Traffic Signal Phase Sequence Guidance Document

Final Report

March 2011

SHA State Highway Administration
Maryland Department of Transportation

SABRA, WANG & ASSOCIATES, INC.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

APPENDIX A: STANDARD FORM

REFERENCES

I. INTRODUCTION

A. Project Description and Purpose

The purpose of this project is to develop a guidance document for the Maryland State Highway Administration (MDSHA) to use in the following:

- Determine applicable conditions to lead vs. lag left turn phases,
- Determine applicable conditions to service left turns twice in the same cycle, and
- Determine the sequence of implementation of side street phases when they are split phased.

The overall project consists of the following sub-tasks:

a) Literature review and survey of the state-of-the-practice,
b) Evaluation of human factors issues,
c) Development of a guidance document, and
d) Development of a standard form to streamline and document the process of getting approvals.

B. Terms and Definitions

a) Left turn Phase Types/Modes

The following terms and definitions are used throughout this report to denote types and modes of left turn phases:

- **PO**: Protected-Only (PO) left turn phase – Left turns are made only when a left-turn GREEN ARROW signal indication is displayed. There is no conflicting vehicular or pedestrian traffic (*1*). The signal display for this mode is illustrated in **Figure 1**. The ring-barrier structure associated is indicated in **Figure 2**.

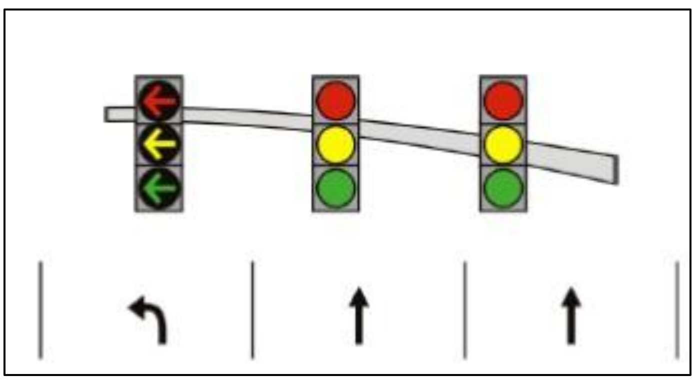

Figure 1: Protected Only (PO) left turn signal display
(Source: Signal Timing Manual, 2008 – FHWA)

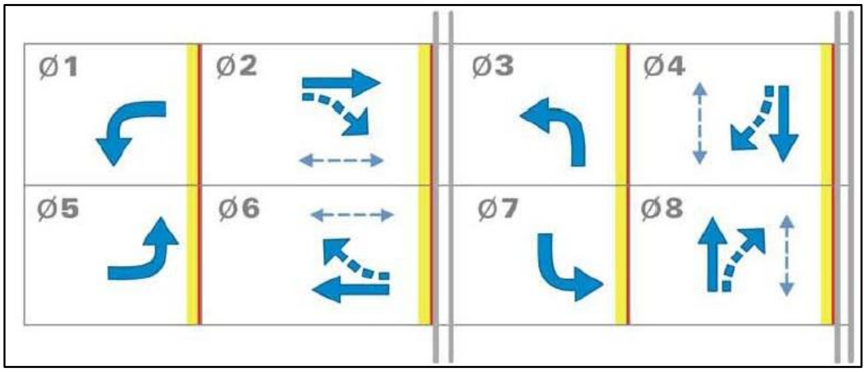

Figure 2: Ring & Barrier Structure for Protected Only (PO) left turn display
(Source: Signal Timing Manual, 2008 – FHWA)

- **Permissive**: Left turns are 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 (*1*). The traffic signal display for this mode is illustrated in **Figure 3**. The ring-barrier structure associated is indicated in **Figure 4**.

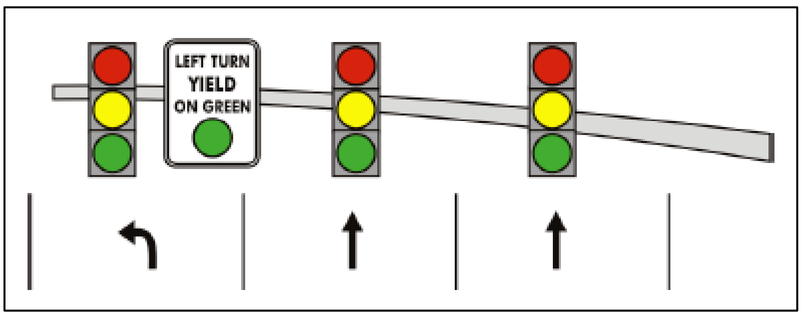

Figure 3: Permissive left turn signal display
(Source: Signal Timing Manual, 2008 – FHWA)

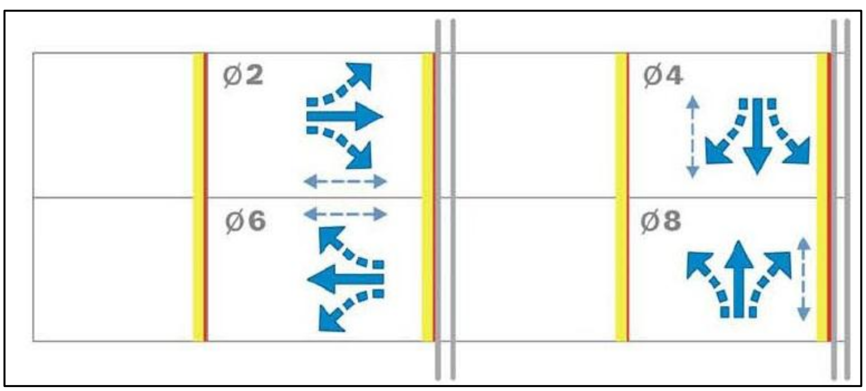

Figure 4: Ring & Barrier Structure for Permissive left turn display
(Source: Signal Timing Manual, 2008 – FHWA)

- **E/P**: Exclusive/Permissive (E/P) or Protected/Permissive left turn phase – is a combination of both the protected-only and permissive modes whereby left turns may be made during the green display as defined under the respective modes (*1*). The traffic signal display for this mode is illustrated in **Figure 5**. The accompanying ring-barrier structure is indicated in **Figure 6**.

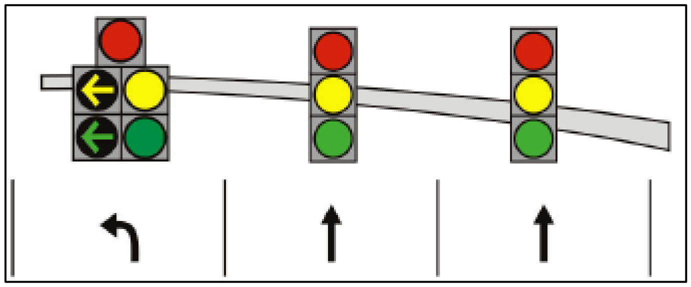

Figure 5: Exclusive/Permissive (E/P) left turn signal display
(Source: Signal Timing Manual, 2008 – FHWA)

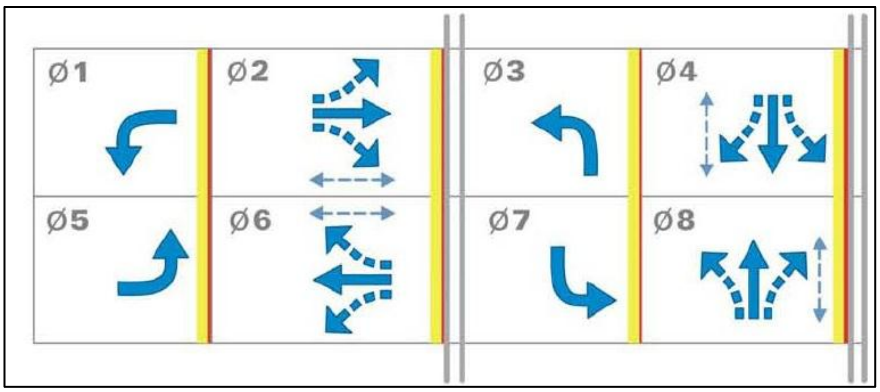

Figure 6: Ring & Barrier Structure for Exclusive/Permissive (E/P) Lead-Lead left turn display
(Source: Signal Timing Manual, 2008 – FHWA)

b) Left Turn Phase Sequencing

- **Lead-Lead Left Turn Phase Sequence:** The Lead-Lead left turn phase sequence has both opposing left-turn phases starting and operating simultaneously (*1*). **Figure 6** shows the ring-barrier structure of a Lead-Lead left turn sequence.
- **Lead-Lag Left Turn Phase Sequence:** The Lead-Lag left turn phase sequence has one of the opposing left turn phases starting and operating concurrent with its respective through movements, and the other left turn phase starting subsequent to the opposing through movement and ending simultaneously with its concurrent through movement (*1*). **Figure 7** indicates the ring-barrier structure of a Lead-Lag left turn sequence.

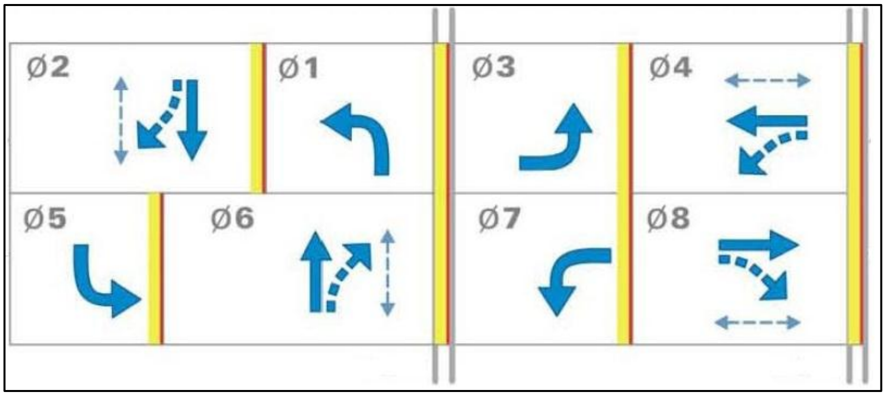

Figure 7: Ring & Barrier Structure for Lead-Lag left turn display
(Source: Signal Timing Manual, 2008 – FHWA)

- **Lag-lag Left Turn Phase Sequence:** The Lag-Lag left turn phase sequence has both opposing left-turn phase sequences starting subsequent to the through movements and ending simultaneously (*1*). **Figure 8** illustrates the ring-barrier structure of a Lag-Lag left turn phase sequence.

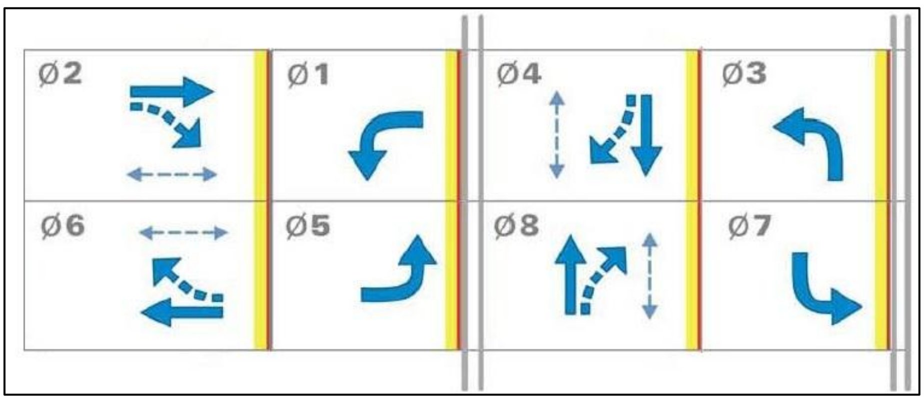

Figure 8: Ring & Barrier Structure for Lag-Lag left turn display
(Source: Signal Timing Manual, 2008 – FHWA)

- **Split Phasing:** Split phasing represents an assignment of the right-of-way to all movements of a particular approach, followed by all of the movements of the opposing approach (*1*). **Figure 9** illustrates the signal head display for a typical side street split phase operation and **Figure 10** indicates the associated ring-barrier structure.

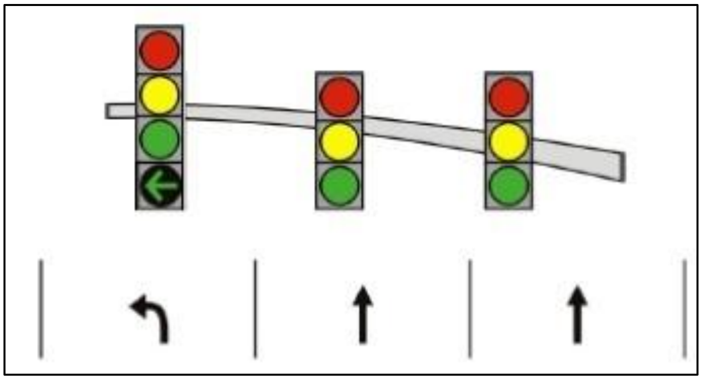

Figure 9: Split phasing signal display
(Source: Signal Timing Manual, 2008 – FHWA)

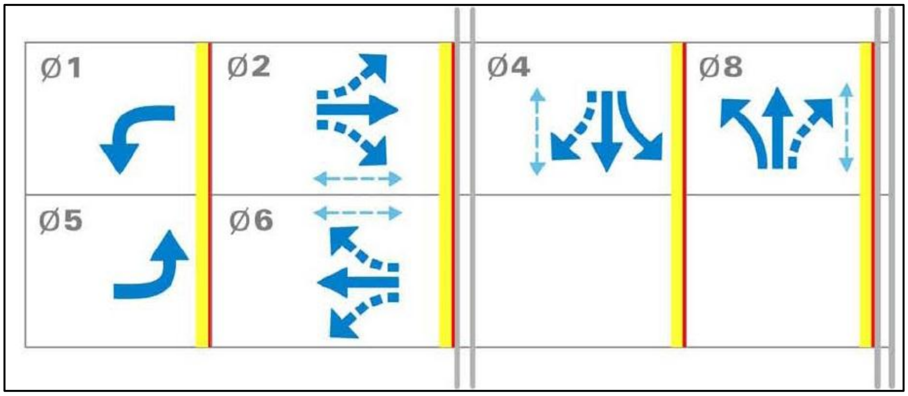

Figure 10: Ring & Barrier Structure for Split phasing operation
(Source: Signal Timing Manual, 2008 – FHWA)

- **TPCLT**: Twice-per-cycle left turn phase – where a PO or E/P left-turn movement is serviced both as a leading AND a lagging left turn phase during the same cycle (*1*). A modified ring-barrier structure with the eastbound and westbound left turns serviced twice within the same cycle is shown in **Figure 11**. Note that the assignment of phase numbers (in this case, ø21 and ø25) vary according to agency preferences.

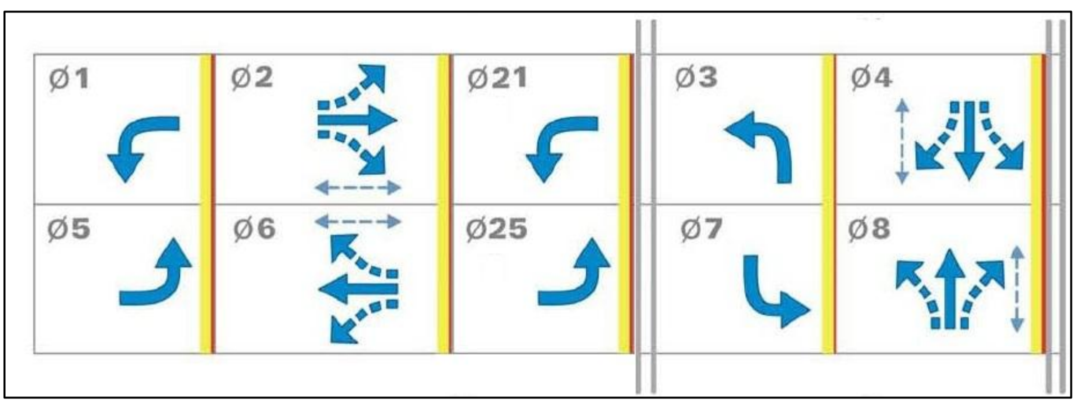

Figure 11: Ring & Barrier Structure for TPCLT operation
(Source: Signal Timing Manual, 2008 – FHWA)

- **Yellow Trap**: Yellow trap or left turn trap is a condition that leads the left-turning driver into the intersection when it is possibly unsafe to do so even though the signal displays are correct (*1*). This occurs when a left-turn driver seeking a gap in oncoming traffic during the permissive phase, first sees the yellow indication, then incorrectly assumes that the opposing traffic also sees a yellow indication, and proceeds to complete the turn without regard for the availability of a safe gap. **Figure 12** in *Section II* illustrates the yellow trap conditions.

II. Literature Review, Agency Contacts and Interviews

A. Summary of Literature Review

This section summarizes the work performed on researching existing literature for guidelines on implementation of various left-turn phase sequences. The main objectives of performing a review of existing reports and publications were:

- To examine research on the safety impacts of various left turn phase sequences.
- To examine research on operational impacts of various left turn phase sequences.
- To identify if any warrants for implementation of various left-turn phase sequences have been developed.

Table 1 outlines the list of documents that were researched during the literature review process:

Table 1: Summary of Literature Review

Title (Publish Date)	Author(s)	Remarks	Conclusions
Guidelines for Use of Leading and Lagging Left-Turn Signal Phasing (1991)	Joseph Hummer, Robert Montgomery, Kumares Sinha	Research study provides guidelines for type of left turn phase sequence	- In coordinated signal systems, use should be made of any phasing sequence on a particular approach that will maximize the through bandwidth. - Lagging left turn phase sequences should be used at isolated signals serving heavy pedestrian traffic. - The research study provided a flowchart to aid in the decision making process for identifying left turn phasing sequence of individual intersections.
Improved Protected-Permitted Left-Turn Signal Displays – The Texas Approach (ITE Journal, October 1992)	Gerry De Camp, Richard Denney	Discusses Dallas Phasing***** methodology for mitigation of yellow trap conditions occurring during lead-lag E/P phasing.	Based on public reaction and studies conducted by TxDOT, Dallas Phasing***** technique appeared to be an effective tool to prevent “Yellow Trap” conditions.

Title (Publish Date)	Author(s)	Remarks	Conclusions
Selection Criteria For Left-Turn Phasing Indication Sequence, And Auxiliary Sign (1993)	Seth Asante, Siamak Ardekani, James Williams	Research study provided guidelines for type of left-turn protection and sequencing based on a three-level decision process.	- Leading sequence recommended for PO and E/P phasing as a default. - Lagging sequence recommended where it is intended to improve intersection safety. - Lead-Lag sequence recommended where there is inadequate space to accommodate dual left operation or to improve progression. -Dallas phasing***** recommended for E/P left turns or if the 3-year accident total exceeds seven but a PO left turn will result in unacceptably high delays. *Dallas Phasing: The 2009 MUTCD prohibits the use of Dallas Phasing in favor of the Flashing Yellow Arrow (FYA) arrangement for new installations (MUTCD Sections 4D.18 and 4D.20)
The 10 Major Pitfalls of Coordinated Signal Timing (ITE Journal, August 1993)	Jeffrey W. Buckholz	Article outlines 10 factors that are typically not taken into account while performing signal coordination	Pitfall No. 5 states that under the right circumstances, the use of a lead-lag operation can be extremely beneficial. However, traffic engineers continue to be wary of implementing it "due to an unreasonable fear of violating driver expectancy", which is unwarranted.
Use of Protected/ Permitted Left-Turn Signal Control in the U.S. (1999)	Kent Kacir, David Noyce, William Kloos & Daniel Fambro	Results of a survey sent to local, county, and state officials to determine the use of E/P signal control in the US	In the US, - 83% of E/P left turns are leading. - 11% of E/P left turns are lagging. - 6% of E/P left turns have lead-lag sequence.
Human Factors Considerations in the Selection of a Uniform Protected/ Permitted Left-Turn Signal Display (1999)	David Noyce	Reviews the human factors aspects of traffic signal operations, focusing on E/P control and the signal display.	Uniform and consistent E/P signal displays can reduce the level of informational complexity placed on drivers.
Twice Per Cycle Left-Turns (2000)	Technical Note, Naztec	Describes the advantages of servicing left turns twice in the same cycle	- TPCLT operation is useful where left turn bays are over capacity and queue spill-over occurs - TPCLT is even more effective when dual-left-turn lanes are used.

Title (Publish Date)	Author(s)	Remarks	Conclusions
Dynamic Change of Left Turn Phase Sequence between Time-Of-Day Patterns – Operational and Safety Impacts (2000)	Douglas Hess, Kanth Nandam	Discusses the operational impacts of the use of lead-lag left turn phasing (at PO left turns) and dynamically changing the phasing sequence by time-of-day.	Dynamic change of left turn sequence by time of day did not have any impact on the safety at the intersections in the study.
Guidelines for Timing and Coordinating Diamond Interchanges with Adjacent Traffic Signals (2000)	Nadeem Chaudhary, Chi-Leung Chu - TTI	Contains guidelines for timing diamond interchanges and for coordinating diamond interchanges with closely spaced adjacent intersections.	Research performed recommends the following control strategies: - Use Texas Three-Phase strategy for compressed diamond interchanges. - Use TTI Four-Phase strategy for tight diamond interchanges. - Use extended Three-Phase strategy for conventional diamond interchanges.
Evaluation Of Traffic Signal Displays For Protected/ Permissive Left-Turn Control (2003)	NCHRP Report 493	Research evaluated the safety and effectiveness of different signal displays and phasing for E/P control through laboratory and field studies.	Comprehensive research into the use of “Flashing Yellow Arrow” (FYA) indication. Concludes that FYA display is an ideal remedy for “Yellow Trap” and can be deployed for E/P lead-lag phasing.
Using Uneven Double Cycles to provide effective Arterial Traffic Signal Operations (2007)	Wayne Kurfees	Describes the use of uneven double cycles including using twice-per cycle left turns in signal retiming.	- Lead-Lag phase sequences and TPCLT were used as potential mitigation measures for short turn bay lengths. - Many minor streets were double-cycled to mitigate long wait times.

Title (Publish Date)	Author(s)	Remarks	Conclusions
Traffic Signal Timing Manual (2008)	FHWA	Provides direction and guidance on signal timing issues.	Section 4.4 Left-Turn Phase Sequence Options, provide the following guidance. In addition, Section 6 provides an example time space diagram that illustrates the benefits of lagging a left turn phase in coordination. - Lead-Lead Left-Turn Phase sequence advantages are that drivers react quickly to the leading green arrow indication, and it minimizes conflicts between left-turn and through movements on the same approach, when the left-turn volume exceeds its available storage length (or no left-turn lane is provided). - Lag-Lag Left-Turn Phase sequence is most commonly used in coordinated systems with closely spaced signals, such as diamond interchanges. Lag-lag offers operational benefits for E/P lefts at T-intersections and at intersections of a 1-way and 2-way street. - Lead-Lag Left-Turn Phase sequence is generally used to accommodate through movement progression in a coordinated signal system, where there is inadequate space in the intersection to safely accommodate the simultaneous service of the opposing left-turn movements and at intersections where the leading left-turn movement is not provided an exclusive lane (or the available left-turn storage is relatively small).
Development of Left-Turn Operations Guidelines at Signalized Intersections (2008)	Lei Yu, Yi Qi, Hongxi Yu, Lei Guo and Xin Chen	Report outlines the guidelines developed for recommending the most appropriate left-turn phasing treatments at signalized intersections in Texas.	Recommendations provided to determine left turn phase operation and sequence. Study yet to be formally adopted by TxDOT. The most-common reason for determining left turn phase sequence was platoon progression and bandwidth. See **Table 2** in *Section G* for all factors considered in this report.

Title (Publish Date)	Author(s)	Remarks	Conclusions
Traffic Signal Operations Handbook (2009)	James Bonneson, Srinivas Sunkari, Michael Pratt – TTI	Handbook describes best practices in signal timing, as identified through interviews with TxDOT engineers and technicians, and identifies conditions where alternative practices are equally workable.	- The decision to implement lead-lag phasing should be based on the evaluation of a time-space diagram, or through the use of a software product that can evaluate left-turn phase options. - Lead-lag phasing can improve quality of progression, but may need to be placed on maximum recall.
Traffic Control Systems Handbook (2005)	FHWA	Handbook serves as a basic reference in planning, designing and implementing traffic control systems.	- Describes various left turn phase sequences and describes phase orders (including lag-lag lefts) for diamond interchanges. - Illustrates conditional re-service of a left turn phase. In Conditional re-service the left turn phase appears twice in the cycle, both before and after its opposing through phase, but only if the through movement is sufficiently light. Note that conditional re-service is similar to Twice Per Cycle Left Turns (TPCLT) except that it can only be applied opposite an uncoordinated movement since the opposing through must be able to "gap-out" after it has timed it's minimum. - Notes that "separated phases" logic, may be used to prevent a leading left turn phase from operating concurrently with a lagging left turn phase from the same street if the two turning movements physically conflict in the middle of the intersection.

Title (Publish Date)	Author(s)	Remarks	Conclusions
Signal Timing Under Saturated Conditions (2008)	FHWA		Recommended strategies for maximizing throughput are: - Lag heavy left turns so that left turn spillover does not block the through queue. - Serve phases more than once in a cycle, such as twice per cycle left turns. 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.

Besides the aforementioned literature, Traffic Engineering Manuals belonging to the State Departments of Transportation in California, Florida, Kentucky, Oregon, Minnesota, Michigan, and Texas were reviewed for guidance on the implementation of various left turn phase sequences. However, beyond a cursory description of the various left turn phase sequences and a cautionary note regarding the “Yellow-Trap” condition, none of the manuals in question provided any set guidelines for implementation.

B. Agency Contacts & Interviews

In addition to the review of existing literature, several agencies across the country were contacted to identify standard operating procedures for implementation of the various left turn phase sequences. The following is a list of agencies who have responded to requests for information:

- Traffic Engineering Division, Howard County Department of Public Works
- Traffic Engineering Division, Anne Arundel County Department of Public Works
- Traffic Engineering, Baltimore City Department of Transportation
- Traffic Engineering and Operations Section, Montgomery County Department of Public Works & Transportation
- Delaware Department of Transportation (DelDOT)
- Virginia Department of Transportation (VDOT)
- Traffic Operations Division, Fort Worth District - Texas Department of Transportation

- Department of Transportation Studies, Texas Southern University
- Texas Transportation Institute, College Station Research Center
- Transportation Department, City of Garland - TX
- Traffic Engineering Division, Public Works Department, City of Santa Clara – CA
- Department of Engineering Services, City of Cheyenne - WY

A summary of responses concerning implementation of specific phase sequences is provided below:

a) **Lead-Lag Left Turn Phase Sequence:** The responses indicated that Lead-Lag phasing is currently being utilized at intersections within the jurisdictions of the City of Baltimore, and Howard, Montgomery and Anne Arundel counties in Maryland, various municipalities in Virginia, the Cities of Richardson and Garland in Texas, the City of Santa Clara in California, MDSHA, DelDOT and VDOT, to name a few. The City of Cheyenne utilized the "Flashing Yellow Arrow" signal display for permissive left turn movements, but the left turn phase was lagged at all locations. The implementation of Lead-Lag left turn phasing was considered to improve progression and coordination along a corridor after evaluating the results of an engineering study. In addition, Lead-Lag phase sequences are utilized at intersections where there is inadequate space to safely accommodate left turns from opposing approaches.

b) **Twice-per-Cycle Left Turn:** The responses indicated that the cities of Garland and Richardson in Texas, the City of Santa Clara in California, Howard and Montgomery counties in Maryland, MDSHA and VDOT utilized TPCLT phasing as a mitigation measure for short turn bays which were over capacity. TPCLT phasing also facilitated better progression along a corridor. The implementation of TPCLT phasing was found to have little to no impact on pedestrian movements. The decision to employ TPCLT was made after evaluating the results of an engineering study.

c) **Split Phasing:** Within the jurisdictions of Anne Arundel County in Maryland, MDSHA and VDOT, the standard operating procedure is to lead the lower-volume side street split phase prior to servicing the higher-volume side street. The controllers at such locations are programmed to transfer any unused green time from the lower-volume side street to the higher-volume side street, which in turn provides for more efficient operating conditions.

d) **Dynamic Modification of Lead-Lag Left-Turn Phasing by Time-of-Day:** Dynamic modification of Lead-Lag left turn phasing by time-of-day refers to the operation of different left turn phase sequences to accommodate traffic volumes which vary by the time of day. Howard County, Maryland; City of Winchester; VDOT; and the City of Boca Raton, Florida are known to employ different phase sequences for left turns and vary them by time-of-day. It should be noted that application of Lead-Lag left turn phasing in these instances was limited to Protected-Only left turn control. The decision to dynamically modify left turn phase sequences by time-of-day was made to improve traffic progression after evaluating the results of an engineering study. The application of lead-lag left turn phasing and dynamically changing the phasing sequence by time-of-day resulted in improved progression with no adverse safety or operational impacts.

A query outlining the various objectives of this project was posted on FHWA's Office of Operations - Operations Knowledge Communities' online discussion board.

C. Evaluation of human factors issues

Human factors relates to the study of human performance, capabilities and behavioral characteristics. This knowledge is critical to ensure that motorists are able to properly interpret, respond to, and obey the various traffic signs and signals. Nearly 83% of the traffic signals with E/P left turns operate in a lead-lead sequence (Kent et al). Since this is an indication that a majority of drivers are less familiar with other forms of left turn phasing, it is essential to investigate driver reaction time and acceptance levels as part of the evaluation of human factors issues. Because drivers are less effective in comprehending complex information in the limited amount of time available to *perceive, decide and react*, it is essential that signal phasing and displays be uniform and consistent. Two commonly held beliefs related to phase sequences are:

1) Changing phase order by time-of-day violates driver expectancy, and
2) Lagging left turn phase sequences require a longer reaction time

However, an examination of existing research, as well as communication with various agencies indicated that the implementation of lead-lag and twice-per-cycle-left turn phasing sequences has yielded positive benefits with no significant impact on driver expectancy or safety (*Evaluation of Traffic Signal Displays For Protected/Permissive Left-Turn Control" – National Cooperative Highway Research Program: Report 493, Howard County Department of Public Works and the City of Garland, Texas)* (*4*)*.* The results of the research study performed by Hess and Nandam (2000), in the City of Boca Raton, Florida, indicated that the application of Lead-Lag left turn phase sequencing with a variation by time-of-day did not have a significant impact on driver expectancy or response times. The study considered the application of lead-lag left turn sequences for PO left turn phases only. Nevertheless, it provides further confirmation that dynamic operation of phase sequences by time-of-day should not be viewed as an impediment to driver expectancy or safety. Further, "*an unreasonable fear of lead-lag operation as it may violate driver expectancy"* was listed as one of the ten major pitfalls of coordinated signal timing (*5*). This leads us to conclude that the implementation of different left-turn phase sequences and dynamic variation of phase sequences by time-of-day is likely to improve traffic operations, without posing a significant impediment to the perception and reaction time of drivers.

As part of the project scope multiple attempts were made to contact FHWA's human factors research group, however no response was received as of the date of drafting this report.

D. Evaluation of pedestrian mobility and safety issues

One of the concerns expressed by MDSHA was the impact of the application of various left turn phasing sequences on pedestrian mobility and safety. Pedestrians are considered to be legitimate users of the transportation system, and they should, therefore, be able to use this system safely and without reasonable delay (*Safety Effects of Marked vs. Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines, FHWA*). Research performed by Hummer et al (*2*) indicated that conflicts of left turning vehicles with pedestrians are almost six times higher with a leading left-turn phase sequence than a lagging left-turn phase, at intersections with high pedestrian volumes. This is caused by pedestrians disregarding the “Don’t Walk” indication (assuming it is safe to walk since the side-street traffic has a “RED” signal), and entering the crosswalk across the approach to which left turning vehicles are destined. Hence, the volume (i.e. high vs. low) and composition (i.e. elderly vs. typical) of pedestrians in a corridor should be taken into account before putting together recommendations for modifying the left-turn phase sequence.

The results of communication with various agencies and interviews with traffic engineers indicated no adverse impacts to pedestrian safety and mobility due to the implementation of the various left-turn phase sequences. However, it should be noted that all concerned parties performed their due diligence in terms of evaluating the results of an engineering study before modifying signal operations.

E. Evaluation of Signal Controller Settings/Hardware issues

MDSHA also expressed concerns about the capability of the current signal controllers to implement the various left turn phasing sequences without causing any conflicts. In particular, where signal phases are operating as an overlap along with an advance warning device such as a Hazard Identification Beacon (HIB) or an Intersection Control Beacon (ICB), situations may arise where a phase may be skipped due to lack of demand and might result in a conflict. However, Mr. Edward Rodenhizer, Division Chief of MDSHA’s Office of Traffic and Safety – Signal Shop, stated that such a conflict does not arise when *Econolite*’s new ASC/3 controllers are used. He also stated that all new traffic signal installations under the purview of MDSHA will be incorporating ASC-3 signal controllers which provide more flexibility for implementation of various left turn phase sequences.

F. Yellow Trap

When exclusive/permissive left turn phases are in operation at an intersection where one approach is lagging the “Yellow Trap” conditions may occur (***Section 1.2.2.6***). Yellow trap or left turn trap is a condition that leads the left-turning driver into the intersection when it is possibly unsafe to do so even though the signal displays are correct (*1*). This occurs when a left-turn driver seeking a gap in oncoming traffic during the permissive phase, first sees the yellow indication, then incorrectly assumes that the opposing traffic also sees a yellow indication, and proceeds to complete the turn without regard for the availability of a safe gap. This condition may occur in the following instances:

i. For "Exclusive/Permissive" left turns in a Lag-Lag phasing sequencing if both the protected left turns do not start simultaneously, a trap condition arises for the left turn adjacent to the first through movement phase to terminate, and occurs during this phase's change period.

ii. For "Exclusive/Permissive" left turns in a Lead-Lag phase sequence, when a permissive left turn is opposed by a lagging protected left turn, the trap condition arises for the permissive phase that is about to terminate and occurs during the phase's change period.

Figure 12 illustrates this condition.

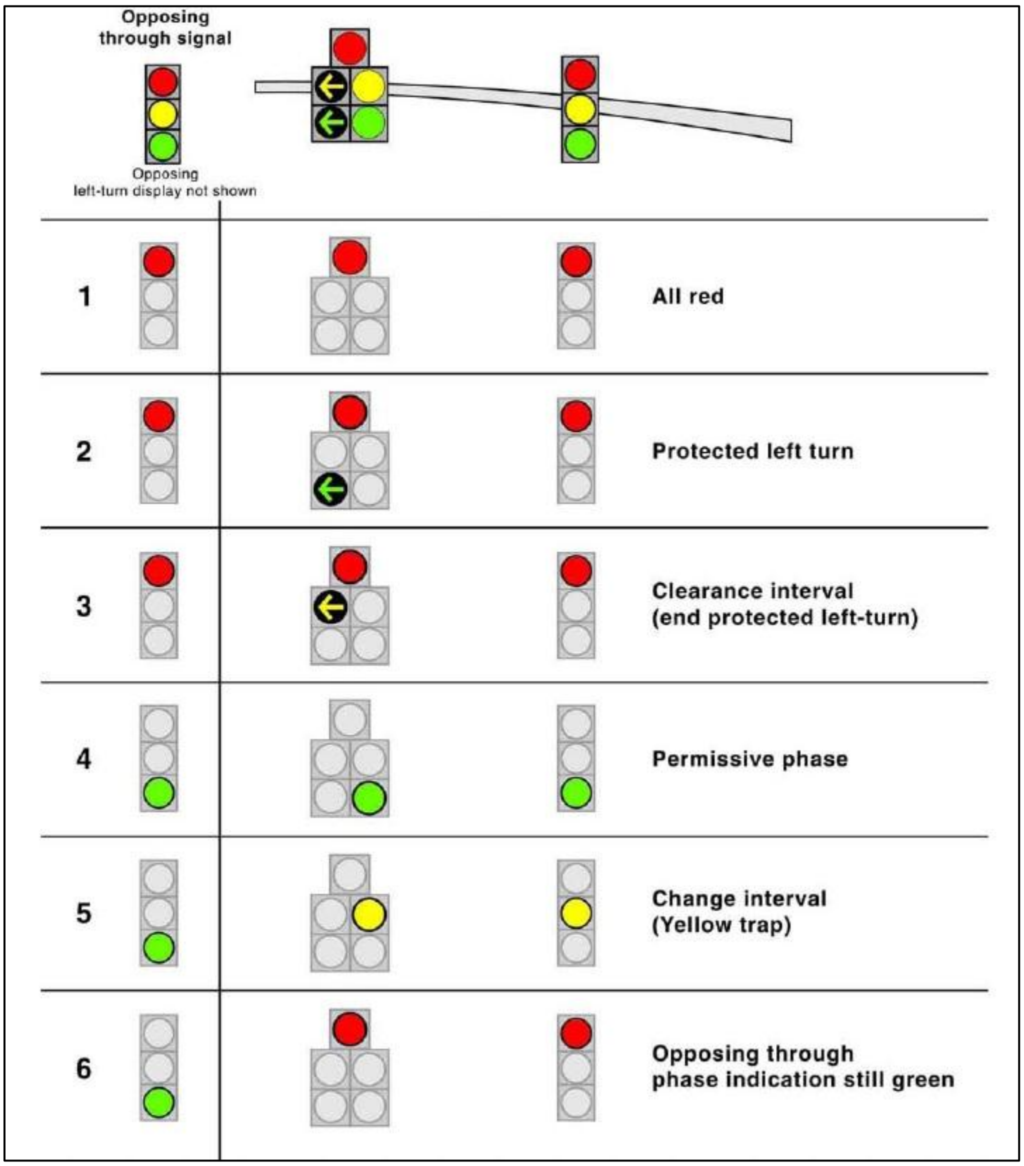

Figure 12: Illustration of "Yellow Trap" condition
(Source: Signalized Intersection Guide, FHWA)

The "Yellow Trap" condition may be mitigated by utilizing the "Flashing Yellow Arrow (FYA)" signal display. **Figure 13** illustrates the FYA display. It should be noted that the 2009 Federal MUTCD prohibits the use of "Dallas Phasing" signal display. "Dallas Phasing" display was a method previously utilized to mitigate the yellow trap conditions.

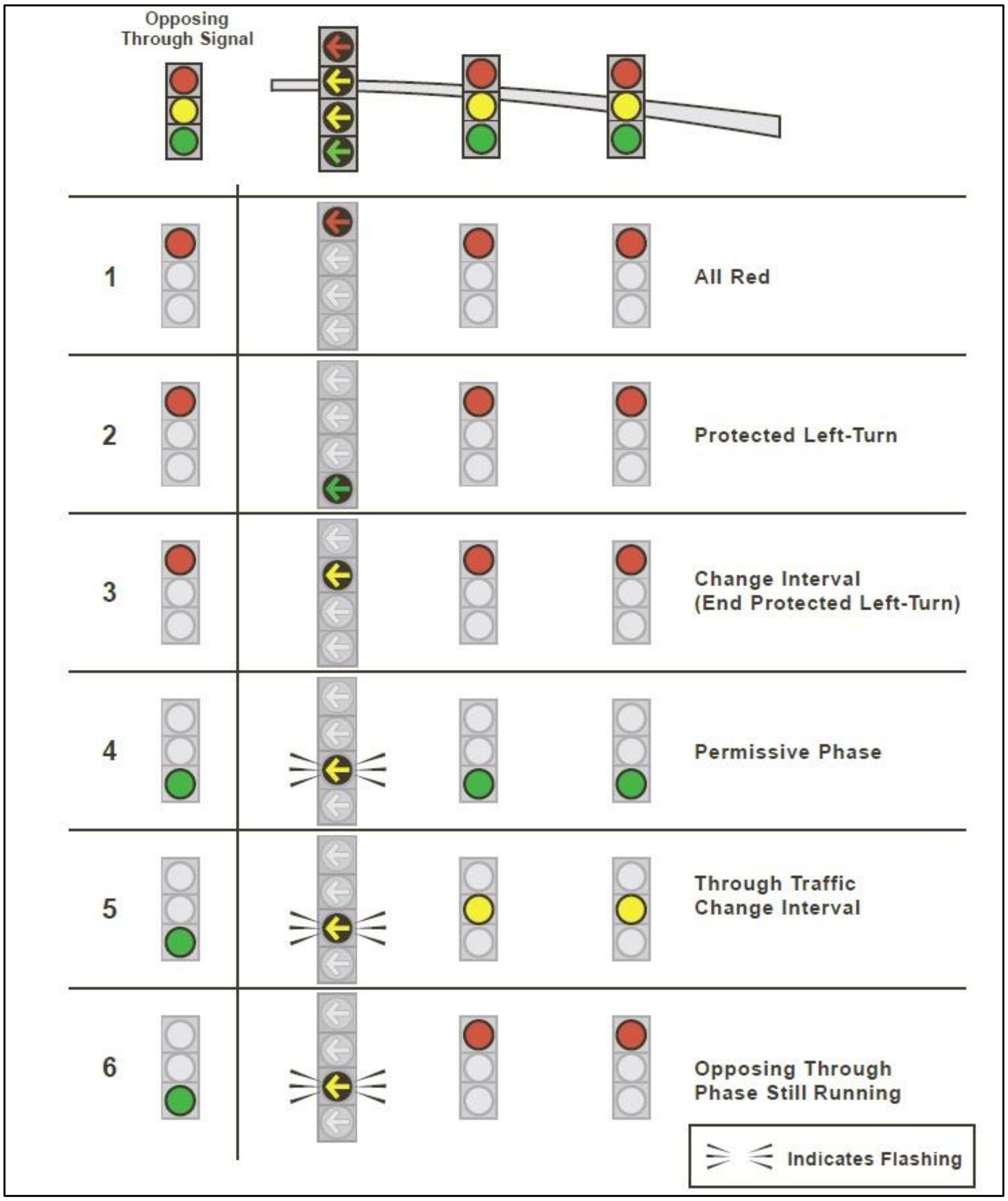

Figure 13: Illustration of Flashing Yellow Arrow Signal Operation
(Source: NCHRP Report 493)

G. Summary of Literature Review and Agency Contacts

The information gathered from the literature review as well agency contacts provided an outline of the operational and safety impacts of the implementation of different left turn phase sequences. Pertinent conclusions and observations from the literature review and communication with various agencies is summarized below:

- Many agencies implement Lead-Lag left turn phase sequences and vary them by time-of-day. The decision to implement Lead-Lag left turn phasing and Twice-Per-Cycle Left Turn phasing was done based on field observations and engineering judgment.
- A majority of the contacted agencies indicated that the decision to implement different left turn phase sequences was taken based on field observations, the results of a traffic study and engineering judgment. Additionally, the decision to modify signal timing and phase orders was undertaken by the "Traffic Operations" or "Signal Timing" groups and formal approvals were reserved within the respective group.
- No existing policy document or internal agency memorandum was found which provides guidelines for implementation of the different types of left turn phase sequences.
- Research reports titled "*Guidelines for Use of Leading and Lagging Left-Turn Signal Phasing"* by Hummer et al (*2*), and "*Selection Criteria for Left-Turn Phasing Indication Sequence and Auxiliary Sign*", by Ardekani et al (*3*), were the only documents obtained which provided a set of criteria for the selection of appropriate left turn phase sequence. The results of these research studies have been extensively quoted in various transportation engineering reference manuals, including ITE's *Traffic Engineering Handbook*.
- The Transportation Department of the City of Garland, Texas indicated that field observation of traffic operations at intersections with Lead-Lag or Twice-Per-Cycle Left Turn phasing did not seem to indicate any violation of driver expectancy. The observations collected from the City of Garland also indicate that there were no significant safety impacts to pedestrian movement with the implementation of lead-lag and twice-per-cycle left turn phase sequence.
- The results of the research study performed by Nandam et al (*6*), in the City of Boca Raton, FL indicated that the application of lead-lag left turn phase sequencing with a variation by time-of-day did not have a significant impact on driver expectancy or response times. It should however be noted that the study considered the application of lead-lag left turn sequences for PO left turn phases. Nevertheless, it provides further confirmation that dynamic operation of phase sequences by time-of-day should not be viewed as an impediment to driver expectancy or safety.
- A survey of field engineers in United States, performed as part of the research study titled "*Development of Left-Turn Operations Guidelines at Signalized Intersections*" for TxDOT (*7*), ranked the parameters considered for determining the sequence of left turn phasing (lead-lead, lead-lag or lag-lag). **Table 2** is a reproduction of the table from the research report. A higher score indicates that importance of the respective parameter in determining the left turn phase sequence. The parameters are sorted in descending order of their scores.

Table 2: Determination of Left-Turn Phase Sequence

Parameter	Score
Platoon Progression and Bandwidth	*4.03*
Intersection Congestion Level (V/C Ratio)	*3.39*
Historical Rate of Left-Turn Related Accidents at Intersection	*3.31*
Driver Acceptance	*3.29*
Median Width	*3.22*
Intersection Alignment	*3.17*
Number of Left-Turn Lanes	*3.08*
Historical Rate of Total Accidents 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*
Vehicle Types/Fleet Compositions (Percent of Heavy Vehicles)	*2.53*
Number of Failed Cycles	*2.14*
Pedestrian and/or Bicycle Crossings	*1.78*

(Source: Development of Left-Turn Operations Guidelines at Signalized Intersections, Qi, Li et al)

As shown in the table, the overriding parameter in considering a particular left turn phase sequence was platoon progression and bandwidth.

- Twice-Per Cycle Left Turn operation was predominantly used to reduce left-turn traffic “spill-over” where existing storage length in the turn bay was insufficient to service all the left turning vehicles thereby preventing “queue spillback” and “blocking” of through traffic. The communication from the City of Garland, Texas and the City of Santa Clara, California indicated that the implementation of TPCLT operation was performed on an “as-needed” basis and after conducting an engineering study.
- No research or policy documentation was found with respect to identifying recommended procedures for reversing order of split phase sequence of side streets.

III. Guidance for Leading and Lagging Left Turn Phases

Some of the common instances where lead-lag left turn phasing could be implemented are outlined in the following and are classified into two broad categories:

A) Typical situations where leading and lagging sequences are a function of the mode of the left turn phase (i.e. PO, E/P, etc.) only, and
B) Typical situations where leading and lagging sequences are a function of the intersection geometry.

A. Left turn sequence as a function of mode of the phase

a) ***PO Left Turn mode on opposing approaches****:* For left turns with PO phasing on opposing approaches, implementation of a Lead or Lag left turn phase sequence is acceptable. See **Figure 14** below:

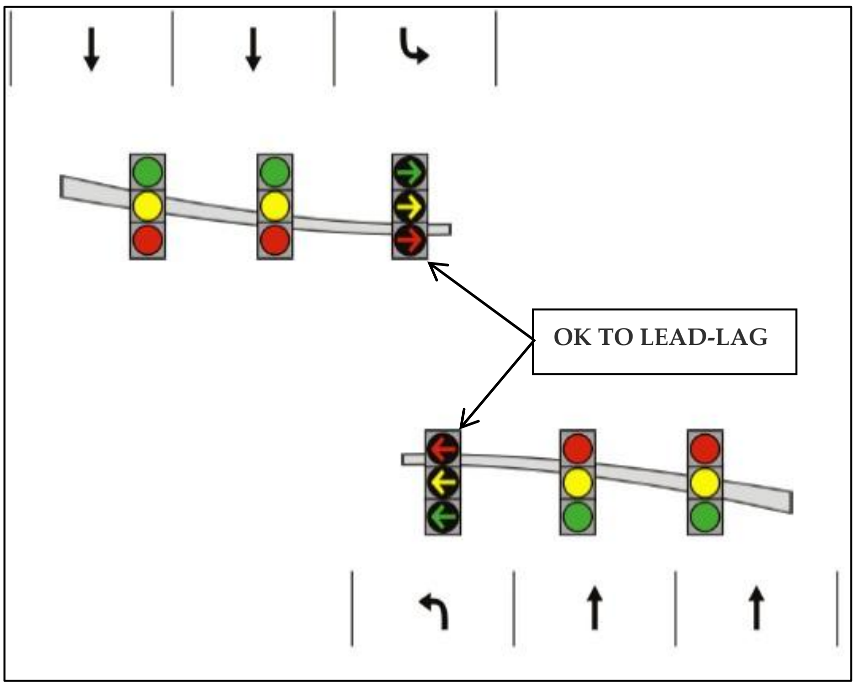

Figure 14: PO Left Turn mode
(Source: Signal Timing Manual, 2008 – FHWA)

b) ***Left turn mode at T-Intersections****:* For left turns with PO or E/P phasing at a T-Intersection, implementation of a Lead or Lag left turn phase sequence is acceptable. Refer to **Figure 15** for an illustration of this case:

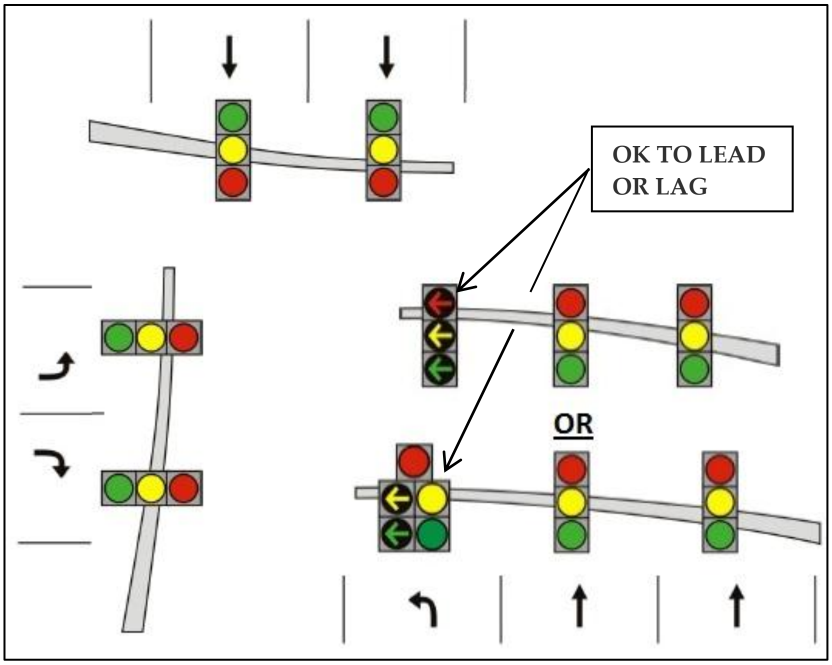

Figure 15: E/P Left Turn mode at T-Intersections
(Source: Signal Timing Manual, 2008 – FHWA)

Some of the common instances where Lead-Lag left turn phasing should not be implemented are outlined in the following paragraphs:

a) ***PO and Permissive left turn modes on opposing approaches***: For left turns with PO and Permissive mode on opposing approaches, implementation of a Lag left turn phase sequence is not recommended. Refer **Figure 16** below for an illustration of the case:

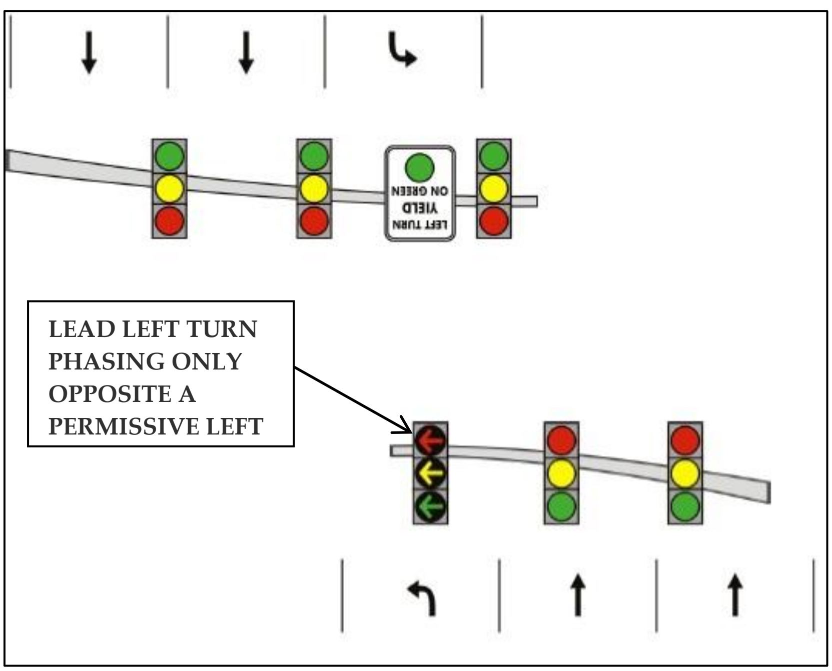

Figure 16: E/P and Permissive Left Turn modes on opposing lanes
(Source: Signal Timing Manual, 2008 – FHWA)

b) ***PO and E/P left turn modes on opposing approaches****:* For PO left turns with E/P phasing on the opposing approach, implementation of Lag left turn phase sequence is not recommended. The E/P phase opposing the PO left turn may implement Lead or Lag phase sequence. Refer to **Figure 17** for an illustration of this case:

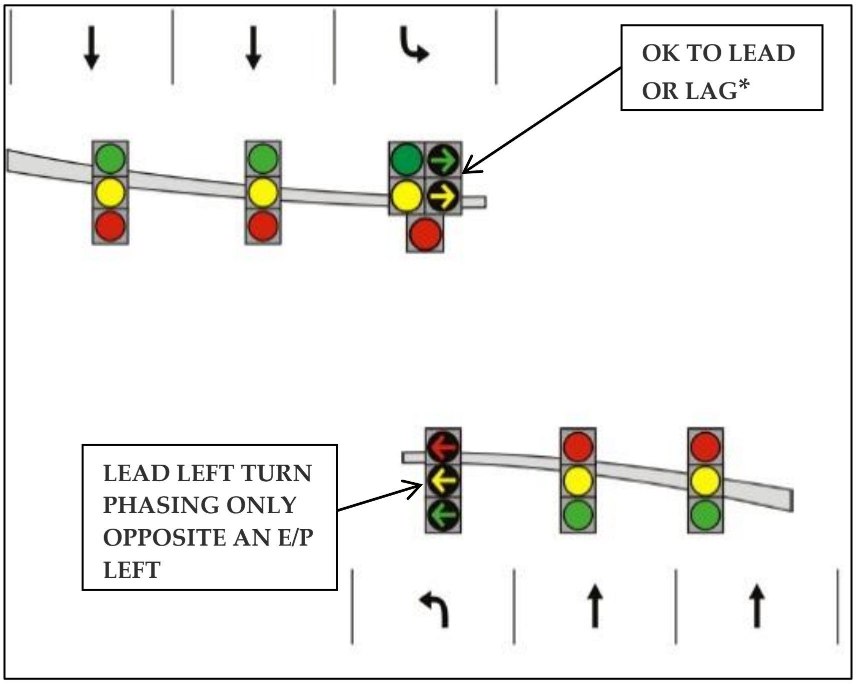

Figure 17: PO and E/P Left Turn modes on opposing lanes
(Source: Signal Timing Manual, 2008 – FHWA)
**Signal Display for E/P phase may be converted to FYA if one phase needs to lag*

c) ***E/P left turn modes on opposing approaches:*** For left turns with E/P phasing on opposing approaches, implementation of lead-lag phasing is not recommended to avoid "Yellow Trap" conditions. Instead, FYA signal displays should be utilized, if one of the left turn phases needs to operate as Lag. Refer to **Figure 18** for an illustration of this case.

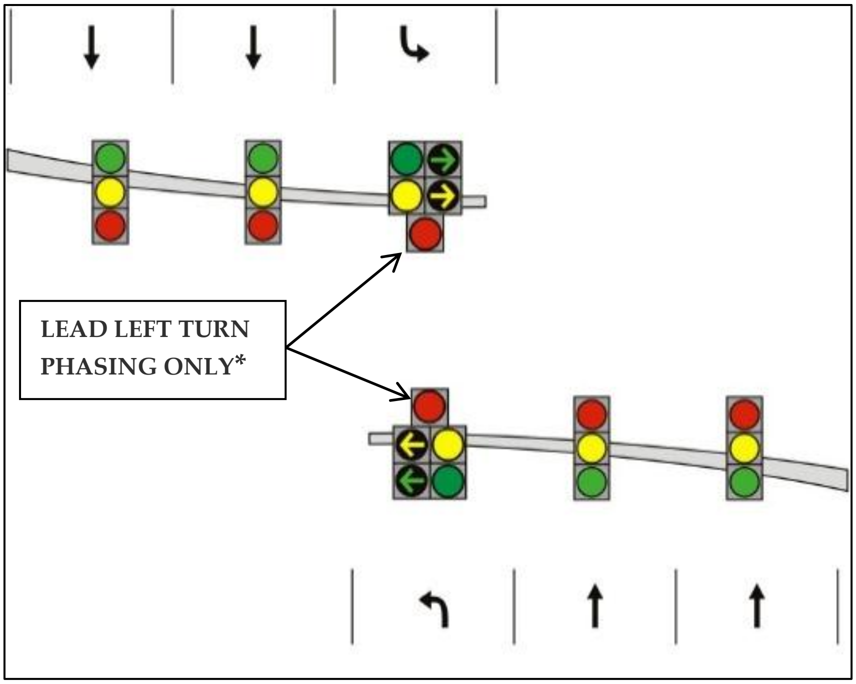

Figure 18: E/P Left Turn modes on opposing lanes
(Source: Signal Timing Manual, 2008 – FHWA)
**Signal Display for E/P phase may be converted to FYA if one phase needs to lag*

B. *Left turn sequence as a function of intersection geometry*

a) ***Left turn path overlap for opposing approaches:*** For left turns with overlapping paths, a Lead-Lag phase sequence should be utilized to safely accommodate the turning traffic from opposing approaches. **Figure 19** below illustrates this condition. MDSHA typically programs the left turn phases of the overlapping approaches in separate barriers within the signal controller to prevent any likelihood of the phases operating concurrently.

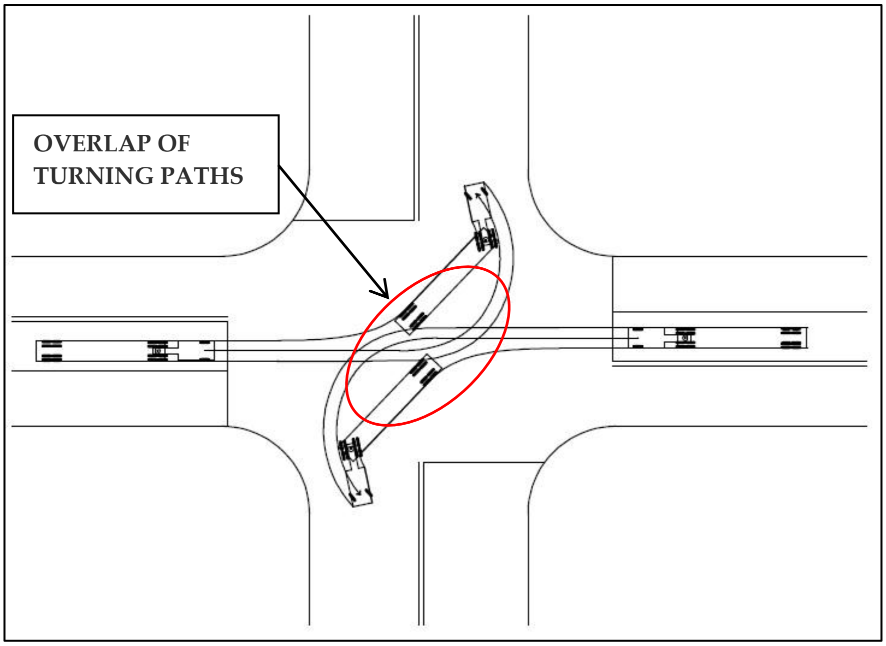

Figure 19: Left Turn path overlap

b) ***Left turn mode at tight diamond interchanges:*** Tight diamond interchanges are characterized by two signalized intersections less than 400 feet apart (*8)*. Traffic control at signals in such close proximity is typically accomplished using a single traffic controller. The signal phasing is comprised of the following components:

i. Left turn phase
ii. Arterial through phase
iii. Ramp (or frontage road) phase

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 which are shown in **Figure 20** and **Figure 21** below. The implementation of a Lead-Lead, Lead-Lag or a Lag-Lag left turn phasing is an implicit part of the two control strategies.

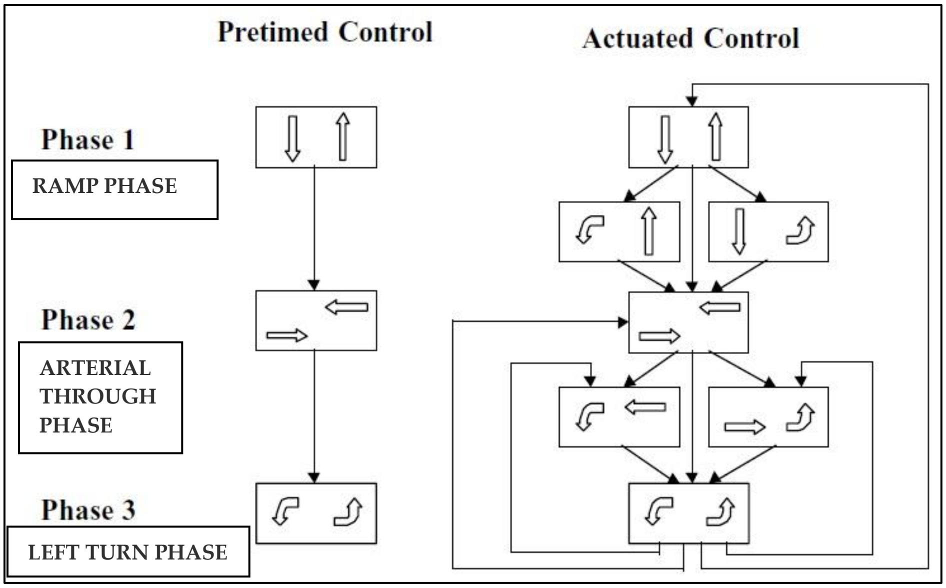

Figure 20: TEXAS Three-Phase Control Strategy
(Source: Guidelines for Timing and Coordinating Diamond Interchanges with Adjacent Traffic Signals, Texas Transportation Institute - 2000)

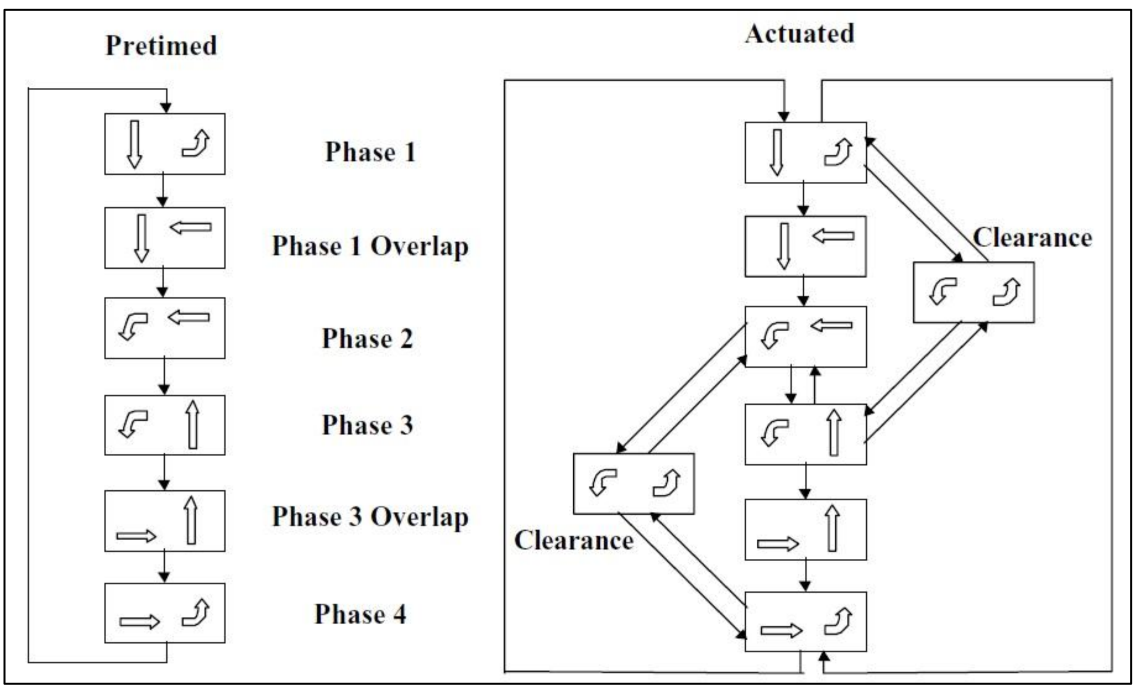

Figure 21: TTI Four-Phase Control Strategy
(Source: Guidelines for Timing and Coordinating Diamond Interchanges with Adjacent Traffic Signals, Texas Transportation Institute - 2000)

Figure 22 shows an aerial map of the interchange of MD 100 and Coca Cola Drive, in Anne Arundel County, Maryland which is an example of a tight diamond.

Figure 22: MD 100 and Coca Cola Drive Interchange
(Source: Bing Maps, Microsoft Inc.)

IV. Guidance for Twice-Per-Cycle Left-Turns (TPCLT)

A common problem encountered at a signalized intersection is the lack of adequate storage length for the left-turn movement, which results in vehicles “spilling-back” from the turn bay onto the through lanes and blocking the through movement. "Twice Per cycle Left-Turn" (TPCLT) operation reduces left-turn "spill-over" by servicing the protected left-turn movement as a leading AND a lagging left-turn. This allows the left-turn bay to empty during the lead left-turn movement and "recharge" during the through movements before being serviced again as a lagging left-turn.

TPCLT operation is typically utilized with PO left turn mode, since an E/P left turn mode allows traffic to turn during the “GREEN BALL” and change interval. The application of TPCLT is subject to the satisfaction of the requirements outlined for operation of a PO mode, in the previous section. TPCLT operation is even more effective for dual-left-turn lanes that are effectively reduced to a single lane when the spillback extends into the through lane of traffic. However, TPCLT inherently leads to an increase in lost time (since clearance intervals increase), and may contribute to a longer intersection cycle length.

Standard operational procedure for determining whether left turns should be serviced twice in the same cycle should include an analysis of queue lengths, delay and level of service for left turns at an intersection. TPCLT should be implemented if an engineering study determines that intersection operations are improved. Prior to making a decision to use TPCLT in a coordinated system, it should be confirmed that adequate time is available within the cycle length to accommodate the additional phases.

V. Guidance for Ordering Side Street Split Phases

The standard operating procedure for MDSHA with respect to the implementation of split phasing for the side street entails leading the low-volume side street followed by the high-volume side street. This is done to transfer any unused green time from the low-volume side street to the high-volume side street to accommodate likely higher demand. It should be noted that the fixed force-off mode, which is the default setting for MDSHA, should be utilized.

A force-off is defined as "*A point within a cycle where a phase must end regardless of continued demand. These points in a coordinated cycle ensure that the coordinated phases are provided a minimum amount of green time*" (*1*). There are two modes of force-offs in a controller:

- *Fixed Force-off*: A force-off mode where force-off points cannot move. Under this mode, non-coordinated phases can use unused time of previous phases, and
- *Floating Force-off*: A force-off mode where force-off points can move depending on the demand of previous phases. Under this mode, non-coordinated phase times are limited to their defined split amount of time and all unused time is dedicated to the coordinated phase. Essentially, the split time is treated as a maximum amount for the non-coordinated phases.

Figure 22 is reproduced from the 2008 *Traffic Signal Timing Manual* (*1*) and illustrates the difference between a fixed and floating force-off.

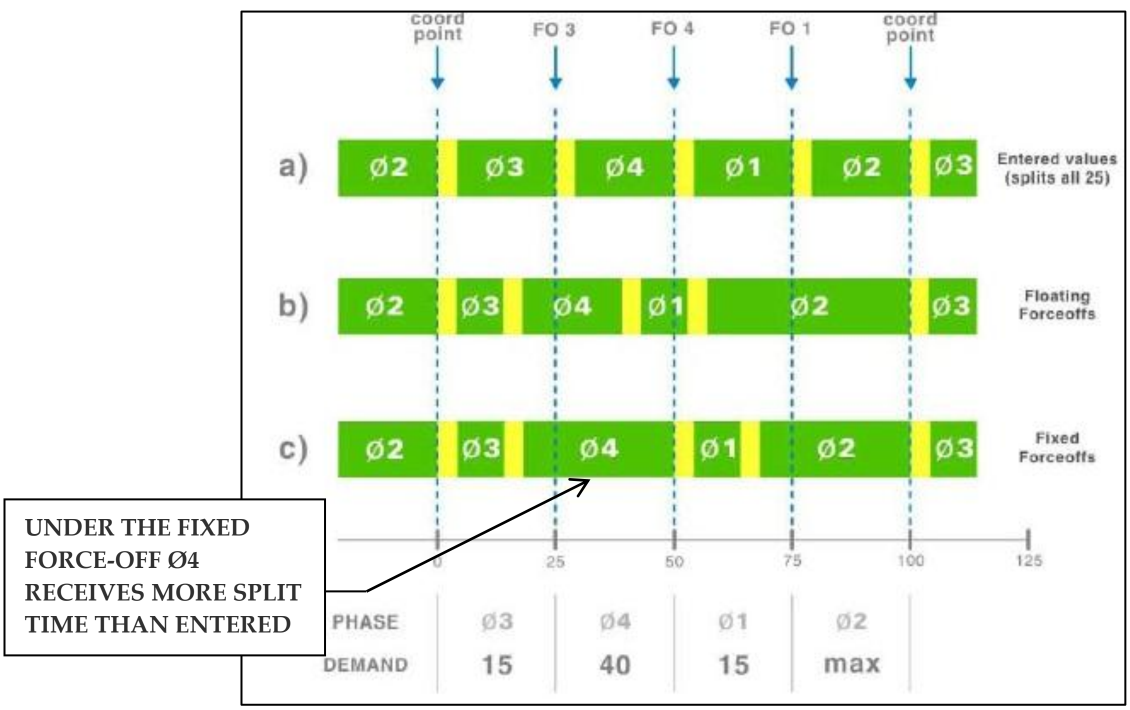

Figure 23: Fixed and Floating Force-offs
(Source: Signal Timing Manual, 2008 – FHWA)

In cases where the directional demand on side streets reverses by time-of-day, it is recommended that the order of split phases be changed to service the appropriate traffic demand.

Consideration must also be given to the potential impact on right turning movements which operate in overlap with the cross street left turn movements. The lost time for a right turning movement could occur twice depending on the order of the side street split and the corresponding left turn. The various instances of the occurrence of lost time for a right turn are shown in **Figure 25**:

LEADING LEFT & SPLIT PHASE APPROACH OPPOSITE TO RIGHT TURN OVERLAP SERVICED LAST (NOTE: TWO LOST TIMES)

LAGGING LEFT & SPLIT PHASE APPROACH OPPOSITE TO RIGHT TURN OVERLAP SERVICED LAST (NOTE: ONE LOST TIME)

LEADING LEFT & SPLIT PHASE APPROACH OPPOSITE TO RIGHT TURN OVERLAP SERVICED FIRST (NOTE: ONE LOST TIME)

LAGGING LEFT & SPLIT PHASE APPROACH OPPOSITE TO RIGHT TURN OVERLAP SERVICED FIRST (NOTE: TWO LOST TIMES)

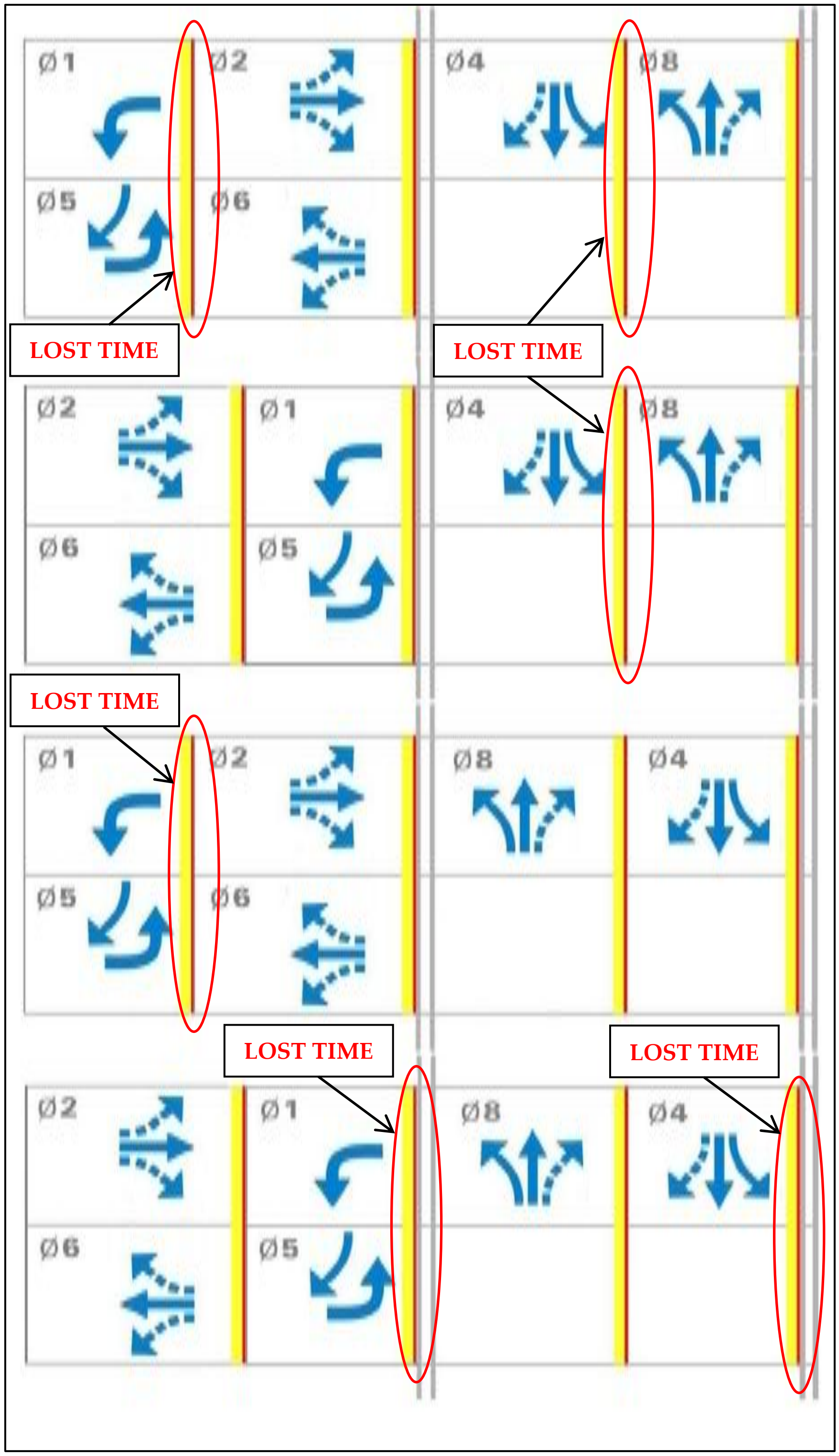

Figure 24: Phase Order & Occurrence of lost times for Right turn overlaps
(Source: Signal Timing Manual, 2008 – FHWA)

VI. Recommendations

A. Left Turn Phase Orders

In general, altering the phase sequence by time-of-day does not appear to have an adverse influence on driver expectancy, driver response nor create any safety concerns. However, it is essential to analyze the impacts on a case by case basis prior to making a decision on the type of phasing sequence to use. When determining the left turn phase order, three general factors should be considered:

- Safety,
- Platoon Progression and Bandwidth, and
- Queuing.

a) Safety

- **Yellow-Trap**: Refer to Section III. If there will be a yellow-trap issue with a particular phase order, change the signal display to a Flashing Yellow Arrow (FYA), or constrain the phase order such that there would not be a yellow trap issue. If hardware changes such as a FYA are required, compare the benefits of changing the phase order to ensure they outweigh the cost of making the change.
- **Simultaneous Left Turns**: Refer to Section IV. Ensure that there are no geometric issues which prevent left turns from operating simultaneously. If there are, set the incompatible phases in different barriers.
- **Pedestrian / Bike Traffic**: Lag Left Turns that turn into crosswalks that are heavily utilized by pedestrian / bike traffic. Pedestrians often ignore the FDW signal and begin their crossing when they see the side street phase terminating. Thus, leading left turns may conflict with when pedestrians *expect* to start crossing.

b) Platoon Progression and Bandwidth

- Left Turn Phase Order may default to a Leading Left Turn phase in lieu of traffic platoon progression analyses and for isolated intersections.
- Left Turn Phase Order should be determined based on optimizing bandwidth and platoon progression, and may vary for each coordinated signal timing plan.
- Lag Left Turns are commonly utilized at diamond interchanges, intersections with wide medians that have crossover road signalized, and at other tightly spaced signals. An analysis of platoon progression must be performed with consideration to platoons both from the mainline roadway as well as from the side street / interchange ramps in order to determine the optimal phase order.

c) Queuing

- Lead and Lag Left Turn Phases in the same cycle (Twice Per Cycle Left Turns) when the left turning queue cannot be accommodated with the turn bay length.

- Lead Left Turns when left turning traffic spills out of the turn bay and blocks through traffic.
- Lag Left Turns when the through queue blocks access to the turn bay and the left turn phase is “starved” of traffic.

B. Side Street Split Phase Order

The following should be considered when determining the order of a side street split phase:

- Lead the low-volume side street to allow the transfer any unused green time from the low-volume side street to the higher-volume side street. Ensure that the fixed force-off mode of coordination is implemented.
- For dual coordination (of both the mainline and side street), determine the phase order based on optimizing bandwidth and platoon progression. The phase order may vary for each coordinated signal timing plan.
- For side street approaches with a right turn overlap (right turn operates concurrently with the mainline left turn), consider ordering the side street split phases such that the side street approach with the right turn overlap precedes the leading left turn on the mainline (last in the side street phase order), or the lagging left turn on the mainline precedes the side street split phase (first in the side street phase order).

C. Approvals

It is recommended that all requests to change existing signal timing and phase sequences be submitted to the Director – Office of Traffic and Safety, for formal approval. A standard form has been developed for documentation and to aid in obtaining inter-department approvals within MDSHA – Office of Traffic and Safety, for signal timing and phase sequence change requests. It is attached in the **Appendix**.

APPENDICES

APPENDIX A – STANDARD FORM

MARYLAND STATE HIGHWAY ADMINISTRATION

Traffic Development & Support Division, Traffic Signal Timing Section

SHA XX.X – XX Revised XX/XX/XX

Traffic Signal Phase Order Change Request

To: (Name), Director, Office of Traffic & Safety **Date:** 3.21.2011

From: ______________________ **County:** ____________

Intersection(s): ______________________

System: ______________________

Recommendation: Phase Order Change, Hardware Change, Twice Per Cycle Left Turns

(Circle Appropriate)

Summary of Problem

Description of Improvements:

Summary of Benefits:

Table 1. Summary of Benefits for *(Intersection)*, Peak Hour: ______, Direction: ______

Scenario	Delay (sec/veh) Movement:________	LOS Movement:________	Bandwidth (sec) Direction: ______
Existing			
Proposed			

Notes: Not all cells have to be completed; and
Copy table to summarize benefits for multiple peaks and / or movements/ directions and different intersections.

Implementation: TDSD will implement with their own forces, Forward to TEDD for design

(Circle Appropriate)

Approvals

____

Director – Office of Traffic & Safety **Date**

REFERENCES

1. *Traffic Signal Timing Manual*, U.S. Department of Transportation, Washington, D.C., June 2008

2. Hummer, J. E., Montgomery, R. E., and Sinha, K. C. *Guidelines for Use of Leading and Lagging Left-Turn Signal Phasing*, Transportation Research Record, No. 1324, TRB, National Research Council, Washington, D.C., 1991.

3. Asante, S. A., Ardekani, S. A., and Williams, J. C., *Selection Criteria for Left-Turn Phasing and Indication Sequence*, Transportation Research Record, No. 1421, TRB, National Research Council, Washington, D.C., 1993.

4. Kacir, K. C., Brehmer, C. L., Noyce, D. A., and Manser, M. P., *NCHRP Report 493: Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control,* Transportation Research Board, National Research Council, Washington, D.C., 2003.

5. Buckholz, Jeffrey W., *The 10 Major Pitfalls of Coordinated Signal Timing*, ITE Journal, Institution of Transportation Engineers, Washington, D.C., 1993.

6. Nandam, Kanth, and Hess, Douglas, *Dynamic Change of Left Turn Phase Sequence between Time-of-Day Patterns — Operational and Safety Impacts,* ITE 2000 Annual Meeting and Exhibit, Institution of Transportation Engineers, 2000.

7. Lei Yu, Yi Qi, Hongxi Yu, Lei Guo, Xin Chen, *Development of Left-Turn Operations Guidelines at Signalized Intersections*, Texas Department of Transportation, Austin, TX, 2009.

8. Chaudhary, Nadeem A., Chu, Chi-Leung, *Guidelines for Timing and Coordinating Diamond Interchanges with Adjacent Traffic Signals*, Texas Department of Transportation, Austin, TX, 2000.