Feasibility Study of Protected-Permitted Phasing at Dual Left Turn Lanes

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PROBLEM STATEMENT

To develop a list of criteria measures for NCDOT and other agencies to use while evaluating protected-permitted (P-P) phasing at dual left turn lanes using flashing yellow arrows (FYAs). To compile a list of intersections in Charlotte and the Triangle that could have P-P left dual left turns. To identify intersections in the Charlotte and Triangle regions that could benefit from P-P left turn phasing without unnecessary safety risks.

OBJECTIVE/MOTIVATION OF STUDY

P-P phasing at dual left turn lanes can greatly increase capacity at signalized intersections. NCDOT has installed this treatment at a few locations in the Triangle. This study can develop a list of criteria to consider, compile research about P-P left turn phasing, and shed light on this topic that has the potential to significantly increase capacity at signalized intersections.

ABSTRACT

Dual left turn lanes have traditionally had protected-only phasing. A few municipalities around the country have had P-P phasing at these types of sites for several years, and NCDOT just started with it a few years ago. This study was done to provide a list of criteria for NCDOT and other agencies to evaluate when considering this treatment. A list of 36 intersections in the Triangle and 47 intersections in Charlotte were identified as potential locations for this treatment. Additionally, information was gathered from different agencies that use this treatment (including NCDOT) and that information is summarized in this report. The main recommendations from this study are to ensure there is adequate sight distance, have the left turn movement on lagging phasing, and install signs to remind drivers to yield on the flashing yellow cycle. For the lists of potential intersections, qualitative data about the traffic volume and sight distance was estimated. These quantities should be used in the analysis of individual intersections.

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INTRODUCTION

Thousands of intersections across the country have dual left turn lanes. It is an effective way to increase the capacity of an intersection, especially when there is a high volume of left turns. At locations with dual left turn lanes, there is protected-only phasing almost 100% of the time. Most states and municipalities in the country have not even considered left turn lanes with any permitted phasing.

A few cities around the United States use protected-permitted (P-P) phasing at dual left turn lanes. This means that left turning vehicles can make their turn while the opposing through movement has a green light if it is clear to go. P-P phasing at dual left turn lanes was first introduced in North Carolina a few years ago, and other municipalities such as Tucson, AZ and Richardson, TX have been using it for several years ("Dual Left Flashing Yellow Arrow" 2015).

Protected-permitted phasing can be done with flashing yellow arrows (FYAs). FYAs are relatively new to the US but are now in widespread use in multiple states (Schattler et al. 2015). For this study, all potential locations would have dual FYAs. Dual FYAs are also currently in use at all P-P dual left turn locations in the Triangle.

Factors to Consider

Several different factors can be taken into consideration when proposing a location for P-P phasing at dual left turn lanes, including:

- Sight distance
- Vehicular volume on the opposing through movement
- Speed limit on the opposing through movement
- Number of lanes (straight and right) on the opposing through movement
- If there is an opposing left turn lane, and if it has an offset (this could affect sight distance)
- Curvature of the roadway beyond the intersection

For this report, the curvature of the roadway beyond the intersection is classified as left, straight, or right. This is the curvature of the approach opposite the dual left turn lanes in question, heading away from the intersection. An example of the roadway curving to the left is shown in Figure 1. In this instance, the westbound left is the left turn in question, and the roadway curves to the left beyond the intersection, which is illustrated by an orange arrow.

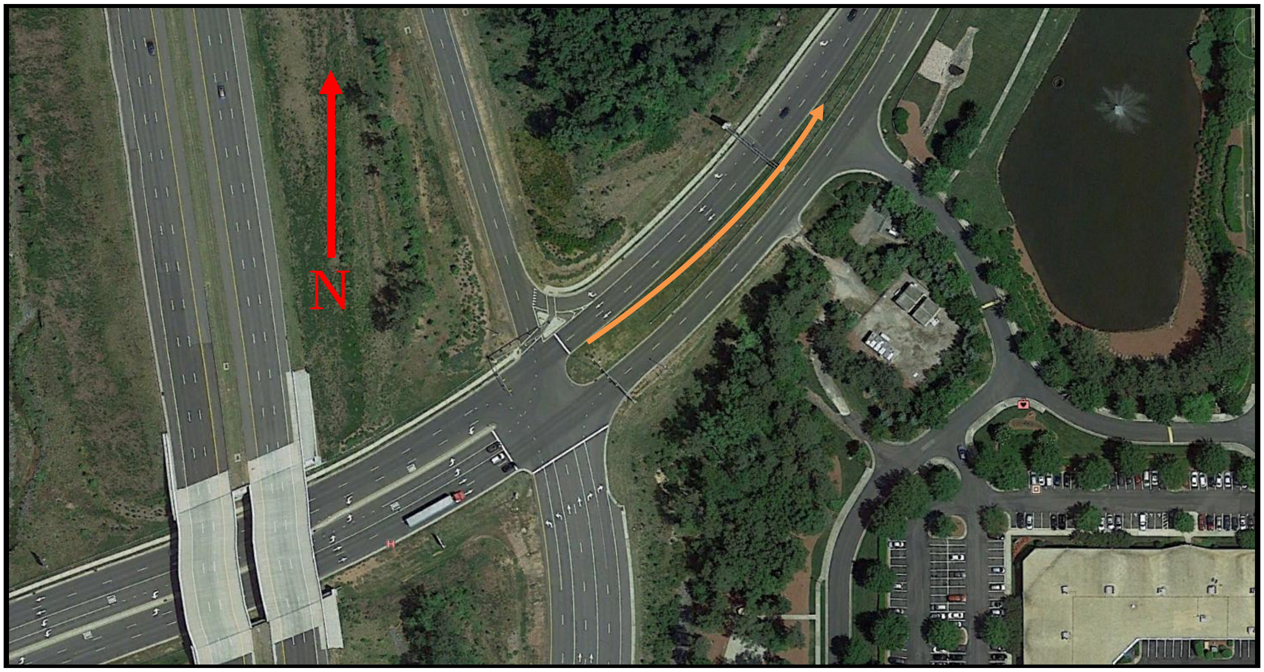

FIGURE 1 Roadway curving to the left after the intersection ("Durham NC 147" 2015).

Current Use in the Triangle

P-P phasing at dual left turn lanes is currently in operation at six intersections around the Triangle. The intersections are described below.

- Evans Road/Weston Parkway
- Harrison Avenue/Interstate 40 WB Ramps
- Knightdale Boulevard and McKnight Road
- Wendell Falls Parkway and US 64 WB Ramps
- Capital Boulevard and Burlington Mills Road
- NC 42 and Cleveland Road

A map of these six intersections is presented in Figure 2.

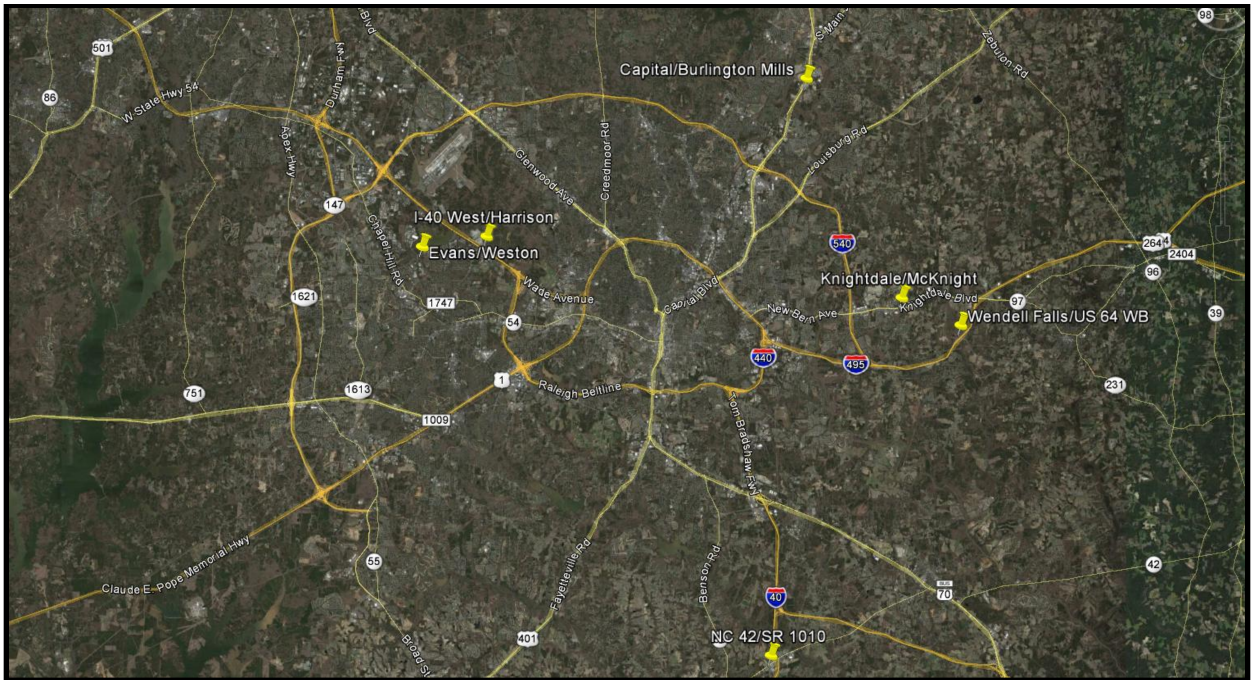

FIGURE 2 Map of current sites in the Triangle with P-P phasing on dual left turn lanes ("Raleigh" 2014).

Literature Review

A search of major publications related to traffic safety yielded no results about protected-permitted phasing at dual left turn lanes. However, there were numerous studies about left turn phasing. Related to crashes, there were very few changes in the total number of crashes at 68 studied intersections in New York City (Chen et al. 2015). Protected only phasing reduces the amount of side impact and pedestrian crashes, but increases other crashes such as rear end and overtaking crashes (Chen et al. 2015). Another study of over 400 intersections in Kentucky revealed that crashes depend on a variety of factors including the phasing of the left turn movement (Stamatiadis et al. 1997). There is no one solution regarding how to determine which treatment is important, and several factors such as sight distance and curvature of the road should be considered. In both studies, two of the main recommendations were that: (1) the trade-off of safety and delay need to be balanced, and (2) several factors must be considered when deciding which phasing to implement (Chen et al. 2015, Stamatiadis et al. 1997). These recommendations are very similar to the recommendations found in this study, which indicates that a variety of factors need to be considered.

The economic impact of left turn phasing has also been analyzed (Wang and Tian 2008). The type of phasing that is selected is normally done after consideration of impacts on mobility and safety. This study used economic impacts instead of other "engineering factors" (sight distance, etc.) to develop guidelines for implementing left turn phasing. One intersection was analyzed as a case study to test the new approach. After an advanced statistical analysis, the researchers found that "...by implementing protected/permitted left-turn control instead of protected only, the benefit from improved efficiency exceeds the cost from increased accidents..." (Wang and Tian 2008). The main take-away from this study is that the cost of crashes associated with permitted left turns is less than the benefit of the decreased delay and increased efficiency of the phasing. This makes sense because if an intersection has less delay and a better level of service, vehicles spend less time stuck in traffic and goods and services can arrive at their destinations quicker, which saves time and money.

There has also been research performed about the effect of sight distance on left turn phasing. Easa et al. (1997) developed a mathematical model to calculate the needed left turn offset at unsignalized and signalized intersections along curves. The model incorporates several factors such as speed, number of lanes, median widths, and lane widths (Easa et al. 1997), all of which are factors identified in this study. Offsetting left turn lanes increases sight distance and can result in safer operations during permitted phasing (Yan and Radwan 2008, Byrd et al. 2000, Hutton et al. 2015). Making the left turn lanes wider in addition to, or instead of, offsetting the left turn lanes can result in increased sight distance (Byrd et al. 2000). The drivers in the vehicles will often move to the left side of the lane, which increases the sight distance for left turning vehicles in both directions. This is essentially the same as offsetting the lanes, but in this case the drivers offset themselves and are not guided by the lane lines (Byrd et al. 2000). The main benefit of offsets are that drivers in the opposing left turn lanes do not block each other's sight distance, which allows for safer operations (Yan and Radwan 2008). If the opposing through movement has a volume of greater than 1,800 vehicles per hour and there is not enough of an offset, the capacity of the left turn movement could be degraded by as much as 70% (Yan and Radwan 2008). Data from the SHRP2 Naturalistic Driving Study also identifies that offsets have an impact on sight distance. In a study (Hutton et al. 2015), after analyzing data from the Driving Study, researchers found that left turn lanes without offset can have less sight distance, which may cause a safety issue.

Leading versus lagging left turn phasing was also identified as a main issue related to protected-permitted phasing. Leading left turns are far more common than lagging left turns (Sheffer and Janson 1999). Left turns with protected phasing were analyzed in a study (Sheffer and Janson 1999) to determine which is safer and more efficient. Saturation flow rates, start-up lost times, crash rates, and fourth-vehicle crossing times were measures examined in the study. All four measures were improved when the left turn phases were lagged (Sheffer and Janson 1999). When protected-permitted left turns are lagged, drivers can pull out into the intersection. Then, when the protected phase starts, left turning vehicles are already in the middle of the intersection which improves the start-up lost time. Also, as the opposing through movement turns yellow and red, the opposing left turn vehicles can see the through vehicles stopping and begin their turn, which further increases capacity (Yang et al. 2013). This concept of having vehicles wait in the intersection during the permitted phase (in a lagging left turn setup) is being implemented in China via pavement markings. During the time when the through traffic is moving straight through the intersection, the left turning vehicles pull out into a dashed area called a left-turn waiting area (Yang et al. 2013). This study analyzed the effect of these waiting areas on saturation headway, start-up lost time, and clearance time. The results indicated that capacity is improved and the start-up lost time is reduced (Yang et al. 2013). Additionally, when the vehicles move out into the waiting area, the entire queue can move forward and allow for more vehicles to enter the left turn lanes on the back end, which can be beneficial if the queue backs into the through lanes because there is not enough storage length (Yang et al. 2013). An image of these left turn waiting areas is shown in Figure 3.

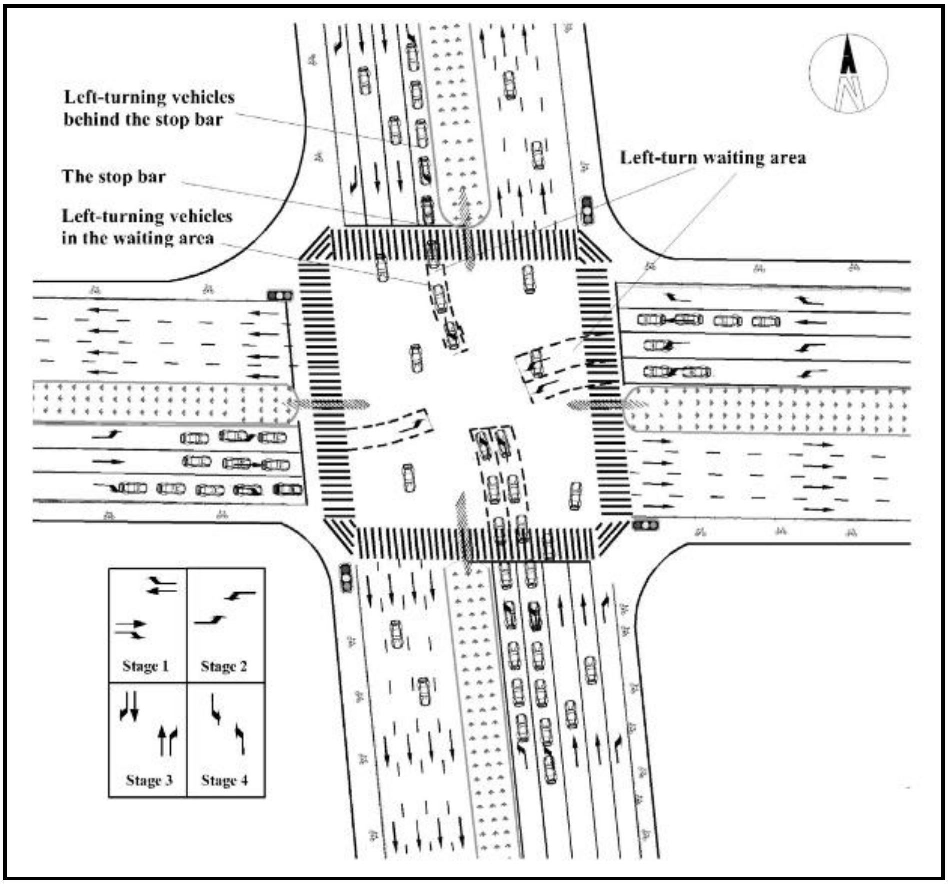

FIGURE 3 Diagram of an intersection with left turn waiting areas (Yang et al. 2013).

There are a variety of signal displays that can be used for permitted left turns, including solid green and flashing yellow arrows. One study found that the traditional 'doghouse' display (2 green, 2 yellow, 1 red) with a sign that says "yield on green" worked well during the permitted phase but was not understood as well during the protected phase (Drakopoulos and Lyles 2000). This study did not analyze flashing yellow arrows. Signs reminding drivers to yield during the permitted phase can be beneficial. Several traffic signals in Peoria, IL were recently upgraded to flashing yellow arrows for the permitted left turns. Some of the signals had signs installed that read "Yield on Flashing Yellow Arrow". The study analyzed crash rates at several test intersections and concluded that the signs result in fewer crashes and cause the entire intersection to be safer (Schattler et al. 2015). The study recommended that the signs should be installed when flashing yellow arrows are first introduced to an area (Schattler et al. 2015). These signs were also observed at dual left flashing yellow arrow sites in Richardson, TX, where dual left turns have had permitted phasing (first with solid green balls, then with flashing yellow arrows) for several years. An example of this sign is shown in Figure 4.

FIGURE 4 Image of a yield sign used with a new flashing yellow arrow signal head (Harlow 2012).

Tucson, AZ has been running protected-permitted phasing at dual left turn lanes for several decades. A study (Catalano 1991) examined the efficiency of this system to see if it was an effective way to relieve traffic congestion. The study found that average crash rates increased from four crashes per million vehicle miles to five crashes per million vehicle miles with the addition of permitted-protected dual left turns. This rate was less than the increased crash rate caused by increased congestion as a result of protected only left turns (Catalano 1991). The study also said that when the opposing through volume is at or above 1,000 vehicles per hour, very few vehicles turn left during the permitted phase (Catalano 1991).

Part of the research for this report included conversations with a traffic engineer from the City of Tucson named Richard Nassi. Several important issues were noted during these conversations:

- Offsets are important for sight distance and allow drivers to see around the opposing left turn vehicles for a clear view of the oncoming through lanes. This is similar to the results from other studies.
- Almost all of the sites use lagging phasing. The lagging phase decreases the start-up lost time and adds capacity to the intersection. Additionally, sometimes the left turning vehicles will completely clear out of the intersection during the permitted phase and the entire protected phase can be skipped. This is true for both single and dual left turn lanes with protected-permitted phasing. The lagging lefts also eliminate the left turn trap and decrease the number of crashes.
- A fully protected left turn will always be safer than a permitted left turn. A site with dual left turns with protected-permitted phasing will see approximately one more crash per approach per year over a site with a single left turn lane with protected-permitted phasing.
- In Tucson, there are more left turn crashes and fewer rear end crashes.

- In an area with a high number of pedestrians, such as near a university, protected only phasing should be used.
- The protected-permitted dual left turns, overall, provided good operational characteristics and low traffic crashes.

As the other studies indicate, sight distance is a very important consideration for protected-permitted left turn lanes, especially at dual left turn lanes. Some of the intersections in Tucson have offsets, and an example is shown in Figure 5. At this intersection (E Speedway Blvd and N Campbell Ave), both roads have three through lanes in each direction with a 40-45 MPH speed limit. The northbound and southbound dual left turn lanes have lagging protected-permitted phasing and are offset from the through lanes.

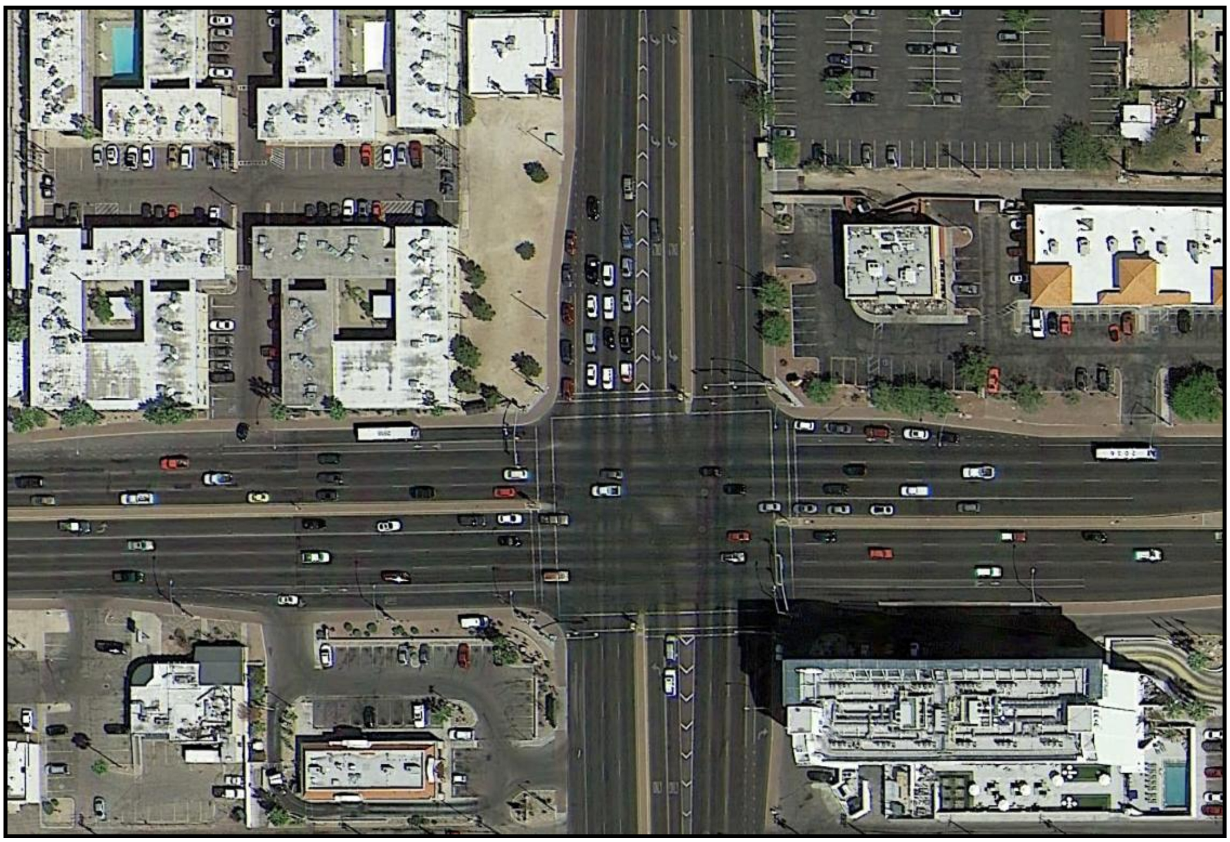

FIGURE 5 Offset dual left turn lanes with protected-permitted phasing in Tucson ("Tucson" 2014).

Lagging left turns in Tucson have resulted in lower insurance rates for drivers there than in other parts of Arizona ("Tucson's left-turn system safer" 2000). One researcher in the insurance industry found that the lower insurance rates were a direct result of fewer left turn crashes because of the lagging phasing. The article also states that when Tucson experimented with leading left turn phasing, engineers at the city got numerous complaints from citizens who wanted the left turns to be lagged ("Tucson's left-turn system safer" 2000).

Dual left P-P phasing via FYAs has the potential to significantly reduce delay, especially during off-peak hours ("Dual Left Flashing Yellow Arrow" 2015). If dual left turn lanes have protected-only phasing, they have to turn green for just one or two vehicles waiting to turn left. Analysis of one intersection in Cary found that having P-P phasing at one dual left turn lane site reduces delay by 50% and also shortens the queue lengths by approximately 25% ("Dual Left Flashing Yellow Arrow" 2015). Hong Hou with the City of Chandler, AZ also explained during a personal interview that an existing dual left turn lane was converted to protected-permitted phasing because of excessive queue lengths. At the corner of Chandler Boulevard and Rural Road, a large employment center produces a large number of vehicles turning left at this location as people leave from work. The opposing through movement had a low traffic volume and there was sufficient sight distance, so the dual left turn lanes were converted to P-P phasing during certain periods of the day only. In addition to the improved operations, crashes were also reduced by 40% during a three year period after the conversion. It is not known whether this percentage is for the entire intersection or just the left turn movement.

Buddy Murr, a State Signals Engineer with NCDOT, summarized that the process for installation of P-P phasing at dual left turn lanes entails meetings with appropriate stakeholders, analysis and measurements of intersections, and numerous site visits during different times of the day. After the change is implemented, NCDOT's Safety Evaluation Group monitors the intersection. Murr also stated that some criteria to consider include:

- Opposing through vehicle volumes
- Speed limits and prevailing speeds
- The number of opposing lanes
- How long and how far it takes to complete the left turn movement
- Crash history
- Whether or not other signals along the corridor have FYAs
- The type of signal controller used and if it needs to be updated

Murr also commented on the cost of a conversion from protected-only phasing to P-P phasing. The biggest factors in determining cost are related to the clearance of a four-section FYA and the type of signal controller. Most signal heads are three sections high, however an FYA has a four section head. The signal wires may have to be raised if the addition of one other signal display causes the clearance between the pavement and the bottom of the signal head to decrease below 16.5 feet. Three section signal heads can also be used and have the flashing yellow and solid yellow on the same display. This type of signal has not been installed at any dual left turn lanes. Also, if a new signal controller and/or cabinet have to be installed to update the traffic signal, the cost could be increased by approximately $15,000. If the clearance is adequate and the signal controller is adequate, the cost is approximately $5,000, which includes materials and installation.

A crash study was performed at the intersection of Harrison Avenue and Interstate 40 WB Ramps. The study analyzed crashes three years before and three years after the dual left turns were converted to P-P phasing (Robinson 2014a). The study found that between the left turn and the opposing through, there were no crashes before and seven crashes after (Robinson 2015). At Knightdale Boulevard and McKnight Road, a crash study (three years before, one year after) showed one crash between vehicles turning from the dual left turn lanes and the opposing through movement before and after (Robinson 2015). At NC 42 and Cleveland Road, a crash study (three years before, two years after) showed six crashes before and 13 crashes after between vehicles on the westbound dual left turn lanes and the opposing through movement (Robinson 2014b).

Use of P-P Dual Left Turns in Richardson, TX

The City of Richardson has a roadway network on a grid system. Several of the main arterials are six lanes wide, and at the intersections of these major roadways, there are dual left turn lanes on many approaches, several of which have P-P phasing. These intersections are similar to the intersection in Tucson presented in Figure 5, except that several of these intersections do not have any offset between the left turn and through lanes.

PROCEDURE

Lists of Potential Sites

The initial lists of intersections in both regions of North Carolina contained almost 100 intersections each. From there, site visits were made to each location to observe characteristics such as grades, curvature, speeds (both speed limits and prevailing speeds), and sight distances. The sites were further analyzed on Google Earth for site distance and curvature and were also compared to the six existing intersections, which served as control locations. This was mainly a qualitative analysis. Finally, the lists were narrowed down to about 40 in each region. These lists can be used by NCDOT for their consideration.

Qualitative data about each of the sites was developed from knowledge of the area, site visits, observations made from aerial imagery, and engineering judgment. The different criteria are:

- Opposing traffic volume - It was not possible to count traffic at every intersection during every period of the day on multiple days, so the amount of opposing traffic was classified as low, medium, or high. These are in reference to peak times. For low traffic locations, during rush hour it would be common to see one or two queued vehicles on the opposing through and right turn movements when the light turns green. For medium traffic, there would be less than 10 vehicles, and for high traffic, there would be more than 10 vehicles queued.
- Curvature beyond intersection - This was determined from site visits and aerial imagery and classified as left, through, or right.
- Sight distance - This was determined from site visits and aerial imagery and classified as short, medium, or long. For each type, it is assumed that a large truck would be waiting in the opposing left turn lane, causing a sight obstruction. This metric analyzes the ability of a driver in the outside left turn lane to see past that truck at opposing traffic. A short sight distance would mean a driver could not see beyond the other side of the intersection. A medium sight distance would mean a driver could see a few hundred feet up the road. A long sight distance would mean the driver could see several hundred feet up the road. If there was no opposing left turn, the sight distance was automatically classified as long.
- Opposing left - This was classified as either having an opposing left turn (Yes) or not (No).

Criteria for Consideration

The final step was to develop a list of criteria for NCDOT and other agencies to use when evaluating whether or not to install P-P phasing at dual left turn lanes. These criteria are explained more in the Results and Analysis/Recommendations sections. The values for each (e.g. the maximum speed limit of the opposing through movement) were influenced by data from the existing sites and the two lists of potential sites.

RESULTS

A total of 36 and 47 sites in the Triangle and Charlotte, respectively, were identified as potential locations for P-P dual left turns. Speed limit data and information about the number of opposing lanes from these sites along with the current sites in the Triangle are presented in Table 1.

TABLE 1 Number of Locations, Speed Limit, and Opposing Laneage Data

Region	Number of Locations	Average Opposing Speed Limit (MPH)	Average Opposing Through Lanes	Average Opposing Right Turn Lanes
Triangle (Current)	6	41.7	1.7	0.3
Triangle	36	40.3	1.7	0.6
Charlotte	47	36.5	1.4	0.5

The average speed limits for both lists of proposed sites are both slightly lower than the average speed limit of the current locations in the Triangle. The number of opposing through lanes and right turn lanes are very similar to the current sites as well, indicating that the lists of proposed locations are similar to the current locations. For the opposing right turn lanes, channelized right turns with yield signs or free flow movements were not included.

For the qualitative data collected, the percentage of each type (e.g. low opposing traffic volume) compared to the total number of locations for each region is calculated and presented below.

TABLE 2 Percentages of Total Locations with the Listed Criteria

Region	Opposing Traffic Volume			Curvature Beyond Intersection			Sight Distance			Opposing Left	
	Low	Medium	High	Left	Straight	Right	Short	Medium	Long	Yes	No
Triangle (Current)	50%	0%	50%	0%	83%	17%	0%	67%	33%	83%	17%
Triangle	25%	28%	47%	19%	72%	8%	0%	39%	61%	64%	36%
Charlotte	43%	36%	21%	21%	55%	23%	0%	62%	38%	79%	21%

Potential locations in the Triangle had a higher percentage of higher opposing traffic volume than locations in Charlotte had. The curvature of the roadways beyond the intersection was similar for both regions. No locations (current or potential) had a short sight distance. The percentage of medium and long sight distance locations for current and potential Triangle locations were approximately opposite of each other, while Charlotte's percentages were similar to the current Triangle percentages.

The complete list of potential locations for both regions can be found in the Appendix.

ANALYSIS/RECOMMENDATIONS

The lists of current and potential intersections contain intersections with all different types of each criteria. Speed limits range from 25 MPH to 50 MPH and opposing lanes range from one to four. The lists also include varying opposing traffic volumes, curvatures beyond the intersection, and sight distances. Additionally, these ranges are also common at sites in other cities such as Tucson and Richardson, with the exception of curvature, since those cities contain mostly straight roads on a grid system. Recommendations formed for some of these criteria are presented below. In general, these guidelines can be applied to single left turn lanes as well.

Signal Heads

All signal heads for P-P dual left turns should be FYAs. They have been implemented in many locations in North Carolina at single left turn lanes. Also, to give drivers an additional reminder/safety check, a sign similar to the one in Figure 4 reminding drivers to yield during the flashing yellow should be installed at all dual left turn P-P locations.

Leading/Lagging Phasing

P-P left turns should have lagging phasing most of the time, especially during off-peak hours. This allows drivers to pull forward into the intersection during the initial permitted phase. If the entire queue dissipates during the permitted phase, the entire protected phase can be skipped. If the protected phase is activated at the end, the drivers are already in the intersection, which helps reduce the start-up lost time substantially. It also eliminates the 'yellow trap' drivers may face if they are in the intersection waiting to turn left when the light turns red.

Lagging phasing also has safety benefits in the event a driver on the perpendicular street runs the red light and a side-impact crash occurs. If the left turn has lead phasing, drivers are pulling out into the intersection directly after the through movement on the perpendicular street has turned red. If a driver runs this light, the chances of them going fast are greater. This would also produce a side-impact crash on the driver's side of the car. If the left turn phase is lagged, through movement drivers are pulling out into the intersection directly after the left turn movement on the perpendicular street has turned red. Left turns are made at a slower speed, so a crash that occurs in this scenario would be less severe and would also not be on the driver's side of the car.

Opposing Traffic Volume

In general, it is better to have a lower opposing through movement volume. This provides more gaps in the opposing traffic stream for drivers to complete their left turn, reduces vehicle conflicts, and can make the left turn queue dissipate faster. However, several current sites (both in NC and other places) have high traffic volumes on the opposing through movement.

Number of Opposing Lanes

The best scenario is to have one opposing through/right turn lane so left turning drivers only have to look at one lane of traffic. This type of situation could be on the side street leading out of a shopping center or development. If the protected phase is skipped and run as permitted-only, a side street phase could be eliminated and more green time would be given to the main road. This situation also correlates to speed limits since side streets typically have lower speed limits.

Opposing Left Movement
If there is no opposing left movement, then there is typically a very large amount of sight distance, giving drivers a view of several hundred feet of the opposing lanes. These types of locations are probably some of the safest places to install P-P phasing on dual left turn lanes and include diamond interchanges (turning left onto the on-ramp) and T-intersections. If there is an opposing left turn movement, it is beneficial to have this lane offset from the through movement to increase sight distance.

Curvature Beyond Intersection
Sight distance increases if the roadway curves to the left past the intersection. The drivers in the left turn lanes can see past the opposing left turning vehicles and have a longer view of the opposing through lanes. If the roadway curves to the right too much, vehicles in the opposing left turn lane may block the view of the through lanes.

Sight Distance
Sight distance is identified as the single most important factor when deciding whether to install P-P dual left turn lanes. The prior two criteria (opposing left movement and curvature beyond intersection) both affect the sight distance. Also, multiple sources from the literature review cite sight distance as the most important factor. Finally, the engineers from the other municipalities and NCDOT also said that sight distance is a very important factor. Richard Nassi from the City of Tucson said it is the most important factor.

Priority Locations for Installation
This section contains priority locations for installation of dual left turn lanes in both regions.

Both Regions

- Locations without opposing left turn movements - These locations often provide the most sight distance of any type of intersection. It is recommended that these locations start being converted to P-P phasing in the order of the amount of traffic they would benefit (i.e. the higher the volume of left turning traffic, the sooner the intersection is converted).

Triangle

- NC 55 and Kit Creek Road (Cary) - This intersection had P-P phasing before dual left turn lanes were added. When the eastbound left had a second lane added, the single westbound left became protected-only as well. Field observations show that this movement has started experiencing significant capacity deficiencies during rush hour. The sight distance in both directions is greater than it is at current dual left P-P locations, and both protected-only approaches slope up away from the intersection, allowing drivers to look over opposing left turning vehicles as well as around them.
- Durant Road and Falls River Avenue (Raleigh) - Along Durant Road, all surrounding intersections have P-P left turn phasing on single left turn lanes; this is the only intersection in the vicinity with protected-only left turns. Also, the opposing left turn lane has a large offset which provides a very long sight distance for both left turn lanes.

Charlotte

- Johnson Road and Brixham Hill Avenue (Charlotte) - This dual left turn movement (eastbound) leads out of Ballantyne Corporate Park, a large office park with several thousand employees. The opposite side of the road leads to a hotel, and this movement often has to turn green for one or two cars. Once these vehicles clear out, several more left-turning vehicles could turn make their turn during a permitted phase. During field observations, as the westbound through movement was green, the entire intersection was empty for most of that time and eastbound left drivers could have made their turns. There is adequate sight distance as well.
- Monroe Road and McAlpine Station Drive (Charlotte) - This dual left turn movement is the exit out of a development. The side street left turn movements in both directions have protected-only phasing. If these were converted to P-P phasing and the protected phase was lagging, the left turn queues could dissipate prior to the protected phase most of the time, which would eliminate the entire phase and give more green time to the main road.

CONCLUSION

This study is about P-P phasing at dual left turn lanes. It included a literature review of the topic as well as interviews with several engineers from agencies that have P-P dual left turn lanes, development of lists of potential locations in both the Triangle and Charlotte, and recommendations for criteria to be evaluated when choosing where to install this treatment. The most important factor to consider was identified as sight distance.

Limitations and Future Study

This study did not analyze crash history or crash statistics at any of the potential locations. Crash studies should be conducted before and after installation of P-P dual left turn lanes to identify any patterns that should be corrected.

This study only provided general qualitative data about traffic volumes and sight distances. When studying an individual intersection, these quantities should be measured more precisely.

Despite P-P phasing being installed at dual left turn lanes in cities like Tucson, AZ and Richardson, TX, there was no literature or research found when searching major transportation journals. In addition, no formal studies of the initial data from the NC sites were found. Conducting a major study about this topic, getting it published in a major journal, and doing presentations about it could help 'get the word out' that this type of treatment can be used to help increase the capacity of intersections. Many agencies have probably never even heard of or considered P-P dual left turn lanes and simply thought that dual left turn lanes automatically have protected-only phasing.

Contribution to Literature

While very little research was found about this topic, there was a lot of information learned from the conversations with various agencies. This study contributes information from those conversations to the literature, as well as a summary of research on P-P phasing in general. It also provides a list of intersections for consideration and gives NCDOT and other agencies a list of criteria to consider when evaluating an intersection.

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APPENDIX

TABLE A-1 List of Potential Sites for Protected-Permitted Dual Left Turn Lanes

Region	ID	Street	Cross Street	Direction	City	Opposing Speed Limit	Opposing Through Lanes	Opposing Right Lanes	Opposing Traffic Volume	Curvature beyond Intersection (left, straight, right)	Sight Distance (short, medium, long)	Opposing Left
Triangle (Current)	1	Evans Rd	Weston Pkwy	SB	Cary	45	2	0	High	Right	Medium	Yes
Triangle (Current)	2	Harrison Ave	I 40 WB Ramp	NB	Cary	45	2	0	Low	Straight	Long	No
Triangle (Current)	3	Knightdale Blvd	McKnight Dr	WB	Knightdale	45	2	1	High	Straight	Medium	Yes
Triangle (Current)	4	Wendell Falls Pkwy	US 64 WB Ramp	WB	Knightdale	45	1	1	Low	Straight	Medium	Yes
Triangle (Current)	5	Burlington Mills Rd	Capital Blvd	WB	Raleigh	35	1	0	Low	Straight	Medium	Yes
Triangle (Current)	6	NC 42	Cleveland Rd	WB	Garner	35	2	0	High	Straight	Long	Yes
Triangle	1	NC 55	Apex Pkwy	NB	Apex	35	3	0	High	Straight	Long	No
Triangle	2	NC 55	US 1 NB Ramp	SB	Apex	45	2	2	High	Straight	Long	No
Triangle	3	Kit Creek Rd	NC 55	EB	Cary	40	1	0	Medium	Straight	Medium	Yes
Triangle	4	NC 55	I 40 WB Ramp	NB	Durham	45	2	1	High	Straight	Medium	Yes
Triangle	5	Fayetteville Rd	MLK Pkwy	NB	Durham	35	2	1	Medium	Straight	Medium	Yes
Triangle	6	Hopson Rd	NC 147 SB Ramp	WB	Durham	45	2	2	Medium	Straight	Long	No
Triangle	7	Davis Dr	NC 147 SB Ramp	WB	Durham	50	2	1	High	Left	Long	No
Triangle	8	Davis Dr	NC 147 NB Ramp	EB	Durham	50	2	0	High	Left	Long	No
Triangle	9	NC 55	I 540 EB Ramp	SB	Cary	50	3	0	High	Straight	Long	No
Triangle	10	US 1 SB Ramp	Ten Ten Rd	NB	Apex	35	1	1	Low	Right	Medium	Yes
Triangle	11	Harrison Ave	Cary Pkwy	NB	Cary	45	2	1	High	Left	Medium	Yes
Triangle	12	Perimeter Park Dr	Airport Rd	EB	Morrisville	25	1	1	Low	Straight	Long	Yes
Triangle	13	I 40 EB Ramp	Page Rd	SB	Durham	35	1	1	Medium	Straight	Medium	Yes
Triangle	14	Globe Rd	Aviation Pkwy	WB	Raleigh	45	2	1	Medium	Straight	Long	No
Triangle	15	Arco Corporate Dr	Lumley Rd	WB	Raleigh	35	1	0	Low	Straight	Medium	Yes
Triangle	16	Creedmoor Rd	Parklake Ave	WB	Raleigh	45	2	1	High	Straight	Medium	Yes
Triangle	17	Trinity Rd	Edwards Mill Rd	EB	Raleigh	45	1	1	Medium	Straight	Medium	Yes
Triangle	18	Blue Ridge Rd	Trinity Rd	NB	Raleigh	45	2	1	High	Straight	Medium	Yes
Triangle	19	Varsity Dr	Western Blvd	NB	Raleigh	35	2	0	Medium	Straight	Long	Yes
Triangle	20	Knightdale Blvd	I 540 NB Ramp	EB	Knightdale	45	3	0	High	Straight	Long	No
Triangle	21	Falls of Neuse Rd	I 540 EB Ramp	NB	Raleigh	45	2	1	High	Left	Long	Yes
Triangle	22	Falls of Neuse Rd	Old Falls of Neuse Rd	NB	Raleigh	45	2	0	High	Straight	Long	Yes
Triangle	23	Forest Pines Dr	Falls of Neuse Rd	SB	Wake Forest	35	1	0	Low	Straight	Medium	Yes
Triangle	24	Wake Union Church Rd	Capital Blvd	WB	Wake Forest	35	1	0	Low	Left	Long	Yes
Triangle	25	Stadium Dr	Capital Blvd	WB	Wake Forest	35	1	0	Medium	Straight	Medium	Yes
Triangle	26	Creedmoor Rd	I 540 WB Ramp	NB	Raleigh	45	2	0	High	Straight	Long	No
Triangle	27	Creedmoor Rd	I 540 EB Ramp	SB	Raleigh	45	2	0	High	Straight	Long	No
Triangle	28	Timber Dr	US 70	NB	Garner	45	2	0	High	Left	Long	Yes
Triangle	29	Poole Rd	Birch Ridge Dr	WB	Raleigh	45	3	0	High	Right	Long	No

Triangle	30	US 64 EB Ramp	New Hope Rd	WB	Raleigh	35	1	0	Low	Right	Medium	Yes
Triangle	31	US 401 BUS	Burlington Mills Rd	EB	Rolesville	35	1	1	Medium	Straight	Long	No
Triangle	32	Thorton Rd	Capital Blvd	WB	Raleigh	25	1	1	Low	Straight	Long	Yes
Triangle	33	Kelly Rd	US 64 EB Ramp	NB	Apex	45	2	0	Medium	Straight	Long	No
Triangle	34	Yates Mill Pond Rd	Tryon Rd	NB	Raleigh	25	1	0	Low	Left	Long	Yes
Triangle	35	Purser Dr	Fayetteville Rd	EB	Raleigh	35	1	1	Low	Straight	Medium	Yes
Triangle	36	Durant Rd	Falls River Ave	EB	Raleigh	45	2	1	High	Straight	Long	Yes
Charlotte	1	Weddington Rd	Bruton Smith Blvd	NB	Concord	35	1	2	Medium	Left	Medium	Yes
Charlotte	2	Perimeter Pkwy	WT Harris Blvd	SB	Charlotte	35	1	0	Low	Left	Long	Yes
Charlotte	3	Northlake Dr	WT Harris Blvd	WB	Charlotte	35	1	0	Low	Straight	Medium	Yes
Charlotte	4	I 485 Inner Ramp	Wilkinson Blvd	NB	Charlotte	35	1	0	Low	Straight	Medium	Yes
Charlotte	5	Lakewood Rd	Wilkinson Blvd	NB	Belmont	35	1	0	Low	Right	Medium	Yes
Charlotte	6	Bradford Dr	Freedom Dr	SB	Charlotte	35	1	0	Medium	Left	Long	Yes
Charlotte	7	Hambright Rd	Old Statesville Rd	WB	Huntersville	35	2	1	Medium	Straight	Medium	Yes
Charlotte	8	Birkdale Commons Pkwy	Sam Furr Rd	SB	Huntersville	35	1	1	Low	Straight	Medium	Yes
Charlotte	9	Langtree Rd	I 77 SB Ramp	WB	Mooresville	45	2	1	Medium	Straight	Long	No
Charlotte	10	Brawley School Rd	Morrison Plantation Park	EB	Mooresville	45	2	1	High	Straight	Long	No
Charlotte	11	Perth Rd	NC 150	SB	Mooresville	35	1	0	Low	Left	Long	Yes
Charlotte	12	Bluefield Rd	NC 150	SB	Mooresville	35	1	1	Medium	Right	Long	Yes
Charlotte	13	Claude Freeman Dr	Mallard Creek Church Rd	SB	Charlotte	35	1	1	Medium	Straight	Medium	Yes
Charlotte	14	Senator Royal Dr	Mallard Creek Church Rd	SB	Charlotte	35	1	2	Medium	Left	Medium	Yes
Charlotte	15	Berkeley Pl Dr	Mallard Creek Church Rd	WB	Charlotte	25	1	0	Low	Right	Medium	Yes
Charlotte	16	Back Creek Church Rd	University City Blvd	NB	Charlotte	35	1	1	Medium	Right	Medium	Yes
Charlotte	17	Matheson Ave	Tryon St	WB	Charlotte	35	1	0	Medium	Straight	Medium	Yes
Charlotte	18	I 85 NB Ramp	Graham St	WB	Charlotte	35	1	0	Low	Right	Medium	Yes
Charlotte	19	I 85 SB Ramp	Graham St	WB	Charlotte	35	1	0	Low	Right	Medium	Yes
Charlotte	20	Tuckasseegee Rd	Freedom Dr	NB	Charlotte	35	2	1	Medium	Left	Medium	Yes
Charlotte	21	Remount Rd	Wilkinson Blvd	NB	Charlotte	35	1	0	Low	Straight	Medium	Yes
Charlotte	22	Yorkmont Rd	Tyvola Rd	SB	Charlotte	35	1	1	Medium	Straight	Medium	Yes
Charlotte	23	Beam Rd	Tryon St	NB	Charlotte	45	2	0	High	Right	Long	No
Charlotte	24	Whitehall Commons Shopping Center Dr	Tryon St	EB	Charlotte	25	1	1	Low	Straight	Medium	Yes
Charlotte	25	Granite St	Westinghouse Blvd	SB	Charlotte	35	1	0	Low	Straight	Medium	Yes
Charlotte	26	South Blvd	Westinghouse Blvd	NB	Charlotte	45	2	1	High	Straight	Medium	Yes
Charlotte	27	Arrowood Rd	I 77 NB Ramp	EB	Charlotte	45	4	0	High	Straight	Long	No
Charlotte	28	Arrowood Rd	I 77 SB Ramp	WB	Charlotte	45	4	0	High	Straight	Long	No
Charlotte	29	Microsoft Way	Arrowood Rd	NB	Charlotte	35	1	1	Low	Straight	Medium	Yes
Charlotte	30	Dixie River Rd	Steele Creek Rd	EB	Charlotte	35	1	1	Low	Left	Long	Yes
Charlotte	31	Pineville Matthews Rd	I 485 Inner Ramp	EB	Charlotte	45	2	2	High	Right	Long	No
Charlotte	32	Community House Rd	Johnson Rd	WB	Charlotte	35	1	1	Medium	Straight	Medium	Yes
Charlotte	33	Brixham Hill Ave	Johnson Rd	WB	Charlotte	25	1	0	Low	Straight	Medium	Yes
Charlotte	34	Ballantyne Corporate Pl	Ballantyne Commons Pkwy	SB	Charlotte	25	1	0	Low	Straight	Medium	Yes

Charlotte	35	Williams Pond Ln	Rea Rd	EB	Charlotte	35	1	1	Low	Left	Medium	Yes
Charlotte	36	Providence Rd	Rea Rd	NB	Charlotte	45	1	1	High	Straight	Long	No
Charlotte	37	Providence Rd W	Johnson Rd	EB	Charlotte	45	1	1	High	Straight	Long	Yes
Charlotte	38	Rivergate Pkwy	Tryon St	NB	Charlotte	25	1	0	Low	Straight	Medium	Yes
Charlotte	39	McAlpine Station Dr	Monroe Rd	EB	Charlotte	35	1	1	Low	Right	Medium	Yes
Charlotte	40	Carmel Rd	Quail Hollow Rd	NB	Charlotte	35	2	1	High	Right	Long	No
Charlotte	41	Colony Rd	Sharon Rd	EB	Charlotte	35	2	0	Medium	Straight	Medium	Yes
Charlotte	42	Morrison Rd	Sharon Rd	WB	Charlotte	35	2	0	Medium	Left	Long	Yes
Charlotte	43	Cameron Valley Pkwy	Fairview Rd	NB	Charlotte	35	2	0	Medium	Straight	Medium	Yes
Charlotte	44	Harrisburg Rd	I 485 Outer Ramp	NB	Charlotte	45	2	0	Medium	Straight	Long	No
Charlotte	45	Harrisburg Rd	I 485 Inner Ramp	SB	Charlotte	45	2	0	Medium	Straight	Long	No
Charlotte	46	Lawyers Rd	Ablemarle Rd	NB	Charlotte	35	1	0	Low	Right	Medium	Yes
Charlotte	47	Sunset Rd	Statesville Rd	EB	Charlotte	45	2	0	High	Left	Long	Yes