IMPROVED SIMULATION OF DRIVER BEHAVIOR: MODELING PROTECTED AND PERMITTED LEFT-TURN OPERATIONS AT SIGNALIZED INTERSECTIONS

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16. Abstract

This report documents the findings from a research project that is focused on modeling protected and permitted left-turn operations at signalized intersection approaches. The project's primary objective is to document the microscopic characteristics of protected and permitted left-turn operational parameters at signalized intersections using the NGSIM datasets. The microscopic characteristics of the following parameters are investigated and documented as part of the project: vehicle turning path, start-up lost time, saturation flow rate, and speed and time headway profiles along the turning path. While the sample size for some of the cases might not be large enough to allow for full statistical analysis, the data presented in this report provides insights on different elements of driver behavior as it relates to left-turn operations.

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EXECUTIVE SUMMARY

The Next Generation Simulation (NGSIM) program was initiated by the United States Department of Transportation (US DOT) Federal Highway Administration (FHWA) in the early 2000's. The program developed a core of open behavioral algorithms in support of traffic simulation with a primary focus on microscopic modeling, and collected high-quality primary traffic and trajectory data intended to support the research and testing of the new algorithms. The program identified a set of priority algorithms that are yet to be developed for modeling arterial system operations. These algorithms include starting/stopping behavior and permitted left-turn behavior at signalized intersections. This report shares the findings of a research study measuring traffic patterns including starting/stopping behavior and permitted left-turn behavior at signalized intersections.

Global X and Global Y vehicle position data in the NGSIM database was used to plot the turning path for different left-turning vehicles. The plots reveal a distinct pattern in the way left-turning vehicles, waiting for an acceptable gap in the opposing traffic, advance with the left-turn movement. Once the permitted interval begins, drivers move forward following their initial direction of travel to a "waiting zone" where they temporarily stop waiting for an acceptable gap in the opposing traffic. The end of this waiting zone seems to be at a right angle with the center of the lane receiving the left-turning vehicles. The exact location of the left-turning vehicle within the waiting zone when it actually executes the left turn to the receiving lane depends on several factors such as the vehicle's waiting time, the presence of other vehicles in the left-turning queue, and the availability of acceptable gaps in the opposition traffic.

The start-up lost time and saturation headways were compared for three different lane uses: through lanes, exclusive left-turn lanes, and shared through and left-turn lanes. The average start-up lost time for though lanes was slightly lower (1.79 seconds) than that for exclusive left-turn lanes (1.91 seconds) and shared through and left-turn lanes (1.86 seconds). The average saturation headway for though-only lanes was lower (2.03 seconds) than that for exclusive left-turn lanes (2.56 seconds) and shared through and left-turn lanes (2.28 seconds). The corresponding saturation flow rate for the three different lane uses are 1773 vehicles per hour, 1406 vehicles per hour, and 1579 vehicles per hour, respectively.

A comparison between the speed profile for left-turn and through vehicles showed that, at the same distance from the stop bar, the average speed of left-turning vehicles is consistently lower than that for through vehicles. The ratio between the average speed for left-turning vehicles and through vehicles ranged from 0.91 to 0.49 with higher values near the stop bar and lower values on the turning path. A comparison between time headway profiles for through and left-turning vehicles does not reveal any clear pattern. The average time headway between the first vehicle in the queue and the following vehicle seems higher in left-turning vehicles than in through vehicles. This is especially true in the first 50 feet from the stop bar. After this distance, the time headway profiles for left-turning and through vehicles do not seem to be significantly different.

CHAPTER 1: DESCRIPTION OF PROBLEM

The Next Generation Simulation (NGSIM) program was initiated by the United States Department of Transportation (US DOT) Federal Highway Administration (FHWA) in the early 2000's (FHWA 2009). The program developed a core of open behavioral algorithms in support of traffic simulation with a primary focus on microscopic modeling, and collected high-quality primary traffic and trajectory data intended to support the research and testing of the new algorithms. The program identified a set of priority algorithms that are yet to be developed for modeling arterial system operations (NGSIM 2009). These algorithms include starting/stopping behavior and permitted left-turn behavior at signalized intersections.

This report documents the findings from a research project that is focused on modeling protected and permitted left-turn operations at signalized intersection approaches, an area that has been identified as high-priority research by the NGSIM program. The project aims to provide new insights on the operation of traffic along arterials using high resolution vehicle trajectory data from an urban arterial in Atlanta, Georgia. The data is used to develop improved understanding of the traffic operations at signalized intersections. The project has two primary objectives:

- Identify and document the microscopic characteristics of protected and permitted left-turn operational parameters at signalized intersections using the NGSIM datasets.
- Understand and describe the left-turn phenomena using the characteristics of these operational parameters.

This report is organized in four main chapters. After the introduction that includes a brief description of the problem, Chapter 2 documents the study’s approach and methodology. Chapter 3 includes the study’s findings followed by the study’s conclusions in Chapter 4.

CHAPTER 2: APPROACH AND METHODOLOGY

Overview

The characteristics of left-turn operations at signalized intersections are influenced by several factors such as the type of control, lane configuration, vehicle mix, turning radius, and the characteristics of opposing traffic. Left-turning vehicles can use a designated left-turn phase (protected, protected-permitted, or permitted-protected) or permitted only operations. They can use exclusive left-turn lanes (bays) or share the same lane with the through and/or the right turning traffic. The mechanism of the turn movement depends on the type of control, the lane configuration, and the traffic flow characteristics of the opposing traffic stream. Protected left-turning vehicles share some characteristics with through-moving vehicles at the beginning and end of the green interval. However, they have different saturation headway distributions and speed and acceleration profiles along the turning path. The mechanism of a permitted left-turn movement involves different stages of motion. In the first stage, the vehicle waiting to make the left-turn moves forward to a point at which it stops, waiting for an opportunity to turn. In the second stage, the vehicle is stopped at the waiting location and monitors the opposing traffic, looking for an acceptable gap to make the turn. The third and final stage involves the turning movement once an acceptable gap is available in the opposing traffic stream. The vehicle waiting time and the availability of an acceptable gap will depend on the characteristics of the headway distribution in the opposing traffic. In a typical traffic stream, three distinct headway-distribution periods can be identified:

1) The queue discharge period where headways are uniformly distributed with an average equal to the saturation headway.
2) The delayed vehicle period that includes vehicles arriving during green but delayed by the queue.
3) The free-flow period with randomly distributed headways.

Vehicle Trajectory and Signal Timing Data Used in the Analysis

The NGSIM dataset used in this project represents vehicle trajectories on a segment of Peachtree Street in Atlanta, Georgia collected during two different time periods: noon-peak period (12:45 PM to 1:00 PM) and afternoon peak period (4:00 PM to 4:15 PM) in November of 2006. The characteristics of the Atlanta corridor are shown in Figure 1. The Peachtree Street corridor is approximately 2,100 feet in length and includes five intersections, four signalized intersections and one unsignalized intersection. Eight high resolution cameras were used to record the traffic operations along the corridor. The coverage area of each of these cameras is shown in Figure 1. High resolution vehicle position data was collected from the recorded videos using advanced object recognition software that tracks the precise location of every vehicle, with an accuracy of one foot or less, on 1/10th of a second (100 milliseconds) basis.

In addition to the vehicle trajectory data, signal indication information was also available for the Atlanta dataset. The corridor is controlled using a coordinated-actuated system with a cycle length of 100 seconds. Table 1 lists the characteristics of the left-turn data in the NGSIM datasets, including the lane assignment, type of left-turn control, and total number of vehicles in each approach. The number of vehicles represents the total number of vehicles in each approach during the two 15-minute time periods for each dataset.

Based on data available in the NGSIM datasets, the characteristics of left-turn operations for both permitted and protected left-turn modes are studied. The microscopic characteristics of the following parameters are investigated and documented as part of the project: vehicle turning path, start-up lost time, saturation flow rate, and speed and time headway profiles along the turning path. While the sample size for some of the cases might not be large enough to allow for full statistical analysis, the data presented in this report provides insights on different elements of driver behavior as it relates to left-turn operations.

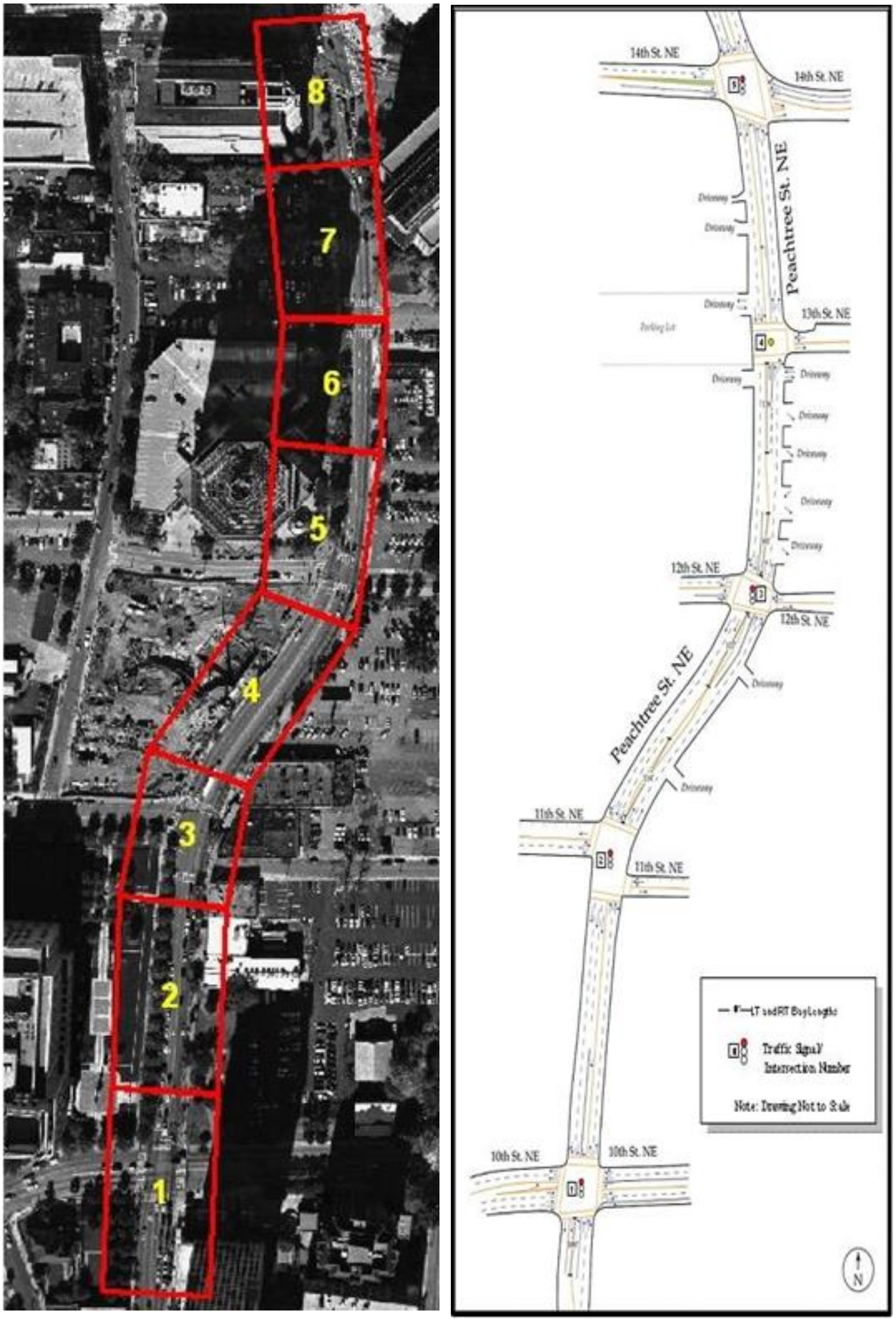

Figure 1: Characteristics of the Peachtree Street corridor in Atlanta, Georgia showing the eight data collection segments.

Table 1: NGSIM Left-Turn Data

Dataset	Intersection	Approach	Lane Assignment	Traffic Control	Number of Vehicles
Peachtree Street Atlanta, GA	10th St. NE	Northbound	Exclusive left-turn lane	Protected/ Permitted	62
		Southbound	Exclusive left-turn lane	Protected/ Permitted	82
	12th St. NE	Northbound	Exclusive left-turn lane	Protected/ Permitted	20
		Southbound	Exclusive left-turn lane	Protected/ Permitted	24
	14th St. NE	Northbound	Exclusive left-turn lane	Protected/ Permitted	26
	11th St. NE	Northbound	Shared lane (TH/LT)	Permitted	232*
		Southbound	Shared lane (TH/LT)	Permitted	63*
	12th St. NE	Westbound	Shared lane (TH/LT/RT)	Permitted	21*

* Total volume using the lane, including both left-turn and through vehicles.

NGSIM Data Dictionary

The NGSIM datasets provide high-resolution vehicle trajectory data. Each row in the NGSIM data represents the temporal and spatial data for a single vehicle reported in 24 different fields that describe its location, length, speed, acceleration, lane, preceding and following vehicles, headway, and origin and destination updated every 0.1 second. A description of the data included in each field is provided in Table 2.

Table 2: Description of the NGSIM Vehicle Trajectory Dataset

Column	Name	Unit	Description
1	Vehicle ID	Number	Vehicle identification number (ascending by time of entry into section)
2	Frame ID	0.1 sec.	Frame identification number (ascending by start time)
3	Total Frames	0.1 sec.	Total number of frames in which the vehicle appears in this dataset.
4	Global Time	0.001 sec	Epoch time, elapsed time since Jan. 1, 1970.
5	Local X	Feet	Lateral (X) coordinate of the front center of the vehicle - perpendicular to the median of the Peachtree Street. Vehicles traveling on the east side of the median have positive local X values, while those traveling on the west side of the median have negative local X values.
6	Local Y	Feet	Longitudinal (Y) coordinate of the front center of the vehicle along the median of Peachtree Street. The start point is at the southern boundary of the study area.
7	Global X	Feet	X coordinate of the front center of the vehicle based on NAD83.
8	Global Y	Feet	Y coordinate of the front center of the vehicle based on NAD83.
9	Vehicle Length	Feet	Length of vehicle
10	Vehicle Width	Feet	Width of vehicle
11	Vehicle Class	Number	Vehicle type: 1 - motorcycle, 2 - auto, 3 - truck
12	Vehicle Speed	ft/sec	Instantaneous speed of vehicle
13	Vehicle Acceleration	ft/sec^2	Instantaneous acceleration of vehicle
14	Lane Identification	Number	Current lane position of vehicle. Lane numbering is incremented from the left-most lane, except for locations where left-turn or right-turn bays exist. Left-turn bays are numbered starting from 11 and are incremented from the left-most left-turn bay.
15	Origin Zone	Number	Origin zones of the vehicles, i.e., the place where the vehicles enter the tracking system. There are 21 origins in the study area, numbered from 101 through 123. Destination 204 and 209 are a one-way off-ramp; hence, there are no associated origin number 104 and 109.
16	Destination Zone	Number	Destination zones of the vehicles, i.e., the place where the vehicles exit the tracking system. There are 22 destinations in the study area, numbered from 201 through 223. Origin 119 is a one-way off-ramp; hence there is no associated destination number 219.
17	Intersection	Number	Intersection in which the vehicle is traveling. Intersections are numbered from 1 to 5, with intersection 1 at the southernmost, and intersection 5 at the northernmost section of the study area.
18	Section	Number	Section in which the vehicle is traveling. Peachtree Street is divided into six sections (south of intersection 1; between intersections 1 and 2, 2 and 3, 3 and 4, 4 and 5, 5 and 6; and north of intersection 6).
19	Direction	Number	Moving direction of the vehicle. 1 - east-bound (EB), 2 - north-bound (NB), 3 - west-bound (WB), 4 - south-bound (SB).
20	Movement	Number	Movement of the vehicle. 1 - through (TH), 2 - left-turn (LT), 3 - right-turn (RT).

Table 3: Description of the NGSIM Vehicle Trajectory Dataset (Cont.)

Column	Name	Unit	Description
21	Preceding Vehicle	Number	Vehicle Id of the lead vehicle in the same lane. A value of ‘0’ represents no preceding vehicle.
22	Following Vehicle	Number	Vehicle Id of the vehicle following the subject vehicle in the same lane. A value of ‘0’ represents no following vehicle.
23	Spacing	Feet	Space headway; spacing provides the distance between the front-center of a vehicle to the front-center of the preceding vehicle.
24	Headway	Second	Time headway; headway provides the time to travel from the front-center of a vehicle (at the speed of the vehicle) to the front-center of the preceding vehicle. A headway value of 9999.99 means that the vehicle is traveling at zero speed (congested conditions).

CHAPTER 3: ANALYSIS AND RESULTS

Turning Path for Left-Turning Vehicles

Global X and Global Y vehicle position data in the NGSIM database was used to plot the turning path for different left-turning vehicles. The global coordinates of different points along the Peachtree Street corridor were used to relate the vehicles' turning path plots to the corridor geometry. Figure 2 shows the turning path plots for the left-turning vehicles turning under permitted turning mode at the Peachtree Street and 10th Street intersection during the noon peak period. Figure 3 shows the same data at the Peachtree Street and 14th Street intersection during the afternoon peak period. Figure 4, however, shows the turning path for left-turn vehicles turning under protected turning mode at the Peachtree Street and 10th Street intersection during the afternoon peak period. The "ideal" shortest circular turning path, as defined in the VISSIM microscopic simulation model (PTV 2010), is shown in the figures as a dash line. In the permitted left-turn mode, some of the vehicles wanting to turn left have to wait for an acceptable safe gap in the opposing traffic to make the left-turn movement. The waiting zone, where vehicles had to wait prior to making the left-turn, is marked in both Figure 2 and Figure 3. Turning path plots for other approaches and intersections are presented in Appendix A.

As can be seen in the Figures, the turning path for most vehicles is not consistent with the ideal circular turning path defined by different geometric design standards and adapted by different microscopic simulation models. Actual turning paths deviate from the ideal path with distances as high as 7.8 feet at some points. This was true for vehicles turning under protected turning mode as well as vehicles turning under permitted turning mode that proceeded with the left-turn movement without having to wait for a gap in the opposing traffic. The plots also suggest that there is a significant variation in the left-turn path executed by different vehicles. While the plots clearly highlight the significant deviation between the actual turning path for left-turning vehicles and the theoretically assumed path, the sample size of the NGSIM data is not large enough to provide a better definition of the turning path of left-turning vehicles under different left-turn modes.

The plots also reveal a distinct pattern in the way left-turning vehicles, waiting for an acceptable gap in the opposing traffic, advance with the left-turn movement. Once the permitted interval begins, drivers move forward following their initial direction of travel to a "waiting zone" where they temporarily stop waiting for an acceptable gap in the opposing traffic. The end of this waiting zone seems to be at a right angle with the center of the lane receiving the left-turning vehicles. The exact location of the left-turning vehicle within the waiting zone when it actually executes the left-turn to the receiving lane depends on several factors such as the vehicle's waiting time, the presence of other vehicles in the left-turning queue, and the availability of acceptable gaps in the opposition traffic.

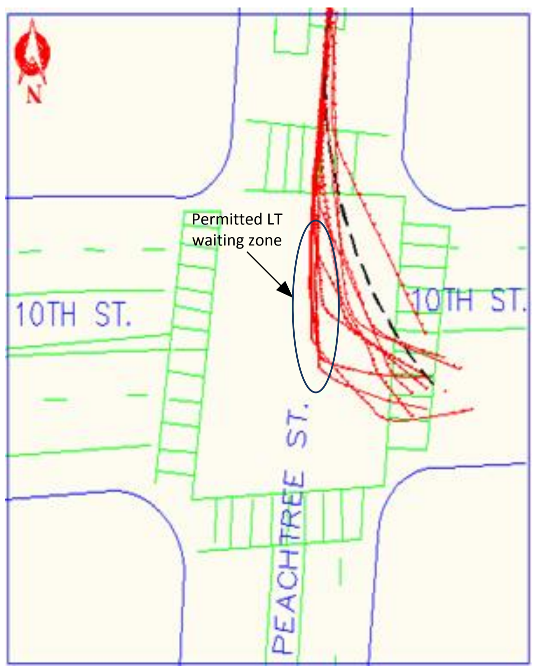

Figure 2: Turning path for left-turning vehicles - permitted LT mode SB Peachtree Street at 10th Street intersection (12:45 PM - 1:00 PM).

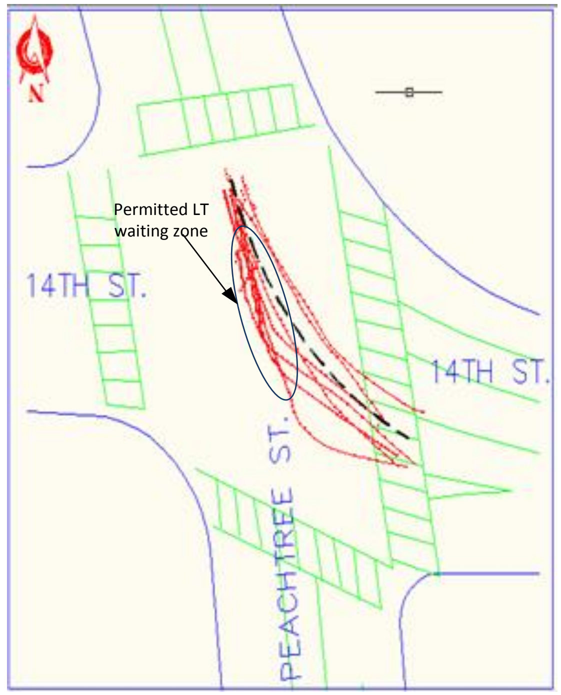

Figure 3: Turning path for left-turning vehicles – permitted LT mode SB Peachtree Street at 14th Street intersection (4:00 PM – 4:15 PM).

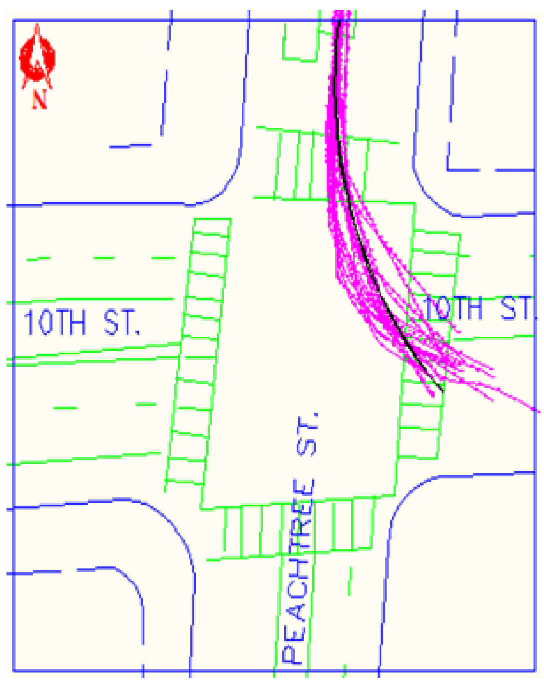

Figure 4: Turning paths for left-turning vehicles –protected LT mode Peachtree Street and 10th Street intersection (4:00 PM – 4:15 PM).

Start-Up Lost Time

According to Traffic Signal Timing Manual (FHWA 2008), start-up lost time is the additional time, in seconds, consumed by the first few vehicles in a queue at a signalized intersection above and beyond the saturation headway, because of the need to react to the initiation of the green phase and to accelerate. Start-up lost time was measured in a fashion similar to that recommended in the Highway Capacity Manual (HCM 2010). Procedures for calculating start-up lost time from the NGSIM dataset are as follows:

1. For the first vehicle in a queue, the headway was measured as the time difference between the start of green and the first vehicle's rear end crossing the stop bar.
2. For the other vehicles in a queue, the headway was measured as the time difference between the preceding vehicle's rear end crossing the stop bar and the following vehicle's rear end crossing the stop bar.
3. A vehicle's speed must be zero for a significant time when it was at the stop bar or near the stop bar. The video was also checked to make a cross check.
4. Saturation headway is the average headways of the vehicles that are in queue starting from the 4th position of the queue to the last position of queue.
5. Start-up lost time was measured as the sum of excess amount of headways of the first three vehicles of the queue to the saturation headways.

Average start-up lost time values and their standard deviation for three different lane uses (through only, exclusive left-turn, and shared though and left-turn) are shown in Table 4. The average start-up lost time for though-only lanes was slightly lower (1.79 seconds) than that for exclusive left-turn lanes (1.91 seconds) and shared through and left-turn lanes (1.86 seconds). T-tests were used to compare the mean values. The results showed that the differences in mean values in the three groups are not statistically significant at the 0.05-level. These results are consistent with HCM2010 assumption that there is no significant difference in the start-up lost time for different lane uses (TRB 2010). The results, however, show that default HCM2010 start-up lost time value of 2.0 seconds is very conservative, especially when dealing with urban corridors.

Table 4 Average Start-Up Lost Time Values for Different Lane Uses

Lane Use	Sample Size	Average (seconds)	Standard Deviation
Through only	69	1.79	0.68
Exclusive left-turn	26	1.91	0.63
Shared through and left-turn	29	1.86	0.77

Saturation Flow Rate

Time headway is defined as the difference between the time when the front of a vehicle arrives at a reference point and the time the front of the next vehicle arrives at the same point (in seconds). When observed during queue discharge at the approach's stop bar, average time headway defines the saturation flow rate for the approach and is referred to as the "saturation headway." This is illustrated in Figure 5. Average saturation headway values and their standard deviation for three different lane uses (through only, exclusive left-turn, and shared though and left-turn) are shown in Table 5. The average saturation headway for though-only lanes was lower (2.03 seconds) than that for exclusive left-turn lanes (2.56 seconds) and shared through and left-turn lanes (2.28 seconds). The results of the t-test to compare the mean values showed that the differences between the three groups are statistically significant at the 0.05-level. The corresponding saturation flow rate for the three different lane uses are 1773 vehicles per hour, 1406 vehicles per hour, and 1579 vehicles per hour, respectively. Again, these results are consistent with the saturation flow rate values suggested in the HCM2010 (TRB 2010).

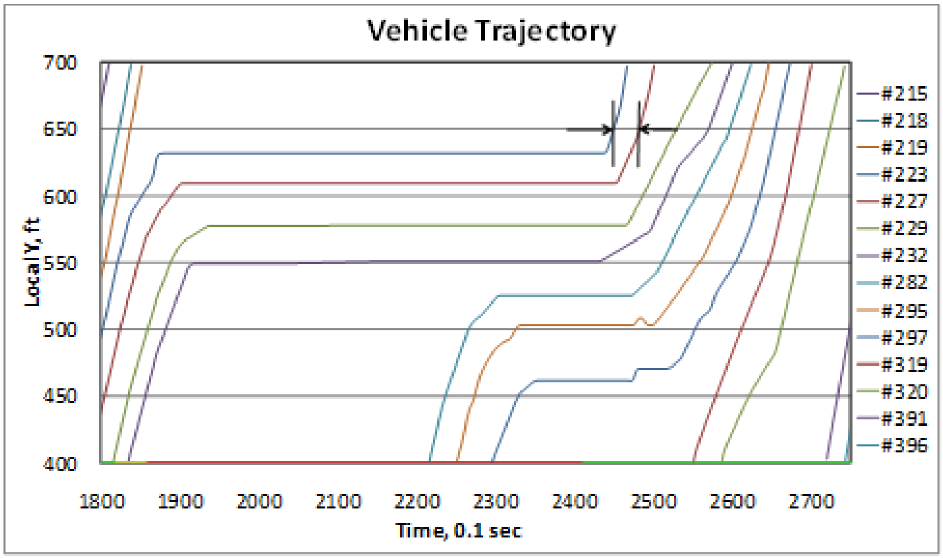

Figure 5: Saturation headway measurements using NGSIM vehicle trajectory data.

Table 5 Average Saturation Headway and Saturation Flow Rate for Different Lane Uses

Lane Use	Sample Size	Saturation Headway (sec)		Saturation Flow Rate (vph)
		Average	Standard Deviation	
Through only	86	2.03	0.66	1773
Exclusive left-turn	39	2.56	0.81	1406
Shared through and left-turn	50	2.28	0.74	1579

Average Speed versus Distance from the Stop Bar

Average speed values as a function of the distance of the stop bar for through and left-turning vehicles are presented in Figure 6 and Figure 7, respectively. The speed profile values are also listed in Table 5. Figure 8 shows plots of the average speed profile for vehicles in queue position 1. The same plots are presented in Figure 9, Figure 10, and Figure 11 for queue position 2, queue position 3, and queue position 4, respectively. The results show a distinct pattern. At the same distance from the stop bar, the average speed of left-turning vehicles is consistently lower than that for through vehicles. The ratio between the average speed for left-turning vehicles and through vehicles ranged from 0.91 to 0.49 with higher values near the stop bar and lower values on the turning path. These ratios are also higher for queue position 1 and queue position 2 than for queue position 3 and queue position 4. This difference can be attributed to the relatively slower vehicle speeds expected on circular paths. As most of the left turning vehicles in the NGSIM data were vehicles turning from the Peachtree Street corridor to side streets, no information was available on the speed profile of these left turning vehicles once they complete the turning path.

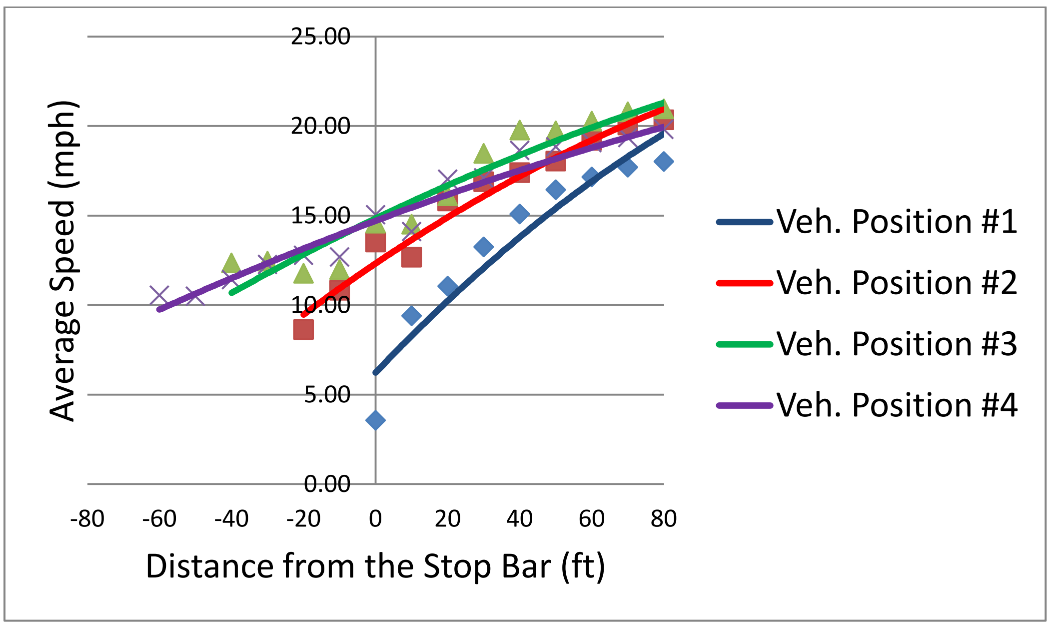

Figure 6: Average speed versus distance from the stop bar (through vehicles).

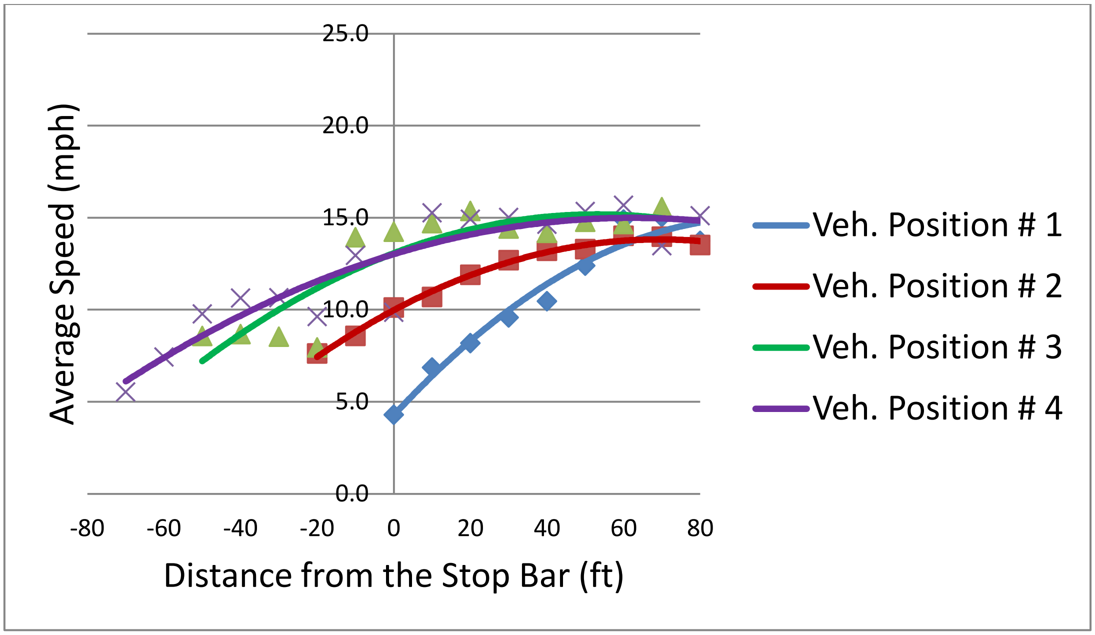

Figure 7: Average speed versus distance from the stop bar (left-turning vehicles).

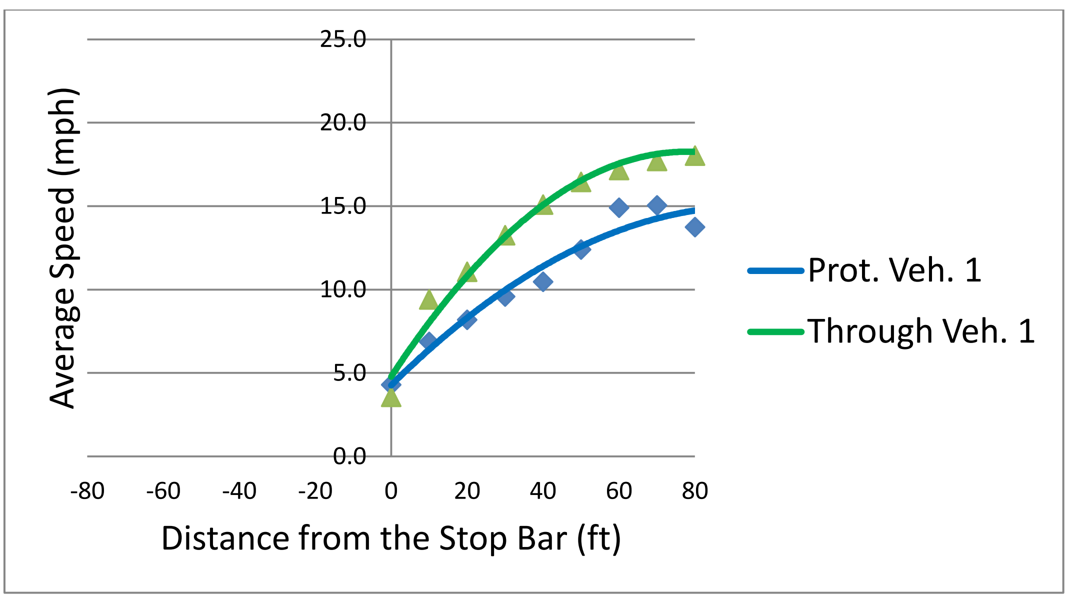

Figure 8: Average speed versus distance from the stop bar (queue position 1).

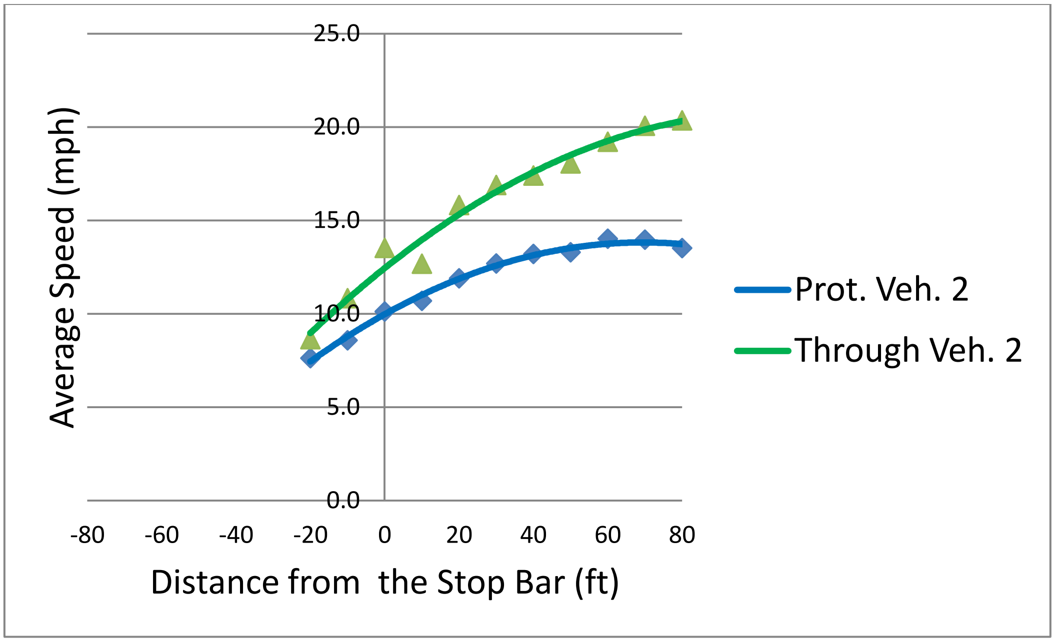

Figure 9: Average speed versus distance from the stop bar (queue position 2).

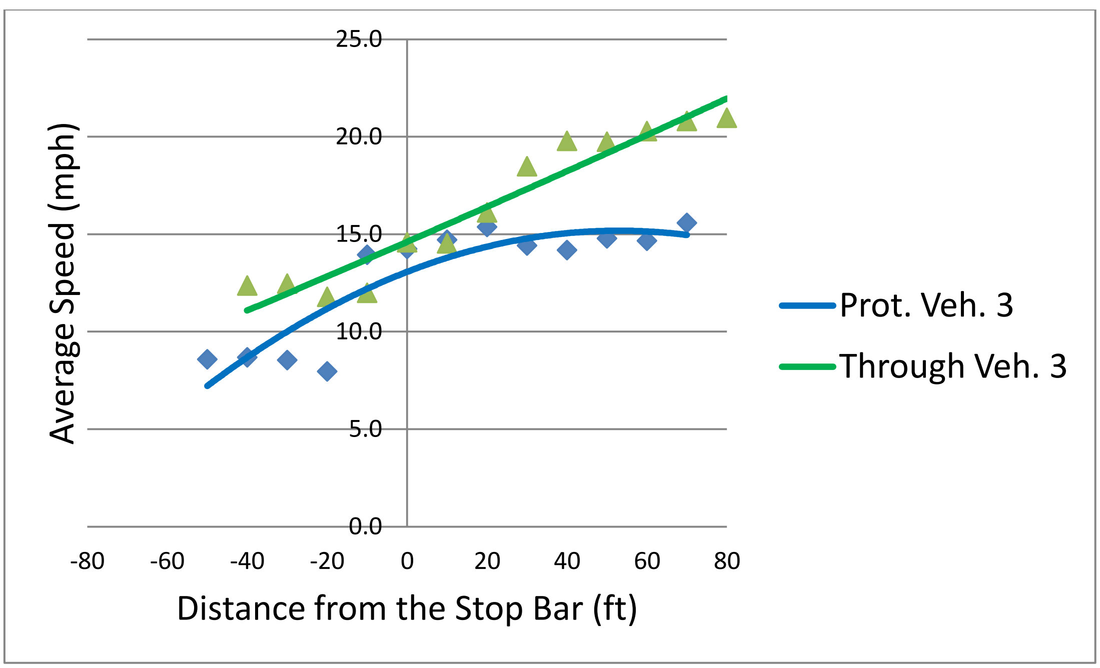

Figure 10: Average speed versus distance from the stop bar (queue position 3).

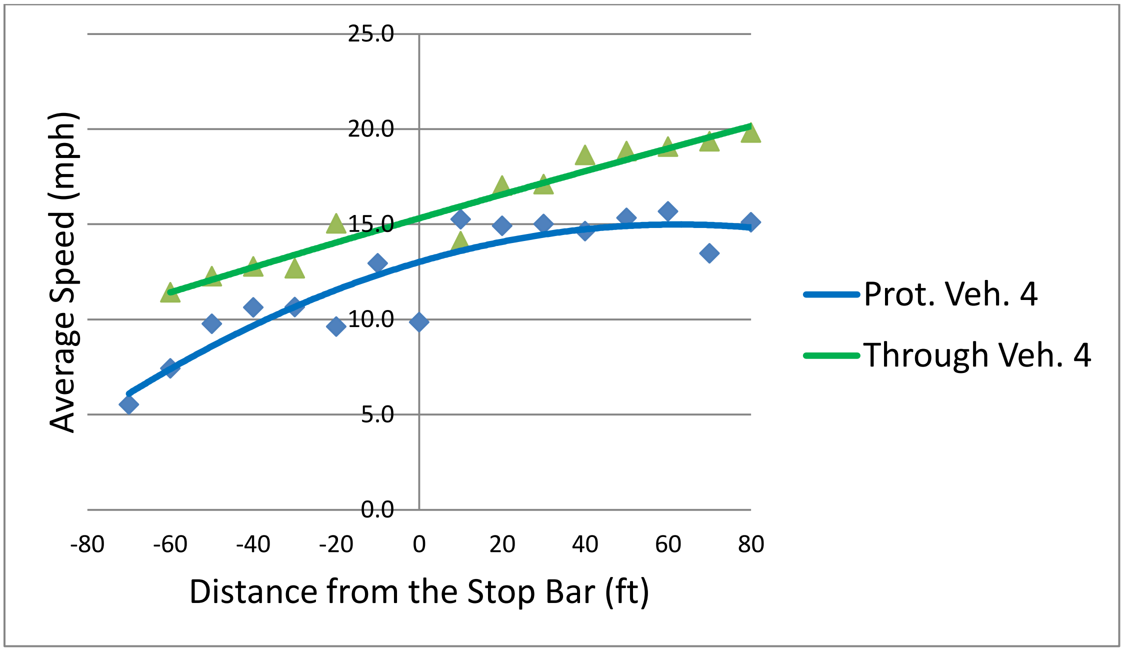

Figure 11: Average speed versus distance from the stop bar (queue position 4).

Table 6: Average Speed versus Distance from the Stop Bar (Through and Left-Turn Vehicles)

Queue Position	Distance From the Stop Bar (ft)	Vehicle Speed (ft/sec)	
		Through Vehicles	Left-Turning vehicles
1	0	5.24	4.29
	10	13.79	6.86
	20	16.23	8.19
	30	19.44	9.58
	40	22.13	10.46
	50	24.12	12.39
	60	25.17	14.90
	70	25.97	15.04
	80	26.43	13.74
	90	27.18	14.44
2	-20	12.67	7.62
	-10	15.89	8.58
	0	19.84	10.12
	10	18.60	10.69
	20	23.20	11.90
	30	24.78	12.69
	40	25.52	13.20
	50	26.47	13.29
	60	28.17	14.02
	70	29.43	13.97
	80	29.85	13.51
	90	29.96	12.15
3	-50	8.40	8.57
	-40	18.13	8.68
	-30	18.27	8.54
	-20	17.28	7.95
	-10	17.58	13.94
	0	21.38	14.24
	10	21.30	14.70
	20	23.63	15.37
	30	27.10	14.41
	40	29.01	14.18
	50	28.95	14.78
	60	29.75	14.66
	70	30.51	15.57
	80	30.75	13.69
	90	31.02	12.67
4	-60	15.48	7.43
	-50	15.40	9.77
	-40	16.76	10.64
	-30	18.00	10.65
	-20	18.75	9.63
	-10	18.62	12.95
	0	22.07	9.86
	10	20.70	15.26
	20	24.99	14.92
	30	25.10	15.02
	40	27.35	14.64
	50	27.64	15.34
	60	27.99	15.68
	70	28.40	13.48
	80	29.07	15.11

Average Time Headway versus Distance from the Stop Bar

Average time headway values as a function of the distance of the stop bar for through and left-turning vehicles are presented in Figure 12 and Figure 13, respectively. These values are also listed in Table 6. Figure 14 shows plots of the time headway profile for vehicles in queue position 2. The same plots are presented in Figure 15 and Figure 16 for queue position 3 and queue position 4, respectively.

A comparison between time headway profiles for through and left-turning vehicles does not reveal any clear pattern. The average time headway between the first vehicle in the queue and the following vehicle seems higher in left-turning vehicles than in through vehicles. This is especially true in the first 50 feet from the stop bar. After this distance, the time headway profiles for left-turning and through vehicles do not seem to be significantly different. Furthermore, there is no significant difference between the time headway profiles for the left-turning and through for queue position 3 and queue position 4. The short duration of the protected left-turn interval may have contributed to this time headway behavior. Drivers seem to maintain as minimal time headway as possible with the leading vehicle while they are on the turning path to clear the intersection before the expiration of the protected left-turn interval. The NGSIM sample size, however, is not large enough to allow for any statistically valid conclusion to be drawn from these comparisons.

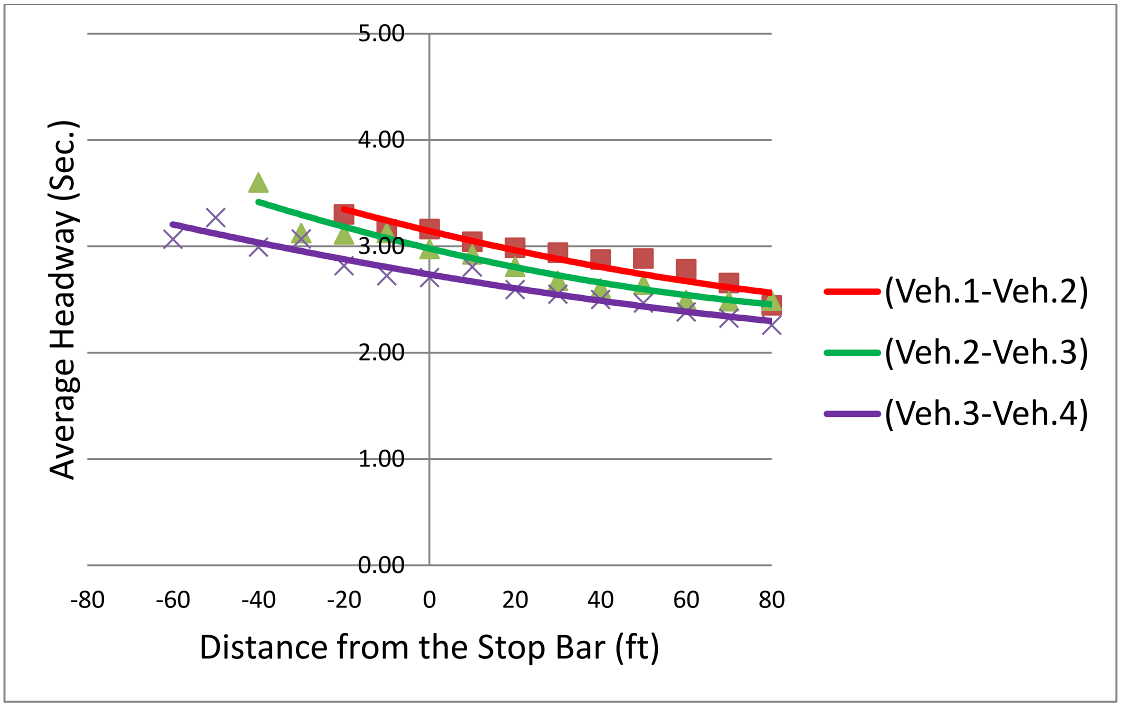

Figure 12: Average time headway versus distance from the stop bar (through vehicles).

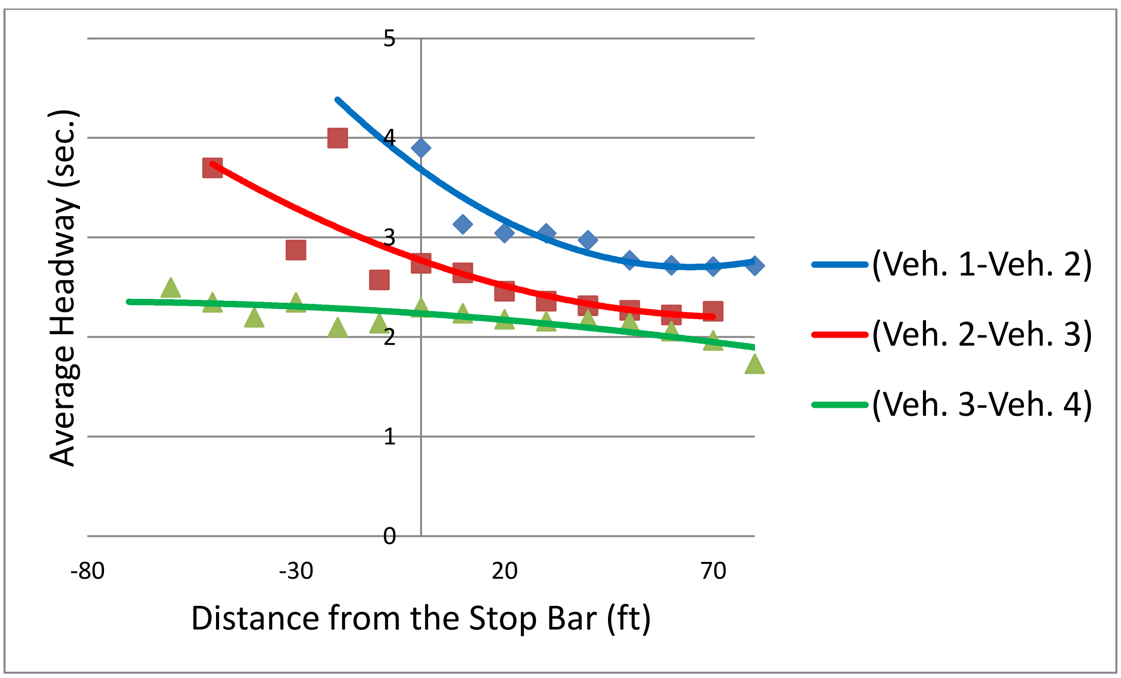

Figure 13: Average time headway versus distance from the stop bar (left-turning vehicles).

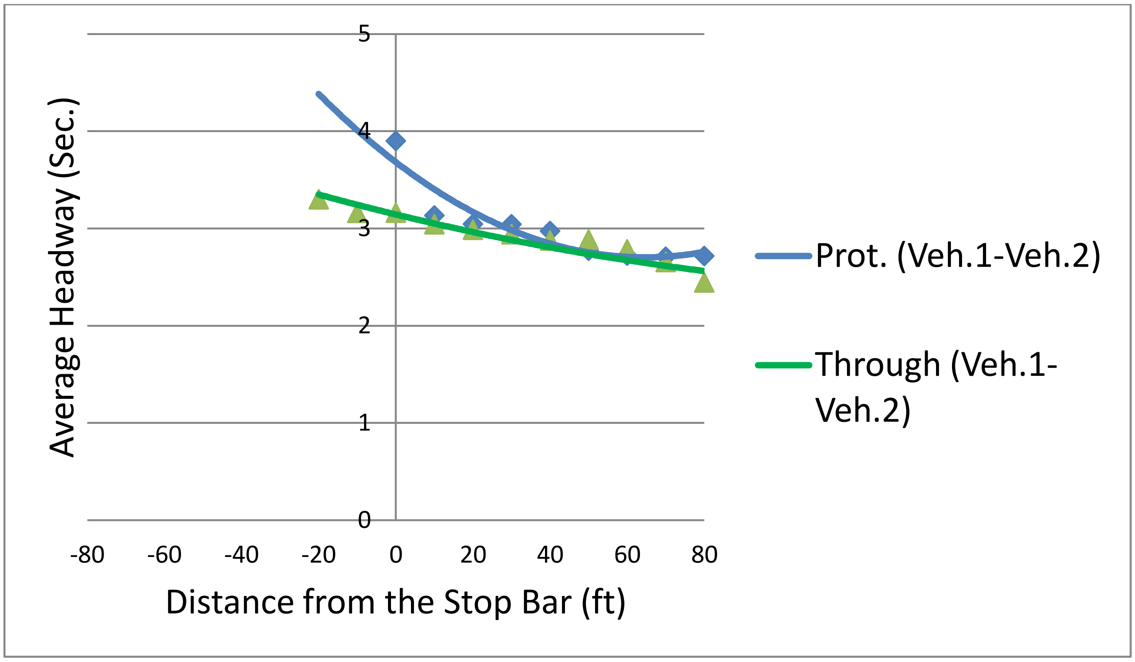

Figure 14: Average time headway versus distance from the stop bar (queue position 2).

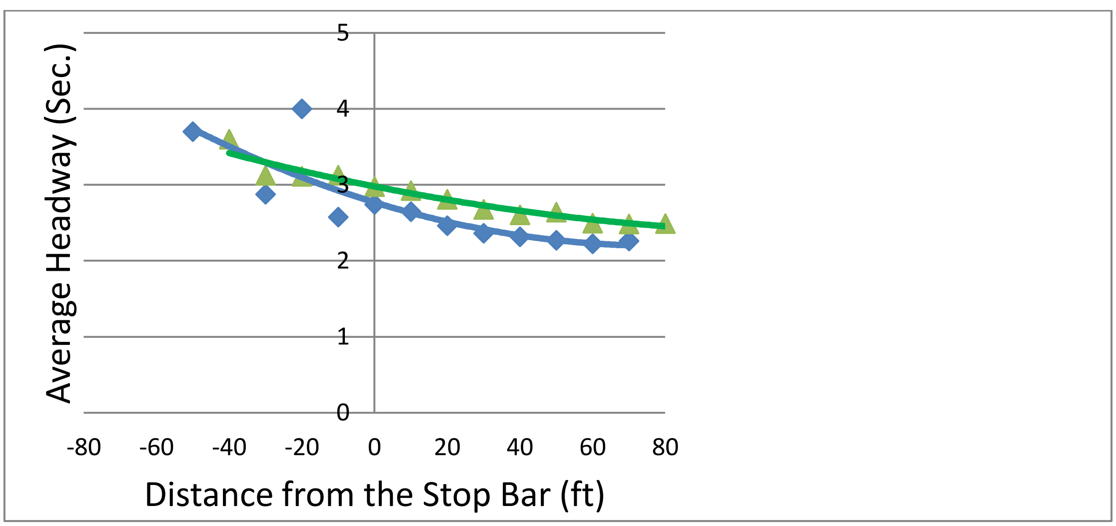

Figure 15: Average time headway versus distance from the stop bar (queue position 3).

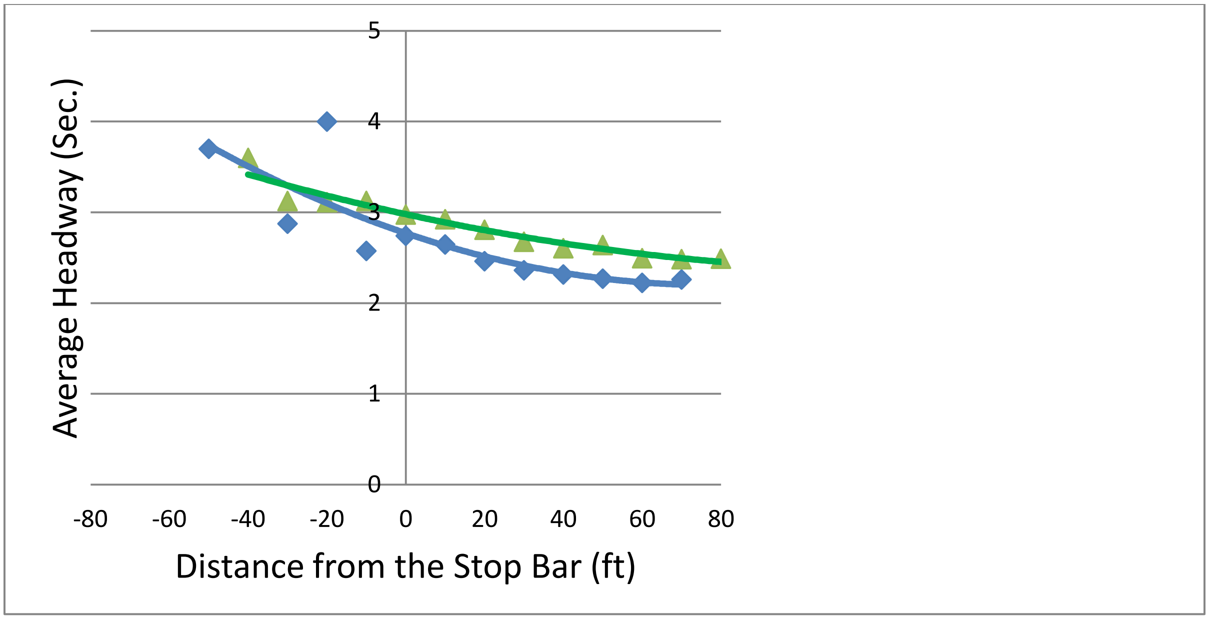

Figure 16: Average time headway versus distance from the stop bar (queue position 4).

Table 7: Average Time Headway for Through and Left-Turning Vehicles

Queue Position	Distance From the Stop Bar (ft)	Time Headway (Seconds)	
		Through Vehicles	Left-Turning vehicles
2	0	3.16	3.90
	10	3.04	3.13
	20	2.99	3.05
	30	2.94	3.04
	40	2.88	2.97
	50	2.89	2.77
	60	2.79	2.72
	70	2.66	2.71
	80	2.45	2.72
	90	2.42	1.40
3	-50	3.55	3.70
	-40	3.60	3.40
	-30	3.13	2.88
	-20	3.11	4.00
	-10	3.13	2.58
	0	2.98	2.74
	10	2.92	2.65
	20	2.81	2.46
	30	2.68	2.36
	40	2.60	2.32
	50	2.64	2.27
	60	2.49	2.22
	70	2.48	2.26
	80	2.49	2.61
	90	2.49	2.27
4	-60	3.07	2.50
	-50	3.27	2.35
	-40	2.99	2.20
	-30	3.07	2.35
	-20	2.82	2.10
	-10	2.72	2.14
	0	2.71	2.30
	10	2.81	2.24
	20	2.59	2.18
	30	2.55	2.16
	40	2.50	2.18
	50	2.47	2.15
	60	2.38	2.06
	70	2.33	1.97
	80	2.26	1.73

CHAPTER 4: CONCLUSIONS

This report documents the findings from a research project that is focused on modeling protected and permitted left-turn operations at signalized intersection approaches. The project's primary objective is to document the microscopic characteristics of protected and permitted left-turn operational parameters at signalized intersections using the NGSIM datasets. The microscopic characteristics of the following parameters are investigated and documented as part of the project:

- Vehicle turning path
- Start-up lost time
- Saturation flow rate
- Speed and time headway profiles along the turning path

While the sample size for some of the cases might not be large enough to allow for full statistical analysis, the data presented in this report provides insights on different elements of driver behavior as it relates to left-turn operations.

- Global X and Global Y vehicle position data in the NGSIM database was used to plot the turning path for different left-turning vehicles. These plots showed that actual turning paths deviate from the ideal turning path, defined by geometric design standards, with distances as high as 7.8 feet at some points. This was true for vehicles turning under protected turning mode as well as vehicles turning under permitted turning mode that proceeded with the left-turn movement without having to wait for a gap in the opposing traffic. The plots also suggest that there is a significant variation in the left-turn path executed by different vehicles.
- The plots also reveal a distinct pattern in the way left-turning vehicles, waiting for an acceptable gap in the opposing traffic, advance with the left-turn movement. Once the permitted interval begins, drivers move forward following their initial direction of travel to a "waiting zone" where they temporarily stop waiting for an acceptable gap in the opposing traffic. The end of this waiting zone seems to be at a right angle with the center of the lane receiving the left-turning vehicles. The exact location of the left-turning vehicle within the waiting zone when it actually

executes the left turn to the receiving lane depends on several factors such as the vehicle's waiting time, the presence of other vehicles in the left-turning queue, and the availability of acceptable gaps in the opposition traffic.

- The start-up lost time and saturation headways were compared for three different lane uses: through lanes, exclusive left-turn lanes, and shared through and left-turn lanes. The average start-up lost time for though lanes was slightly lower (1.79 seconds) than that for exclusive left-turn lanes (1.91 seconds) and shared through and left-turn lanes (1.86 seconds). The differences in mean values in the three groups are not statistically significant at the 0.05-level.
- The average saturation headway for though-only lanes was lower (2.03 seconds) than that for exclusive left-turn lanes (2.56 seconds) and shared through and left-turn lanes (2.28 seconds). The results of the t-test to compare the mean values showed that the differences between the three groups are statistically significant at the 0.05-level. The corresponding saturation flow rate for the three different lane uses are 1773 vehicles per hour, 1406 vehicles per hour, and 1579 vehicles per hour, respectively.
- A comparison between the speed profile for left-turn and through vehicles showed that, at the same distance from the stop bar, the average speed of left-turning vehicles is consistently lower than that for through vehicles. The ratio between the average speed for left-turning vehicles and through vehicles ranged from 0.91 to 0.49 with higher values near the stop bar and lower values on the turning path. These ratios are also higher for queue position 1 and queue position 2 than for queue position 3 and queue position 4.
- A comparison between time headway profiles for through and left-turning vehicles does not reveal any clear pattern. The average time headway between the first vehicle in the queue and the following vehicle seems higher in left-turning vehicles than in through vehicles. This is especially true in the first 50 feet from the stop bar. After this distance, the time headway profiles for left-turning and through vehicles do not seem to be significantly different. Furthermore, there is no significant difference between the time headway profiles for the left-turning and through for queue position 3 and queue position 4.

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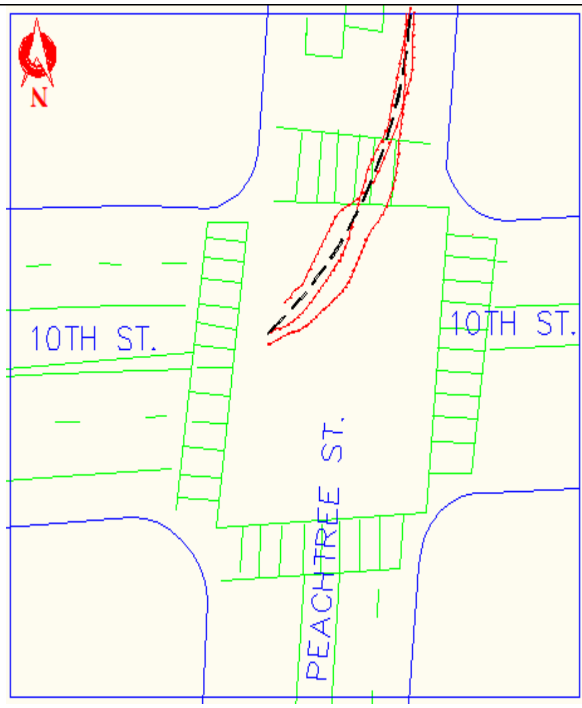
U.S. Department Of Transportation

APPENDIX A: TURNING PATH FOR LEFT TURNING VEHICLES



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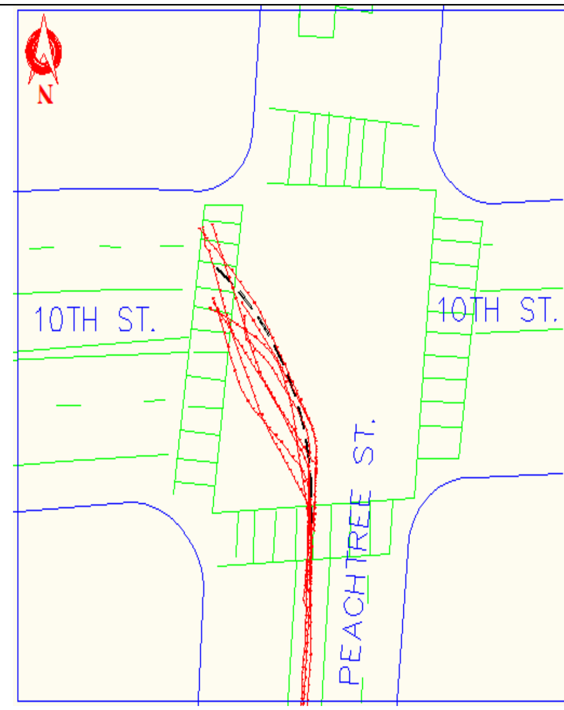

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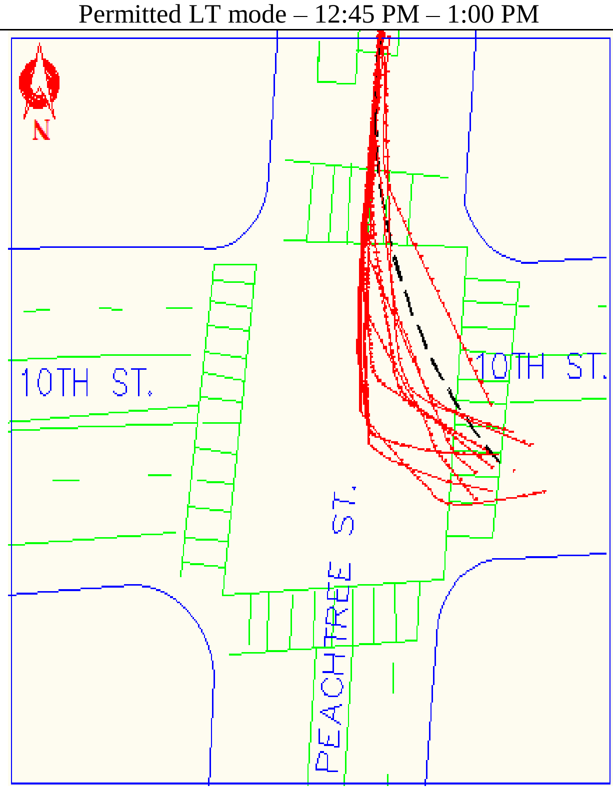

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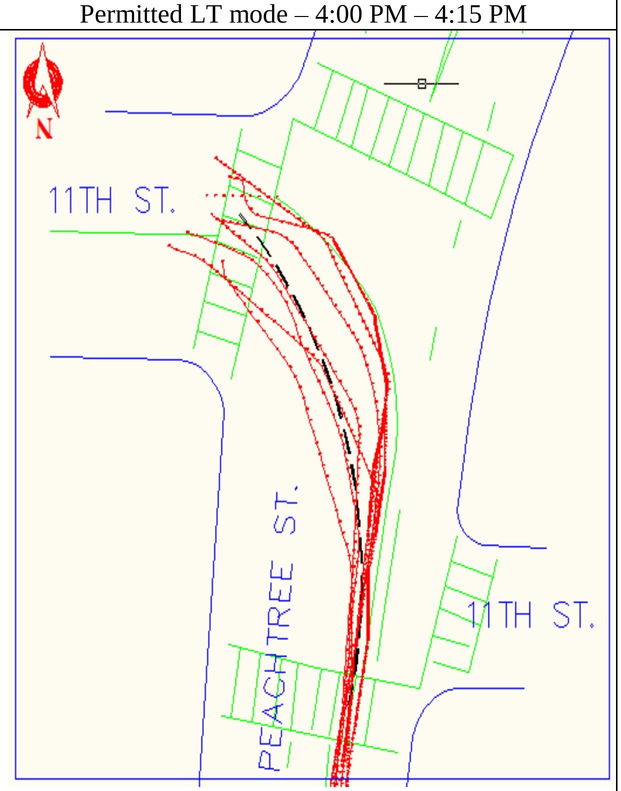

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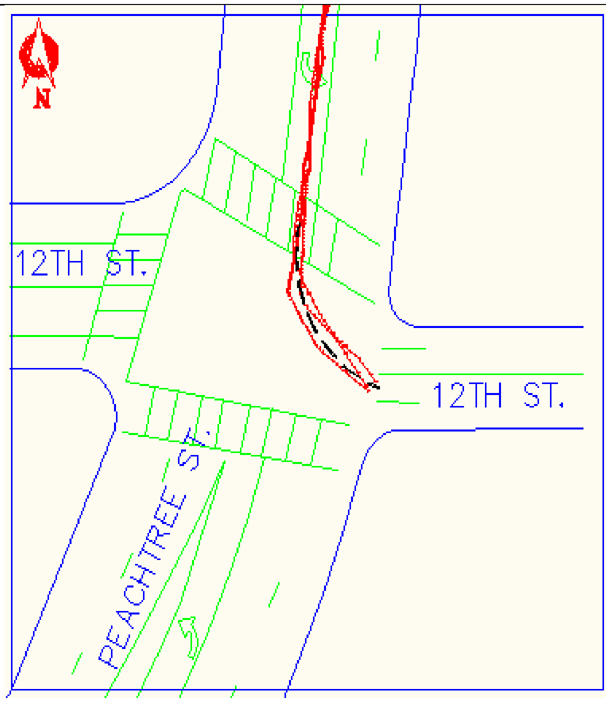

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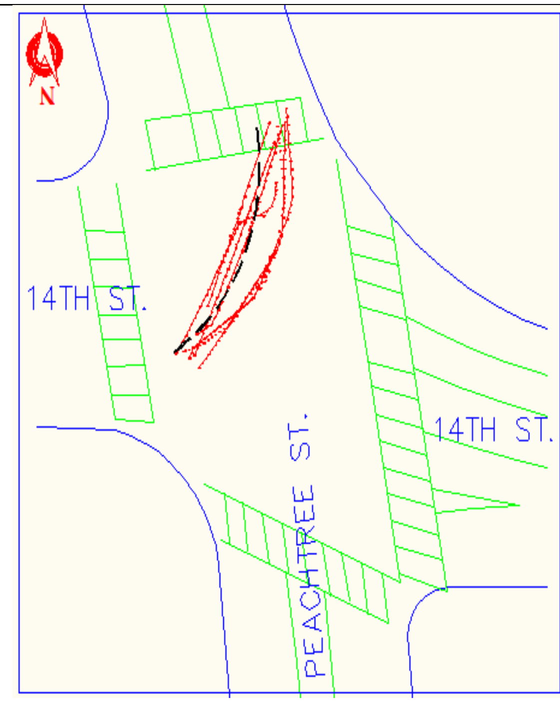

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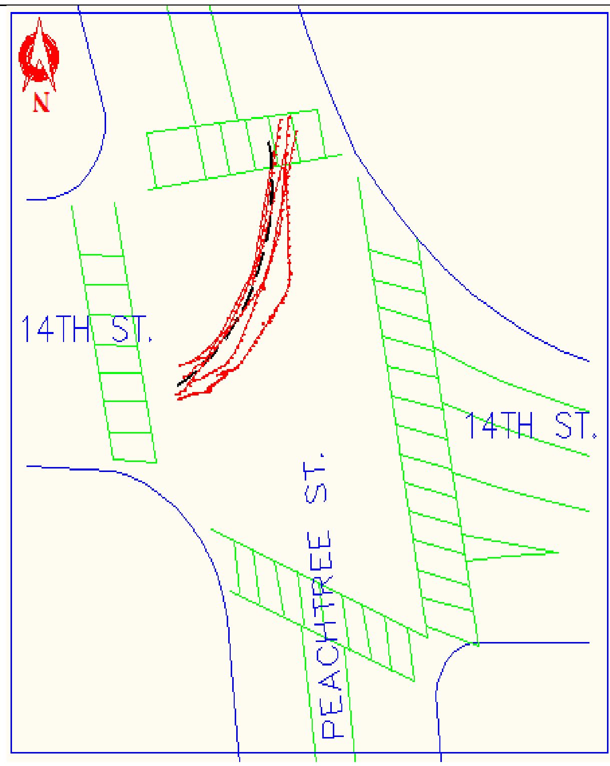

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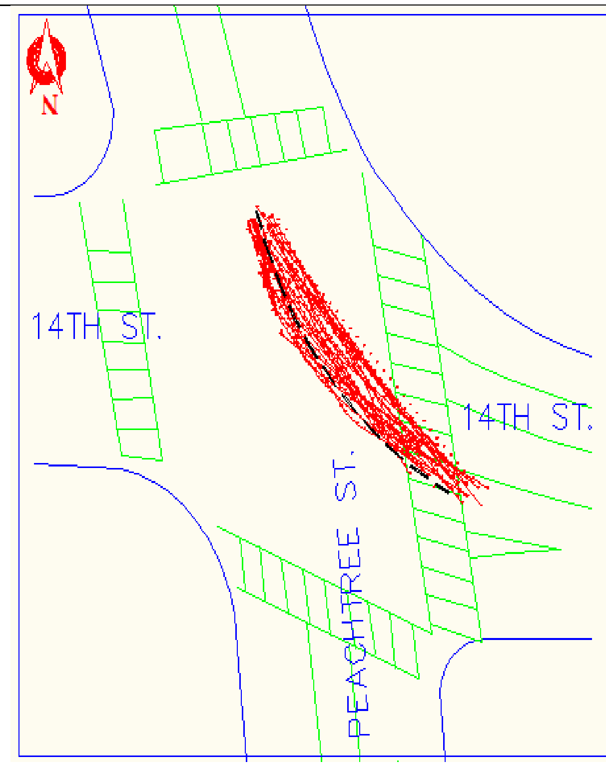

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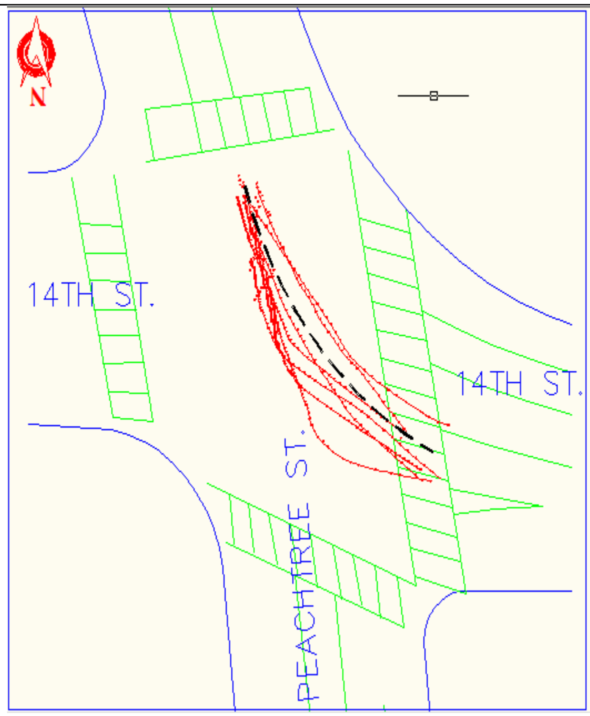

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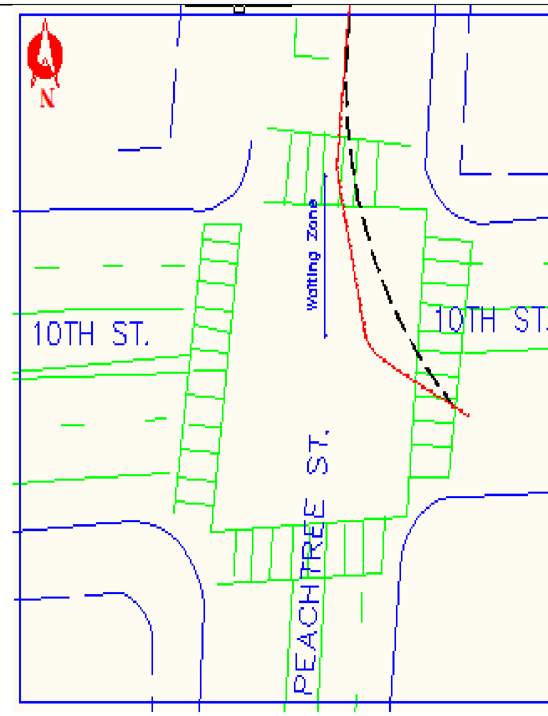

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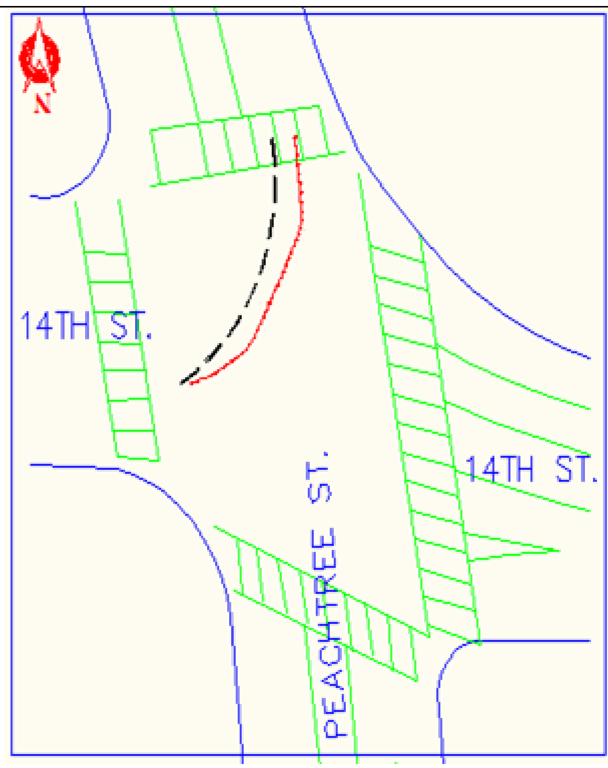

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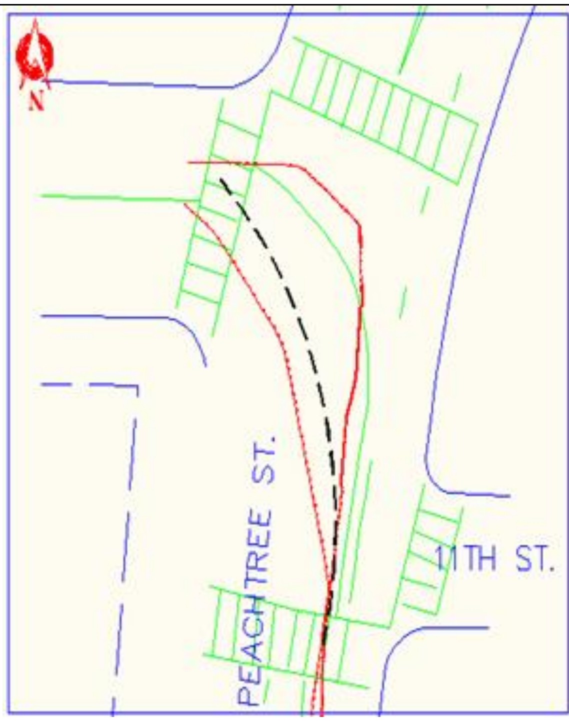

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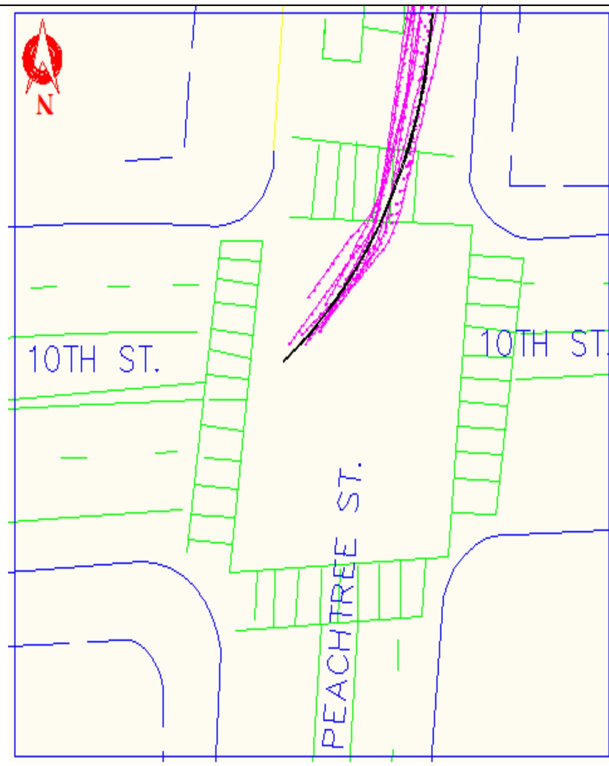

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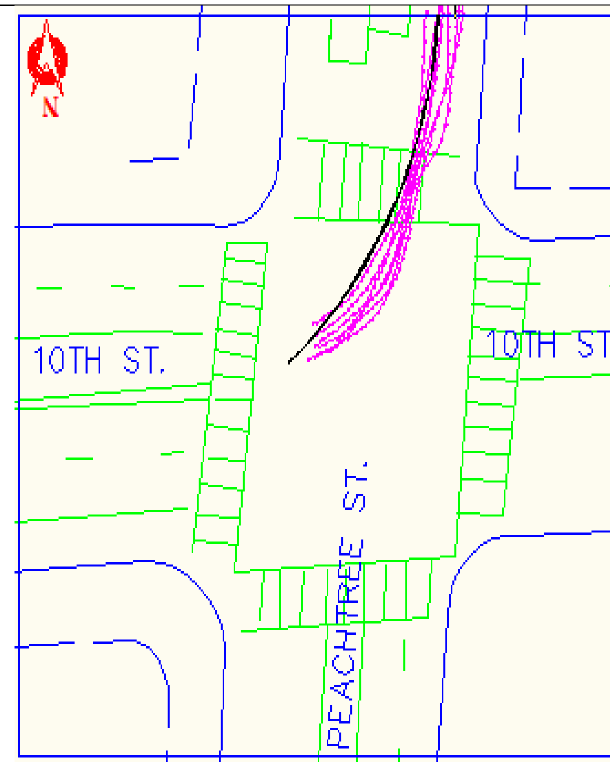

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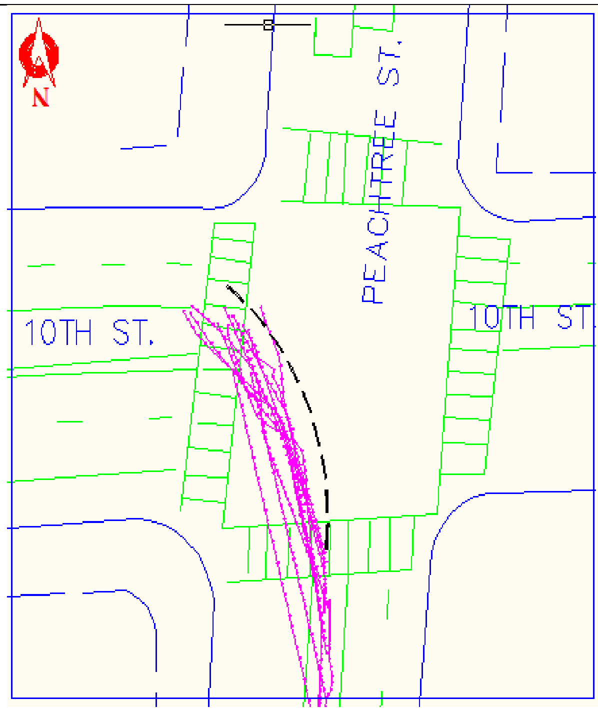

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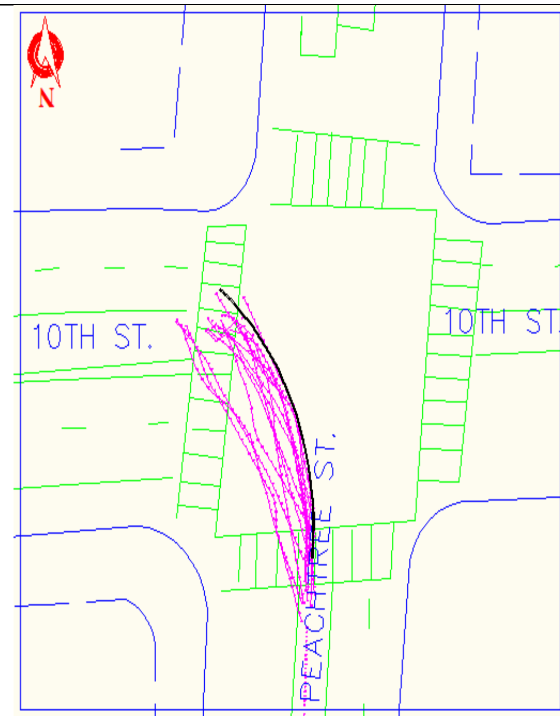

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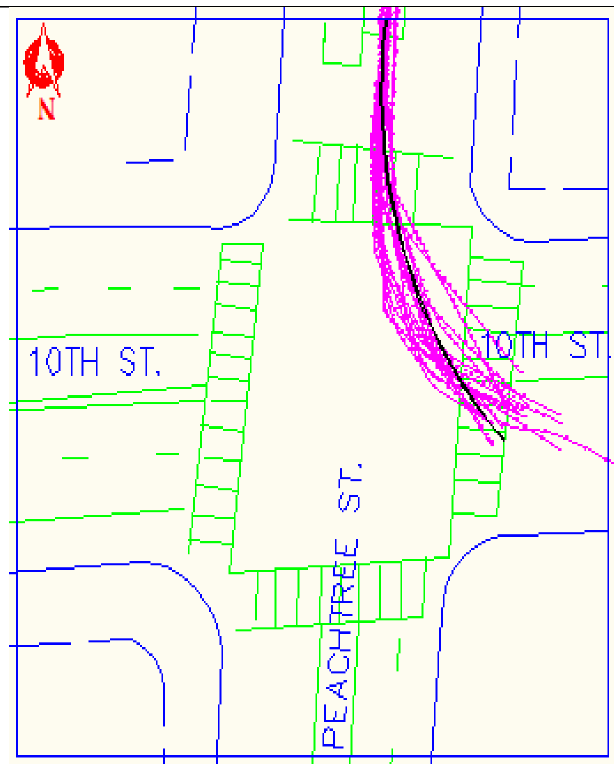

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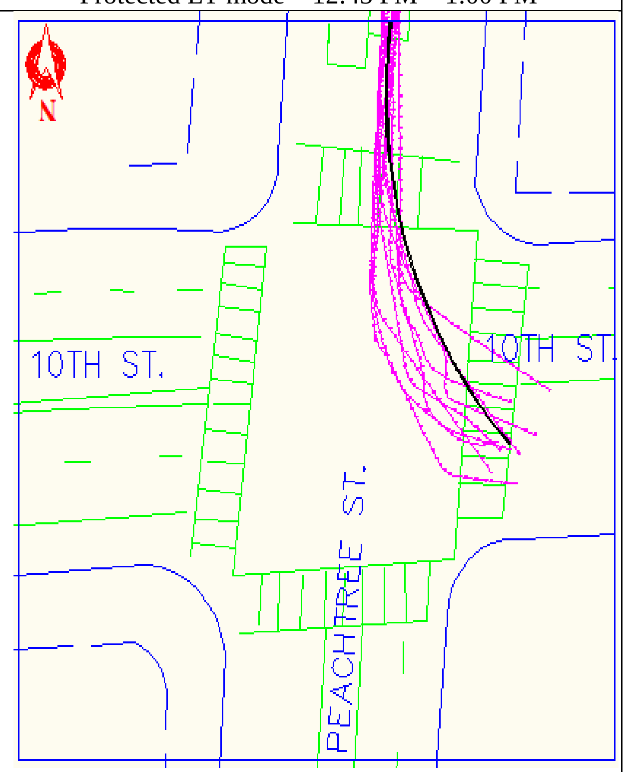

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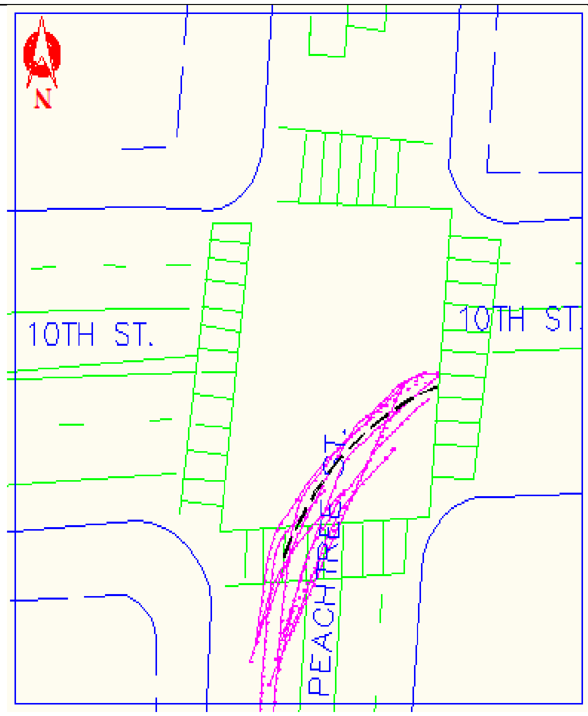	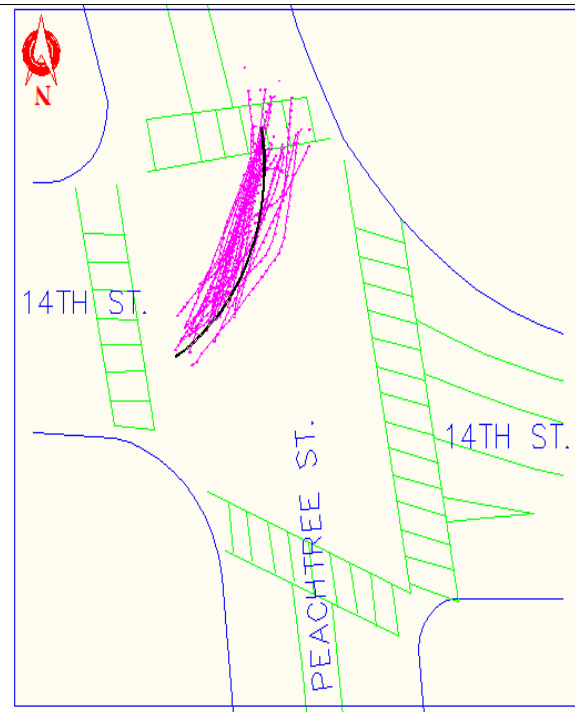
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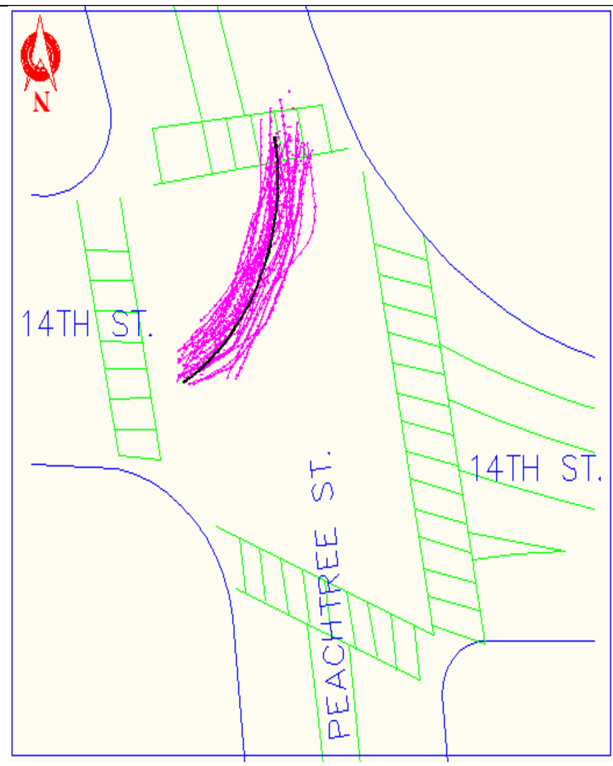	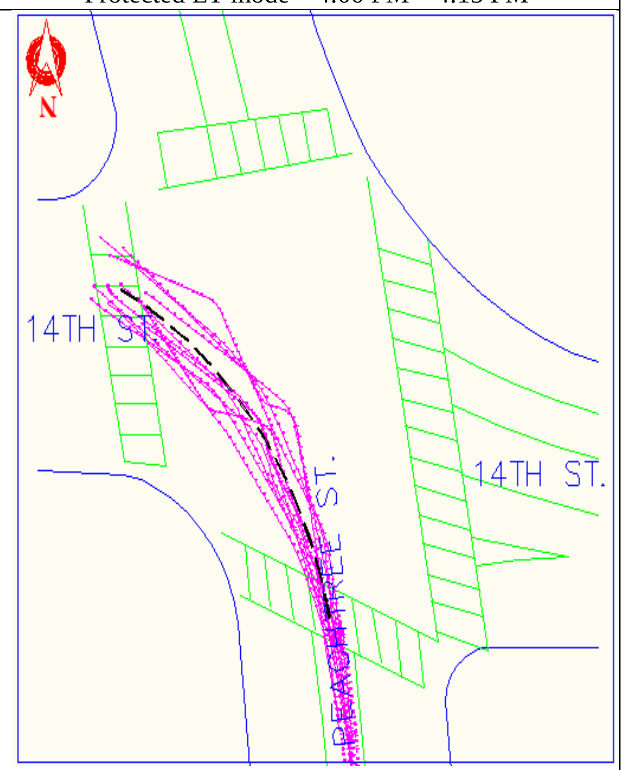
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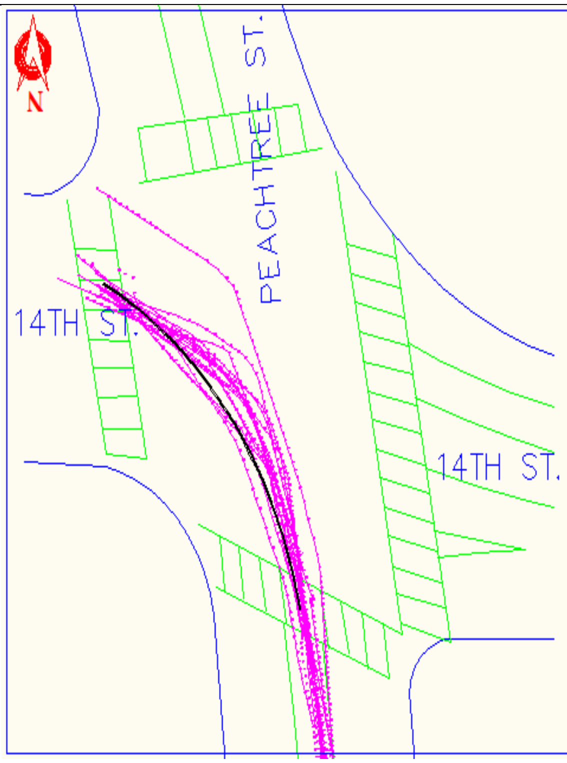	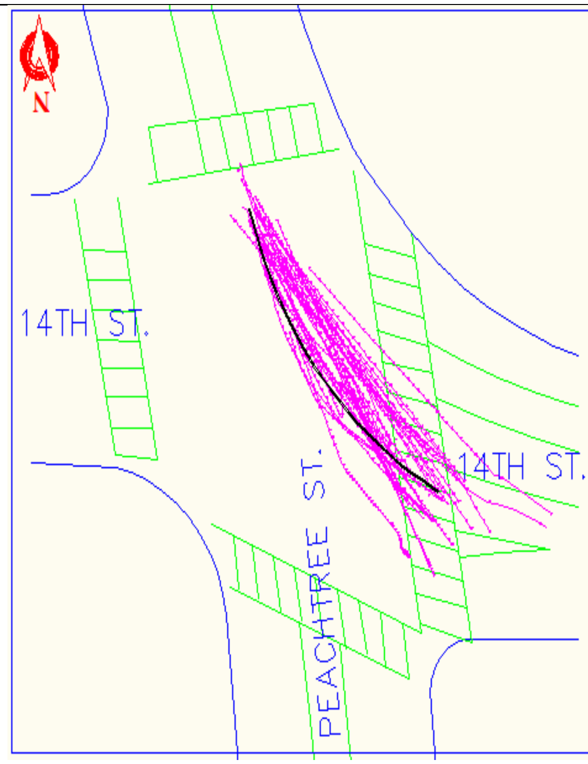
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