



Guidance for Determination and Documentation of Left-Turn Phasing Mode

Version 1.0



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INTRODUCTION

Upon adoption of the 2009 Manual on Uniform Traffic Control Devices (MUTCD), VDOT Central Office – Traffic Engineering Division (CO-TED) received numerous inquiries regarding use of the newly-approved flashing yellow arrow signal indication which had recently been added to the MUTCD. Recognizing that the use of flashing yellow arrow was appropriate only after it was determined that permissive phasing mode was appropriate, CO-TED began to investigate how left-turn phasing decisions were made across VDOT as well as at other state DOTs. In 2013 CO-TED, working with their professional on-call consultant VHB, prepared two syntheses on left-turn phasing mode selection, one for existing state DOT and VDOT practices and another for existing literature recommendations. These syntheses are included as appendices to this document.

In late 2013, CO-TED hosted VDOT personnel representing multiple disciplines and regions for a workshop on statewide signal phasing practices. At the workshop, CO-TED presented the synthesis and literature review findings, and, through discussion and audience polling, solicited feedback about existing regional left-turn phasing practices. The workshop discussions highlighted significant regional variations in left-turn phasing selection, and affirmed a desire for greater consistency in left-turn phasing selection across the state. Workshop participants, while supporting greater consistency, also made clear their preference for flexibility in making left-turn phasing determinations; this led to a decision to develop statewide guidance as opposed to policy on left-turn phasing selection.

In 2014, VDOT convened a statewide committee to consider the findings of the synthesis documents, the statewide workshop recommendations, existing VDOT business needs, and VDOT's engineering expertise in developing statewide guidance on left-turn phasing mode selection. The Statewide Committee on Left-Turn Phase Selection, and its composite subcommittees, collaborated over the course of six months to establish and refine VDOT's position on left-turn phasing mode determination and documentation. The resulting products from that endeavor include clarification added to Traffic Engineering Division Memorandum 362.1 (TE-362.1 Signing and Sealing of Plans and Documents by Licensed PEs), the Left-Turn Signal Phasing Assessment Workbook, and this document.

The intent of this guidance is to provide a framework for evaluation of an array of factors that inform left-turn phasing mode selection, and a structure for documenting that assessment. This guidance is not meant to be prescriptive, but rather a means to equip traffic engineers in Virginia with the appropriate tools to make informed and thoughtful decisions on left-turn phasing mode selection and to document the factors and engineering judgment used to formulate the ultimate decision in a consistent manner.

CRITICAL EVALUATION QUESTIONS

At its core, the process of determining left-turn phasing mode can be reduced to two critical questions:

- 1) From a safety perspective, can permissive left-turn movements be allowed on an approach?
- 2) Should some level of left-turn protection (i.e., Protected/Permissive mode) be provided for efficiency reasons?

These questions should be considered in the order listed above. If the answer to the first question – whether permissive left-turn movements can be allowed – is “no,” then Protected Only mode should be considered and the second question becomes inconsequential. If the answer to the first question is “yes,” then the engineer should proceed to the second question in order to determine whether to select Protected/Permissive mode to efficiently process left-turn demand.

Certain factors presented in the guidance document address one or the other critical question. For example, sight distance addresses only the first critical question; if there is insufficient sight distance, then Protected Only mode should be considered. Critical crossing gap applies to the second critical question, as it is used to determine whether to select Protected/Permissive mode or Permissive Only mode. Other factors, such as pedestrian considerations, assist in answering both critical questions.

This guidance helps the traffic engineer answer these two questions through consideration of an array of factors that are examined in greater detail later in this document. Note that this guidance addresses determination of left-turn phasing mode, but does not address left-turn phasing sequence (see definition of sequence below).

DEFINITIONS

Left-Turn Phasing Mode – The assignment of right-of-way to left-turning vehicles (i.e., Protected Only, Permissive Only, Protected/Permissive).

Left-Turn Phasing Sequence – The order that the left-turn movements at an intersection are serviced within the signal cycle (i.e., lead-lead, lag-lag, or lead-lag).

Protected Only Mode – A mode of traffic control signal operation in which left turns can be made only when a left-turn GREEN ARROW signal indication is displayed.

Permissive Only Mode – A mode of traffic control signal operation in which left turns can be made on a CIRCULAR GREEN signal indication, a flashing left-turn YELLOW ARROW signal indication, or a flashing left-turn RED ARROW signal indication after yielding to pedestrians, if any, and/or opposing traffic, if any.

Protected/Permissive Mode – Both modes can occur on an approach during the same cycle.

Variable Mode – The operating mode changes between Protected Only mode, Protected/Permissive mode, and/or Permissive Only mode during different periods of the day, or as traffic conditions change.

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- Ms. Anne Booker, Southwest Region Operations (Vice Chair)
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GENERAL

1. Does VDOT have a statewide left-turn phasing mode selection policy?

No, VDOT does not have a statewide policy on left-turn phasing mode selection, and does not intend to establish such a policy.

Instead, this document is intended to serve as statewide guidance on left-turn phasing mode selection and documentation. This guidance is not meant to establish a prescriptive methodology for determination of left-turn phasing mode selection or documentation; as such, there are no “shall” statements. Rather, it is meant to provide a framework for consideration by the engineer when evaluating the myriad factors that influence left-turn mode selection and documenting for the record the engineering judgment that informed the ultimate decision.

At this time, VDOT does not have an established policy or guidance related to the determination of left-turn phasing sequence.

2. Why is statewide guidance needed for left-turn phasing mode selection?

Left turns represent perhaps the riskiest and most disruptive movements in the operation of a signalized intersection. As a result, safe and efficient left-turn operation is a critical component of any signalized intersection. Selection of left-turn phasing mode can have a significant impact on the safety, level of delay, and throughput of an intersection.

The 2013 workshop on signal phasing revealed that a lack of statewide left-turn phasing mode selection guidance had led to inconsistencies and regional variations in left-turn phasing mode decisions – and documentation of those decisions – around the state. CO-TED determined that statewide guidance was needed to establish a consistent approach to left-turn phasing mode selection, as well as consistent documentation that can serve as an historical record of phasing decisions. CO-TED intentionally did not pursue a statewide left-turn phasing mode selection policy based on overwhelming support from VDOT traffic engineers for guidance over policy.

This guidance document, developed in tandem with the Workbook, is intended to support completion of an engineering assessment for left-turn phasing mode selection.

3. What are the primary factors that should be considered in determining left-turn phasing mode?

The Statewide Committee on Left-Turn Phase Selection, through agency input and comprehensive literature and state of the practice reviews, investigated eight primary factors that most influence left-turn phasing mode selection.

Those eight factors are:

- Sight Distance and related characteristics
- Number of Left-turn Lanes and Intersection Geometry
- Crossing Distance / Number of Opposing Lanes
- Intersection and Receiving Facility Characteristics
- Critical Crossing Gap
- Correctable Left-Turn Crashes
- Pedestrian Considerations
- Corridor Consistency and Other Network Considerations

Guidance related to each of these factors is provided in the sections that follow. The Committee recognized that consideration of other, site-specific conditions may be necessary in making final left-turn phasing decision. This document is not designed to cover every possible scenario; engineering judgment is critical in applying this guidance in tandem with site-specific condition considerations.

4. Should one or more of the factors be weighted more heavily than the others?

In general, the eight primary factors should be considered both individually and collectively in determining left-turn phasing mode. However, for three factors – sight distance, number of left-turn lanes, and critical crossing gap – specific thresholds are identified in this guidance that, if exceeded, should trigger careful evaluation before implementing less restrictive left-turn phasing modes, independent of the other factors.

While all factors can and often will contribute to left-turn phasing mode selection, any one of these factors may have sufficient impact to justify the inclusion of left-turn protection or the allowance of permissive movements, rendering consideration of all other factors unnecessary.

5. Is left-turn phasing mode selection strictly a quantitative, objective process?

No, VDOT has determined that left-turn phasing mode selection should not be a solely threshold-based quantitative evaluation of measurable inputs. While this guidance may refer to discrete values and specific thresholds, engineering judgment plays a significant role in all left-turn phasing mode selection decisions.

By following the guidance in this document, engineers will be working within the same framework and with the same types of inputs and information; however, due to engineering judgment in the application of this guidance, it is entirely possible that two engineers can come up with different left-turn phasing mode selection decisions using the same set of inputs. The application of engineering judgment and documentation are expected and are critical to the utility of this statewide guidance.

6. How should decisions on left-turn phasing mode selection be documented?

Documentation should describe physical and operational conditions, the rationale behind the ultimate phasing decision, the extent to which engineering judgment is applied, and the conclusion of the assessment. More detailed documentation may be needed depending on an intersection's complexity. There is no minimum level of detail required for documentation. The documentation could be as simple as a few short sentences, or more elaborate as necessary to fully describe the situation, the engineer's findings, and final conclusions. Figures, plan mark-ups and/or field notes are effective methods to document many decisions. The Workbook developed by VDOT TED is sufficient to meet the intent of sealing and signing left-turn phasing decisions as required by TE-362.1.

If one or more factors clearly supports selection of Protected Only phasing, as addressed in Item 4, full documentation for consideration of other factors is not required but may be appropriate to more clearly define the context of the situation. Documentation of the rationale and variables used in considering left-turn phasing is a valuable tool for future review of phasing mode decisions.

7. How should speed factor in determining left-turn phasing mode?

While common practice in other states is to suggest or prescribe Protected Only phasing in locations where the opposing speed limit exceeds a certain threshold – most often 45 mph – VDOT has chosen not to establish any criteria for considering opposing speed as a standalone factor. Speed is a component of the assessment of sight distance, crossing distance, and critical crossing gaps.

8. Can two opposing approaches have different left-turn phasing modes?

Historically, it has been common – but not exclusive – practice in Virginia to apply the same left-turn phasing mode to opposing directions of an intersection in the spirit of driver expectancy. This practice is no longer supported as decisions on left-turn mode should be made on an approach-by-approach basis, and should be based on site-specific conditions for a particular approach. That may in some cases result in the selection of different left-turn modes for opposing approaches. When implementing differing left-turn phasing modes, the engineer should ensure that a yellow trap condition cannot occur within the potential phase sequences.

9. When are left-turn phasing mode decisions made?

Consideration of left-turn phasing mode can occur at numerous points in project development, and this guidance document may be used to evaluate left-turn phasing at any point in the process. However, this guidance document is primarily intended to be used to guide and support left-turn phasing mode decisions made during the

preparation of signal design plans or changes to signal timing plans that include changes to phasing.

10. What else can influence left-turn phasing mode determinations?

Implementation of and changes to left-turn phasing modes can have significant impacts on the effectiveness and efficiency of the overall signal operations, and thus should be done in conjunction with a comprehensive analysis that also examines other operational and safety improvements. Left-turn phasing mode is one tool available to traffic engineers to balance safety and operational efficiency at an intersection. Before reaching a conclusion on a restrictive left-turn phasing mode(s), an engineer should consider other measures that may mitigate safety or operational concerns, as often those concerns can be addressed through means other than left-turn phasing mode.

It should also be noted that, before an intersection is signalized, all of its left turns are by necessity permissive. If the left turns on an approach are operating safely and efficiently while unsignalized, strong consideration should be given to allowing permissive left-turn movements on that approach once the intersection becomes signalized.

11. How can dynamic conditions influence left-turn phasing mode determinations?

The engineer should consider how the answers to the two Critical Questions may vary by hour, day, or season. Several factors that influence left-turn phasing mode selection may be dynamic depending on ambient conditions and/or traffic demand. For example, traffic volumes can fluctuate significantly over the course of the day. The engineer may consider time-of-day left-turn phasing mode in situations in which one or more factors exhibit such fluctuations throughout the day.

SIGHT DISTANCE

12. How does intersection sight distance impact left-turn phasing mode selection?

Adequate intersection sight distance is critical to ensure that a left-turning driver has an unobstructed view of oncoming traffic and can determine if there is a sufficient gap to complete a permissive left-turn movement. Permissive left-turn phasing should not be used if the sight distance is not adequate.

Sight distance to opposing traffic includes conflicting pedestrian movements. If pedestrians can reasonably be expected to cross the receiving lanes, drivers executing a permissive left-turn movement must have an adequate view of the spot where the pedestrians will be waiting and/or crossing the left-turn.

12a. How and from what location in the intersection should sight distance be measured?

The intersection sight distance measurement procedure is prescribed in AASHTO's "A Policy on Geometric Design of Highways and Streets" (more commonly referred to as the "Green Book") section on sight distance for left-turning vehicles, Case F.

Instead of using design speed as directed by AASHTO, engineers should use the 85th percentile approach speed if collected speed data is available, or the posted speed limit plus 7 mph if speed data is not available. These values are based upon previous research conducted at signalized intersections and are used as the default in other VDOT traffic analyses. For newly constructed roadways or roadways without posted speeds, the design speed or a speed determined based on engineering judgment may be used. The Green Book formula inputs for passenger vehicles should be used, unless there is a specific reason to use another design vehicle.

Sight distance should always be measured in accordance with AASHTO's methodology (i.e., from the driver's eye perspective from a vehicle positioned at the stop bar). It is recognized that drivers may make left-turn decisions at other location(s) within the intersection; therefore, the measurement may also be recorded from a location where a driver will wait to make a left turn. Based upon driver behavior, an alternate measuring location may be considered to reflect where drivers actually wait to make a left-turning decision.

If an intersection has not yet been constructed, design plans (plan view and profile) may be used to estimate the intersection sight distance; however, for existing intersections, field measurements should be used.

12b. What are the thresholds for sight distance that would trigger consideration of Protected Only mode?

The intersection sight distance value should be calculated from the Green Book formula to ensure that adjustments for grade and additional lane crossings are taken into consideration – the table values should not be used.

In general if the calculated intersection sight distance value is not met, Protected Only phasing should be used for the left-turn movement. If the minimum sight distance requirement is met, then other factors should be examined to determine the most appropriate left-turn phasing for the approach. See Item 12e for guidance on situations in which measured sight distance is marginally less than the AASHTO sight distance requirement.

12c. Should opposing left-turning vehicles be considered in determining sight distance?

Opposing left-turning vehicles may obstruct sight distance of oncoming vehicles. Whether or not this condition will occur depends on the geometry of the left-turn lanes, the median width, the location where drivers make left-turn decisions and queue lengths (which can vary throughout the day/week/year). Engineers making field observations should recognize and consider that opposing left-turning vehicles may or may not be present at the time the intersection is being studied; it may be appropriate to make several measurements at different times. Additionally, special attention should be given to measuring from the location where drivers make the left-turn decision as sight distance may be obstructed at the stop line, but not at this location.

Engineering judgment should determine if the opposing left-turning vehicles present a sight distance obstruction that will affect permissive left-turning movements based on their prevalence during normal operation. If the engineer determines that the opposing left-turning vehicles are a consistent sight distance obstruction and the resulting sight distance is below the Green Book value, then Protected Only mode may be appropriate. Alternatively, Protected/Permissive mode may be appropriate so that vehicles may turn during the permissive portion of the cycle if sight distance is not obstructed or wait for the protected portion of the cycle.

Time-of-day phasing may be considered at locations where the sight distance obstruction is typically present only during a well-defined period.

12d. What conditions related to sight distance contribute to the ability of a left-turning driver to make a decision to turn under permissive left-turn operations?

Even when intersection sight distance is adequate, several other physical and environmental conditions can impact visibility or perception of oncoming vehicles. Beyond evaluating intersection sight distance, consideration of these conditions may be appropriate based on engineering judgment and the specifics of the approach being assessed. This list is not exhaustive, but is based on the Committee's varying experiences.

These conditions include, but are not limited to:

- horizontal curvature of the opposing approach that can detract from perception of an oncoming vehicle's location;
- vegetation which may differ throughout the year;
- speed differential or uneven flow in opposing traffic;
- glare, shadows, and lighting that may vary throughout the year and visually obscure an oncoming vehicle;
- background contrast or clutter that may visually obscure an oncoming vehicle;
- traffic signal head placement such that the left-turning driver cannot see the signal head from the left-turn decision point; and
- other unique field conditions that may impact or influence a driver's decision to make a permissive left turn.

12e. If it is determined that sight distance does not meet AASHTO requirements, does that mean permissive left turns absolutely cannot be allowed on that approach?

There may be some instances when engineering judgment determines that there are mitigating factors or critical operational impacts that allow permissive left-turn movements despite conditions where intersection sight distance is less than the AASHTO value. These instances should be rare and the engineer should carefully document the reasons why permissive phasing is acceptable.

12f. Other than prohibiting permissive left turns, what measures can be considered if there is insufficient intersection sight distance on an approach?

Consideration should be given to removing or relocating an obstruction if doing so improves intersection sight distance and would facilitate a less restrictive phasing. This may be an alternative to instituting a more restrictive phasing. Other measures include implementing offset left-turn lanes, landscaping or grading, vehicle-detector-based intelligent transportation systems devices, or time-of-day phasing.

TURN LANES AND INTERSECTION GEOMETRY

13. How should the number of left-turn lanes be considered in left-turn phasing mode selection?

Most state and local agencies are willing to consider permissive mode left turns on approaches with a single left-turn lane, and restrict left turns on approaches with two or more exclusive turn lanes to Protected Only phasing; however, no specific language restricting phasing according to the number of left-turn lanes has been identified in the Manual on Uniform Traffic Control Devices (MUTCD) or AASHTO's Green Book. There are several examples of localities throughout the country that consider permissive mode left-turns from dual left-turn lanes.

13a. Should permissive left turns be considered on approaches with dual left-turn lanes?

Considering permissive left-turns from dual left-turn lanes is atypical, but is not explicitly prohibited. Protected Only mode should be considered for approaches with dual turn lanes; however, Protected/Permissive mode phasing may be considered if complementary measures such as offset left-turn lanes or flashing yellow arrow displays are in place. Flashing yellow arrow signal heads allow for effective implementation of time-of-day plans that would allow for Protected/Permissive or Permissive phasing during the off-peak or overnight hours when the volumes would suggest permissive phasing.

Recognizing that permissive left-turns from dual left-turn lanes is a significant change in VDOT practice, VDOT Traffic Engineering Division should be notified before implementation of permissive phasing on approaches with more than one exclusive left-turn lane.

Permissive left-turns should not be considered for approaches with three or more left-turn lanes.

13b. What is the recommended left-turn phasing for intersections where the intersection geometry does not accommodate concurrent opposing left turns?

For intersections where the geometry is such that there are overlapping opposing left-turn radii, the opposing left-turn movements should not run concurrently. An alternative left-turn phasing sequence should be considered so that the two opposing left-turns do not operate concurrently in such cases, regardless of mode.

CROSSING DISTANCE / OPPOSING LANES

14. How should crossing distance be considered in left-turn phasing mode selection?

Crossing distance is an attempt to assign a value to the driver's ability to determine if he or she will be able to correctly judge the amount of time it will take to clear the intersection. The number of opposing lanes is often used as a proxy for crossing distance. Crossing distance can also be represented by an actual measured value, *W*.

14a. Is it preferable to consider the number of opposing lanes and/or intersection width (*W*) in determining left-turn phasing mode?

Engineers may consider either the number of opposing lanes or a *W* value in left-turn phasing mode selection. The number of opposing lanes is a good indicator of the general complexity of the intersection. *W* incorporates elements such as median width and stop bar placement, and captures travel time considerations (start-up, acceleration, speed). Both of these values are useful for informing decisions on left-turn phasing.

14a-(1) What thresholds for number of opposing lanes should trigger consideration of Protected Only mode?

The presence of three or more opposing lanes should prompt consideration of Protected Only mode; however, this factor alone should not be the sole determining factor in left-turn phasing mode selection.

14a-(2) Should an opposing right-turn lane be included in the number of opposing lanes?

Generally, right-turn lanes should be included in the number of opposing lanes if the right turns operate under signal control and conflict with the subject left turns when entering the receiving lanes. This is consistent with the calculation of intersection width (*W*), which measures distance to the edge of the farthest travel lane. Engineering judgment may lead the engineer to exclude the right-turn lane from the number of opposing lanes.

14a-(3) How should the *W* value be calculated?

Refer to TE-306.1 (Yellow Change Intervals and Red Clearance Intervals) and the FAQ for TE-306.1.

14a-(4) What thresholds or ranges of values for W should trigger consideration of Protected Only mode?

Engineers should consider Protected Only mode for intersection travel path widths exceeding 150 feet ($W > 150$). This threshold was derived from AASHTO's crossing maneuver equations. Consideration of intersection width (W) will entail some level of engineering judgment and should be documented in detail accordingly.

14b. Other than limiting or prohibiting permissive left-turns, what measures can be considered to reduce crossing distance?

Engineers may consider offsetting left-turn lanes, moving the stop bar forward, or providing a separated receiving lane for opposing right turns in order to reduce the distance needed for left-turn movements to clear the intersection, among other geometric considerations. Any such alterations to the intersection should be appropriately evaluated for other safety and operational impacts beyond reduction of crossing distance.

INTERSECTION AND RECEIVING FACILITY CHARACTERISTICS

15. How should the intersection and receiving facility characteristics be considered in left-turn phasing mode selection?

The left-turning vehicle should maintain ideal turning speed in reaching and then entering a receiving lane(s). Geometric characteristics within the intersection or in the receiving lane(s) can cause the turning maneuver to be made at less than ideal speeds. Such conditions are qualitative measures that can be best approximated by evaluating a number of characteristics of the left-turn path and the subsequent functional area of the receiving lanes:

- number of receiving lanes;
- width of receiving lane(s) (refer to the VDOT Road Design Manual);
- vertical elevation differences between the left-turn lane and receiving lane;
- presence of an apron, valley gutter or other non-contiguous pavement through the turning movement;
- surface condition of the receiving lane(s);
- proximity of guardrail or other roadside objects to the receiving lane(s);
- internal configuration of a parking lot or parcel to which the left-turning vehicle is destined; and
- other access management issues in close proximity to the intersection.

Generally, as these receiving facility characteristics present themselves, consideration of left-turn protection should increase. Consideration of some of these characteristics may be subjective and can be anecdotal as opposed to an exact quantified measure of speed differential. Engineering judgment will play a critical role in consideration of this factor, and should be documented appropriately and in detail.

CRITICAL CROSSING GAPS

16. How should traffic volumes be considered in left-turn phasing mode selection?

Left-turning vehicles require adequate gaps in opposing traffic in order to safely clear an intersection. A gap analysis measures the availability of gaps of a sufficient size (time) for left-turning vehicles to clear the intersection with a prescribed level of comfort. The ITE Manual of Traffic Studies provides additional detail on the procedures for a gap analysis. Other cost effective volume-based measures – specifically volume cross-product – serve as a proxy for a formal gap analysis using more readily available data.

The volume cross-product equals the left-turn hourly volume multiplied by the opposing through movement hourly volume divided by the number of opposing through lanes (note that the engineer may elect to include right turn lane(s) in the calculation of number of opposing through lanes). The higher the cross-product, the fewer the available gaps and the greater the need for left-turn protection. Generally, the cross product is evaluated for the peak hours; however, when count data is available for other times of the day/week, those times should also be evaluated, as traffic volumes can fluctuate significantly over time, which may lead to differing phasing modes being used throughout the day or week.

If field observations suggest that the cross-product analysis is not representative of actual conditions, a formal gap analysis may be considered to support left-turn phasing mode determination.

16a. What threshold or range of values for traffic volumes should trigger consideration of Protected/Permissive mode?

If the cross-product is greater than 50,000 for any evaluated hour, the engineer should consider Protected/Permissive mode phasing.

16b. What threshold or range of values for traffic volumes should trigger consideration of Protected Only mode?

There is no volume cross-product threshold, or other volume-based threshold, that would trigger consideration for Protected Only phasing. Even in cases when a relatively high cross-product indicates that there are insufficient gaps for left-turning vehicles, it may be desirable to allow for permissive left turns, especially in saturated conditions, so that a few vehicles may take advantage of any gaps that present themselves.

CORRECTABLE LEFT-TURN CRASHES

17. In what way(s) can crash history impact left-turn phasing mode selection?

The crash history should be examined to determine the extent of correctable left-turn crashes occurring at the subject intersection. A correctable left-turn crash is a crash that involves left-turning vehicles that can be corrected by adjusting the left-turn phasing or through some other mitigation. For example, an angle crash where a left-turning vehicle struck an oncoming vehicle is likely a correctable left-turn crash as this crash would be less likely to have occurred under protected left-turn phasing. A vehicle that crosses the centerline near the intersection due to a medical emergency is just one example of a non-correctable crash. Crash reports should be reviewed to isolate the correctable left-turn crashes from non-correctable.

In many cases, the relationship of correctable left-turn crashes to left-turn phasing mode determination is a matter of relativism as opposed to absolutism – the crash experience at the subject intersection compared to intersections in the vicinity or regionally with similar characteristics. A large discrepancy in correctable left-turn crash frequency or rate compared to other similar nearby intersections may suggest the use of Protected Only mode as a possible mitigation measure; however, this is not the only mitigation measure that can be implemented to address crash concerns.

17a. Are there specific numerical values that should trigger consideration of Protected Only mode?

While there is not a specific threshold for correctable left-turn crashes that would trigger consideration of Protected Only mode, analysis of VDOT intersections has shown generally that an approach with 3 to 5 correctable left-turn crashes per year may prompt a review of permissive left-turns. Approaches with crash experience that falls within or above this range may be considered for Protected Only mode. This range may vary based on localized conditions, traffic volumes, and other factors.

The ideal metric for establishing a threshold for Protected Only left-turn phasing would be derived through the development of a statistical model to identify features that are statistically significant to causation (perhaps on a regional basis). A predictive analysis (e.g., Empirical Bayes) could then be used to compare an intersection's actual crash experience to the predicted crashes based upon the statistically significant inputs for that intersection. This method is data and labor intensive and not necessarily cost-effective or practical on a case-by-case basis. VDOT is engaged in ongoing processes to perform statistical analysis which in turn may provide in the future a series of threshold values that can be used as a starting point for assessment of correctable left-turn crashes relative to left-turn phasing.

Alternatively, crash rates may be used as a relatively decent proxy, since AADT has been shown to be one of the few significant factors in predicting left-turn crashes. These values would be based upon the entering AADT of the intersection to account for exposure.

In addition to the traffic volume influencing the number of crashes, driver behavior can vary significantly from one region of the Commonwealth to another, and can even vary within different portions of the same region. In addition, some other conditions, such as approach speed and number of lanes to be crossed, or other less-tangible conditions like driver distractions, can introduce significant variation into the number of crashes occurring at a particular location. Therefore what may seem on the surface to be a significant correctable left-turn crash problem at one location if evaluated in isolation may not be when compared to other similar locations.

If the phasing for an intersection with Protected Only left-turn phasing is being evaluated, or if a newly constructed intersection is being evaluated, the crash history at similar nearby intersections with permissive left turns (or no signalization) may be examined as a surrogate. Highway Safety Manual (HSM) or other predictive models may also be used to anticipate the probability of left-turn crashes occurring at a future planned intersection.

17b. Other than limiting or prohibiting permissive left turns, what countermeasures can be considered if there is a pattern of correctable left-turn crashes at an intersection?

Engineers may want to consider other safety countermeasures instead of removing permissive phasing on approaches with a pattern of correctable left-turn crashes. The Highway Safety Manual and the FHWA CMF Clearinghouse are two prominent references that describe various countermeasures and their effectiveness (in terms of their potential to reduce crash frequency, defined as the crash modification factor).

PEDESTRIAN CONSIDERATIONS

18. In what way(s) can the level of pedestrian activity at an intersection impact left-turn phasing mode selection?

The engineer should observe pedestrian activity when performing traffic counts and when making field observations and should also consider the presence of nearby pedestrian generators such as schools or bus stops when assessing the interaction between pedestrians and left-turning vehicles. Where pedestrian volumes are high across the receiving lanes, the engineer may consider reducing conflicts by using Protected Only mode.

18a. Is there a specific threshold or range of values for pedestrian volumes that would trigger consideration of Protected/Permissive or Protected Only mode?

No, there is not a specific pedestrian volume threshold or range of values that would trigger consideration of Protected/Permissive or Protected Only left-turn phasing. Engineering judgment should be applied to determine if the level of observed or anticipated pedestrian activity as well as the pedestrian operational characteristics is significant enough to present conflicts with left-turning vehicles that would prompt consideration of Protected Only mode.

18b. Other than limiting or prohibiting permissive left turns, what measures can be considered if there are significant pedestrian volumes at an intersection?

Some alternative measures include providing leading pedestrian intervals or providing time-of-day restrictions on the left-turn movement. These strategies would allow pedestrians to get a head start when crossing and reduce conflicts between left-turning vehicles and pedestrians.

Another mitigation measure that has been used in Virginia is the use of dynamic signal phasing accommodated by flashing yellow arrow signal heads. When a pedestrian phase is activated via the pushbutton, the conflicting left-turn movement is operated under Protected Only phasing; but otherwise, the approach operates under Protected/Permissive or Permissive Only phasing. This can only be achieved through the use of appropriate traffic signal heads to be able to display both modes on the same signal head in accordance with the MUTCD.

CORRIDOR CONSISTENCY AND OTHER NETWORK CONSIDERATIONS

19. To what extent should operations be considered in left-turn phasing mode selection?

In some cases, it may be necessary to consider the needs of the overall corridor rather than considering an intersection in isolation. If one intersection's left-turn phasing may cause a detrimental effect to an entire corridor, engineering judgment may determine that the phasing should be examined from a corridor perspective. The objective of the engineer is to balance safety with operational efficiency. Some circumstances may necessitate concessions to one at the expense of the other.

The impact of spillback of left-turn queues and signal timing on the operation of the corridor should be considered as part of the phase selection. These considerations should be based upon field observations or validated microsimulation models that have been calibrated according to the characteristics of the corridor. Left-turn phasing is but one tool to achieve balance between safety and operations at an intersection. To maintain that balance, allowing permissive left turns may be the most appropriate decision despite other factors suggesting a more restrictive mode. The Workbook provides a means to document the engineering judgment that supports the decision for Protected/Permissive or Permissive Only phasing based upon a holistic approach to mode selection.

20. Should left-turn phasing mode be consistent along a corridor?

Consistency in left-turn phasing has two facets: the type of left-turn phasing selected and the traffic control devices (signs and traffic signals) used to implement the phasing. While it is important to maintain some consistency in order to avoid violating driver's expectations, consistency should not typically override the appropriate use of engineering judgment and evaluation of the unique characteristics at each site. However, there may be some areas where consistency in phasing selection is appropriate for access management.

CLOSING

There is no set prescriptive process that an engineer should use to select the left-turn mode for an intersection, as no two intersections are identical. The site conditions at any given location must be evaluated on a case-by-case basis by the engineer. The factors that are important for the left-turn phasing mode selection at one intersection may not be as significant at another intersection. Therefore, the engineer will need to decide the relative importance of each factor during the evaluation process.

Each of the factors addressed in this guidance document should be investigated independently to determine each factor's impact on the safety and operations of the intersection. Since sight distance and critical crossing gap have specific thresholds that should trigger strong consideration of left-turn protection, these two factors should be evaluated first. If the outcome of those two evaluations do not point to a clear left-turn phasing mode decision, then all of the factors should be examined collectively in determining mode. The engineer will need to qualitatively evaluate the relative importance of each factor at a specific location based on the available data.

APPENDIX A:
LEFT-TURN PHASING SELECTION GUIDANCE
LITERATURE REVIEW

November 2012

**** Revised August 2013 ****

Prepared for:



Prepared by:



Vanasse Hangen Brustlin, Inc.

INTRODUCTION

Left turns represent perhaps the riskiest and most disruptive movements in the operation of a signalized intersection. As a result, safe and efficient left-turn operation is a critical component of any signalized intersection. Selection of left-turn phasing can have a significant impact on the safety, level of delay, and throughput of an intersection.

The selection of left-turn phasing entails two primary steps: 1) the selection of the left-turn phasing mode (i.e., protected, permissive, protected/permissive); and 2) if separate left-turn phasing is selected, the selection of the left-turn phasing sequence (i.e., lead-lead, lag-lag, lead-lag). These steps are generally carried out discretely, with the selection of mode preceding the selection of sequence. The vast majority of the existing literature reflects the discrete nature of left-turn phasing selection, as papers tend to address either mode selection or sequence selection, but not both. With that in mind, this literature review divides the evaluation of existing literature into two sections: the literature that covers left-turn phasing mode and the literature that covers left-turn phasing sequence.

This literature review represents the first piece of an effort to develop a policy and/or guidance document on the selection of left-turn phasing at signalized intersections in Virginia. VHB examined literature dating back to 1989, with a focus on literature since 2002.

LEFT-TURN PHASING MODE

(Note that, for the purposes of this literature review, “mode” refers to the use of protected-only left turns, permissive-only left turns, and protected/permissive left turns.)

NCHRP’s *Left Turn Treatments at Intersections* (Pline 1996) provides representative examples of traffic volume related criteria used by state departments of transportation to justify separate left-turn phasing:

- The product of left-turning vehicles and conflicting through vehicles during the peak hour is greater than 100,000.
- Left-turn volumes greater than 100 vehicles during the peak hour.
- Left-turn peak period volumes greater than two vehicles per cycle per approach still waiting at the end of green (for pre-timed signals).

Several authors noted that the selection of the appropriate left-turn phasing mode is a process that often entails tradeoffs between safety and delays; in general, protected left turns provide a greater degree of safety, but often at the cost of efficiency in the form of reduced throughput and increased delay (Stamatiadis et al. 1997). Chen, Chen and Ewing (2012) found that protected-only mode significantly

reduces left-turn crashes due to reduced conflicts with opposing vehicles; however, the reduction in left-turn crashes may be offset in part by the possible increase in overtaking and rear-end crashes.

Protected/permissive mode is widely considered the most efficient left-turn mode, as it reduces conflicts between left-turning vehicles and opposing vehicles while providing an opportunity for the left-turn bay to clear and for further throughput during the permissive portion of the phase (Qi, Yu and Yu 2010). However, with increased opposing volume, the benefits of protected/permissive mode – namely efficiency – are reduced as drivers have more difficulty finding acceptable gaps to make permissive left turns. Protected/permissive mode also may not be safe to implement under other conditions, including high speed or limited sight distance (Qi, Yu and Yu 2010).

While the literature focuses most closely on safety and efficiency – and the tradeoffs between the two – there is considerable attention paid to an array of other factors to be included in mode selection. Following are factors most cited as critical to the mode selection process (Ozmen et al. 2009; Qi, Yu and Yu 2010):

- Volume
 - Left-turn volume
 - Opposing through volume
 - Volume Cross Product (VCP)
- Crash Experience
 - Left-turn crashes – single approach
 - Left-turn crashes – opposite approaches
 - Left-turn conflicts
- Intersection Geometry
 - Sight distance
 - Number of opposing through lanes
 - Number of left-turn lanes
- Speed
 - Opposing through speed

Yu et al. (2008) not only identified factors considered in the mode selection process, but assigned a score to each factor based on survey responses from state and local DOTs (Table 1).

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Table 1: Factors' Rank in Determination of Left-turn Phasing Mode (Yu et al. 2008)

Parameter	Score
Number of Left-turn Lanes	4.50
Historical Rate of Left-turn Crashes	4.47
Sight Distance	4.33
Left-turn Traffic Volume	4.31
Intersection Alignment	4.03
Opposing Traffic Volume	3.97
Intersection Congestion Level (V/C Ratio)	3.97
Number of Opposing Lanes	3.83
Posted Speed Limit	3.78
Historical Rate of Total Crashes at Intersection	3.61
Median Width	3.56
Left-turn Storage Length	3.47
Left-turn Delay	3.47
Intersection Delay	3.47
Driver Acceptance	3.44
Platoon Progression and Bandwidth	3.42
Percent of Heavy Vehicles	2.97
Number of Failed Cycles	2.57
Pedestrian and/or Bicycle Crossings	2.19

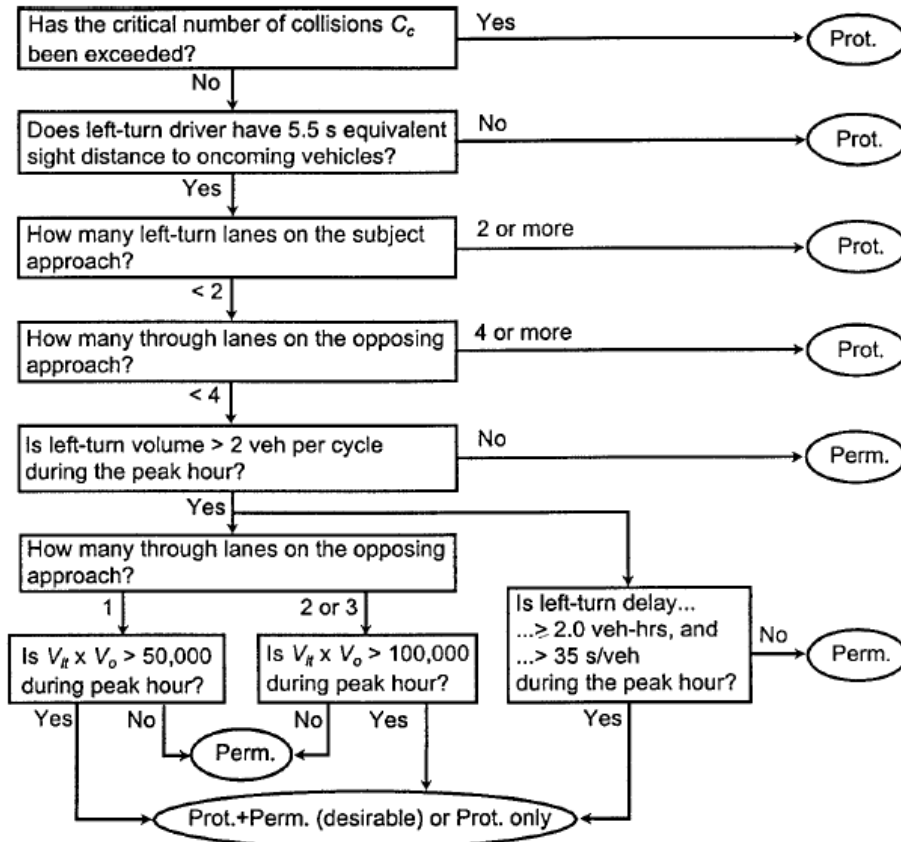
In the absence of uniform guidance on the selection of left-turn phasing mode, multiple papers included guidelines for consideration in mode selection, and used flowcharts to demonstrate the decision process for selecting mode. Bonneson and Fontaine (2001) created a flowchart that entails a relatively

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straightforward approach, with safety-related factors taking precedence over volume and geometry (Figure 1).

Figure 1: Bonneson and Fontaine (2001) Guidelines for Selection of Left Turn Phasing Mode



Critical Number of Collisions C_c

On one approach, $C_c = 4$ left-turn collisions per 1 year or 6 left-turn collisions per 2 years.

On both approaches, $C_c = 6$ left-turn collisions per 1 year or 10 left-turn collisions per 2 years.

Variables

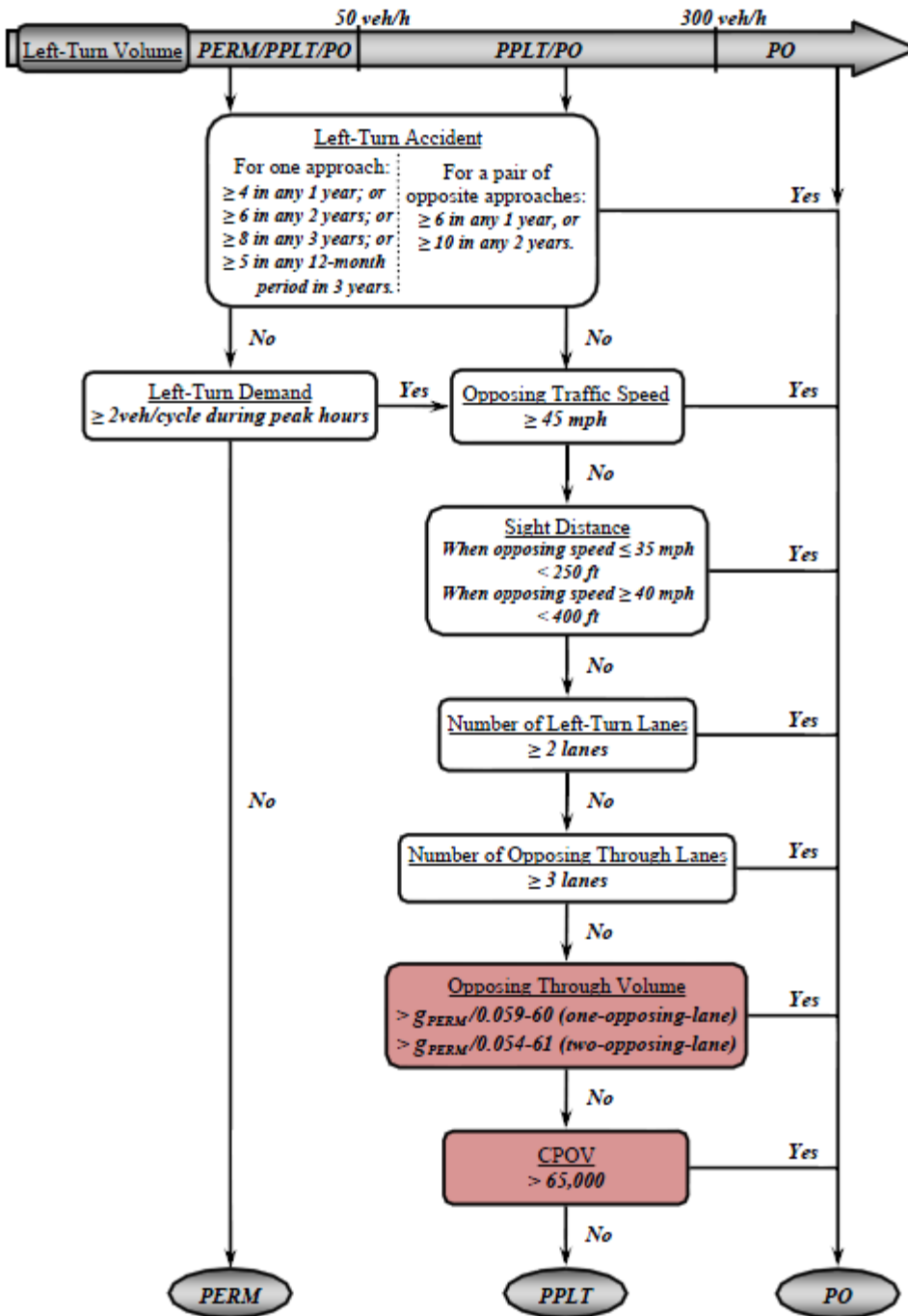
V_{lt} = left-turn volume on the subject approach, veh/h

V_o = through plus right-turn volume opposing the subject left-turn movement, veh/h

Qi, Yu and Yu (2010) also developed criteria for mode selection, although they use traffic volume as the guiding criteria, followed by safety related factors including crash history and opposing traffic speed (Figure 2).

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Figure 2: Qi, Yu and Yu (2010) Guidelines for Selection of Left Turn Phasing Mode



NCHRP's *Left Turn Treatments at Intersections* (Pline 1996) includes detailed guidelines for selection of protected-only phasing:

- Use protected-only phasing when any two of the following conditions are met:
 - Peak 15-minute flow rate for the left-turning traffic is greater than 320 vph
 - Peak 15-minute flow rate for the opposing traffic is greater than 1100 vph
 - Opposing traffic speed limit is greater than or equal to 45 mph
 - Two or more left-turn lanes.
- Use protected-only phasing when any one of the following conditions is met:
 - Where four or more lanes must be crossed by the left-turn movement
 - Three opposing traffic lanes and the opposing speed is 45 mph or greater
 - Left-turn volume exceeds 320 vph and the percent of heavy vehicles exceeds 2.5
 - Opposing volume exceeds 1,100 vph and the percent of heavy left-turn vehicles in the left-turn traffic exceeds 2.5
 - Seven or more left-turn related accidents within 3 years for protected/permissive option
 - More than 260 left-turn related conflicts per million vehicles squared for protected/permissive option
 - The average stopped delay to left-turning traffic is acceptable for protected-only phasing and it is the engineering judgment that more left-turn accidents would occur under the protected/permissive option.

Several authors sought to highlight the shortcomings of existing guidelines for selecting mode. Ozmen et al. (2009) were critical of the use of flowcharts in mode selection, suggesting that flowcharts can lead to an imbalanced decision process by allowing a single variable to dominate. Stamiadis et al. (1997) echoed that sentiment, stressing that the use of a single criteria is rarely adequate to determine the appropriate mode. Qi, Yu and Yu (2010) pointed out that existing criteria use constant thresholds for traffic volume, which cannot account for differing conditions at different intersection types.

Qi, Chen, Guo, Yu (2010) present a new approach for analyzing the operational benefits and safety risks associated with the use of protected/permissive mode. They provide a step-by-step process to estimate the benefit (in terms of reduction in delays) and the cost (in terms of safety risk) of using protected/permissive mode, and then convert the benefit and cost into dollar values for purposes of comparison.

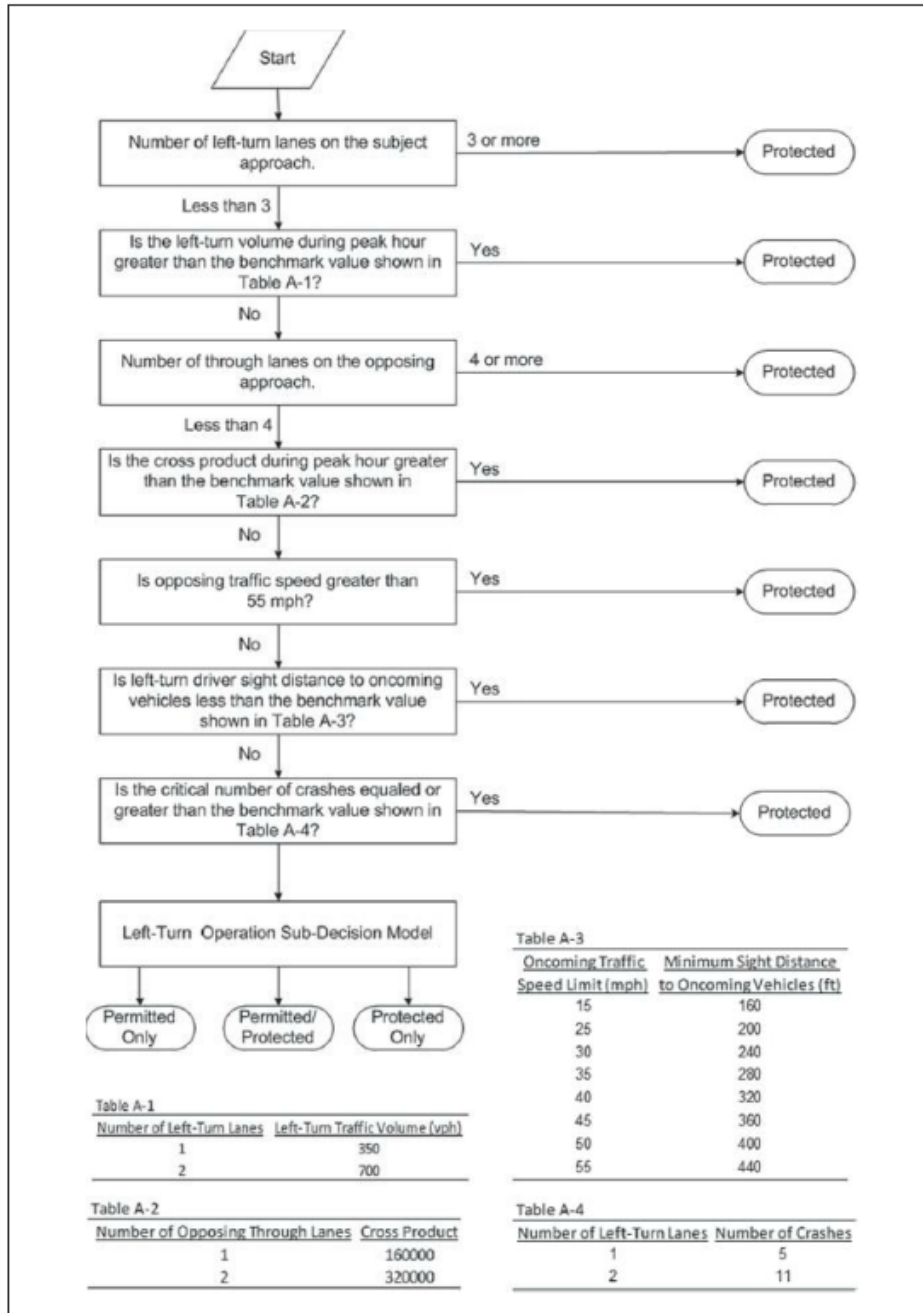
Hu, Tian, Zang present a new guideline for mode selection based on Analytic Hierarchy Process (AHP), in an attempt to provide a more balanced and nuanced decision making process. The authors have designed a decision model that allows for more conservative or more aggressive decision making through assignment of varying weights to selection criteria. The left turn control type with the highest ranking score after weighting selection criteria is recommended for implementation. The authors include a

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flowchart for selection of protected-only mode under the most obvious conditions (Figure 3). In the absence of a clear mode selection recommendation via the flowchart, the authors suggest using AHP to determine mode selection for more complex left turn control decision scenarios.

Figure 3: Hu, Tian, and Zang's Mode Selection Flowchart



Additional guidance on left-turn phasing included:

- Overlapping the adjacent right turn phase with the protected left-turn phase will allow for improved operation of the right turn movements at the intersection (Antonucci et al. 2004).
- Protected-only phasing should be implemented only where separate left-turn channelization exists (Antonucci et al. 2004). This guidance does not apply to intersections under split phase operation.
- If there is more than one left-turn lane, protected-only mode is recommended (Ozmen et al. 2009).

LEFT-TURN PHASING SEQUENCE

(Note that, for the purposes of this literature review, “sequence” refers to the placement of the left-turn phase within a cycle: lead-lead, lag-lag, or lead-lag).

An analysis of multiple studies of signal phasing sequencing found that, *for protected-only mode*, lead-lag is the safest sequence, followed by lead-lead and then lag-lag (Qi, Yu and Guo 2009). Sheffer and Janson, meanwhile, found that the concern of some traffic engineers that lagging sequencing leads to safety risks and increased lost time due to driver expectancy appears to be unfounded (1999). In fact, Asante (1993) recommended lagging left turns when intersection safety is a high priority. Hummer et al. (1991) found that lagging left turns were the safest sequence at intersections with significant pedestrian volumes.

In general, traffic engineers are hesitant to use lead-lag sequencing in *protected/permissive mode*, due to safety concerns related to the “yellow trap” (Sheffer and Janson 1999). Data from a 1999 national survey of traffic engineers bears this out, as it revealed that 83 percent of protected/permissive left turns used lead-lead sequencing, 11 percent used lag-lag sequencing, and six percent used lead-lag sequencing (Kacir 1999).

Despite these commonly held concerns related to the use of lead-lag sequencing in *protected/permissive mode*, an examination of existing literature and communication with various agencies indicated that implementation of lead-lag sequencing has yielded positive benefits with no significant impact on driver expectancy of safety (Sabra Wang 2011). Nandam and Hess (2000) found that mean crash rates before and after implementation of lead-lag sequencing did not show any statistically significant difference, suggesting that any violation of driver expectancy due to change in sequencing did not have an impact on safety.

Regardless of the selected sequencing for left-turn phasing, Qi, Yu and Guo (2009) stressed the need for consistency, noting that the mixed application of signal phasing sequences increases the risk of crashes. Nandam and Hess (2000), meanwhile, found that the dynamic change of left-turn sequence by time of

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day did not have any impact on safety. Adaptive signal control, which allows for variation in left-turn phasing based on current traffic conditions, has grown increasingly popular in recent years.

Yu et al. (2008) identified factors considered in the sequence selection process and assigned a score to each factor based on survey responses from state and local DOTs (Table 2).

Table 2: Factors' Rank in Determination of Left-turn Phasing Sequence (Yu et al. 2008)

Parameter	Score
Platoon Progression and Bandwidth	4.03
Intersection Congestion Level (V/C Ratio)	3.39
Historical Rate of Left-turn Crashes	3.31
Driver Acceptance	3.29
Median Width	3.22
Intersection Alignment	3.17
Number of Left-turn Lanes	3.03
Historical Rate of Total Crashes at Intersection	3.03
Left-turn Storage Length	3.03
Left-turn Traffic Volume	2.97
Intersection Delay	2.94
Left-turn Delay	2.89
Opposing Traffic Volume	2.75
Sight Distance	2.72
Number of Opposing Lanes	2.61
Posted Speed Limit	2.56
Percent of Heavy Vehicles	2.53
Number of Failed Cycles	2.14
Pedestrian and/or Bicycle Crossings	1.78

In terms of operational impacts of sequencing in *protected-only mode*, lead-lag sequencing showed significant advantages over other sequences in maximizing progression bandwidth (Tian et al. 2009, Asante et al. 1993). Hummer et al. (1991) examined coordinated signal systems, and emphasized that maximizing bandwidth should be the primary factor in phasing sequence selection. Li et al. (2003) found that, in coordinated signal systems, lagging left turns for the downstream signal results in reduced delay regardless of which left-turn sequence is used at the upstream signal. Furthermore, lagging left turns at all intersections in a coordinated system produces the lowest level of overall intersection delay (Li et al. 2003). Bonneson et al. (2009) recommended using computer software and/or the evaluation of a time-space diagram in making determinations about left-turn sequence.

Qi, Yu and Guo (2008) identify two primary challenges in left-turn operation: left-turn lane spillback and blockage of access to the left-turn lane by through vehicles. To address significant spillback problems, the left-turn movement should start earlier than the through movement. Conversely, to address blockage problems, the through movement should start earlier than the left-turn movement (Qi, Yu and Guo 2008). The length of signal phase and cycle length should be compatible with the length of the turn lane. Turn lanes that are too short may be blocked by through vehicles, making the lane inaccessible and negating the effectiveness of a lead left-turn phase (Antonucci et al. 2004).

FHWA's *Traffic Signal Timing Manual* (2008) includes a helpful overview of common applications and benefits of the various left-turn phase sequencing:

- Lead-lead sequencing
 - Drivers react quickly to the leading green arrow indication.
 - Minimizes conflicts between left turns and through movements on the same approach when the left-turn volume exceeds its storage length.
- Lag-lag sequencing
 - Most common use of lag-lag sequencing is found in coordinated systems with closely spaced signals, such as diamond interchanges.
 - Offers operational benefits for protected/permissive lefts at T-intersections and at intersections of a one-way and two-way street.
- Lead-lag sequencing
 - Generally used to accommodate through movement progression in a coordinated signal system, where there is inadequate space in the intersection to safely accommodate simultaneous opposing left turns and at intersections where the leading left-turn movement is not provided an exclusive lane.

FHWA also provides recommended strategies for maximizing throughput through left-turn sequencing selection (*Signal Timing under Saturated Conditions, 2008*):

- Lag heavy left turns so that left-turn spillover does not block the through queue.

- Use special logic, such as terminating the side street if remaining cars are right turns that can be served during the complementary left-turn phase.
- Serve phases more than once in a cycle, such as Twice per Cycle Left Turns (TPCLT). The report notes that the greater the imbalance of heavy to light movements, the more likely the heavy movements are to benefit. This allows the minor movements to fill up sufficiently to make use of the minimum times.
- Phase Re-service: provide green signals more than once in the cycle, or to alternate movements to every other cycle. One example in the report illustrates a cycle twice the coordination cycle to serve split-phase side-street movements on alternating cycles. These movements were light, and serving them on alternate cycles made better use of the minimum green time, which was controlled by pedestrian clearance time.

CONCLUSION

This literature review, along with the accompanying summary of existing left-turn phasing policies from state DOTs and VDOT regional offices, seeks to synthesize the latest and most salient research findings, guidance, and consensus regarding selection of left-turn phasing. Both the literature review and the state policy summary will directly inform the development of a Left Turn Phasing Policy/Guidance document for VDOT.

With respect to selection of left-turn phasing mode, the literature is relatively consistent in identifying protected-only as the safest mode, albeit one that can entail significant tradeoffs in efficiency. Protected/permissive mode, meanwhile, is widely regarded as the most efficient left-turn mode; however, this efficiency erodes as opposing volumes increase.

The literature is also relatively consistent in identifying the criteria to be considered in selecting mode, with general agreement that mode selection should include consideration of each of the following factors: crash history, sight distance, left-turn volume, opposing through volume, number of left-turn lanes, and number of opposing through lanes. Another widely cited criterion is the speed limit on opposing through lanes. Nearly all of the papers examined include quantitative thresholds for each of the criteria included in mode selection guidelines.

There is no clear consensus on guidance for selection of phasing sequence. Corridor progression and bandwidth were identified as leading criteria for sequence selection. Most authors acknowledge traffic engineers' hesitation to use lead-lag sequencing with protected/permissive mode due to concerns about the "yellow trap"; however, multiple authors felt that safety concerns with lead-lag sequencing were overblown, and that lead-lag offers significant efficiency benefits that warrant consideration. For protected-only mode, lead-lag was found to be both the safest and most efficient sequence, although lagging left turns may be the most efficient in coordinated systems with closely spaced intersections.

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APPENDIX B:
LEFT-TURN PHASING SELECTION GUIDANCE

REVIEW OF EXISTING STATE DOT GUIDANCE
AND VDOT REGION OFFICE GUIDANCE

November 2012

**** Revised August 2013 ****

Prepared for:



Prepared by:



Vanasse Hangen Brustlin, Inc.

Summary of State DOT Guidance on Left-Turn Phasing

The first section of this document provides a summary of the left-turn phasing guidance from nine state Departments of Transportation. Note that this summary document draws a distinction between “mode” and “sequence.” “Mode” refers to the assignment of right-of-way to left-turning vehicles (i.e., Protected Only left turns, Permissive Only left turns, Protected/Permissive left turns, or prohibited left turns). “Sequence” refers to the order that the left-turn movements at an intersection are serviced within the signal cycle (i.e., lead-lead, lag-lag, or lead-lag).

Eight of the nine DOT guidelines that were reviewed include criteria for selection of mode; of those, only Texas and Louisiana include detailed guidance on the selection of sequencing as well. Georgia includes general guidance on sequencing selection. The ninth DOT, Maryland, has no formal statewide policy on mode selection, but has solicited the development of guidance on sequencing. The proposed sequencing guidance is included in this report despite not having been formally adopted/endorsed by Maryland State Highway Administration.

Following is a summary table of criteria used in selection of left-turn phasing mode by the states reviewed in this document.

	Criteria for Consideration in Mode Selection*									
	LT Volume	Crash History	Sight Distance	No. of LT Lanes	Opp. Speed Limit	Opp. Thru Lanes	Intersection Geometry	Ped Volume	LT Demand	Existing Sequence
AZ	✓	✓	✓	✓	✓	✓				
GA	✓	✓	✓	✓	✓	✓	✓	✓		
LA	✓	✓	✓	✓		✓	✓			
MI	✓	✓	✓		✓	✓	✓			
MN	✓	✓	✓	✓		✓	✓			✓
OR	✓	✓	✓	✓	✓	✓	✓	✓		✓
TX	✓	✓	✓	✓	✓	✓			✓	
WA	✓	✓	✓	✓	✓	✓	✓			✓

* Maryland is not included in this table because it has no statewide mode selection guidelines.

The matrix on the next page summarizes each state’s guidance for 10 different selection criteria for left turn phasing mode. Additional details on each state’s policies can be found later in the document.

Note that the following left-turn phasing guidance pertains to state-operated intersections in the respective states. Locally maintained intersections follow state guidance in many instances; however, a number of jurisdictions in the states covered below have adopted localized variations of their state guidelines on left-turn phasing selection.

Summary of Criteria Used in Selection of Protected-Only Mode, by State*†

	Left Turn Volume	Crash History	Sight Distance	Number of Left Turn Lanes	Opposing Speed Limit	Opposing Thru Lanes	Intersection Geometry	Pedestrian Volume	Left Turn Demand	Existing Sequence
AZ		4 / 6 LT crashes in one year (1 app / 2 opp. app); or 6 / 10 in 2 years	Limited sight distance due to geometry or opposing LT vehicles	Mainline has 2 or more LT only lanes	Opposing speed limit > 45 mph	3 or more opposing thru lanes				
GA		5 or more LT crashes in 2 years	Limited sight distance	Mainline has 2 or more LT only lanes	Opposing speed ≥ 45 mph AND 3 or more opposing thru lanes	3 or more opposing thru lanes AND opposing speed ≥ 45 mph	Unusual intersection geometry	High pedestrian volumes		
LA		4 / 6 LT crashes in one year (1 app / 2 opp. app); or 6 / 10 in 2 years	Limited sight distance (see table in following section)	Mainline has 2 or more LT only lanes	Opposing speed ≥ 45 mph AND 3 or more opposing thru lanes	3 or more opposing thru lanes AND opposing speed ≥ 45 mph	Intersection geometry creates a conflicting left-turn path			
MI		4 / 6 LT crashes in any 12-month period (1 app / 2 opp. app); or 6 / 10 in 2 years	Limited sight distance due to geometry or opposing LT vehicles		Opposing speed limit > 45 mph	3 or more opposing thru lanes				
MN	Peak hour LT volume > 250 vehicles or cross-product > 80,000; AND speed limit ≥ 45 mph	5 or more LT crashes over 3 years	Mainline LT has limited sight distance (per AASHTO)	Mainline has 2 or more LT only lanes		3 or more opposing thru lanes	Intersection geometry creates a conflicting left-turn path			Lead-lag sequence is already in use
OR	LT volume > 300 vph OR volume cross-product > 150,00 / 300,000 (1 / 2 opposing lanes)	LT crashes ≥ 5 per approach in any 12-month period in 3 years	Limited sight distance (see table in following section)	Mainline has 2 or more LT only lanes	Opposing speed limit > 45 mph	3 or more opposing thru lanes				Lead-lag is required for efficient operation but a flashing yellow arrow display cannot be installed
TX	Volume cross-product > 133,000 (1 opp. thru lane) or > 93,000 (2 opp. thru lanes)	LT crashes ≥ 5 in any 12-month period in 3 years; ≥ 4 in any 1 year; ≥ 6 in any 2 consec. years; ≥ 8 in any 3 consec. years	Opp. speed ≤ 35 mph and SD < 250 ft; or opp. speed > 35 mph and SD < 400 ft	Mainline has 2 or more LT only lanes	Opposing speed limit ≥ 45 mph	3 or more opposing thru lanes			LT demand ≥ 2 vehicles per cycle in peak hour AND opposing speed limit ≥ 45 mph	
WA		LT crashes on any approach ≥ 3/year or ≥ 5 in two consec. years	Opp. speed ≤ 35 mph and SD < 250 ft, or opp. speed > 35 mph and SD < 400 ft; AND peak hour LT volume exceeds storage capacity	Mainline has 2 or more LT only lanes	Opposing speed limit > 45 mph AND peak hour LT volume exceeds storage capacity	3 or more opposing thru lanes (incl. RT lanes) AND peak hour LT volume exceeds storage capacity	Geometry or channelization is confusing AND peak hour LT volume exceeds storage capacity			

* Consideration of Protected Only mode is warranted by fulfillment of any one of these criteria.

† Maryland is not included in this table because it has no statewide mode selection guidelines.

MINNESOTA

MnDOT's *Signal Design Manual* (2012) includes a subsection on left-turn phasing, with guidelines for selection of Protected Only mode. The manual does not provide specific guidance for Protected/Permissive mode, and provides only a passing reference to sequencing as it pertains to selection of mode.

Protected Only left-turn phasing is recommended upon fulfillment of any one of the following conditions; however, the guidelines state that "engineering judgment and site-specific considerations of safety and efficiency may cause deviations from the operation indicated by these guidelines."

- 1) When railroad preemption is used and the movement is opposite the track clearance movement or turns across the tracks unless other measures are implemented to address this conflict.
- 2) Lead-lag left-turn sequence is utilized.
- 3) Intersection geometrics create a conflicting left-turn path.
- 4) The left turner faces three or more opposing through lanes. Note that an opposing right turn only lane typically will not be counted along with opposing through lanes.
- 5) The mainline left turner has limited sight distance as defined in the current AASHTO "*A Policy on Geometric Design of Highways and Streets*." According to AASHTO, opposing left-turning vehicles can be considered as blocking sight distance.
- 6) Protected/Permissive operation is in place and there are 5 or more left-turn related collisions per year over a 3-year period susceptible to correction by protected-only phasing.¹
- 7) Mainline has dual left-turn lanes.
- 8) Speed 45 MPH or greater AND a peak hour left-turn volume greater than 240 vehicles or a peak hour cross-product greater than 80,000 (100,000 if two opposing lanes).

¹ Note that the use of "correctable crashes" in this document refers to crashes between a left turning vehicle and an opposing through or right turning vehicle that can be avoided with the implementation of Protected Only phasing.

ARIZONA

Section 600 of ADOT's *Traffic Engineering Policies, Guidelines, and Procedures* (2011) includes guidelines for left-turn signal phasing. The guidelines apply to the consideration of left-turn phasing generally, and also to selection of Protected Only mode. There are no specific guidelines for left-turn phasing sequence.

General Guidelines

The guidelines for selection of a separate left-turn phase include three factors: traffic volumes, stopped-time delay, and crash experience.

1) *Traffic Volumes*

Following are the traffic volume cross-product thresholds for consideration of left-turn phasing:

	2-Lane Street	4-Lane Street	6-Lane Street
Rural	50,000	100,000	150,000
Urban	75,000	150,000	225,000

The left-turn volume should be greater than two vehicles per cycle during the peak hour. Engineering judgment is used in determining what percentage, if any, of right turning vehicles are included in the sum of opposing traffic.

2) *Stopped-time Delay*

Left-turn phasing may be considered if the left-turn delay is 2.0 vehicle hours or more during a peak hour on an approach. The left-turn volume should be greater than two vehicles per cycle during the peak hour. The average delay per left-turning vehicle should equal or exceed 35 seconds.

3) *Crash Experience*

Following are crash thresholds for consideration of left-turn phasing:

	One Year Period	Two Year Period
One Approach	4	6
Two Opposing Approaches	6	10

Protected Only Mode

Protected Only mode may be considered if any of the following conditions exist:

- Three or more through lanes of traffic on the opposing leg.

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- Posted speed limit of opposing traffic is greater than 45 mph.
- Dual left-turn only lanes.
- Sight distance restrictions to opposing traffic due to geometry or opposing left-turn vehicles.
- Use of Protected/Permissive phasing has resulted in left-turn crash experience that meets the values in the Left-turn Crash Experience table on the previous page.

MARYLAND

NOTE: *Traffic Signal Phase Sequence Guidance* (2011) was developed for the Maryland State Highway Administration (MDSHA) by Sabra, Wang and Associates. The guidance has not been adopted wholesale by MDSHA, although the state has begun using lead-lag sequencing more widely since the report was issued.

Traffic Signal Phase Sequence Guidance provides guidance on left-turn phasing sequence, and only mentions mode as it pertains to selection of sequence. The guidance is classified according to two categories: situations in which sequence is a function of mode; and situations in which sequence is a function of intersection geometry.

Left Turn Sequence as a Function of Mode:

- 1) For left-turns with Protected Only phasing on opposing approaches, implementation of a lead or lag left-turn phase sequence is **acceptable**.
- 2) For left turns with Protected Only or Protected/Permissive phasing at a T-intersection, implementation of a lead or lag left-turn phase sequence is **acceptable**.
- 3) For left turns with Protected Only and permissive mode on opposing approaches, implementation of a lag left-turn phase sequence is **not recommended**.
- 4) For Protected Only left turns with Protected/Permissive phasing on the opposing approach, implementation of lag left-turn phase sequence is **not recommended**. The Protected/Permissive phase opposing the Protected Only left turn may implement lead or lag phase sequence.
- 5) For left turns with Protected/Permissive phasing on opposing approaches, implementation of lead-lag phasing is **not recommended** to avoid “Yellow Trap” conditions. Instead, flashing yellow arrow (FYA) signal displays should be utilized if one of the left-turn phases needs to operate as lag.²

² Note that this recommendation conflicts with guidance in the 2011 Maryland MUTCD, which states that “flashing yellow arrow indications shall not be used in Maryland.”

Left Turn Sequence as a Function of Intersection Geometry:

- 1) For left turns with overlapping paths, a lead-lag phase sequence should be utilized to safely accommodate the turning traffic from opposing approaches.
- 2) Tight diamond interchanges are characterized by two signalized intersections less than 400 feet apart. Traffic control at signals in such close proximity is typically accomplished using a single traffic controller. The phasing at tight diamonds is a function of whether traffic volumes along the arterial and the ramps are balanced or unbalanced, the presence of other signalized intersections in the vicinity and the width of the interchange. Control strategies for operation include the Texas Three-Phase and the TTI Four-Phase operation. The implementation of a lead-lead, lead-lag or a lag-lag left-turn phasing is an implicit part of the two control strategies.

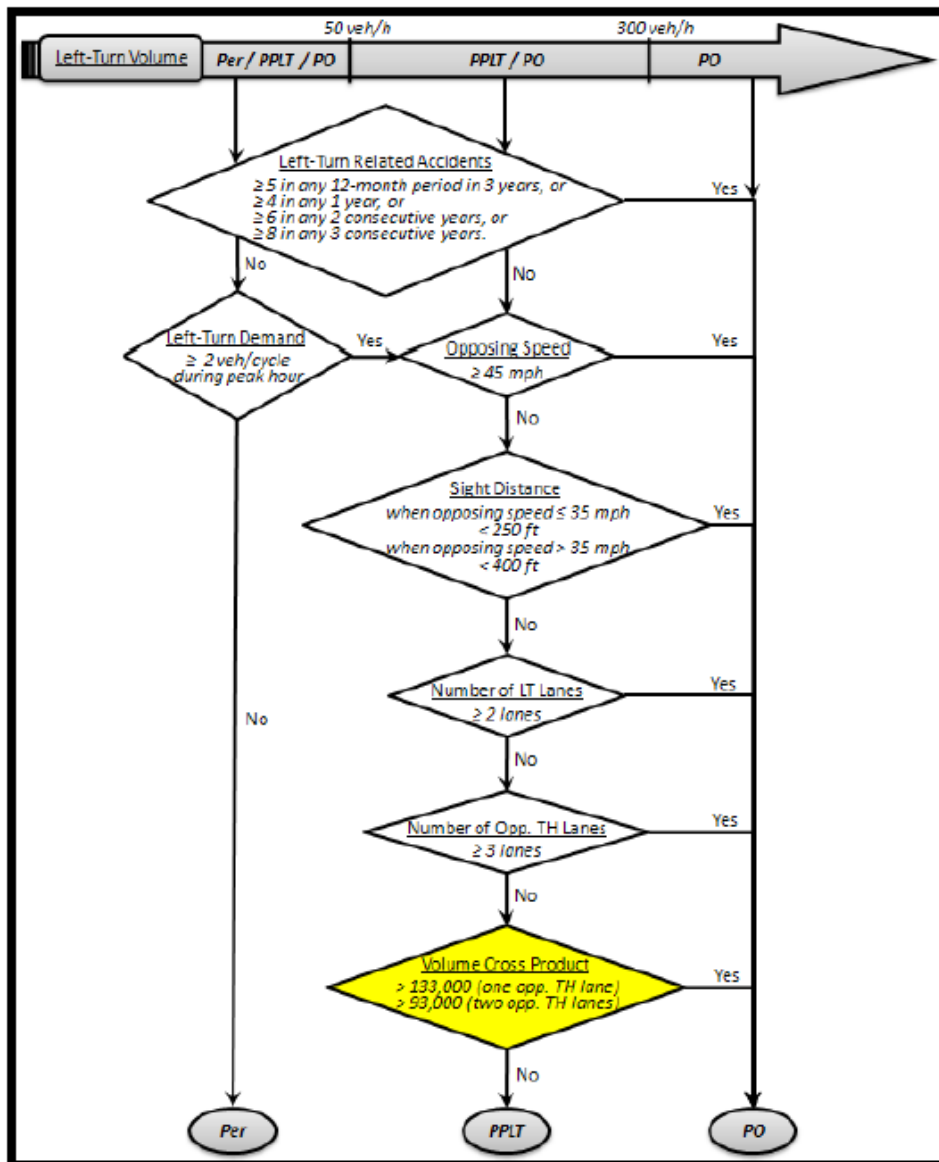
TEXAS

NOTE: While TxDOT has sponsored a considerable amount of research on left-turn phasing – including the development of selection guidelines – through Texas Southern University and the Texas Transportation Institute (TTI) at Texas A&M University, the state has not formally adopted any of the guidelines developed by these institutions.

Development of Left Turn Operations Guidelines at Signalized Intersections (2008), developed for TxDOT by Texas Southern University, includes guidance on both the selection of mode and the selection of sequencing. The guidance for selection of left-turn phasing mode is described in detail in the report, but is best represented in the form of a flowchart (see next page).

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Note: "Per" means permissive mode; "PPLT" means protected/permissive mode; "PO" means protected-only mode.

Development of Left turn Operations Guidelines at Signalized Intersections includes the following guidance for the selection of sequencing, considered separately for Protected Only mode and Protected/Permissive mode.

Guidelines for Selection of Sequencing for Protected-only Mode:

- 1) If the intersection has heavy pedestrian volume, the lead-lead sequence or lead-lag sequence should be avoided, unless there are other measures that could effectively prevent conflicts between left-turn vehicles and pedestrians.

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- 2) Lead-lag sequence should be considered before lag-lag or lead-lead sequences, especially when left-turn volume is high. The approach with higher left-turn volume should use the leading phase.³
- 3) Use the phasing sequence that is most common along the arterial and in a region.
- 4) When the signals in an arterial are two-way coordinated, choose the signal phasing sequence that will provide the widest two-way through bandwidth to achieve better signal progression. When the signals in an arterial are one-way coordinated (e.g., during the peak hour period), the lead-lag sequence should be considered and the approach in the coordinated direction should use the leading phase.

Guidelines for Selection of Sequencing for Protected/Permissive Mode:

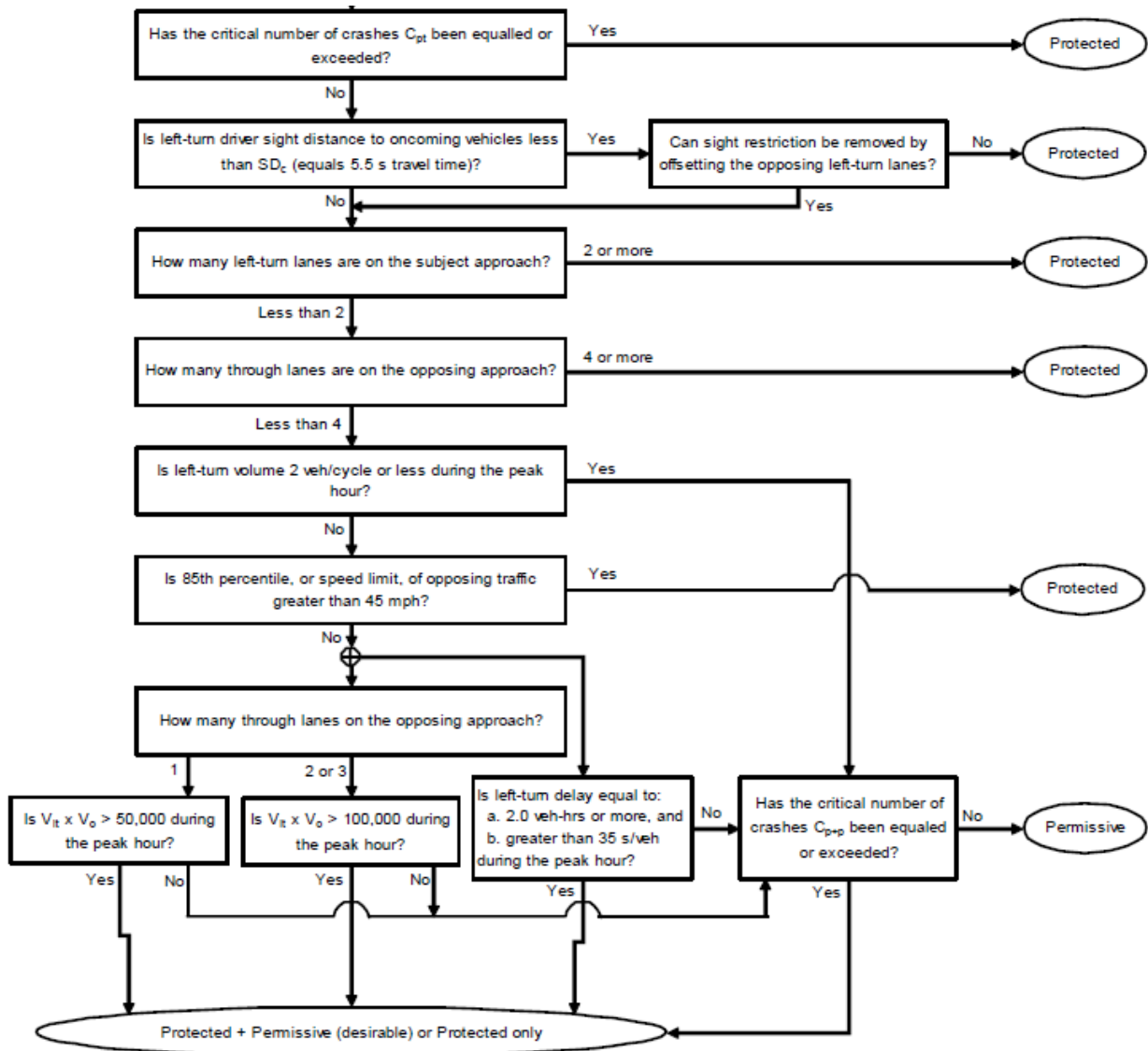
- 1) If the intersection has heavy pedestrian volume the lead-lead sequence or lead-lag sequence should be avoided, unless there are other measures that could effectively prevent conflicts between left-turn vehicles and pedestrians.
- 2) If the left-turn volume level is below 150 vehicles/hr, lead-lead sequence is recommended. If the left-turn volume is higher than 150 vehicles/hr, lead-lag sequence should be considered.
- 3) If lead-lag sequence is selected, Arlington or Dallas phasing should be considered to prevent the yellow trap problem. (NOTE: The 2009 MUTCD prohibits the use of Dallas phasing in favor of FYA).
- 4) Use the phasing sequence that is most common along the arterial and in a region.
- 5) When the signals in an arterial are two-way coordinated, choose the signal phasing sequence that will provide the widest two-way through bandwidth to achieve better signal progression. When the signals in an arterial are one-way coordinated (e.g., during the peak hour period), the lead-lag sequence should be considered and the approach in the coordinated direction should use the leading phase.

TTI's *Traffic Signal Operations Handbook* (2009) also includes guidance for selection of left-turn phasing mode, in the form of a flowchart. This flowchart developed by TTI, also appears in FHWA's *Traffic Signal Timing Manual*.

³ Note that Texas' guidance that the approach with the higher left turn volume should use the leading phase runs counter to existing practice in the VDOT Central Region.

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Number of Left-Turn Movements on Subject Road	Period during which Crashes are Considered (years)	Critical Left-Turn-Related Crash Count When Considering	
		Protected-only, C_{pt} (crashes/period)	Prot.+Perm, C_{p+p} (crashes/period)
One	1	6	4
One	2	11	6
One	3	14	7
Both	1	11	6
Both	2	18	9
Both	3	26	13

Oncoming Traffic Speed Limit (mph)	Minimum Sight Distance to Oncoming Vehicles, SD_c (ft)
25	200
30	240
35	280
40	320
45	360
50	400
55	440
60	480

Variables

V_{lt} = left-turn volume on the subject approach, veh/h

V_o = through plus right-turn volume on the approach opposing the subject left-turn movement, veh/h

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TTI developed an Excel-based left-turn mode worksheet, which can be found on pages A-19 and A-20 of *Development of a Traffic Signal Operations Handbook* (note the slightly different title than the aforementioned TTI publication).

WASHINGTON

The *WSDOT Design Manual* (2009) includes a subsection on left turn phasing, with guidelines for selection of mode. The manual does not address sequencing.

The manual notes that it is not necessary that the left-turn mode for an approach be the same throughout the day. Varying the left-turn mode on an approach among the permissive only, Protected/Permissive, and Protected Only left-turn modes during different periods of the day is acceptable.

Protected-Only

Following are WSDOT's guidelines for protected-only mode:

- 1) Protected phasing is always required for multilane left-turn movements.
- 2) Use protected left-turn phasing when left-turning type collisions on any approach equal three per year or five in two consecutive years. This includes left-turning collisions involving pedestrians.
- 3) Use protected left-turn phasing when the peak hour turning volume exceeds the storage capacity of the left-turn lane because of insufficient gaps in the opposing through traffic and where one or more of the following conditions is present:
 - a) Either the posted speed or the 85th percentile speed of the opposing traffic exceeds 45 mph.
 - b) The sight distance to oncoming traffic is less than 250 feet when the 85th percentile speed is 35 mph or below, or less than 400 feet when the 85th percentile speed is above 35 mph.
 - c) The left-turn movement crosses three or more lanes (including right turn lanes) of opposing traffic.
 - d) Geometry or channelization is confusing.

Protected/Permissive

Where left-turn phasing will be installed and conditions do not warrant Protected Only operation, consider Protected/Permissive left-turn phasing. Protected/Permissive left-turn phasing can result in

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increased efficiency at some types of intersections, particularly “T” intersections, ramp terminal intersections, and intersections of a two-way street with a one-way street where there are no opposing left-turn movements.

Protected/Permissive left-turn phasing is NOT ALLOWED under the following conditions:

- 1) On the approaches of a signal where MUTCD Warrant 7 (Crash Experience) is met and there are five left-turning collisions on that approach included in the warranting collisions.
- 2) When documentation shows that existing protected left-turn phasing was installed due to left-turn collisions.
- 3) When sight distance for left-turning vehicles, as outlined in AASHTO’s *A Policy on the Geometric Design of Highways and City Streets*, cannot be met.
- 4) On intersection approaches where the opposing approach has three or more lanes (including right turn lanes) and either the posted speed limit or 85th percentile speeds for the opposing approach are at or above 45 mph.
- 5) On intersection approaches that have dual left-turn lanes.
- 6) At intersections where lead-lag phasing is employed.

GEORGIA

GDOT published a *Transportation Online Policy & Procedure System (TOPPS)* on left-turn phasing selection (2008). The TOPPS publication includes specific guidelines for the consideration of left-turn phasing and the selection of Protected Only mode. This publication also includes more general guidance on left-turn phasing sequence.

General Guidelines

Left-turn phases will only be considered at those locations where one or more of the following requirements are met:

- 1) The cross-product, one hour left-turn volume times the opposing one hour through movement volume divided by the number of lanes for the opposing through movement, is greater than 50,000.
- 2) The left-turn volume exceeds 125 vehicles per hour.
- 3) Correctable crashes equal or exceed 4 crashes in one year or 6 crashes in two years.

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- 4) Additional criteria including but not limited to sight distance, speed of opposing traffic, number of left-turn lanes, number of opposing through lanes, delay, the angle of the left turn and if the signal is included in a coordinated signal system will also be taken into consideration when evaluating requests for left-turn phases.

Left-turn phases should not be used at intersection approaches where a left-turn lane has not been provided.

Mode

Only when conditions satisfy one or more of the following criteria will a Protected Only left-turn phase be allowed:

- 1) Left-turn crashes under a protected/permissive phasing equal or exceed 5 crashes in 2 years.
- 2) Dual left turns.
- 3) Limited sight distance will not allow permissive turns.
- 4) Left-turn movements where opposing through traffic is approaching in three or more lanes at speeds greater than or equal to 45 mph.
- 5) Additional criteria such as intersection skew, high volume of pedestrians and unusual intersection geometrics.

Sequence

Left-turn phases will typically be installed as a leading left-turn movement. Lagging left-turn phases should only be used at locations where it can be demonstrated that significant benefits can be derived by its use with no sacrifice of safety or signal progression.

MICHIGAN

The Michigan DOT's *Left Turn Phasing Signal Guidelines* (2006) include guidance for selection of a separate left-turn phase and for selection of mode. The guidelines do not address selection of sequencing.

General Guidelines

Left-turn protection should be considered at signalized intersections when:

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- 1) The left-turn peak hour volume exceeds 90 vehicles per hour (VPH) or 50 VPH on streets with through traffic over 45 mph, or
- 2) The product of opposing through hourly volume (VPH) and left-turn hourly volumes (VPH) exceeds 50,000 if there is one opposing lane, or 100,000 if there are two opposing lanes, or
- 3) A crash pattern is evident at the intersection that could be corrected with left-turn phasing.

Mode

Protected-Only

Protected-only left-turn phasing should be considered when the need for phasing has been identified and the above listed conditions for permissive/protected operation cannot be met for any of the following conditions:

- 1) Any intersection where the sight distance to opposing traffic is poor due to geometry or opposing left-turn vehicles.
- 2) The left-turn traffic must cross three or more lanes of opposing through traffic.
- 3) Previous use of permissive/protected phasing has resulted in four correctable crashes in one consecutive 12-month period or six correctable crashes in two years for one approach, or six correctable crashes in one consecutive 12-month period or 10 correctable crashes in two consecutive years for two opposing approaches.
- 4) At intersections where the posted speed limit of opposing traffic is greater than 45 mph.

Protected/Permissive

Protected/permissive left turn phasing should be considered, when left-turn demand is present but cannot be accommodated on two phase signal operation alone, or when a crash pattern that could be corrected with left-turn phasing is evident at this intersection and the following is met:

- 1) Adequate sight distance for left-turning vehicles and opposing through traffic is available.
- 2) There are no more than two lanes of opposing through traffic (including shared through lanes).
- 3) Intersection geometrics do not promote hazardous conditions.

OREGON

ODOT’s *Traffic Signal Policy and Guidelines* (2006) feature a subsection on left turn phasing, which includes guidance on selection of mode. The guidelines provide only a passing reference to sequencing as it pertains to selection of mode.

Protected-Only

- 1) Protected-only left-turn phasing shall be used when an engineering study indicates sight distance to oncoming traffic is less than the distances below.

Posted Speed (mph)	Required Sight Distance (ft) One Opposing Through Lane	Required Sight Distance (ft) Two Opposing Through Lanes
20	165	180
25	205	225
30	245	270
35	285	310
40	325	355
45	365	400
50 (*)	425	465
55 (*)	495	540

Source: A policy on Geometric Design of Highways and Streets 2001 Fourth Edition, AASHTO – Table 9-67.

(*) – For speeds > 45 mph, the Stopping Sight Distance (higher value from Table 9-67) is used instead of Intersection Sight Distance.

- 2) Protected-only left-turn phasing should be considered when an engineering study indicates one of the following conditions is present. Intersection capacity and delay should be considered in the engineering study.
 - a) Crash history indicates 5 or more left-turning type crashes per approach in a consecutive 12-month period within the last three years (include left-turning crashes involving pedestrians).
 - b) The signal is located in a traffic signal system and lead-lag phasing is required for efficient operation but a flashing yellow arrow display cannot be installed.
 - c) Left-turn volume routinely exceeds 300 vehicles per hour or the product of opposing and left-turn hourly volumes exceeds 150,000, if there is one opposing lane, or 300,000, if there are two opposing lanes. Where there is a significant lane imbalance, twice the highest single lane volume can be substituted for the total opposing hourly volume when making this calculation.
 - d) The posted speed of opposing traffic exceeds 45 mph.
 - e) The left-turn movement crosses three or more lanes of opposing through traffic.
 - f) Multiple left-turn lanes are provided.
 - g) U-turns are permitted.

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- h) Additional factors such as high pedestrian volumes, traffic signal progression, intersection geometric design, maneuverability of particular classes of vehicles, adequacy of gaps, or preemption-related operational requirements unique to preemption systems.
- i) High percentage of left-turning trucks.

Protected/Permissive

Note that, for all state highway installations, the standard display for protected/permissive phasing is the flashing yellow arrow (FYA) display.

Protected/permissive left turns should be considered when any one of the following criteria is satisfied:

- 1) Left-turn volume routinely exceeds 200 vehicles per hour or the product of opposing and left-turn hourly volumes exceeds 50,000, if there is one opposing lane; or 100,000, if there are two opposing lanes. Where there is a significant lane imbalance, twice the highest single lane volume can be substituted for the total opposing hourly volume when making this calculation.
- 2) Projected volumes would warrant it within five years after the traffic signal is placed in service.
- 3) The opposing left-turn approach has a protected/permissive turn signal or meets one or more of these criteria.

LOUISIANA

The Louisiana DOTD's *Traffic Signal Design Manual* (2002) includes guidance on selection of both mode and sequence.

According to the manual, LADOTD EDSM, Volume VI, Chapter 3, Section 1, Directive 3 states: "Where separate left-turn lanes are provided, a separate left-turn phase should normally be included unless the addition of such a phase causes capacity problems. Each location shall be analyzed for capacity and a decision shall be made by the traffic engineer based on these results."

The manual also includes warrants for selection of a separate left-turn phase for intersections without separate left-turn lanes.

Mode

Protected-Only

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Protected Only mode should be considered when any of the following conditions exist:

- 1) Limited left-turn sight distance – the view of opposing through and opposing right turn traffic is restricted. See table below.

OPERATING SPEED (MPH)	SAFE SIGHT DISTANCE (FT.)		
	2-LANE	4-LANE	6-LANE
20	240	260	280
30	360	390	420
40	470	520	560
50	590	650	700
60	710	780	840

Source: Northwestern University Traffic Institute

- 2) Excessive street width – left-turning traffic must cross three or more lanes and the speed of the opposing traffic is 45 MPH or greater.
- 3) Inadequate geometry – at intersections where there is inadequate room for opposing left-turn movements on the same street to move simultaneously without conflicting or crossing. Either lead-lag or split phasing must be used.
- 4) Left-turn crashes – if the peak hour left-turn volume is at least 50 vehicles and the following number of left-turn accidents have occurred:
 - One approach – 4 left-turn accidents in one year or 6 left-turn accidents in two years.
 - Two opposing approaches – 6 left-turn accidents in one year or 10 left-turn accidents in two years.
- 5) Dual left turns – on approaches where two side by side left-turn lanes exist.

Protected/Permissive

Protected/permissive mode should be considered when any of the following conditions exist:

- 1) Left turn volumes – where an approach has a peak hour left-turn volume of at least 50 vehicles, and a peak hour product of left-turning vehicles and opposing traffic exceeding 100,000 for four lane streets or 50,000 for two lane streets. (Opposing traffic consists of opposing through and opposing right turning traffic.)
- 2) Capacity – where intersection capacity is limited and maximum efficiency of the traffic operations is needed.
- 3) Left turn storage – where left-turn lanes are not present or left-turn lanes are of inadequate length to store the actual left-turn traffic volumes.

- 4) Left turn accidents – where the left-turn signal phase is not justified by the left-turn accident warrant described in the Protected Only guidance above.

Sequence

Leading Left Turn

Leading left turns should be used in the following circumstances:

- 1) Lack of left-turn lanes – a leading left-turn signal phase increases the approach capacity on one and two lane approaches without left-turn lanes. This assures that all traffic moves on the approach at the beginning of the green signal phase.
- 2) Signal coordination – where a time-space diagram indicates that a leading left-turn signal phase will increase the arterial green bandwidth and improve the signal progression.
- 3) Minimizing conflicts – to minimize conflicts between left-turn and opposing through vehicles by clearing the left turns through the intersection first.
- 4) Maximize efficiency – left-turning motorists tend to react quicker to a leading left turn than to a lagging left turn.

Lagging Left Turn

Lagging left turns may be used in the following circumstances:

- 1) Minimize through delay – where left-turn lanes exist, it minimizes the use and length of the protected left-turn phase by allowing left turns to be made during the preceding through green phase when adequate gaps occur in opposing traffic.
- 2) Signal coordination – where a time-space diagram indicates that a lagging left-turn signal phase will increase the arterial green bandwidth and improve signal progression.

Lead-Lag Left Turn

Lead-lag left turns may be used in the following circumstances:

- 1) Lack of left-turn lanes – on one and two lane approaches that lack left-turn lanes.
- 2) Signal coordination – where a time-space diagram indicates that a lead-lag left-turn combination in the proper direction will increase the arterial green bandwidth and improve signal progression.

- 3) Unequal left-turn volumes – to allow for the separate timing of each left-turn phase when using a pre-timed controller.
- 4) Inadequate intersection geometry – at intersections where there is inadequate room for opposing left-turn movements on the same street to move simultaneously without conflicting or crossing. Protected-only left turns must be used.

Summary of VDOT Regional Guidance on Left-Turn Phasing

VHB solicited feedback from the VDOT Regional Offices regarding existing guidelines, practices and rules-of-thumb employed by the districts/regions in left-turn phasing selection. Four of the five Regional Operations offices responded to the inquiry. Responses are summarized below.

VDOT CENTRAL REGION OPERATIONS

In assessing the need for left-turn protection, the VDOT Central Region Operations (CRO) uses the following criteria:

- Adequate sight distance including assessment of opposing left-turn sight distance obstruction
- Number/rate of crashes for existing permitted operations
- Opposing volume (no indication if this includes opposing right turn volume)
- Speed limit

If there are three or more opposing through lanes, the CRO recommends Protected Only mode.

In determining the mode and sequence of left-turn signal phasing, the CRO gives priority to the following factors (in order of priority):

- 1) Safety
- 2) Traffic volume
- 3) Roadway geometry
- 4) Traffic conditions (including queuing, delay, V/C ratio, ped/bike volumes, heavy vehicles, speed limit)
- 5) Driver gap acceptance

While the CRO provided a prioritized list of factors to consider in determining left-turn phasing mode and sequence, the CRO did not provide specific parameters or thresholds for those factors.

The CRO had the following feedback regarding left-turn phasing sequence:

“It is very helpful as a signal timer to have the ability to lead-lag left-turn movements on the arterial in order to maximize green bandwidth. The CRO uses lead-lead only sequencing for five-section

Protected/Permissive left-turn operation, which seriously impacts the ability to obtain two-way progression and keep the cycle length reasonably short.”

VDOT NORTHERN REGION OPERATIONS

The Northern Virginia Region Operations (NRO) developed a series of guidelines for left-turn phasing in 2003, and is currently in the process of revising this document to bring it more in line with current practice and to correct a few problems in the prior version. The new version of the guidelines has not been finalized as of August 2013. Both the old and new guidelines address left-turn mode selection only.

Mode

(The mode selection guidance below comes from a draft of the 2012 guidelines.)

Protected Only phasing shall not be used on an approach without an exclusive left-turn lane, except where all lanes of the approach are served by only one phase. This condition is typical of approaches served by split phasing.

Protected Only left-turn phasing shall be used on an approach to a traffic signal where either of the following conditions exists:

- Sight distance on the approach is insufficient to safely judge a gap in opposing traffic; or
- There is more than one left-turn lane on the approach.

Unless the exception below applies, Protected Only phasing shall be used on an approach where either of the following is true:

- Where there are two or fewer lanes on the opposing approach that can be used by through traffic and the speed limit* on the opposing approach is 55 mph or greater.
- Where there are three or more lanes on the opposing approach that can be used by through traffic and the speed limit* on the opposing approach is 50 mph or greater.

** Where the speed limit is not available or not representative of traffic conditions, an alternative measure, such as the 85th-percentile speed, may be used.*

Unless the exception below applies, Protected Only phasing should be used on an approach where either of the following is true:

- On approaches that allow permissive turns, a pattern of angle crashes exists that could be corrected by converting to Protected Only phasing.
- The opposing approach operates with Protected Only phasing. Preliminary VDOT research suggests that crash rates are greater where one approach uses Protected Only lefts and the

opposing direction uses Protected/Permissive lefts. (However, further research is needed to better understand this trend.)

Exception: Even on an approach that satisfies one or more conditions in the previous two paragraphs, Protected/Permissive phasing should be used if traffic volumes are so high that, if Protected Only phasing were used, a queue would frequently extend out of the left-turn bay, impeding through traffic and potentially contributing to a rear-end crash problem.

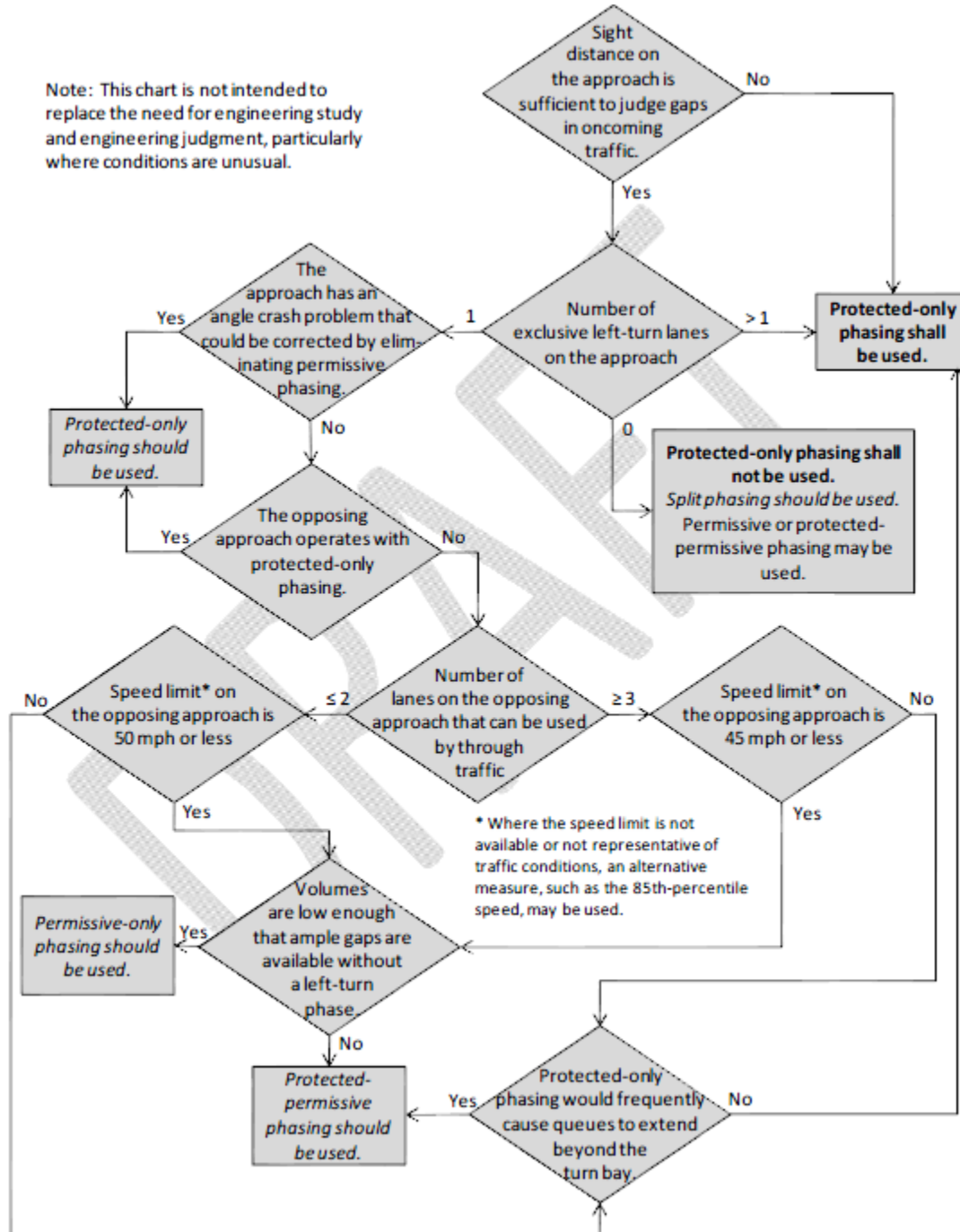
Permissive Only left-turn phasing should be used on an approach where all of the following are true:

- The volume of turning traffic and opposing through traffic is low enough that a sufficient number of gaps are available for left-turning traffic to proceed with reasonable delay without a protected phase.
- Sight distance on the approach is sufficient to safely judge a gap in opposing traffic.
- The approach does not have a pattern of angle crashes that could be corrected using Protected Only phasing.

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The Northern Virginia District's new guidelines also include a flowchart (see below) to assist in left-turn mode selection.



Sequence

The following information on left-turn sequence selection was provided by the NRO office via email correspondence, and represents general practices and rules of thumb rather than formal guidelines.

In the NRO, typical practice is to use lead-lead phasing for left turns unless there is a reason to do otherwise. The NRO plans to use lead-lag phasing more aggressively in the future to improve corridor progression, but this has been very limited so far. Usually lagging lefts are used only where needed because of geometric constraints (e.g., overlapping left-turn travel paths) or safety reasons (e.g., avoiding a yellow trap).

Lagging lefts can have a disadvantage at coordinated signals when they do not use the full phase duration. The NRO defines the coordination point as the end of mainline green, and as such, a lagging mainline left takes away the controller's ability to vary the length of the left-turn phase without also cutting short the concurrent mainline green. In some cases, NRO has placed the lagging left on max recall to prevent the mainline from ending early, and in other cases NRO has allowed the mainline to end early when the lagging left gaps out. Both of these approaches have disadvantages.

VDOT SOUTHWEST REGION OPERATIONS

The Southwest Region Operations (SWRO) responded to each survey question individually. Following are the SWRO's response to each question.

Q: Does your region have uniform, formal policy or guidance on left-turn phasing at signalized intersections on state-maintained roads? If so, is this policy/guidance available online?

A: SWRO uses guidelines provided in the *Signal Timing Manual* (Figure 4-11), a FHWA document that is available online for free. (NOTE: The same left-turn mode selection flowchart used by SWRO is included in the Texas Transportation Institute's mode selection guidelines, highlighted in the summary of state DOT guidelines above).

In addition to safety, the geometrics of the intersection are considered as primary elements and are interrelated when considering whether permissive left-turn movements are appropriate.

1. Crash history
2. Sight distance
3. Left-turn and opposing through volumes
4. Number of opposing through lanes
5. Speed of opposing traffic

SWRO also considers the following parameters related to operations to determine phasing at signalized intersections.

6. Delay
7. Queuing
8. Cycle length

Q: What are the existing criteria/guidelines for determining the mode and sequence of left-turn signal control in your region?

A: Typically, SWRO uses guidelines provided in the *Signal Timing Manual* and ITE Manual (*Traffic Control Device Handbook 2001*) to determine mode for left-turn movements. Mostly, SWRO provides a lead-lead left-turn phasing sequence. However, depending upon the width of intersection, ability to turn lefts concurrently for opposing left-turning movements especially at intersections with dual left-turn lanes, and demand of traffic volumes SWRO provides lead-lag left-turn phasing. Furthermore, based on the roadway geometry (storage bay length) and demand of traffic volume SWRO considers lag-lag left-turn phasing as well. Please note that SWRO provides Protected Only left-turn phases when lead-lag left-turn phasing is considered.

In addition, field observations and use of traffic engineering software are also considered while selecting mode and sequence of left-turn phases.

Q: In determining the mode and sequence of left-turn signal phasing, what priority do you give to the following parameters:

- Volume
- Roadway geometry (e.g., intersection sight distance, signal sight distance, lateral offset between opposing left-turn lanes, etc.)
- Safety (e.g., crash history / expectancy)
- Signal timing (e.g., green share, corridor progression & bandwidth)
- Traffic conditions (e.g., queuing, delay, V/C ratio, ped/bike volumes, heavy vehicles, posted speed limit)
- Driver gap acceptance

A: SWRO considers safety as the first priority followed by roadway geometry, traffic conditions, volume, driver gap acceptance, and signal timing while determining mode and sequence of left-turn phasing. It is assumed that there is no deficiency in roadway geometry while providing the above list. The crash threshold provided in the *Signal Timing Manual* may be high for Southwest Region because of rural settings. Therefore, SWRO also uses engineering judgment while evaluating mode for left-turn movements based on frequency of left-turn crashes at signalized intersections.

Q: Do you have any suggestions or good experiences about the determination of the mode or the sequence of left-turn signal phasing that you can share?

A: In addition to the guidelines, SWRO considers field observations and sound engineering judgment as critical components while determining the mode and/or sequence of left-turn phasing. Depending upon

the demand of left-turning vehicular traffic and left-turn storage length, SWRO also considers providing protected-only left-turn phase twice in a cycle where a left-turn permissive phase is deemed unsafe because of inadequate sight distance, inadequate available safe gaps for left-turning vehicular traffic to complete their maneuver during the permissive phase and so forth. In addition, considering the driver's expectancy and to provide consistency, SWRO attempts to provide similar left-turn mode along a corridor as geometrics allow.

Some rules of thumb (based on HCM 2000) that SWRO considers are:

- 1) If left-turn volumes are less than 60 vehicles in an hour, use permissive mode assuming two (2) sneakers per cycle of 120 seconds of cycle length.
- 2) If left-turn volumes are greater than or equal to 100 vehicles per hour, provide a separate left-turn lane (protected/permissive or protected-only depending on various factors provided in the response to first question earlier). However, if right of way is available, SWRO prefers to provide a designated left-turn lane even though peak hour left-turning volume is lower than 100 vehicles to improve safety and operations of an intersection.
- 3) If left-turn volumes are greater than or equal to 300 vehicles per hour, provide dual left-turn phase (protected-only).

VDOT NORTHWEST REGION OPERATIONS

The NWRO, after consultation with their Project Delivery Group, which is responsible for design of signals, responded that they “do not have any internal policies beyond those offered in the ITE and MUTCD manuals”. The FHWA's *Traffic Signal Timing Manual* was also cited as a potential resource on the occasion that left-turn phasing at an intersection comes into question.

APPENDIX A: Left-Turn Phasing Selection Guidance and Practices from Online ITE Member Forum

VHB solicited feedback from ITE members regarding existing state DOT guidance for left-turn phasing selection. Responses highlighted several states' guidelines, which are summarized in the first section of this document. Other responses included local guidelines, as well as practices and rules of thumb employed by traffic engineering professionals in left-turn phasing selection. Those responses are included below.

From an ITE member who works for the City of Federal Way, WA:

My basic philosophy is the best left-turn phase is a skipped left-turn phase. Waiting for "green for hosts" is a pet peeve of mine, so I avoid protected lefts like the plague.

Here is our current formal policy language:

"Left-turn phasing shall be the least restrictive possible:

- 1. Default to permitted.*
- 2. Protected/Permitted if needed for capacity. If exclusive left-turn lanes are provided, flashing yellow arrow displays shall be used.*
- 3. Protected if sight distance inadequate (based on AASHTO intersection sight distance criteria for left-turns into minor approach - Case F), high pedestrian volumes, high conflicts or accident experience, more than one left-turn lane, or for lead/lag operation."*

Current practice is evolving to flashing yellow arrow everywhere there is a dedicated left-turn lane, and then make the decision about how to run it. One advantage of installing FYA where permitted would otherwise work just fine is in pre-emption, but I also like having the flexibility to address transient peaks in left-turn volumes due to detours or incidents. I also have a location that we will eventually put in FYA even though it's a dual left, and there may be more, even against 3 or 4 opposing lanes, at least by time-of-day. I will run a FYA approach in protected only mode by TOD if there are no gaps available.

As for sequence, if the corridor is coordinated, I'll run whatever gives me the best greenbands. I try to lag heavier movements. If the approach isn't coordinated, I lead most protected lefts (but I lag them if they are particularly heavy), and lag all FYA approaches and have the left-turn detection extend the opposing through movements to maximize the opportunity for the left turn to move without calling up the left-turn phase.

We use 5 left-turn collisions per approach per year as the threshold to go to Protected Only phasing. Other than that and sight distance, I'm really leaning towards LADOT's use of gap availability by TOD.

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From a Canadian ITE member:

A very old rule of thumb that I have used for 40+ years is:

- *If there are more than 100 left turns, then a separate left-turn lane is probably required*
- *If there are more than 100 left turns and the opposing volume is more than 400 vph, then a separate left-turn phase is probably required.*

From an ITE member from Sunnyvale, CA:

The beauty of the four section, all arrow P/P left-turn signal is that you can have:

- *protected only, when traffic is heavy and gaps in opposing traffic are few or nil*
- *protected then permitted or, with a queue detector or a delay function on the detector sensor, permitted then protected*
- *permitted left turns when traffic is light, which in a 24 day is most of the time.*

With the "dog house" P/P signals, you cannot prevent a permitted left turn whilst the left-turn green arrow is not displayed and the adjacent through traffic is shown the circular green signal. This can occur when a protected only left turn is the better solution.

Another discussion thread from the ITE online forum included a question regarding criteria for changing from Protected/Permissive mode to Protected Only mode. Following are select responses from that thread.

From an ITE member who works for MassDOT:

One gauge I use is checking conflicting volumes by taking the left-turn volume and multiply it by the opposing through movement and if that number comes out to be over 80,000 then I start considering protecting the left turns. The idea is that the number of conflicting movements don't allow for enough left turns to process which in turn increase the left-turn delay (which will probably show in the analysis). This may cause these motorists to take chances they are typically not comfortable making. Crash history definitely needs to be looked at (not only as good practice) but to determine how frequent crashes are occurring for a particular intersection and compare them to the state averages per million vehicles entering. Looking at the actual police reports may also shed some light on why the crashes are happening such as bad sight distance, ped conflicts, lack of storage, etc. so there may be other ways to fix the issue.

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From an ITE member who works for VDOT:

Signal Timing Manual has pretty good guidelines on how to determine permissive vs protected or Protected/Permissive phase. A few parameters to consider are listed below:

1. *Left-turn and opposing through volumes*
2. *Number of opposing through lanes*
3. *Cycle length*
4. *Speed of opposing traffic*
5. *Sight distance*
6. *Crash history*
7. *Delay/Queue*

From an ITE member who works for the city of Boulder, CO:

Actually we've had good success with using Protected/Permissive phasing (by time of day) on dual left-turn lane approaches. We are certainly not the only community in Colorado to do this either. I've yet to see any data that supports the premise that multiple left-turn lanes requires protected only phasing. I've always considered that to be "Folklore".

The ITE Handbook provides both a volume criteria and a safety criteria (4 correctable accidents in one year or 6 correctable accidents in two years) to provide protected phasing. This is the criteria that we use to assess a need for protected phasing. Furthermore we make this assessment by time of day (if all the accidents occur in the PM peak we only provide protected phasing in the PM peak).

From an ITE member from Las Vegas, NV:

Allow me to add credence to it being "Folklore" that dual lefts require protected only. When I was starting my municipal traffic engineering career in Richardson (TX) in the early 1980's, dual left-turn lanes were the BIG NEW THING. We went ahead and built signals at all of our major-crossing-major intersections having dual left turns with 5-section left-turn heads, and they almost all ran PPLT 24x7x365. The drivers became accustomed to it, and didn't crash (at a too-high rate).

You can Google Street View just about any major arterial intersection in Richardson today, and you'll see this practice survives 30 years on.

From an ITE member from Sunnyvale, CA:

Denver Colorado has at least one double left-turn lanes permitted left turn crossing a two lane approach. I observed the operation and it seemed to function as intended, safely. Also, I installed eight (four intersections) single lane permitted left turns, six of which crossed three lane approaches and the

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other two[.] All enjoyed excellent safety records. One element to success is visibility. If left-turning traffic can see oncoming traffic, they usually make good decisions. When there are no or few adequate gaps in approaching traffic, a protected left turn is necessary, however, there are times in the 24 hour day when a permitted left turn is perfectly safe, regardless of the number of lanes. Then, there are time[s] in between when P/P is best.

From an ITE member who works for the city of Kennewick, WA:

It is not necessarily true that two lanes require Protected Only phasing. We run two locations like that. Our first location was turned on December 20th, 2004. It now serves a Home Depot, Walgreen's, Starbuck's, Pet Smart, and a few other small shops while the other side is single turn lane and serves Wal-Mart, Burger King, Best Western, McDonalds and a gas station.

This setup works fine because the two lanes both have clear vision of oncoming traffic, the opposing traffic is random arrival, and has adequate gaps. The two-lanes were needed for storage due to [its] close proximity to a US Highway. Both turn lanes get used regularly and simultaneous traffic turning from the two lanes is not uncommon. I checked statistics and the actual left turn on the dual lane side gets triggered 20% of cycles or less. The Wal-mart side gets triggered about 50% of the time through the peak hours.

We converted a similar location in 2008 from Protected Only to PPLT with FYA that also works fine.

If you want to check them out use Bing for aerials because Google maps are too old to show current configuration. If you want street level, then use Streetview in Google maps. The first intersection is 27th Avenue and Quillan Street and the second is 10th Avenue and Huntington Street.

From an ITE member who works for the city of Wilmington, NC:

For single left-turn lanes, I rarely find that the signal needs protection 24/7/365. Herein lies one of the wonderful applications of the FYA. It affords the ability to run the needed indication according to the conditions. For duals, we have seen permitted operation and have just discovered the NCDOT is experimenting with them. We have one location out of 212 that we think may lend itself to this operation. Like the previous point, rarely do we need duals in the overnight hours. I think the technology will evolve that we can vary the duals by TOD. Therefore the outside turn lane would run with a standard three section head and the inside with a 4 section FYA. During times when the duals are needed, the FYA would be extinguished and full protection afforded. Later, when appropriate the FYA activated and the outside lane closed with a blankout sign. The three section[s] would stay red and the blankout sign would flash if the detector for that lane became active.

Point here, as technology changes we should seriously examine the past paradigms to see whether application of this technology can provide better service to our customers without sacrificing safety. By

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displaying the correct design for the conditions, we are also most likely to gain the best compliance from our roadway users and generate respect for the work we do. Let's also remember that most signals are designed to handle the peak hour load which by logic of the K factor represents only 20% of our users. What about the other 80%?

From an ITE member who works for the city of Irvine, CA:

Very good question. This is something we have had to address more often in my City. In addition to the previous excellent responses, I would like to add two more things to consider: (1) I'm told that the 100,000 product (LT vs. opposing thru) is losing its luster as a good "threshold" warrant. If that value is attained, fine, but more consideration needs to be given to peaking characteristics of both the LT and opposing thru volumes, and how the volume "curve" looks throughout the day.

*(2) Perhaps the bigger issue is the presence of pedestrians. I have received many calls from pedestrians about near-miss incidents where the ped phase serves at the same time as the green ball (i.e., unprotected LT phase). As it turns out (every time!), the pedestrian believes that the ped crossing is exclusive to pedestrians because he/she is not cognizant of what signal indication the motorist is seeing. At the same time, the left-turning motorist is not only surprised that the pedestrian is already out in the crosswalk, but also fails to yield. The upshot is that I'm writing more work orders for the new R10-15 sign with a **left** arrow. Of course, adding the protected LT would resolve virtually all of the uncertainty. Pedestrians view this as a distinct safety enhancement. [Note: Irvine, CA, has protected LT phasing at the vast majority of its signalized intersections; thus, both drivers and peds are subconsciously used to this, which means that the permissive LT is problematic if driver and/or ped is somehow distracted]*

From an ITE member who works for the city of Bellevue, WA:

We no longer view it as a 24/7 decision usually. If you have 5 accidents and they are also in a certain time block (congestion maybe?) we use the FYA displays and just run Protected only during this time block.

In our CBD because of the pedestrian conflicts we use to go to protected quite often, but with FYA we have many we run protected during the day (~12 hours) and FYA overnight (~12 hours). We have been running this for 2 years with no issues. We more recently developed a FYA Ped Protect logic that omits the FYA during the Walk and FDW phase, then can reserve the FYA on mainline if there is enough split left to serve min green and clearance. This is allowing us to use FYA during the day in the CBD, when the only issue was pedestrian conflict complaints.

We have one location that the FYA crosses 3 lanes and is steep uphill (slow acceleration) and has been running without problems for 2 years. I agree with Rick Perez (Federal Way) that the number of lanes crossing has been over-used as a criteria.

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I would use FYA displays as the base display, then you have the flexibility to run permissive only, Protected/Permissive, protected only.....you can also lead/lag.

We haven't done dual left-turn lanes with FYA, but are contemplating it. The cross product method several state DOT use may give you an idea of times you need to examine for acceptable gaps and potentially go protected only.