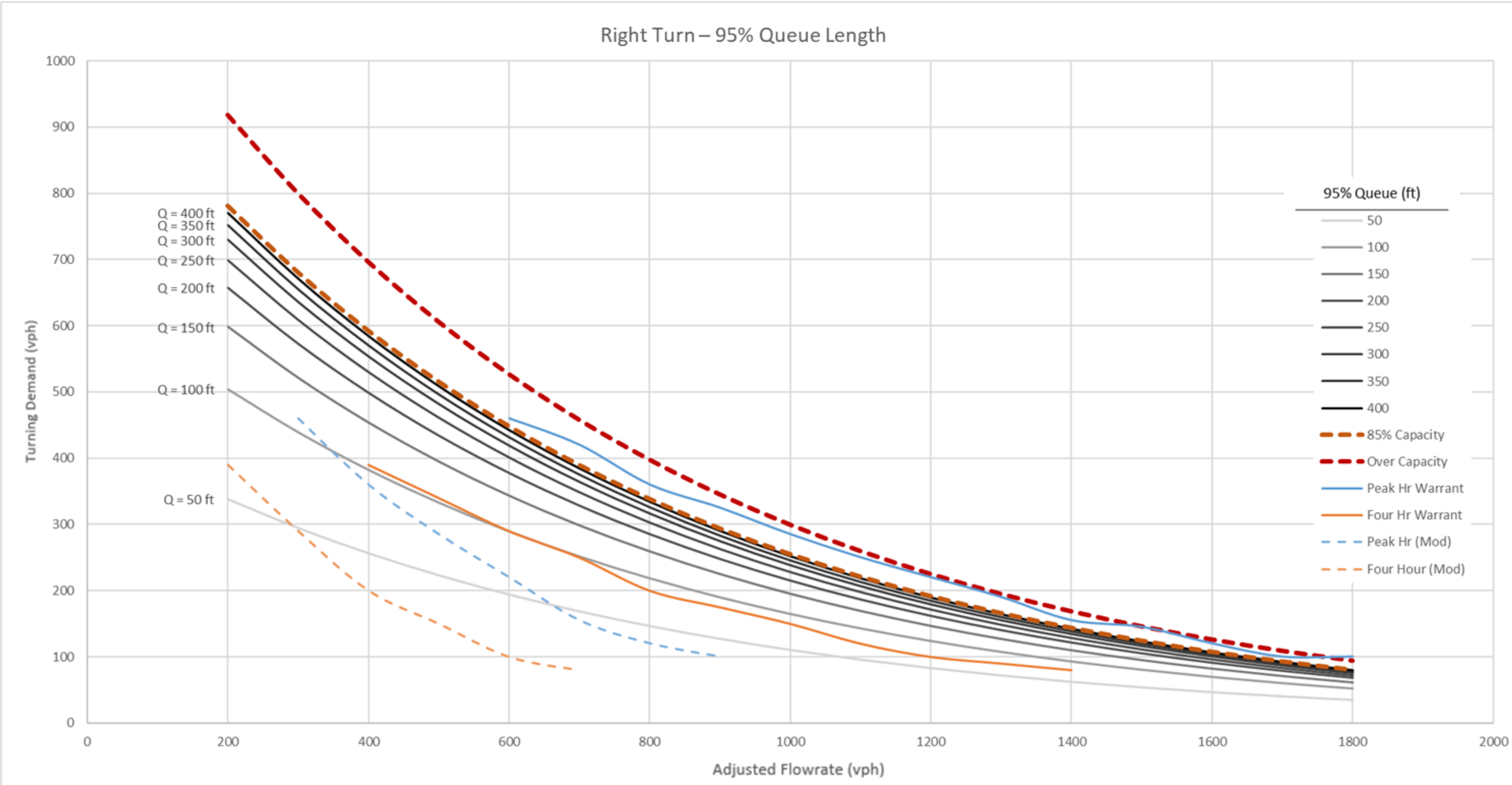


Figure B3. 95% right turn queue length compared to MUTCD peak hour and four hour warrants.

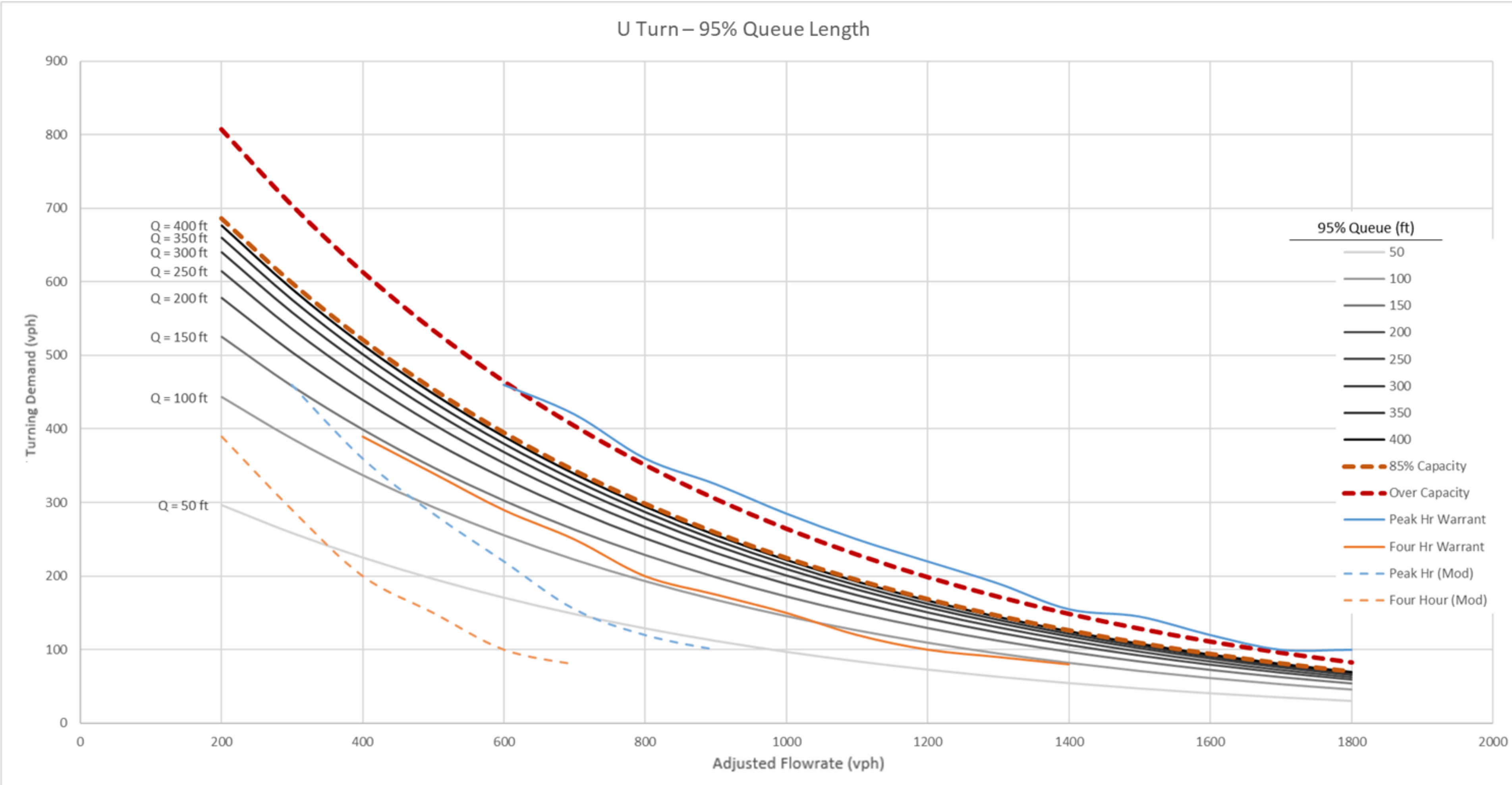


Figure B4. 95% U turn queue length compared to MUTCD peak hour and four hour warrants.

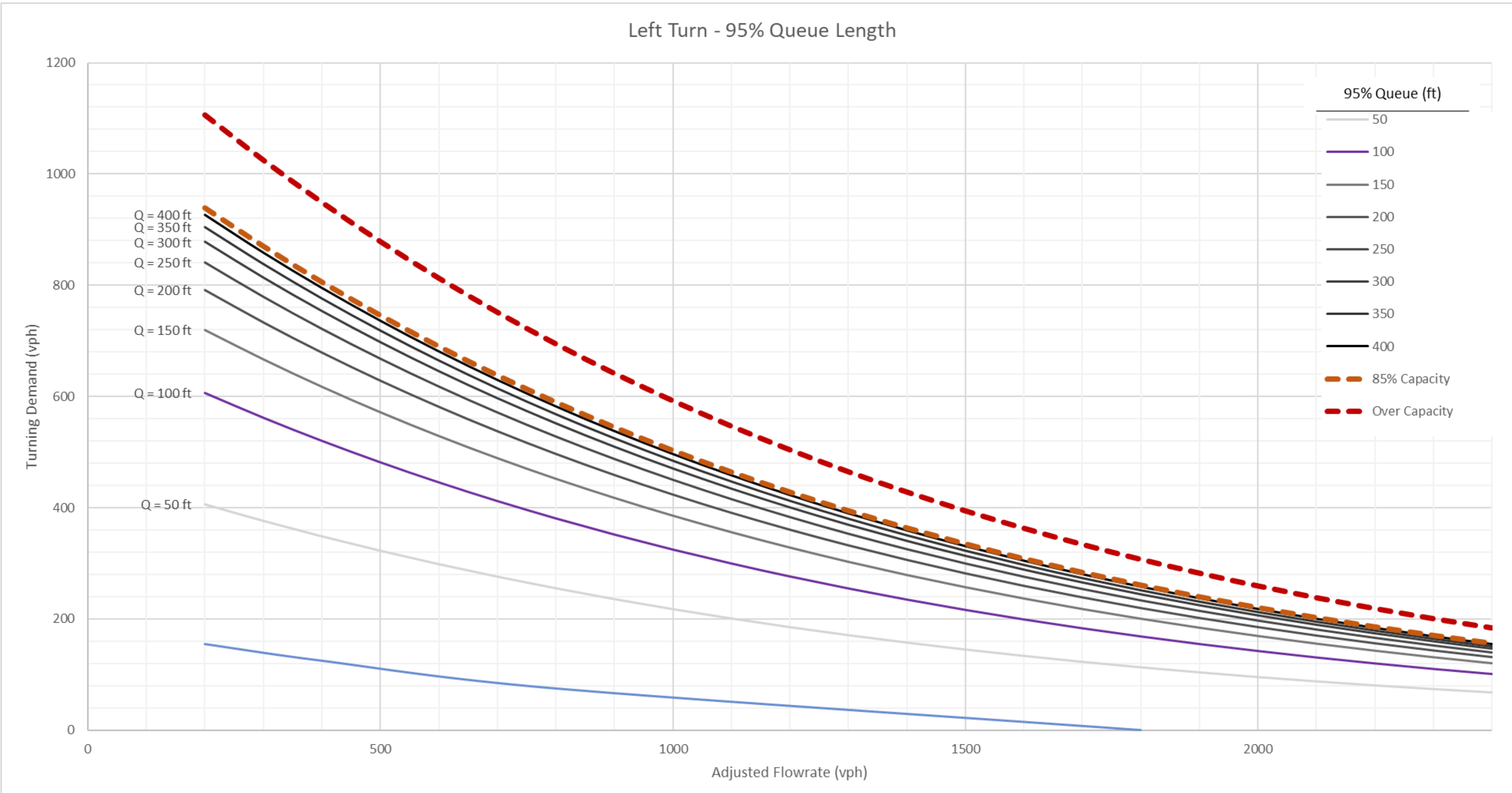


Figure B5. 95% light turn queue length compared to NCDOT Policy on Street and Driveway Access.

9 APPENDIX C – SIGNALIZATION GUIDELINE CHARTS

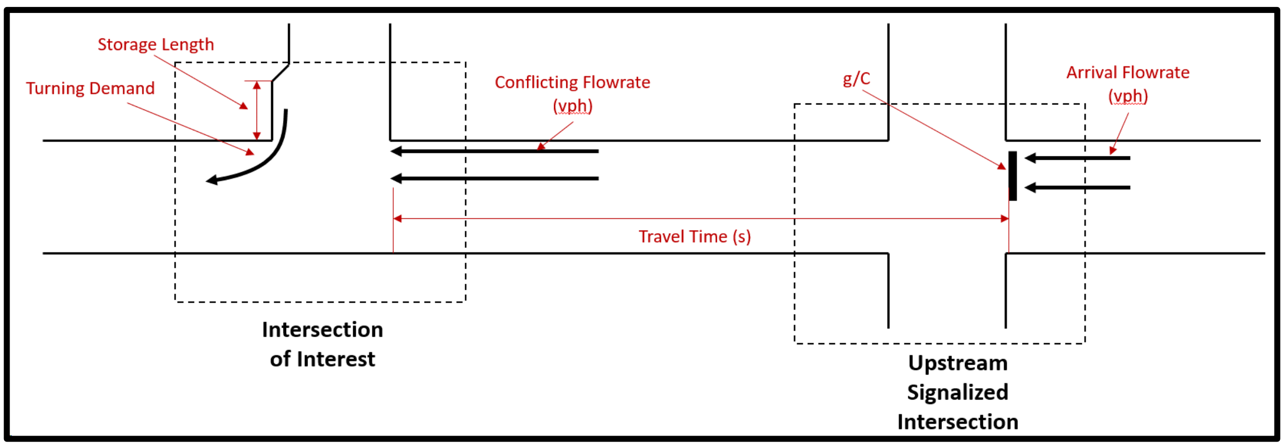
NCDOT Two or Three Leg Signalization Guidelines Charts

These guidelines have been developed for use in determining signalization needs at intersections with fewer than four legs. The intersections may have left turns, right turns, or u turns crossing or merging with two lanes of conflicting traffic. These movements are frequently, although not exclusively, found along four lane divided roadways with leftovers, T intersections, and median u turn openings.

Needed Information

To analyze an intersection using the provided charts, the following quantities must be known:

- Movement type (right, left, or u)
- Turning demand (vph)
- Conflicting volume (vph)
- Queue storage length (ft)
- Presence of an upstream signalized intersection; if yes:
    - Travel time from the upstream intersection to the intersection of interest (s)
    - Arrival rate of inbound, mainline vehicles at the upstream intersection (vph)
    - Approximate green-to-cycle length time of the upstream inbound mainline movement OR the number of critical phases at the intersection



Assumptions

The Conflicting Volume Adjustment Factor (CVAF) chart assumes a cycle length at the upstream intersection between 60 s and 120 s. It does not consider the impact of side street turning movements joining the inbound vehicles. It is intended to be used when it can be reasonably assumed all critical phases are called regularly.

The left turn queue length chart is intended for use under the following scenario

- The yielding movement is a left turn from the major to the minor,
- Two lanes of conflicting traffic,
- Conflicting traffic has a posted speed limit of 45 or 55 mph, and
- The target lane is not expected to experience queue spillback to the turning point

The right turn queue length chart is intended for use under the following scenario

- The yielding movement is a right turn from the minor to the major,
- Two lanes of conflicting traffic,
- Conflicting traffic has a posted speed limit of 45 or 55 mph, and
- The target lane is not expected to experience queue spillback to the turning point

The u turn queue length chart is intended for use under the following scenario

- The yielding movement is a u turn,
- Two lanes of conflicting traffic,
- Conflicting traffic has a posted speed limit of 45 or 55 mph, and
- The target lane is not expected to experience queue spillback to the turning point

Process

1. Using the STEP 1 chart that corresponds to the turning movement at the interesection of interest and green-to-cycle length ratio at the upstream intersection, determine the Conflicting Volume Adjustment Factor (CVAF). If there is no upstream signalized intersection, the CVAF = 1.0.
   a. Determine the green-to-cycle length ratio for the inbound mainline movement at the upstream intersection. Alternatively, the number of critical phases can be used. Care should be used in considering if all phases of the upstream intersection are regularly served.

      Example
      A two critical phase signal is located upstream to serve a mainline u turn. The u turn phase operates protected/permitted with a 15 second delay for the protected phase. The local engineer knows the protected phase is called approximately once per hour.

      The intersection of interest should be analyzed as an isolated intersection. Applying a Conflicting Volume Adjustment Factor (CVAF) other than 1.0 would inflate the capacity at the intersection of interest in a manner not typically observed in the field.

   b. Using the CVAF chart that corresponds to the turning movement at the intersection of interest, and the g/C at the upstream intersection, find the travel time between the intersections on the x-axis and move in the positive-y direction until reaching the line for the arrival flowrate* of the inbound mainline movement at the upstream intersection. Move to the left to find the CVAF.
2. Multiply the CVAF with the measured conflicting flowrate* at the intersection of interest to calculate the adjusted conflicting volume.
3. Using the STEP 3 chart that corresponds to the turning movement at the intersection of interest, find the intersection of the turning movement demand and the adjusted conflicting volume. Move in the positive-y direction to the next plotted line to determine the expected 95% queue length or the expected volume-to-capacity.

Analysis

It is recommended that two conditions would result in further investigation of a signal:

- The expected 95% queue length exceeds the available storage capacity, or
- The turning movement volume-to-capacity ratio exceeds 85%.

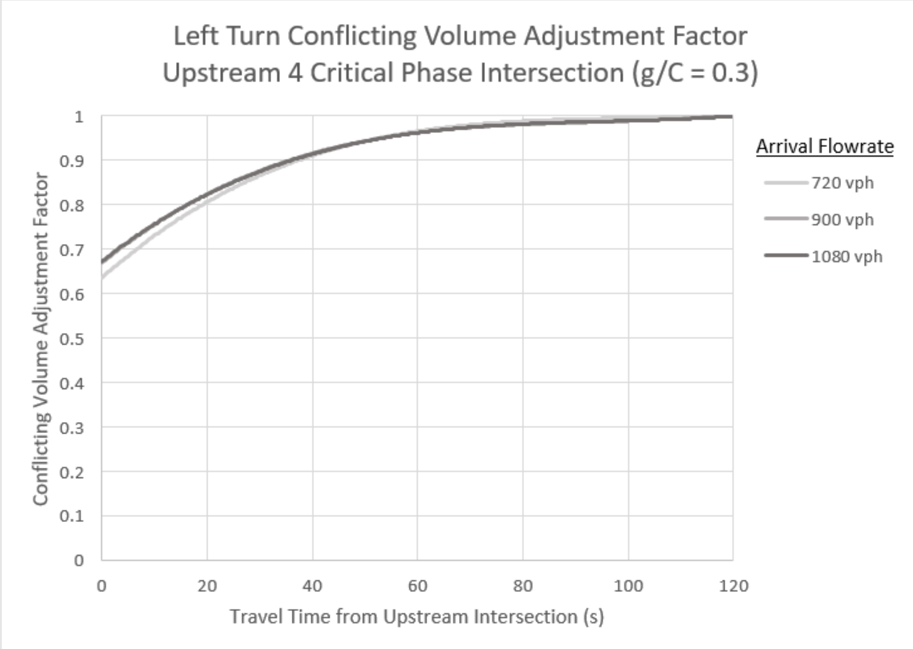
If only the first criterion is met, it would also be appropriate to consider extending the storage capacity in lieu of signalization.

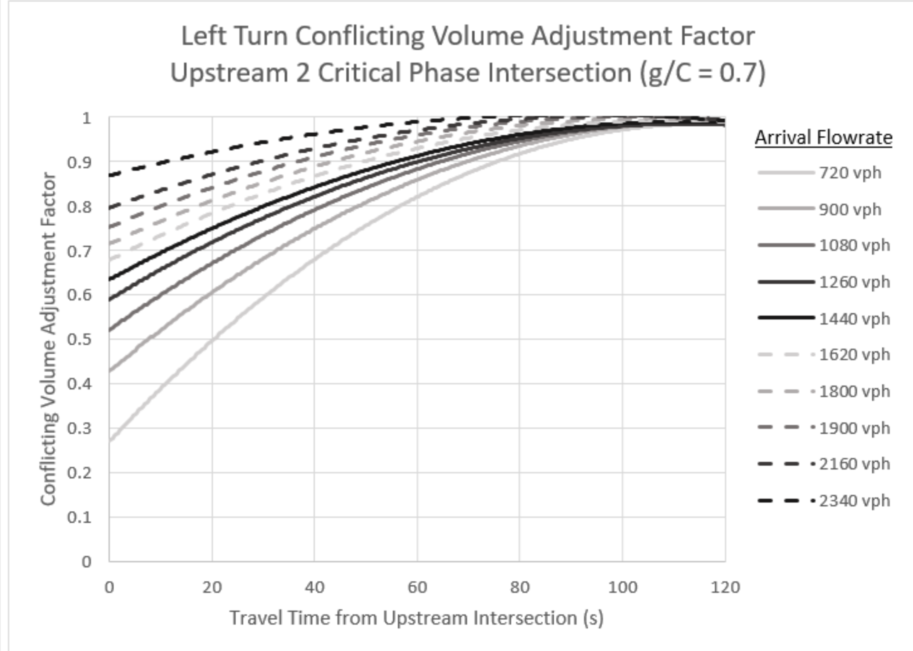
* The arrival flowrate does not include vehicles which have turned onto the mainline from the upstream sidestreet. As such, the arrival flowrate may be slightly lower than the conflicting flowrate.

ITRE

NCDOT Two or Three Leg Signalization Guidelines Charts - STEP 1

Version 1





The Conflicting Volume Adjustment Factor can also be determined mathematically wih the following equation, where t is the travel time from the upstream intersection in seconds.

$$CVAF = at^2 + bt + c$$

Upstream Mainline Arrival Rate (vph)	g/c	a	b	c
720	0.3	0.00004	0.0076	0.6590
720	0.7	0.00005	0.0124	0.2707
900	0.3	0.00004	0.0066	0.6930
900	0.7	0.00004	0.0097	0.4284
1080	0.3	0.00004	0.0066	0.6943
1080	0.7	0.00004	0.0082	0.5217
1260	0.7	0.00004	0.0070	0.5899
1440	0.7	0.00004	0.0063	0.6342
1620	0.7	0.00004	0.0058	0.6786
1800	0.7	0.00004	0.0054	0.7145
1980	0.7	0.00004	0.0049	0.7528
2160	0.7	0.00004	0.0042	0.7956
2340	0.7	0.00004	0.0030	0.8685

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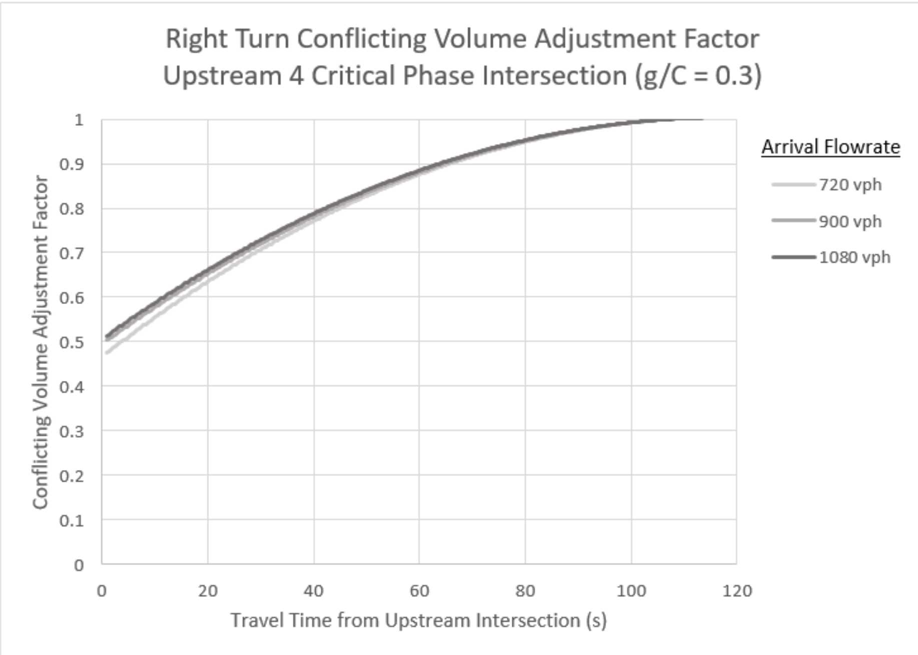
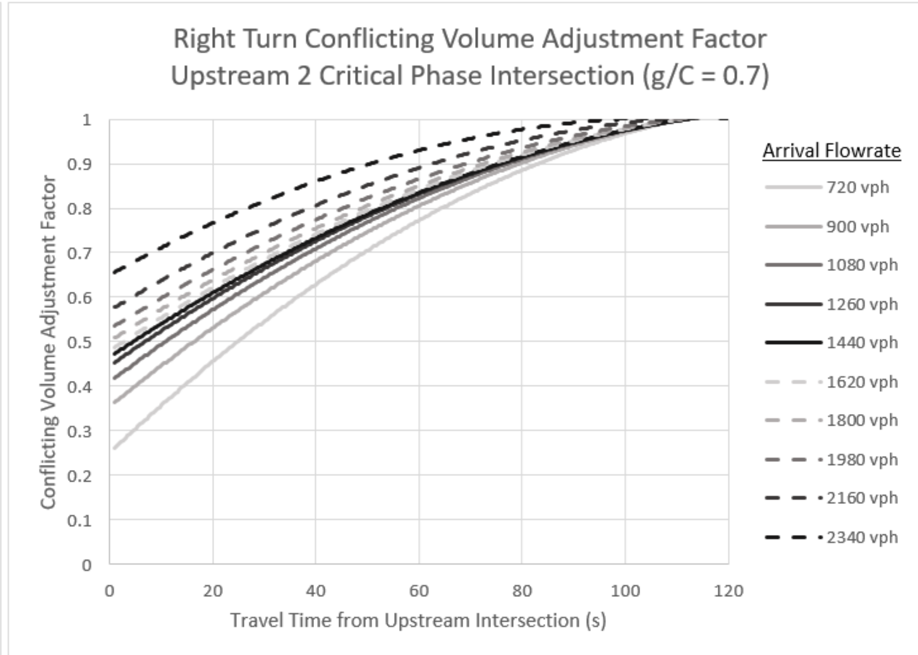
STEP 1

NCDOT Two or Three Leg Signalization Guidelines Charts - STEP 1

Version 1





The Conflicting Volume Adjustment Factor can also be determined mathematically wih the following equation, where t is the travel time from the upstream intersection in seconds.

$$CVAF = at^2 + bt + c$$

Upstream Mainline Arrival Rate (vph)	g/c	a	b	c
720	0.3	0.00004	0.0090	0.4736
720	0.7	0.00004	0.0108	0.2587
900	0.3	0.00004	0.0084	0.5010
900	0.7	0.00003	0.0093	0.3609
1080	0.3	0.00004	0.0083	0.5121
1080	0.7	0.00003	0.0085	0.4162
1260	0.7	0.00003	0.0080	0.4518
1440	0.7	0.00003	0.0076	0.4712
1620	0.7	0.00003	0.0075	0.4856
1800	0.7	0.00003	0.0072	0.5071
1980	0.7	0.00003	0.0070	0.5338
2160	0.7	0.00003	0.0069	0.5756
2340	0.7	0.00003	0.0063	0.6548

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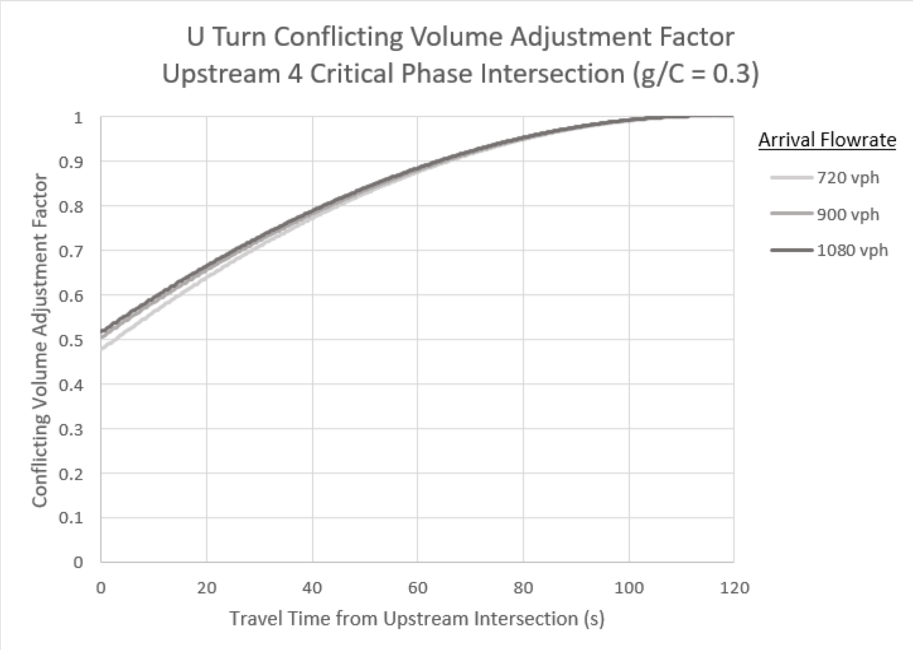
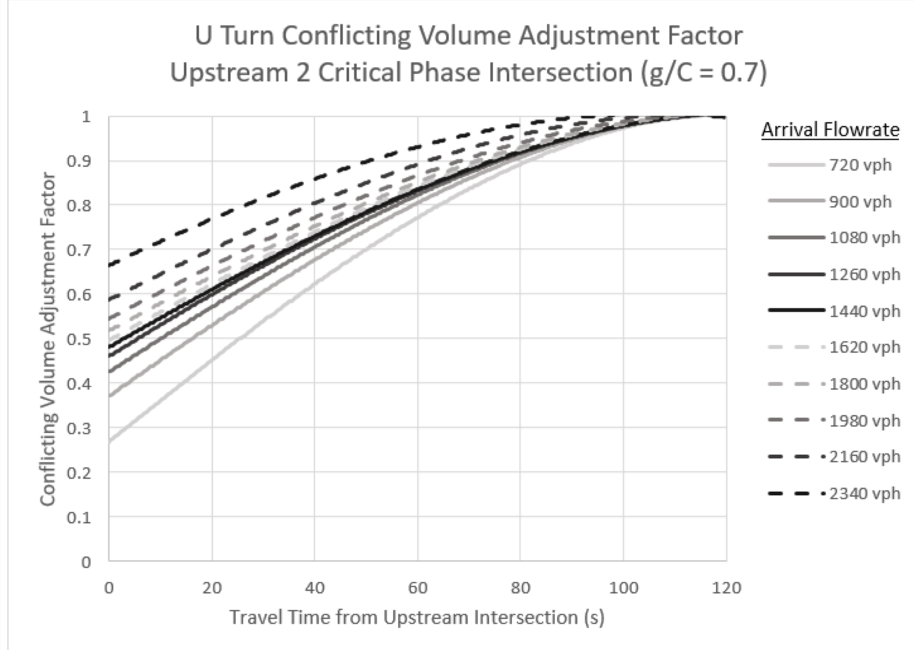
STEP 1

NCDOT Two or Three Leg Signalization Guidelines Charts - STEP 1

Version 1





The Conflicting Volume Adjustment Factor can also be determined mathematically wih the following equation, where t is the travel time from the upstream intersection in seconds.

$$CVAF = at^2 + bt + c$$

Upstream Mainline Arrival Rate (vph)	g/c	a	b	c
720	0.3	0.00004	0.0089	0.4765
720	0.7	0.00004	0.0108	0.2568
900	0.3	0.00004	0.0084	0.5035
900	0.7	0.00003	0.0093	0.3619
1080	0.3	0.00003	0.0083	0.5155
1080	0.7	0.00003	0.0085	0.4171
1260	0.7	0.00003	0.0079	0.4544
1440	0.7	0.00003	0.0076	0.4737
1620	0.7	0.00003	0.0074	0.4886
1800	0.7	0.00002	0.0072	0.5106
1980	0.7	0.00003	0.0070	0.5374
2160	0.7	0.00003	0.0068	0.5795
2340	0.7	0.00003	0.0062	0.6592

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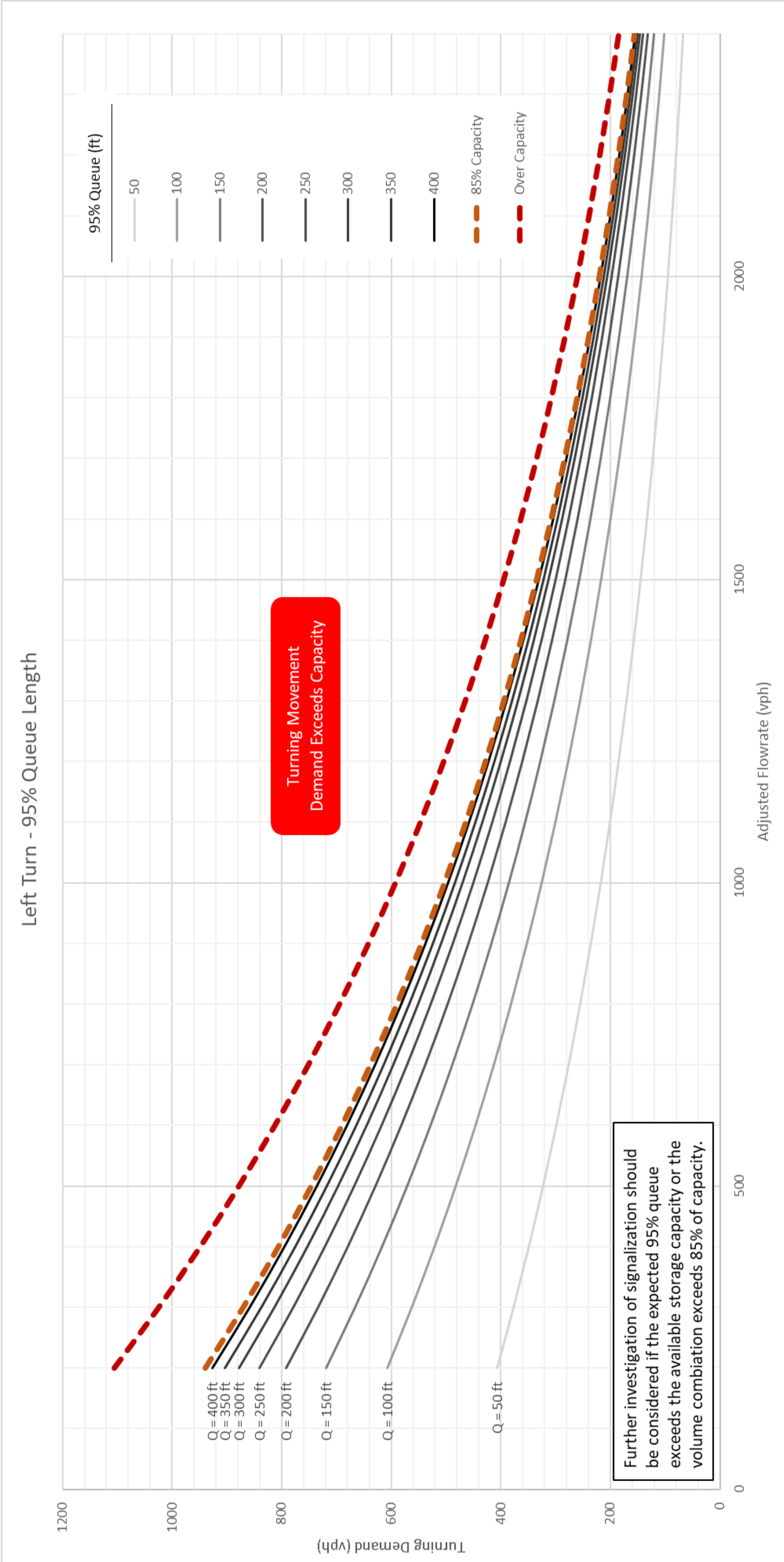
STEP 1

NCDOT Two or Three Leg Signalization Guidelines Charts - STEP 3

Version 1

STEP 3



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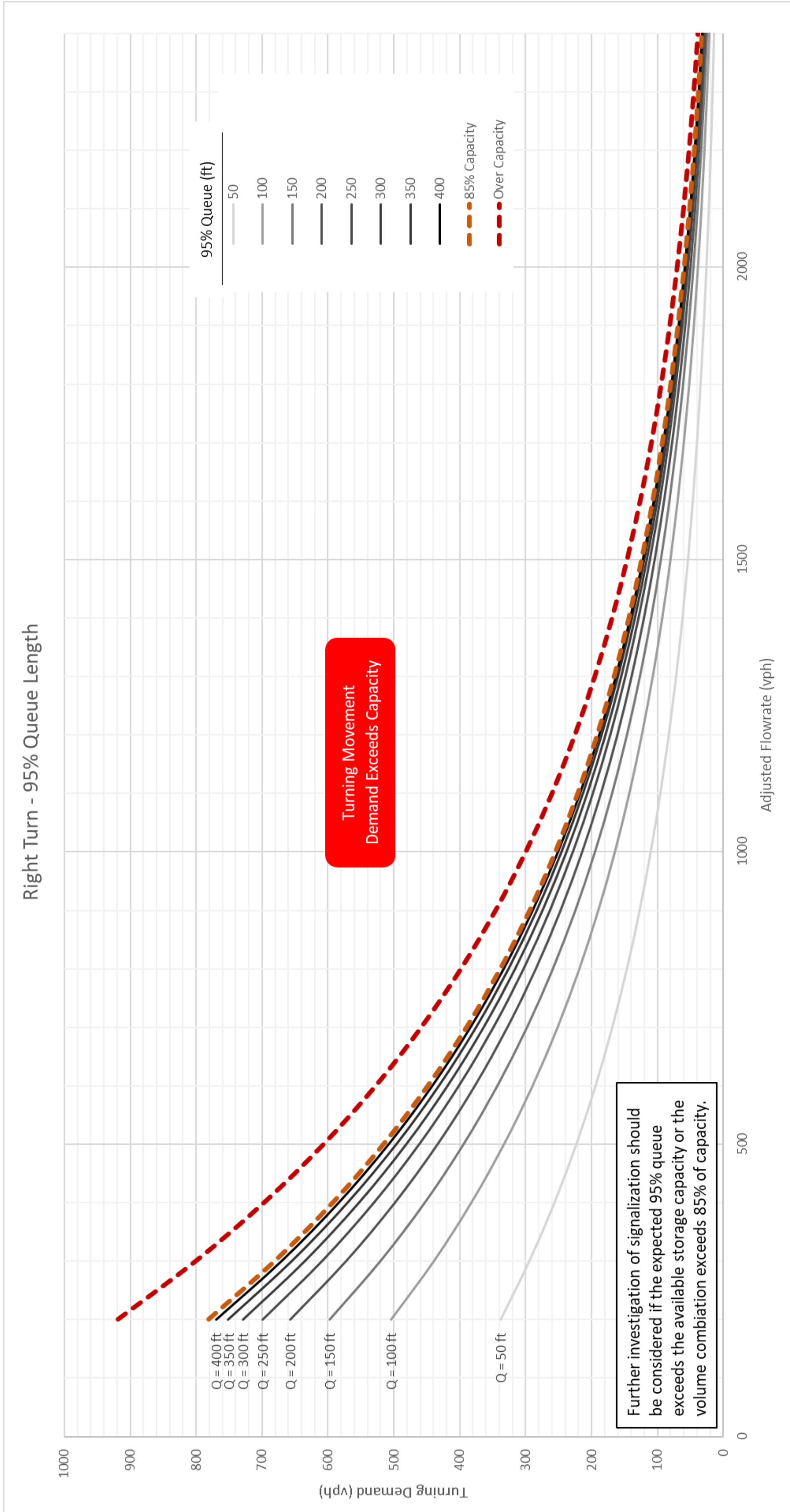
NCDOT Two or Three Leg Signalization Guidelines Charts - STEP 3 **Version 1**

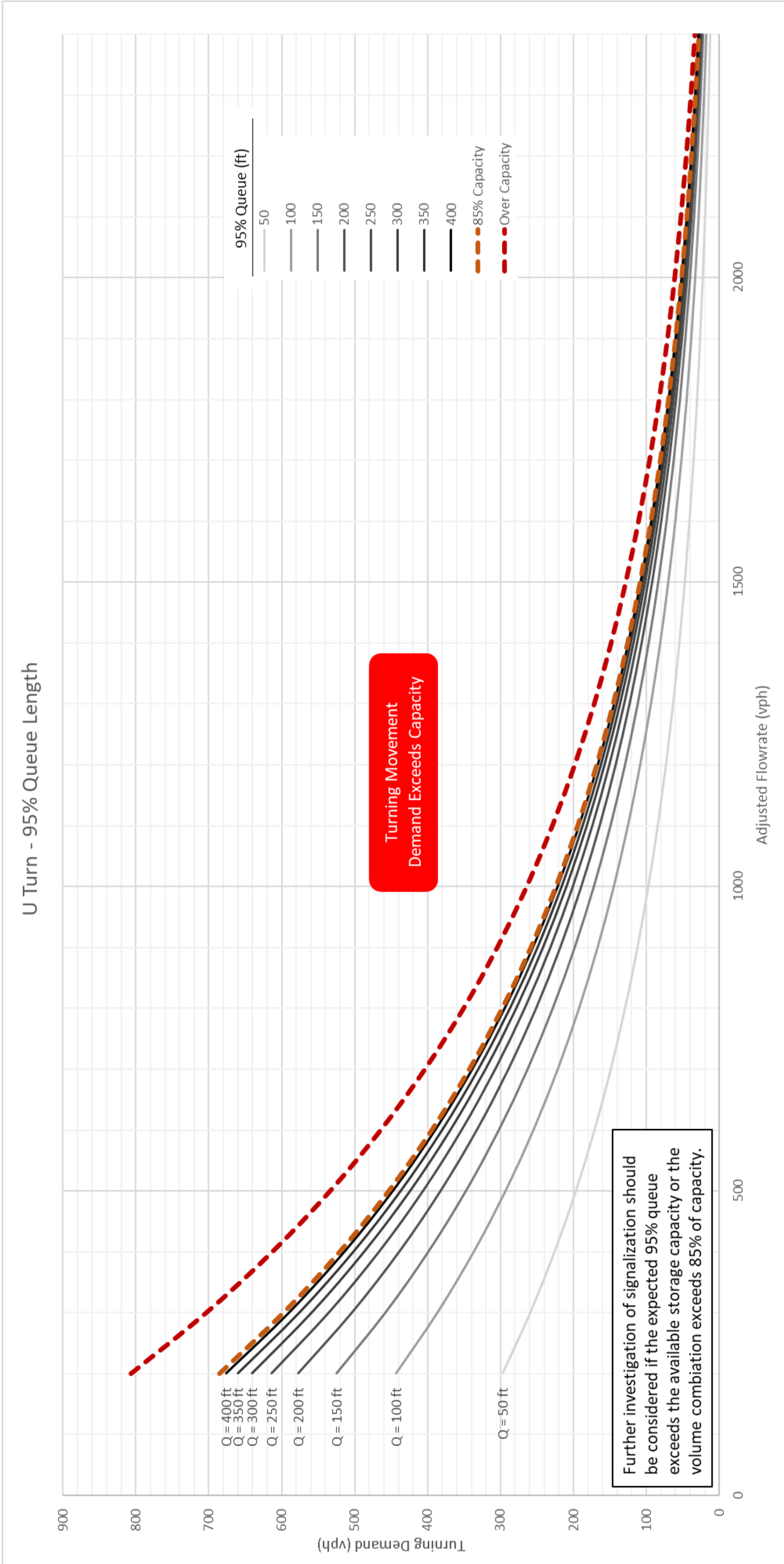
STEP 3



ITRE

NCDOT Two or Three Leg Signalization Guidelines Charts - STEP 3 | Version 1

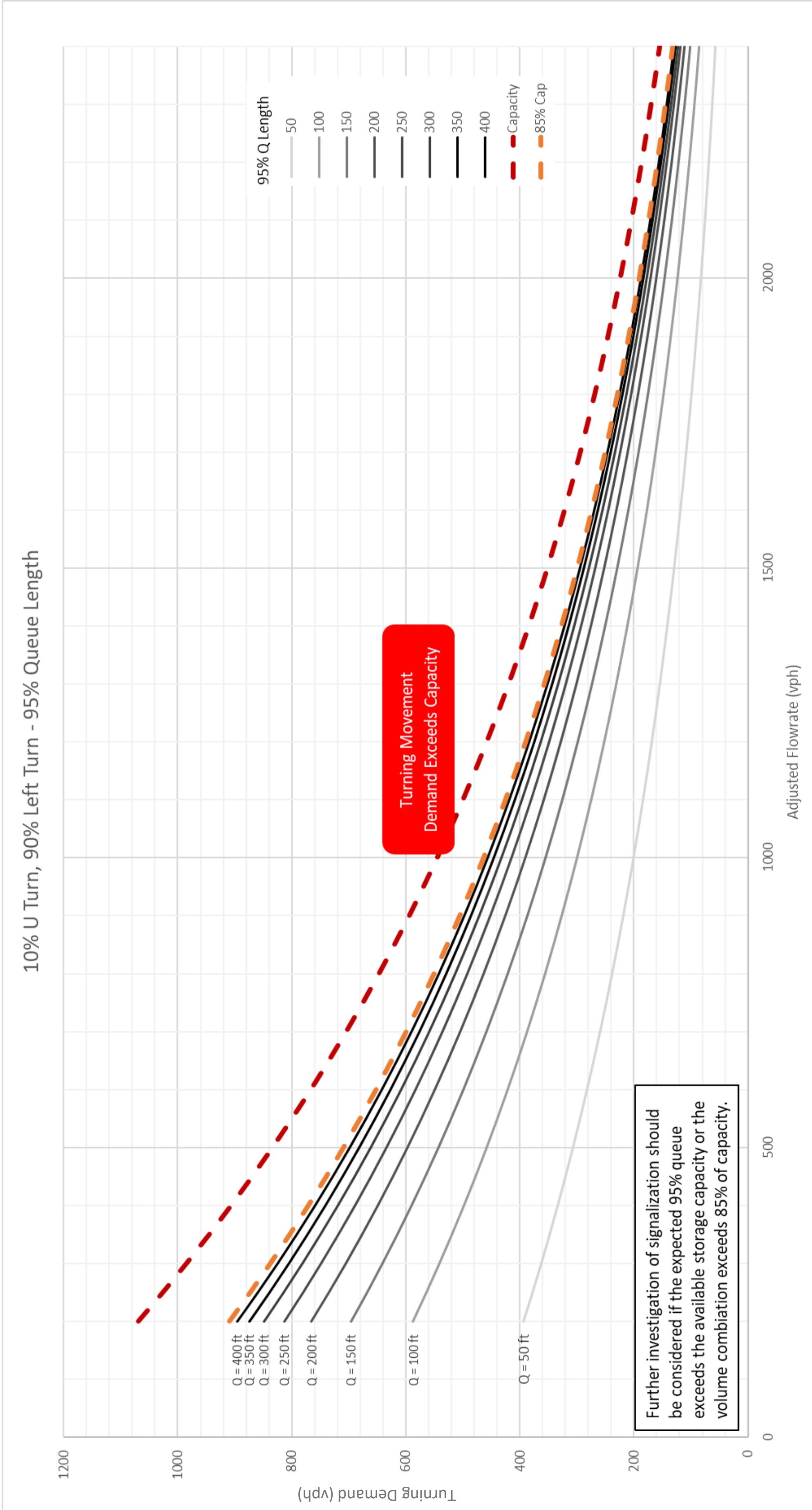
STEP 3



10 Appendix D – Queue Length Charts for Mixed Left and U Turn Movements

NCDOT Two or Three Leg Signalization Mixed Movement Queue Length Charts

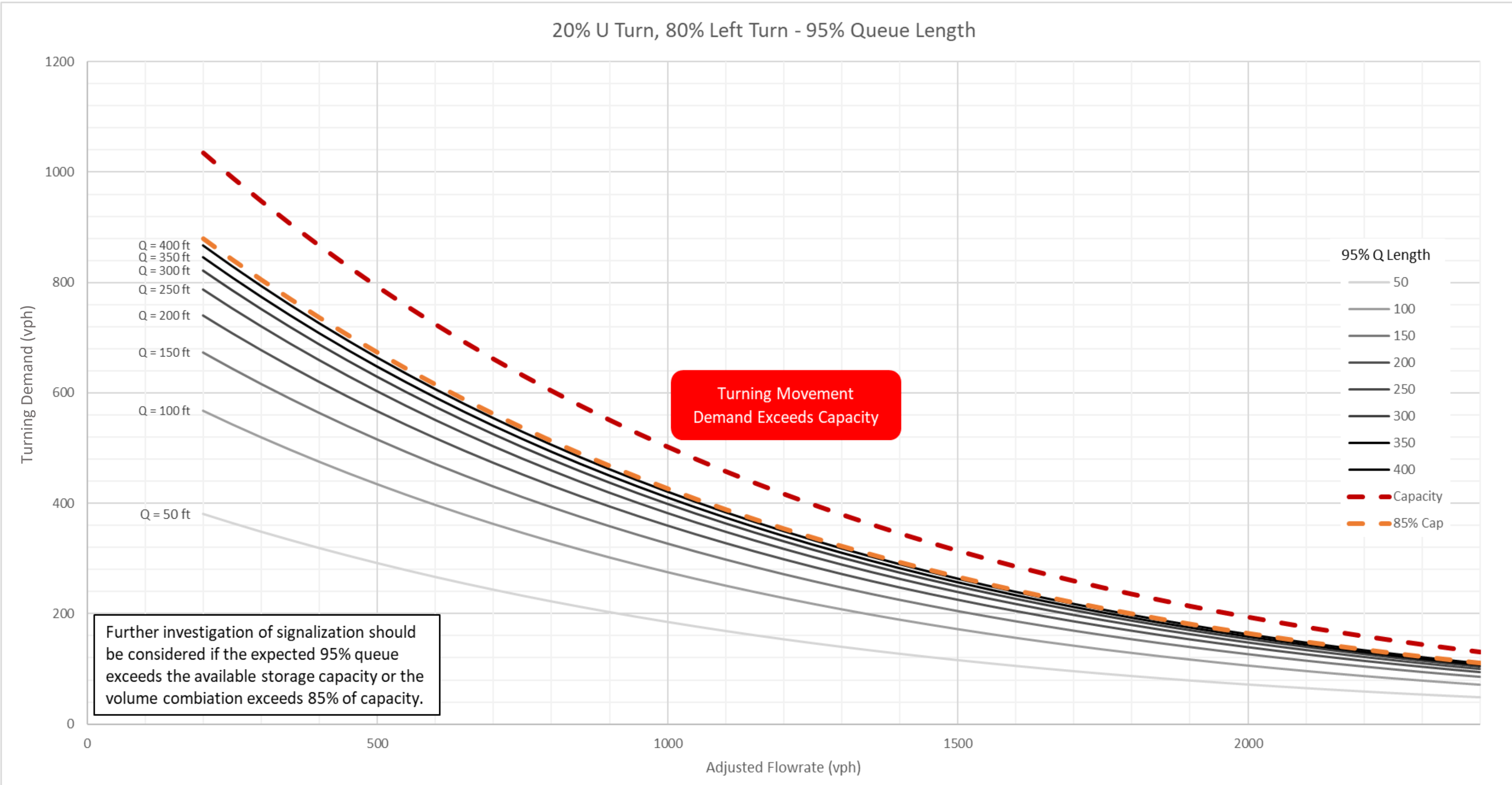
Version 1



These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

STEP 3

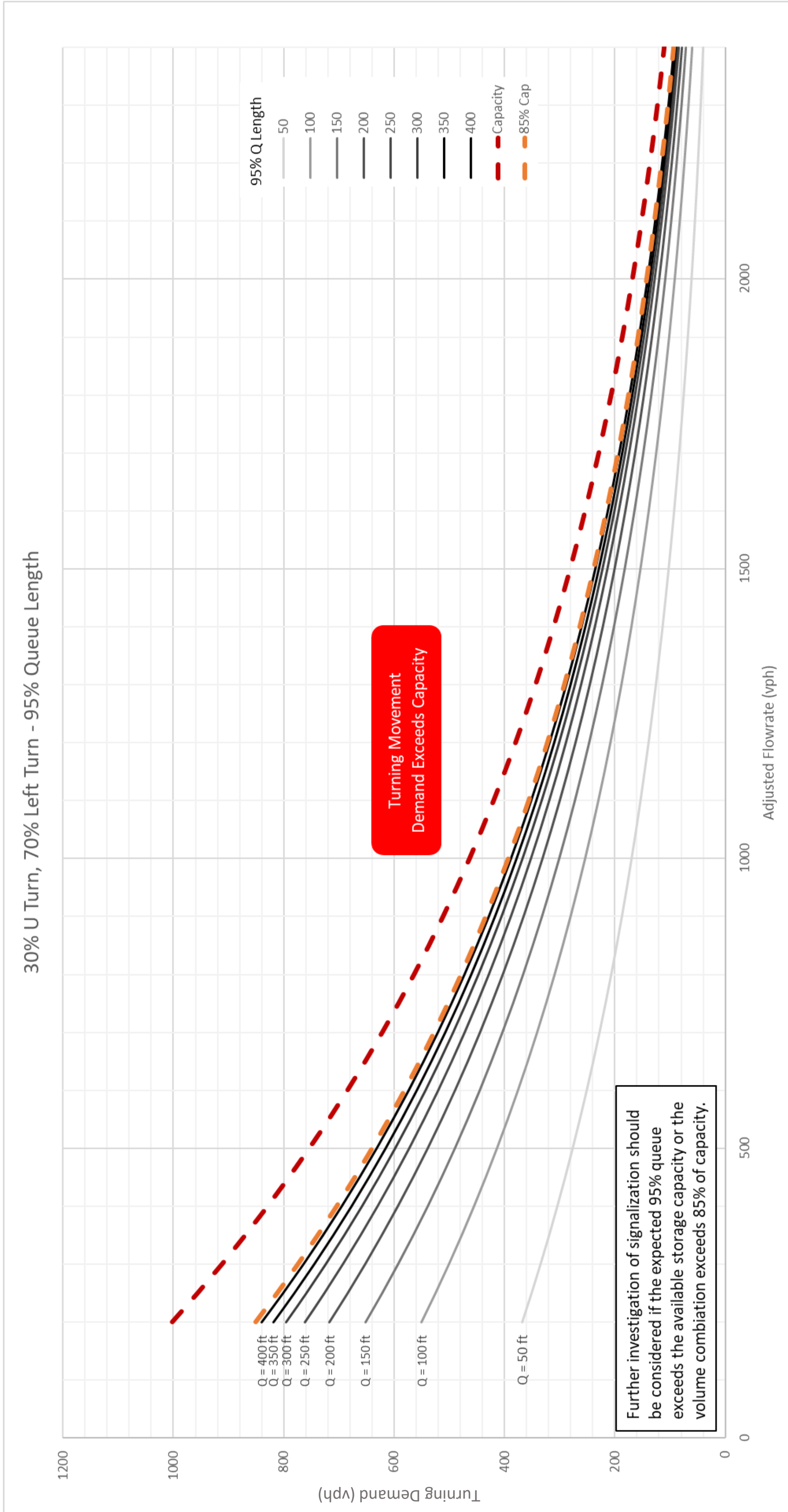
ITRE



These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

STEP 3

NCDOT Two or Three Leg Signalization Mixed Movement Queue Length Charts **Version 1**

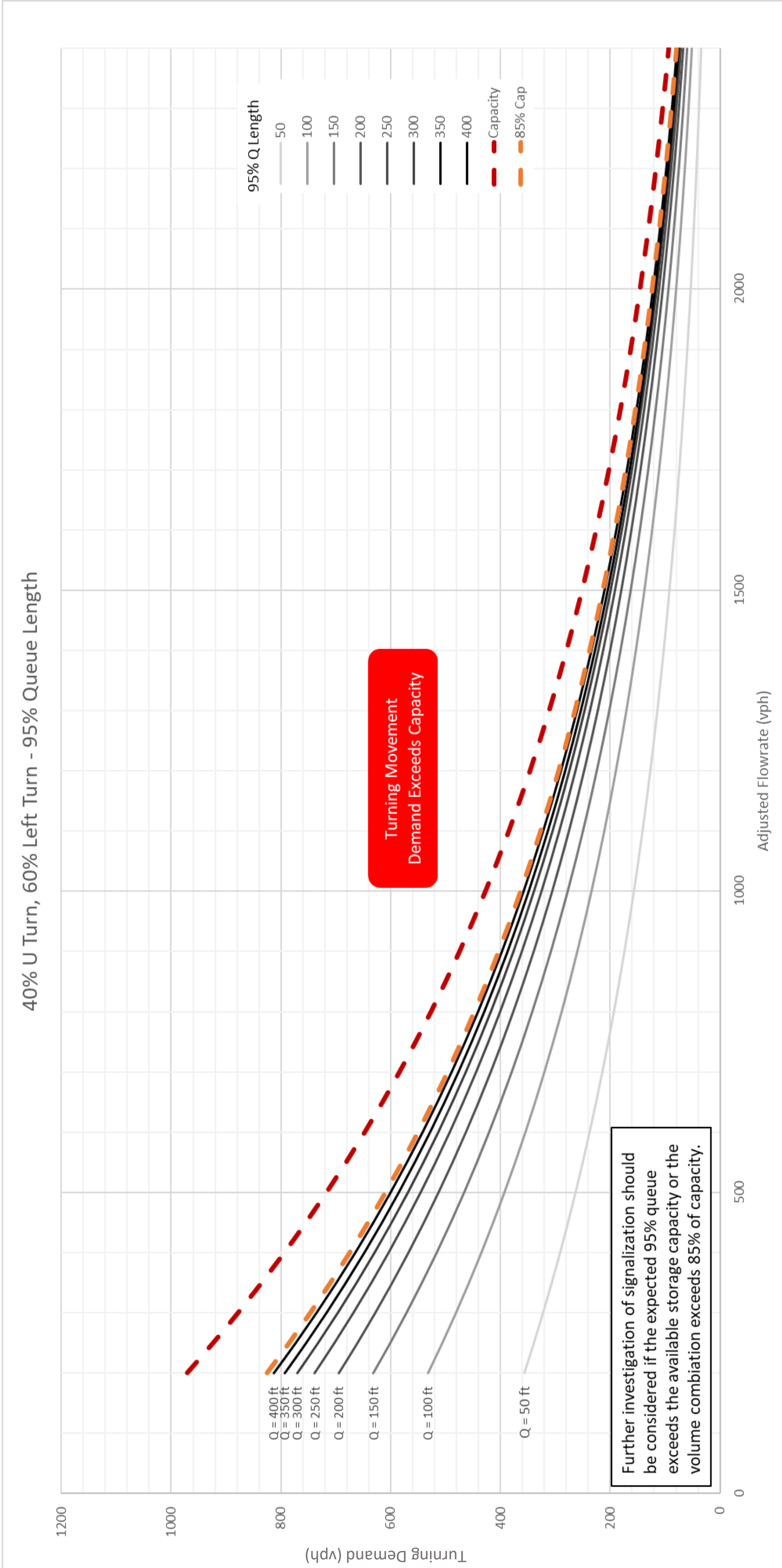


STEP 3

These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

ITRE

NCDOT Two or Three Leg Signalization Mixed Movement Queue Length Charts — Version 1



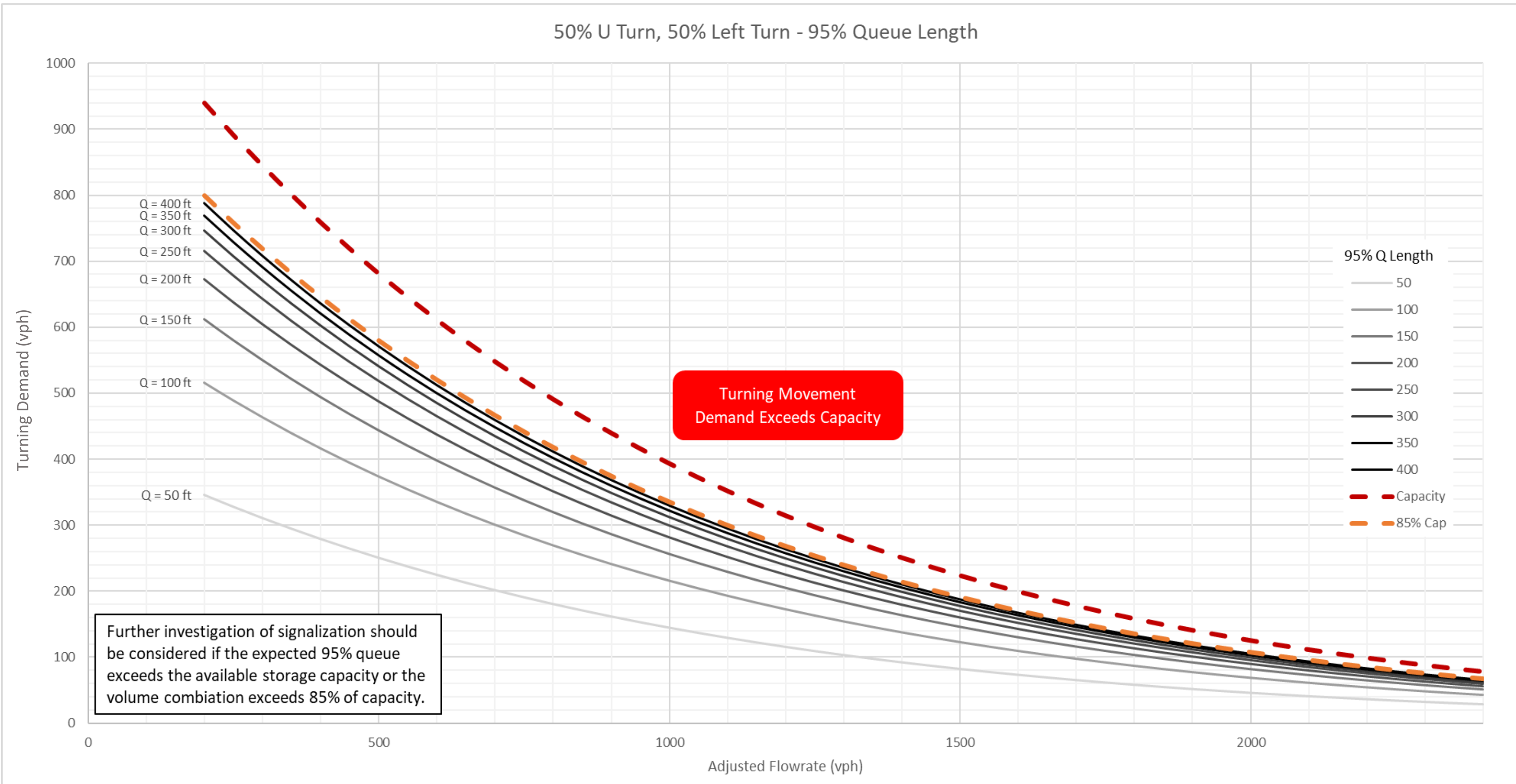
STEP 3

These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

ITRE

NCDOT Two or Three Leg Signalization Mixed Movement Queue Length Charts

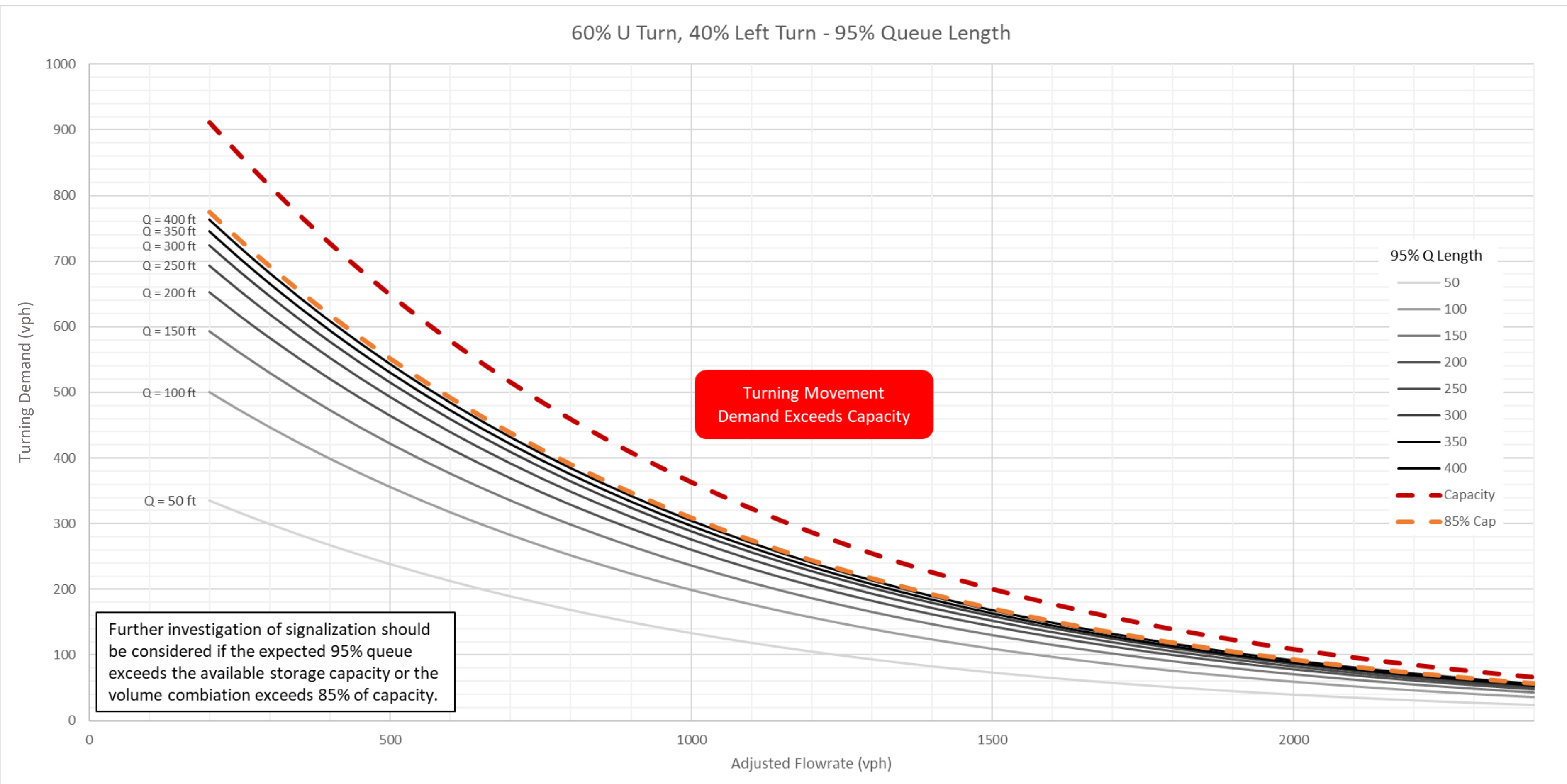
Version 1



ITRE

These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

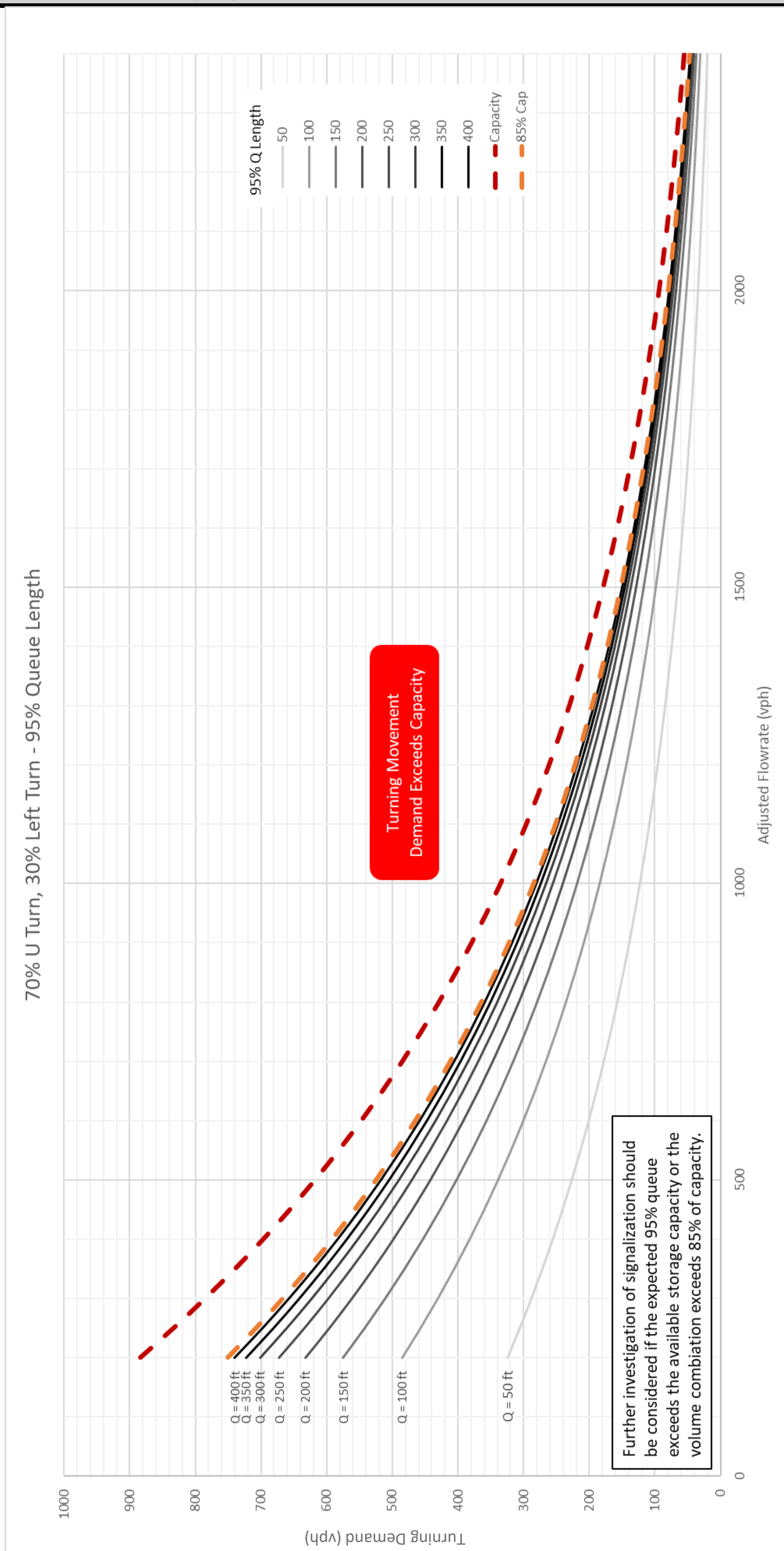
STEP 3



These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

STEP 3

NCDOT Two or Three Leg Signalization Mixed Movement Queue Length Charts **Version 1**

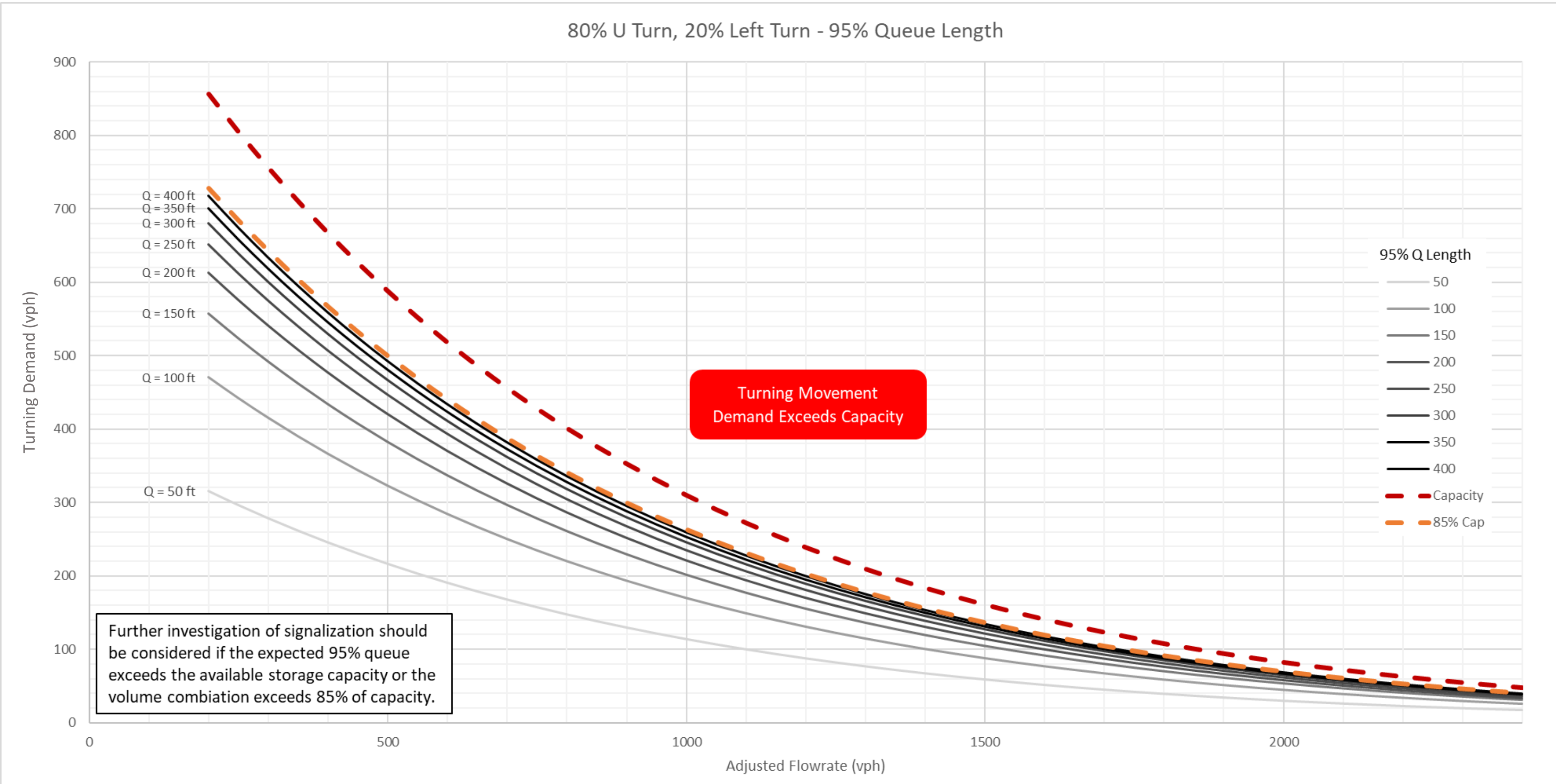


These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

STEP 3

ITRE

NCDOT Two or Three Leg Signalization Mixed Movement Queue Length Charts **Version 1**



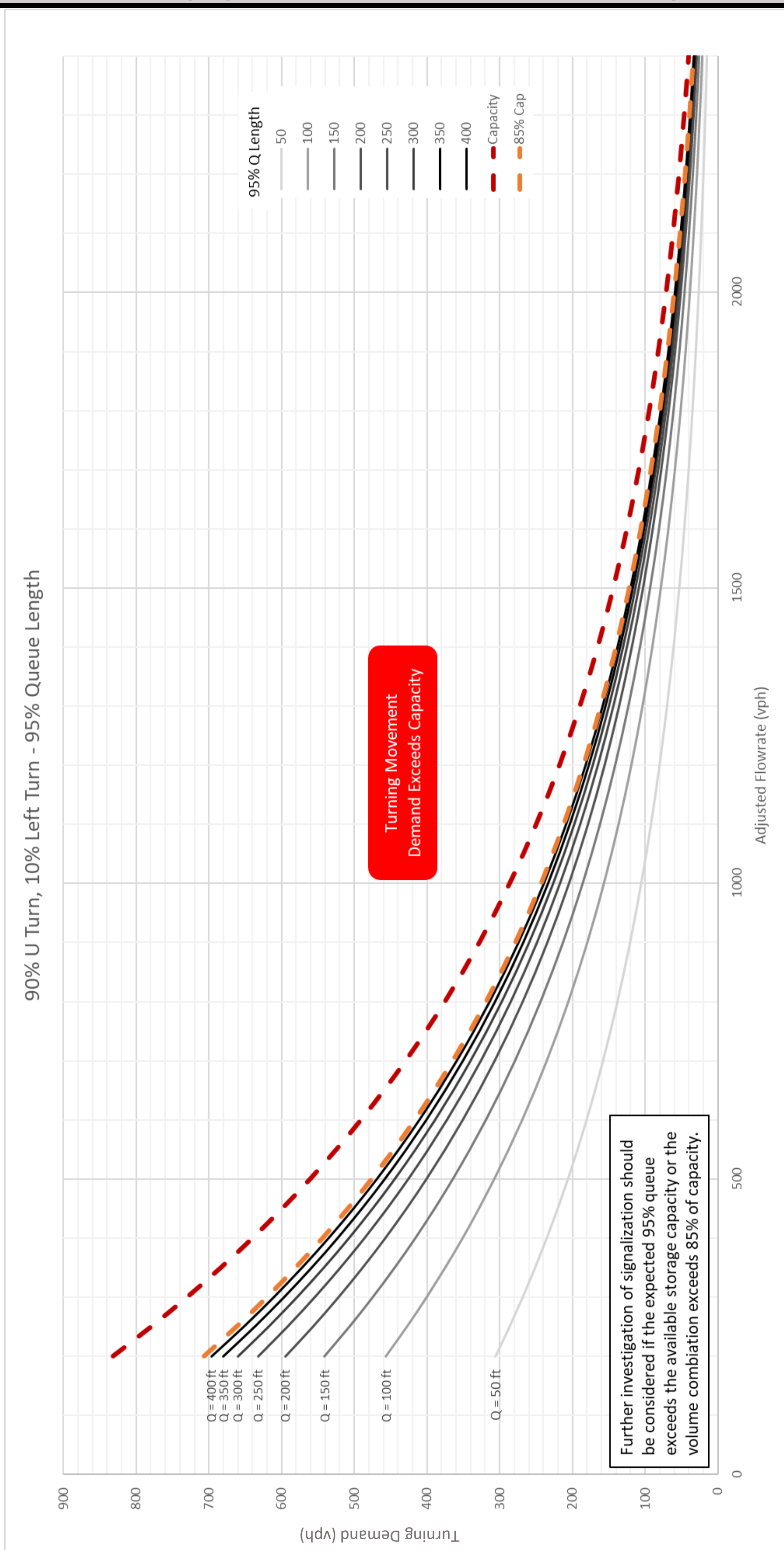
ITRE

These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

STEP 3

NCDOT Two or Three Leg Signalization Mixed Movement Queue Length Charts

Version 1



STEP 3

These charts may be used in place of the single movement 95% queue length charts when the turning lane at the intersection of interest is used for both left and U turns.

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11 APPENDIX E – CHART APPLICATION EXAMPLE

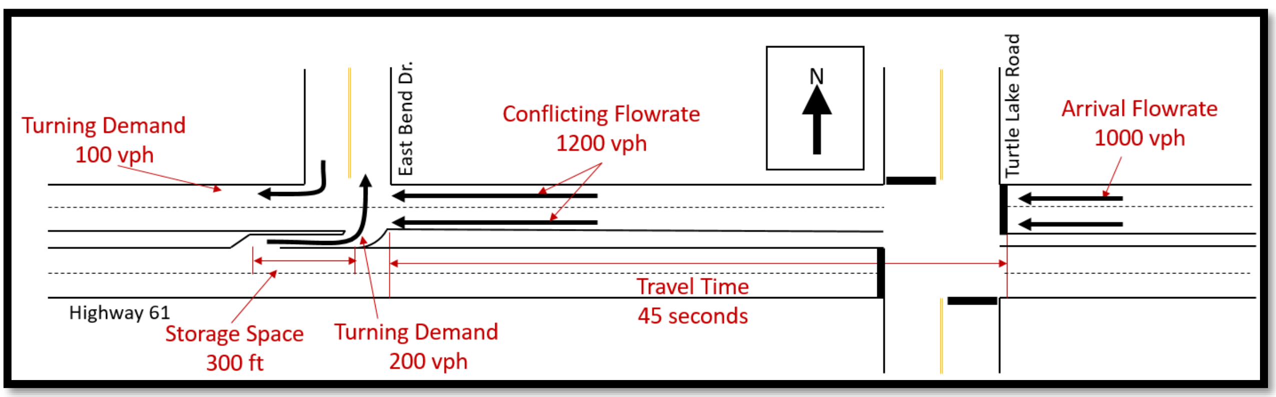
Site Description

An analyst is conducting an initial review for signalization need at East Bend Drive and Highway 61. The intersection layout is presented below. The speed limit on Highway 61 is 50 mph. The next signalized intersection to the west of East Bend Drive is 5 miles downstream.

During the peak hour, the right turn demand from East Bend Drive to Highway 61 is 100 vehicles per hour. The left turn demand from Highway 61 to East Bend Drive is 200 vph with a storage space of 300 feet. Highway 61 has a conflicting flowrate of 1,200 vehicles per hour.

Upstream of East Bend Drive, there is a 4 critical phase signalized intersection (cycle length = 100 seconds) at Turtle Lake Road. The travel time between the two intersections is 45 seconds. The westbound arrival flowrate is 1,000 vehicles per hour. It can be assumed all four critical phases are regularly served.

Note: The upstream arrival flowrate is 200 vehicles per hour less than the flowrate at East Bend Drive. This indicates 200 more vehicles per hour turn from Turtle Lake Road onto Highway 61 than turn from Highway 61 onto Turtle Lake Road.



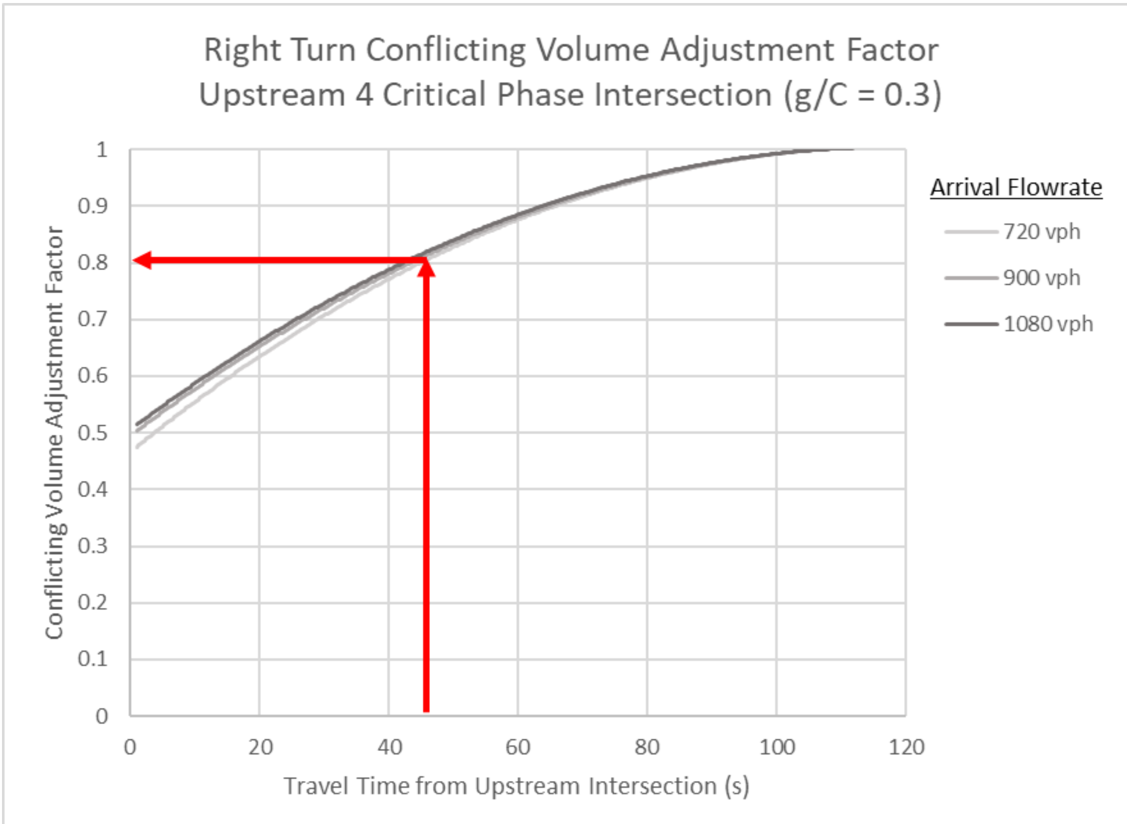
Assumptions

- ✓ The right turn and left turn of interest both occur from a single lane
- ✓ The upstream intersection cycle length is between 60s and 120 s
- ✓ All four critical phases are called regularly
- ✓ Two conflicting lanes of traffic
- ✓ A downstream queue is highly unlikely to spill back onto East Bend Drive.

Process

First, analyze the right turn from East Bend Drive to Highway 61.

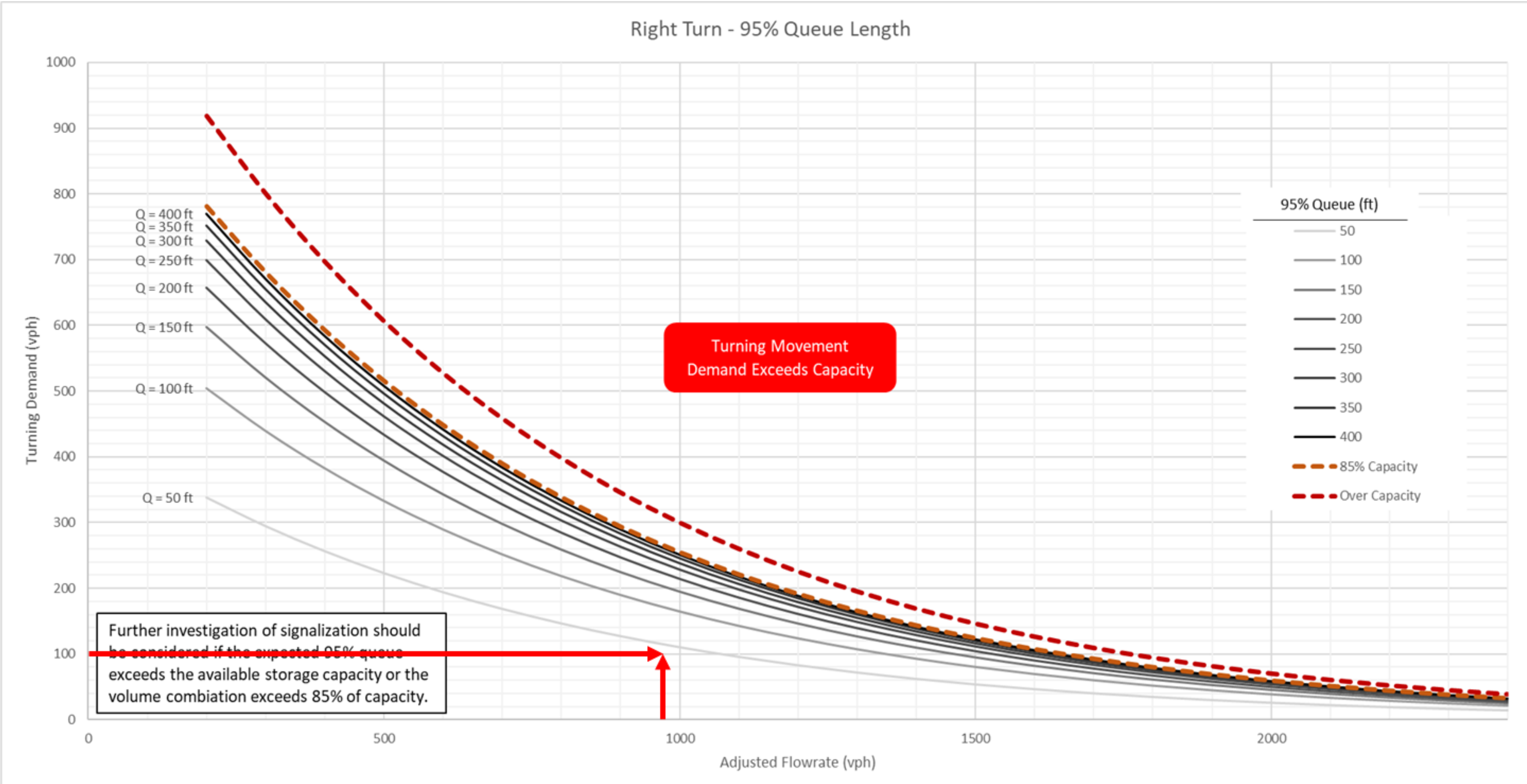
1. We'll use the Right Turn STEP 1 chart. Since the g/C ratio for the westbound movement is unknown, we will assume a default g/C = 0.3 as the signal has four critical phases. Using the right turn, 4 critical phase chart, we start at a travel time of 45 seconds and move upward until we reach the volume line for 1,000 vph, which is the flowrate at the upstream signal. Since the 1,000 vph value does not have a unique line, we interpolate between 900 vph and 1,080 vph. Then, we move to the left to find a CVAF of 0.8.



2. The CVAF (0.8) is then multiplied by 1,200 vph – the conflicting volume at East Bend Drive – to find the Adjusted Conflicting Volume:

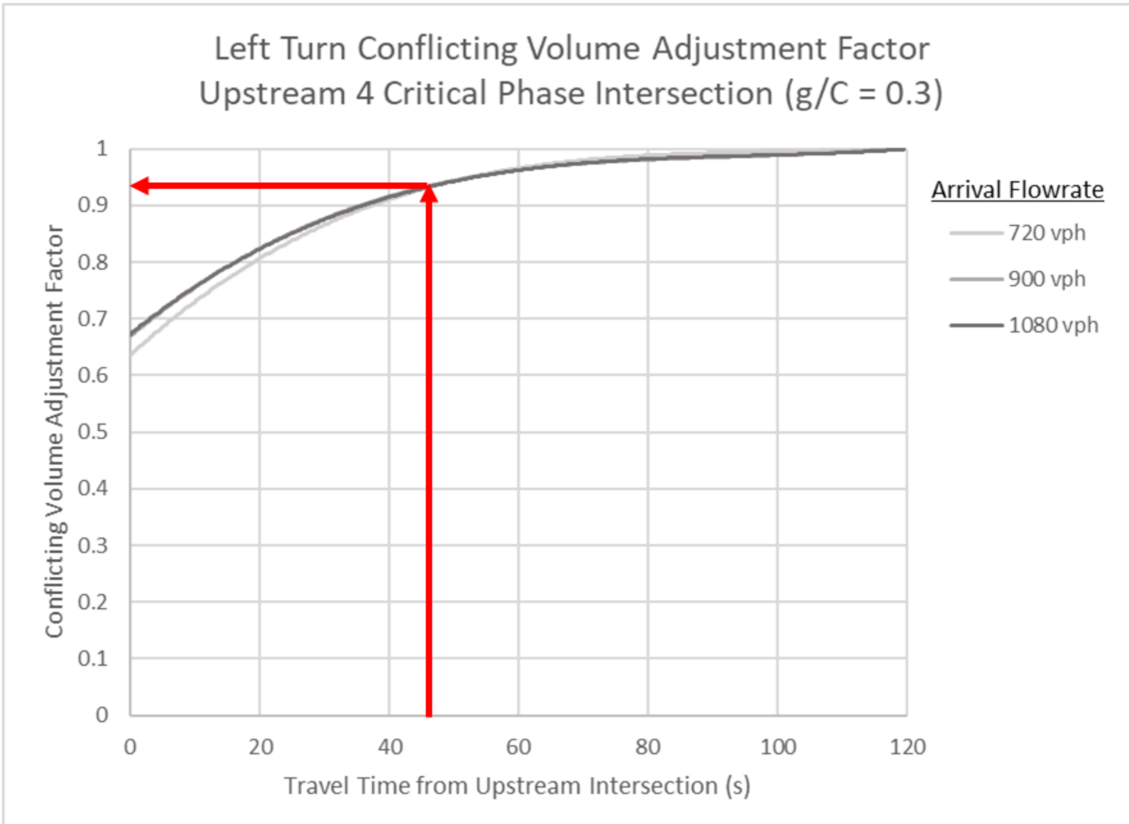
$$0.8 \times 1{,}200 \text{ vph} = 960 \text{ vph}$$

3. Using the Right Turn Step 3 Chart, we find the intersection of 960 vph along the x axis – the Adjusted Conflicting Volume – and 100 vph on the y axis – the right turn demand. The intersection is below the line representing a queue length of 50 feet. We can therefore expect the 95% queue length for the right turn under the given volumes to be less than 50 feet. Additionally, the movement operates well below the 85% capacity line.


Right Turn - 95% Queue Length
Turning Demand (vph)
Adjusted Flowrate (vph)
1000
900
800
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
Q = 400 ft
Q = 350 ft
Q = 300 ft
Q = 250 ft
Q = 200 ft
Q = 150 ft
Q = 100 ft
Q = 50 ft
Turning Movement Demand Exceeds Capacity
95% Queue (ft)
50
100
150
200
250
300
350
400
85% Capacity
Over Capacity
Further investigation of signalization should be considered if the expected 95% queue exceeds the available storage capacity or the volume combiation exceeds 85% of capacity.

Next, we analyze the left turn from Highway 61 to East Bend Drive.

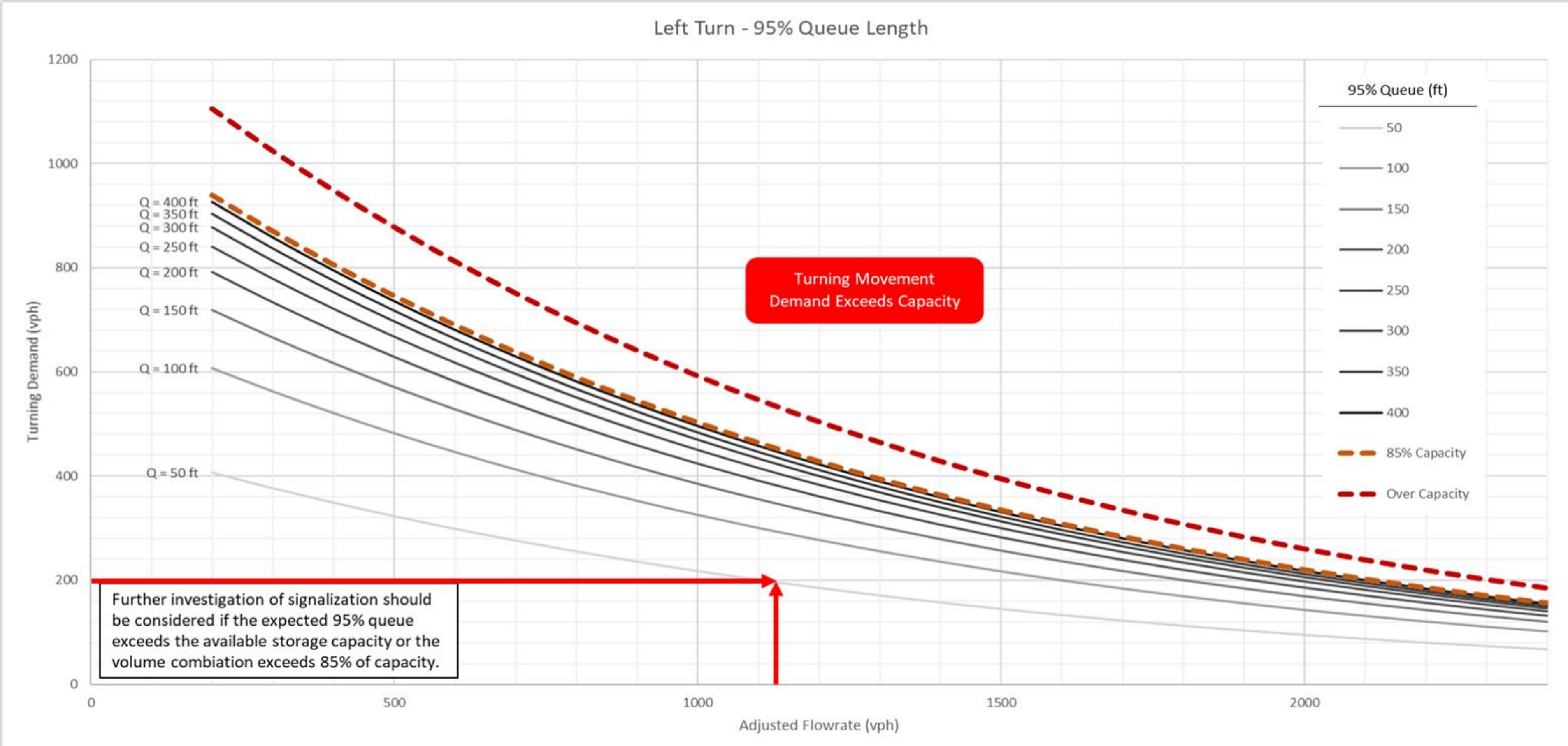
1. Use the Left Turn STEP 1 chart. Since the g/C ratio for the westbound movement is unknown, we will assume a default g/C = 0.3 as the signal has four critical phases. Using the left turn, 4 critical phase chart, we start at a travel time of 45 seconds and move upward until we reach the line for 1,000 vph – the flowrate at the upstream signal. In this case, 1,000 vph does not have a unique line, so we interpolate between the 900 vph and 1,080 vph lines. Then, we move to the left to find a CVAF of 0.93.



2. The CVAF (0.93) is then multiplied by 1,200 vph – the conflicting volume at East Bend Drive – to find the Adjusted Conflicting Volume:

   $$0.93 \times 1{,}200 \text{ vph} = 1{,}116 \text{ vph}$$

3. Using the Left Turn Step 3 Chart, we find the intersection of 1,116 vph along the x axis – the Adjusted Conflicting Volume – and 200 vph on the y axis – the left turn demand. The intersection is at the line representing a queue length of 50 feet. We can therefore expect the 95% queue length for the left turn under the given volumes to be 50 feet. Additionally, the movement operates well below the 85% capacity line.


Left Turn - 95% Queue Length
1200
1000
800
600
400
200
0
Turning Demand (vph)
0
500
1000
1500
2000
Adjusted Flowrate (vph)
Q = 400 ft
Q = 350 ft
Q = 300 ft
Q = 250 ft
Q = 200 ft
Q = 150 ft
Q = 100 ft
Q = 50 ft
Turning Movement Demand Exceeds Capacity
95% Queue (ft)
50
100
150
200
250
300
350
400
85% Capacity
Over Capacity
Further investigation of signalization should be considered if the expected 95% queue exceeds the available storage capacity or the volume combiation exceeds 85% of capacity.

<u>Analysis</u>

The expected 95% queue for the right turn is less than 50 feet. As the only movement allowed on that approach is the right turn, there is no limit on the storage space available. Further, the movement is not expected to exceed capacity.

The expected 95% queue for the left turn is 50 feet. With 300 feet of storage space, there should be sufficient space to handle the queue without installing a signal. The movement is not expected to exceed capacity.

<u>Result</u>

Since there is sufficient queue storage for both the right and left turn, neither movement is near or at capacity, and the queue lengths are not unreasonable, no further investigation of a signal is recommended unless the intersection meets one of MUTCD warrants 4 – 9.