Project No. 03-100

EVALUATING THE PERFORMANCE OF CORRIDORS WITH ROUNDABOUTS

FINAL REPORT – Appendices B–J

Prepared for:
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

By:
Kittelson & Associates, Inc.

In association with:
Institute for Transportation Research and Education
Texas Transportation Institute
Write Rhetoric

December 2013

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B. MD 216, SCAGGSVILLE, MARYLAND

The first roundabout corridor visited by the project team, on November 14-16, 2011, was MD 216 in Scaggsville, Maryland. This is a suburban area between Washington, D.C., and Baltimore, Maryland. MD 216 is a four-lane divided roadway and has four roundabouts, two of which are at interchange ramp terminals. There are no intermediate access points between any of the roundabouts. The corridor is auto-dominated, with little pedestrian or bicycle activity.

B.1. DATA COLLECTION PROCEDURES

The data collected at this roundabout corridor, which consisted of four roundabouts in series, included turning movement counts, travel times, spot speeds, geometric delay, approach delay, maximum queue lengths, and lane utilization counts at all four roundabouts, and entry-exit counts at the two ends of the corridor. These data were obtained from video recordings captured through field-mounted cameras, in-vehicle GPS units, Bluetooth readers, and a laser gun. Data were collected during the period of November 14–16, 2011. Exhibit B-1 shows the MD 216 corridor. Camera locations are indicated with red dots and Bluetooth reader locations are shown with yellow stars.

Exhibit B-1 Aerial View of the MD 216 Roundabout Corridor with Camcorder and Bluetooth Placement

B.1.1. VIDEO DATA COLLECTION PROCEDURE

In order to observe and obtain a permanent record of traffic at each of the four roundabouts, the research team collected video recordings of the activities at the intersections during the onsite data collection period. The data collection procedure used a series of eight camcorders temporarily installed in strategic locations to record the activity at each intersection. Under specific conditions, one camcorder could be used to capture the necessary images for an entire intersection; however, for much of the study period in this pilot study, it was

necessary to use two camcorders to capture a field of view that covered all approaches to each roundabout. The team had estimated the position of each camera from images obtained through Google Earth (both satellite and Street View perspectives), but the final decision on the exact placement of each camcorder was made in the field after assessing the actual conditions at the site.

The ground-based approach to installing the cameras created a number of challenges, and the research team focused on using the infrastructure available at the site (e.g., sign posts, luminaire poles, etc.) to install the camcorders with as much elevation as possible. The team soon discovered, however, that the surrounding terrain further hindered the ability to install the cameras. Many of the available luminaire poles were installed in locations where the ground surface sloped away from the road, limiting the effective height of the ladders that the team used to install the cameras. As a result, the team was not able to install the cameras at elevations that were as high as desired.

The large size of Roundabout #3 and #4 (the roundabouts at the US 29 interchange) also compounded the difficulty in capturing the needed point of view, requiring strategic placement of the cameras, as well as specific zoom settings, to record all four approaches to each intersection. An additional impediment was the terrain at Roundabout #4 itself, which sloped downward to the north and east. This also increased the need to place the camcorders at higher elevations to compensate for the topography. The combination of terrain, available infrastructure, and intersection size presented a substantial challenge to positioning the cameras, and the resulting point of view was barely able to capture all of the approaches in the video recordings.

One other compounding factor was the weather; conditions were dry on the first day of the study period, but there were periods of very light rain on the second and third days. The research team created temporary covers for the cameras to protect them from the rain, but the rain and the cover occasionally confused the auto-focus setting on one of the cameras, which then zoomed in to focus on the cover or the raindrops instead of the intersection, rendering those portions of the video recordings unusable for data reduction.

It also took a great deal of time to set up the cameras on site, accounting for the amount of time spent determining the precise location to install each unit. Setting up the cameras on the second day was much more efficient than the first, but much of the morning on the first day was spent installing the equipment, which was more time than originally estimated in the proposed data collection plan.

Additionally, transporting the cameras and equipment was more difficult and costly than anticipated. The procedure was designed to be able to transport the equipment as checked airline luggage, but the size and weight of the equipment container was just under the physical limits of one person to accommodate and just below the limits of the maximum dimensions of items that airlines will accept as checked luggage, even with high additional baggage fees.

In summary, the research team used the initial data collection protocol at this pilot site to obtain data from the recordings, but there were a number of challenges to overcome. The use of video is still very much a viable means of

collecting the data, but the specific equipment and installation methods used in this pilot test are not nearly as efficient as initially projected.

B.1.2. TRAVEL TIME (GPS AND BLUETOOTH) DATA COLLECTION PROCEDURE

The first method to record travel times along the MD 216 roundabout corridor was to use Bluetooth units that sample a portion of the vehicles that pass through the corridor. Two of these Bluetooth units were set up at either end of the corridor, and two more were set up internally, as displayed in Exhibit B-1. It should be noted that the two internal units were deployed at the same location to test two different Bluetooth antennae. As with the cameras, the research team estimated the positions of the Bluetooth readers based upon Google Earth imagery prior to the site visit and made a final determination of reader placement in the field after assessing actual conditions.

As discussed in Chapter 2 of this Interim Report, set-up of the Bluetooth units was easier and faster than anticipated. The units are equipped with large metal bands that allow them to be securely mounted to poles of varying sizes and, unlike the cameras, there is no need to obtain specific vantage points.

Bluetooth provides a large sample of travel time data from all hours of the day. However, it does not provide information on specific events between Bluetooth reader units, such as geometric and control delay at roundabout entries and any fluctuations in speed between roundabouts that may exist. To address these limitations, the research team also conducted traditional floating car travel time runs with an on-board GPS unit. The travel time runs also gave the research team first-hand experience with the operation of the corridor.

A total of six routes were used to conduct the GPS travel time study (see Exhibit B-2):

1. Eastbound through the entire corridor;
2. Westbound through the entire corridor;
3. Starting from the east end, then turning left through roundabout 4;
4. Starting from south of roundabout 4, then turning left through the roundabout and proceeding to the west end;
5. Starting from the west end, then turning left through roundabout 2; and
6. Starting from north of roundabout 2, then turning left through the roundabout and proceeding to the east end.

The last four routes were used to capture left turns through the two roundabouts that the team deemed the most congested.

Exhibit B-2 MD 216 Roundabout Corridor GPS Travel Time Routes

B.1.3. SPOT SPEED DATA COLLECTION PROCEDURE

The team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at the easternmost and westernmost roundabouts using a laser speed gun. These speed profiles will primarily obtained for the purpose of calibrating the VISSIM model of the roundabout corridor, but they also provide an indication of the safety and performance of the roundabouts. Finally, the speeds provide a more realistic estimation of operating speeds at the roundabouts than the GPS travel time runs. A total of 30 spot speed measurements were taken at each point.

B.2. DATA COLLECTION RESULTS

B.2.1. TRAFFIC COUNTS

Using the video recordings, the research team reviewed traffic conditions at all four roundabouts in the corridor and extracted multiple traffic counts. Specifically, the research team conducted turning movement counts for each intersection for three key half-hour time periods: 11:30 a.m. to noon, 2:00 to 2:30 p.m., and 4:30 to 5:00 p.m. These three time periods were chosen because there were recordings available for all four roundabouts at these time periods, and because they corresponded to different traffic conditions. The late morning period represented an off-peak time, the mid-afternoon period provided conditions when traffic changed from off-peak to school-peak volumes, and the late period was the beginning of the evening peak and the latest time that sufficient daylight was available in the video to accurately count the vehicles.

In addition to the turning movement counts, the research team also recorded the maximum queue length and the lane utilization (for two-lane approaches) on each approach for the same three time periods. Finally, an entry-exit count was conducted at the two ends of the corridor (the west leg of Roundabout #1 and the east leg of Roundabout #4) to determine the total number of vehicles entering and exiting the corridor at either end. The entry-exit count was conducted from 11:30 a.m. to 5:30 p.m.

The following sections of this technical memorandum summarize the traffic data obtained from the video and provide graphical and/or tabular representations of the various counts.

B.2.1.1. *Turning Movements*

The research team performed three half-hour turning movement counts for each roundabout by reviewing the video recordings. Exhibit B-3 provides a summary of the turning movement data for the three half-hour periods; graphical representations of the turning movement diagrams (for all time periods combined) are shown at the end of this Appendix.

The eastbound and westbound through movements on MD 216 were overwhelmingly the predominant movement at each intersection, reflecting the nature of MD 216 as a primary arterial. The total number vehicles entering or exiting each intersection on MD 216 was consistently between 1600 and 2100 total vehicles for the entirety of the three half-hours, compared to total volumes between 100 and 800 on the north and south legs of each intersection. Through movements on the north and south approaches totaled 170 vehicles for all intersections and all time periods, confirming that either the origin or the destination for most vehicles was MD 216, even for vehicles that did not travel the entire length of the corridor.

Roundabout #1, the westernmost intersection, had the lowest volumes of the four intersections on the corridor. Of the 2068 observed entering vehicles, 1446 (70 percent) were through vehicles traveling eastbound or westbound. The southern leg had particularly low volumes, reflecting the nature of Old Columbia Boulevard as a street intended for local traffic, much of which was related to the park-and-ride lot adjacent to the intersection. The northern leg served traffic at the western edge of the nearby retail center, which generated a noticeable traffic volume, but not as much as was served by Intersection #2.

Roundabout #2 is a T-intersection and has only three legs. Of the 2418 observed entering vehicles, 1627 (67 percent) were through vehicles traveling eastbound or westbound. Traffic on the northern leg consisted of vehicles entering and exiting the retail center north of MD 216; 75 percent of southbound traffic turned east toward US 29 and residential developments beyond the highway, and 73 percent of the traffic entering the retail center also originated from the east.

Roundabout #3 includes access to the ramp that serves southbound traffic on US 29, as well as a local street (Old Scaggsville Road) that provides access to a mix of residential and commercial traffic. Of the 2428 observed entering vehicles, 1623 (67 percent) were through vehicles traveling eastbound or westbound; in fact, 96 percent of the 984 eastbound entering vehicles continued east through the intersection. Vehicles entering the roundabout on the southern leg from the US 29 ramp were predominantly bound for a destination to the west, while traffic from Old Scaggsville Road frequently headed east, resulting in a high share of left turns from both minor approaches.

Exhibit B-3. Summary of Turning Movement Data for Vehicles Approaching Roundabouts in the MD 216 Corridor.

Roundabout #1 – MD 216 @ Old Columbia Rd (NB) and Westside Blvd (SB)																					
App	NB					SB					EB					WB					
Time	T	R	L	U	Total	T	R	L	U	Total	T	R	L	U	Total	T	R	L	U	Total	Grand
11:30	2	6	0	0	8	0	19	18	0	37	71	1	11	1	84	61	16	4	0	81	210
11:45	2	2	1	0	5	3	9	8	0	20	64	2	7	2	75	70	19	1	2	92	192
2:00	0	7	0	0	7	0	16	21	0	37	68	2	8	0	78	97	22	4	2	125	247
2:15	1	12	4	0	17	1	21	23	0	45	231	2	23	0	256	88	21	7	0	116	434
4:30	2	13	10	0	25	0	29	36	0	65	151	0	18	0	169	165	32	8	0	205	464
4:45	0	17	5	0	22	1	33	35	0	69	158	3	13	0	174	222	30	4	0	256	521
Total	**7**	**57**	**20**	**0**	**84**	**5**	**127**	**141**	**0**	**273**	**743**	**10**	**80**	**3**	**836**	**703**	**140**	**28**	**4**	**875**	**2068**
Roundabout #2 – MD 216 @ Maple Lawn Blvd (SB)																					
11:30	N/A					N/A	11	45	0	56	87	N/A	7	0	94	70	44	N/A	0	114	264
11:45							14	33	0	47	62		13	0	75	75	45		0	120	242
2:00							14	37	0	51	95		16	0	111	106	31		2	139	301
2:15							19	46	0	65	230		25	1	256	99	53		2	154	475
4:30							19	69	0	88	179		17	0	196	198	43		1	242	526
4:45							22	70	0	92	188		26	0	214	238	65		1	304	610
Total							**99**	**300**	**0**	**399**	**841**		**104**	**1**	**946**	**786**	**281**		**6**	**1073**	**2418**
Roundabout #3 – MD 216 @ Exit Ramp from SB US-29 (NB) and Old Scaggsville Rd (SB)																					
11:30	7	1	40	0	48	3	3	7	0	13	100	0	4	1	105	72	4	19	0	95	261
11:45	3	2	37	0	42	4	8	9	0	21	74	0	6	1	81	75	9	16	0	100	244
2:00	8	1	42	0	51	4	5	19	0	28	87	0	4	1	92	100	10	14	1	125	296
2:15	16	0	38	0	54	3	6	14	0	23	261	0	1	2	264	22	99	5	0	126	467
4:30	10	1	50	0	61	4	10	16	0	30	207	1	9	0	217	189	27	32	0	248	556
4:45	8	2	60	0	70	3	14	19	0	36	217	1	7	0	225	219	18	36	0	273	604
Total	**52**	**7**	**267**	**0**	**326**	**21**	**46**	**84**	**0**	**151**	**946**	**2**	**31**	**5**	**984**	**677**	**167**	**122**	**1**	**967**	**2428**
Roundabout #4 – MD 216 @ Ice Crystal Dr (NB) and Exit Ramp from NB US-29 (SB)																					
11:30	14	11	21	0	46	5	1	13	0	19	78	24	33	0	135	56	1	15	1	73	273
11:45	9	22	15	0	46	3	0	8	0	11	64	23	42	0	129	52	0	18	0	70	256
2:00	10	11	15	0	36	4	0	12	0	16	111	22	35	0	168	73	0	16	0	89	309
2:15	15	14	17	0	46	5	0	11	0	16	212	26	90	0	328	72	0	26	0	98	488
4:30	Poor Video -- Rain					8	1	31	0	40	235	34	88	1	358	148	2	18	0	168	566
4:45						12	0	32	0	44	215	34	80	0	329	184	1	31	0	216	589
Total	**48**	**58**	**68**	**0**	**174**	**37**	**2**	**107**	**0**	**146**	**915**	**163**	**368**	**1**	**1447**	**585**	**4**	**124**	**1**	**714**	**2481**

App = Approach
T = Through, R = Right, L = Left, U = U-turn
N/A = Not applicable

Roundabout #4 includes access to the ramp that serves northbound traffic on US 29, as well as a local street (Ice Crystal Drive) that provides access to residential developments south of MD 216. Of the 2481 observed entering vehicles, 1500 (60 percent) were through vehicles traveling eastbound or westbound. A period of light rain during the late afternoon period adversely affected the quality of the video recording for the southern approach, but data from the other two periods suggests a relatively even distribution between left, through, and right movements. On the northern approach, more than two-thirds of entering vehicles made a left turn to travel east on MD 216, many of them during the late afternoon peak period.

B.2.1.2. *Lane Utilization*

Most of the approaches to the intersections in this corridor have two lanes. The research team was interested to know the lane use by approaching vehicles, and they reviewed the video recordings to count the number of vehicles in each approach lane during the three half-hour time periods. Exhibit B-4 provides a summary of the lane utilization data for the three time periods.

At Roundabout #1, all of the right-turning vehicles on the northbound leg used the right lane. Traffic on the southbound leg was fairly evenly distributed, similar to the distribution of right turns and left turns. On the westbound approach, the number of vehicles in the right lane was 91 more than the number in the left lane, likely a reflection of the right-turn volume. On the eastbound approach, however, nearly twice as many vehicles used the left lane as the right lane. Some of these left-lane vehicles undoubtedly turned left at the intersection, but the uneven distribution is quite likely a function of the upstream lane configuration, where MD 216 widens from one lane in each direction to two. Through drivers may have simply chosen to stay in what became the left lane, rather than move into the added right lane. Also, as will be shown in the discussion of Roundabouts #3 and #4, there is an advantage to using the left lane when crossing US 29; through drivers who regularly travel the corridor likely had this in mind when choosing the left lane at the western end of the corridor, to avoid having to make another lane change downstream.

At Roundabout #2, there is no northbound approach. Southbound drivers chose the left lane by a 5-to-3 margin, reflective of the large number of left turns observed from that leg. Eastbound drivers again chose the left lane more often than the right lane, though not by a margin as pronounced as at Roundabout #1. Westbound drivers preferred the right lane by about a 3-to-2 margin; that difference of 224 vehicles is almost the same as the number of right-turning vehicles, indicating that through drivers were almost evenly split between the left and right lanes.

At Roundabout #3, the southbound leg had two approach lanes, but one was for right-turns only. Through drivers had no choice of which lane to use, so the lane utilization review was not conducted on this leg. Similarly, the northbound leg had only one lane approach the intersection; a right-turn-only lane was present but it was physically separated from the approach to the roundabout and was not included in the review. On the eastbound leg, drivers preferred the left lane

by more than 2-to-1, even after accounting for turning traffic. The reason for this is that MD 216 narrows from two lanes to one as it approaches the bridge over US 29, to accommodate the right-turn-only lane that comes from the northbound leg. Drivers that commonly travel this corridor would know that using the left lane in the roundabout would eliminate the need to make a lane change in the limited lane-drop transition area between the roundabout and the bridge, so heavier use of the left lane would be logical. On the westbound leg, more drivers used the right lane than the left, but after removing turning traffic from each lane, the number of through drivers was divided almost evenly between the two lanes (336 to 342, including the single U-turning driver).

Exhibit B-4 Lane Utilization at MD 216 Roundabouts

Roundabout #1 – MD 216 @ Old Columbia Rd (NB) and Westside Blvd (SB)								
App	NB		SB		EB		WB	
Time	Left	Right	Left	Right	Left	Right	Left	Right
11:30	0	8	10	27	55	29	31	50
11:45	3	2	4	16	50	25	43	49
2:00	0	7	20	17	54	24	54	71
2:15	5	12	24	21	150	106	44	72
4:30	13	12	36	29	124	45	94	111
4:45	6	16	36	33	116	58	126	130
Total	**27**	**57**	**130**	**143**	**549**	**287**	**392**	**483**
Roundabout #2 – MD 216 @ Maple Lawn Blvd (SB)								
11:30	N/A		37	18	50	46	33	81
11:45			29	18	43	32	42	78
2:00			31	20	60	51	59	80
2:15			41	24	139	117	49	102
4:30			56	32	119	77	106	136
4:45			54	38	125	89	134	170
Total			**248**	**150**	**536**	**412**	**423**	**647**
Roundabout #3 – MD 216 @ Exit Ramp from SB US 29 (NB) and Old Scaggsville Rd (SB)								
11:30	N/A		N/A		82	23	44	51
11:45					60	21	54	46
2:00					64	28	61	64
2:15					166	98	59	67
4:30					160	57	114	134
4:45					145	80	126	147
Total					**677**	**307**	**458**	**509**
Roundabout #4 – MD 216 @ Ice Crystal Dr (NB) and Exit Ramp from NB US 29 (SB)								
11:30	N/A		N/A		75	59	45	29
11:45					58	75	47	20
2:00					80	90	55	40
2:15					183	145	68	29
4:30					186	172	109	66
4:45					162	167	131	86
Total					**744**	**708**	**455**	**270**

App = Approach
N/A = Not applicable

Roundabout #4 had a similar lane configuration and similar lane utilization to Roundabout #3. The ramp from US 29 on the north leg of the intersection had one lane approach the roundabout, plus a physically separated right-turn lane. The south leg of the intersection (Ice Crystal Drive) had only one approach lane that was used by all movements. The westbound approach on MD 216 had a lane distribution that was analogous to the eastbound approach at Roundabout #3, though left-lane usage was not as pronounced after accounting for left-turning vehicles, indicating that more westbound drivers had to make a lane change

between Roundabout #4 and the bridge over US 29 than their eastbound counterparts at Roundabout #3. Finally, the lane utilization for eastbound traffic at Roundabout #4 was evenly split; removal of left- and right-turning traffic from the count reveals a preference for the right lane by a count of 545 to 376.

B.2.1.3. *Maximum Queues*

One of the key comparisons between roundabouts and traditional traffic control devices is the queue of vehicles that accumulates while waiting to enter the intersection. The research team reviewed the video recordings to document the longest queues observed count the number of vehicles at each approach during the three half-hour time periods. Exhibit B-5 provides a summary of the observed maximum queue data; queue values shown are the sum of both lanes where two approach lanes were present.

Exhibit B-5 Maximum Queue Lengths (# vehicles) at MD 216 Roundabouts in 15-minute bins

Roundabout #1				
App	NB	SB	EB	WB
11:30	0	2	2	1
11:45	1	2	2	0
2:00	0	2	2	2
2:15	2	3	6	2
4:30	Poor Video	5	6	4
4:45		4	6	2
Maximum	**2**	**5**	**6**	**4**
Roundabout #2				
11:30	N/A	2	3	2
11:45		3	3	2
2:00		2	3	1
2:15		3	6	3
4:30		4	7	3
4:45		5	8	5
Maximum		**5**	**8**	**5**
Roundabout #3				
11:30	3	1	3	3
11:45	3	1	2	6
2:00	3	3	5	4
2:15	7	3	4	6
4:30	5	4	12	6
4:45	6	5	4	7
Maximum	**7**	**5**	**12**	**7**
Roundabout #4				
11:30	2	1	3	6
11:45	3	2	5	3
2:00	2	2	4	4
2:15	3	3	7	5
4:30	Poor Video	3	Poor Video	7
4:45		4		18
Maximum	**3**	**4**	**7**	**18**

App = Approach
N/A = Not applicable

The queue data were generally unremarkable during the off-peak periods, with most queues consisting of three or fewer vehicles. Even in the mid-afternoon period with heavier volumes, the maximum queue for most approaches in the observed time period was five or fewer vehicles, though the latter half of the school-release period showed some queues of six or seven vehicles. The late

afternoon peak period had consistently longer queues, ranging from three to 18 vehicles. In the case of the largest queue, the westbound approach between 4:45 and 5:00 had a brief queue of 18 vehicles stored in the two approach lanes, a result of the nearest upstream signal releasing a platoon to arrive at the same time that several eastbound vehicles made left turns to enter the US 29 on-ramp.

With the exception of Roundabout #4, where weather-related issues reduced the quality of the video, the eastbound approach tended to have the longest queues at each intersection, while the southbound and westbound approaches had similar queues except for the peak of 18 in the final 15-minute period. The longer queues on the eastbound approaches could be related to the unbalanced lane utilization; as more vehicles traveled in the left lane, the likelihood decreased that a gap in circulating traffic could be used by two side-by-side eastbound vehicles. The more balanced flow in the westbound direction could contribute to lower queues for westbound traffic, though it could also increase the queue for southbound traffic, despite the lower volumes on the southbound approaches. Because westbound traffic was making more efficient use of gaps in circulating traffic, it kept westbound queues at a minimum but it reduced the number of available gaps for southbound traffic. Northbound volumes at Roundabouts #1 and #4 were low, keeping queues correspondingly low, but the increased volumes at Roundabout #3 helped to also increase the queues to lengths similar to those on the westbound and southbound legs.

B.2.1.4. *Entry/Exit Counts*

To get a greater appreciation for the traffic volumes on the MD 216 corridor, an entry-exit count was conducted at the two ends of the corridor (the west leg of Roundabout #1 and the east leg of Roundabout #4). This count identified the total number of vehicles entering and exiting the corridor at either end, which could suggest an approximate number of vehicles that traveled from one end of the corridor to the other. The entry-exit count was conducted from 11:30 a.m. to 5:30 p.m., using video recordings from the two days of data collection. Exhibit B-6 shows the entry-exit volume counts for each 15-minute period at either end of the corridor, and Exhibit B-7 and B-8 display the counts graphically.

The data in Exhibit B-6 confirm the off-peak nature of the traffic volumes during the late morning and early afternoon timeframe. At Roundabout #1, 15-minute directional volumes are typically less than 100 until about 2:00 p.m. Entering volumes at Roundabout #4 also follow this pattern, though exiting volumes are consistently above 100 with one exception between 11:45 a.m. and noon.

After 2:00 p.m., entering volumes at Roundabout #1 increase substantially, coinciding with the release of school; a large spike sends entering volumes above 200 between 2:15 and 2:30, then volumes settle into a range between 150 and 180 vehicles per hour for most of the remainder of the afternoon. Meanwhile, exiting volumes at Roundabout #1 steadily climb in the late afternoon, as more people visit the adjacent shopping center and leave the park-and-ride lot over the course of the day. As a result, exiting traffic outpaces entering traffic over the course of the observation period.

At Roundabout #4, there is a similar spike in exiting volumes as the wave of school-related traffic makes its way through the corridor to the eastern end in the 2:15 to 2:30 p.m. period. Subsequent volumes briefly settle to lower levels before increasing again and remaining around 200 vehicles every 15 minutes after 3:00 p.m. Entering volumes also steadily increase throughout the late afternoon, with a small increase around 2:30 p.m. and larger sustained increase in the 3:45 p.m. period, again assumed to correspond to increased activity running errands and other activities after the conclusion of the school day and the work day.

As with Roundabout #1, the exiting volume at Roundabout #4 was larger than entering volume over the course of the afternoon and late morning, indicating that a substantial amount of traffic entered the corridor at the two ramps leading from US 29.

Exhibit B-6 Entry/Exit Count at MD 216 Endpoint Roundabouts

Time Period	Roundabout #1		Roundabout #4	
	EB	WB	WB	EB
	Enter	Exit	Enter	Exit
11:30	81	80	75	108
11:45	83	87	77	93
12:00	83	78	69	114
12:15	68	78	82	117
12:30	88	77	68	156
12:45	85	74	93	126
1:00	84	94	80	108
1:15	92	95	83	116
1:30	100	100	97	118
1:45	91	114	86	100
2:00	72	119	94	146
2:15	220	119	99	221
2:30	153	104	110	162
2:45	121	147	115	152
3:00	137	151	104	188
3:15	189	132	116	212
3:30	167	152	103	164
3:45	153	165	158	192
4:00	160	200	170	180
4:15	142	221	163	197
4:30	170	210	175	217
4:45	174	248	219	228
5:00	183	240	192	273
Total	**2896**	**3085**	**2628**	**3688**
15-minute Average	**126**	**134**	**114**	**160**

Exhibit B-7 Plot of Entry/Exit Counts at Roundabout #1

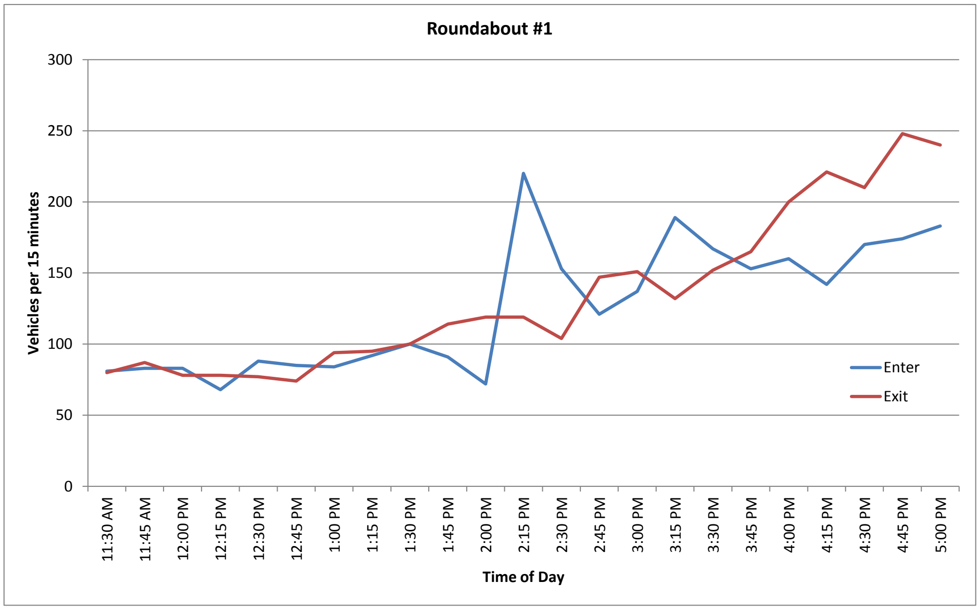
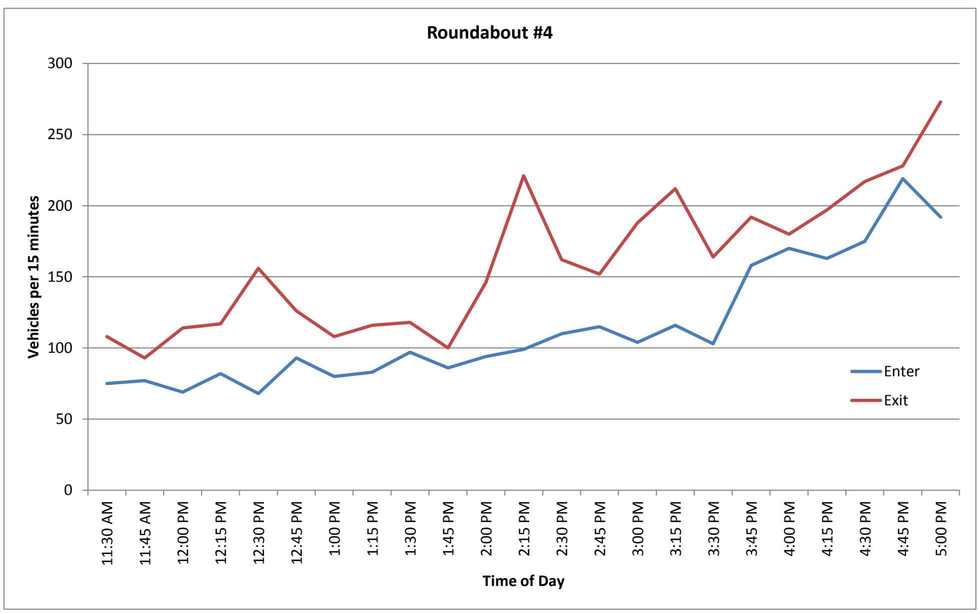


Exhibit B-8 Plot of Entry/Exit Counts at Roundabout #4



B.2.2. TRAVEL TIME

Travel time was recorded using both Bluetooth readers and GPS units in vehicles conducting floating car travel time runs

B.2.2.1. *Bluetooth*

Exhibits B-9 and B-10 below show the number of hits recorded by the four Bluetooth readers. The locations of these readers were previously shown in Exhibit B-1. Note that station 1 and station 3 were at the same location, but station 3 recorded three times as many hits. Based upon this result, the team

intends to use the type of antenna used at station 3 in the future. The team estimated ADT for the corridor in order to approximate the detection rate of the Bluetooth readers. The exhibits below also display the detection rate (assuming 20,000 ADT and 10,000 directional ADT, respectively). These ADTs were estimated from the hourly volumes collected for this project.

Exhibit B-9 Number of Bluetooth Detections by Station

Station	Detections	Rate (20,000 ADT)
1	1251	3.1%
2	2377	5.9%
3	3957	9.9%
4	3743	9.4%

Exhibit B-10 Number of Bluetooth Detections by Segment

Segment	Detections	Rate (10,000 ADT)	Avg. Travel Time	St. Dev.
1 to 2	239	1.2%	1.31	0.26
1 to 3	619	3.1%	0.07	0.06
1 to 4	335	1.7%	1.56	0.19
2 to 1	403	2.0%	1.33	0.24
2 to 3	754	3.8%	1.38	0.26
2 to 4	403	2.0%	2.89	0.38
3 to 1	667	3.3%	0.09	0.08
3 to 2	738	3.7%	1.48	0.49
3 to 4	794	4.0%	1.49	0.22
4 to 1	211	1.1%	1.71	0.26
4 to 2	363	1.8%	3.04	0.49
4 to 3	816	4.1%	1.56	0.26

Exhibits B-11 and B-12 provide a sample of these data taken along the eastbound (left) and westbound (right) directions. The exhibits indicates that most of the BlueTooth data were recorded from 6am to 6pm, with the highest travel times being recorded in the westbound direction during the a.m. peak hour.

Exhibit B-11 Eastbound 48 Hour Bluetooth Travel Time Sample

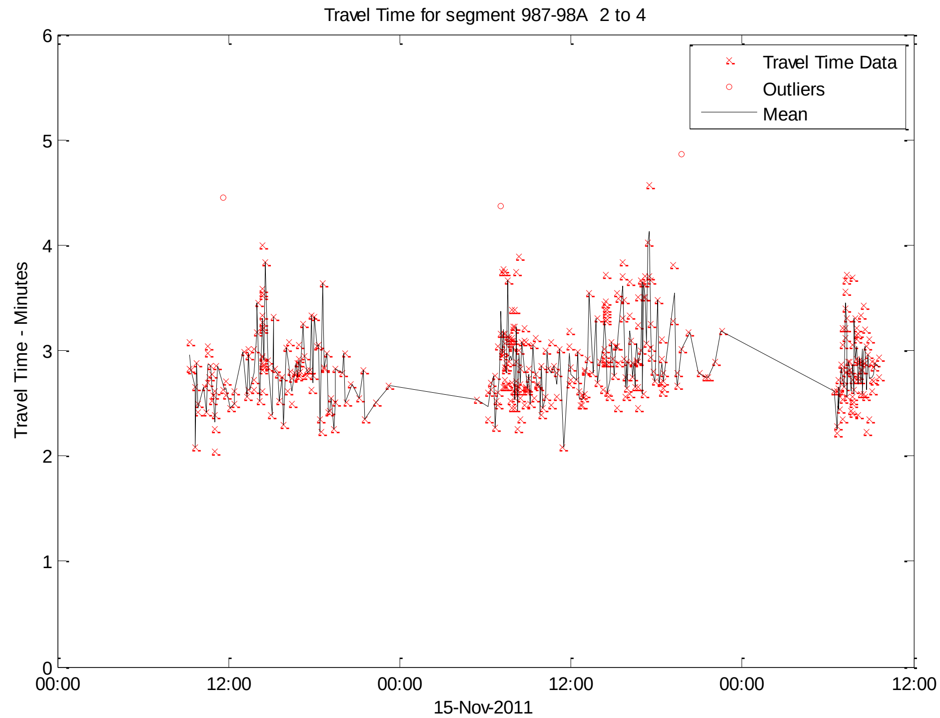
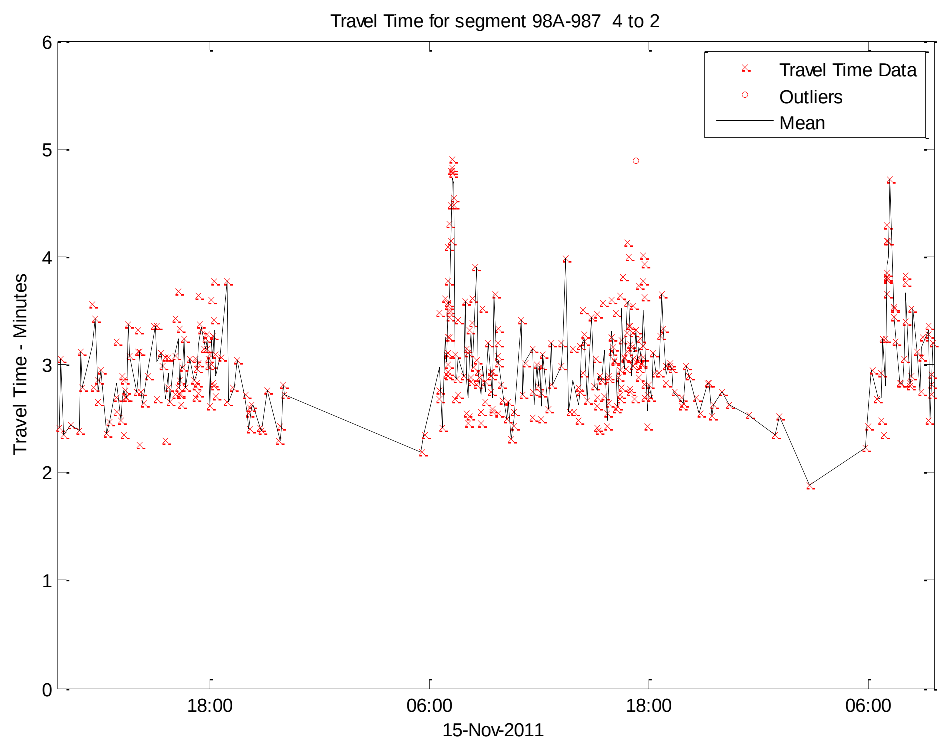


Exhibit B-12 Westbound 48 Hour Bluetooth Travel Time Sample



The travel time data were further processed to produce summary statistics and the level of service for the corridor during each hour of the day. Exhibits B-13

and B-14 display this summary. The average, minimum, and maximum travel times recorded during each hour (aggregated over the 48-hour period) are recorded in the table, as well as the average speed and number of observations. The peak hours were identified as 7:00 to 8:00 a.m. and 5:00 to 6:00 p.m. and were further broken down into 15-minute intervals. Finally, the Level of Service (LOS) during each period was calculated based upon the Urban Streets procedure in the Highway Capacity Manual 2010. In the Urban Streets procedure, LOS is determined based upon the ratio of travel speed to base free-flow speed. The specific LOS thresholds are provided in Exhibit 16-4 and 17-2. Bluetooth data provided measurement of these two speeds, enabling the research team to determine LOS by simply computing the ratio of the speeds rather than estimating them with the HCM's calculations. Free flow speed was assumed to be equal to the lowest average speed observed during any daytime hour. The results indicate that the corridor was generally uncongested.

Exhibit B-13 Eastbound Bluetooth Travel Time and LOS

Start Hour	Average TT	Average Speed (mph)	S.D. TT	Min TT	Max TT	LOS	Sample Size
6:00	2.60	33.01	0.22	2.22	3.05	A	22
7:00	3.15	27.23	0.47	2.34	4.37	B	21
7:15	3.00	28.60	0.37	2.57	3.74	A	18
7:30	2.79	30.77	0.35	2.40	3.69	A	16
7:45	2.93	29.33	0.29	2.45	3.38	A	17
8:00	2.85	30.10	0.35	2.23	3.89	A	53
9:00	2.72	31.52	0.23	2.08	3.12	A	26
10:00	2.69	31.94	0.23	2.25	3.08	A	22
11:00	2.83	30.30	0.59	2.04	4.45	A	13
12:00	2.63	32.67	0.16	2.46	2.99	A	13
13:00	2.92	29.37	0.28	2.57	3.54	A	14
14:00	3.11	27.58	0.37	2.38	4.00	B	46
15:00	3.00	28.60	0.42	2.29	3.83	A	22
16:00	2.94	29.17	0.32	2.45	3.67	A	32
17:00	3.37	25.50	0.41	2.58	3.71	B	6
17:15	3.48	24.66	0.64	2.82	4.57	B	7
17:30	3.00	28.62	0.34	2.76	3.67	A	6
17:45	2.95	29.10	0.35	2.63	3.33	A	5
Night	2.85	30.17	0.46	2.23	4.87	A	44

Travel times are in minutes

Exhibit B-14 Westbound Bluetooth Travel Time and LOS

Start Hour	Average TT	Average Speed (mph)	S.D. TT	Min TT	Max TT	LOS	Sample Size
6:00	3.27	26.24	0.56	2.35	4.31	B	29
7:00	4.20	20.45	0.57	3.25	4.90	C	18
7:15	3.22	26.66	0.32	2.68	3.53	B	8
7:30	2.78	30.89	0.08	2.73	2.83	A	2
7:45	3.15	27.25	0.29	2.83	3.58	B	6
8:00	3.06	28.09	0.42	2.45	3.91	A	28
9:00	2.90	29.62	0.32	2.35	3.65	A	27
10:00	2.66	32.25	0.35	2.31	3.41	A	10
11:00	2.93	29.25	0.30	2.51	3.56	A	13
12:00	2.77	31.03	0.29	2.37	3.21	A	12
13:00	2.93	29.27	0.39	2.35	3.98	A	18
14:00	2.95	29.09	0.36	2.26	3.50	A	16
15:00	2.91	29.47	0.34	2.30	3.60	A	31
16:00	3.10	27.67	0.39	2.58	4.13	A	40
17:00	3.14	27.35	0.60	2.68	4.89	B	12
17:15	3.19	26.89	0.30	2.73	3.73	B	12
17:30	3.34	25.71	0.40	2.82	4.01	B	12
17:45	2.92	29.43	0.33	2.43	3.60	A	10
Night	2.78	30.87	0.37	1.88	3.78	A	59

Travel times are in minutes

B.2.2.2. *GPS Travel Time Runs*

Space-time trajectories and speed profiles for each of the six routes are located at the end of this appendix. Each diagram displays every travel time run that was conducted (including a.m., p.m., and off-peak runs). The diagrams indicate that the travel time runs were fairly consistent with the exception of a few runs from the a.m. peak hour that were influenced by heavy school traffic at the western end of the corridor (beyond the roundabouts).

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening". A vehicle stop is denoted by a purple dot. The horizontal lines in the diagrams correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor therefore is an indication of the variability in the observed data. The distance along the x-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

The team isolated the free-flow travel time runs from the rest of the dataset. Exhibit B-15 summarizes these free-flow runs. Exhibit B-16 presents more

detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in mph, and all travel times are displayed in minutes. Using the free-flow data, the table shows HCM Urban Streets LOS and average roundabout LOS. The team determined Urban Street LOS for the GPS data the same way that they determined it for the Bluetooth data. Roundabout LOS was based upon average control delay in seconds and the LOS thresholds in the HCM2010.

Exhibit B-15 Free-flow Travel Time Runs

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)			
		Mean	Std. Dev.	Max	Min	Mean	Std. Dev.	Max	Min
1. West-to-East	9	34.4	2.1	37.8	32.2	1.9	0.1	2.1	1.8
2. East-to-West	9	35.2	1.3	37.0	33.2	1.9	0.1	1.9	1.8
3. East-to-South	10	33.3	2.3	36.2	30.5	0.6	0	0.6	0.5
4. South-to-West	10	31.4	2.9	35.1	28.2	1.5	0.1	1.7	1.4
5. West-to-North	10	29.4	3.1	35.0	26.7	0.6	0.1	0.6	0.5
6. North-to-East	9	31.5	3.1	36.3	28.3	1.6	0.1	1.8	1.4
Total	57	32.5	3.1	37.8	26.7	1.3	0.6	2.1	0.5

B.2.3. GEOMETRIC AND APPROACH DELAY FROM GPS

Exhibit B-17 displays the impeded delay (equal to the difference between the average travel time and the unimpeded travel time) and total delay (equal to the difference between the average travel time and the free flow travel time) for each approach route. Each approach was split into the upstream and downstream segments, where the upstream segment extends from the yield bar to the upstream midblock point, and the downstream segment extends from the yield bar to the downstream midblock point

Exhibit B-17 Summary of Field Travel Time and Delay

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT1-East Approach (Upstream)	**9.3**	**332**	**38**	**6.0**	**7.5**	**1.5**	**1.8**	**3.4**
AM	11.6	332	38.0	6.0	7.5	1.5	4.1	5.6
Off	7.8	332	38	6.0	7.5	1.5	0.3	1.8
PM	9.7	332	38	6.0	7.5	1.5	2.2	3.7
RBT1-East Approach (Downstream)	**25.3**	**1088**	**38**	**19.5**	**21.5**	**2.0**	**3.8**	**5.7**
AM	32.4	1088	38.0	19.5	21.5	2.0	10.9	12.9
Off	21.9	1088	38	19.5	21.5	2.0	0.4	2.4
PM	24.1	1088	38	19.5	21.5	2.0	2.6	4.6
RBT1-West Approach (Upstream)	**17.9**	**864**	**38**	**15.5**	**16.0**	**0.5**	**1.9**	**2.4**
AM	17.5	864	38.0	15.5	16.0	0.5	1.5	2.0
Off	16.7	864	38	15.5	16.0	0.5	0.7	1.2
PM	20.0	864	38	15.5	16.0	0.5	4.0	4.5
RBT1-West Approach (Downstream)	**11.9**	**451**	**38**	**8.1**	**11.0**	**2.9**	**0.9**	**3.8**
AM	12.2	451	38.0	8.1	11.0	2.9	1.2	4.1
Off	11.4	451	38	8.1	11.0	2.9	0.4	3.3
PM	12.3	451	38	8.1	11.0	2.9	1.3	4.2
RBT2-East Approach (Upstream)	**12.6**	**469**	**38**	**8.4**	**11.0**	**2.6**	**1.6**	**4.2**
AM	12.9	469	38.0	8.4	11.0	2.6	1.9	4.4
Off	11.2	469	38	8.4	11.0	2.6	0.2	2.8
PM	14.3	469	38	8.4	11.0	2.6	3.3	5.9
RBT2-East Approach (Downstream)	**10.4**	**477**	**38**	**7.6**	**9.0**	**1.4**	**1.4**	**2.8**
AM	13.0	477	38.0	7.6	9.0	1.4	4.0	5.4
Off	9.0	477	38	7.6	9.0	1.4	0.0	1.5
PM	10.2	477	38	7.6	9.0	1.4	1.2	2.6

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT2-West Approach (Upstream)	**10.7**	**353**	**38**	**6.3**	**9.5**	**3.2**	**1.2**	**4.3**
AM	10.1	353	38.0	6.3	9.5	3.2	0.6	3.8
Off	9.9	353	38	6.3	9.5	3.2	0.4	3.6
PM	12.3	353	38	6.3	9.5	3.2	2.8	6.0
RBT2-West Approach (Downstream)	**12.1**	**560**	**38**	**10.0**	**11.0**	**1.0**	**1.1**	**2.1**
AM	12.4	560	38.0	10.0	11.0	1.0	1.4	2.4
Off	11.5	560	38	10.0	11.0	1.0	0.5	1.4
PM	12.9	560	38	10.0	11.0	1.0	1.9	2.8
RBT3-East Approach (Upstream)	**17.8**	**816**	**45**	**12.4**	**15.5**	**3.1**	**2.3**	**5.4**
AM	19.3	816	45.0	12.4	15.5	3.1	3.8	6.9
Off	15.9	816	45	12.4	15.5	3.1	0.4	3.5
PM	19.3	816	45	12.4	15.5	3.1	3.8	6.9
RBT3-East Approach (Downstream)	**13.0**	**643**	**38**	**10.4**	**12.5**	**2.1**	**0.7**	**2.5**
AM	13.0	643	38.0	10.4	12.5	2.1	0.5	2.6
Off	12.3	643	38	10.4	12.0	1.6	0.3	1.9
PM	13.9	643	38	10.4	12.5	2.1	1.4	3.5
RBT3-West Approach (Upstream)	**9.9**	**412**	**38**	**7.2**	**8.5**	**1.3**	**1.4**	**2.7**
AM	9.9	412	38.0	7.2	8.5	1.3	1.4	2.8
Off	9.1	412	38	7.2	8.5	1.3	0.6	2.0
PM	10.8	412	38	7.2	8.5	1.3	2.3	3.6
RBT3-West Approach (Downstream)	**19.8**	**1037**	**38**	**18.1**	**19.0**	**0.9**	**0.8**	**1.7**
AM	19.7	1037	38.0	18.1	19.0	0.9	0.7	1.6
Off	19.5	1037	38	18.1	19.0	0.9	0.5	1.4
PM	20.3	1037	38	18.1	19.0	0.9	1.3	2.2

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT4-East Approach (Upstream)	**23.0**	**1297**	**45**	**19.7**	**21.0**	**1.3**	**2.0**	**3.3**
AM	22.6	1297	45.0	19.7	21.0	1.3	1.6	2.9
Off	21.1	1297	45	19.7	21.0	1.3	0.1	1.4
PM	26.0	1297	45	19.7	21.0	1.3	5.0	6.4
RBT4-East Approach (Downstream)	**17.7**	**993**	**45**	**14.0**	**17.0**	**3.0**	**0.7**	**3.7**
AM	17.7	993	45.0	14.0	17.0	3.0	0.7	3.6
Off	17.1	993	45	14.0	17.0	3.0	0.1	3.1
PM	18.6	993	45	14.0	17.0	3.0	1.6	4.5
RBT4-West Approach (Upstream)	**19.1**	**813**	**38**	**14.2**	**14.5**	**0.3**	**4.6**	**4.9**
AM	17.4	813	38.0	14.2	14.5	0.3	2.9	3.2
Off	16.5	813	38	14.2	14.5	0.3	2.0	2.3
PM	24.1	813	38	14.2	14.5	0.3	9.6	9.8
RBT4-West Approach (Downstream)	**24.5**	**1396**	**45**	**21.2**	**24.0**	**2.8**	**0.5**	**3.4**
AM	24.5	1396	45.0	21.2	24.0	2.8	0.5	3.4
Off	24.2	1396	45	21.2	24.0	2.8	0.2	3.1
PM	25.0	1396	45	21.2	24.0	2.8	1.0	3.8

B.2.4. SPOT SPEEDS

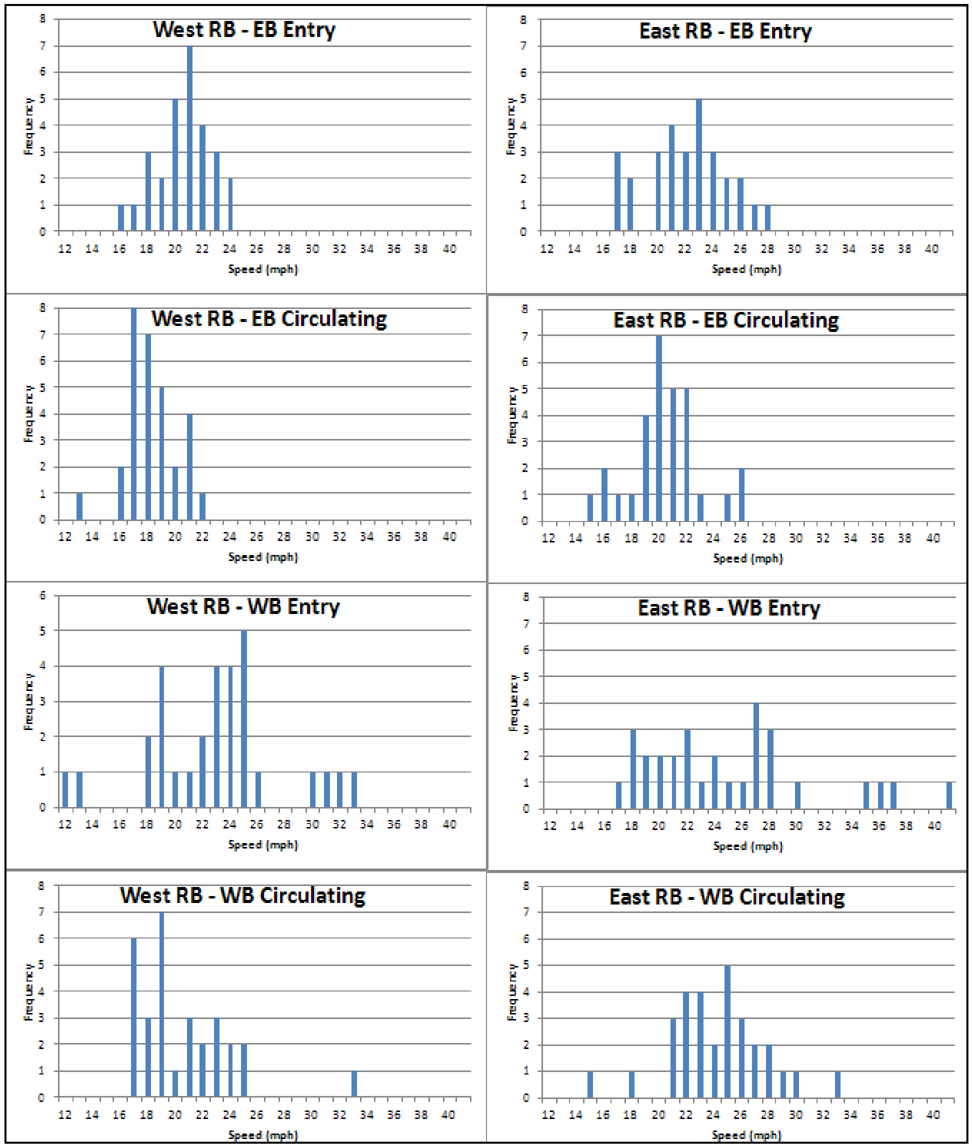
Spot speeds collected by the research team with a laser gun the endpoint roundabouts are shown below in Exhibit B-18. Thirty samples were recorded at each location.

Exhibit B-18 Spot Speeds from Laser Gun

RBT #	1 West	1 West	1 West	1 West	4 East	4 East	4 East	4 East
Location	**EB - Entry**	**EB - Circ**	**WB - Entry**	**WB - Circ**	**EB - Entry**	**EB - Circ**	**WB – Entry**	**WB - Circ**
Mean Speed (mph)	20.6	18.3	22.9	20.5	22.1	20.4	25.0	24.3
St.Dev. (mph)	2.0	1.9	4.8	3.5	3.0	2.6	6.1	3.6

The speed measurements were also analyzed using histogram frequency distributions—all eight are displayed in Exhibit B-19. In this case the horizontal scales are kept the same to show the skew, but the vertical scales vary. From inspection of the figure it appears that the speeds at the westbound entry appear to be the highest at either roundabout. The circulating speeds tended to be higher for the westbound ends than on the eastbound ends.

Exhibit B-19 Spot Speed Histogram

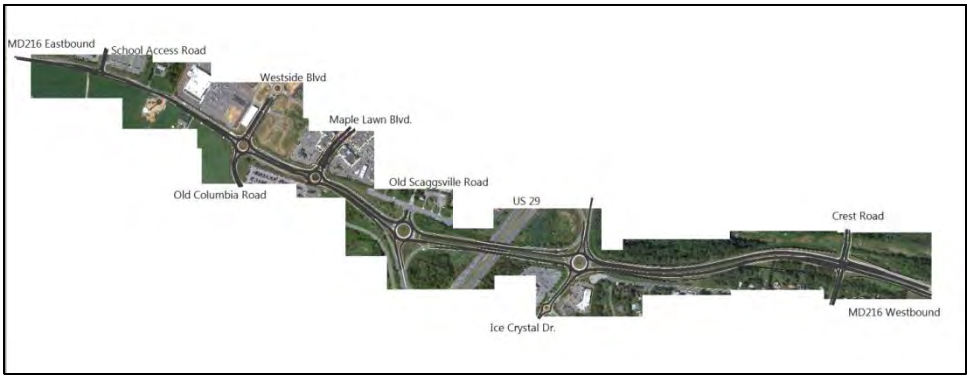


B.3. SIMULATION MODELING

The team modeled the MD 216 corridor in the VISSIM microsimulation tool. The main objectives of the modeling were to 1) compare the model results with field observations, and 2) compare the roundabout corridor performance with the signalized comparison corridor. Details on the VISSIM modeling approach are presented in Appendix C.

Exhibit B-20 shows a screenshot of the base model for the MD 216 corridor as coded in VISSIM. The model included the four subject roundabouts and extended through the adjacent signals, although signal operations at these intersections were not modeled.

Exhibit B-20 Screenshot of MD216 VISSIM Base-Model



The performance assessment in VISSIM included route-based measures (travel time and route delay), and node-based measures (control delay and other measures). Nodes were numbered from 1 to 4 going west to east, with the Old Columbia Road/Westside Blvd roundabout being node 1 and the US 29 Northbound Ramps/Ice Crystal Drive roundabout being node 4.

The route evaluation was performed for the east-to-west and west-to-east through routes, as well as four left-turn routes. The turnaround point for the west-to-north and north-to-east routes was at the northern approach of Maple Lawn Blvd (Node 2); for the east-to-south and south-to-west the turnaround point was on the southern approach of Ice Crystal Drive (Node 4).

Exhibit B-21 shows the average and standard deviation of travel times for all six routes for the a.m. Peak, p.m. Peak, and a midday off-peak period. All results represent the average of 10 simulation runs.

Exhibit B-21 MD 216 Route Travel Times (sec)

Route		a.m. Peak		Midday		p.m. Peak	
		Mean	SD	Mean	SD	Mean	SD
Through Routes	East to West	130.1	1.2	134.3	1.9	148.9	3.2
	West to East	128.4	1.5	132.3	0.7	138.8	1.0
Left Turns	North to East	101.6	1.2	104.1	1.8	115.9	2.4
	East to South	42.7	0.6	46.2	1.4	57.3	3.5
	South to West	122.9	2.4	130.8	3.2	152.5	8.2
	West to North	52.7	1.6	55.3	1.0	56.8	1.0

The results in Exhibit B-21 show very little travel time variability between the three observed time periods for each of the routes. This indicates high reliability of the four roundabouts throughout the day, with some added travel times in the p.m. Peak period. Exhibit B-22 offers a closer look at the variability by separating travel time from vehicle control delay experienced over the route. It is emphasized here that VISSIM does not include geometric delay (for example, at roundabout entry) in its delay estimations.

Exhibit B-22 MD 216 Route Delay

Route		a.m. Peak		Midday		p.m. Peak	
		Mean	SD	Mean	SD	Mean	SD
Through Routes	East to West	6.6	0.6	11.0	1.1	24.9	3.3
	West to East	5.2	0.5	9.5	0.4	15.3	1.0
Left Turns	North to East	5.6	0.4	8.6	1.0	19.7	2.3
	East to South	3.9	0.5	7.9	1.2	18.6	3.8
	South to West	8.9	1.7	15.8	2.8	36.6	7.9
	West to North	3.2	0.8	5.1	0.3	6.3	0.5

The results in Exhibit B-22 support the notion that all routes experience very low delay (less than 10 seconds) throughout the a.m. peak period, as well as for the midday off-peak period. Some additional midday delay is evident in the east-to-west and south-to-west routes, which may be attributed to lunchtime restaurant activity in adjacent developments.

Increased delay is evident in the p.m. peak period, with highest delays experiences in the east-to-west and south-to-west routes. The majority of that delay is attributed to performance at the two interchange roundabouts (nodes 3 and 4) and especially the easternmost node at the intersection with Ice Crystal drive. However, even these peak-hour delays are very low considering the corresponding average intersection delay across the route. Exhibit B-23 separates the incurred vehicular delay for each of the four nodes.

Exhibit B-23 MD 216 Node Delay

Node	a.m. Peak		Midday		p.m. Peak	
	#Veh.	Delay	#Veh.	Delay	#Veh.	Delay
1	179	1.0	305	1.4	460	2.9
2	220	1.1	340	1.5	503	3.1
3	234	1.5	387	2.5	544	4.7
4	300	3.0	454	4.9	647	12.1

The exhibit confirms the results from the route evaluation, showing very low average delays at all four roundabout nodes. Comparing the node delay to the HCM2010 Levels of Service (LOS) categories for roundabouts, most of the roundabouts operate at LOS A (average delay less than 10 seconds) or LOS B (delay between 10 and 15 seconds).

B.3.1. COMPARISON TO FIELD DATA

This section compares the modeled roundabout corridor performance to the field-measured GPS travel time data and route delay as estimated from the GPS routes. These results correspond to the calibrated VISSIM model, although it should be emphasized that no iterative re-calibration was performed to achieve further improved performance. In other words, the team used field-measured volumes and speed observations to calibrate initial model inputs, but did not perform any additional calibration to improve the match between model and field data. This approach was deliberate, as the team wanted to avoid over-fitting

a model to a specific observed roundabout corridor. Instead, the team believes that the results achieved are quite generalizable to other roundabout corridors, only requiring custom speed and volume observations as input. The team will be able to refine modeling guidance to include other simulation settings (for example, entry gap acceptance), but for now all other parameters were left at the VISSIM defaults.

In the first comparison, Exhibit B-24 shows the comparison of route travel times. The data are presented as the absolute and percent difference of VISSIM roundabout performance minus GPS field data. A positive number therefore corresponds to VISSIM predicting higher travel times than the field; a negative number corresponds to a lower simulation estimate than the field observations. The actual GPS travel time is not shown, but can be estimated by combining results from this table with VISSIM travel time results in Exhibit B-21.

Exhibit B-24 Travel Time Comparison: VISSIM Minus GPS Field Data

Route		a.m. Peak		Midday		p.m. Peak	
		Diff	**% Diff**	**Diff**	**% Diff**	**Diff**	**% Diff**
Through Routes	East to West	-19.9	-15.3%	14.3	10.7%	4.9	3.3%
	West to East	-9.6	-7.5%	0.3	0.2%	-17.2	-12.4%
Left-Turns	North to East	-12.4	-12.2%	-3.9	-3.7%	-22.1	-19.1%
	East to South	0.7	1.5%	4.2	9.0%	9.3	16.3%
	South to West	-9.1	-7.4%	28.8	22.0%	38.5	25.2%
	West to North	10.7	20.4%	19.3	34.9%	8.8	15.5%

The travel time comparison results show a fairly good match between VISSIM results to field-estimated travel times. For most of the route pairs, percent differences are in the 10 to 15% error range or below. Especially the through routes show a good match to the field data. Some of the left turns show a higher percent difference, which is at least partially attributable to a low base travel time value. In other words a difference of 19.3 seconds relative to a travel time of 55.3 seconds (west-to-north, midday) results in a percent difference of 34.9%, while a difference of 19.9 seconds relative to a base travel time of 130.1 seconds (east-to-west, a.m. Peak) only results in a 15.3% difference. This trend is even more pronounced in the route delay estimates in Exhibit B-25.

Exhibit B-25 Route Delay Comparison: VISSIM Minus GPS Field Data

Route		a.m. Peak		Midday		p.m. Peak	
		Diff	**% Diff**	**Diff**	**% Diff**	**Diff**	**% Diff**
Through Routes	East to West	-2.3	-35.4%	9.0	81.8%	17.1	68.7%
	West to East	-0.8	-14.5%	4.7	49.4%	4.8	31.2%
Left-Turns	North to East	1.4	24.9%	6.3	73.2%	9.5	48.3%
	East to South	2.2	56.9%	7.1	89.9%	16.0	86.1%
	South to West	-1.8	-20.7%	12.5	79.1%	30.4	83.1%
	West to North	2.0	61.9%	4.5	88.3%	3.6	57.3%

It is evident that VISSIM was able to match route delay reasonably well in terms of absolute difference, but shows quite high percent difference, especially for routes with low base delay.

It is interesting to note that while VISSIM underestimated route travel time (negative travel time difference), it tended to overpredict route delay (positive difference). A potential explanation here is a difference in delay definition used in GPS analysis (route travel time versus free-flow travel time) versus VISSIM (actual speed versus desired speed, integrated over the route, and not accounting for geometric delay). The team will further investigate these delay definitions to assure consistency in reporting moving forward.

B.3.2. EQUIVALENT SIGNALIZED CORRIDOR COMPARISON

In this section, the performance of the roundabout corridors is compared to the performance of equivalent signalized corridors. The discussion initially describes how the comparison corridor was developed, followed by the modeling results.

B.3.2.1. *Developing Signalized Alternatives*

The research team developed lane configurations and traffic signal timings for a signalized equivalent to the MD 216 roundabout corridor based on traffic volumes, functional classification, the surrounding road network, and surrounding land uses. Synchro software was used to assess lane configurations and develop timing plans.

The signalized MD 216 corridor developed by the research team is a four-lane, divided roadway with a speed limit of 40 mph. Signals are actuated-coordinated and operate at a 150-second cycle for all times of day. The research team selected this cycle length based upon their experience with studies and retimings of actual signalized corridors in Maryland.

Intersection #1, at Old Columbia Road, has eastbound and westbound left turn lanes on MD 216 with protected-permitted phasing. Northbound and southbound approaches on Old Columbia Road have a left turn lane with permissive phasing and a shared through/right lane.

Intersection #2, a 3-leg intersection at Maple Lawn Boulevard, has an eastbound left turn lane on MD 216 with protected-permitted phasing. The southbound approach on Maple Lawn Boulevard has a left turn-only and a shared left/right turn lane.

Intersection #3, at the US 29 southbound ramps and Old Scaggsville Road, has eastbound and westbound left turn lanes on MD 216 with protected-permitted phasing and a channelized right turn lane from MD 216 eastbound to the US 29 southbound on-ramp. The side streets operate split-phase. The southbound leg (Old Scaggsville Road) has a left turn lane and a through/right lane. The northbound leg (US 29 off-ramp) has a left turn-only lane, a shared left/through lane, and a channelized right turn lane

Intersection #4, at the US 29 northbound ramps and a development access, has double eastbound left turn lanes, a single westbound left turn lane, and a channelized right turn lane from MD 216 westbound to the US 29 northbound

on-ramp. The left turns on MD 216 operate with protected-only phasing. The southbound leg (US 29 off-ramp) has a left turn-only lane, a through lane, and a channelized right turn lane. The northbound leg (development access) has a left turn-only lane and a shared through/right lane. Side street left turns operate with protected-permitted phasing.

B.3.2.2. *Signals and Roundabouts Comparison*

The performance of the roundabout and signalized corridors is presented in terms of route travel time, route delay, and node delay performance. The route travel time results are shown in Exhibit B-26. The exhibit shows the absolute and percent difference of subtracting signalized performance from roundabout performance. A positive number therefore corresponds to higher travel times for the roundabouts; a negative number corresponds to lower travel times for roundabouts.

Exhibit B-26 Travel Time Comparison: Roundabouts Minus Signals

Route		a.m. Peak		Midday		p.m. Peak	
		Diff	% Diff	Diff	% Diff	Diff	% Diff
Through Routes	East to West	29.7	22.8%	29.6	22.0%	20.9	14.0%
	West to East	27.3	21.3%	26.5	20.0%	29.1	21.0%
Left-Turns	North to East	-36.1	-35.6%	-29.9	-28.7%	-20.8	-18.0%
	East to South	-58.8	-137.8%	-52.7	-114.2%	-43.6	-76.0%
	South to West	-29.7	-24.2%	-25.8	-19.7%	5.1	3.3%
	West to North	13.8	26.2%	15.5	28.1%	11.5	20.2%

The results show a clear distinction between the through and left-turn routes. For all through routes, the signalized corridors resulted in lower travel time estimates compared to the roundabouts. This is mostly explained by the higher design speeds at the signalized intersections, where many through vehicles can readily progress through the intersection at the speed limit of 40 mph. Given that prior roundabout analysis showed relatively low delays, it is presumed that the geometric constraints on roundabout through movements contribute to this difference in travel times.

The left turn routes on the other hand, show longer travel times for the signals than the roundabouts in most cases, with some of the differences being quite large. This is explained by some speed reduction of left turns at signals (similar to routes), but likely more so related to signal-induced control delay at the left-turn movements. To test that hypothesis, Exhibit B-27 shows the comparison of route control delay of roundabouts versus signals. Again, a negative number corresponds to lower delay for the roundabouts.

Exhibit B-27 Route Delay Comparison: Roundabouts Minus Signals

Route		a.m. Peak		Midday		p.m. Peak	
		Diff	% Diff	Diff	% Diff	Diff	% Diff
Through Routes	East to West	-5.8	-88.9%	-5.8	-52.9%	-14.9	-59.9%
	West to East	-7.1	-136.3%	-7.5	-79.0%	-5.6	-36.4%
Left-Turns	North to East	-60.9	-1089%	-54.3	-633.1%	-45.8	-232.2%
	East to South	-68.4	-1736%	-61.9	-785.1%	-53.2	-285.0%
	South to West	-65.8	-741.6%	-62.7	-396.6%	-32.6	-89.0%
	West to North	-1.8	-57.8%	-0.5	-10.7%	-4.9	-77.4%

The results in Exhibit B-27 show a difference in control delay on the order of 5 to 15 seconds for the two through routes across all time periods, with the roundabouts showing lower delay relative to the signals in all instances. Combining these results with the travel time findings above, the through routes at the signals result in lower overall travel time (through higher design speeds), but incur some additional control delay across the route.

For the left-turn routes, the signalized corridors show a large increase in delay for all scenarios. The impact is lowest for the west-to-north route, which is the shortest of the four routes. For the remaining routes, left-turn routes experience on the order of 40 to 50 seconds of increased delay at the signals compared to the roundabouts.

In the final comparison, Exhibit B-28 compares the total control delay at the node level for roundabouts and signals.

Exhibit B-28 Node Delay Comparison: Roundabouts Minus Signals

Node	a.m. Peak		Midday		p.m. Peak	
	Diff	% Diff	Diff	% Diff	Diff	% Diff
1	-6.9	-713.4%	-5.8	-426.5%	-6.1	-213.1%
2	-13.8	-1204%	-9.6	-624.1%	-12.5	-402.8%
3	-6.1	-395.9%	-7.0	-283.5%	-5.4	-114.7%
4	-26.1	-878.9%	-22.5	-455.8%	-17.7	-146.3%

The exhibit confirms a statistically significant increase in delay for signals relative to roundabouts (negative number). The results correspond to total node delay, but it is expected that the majority of the delay is incurred by left-turning movements and side-street approaches, which are often at a disadvantage in a coordinated signal system.

In an effort to get a closer look at the node performance and comparison between roundabouts and signals, the team selected two nodes to show a movement-based comparison of delay. Exhibits B-29 and B-30 show average movement delay for nodes 1 and 4, respectively. Node 1 is the western terminus roundabout and provides access to a shopping center to the north and a park-and-ride lot to the south. Node 4 is the eastern terminus roundabout located at the interchange with US 29.

The exhibits show the average control delay from ten simulation runs of the roundabout intersection versus signalized control. As before, a negative difference corresponds to lower delay for the roundabout. Data are shown for the p.m. peak hour and the midday off-peak period.

Exhibit B-29 Node 1 Movement Delay Comparison: Roundabouts Minus Signals

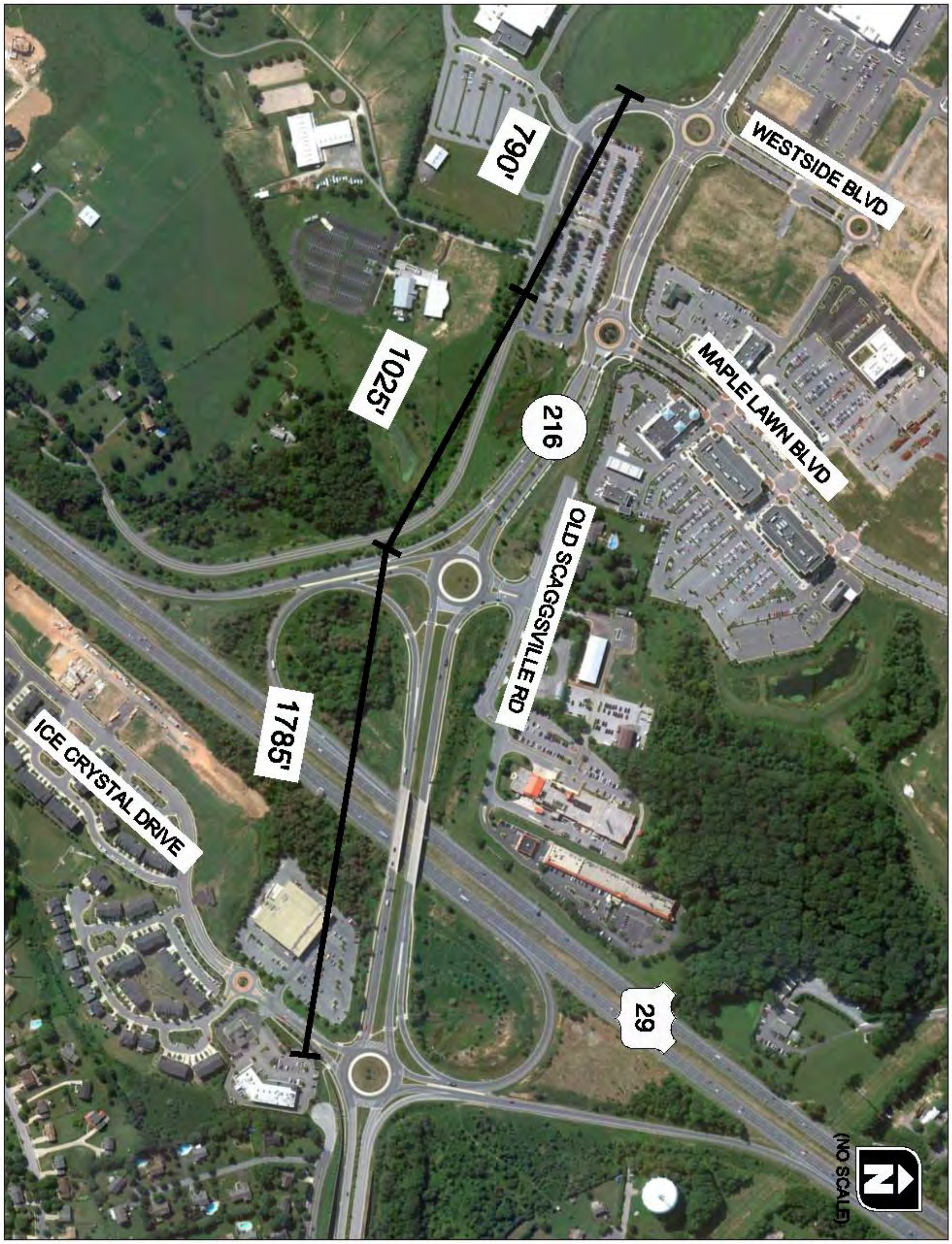
Movement		p.m. Peak				Off-Peak			
		RBTs	Sig.	Delta	% Diff	RBTs	Sig.	Delta	% Diff
East	RT	1.3	1.3	0.0	-2%	0.4	1.0	-0.6	-143%
	T	2.3	1.8	0.5	22%	0.9	0.9	0.0	-2%
	LT	2.6	4.1	-1.5	-58%	1.0	3.5	-2.4	-244%
North	RT	0.6	6.9	-6.4	-1081%	0.2	7.0	-6.8	-4004%
	T	3.6	18.0	-14.4	-400%	0.8	21.1	-20.4	-2700%
	LT	2.2	67.4	-65.2	-2942%	1.3	70.6	-69.3	-5300%
South	RT	2.0	9.5	-7.6	-386%	1.6	8.1	-6.5	-395%
	T	8.7	58.1	-49.4	-570%	2.1	41.9	-39.8	-1855%
	LT	16.8	58.9	-42.1	-251%	5.5	46.1	-40.6	-738%
West	RT	1.2	1.4	-0.2	-18%	0.9	1.4	-0.5	-57%
	T	2.2	3.3	-1.1	-51%	1.3	2.0	-0.7	-55%
	LT	3.9	6.6	-2.6	-67%	2.7	3.4	-0.7	-27%
TOTAL	ALL	2.9	9.0	-6.1	-213%	1.4	7.2	-5.8	-426%

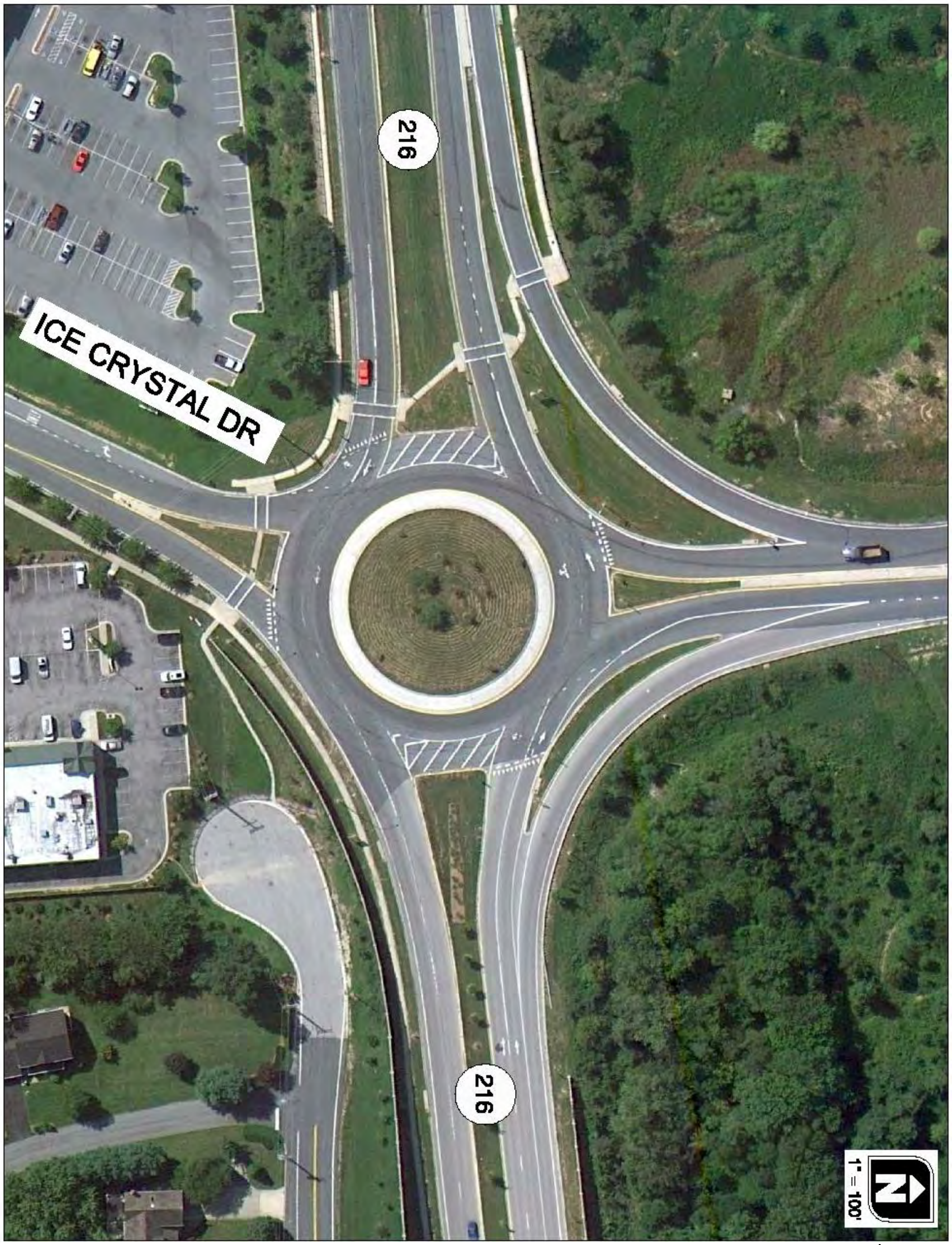
Exhibit B-30 Node 4 Movement Delay Comparison: Roundabouts Minus Signals

Movement		p.m. Peak				Off-Peak			
		RBTs	Sig.	Delta	% Diff	RBTs	Sig.	Delta	% Diff
East	RT	0.0	0.0	0.0	n/a	0.0	0.0	0.0	n/a
	T	17.1	9.2	7.9	46%	6.5	11.2	-4.7	-72%
	LT	18.4	72.3	-53.9	-293%	7.3	69.3	-62.0	-844%
North	RT	0.0	0.0	0.0	n/a	0.0	0.0	0.0	n/a
	T	16.0	67.7	-51.7	-322%	5.5	70.3	-64.8	-1186%
	LT	11.2	58.6	-47.3	-421%	3.8	65.8	-62.0	-1618%
South	RT	18.0	34.9	-16.9	-94%	6.6	36.8	-30.3	-460%
	T	27.9	71.4	-43.6	-156%	12.5	71.6	-59.1	-474%
	LT	30.7	56.4	-25.7	-83%	13.0	59.8	-46.8	-361%
West	RT	4.1	6.0	-2.0	-48%	1.7	5.2	-3.6	-216%
	T	5.5	8.6	-3.1	-56%	2.4	8.4	-6.0	-249%
	LT	8.0	83.0	-75.0	-933%	4.0	72.5	-68.6	-1733%
TOTAL	ALL	12.1	29.8	-17.7	-146%	4.9	27.4	-22.5	-456%

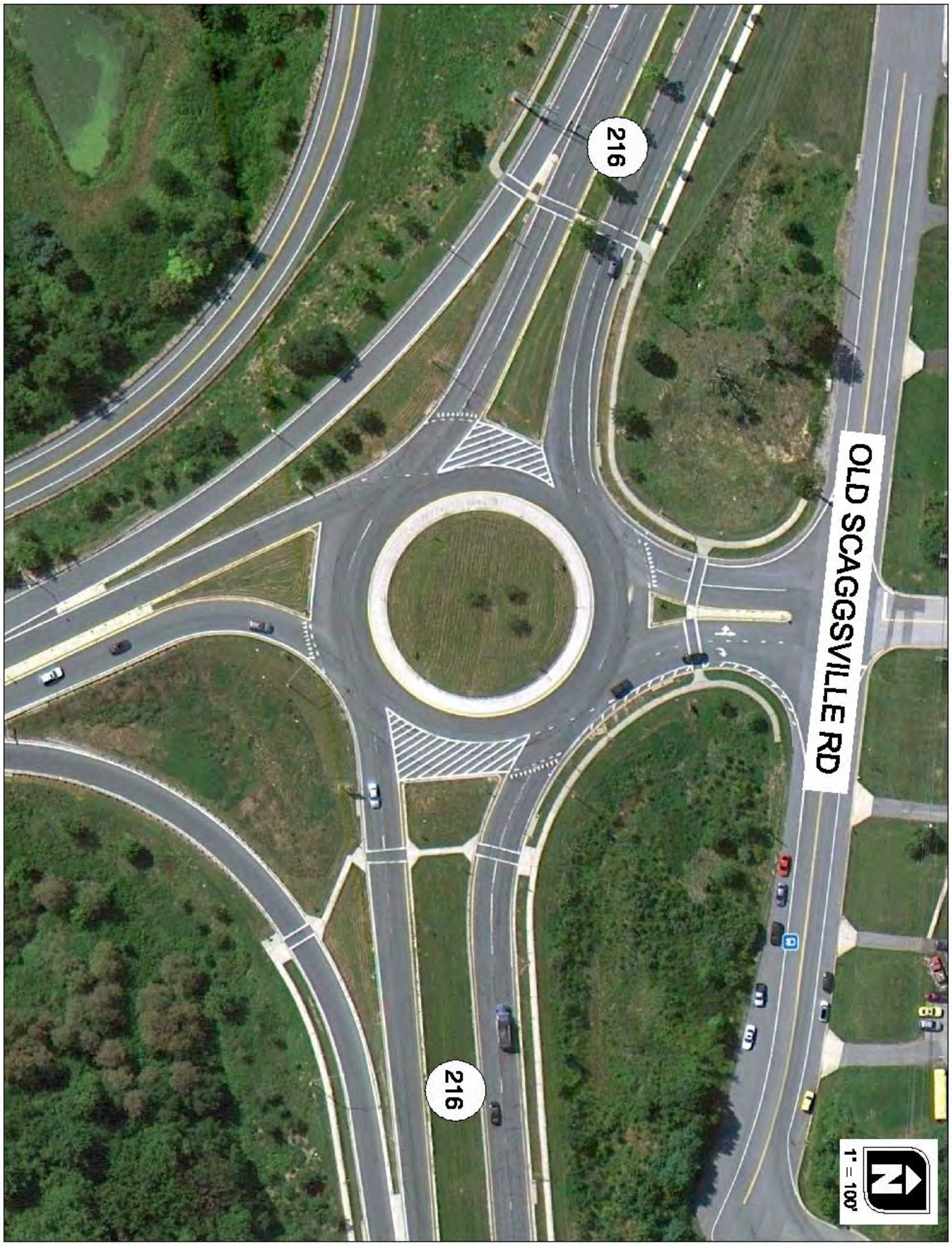
Exhibits B-29 and B-30 shows that the roundabout outperforms the signal for almost all movements. Nearly all movements experience lower delay with the roundabout. The difference is most pronounced for left-turning movements, as well as the north and south side-street approaches. It should be noted that the right turns for east and north approaches at Node 4 were modeled as channelized movements to and from the freeway in both cases, and therefore incurred zero delay.

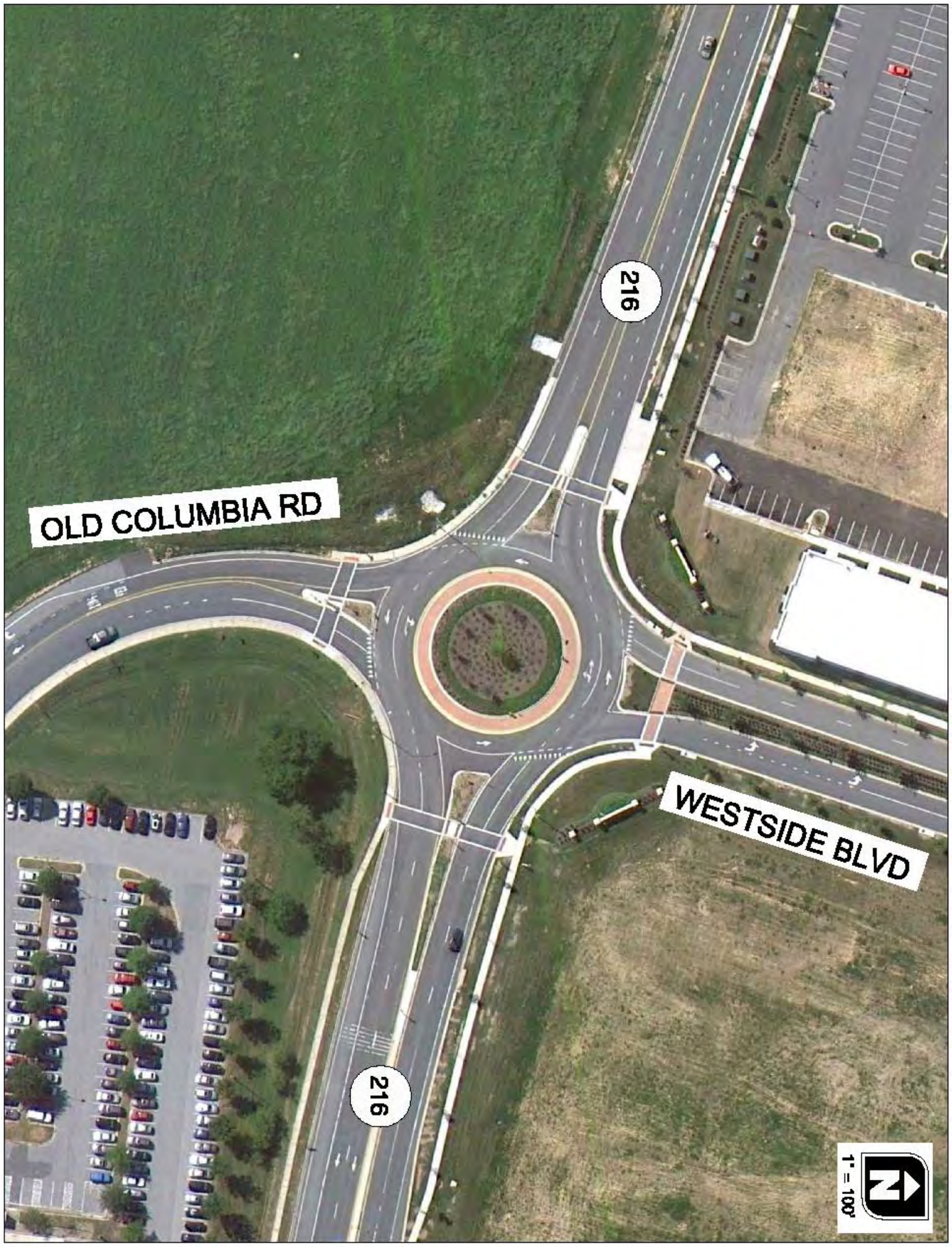
APPENDIX B1: AERIAL IMAGERY


790'
1025'
1785'
216
29
WESTSIDE BLVD
MAPLE LAWN BLVD
OLD SCAGGSVILLE RD
ICE CRYSTAL DRIVE
(NO SCALE)
N


ICE CRYSTAL DR
216
216
1" = 100'
N

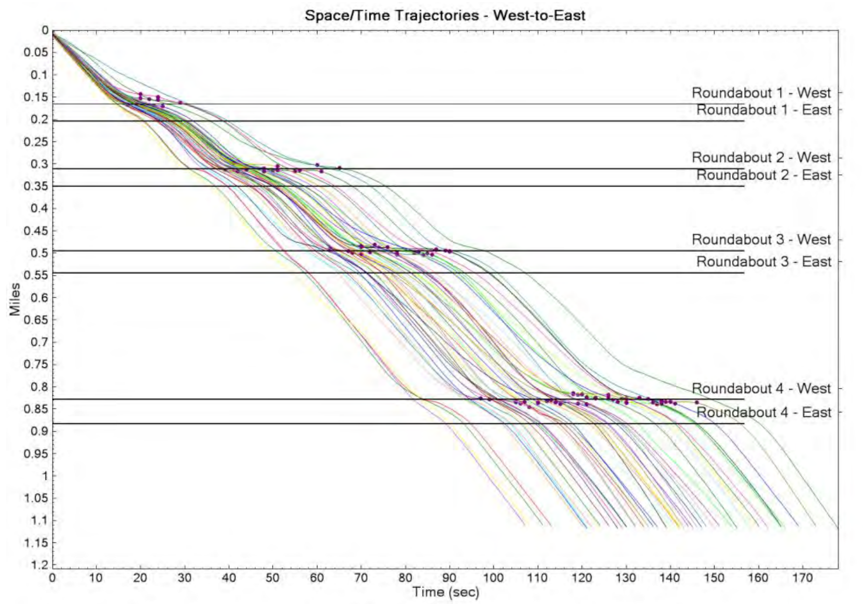

216
216
MAPLE LAWN BLVD
1" = 100'

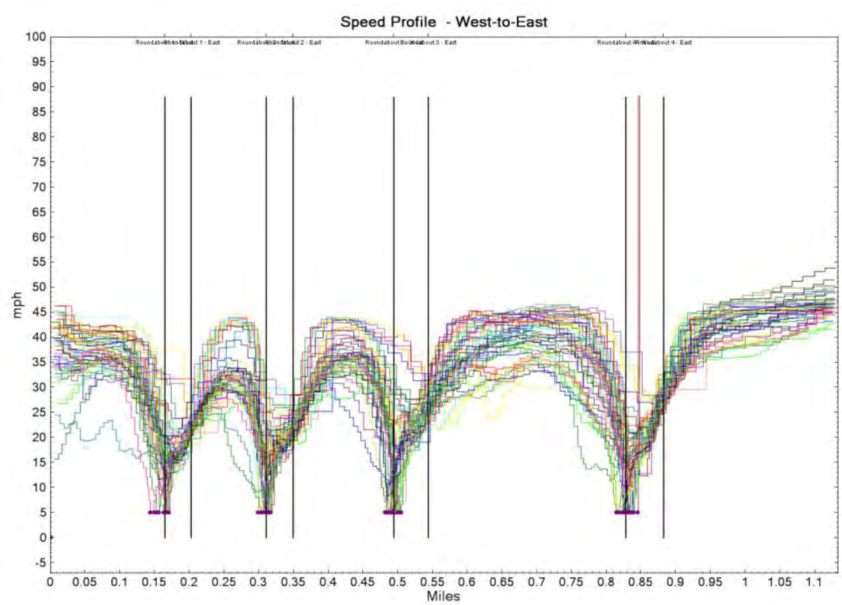

216
OLD SCAGGSVILLE RD
216
1" = 100'
N


OLD COLUMBIA RD
216
WESTSIDE BLVD
216
1" = 100'

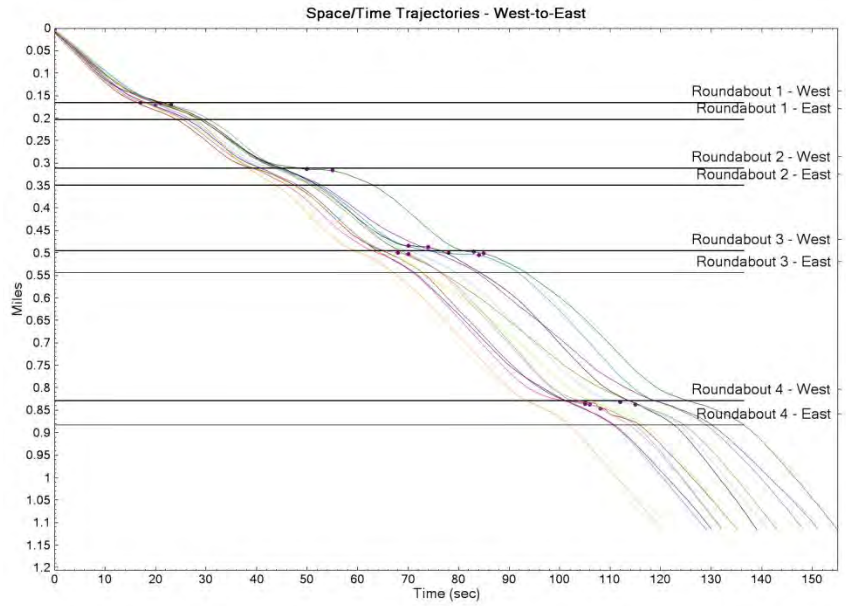
APPENDIX B2: SPEED PROFILES AND TRAVEL TIME TRAJECTORIES

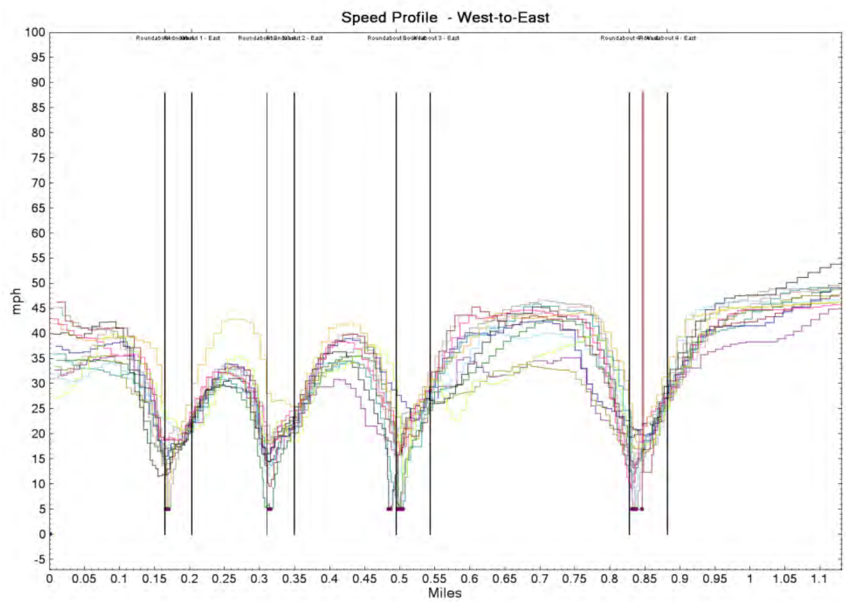
West-to-East All



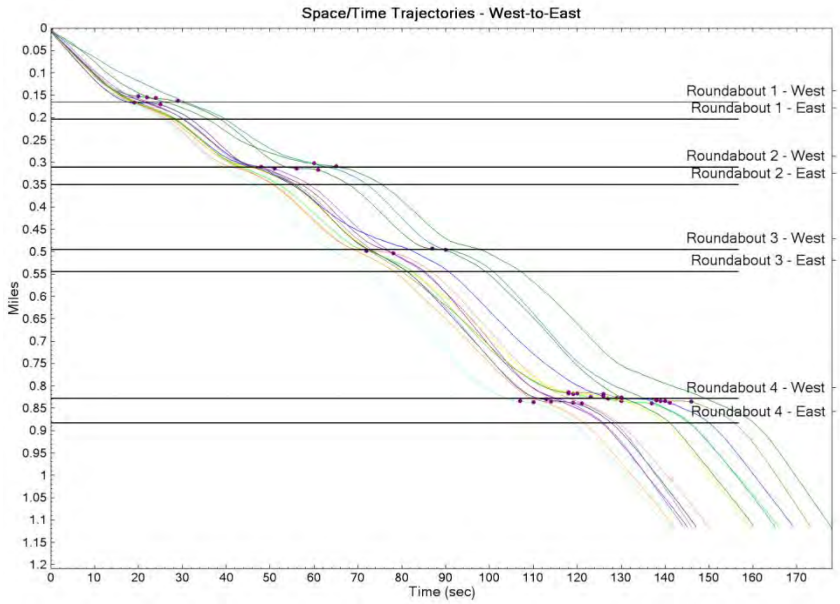


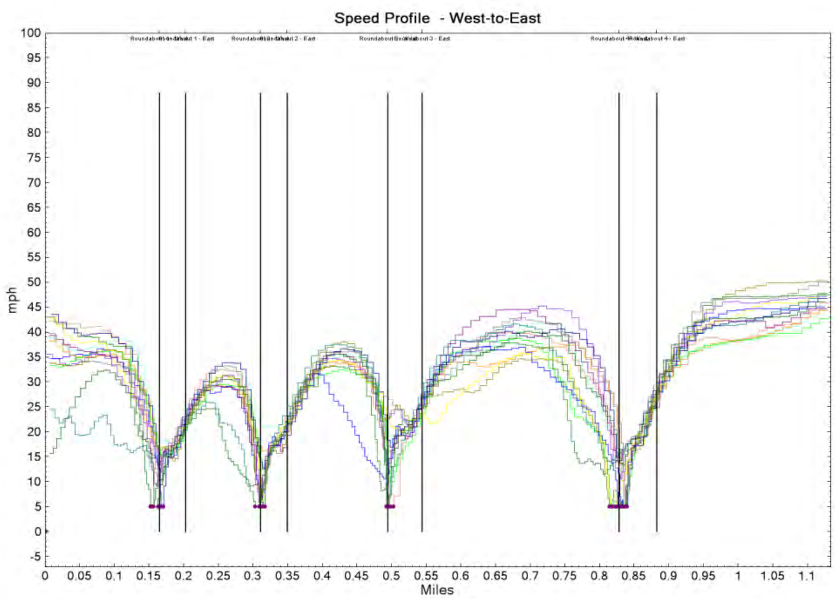
West-to-East AM (7-9)



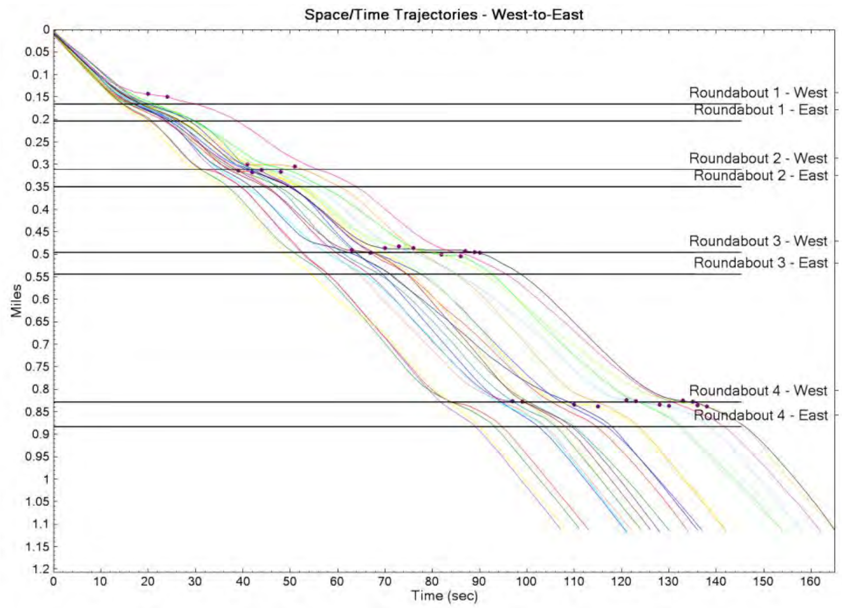


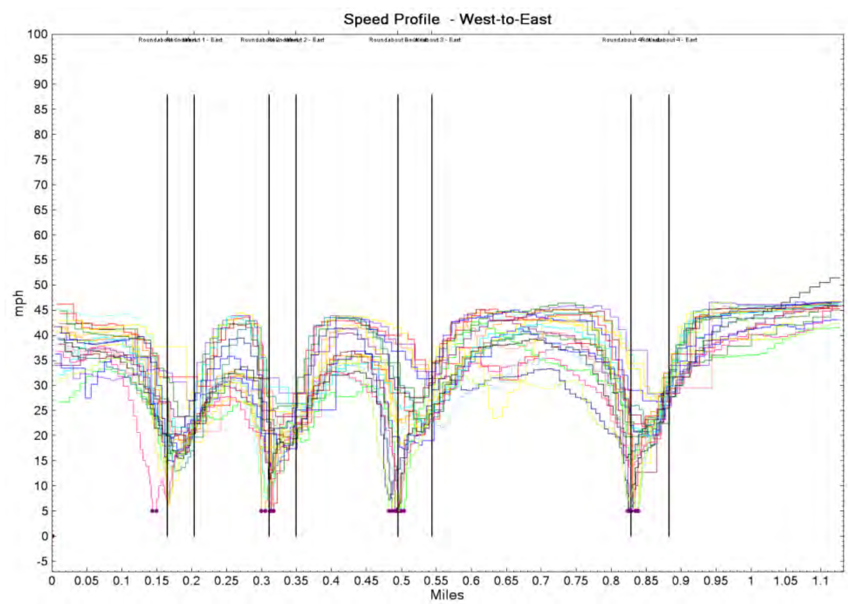
West-to-East PM (4-6)



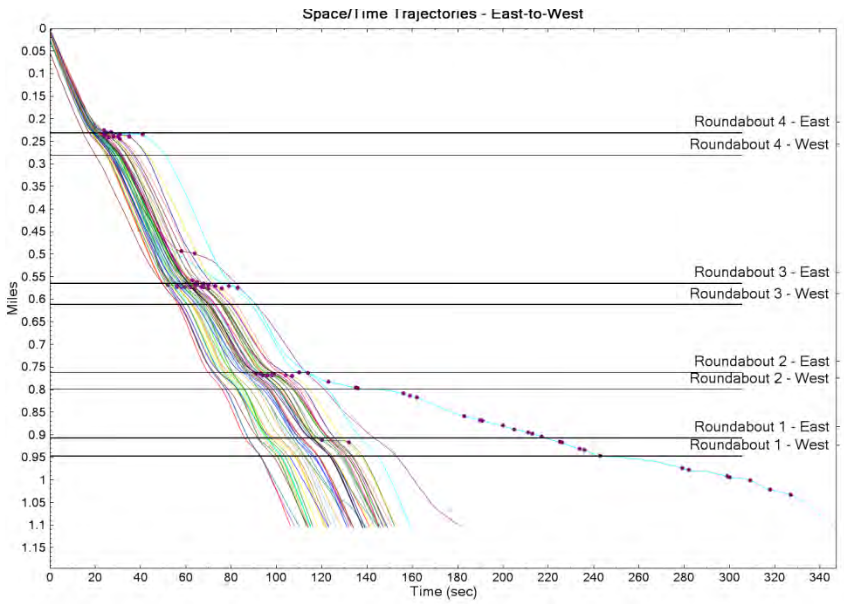


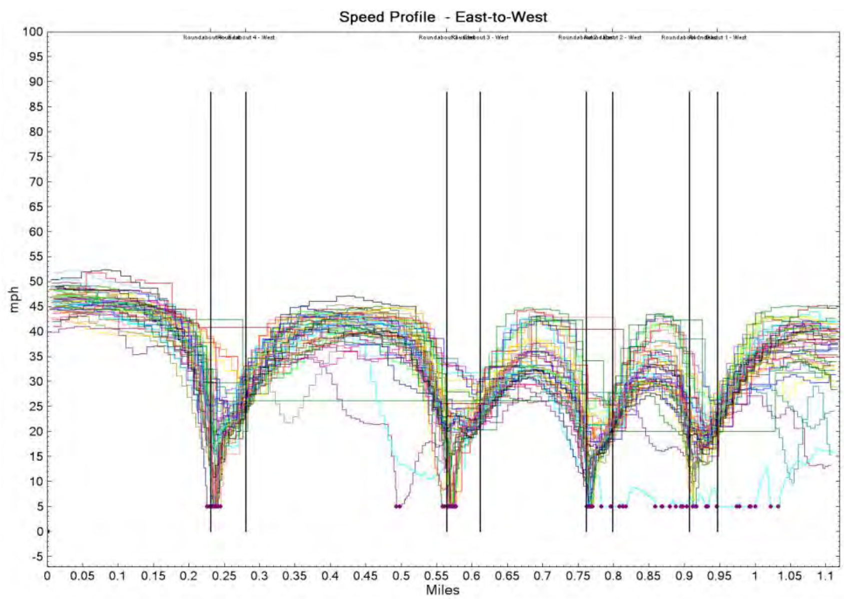
West-to-East Off



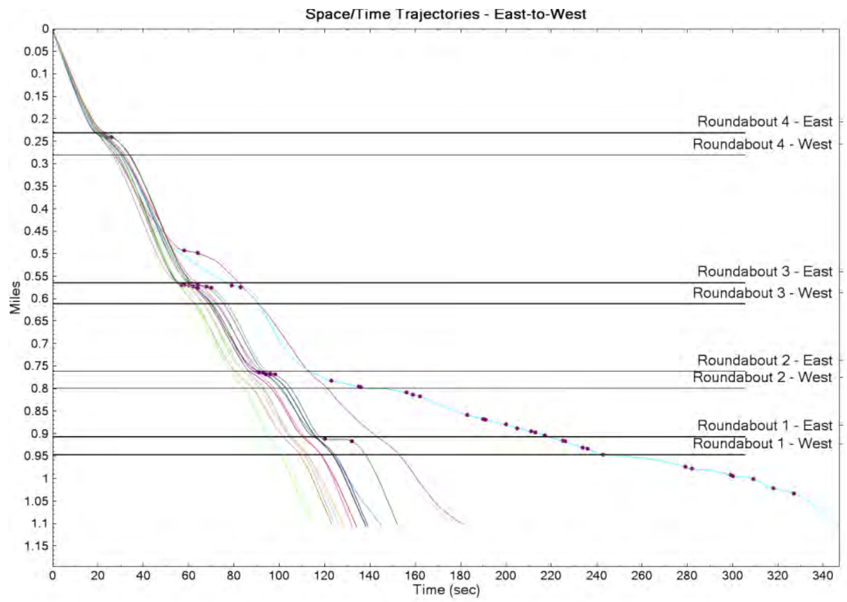


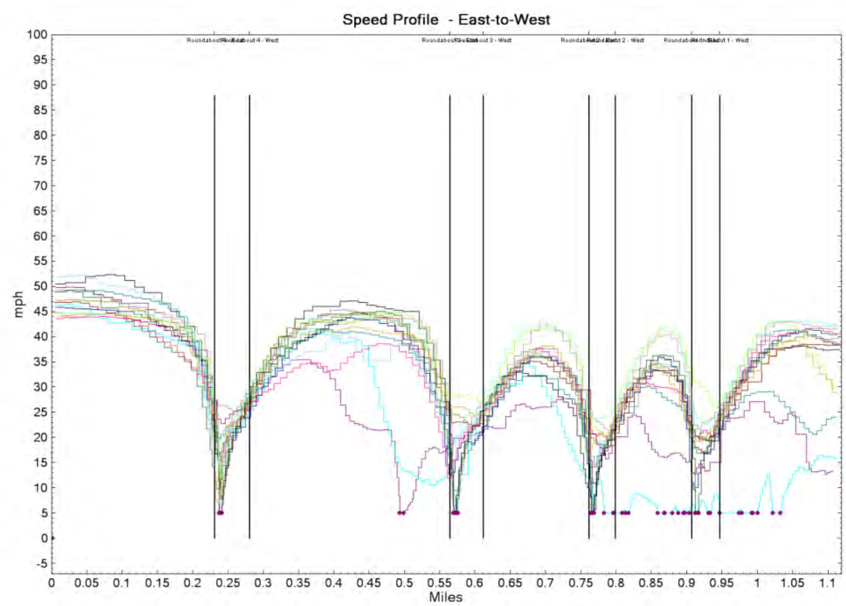
East-To-West All



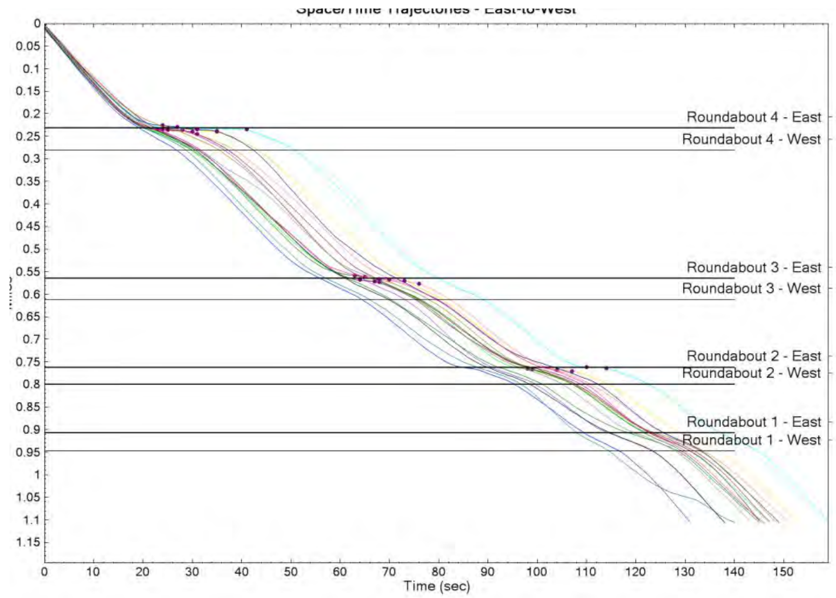


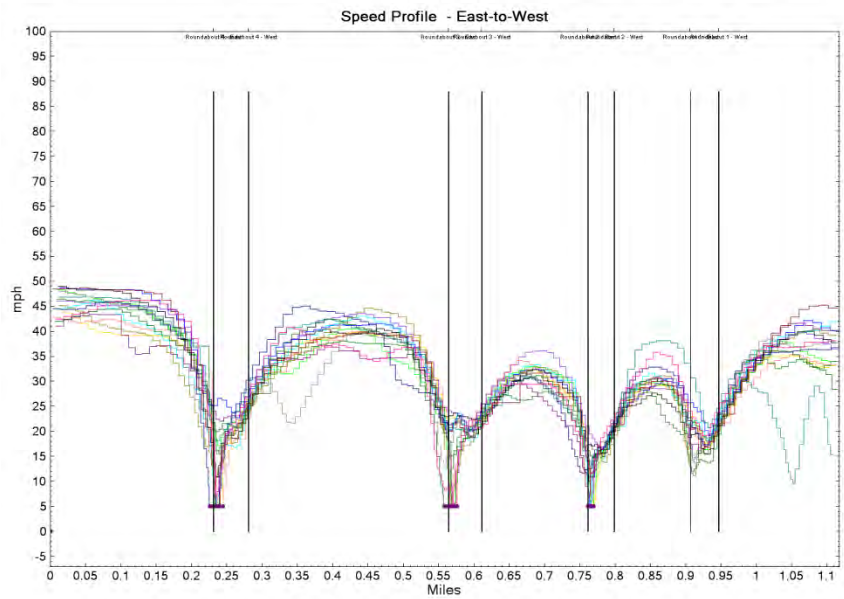
East-To-West AM (7-9)





East-To-West PM (4-6)





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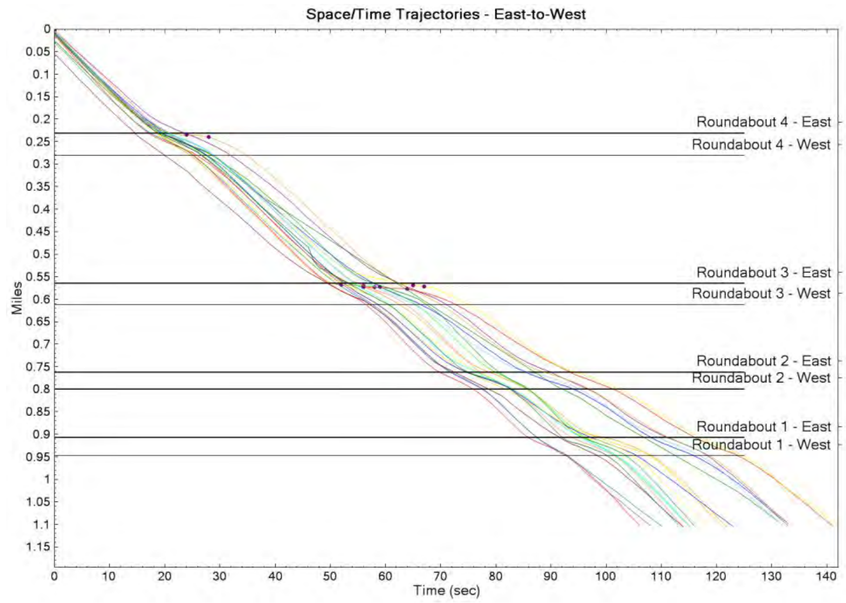
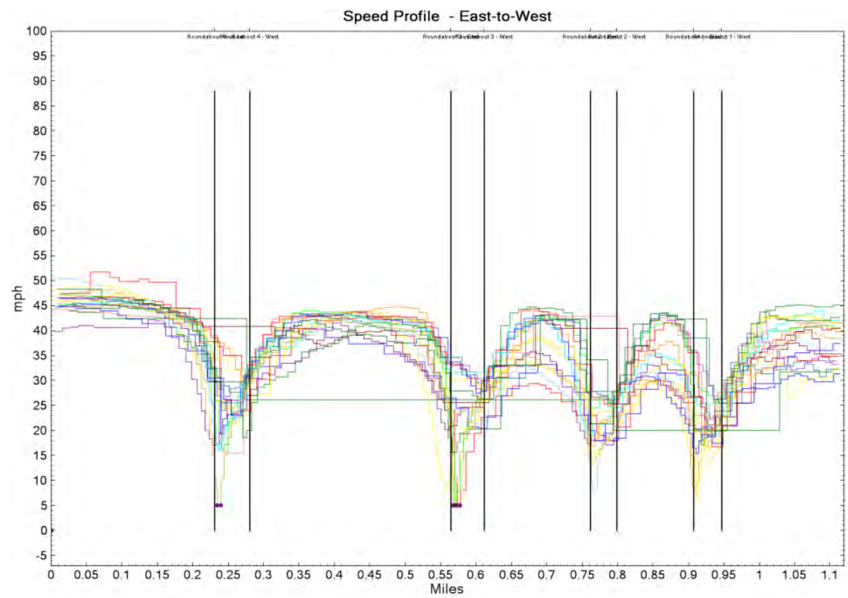
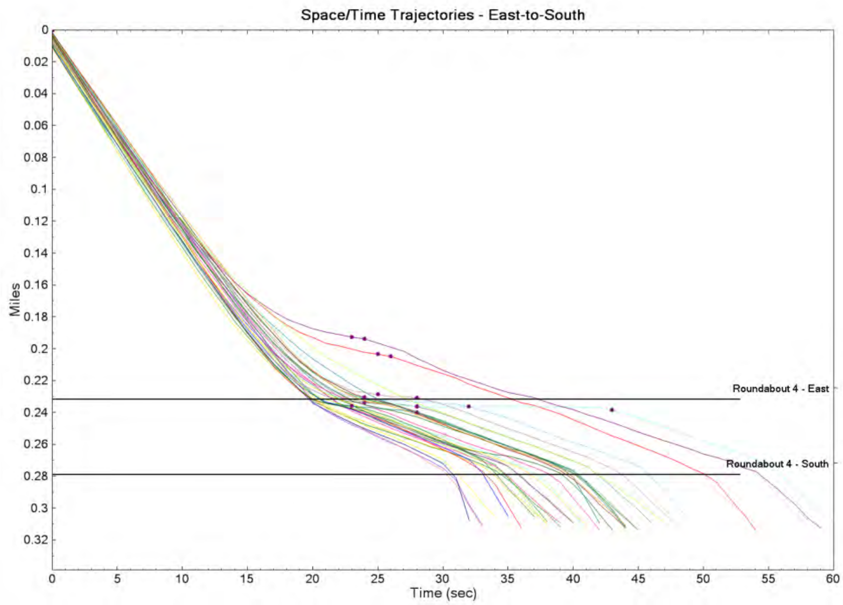
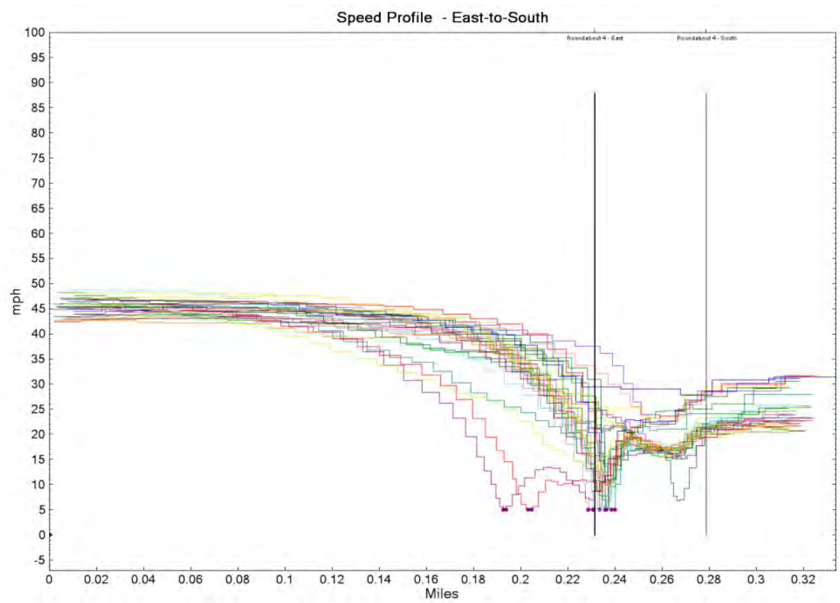


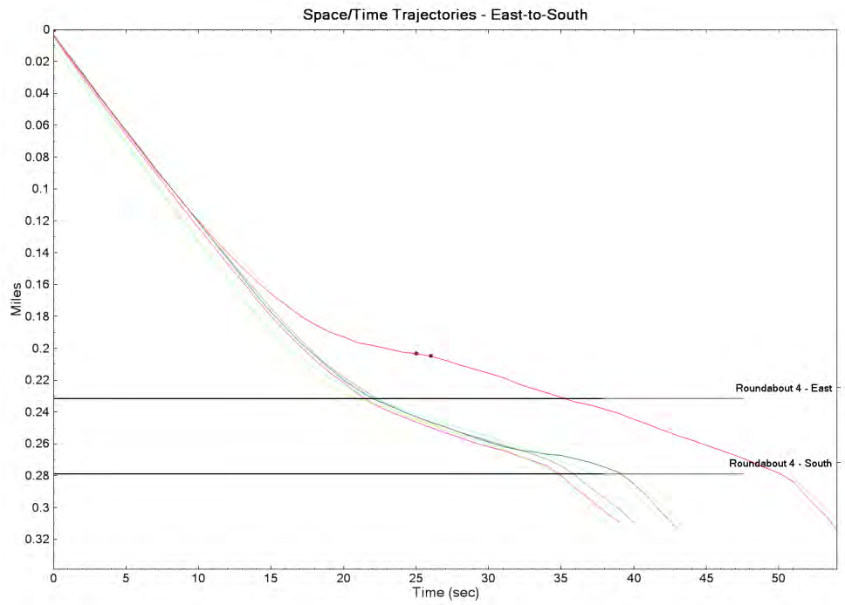


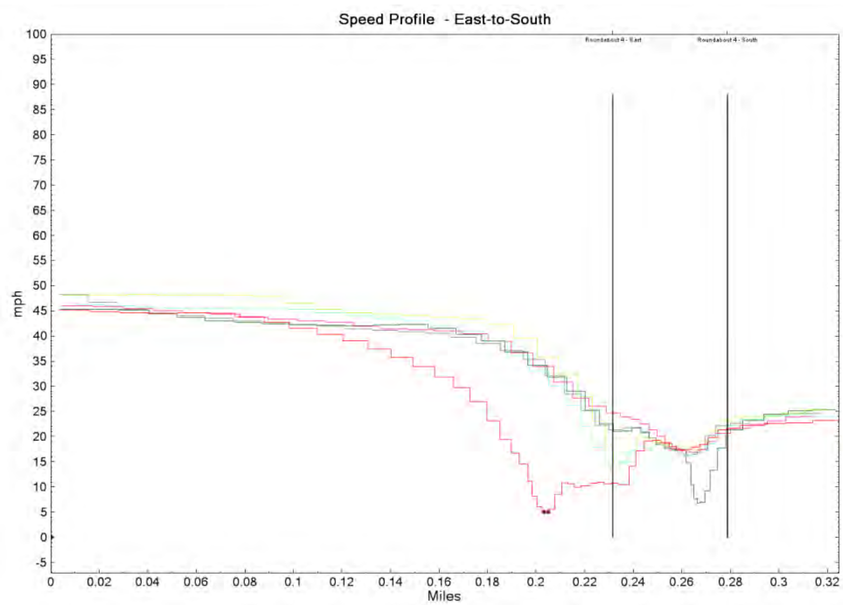
East-to-South All





East-to-South AM (7-9)





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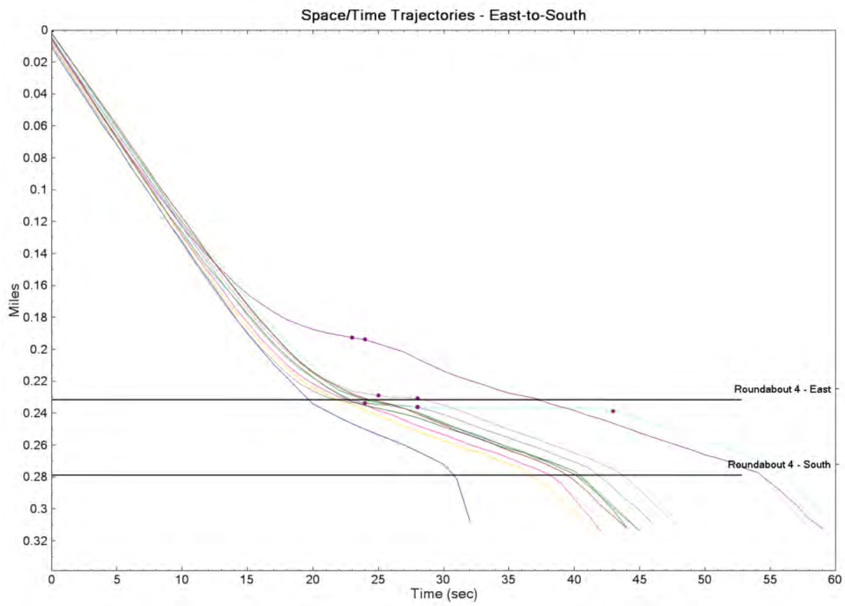
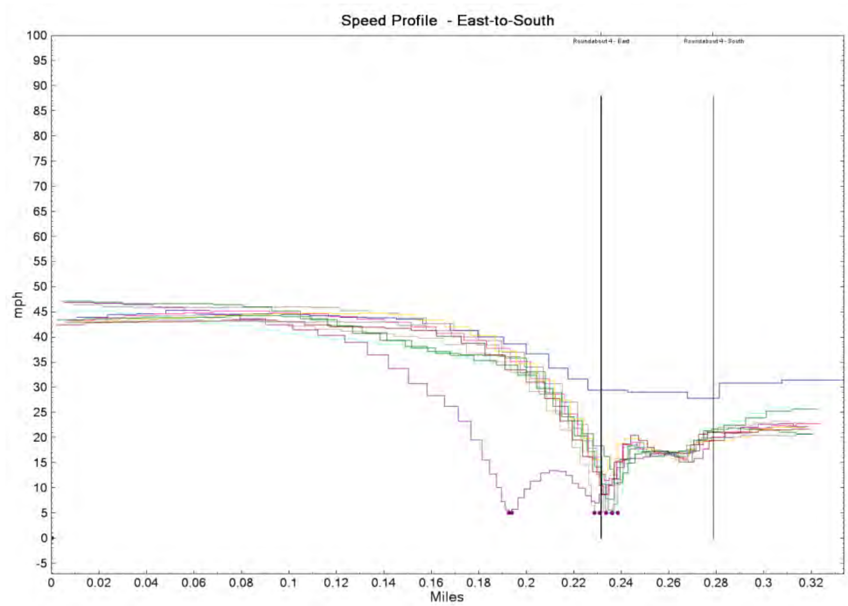
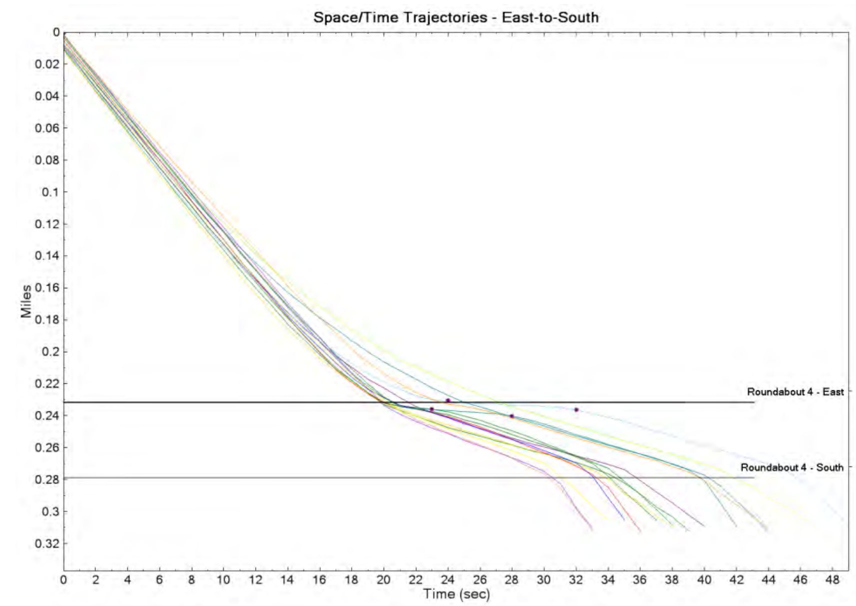
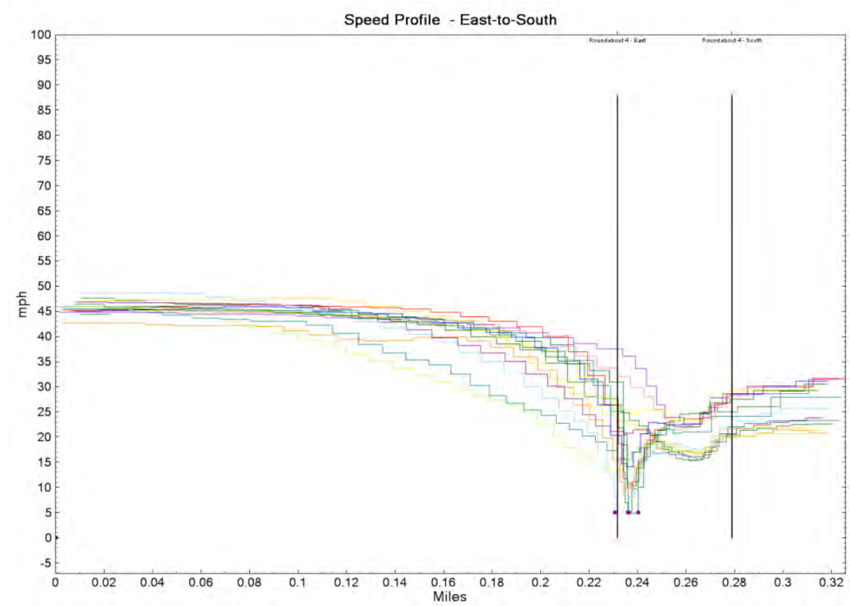


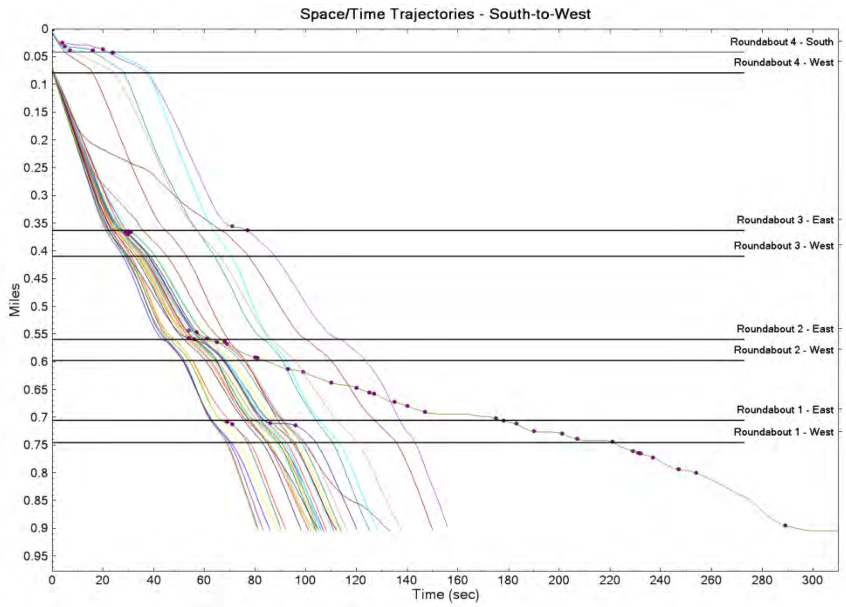


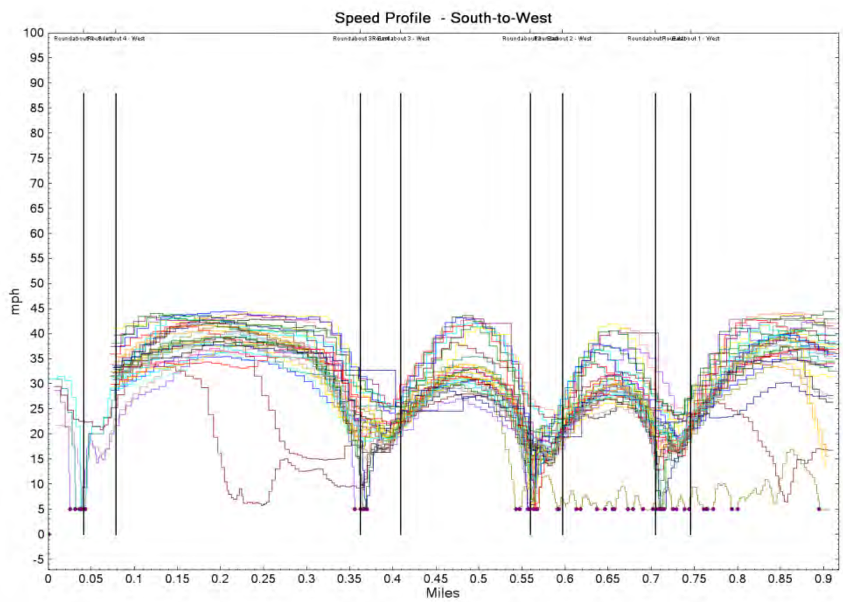
East-to-South Off



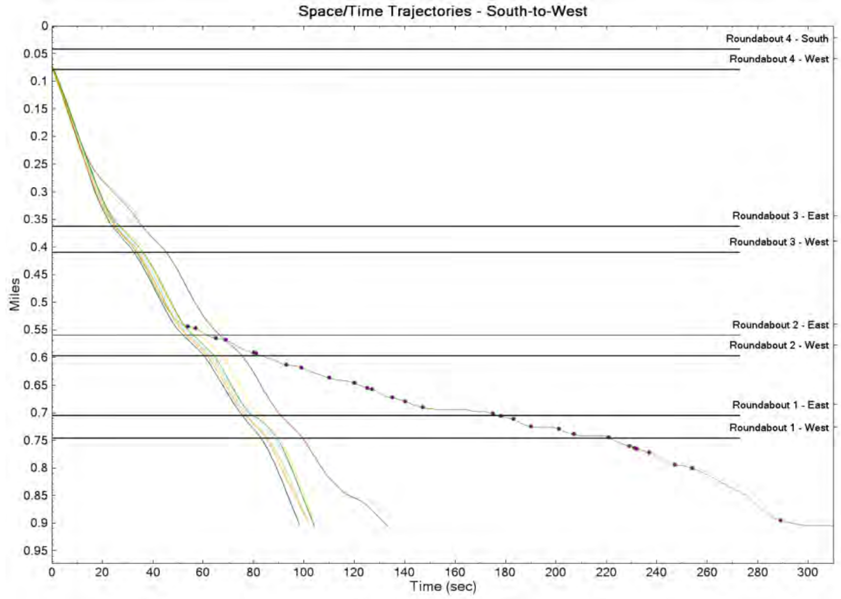


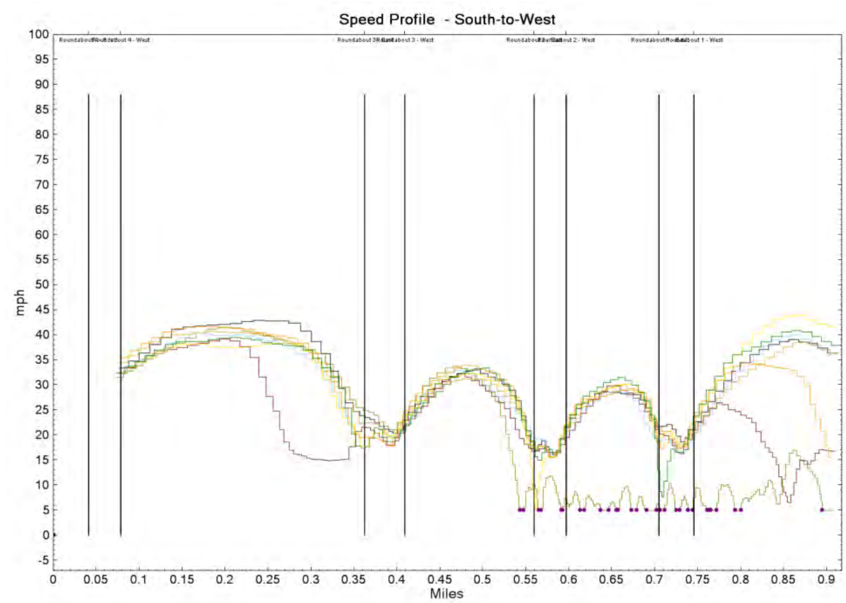
South-to-West All



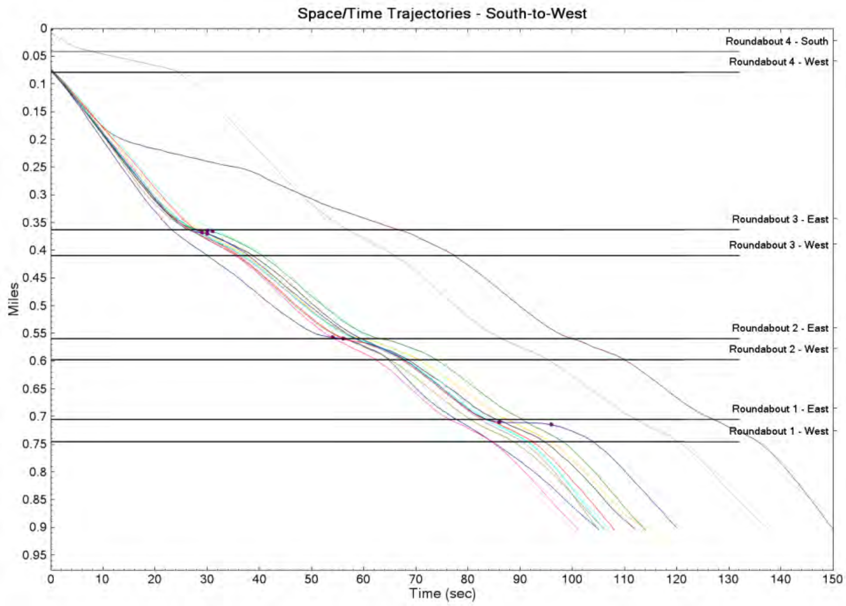


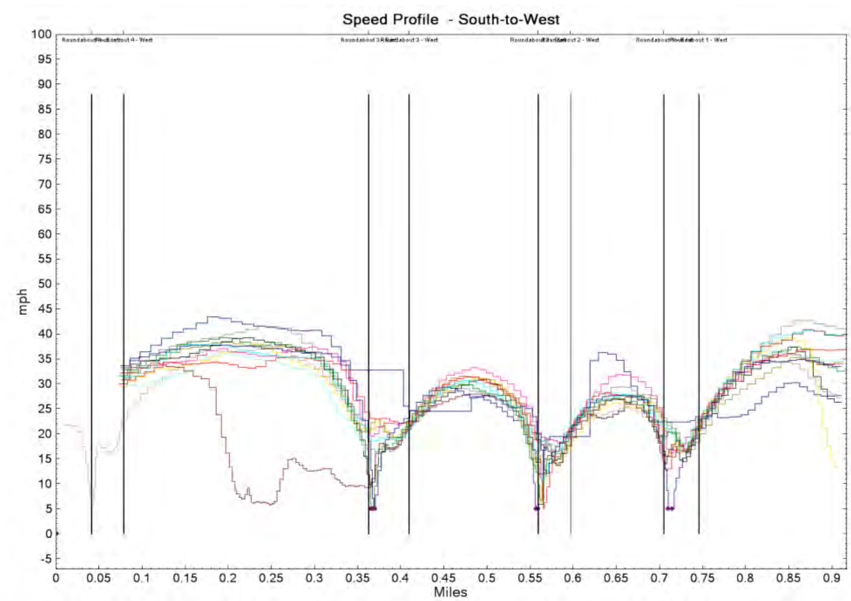
South-to-West AM (7-9)



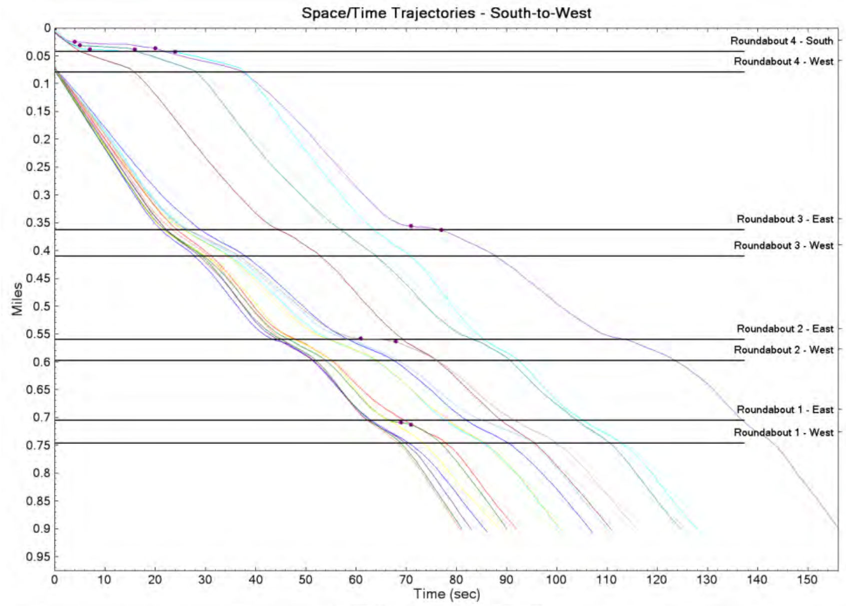


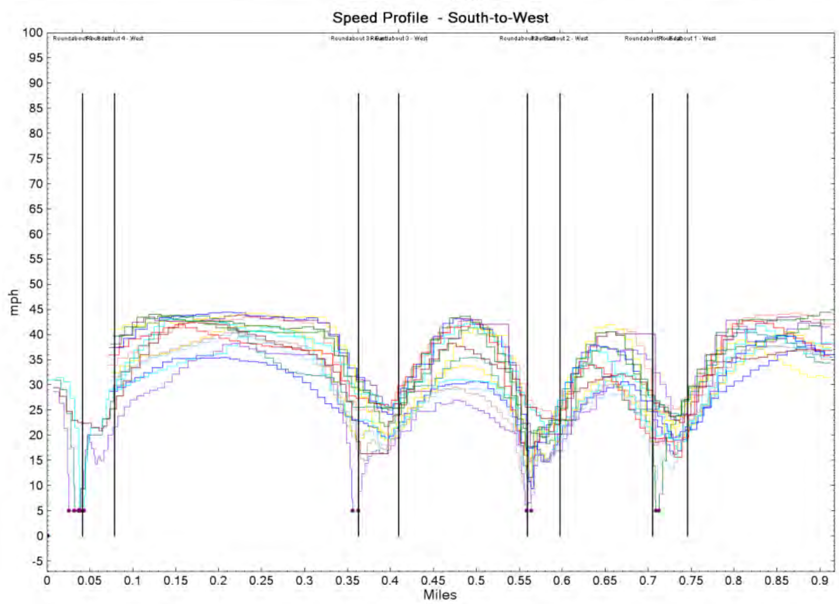
South-to-West PM (4-6)



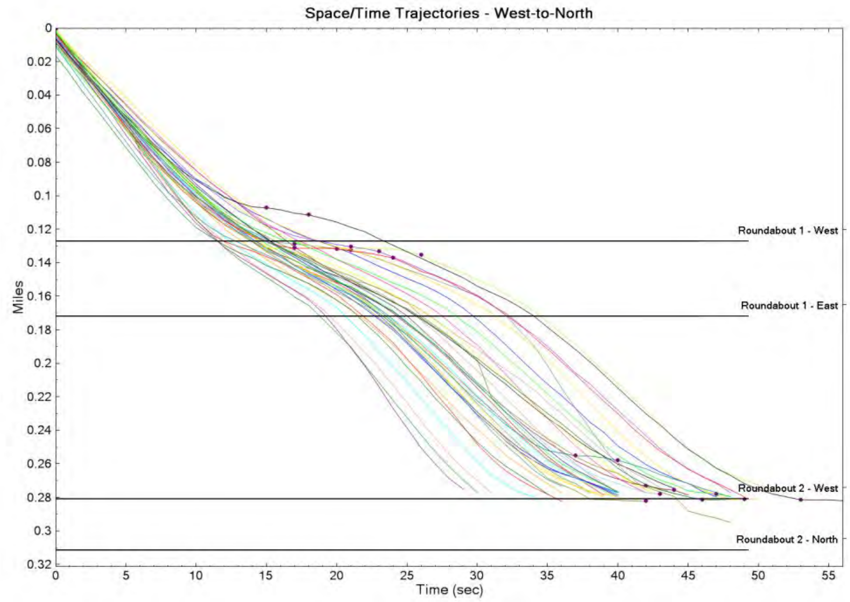


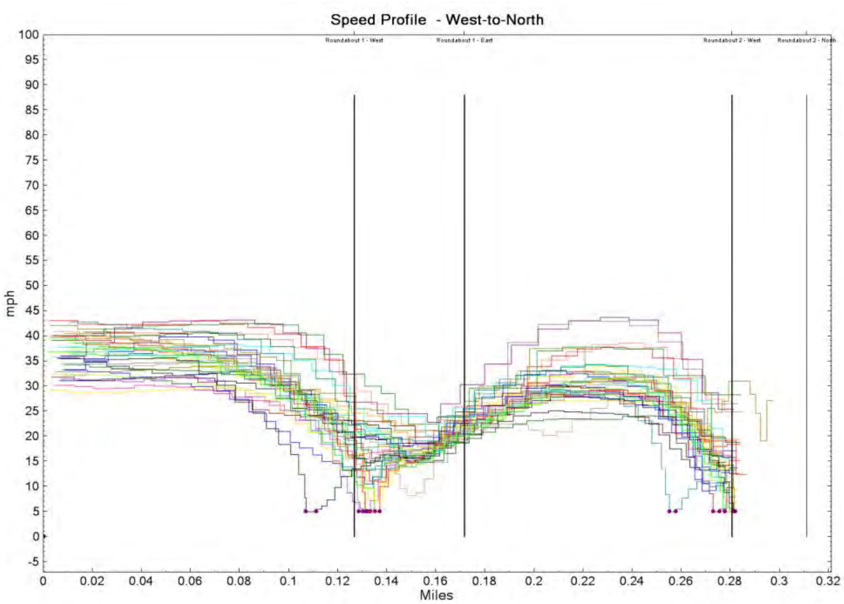
South-to-West Off





West-to-North All





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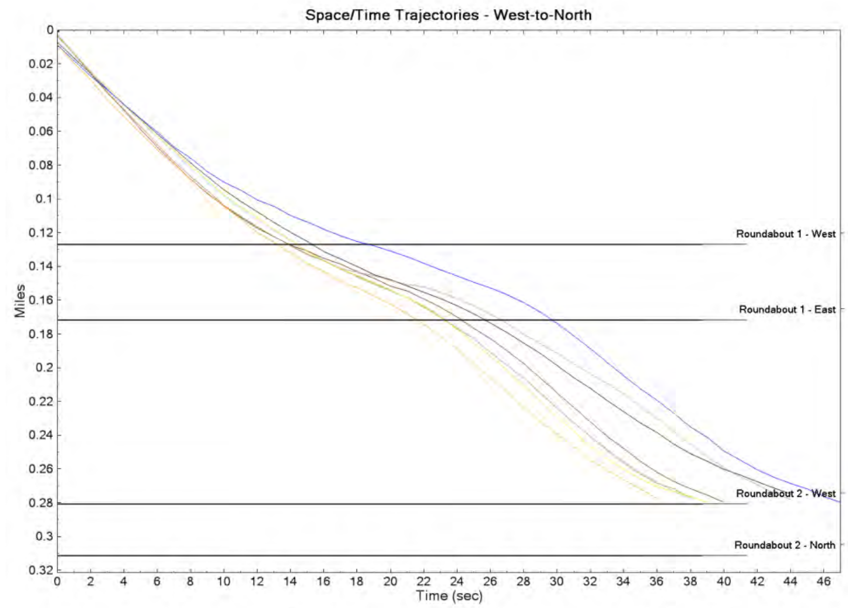

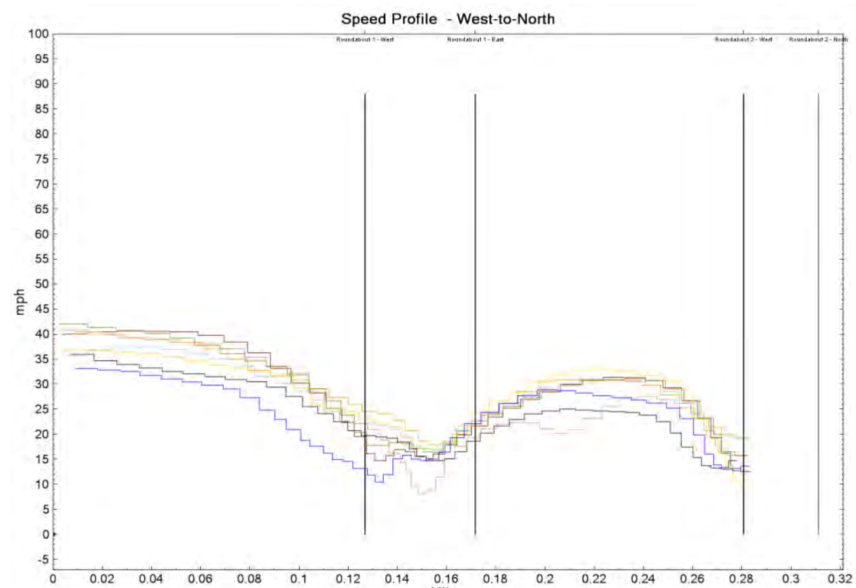

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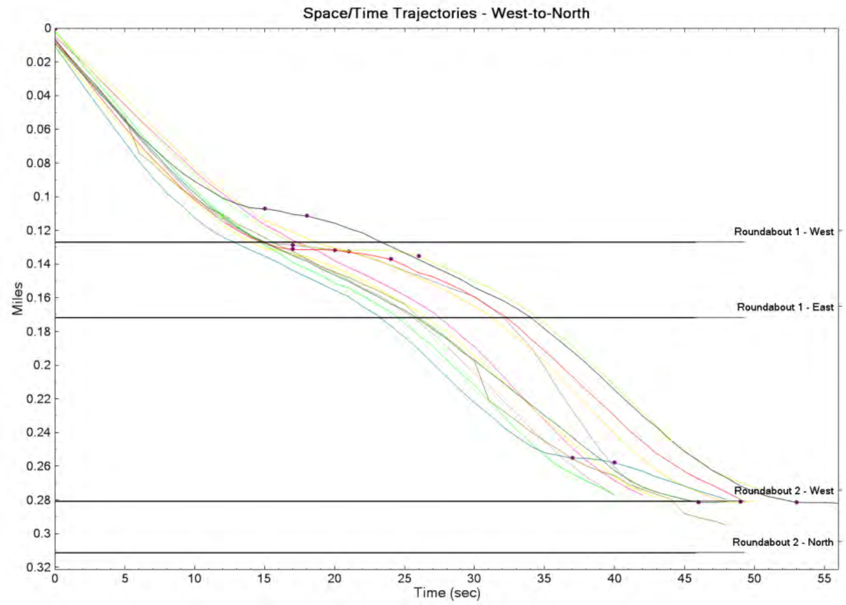

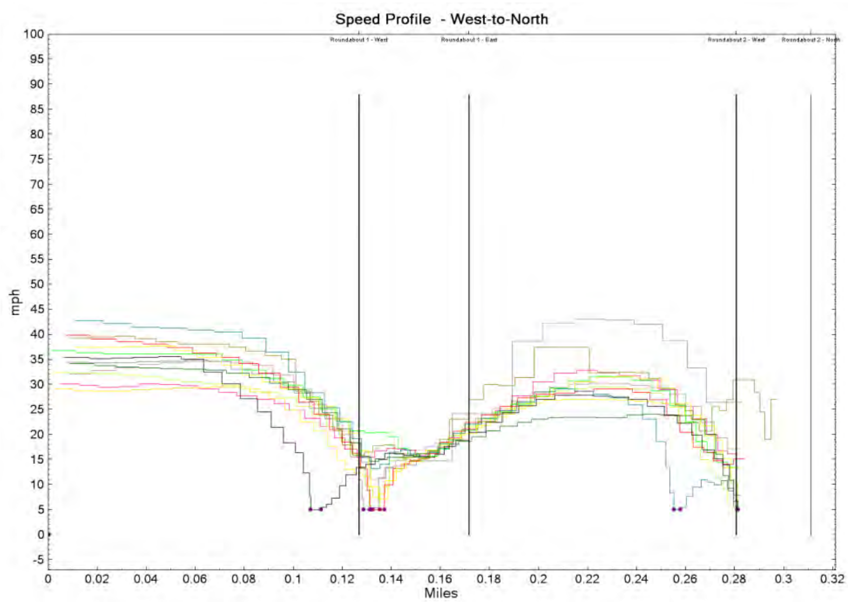

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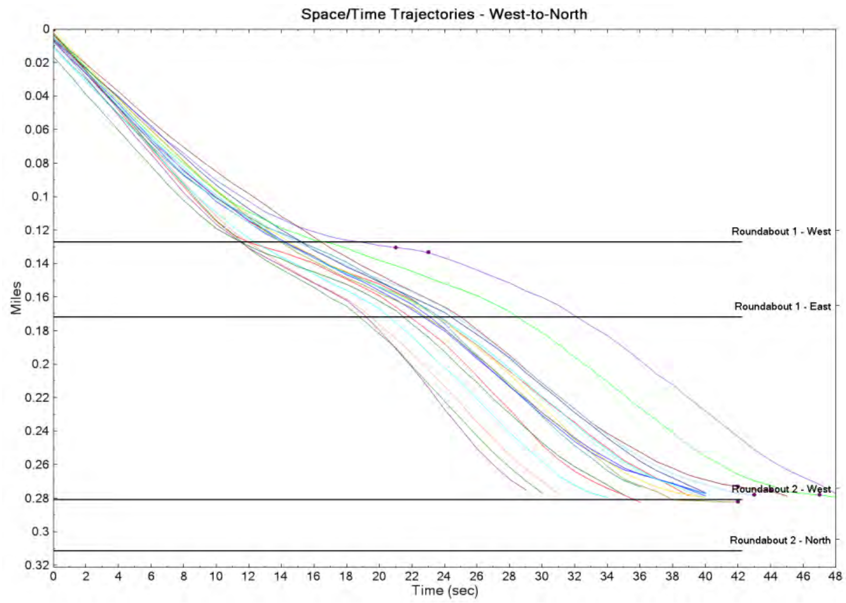

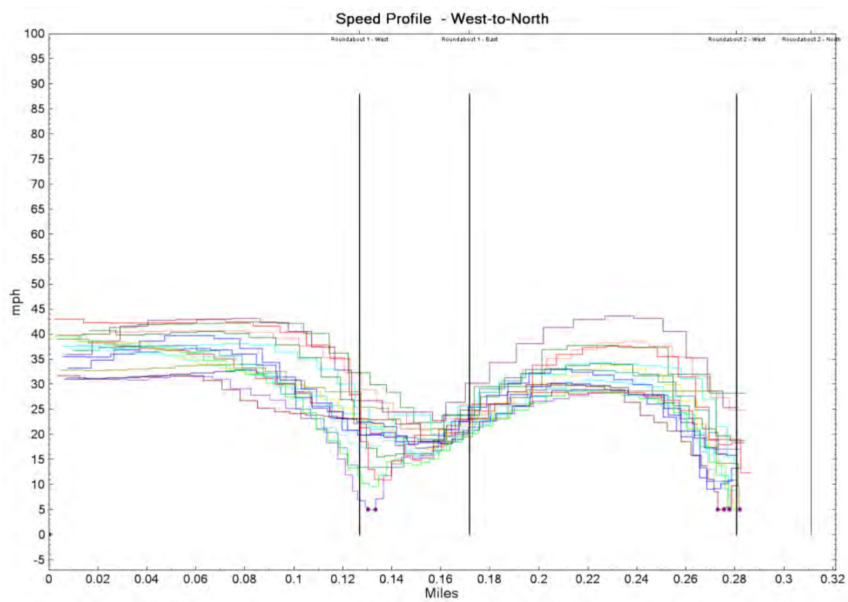

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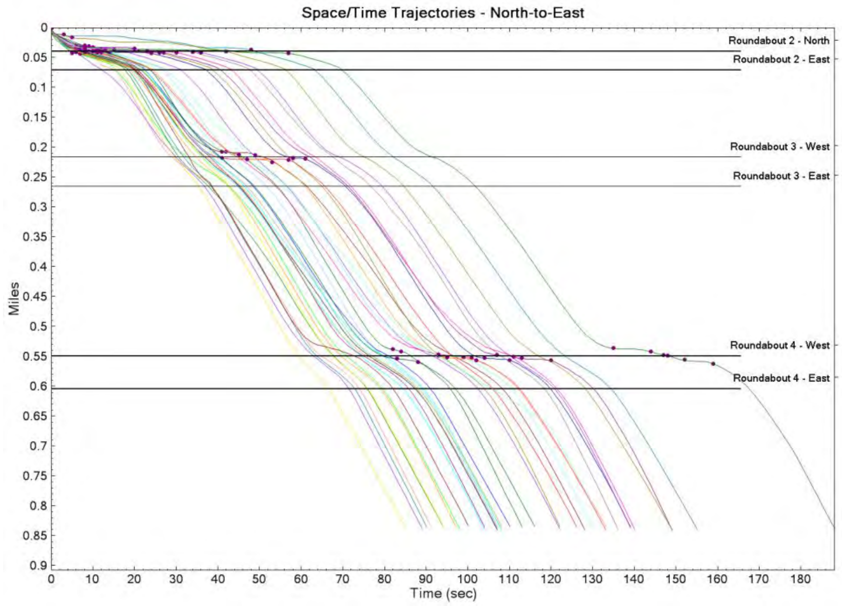

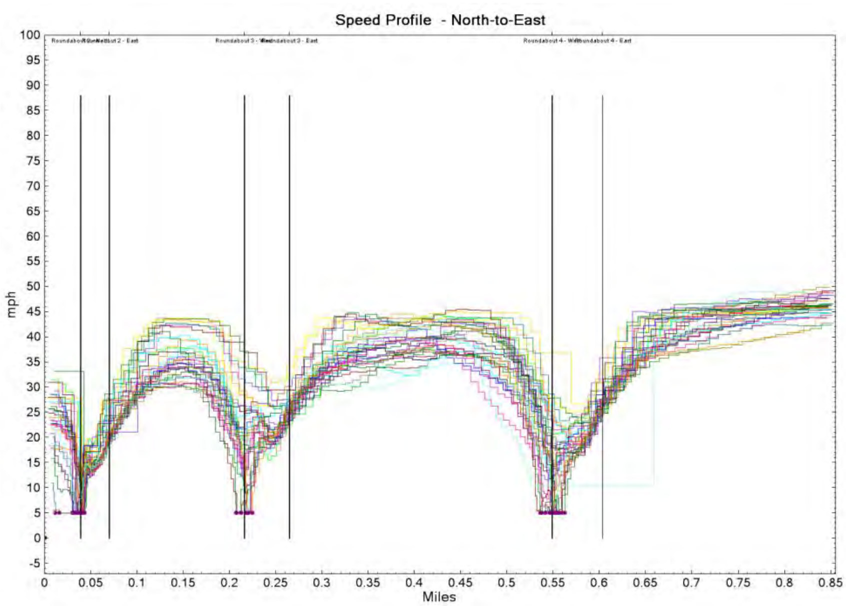

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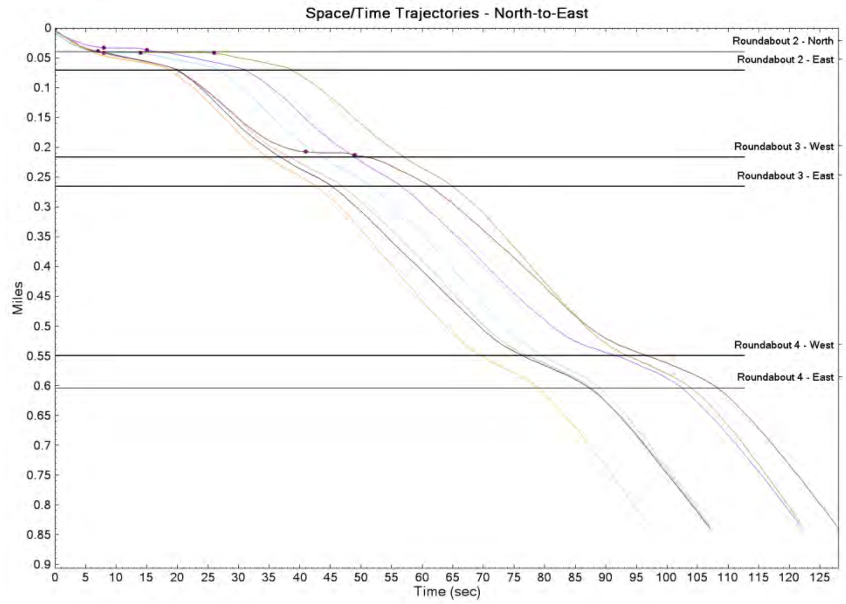

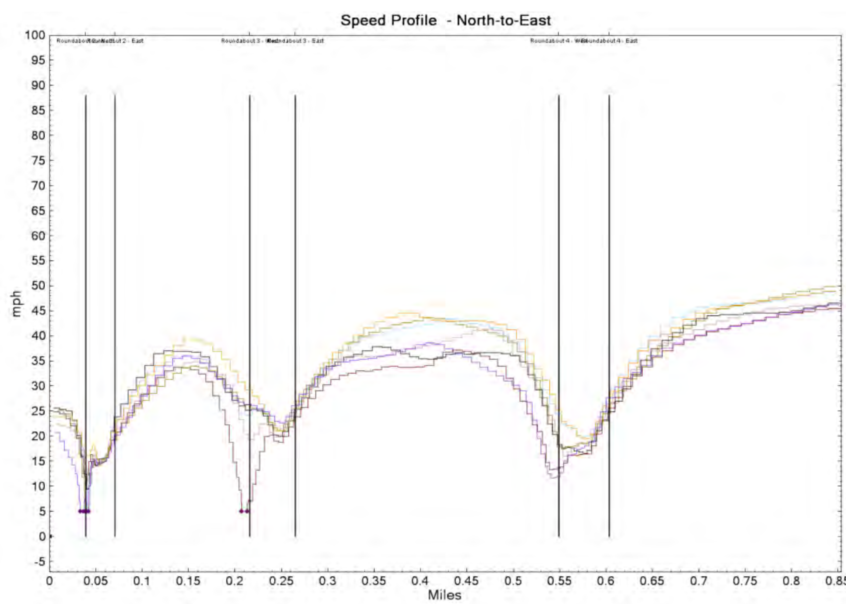

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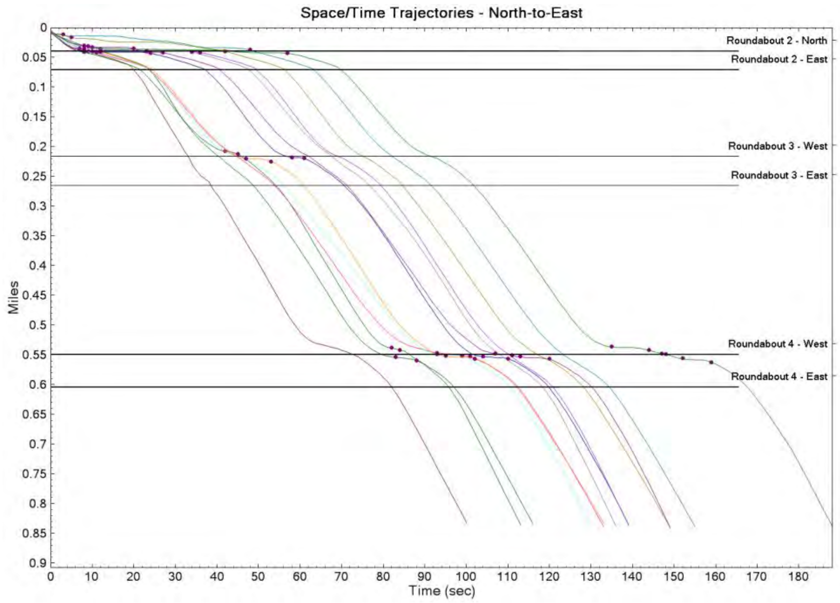
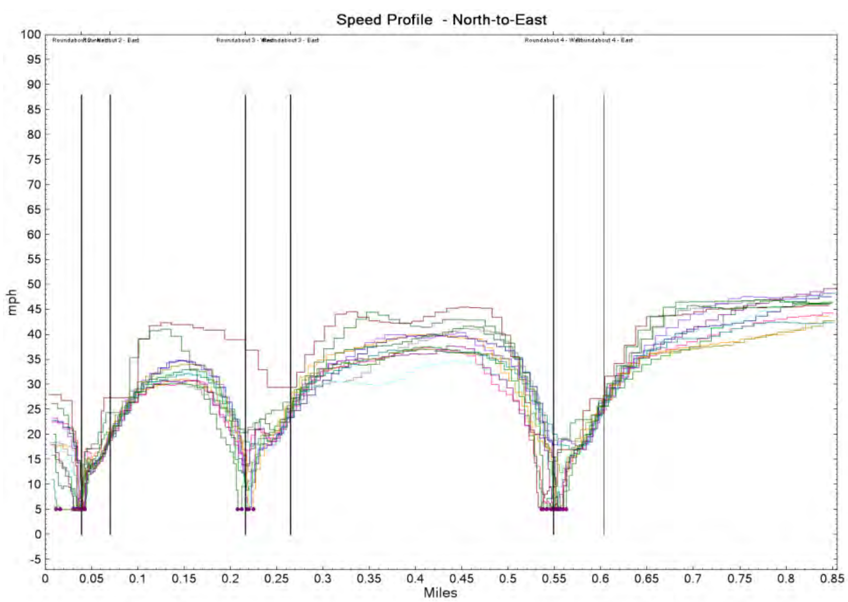
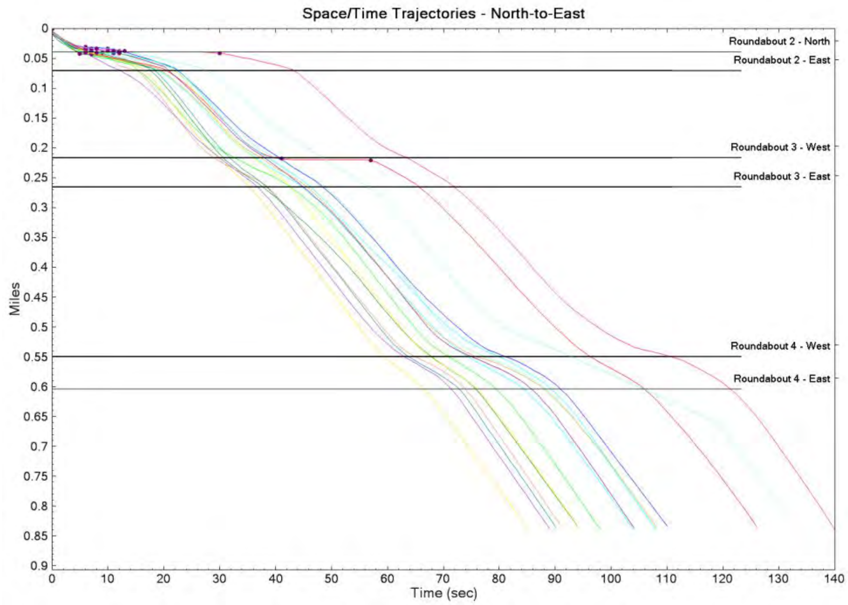
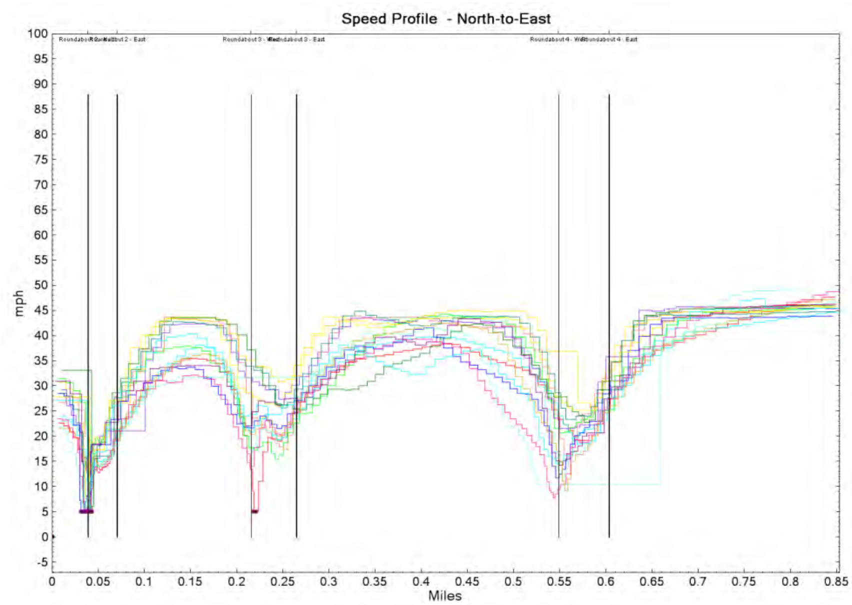




North-to-East Off





C. LA JOLLA BOULEVARD, SAN DIEGO, CALIFORNIA

The second roundabout corridor visited by the project team, on December 11-14, 2011, was La Jolla Boulevard in the Bird Rock neighborhood of San Diego, California. Rain fell at the corridor during much of this time period. La Jolla Boulevard in its present form is a two-lane divided roadway with five roundabouts. Much of roadway has bicycle lanes and on-street parking (either parallel or diagonal). All intermediate access points are right-in, right-out; most are driveways to houses or parking lots with 20 or fewer spaces. The corridor has an urban character with a moderate degree of pedestrian and bicycle activity.

C.1. DATA COLLECTION PROCEDURES

The data collected at this roundabout corridor included turning movement counts, travel times, spot speeds, geometric delay, and approach delay at all four roundabouts and a daily volume profile in the middle of the corridor. These data were obtained from video recordings captured through field-mounted cameras, in-vehicle GPS units, Bluetooth readers, and a laser gun. Exhibit C-1 shows the La Jolla Boulevard corridor. Black numbers denote roundabouts, and yellow dots denote the placement of BlueTooth units, which are hereafter referred to as "north," "south," "east," and "mid-block."

Exhibit C-1 Aerial View of the La Jolla Boulevard Roundabout Corridor with Bluetooth Reader Placement

C.1.1. VIDEO DATA COLLECTION PROCEDURE

As discussed in Chapter 2 of this Interim Report #2, the research team used the services of Quality Counts, LLC (a subsidiary of Kittelson & Associates, Inc.) to collected video recordings of the roundabouts. Quality Counts' cameras are enclosed in a box that provides protection from wet weather and storage for a battery. The battery is capable of powering a camera for approximately 60 hours, and cameras are equipped with two memory cards which are capable of recording approximately 80 hours of video. The camera is equipped with a "fish eye" lens which provides a wide angle of view and generally enables an entire intersection to be filmed with one camera. Quality Counts generally mounts the cameras to poles, although some were mounted to palm trees on La Jolla Boulevard to leverage better vantage points. Exhibits C-2 and C-3 show a Quality Counts camera installed at La Jolla Boulevard.

Exhibit C-2 Video Camera Box installed on Palm Tree at La Jolla Boulevard

Exhibit C-3 Close-up of Video Camera Box installation at La Jolla Boulevard

Following field data collection, Quality Counts performed a 12-hour volume count at near the middle of the corridor (between Bird Rock Avenue and Forward Street). The research team then identified time periods of interest and Quality Counts performed a turning movement count for these times. Quality Counts also provided all video footage to the research team on a hard drive.

Overall, research team considered the use of Quality Counts to be highly successful. Video was captured continuously during the study period, even when it was raining, and researchers had increased time to devote to other aspects of data collection. The cost of the services provided by Quality Counts was comparable to the cost of an additional researcher travelling to the site with cameras, staying for the duration of the visit, and then performing the turning movement counts.

C.1.2. TRAVEL TIME (GPS AND BLUETOOTH) DATA COLLECTION PROCEDURE

The first method to record travel times along the La Jolla Blvd roundabout corridor was to use BlueTooth units that sample a portion of the vehicles that pass through the corridor. Two of these BlueTooth units were set up at either end of the corridor, one was set up three blocks east of roundabout 3, and one was set up internally between roundabouts 3 and 4 (Exhibit C-1). Using these data the team was able to study the travel times along the entire corridor as well as in between the roundabouts themselves and left turns at roundabout 3. Although this method does not record the travel time for every vehicle passing through the system, the team was able to record an acceptable number of observations given the volume of traffic passing through the corridor. Exhibits

C-4 and C-5 display the number of detections at each station and segment, respectively.

Exhibit C-4 Number of Bluetooth Detections by Station

Station	Detections
North	3479
South	2957
MidBlock	3310
East	329

Exhibit C-5 Number of Bluetooth Detections by Segment

Segment	Detections
North to South	719
South to North	708
North to East	25
East to South	14

The travel time through the corridor was also measured using vehicle-mounted GPS units. A total of six routes were used to conduct the GPS travel time study (see Exhibit C-6):

1. Northbound through the entire corridor;
2. Southbound through the entire corridor;
3. Starting from east of roundabout 3, then turning left through the roundabout and proceeding to the south end;
4. Starting from south of roundabout 1, then turning left through roundabout 4;
5. Starting from west of roundabout 4, then turning left through the roundabout and proceeding to the north end; and
6. Starting from north of roundabout 5, then turning left through roundabout 3.

The last four routes were used to capture left turns through the two roundabouts that the team believed would be most representative.

Exhibit C-6 La Jolla Boulevard GPS Travel Time Routes

Image is oriented with north to the left

C.1.3. SPOT SPEED DATA COLLECTION PROCEDURE

The team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at the northernmost and southernmost roundabouts using a laser speed gun. These speed profiles will primarily obtained for the purpose of calibrating the VISSIM model of the roundabout corridor, but they also provide an indication of the safety and performance of the roundabouts. Finally, the speeds provide a more realistic estimation of operating speeds at the roundabouts than the GPS travel time runs. A total of 30 spot speed measurements were taken at each point.

C.2. DATA COLLECTION RESULTS

C.2.1. TRAFFIC COUNTS

As previously discussed, a 12-hour, bidirectional count was performed near the middle of the corridor and three 30-minute turning movement counts were conducted for each roundabout. The following sections of this technical memorandum summarize the traffic data obtained from the video and provide graphical and/or tabular representations of the various counts.

C.2.1.1. *Turning Movements*

Exhibit C-7 provides a summary of the turning movement data for the three half-hour periods.

Exhibit C-7 La Jolla Boulevard Turning Movement Counts

Roundabout #1 – La Jolla Boulevard @ Colima Street																					
App	NB					SB					EB					WB					
Time	L	T	R	U	Total	L	T	R	U	Total	L	T	R	U	Total	L	T	R	U	Total	Grand
8:45	0	143	6	2	151	5	66	0	4	75					0	12	0	10	0	22	248
9:00	0	123	2	0	125	3	86	0	2	91					0	4	0	4	0	8	224
2:15	0	106	1	1	108	2	106	0	3	111					0	1	0	4	0	5	224
2:30	0	88	1	0	89	6	139	0	3	148					0	2	0	3	0	5	242
5:00	0	106	3	1	110	3	140	0	0	143					0	4	0	3	0	7	260
5:15	0	100	3	2	105	5	165	0	2	172					0	4	0	6	0	10	287
Total	**0**	**666**	**16**	**6**	**688**	**24**	**702**	**0**	**14**	**740**	**0**	**0**	**0**	**0**	**0**	**27**	**0**	**30**	**0**	**57**	1485
Roundabout #2 – La Jolla Boulevard @ Midway Street																					
8:45	8	153	2	4	167	8	74	3	1	86	2	0	4	0	6	2	2	3	0	7	266
9:00	3	117	2	2	124	10	80	1	5	96	2	2	4	0	8	1	1	3	0	5	233
2:15	4	101	7	1	113	6	109	5	2	122	4	1	3	0	8	0	0	4	0	4	247
2:30	3	91	1	2	97	10	137	6	9	162	1	0	5	0	6	5	3	5	0	13	278
5:00	1	97	7	4	109	7	128	4	1	140	2	5	5	0	12	6	4	6	0	16	277
5:15	5	98	3	3	109	12	157	6	2	177	2	2	8	0	12	3	1	5	0	9	307
Total	**24**	**657**	**22**	**16**	**719**	**53**	**685**	**25**	**20**	**783**	**13**	**10**	**29**	**0**	**52**	**17**	**11**	**26**	**0**	**54**	1608
Roundabout #3 – La Jolla Boulevard @ Forward Street																					
8:45	6	150	2	2	160	5	82	8	17	112	4	0	2	1	7	3	5	9	0	17	296
9:00	10	119	3	1	133	4	80	8	13	105	9	0	10	1	20	6	2	6	0	14	272
2:15	6	93	2	5	106	9	117	7	11	144	3	0	3	0	6	1	3	5	0	9	265
2:30	5	95	1	3	104	9	143	8	7	167	2	1	11	0	14	2	0	6	0	8	293
5:00	10	90	1	2	103	15	131	8	9	163	7	1	8	1	17	3	2	6	0	11	294
5:15	1	104	2	2	109	5	171	4	3	183	6	4	5	0	15	1	4	4	0	9	316
Total	**38**	**651**	**11**	**15**	**715**	**47**	**724**	**43**	**60**	**874**	**31**	**6**	**39**	**3**	**79**	**16**	**16**	**36**	**0**	**68**	1736
Roundabout #4 – La Jolla Boulevard @ Bird Rock Avenue																					
8:45	5	146	5	21	177	1	89	8	2	100	6	1	2	0	9	4	1	6	0	11	297
9:00	6	122	6	13	147	2	94	0	2	98	2	0	3	0	5	3	0	7	0	10	260
2:15	3	110	2	9	124	3	133	3	1	140	4	2	3	0	9	4	0	1	0	5	278
2:30	3	100	7	6	116	9	141	7	6	163	4	0	3	0	7	1	0	2	0	3	289
5:00	3	97	3	10	113	5	133	5	7	150	5	4	4	0	13	2	1	2	0	5	281
5:15	2	117	5	8	132	10	173	3	4	190	4	0	3	0	7	2	0	4	0	6	335
Total	**22**	**692**	**28**	**67**	**809**	**30**	**763**	**26**	**22**	**841**	**25**	**7**	**18**	**0**	**50**	**16**	**2**	**22**	**0**	**40**	1740
Roundabout #5 – La Jolla Boulevard @ Camino De La Costa																					
8:45	4	146	2	1	153	3	87	6	0	96	4	1	5	0	10	4	0	29	0	33	292
9:00	2	126	2	2	132	5	95	1	0	101	4	2	1	0	7	2	1	18	0	21	261
2:15	3	108	4	0	115	13	138	8	0	159	2	2	4	0	8	0	5	16	0	21	303
2:30	3	97	0	5	105	14	150	2	0	166	2	0	4	0	6	0	3	8	0	11	288
5:00	3	100	3	3	109	13	145	5	2	165	2	2	3	0	7	3	1	16	0	20	301
5:15	1	120	1	3	125	12	182	4	0	198	2	0	3	1	6	0	2	13	0	15	344
Total	**16**	**697**	**12**	**14**	**739**	**60**	**797**	**26**	**2**	**885**	**16**	**7**	**20**	**1**	**44**	**9**	**12**	**100**	**0**	**121**	1789

App = Approach

T = Through, R = Right, L = Left, U = U-turn

N/A = Not applicable

The periods were:

- 8:45 – 9:15 a.m.
- 2:15 – 2:45 p.m.
- 5:00 – 5:30 p.m.

These time periods represent the a.m. peak, midday peak, and p.m. peak and were identified based upon the 12-hour bidirectional count (see next section). Counts were performed from video collected on Tuesday, December 13, 2011.

As shown in the Exhibit, the corridor primarily serves through traffic. The total number of vehicles on La Jolla Boulevard entering each intersection was approximately 700 to 900 for the 90 minutes which were counted. During the same 90 minutes, the highest volume side street approach had 121 vehicles and no other side street approach had more than 100 vehicles. All side streets are part of a grid street network.

Roundabout #1, the southernmost intersection, is a T-intersection and had the lowest volumes on the corridor. Of the 1485 observed entering vehicles, 1368 (92 percent) were through vehicles traveling northbound or southbound. The eastern leg had 57 entering vehicles.

Roundabout #2 had 1608 entering vehicles, 1342 (83 percent) of which were through vehicles traveling northbound or southbound. The eastern leg had 54 entering vehicles and the western leg had 52 entering vehicles

Roundabout #3 had 1736 entering vehicles, 1375 (79 percent) of which were through vehicles traveling northbound or southbound. The eastern leg had 68 entering vehicles and the western leg had 79 entering vehicles

Roundabout #4 had 1740 entering vehicles, 1455 (84 percent) of which were through vehicles traveling northbound or southbound. The eastern leg had 40 entering vehicles and the western leg had 50 entering vehicles

Roundabout #5 had 1789 entering vehicles, 1494 (84 percent) of which were through vehicles traveling northbound or southbound. The eastern leg had 121 entering vehicles and the western leg had 44 entering vehicles.

C.2.1.2. *Lane Utilization*

All approaches to all roundabouts at this site are single-lane, so no lane utilization analysis was conducted.

C.2.1.3. *Entry/Exit Counts*

To get an understanding of traffic volumes on the La Jolla Boulevard corridor throughout the day and to identify the times to conduct the turning movement counts, a 12-hour, bi-directional count was performed from video footage collected between Roundabout #3 and Roundabout #4 between 7 a.m. and 7 p.m. on Tuesday December 12, 2011.

Exhibit C-8 shows the volume counts by 15-minute period, and Exhibit C-9 displays the counts graphically.

Exhibit C-8 Corridor Volumes in 15 Minute Bins

	NB	SB	Interval Totals
7:00 AM	136	56	192
7:15 AM	110	86	196
7:30 AM	117	69	186
7:45 AM	157	59	216
8:00 AM	151	88	239
8:15 AM	169	78	247
8:30 AM	144	80	224
8:45 AM	173	107	280
9:00 AM	142	101	243
9:15 AM	144	113	257
9:30 AM	130	87	217
9:45 AM	139	106	245
10:00 AM	113	123	236
10:15 AM	108	86	194
10:30 AM	120	104	224
10:45 AM	107	93	200
11:00 AM	127	145	272
11:15 AM	114	133	247
11:30 AM	122	121	243
11:45 AM	128	107	235
12:00 PM	106	158	264
12:15 PM	116	123	239
12:30 PM	102	114	216
12:45 PM	114	120	234
1:00 PM	104	125	229
1:15 PM	96	107	203
1:30 PM	99	121	220
1:45 PM	128	107	235
2:00 PM	130	126	256
2:15 PM	116	147	263
2:30 PM	109	165	274
2:45 PM	106	125	231
3:00 PM	104	160	264
3:15 PM	99	143	242
3:30 PM	89	162	251
3:45 PM	111	131	242
4:00 PM	113	136	249
4:15 PM	113	157	270
4:30 PM	104	159	263
4:45 PM	131	141	272
5:00 PM	117	167	284
5:15 PM	114	180	294
5:30 PM	86	156	242
5:45 PM	113	151	264
6:00 PM	96	130	226
6:15 PM	89	127	216
6:30 PM	75	108	183
6:45 PM	89	116	205
Totals	**5620**	**5804**	**11424**

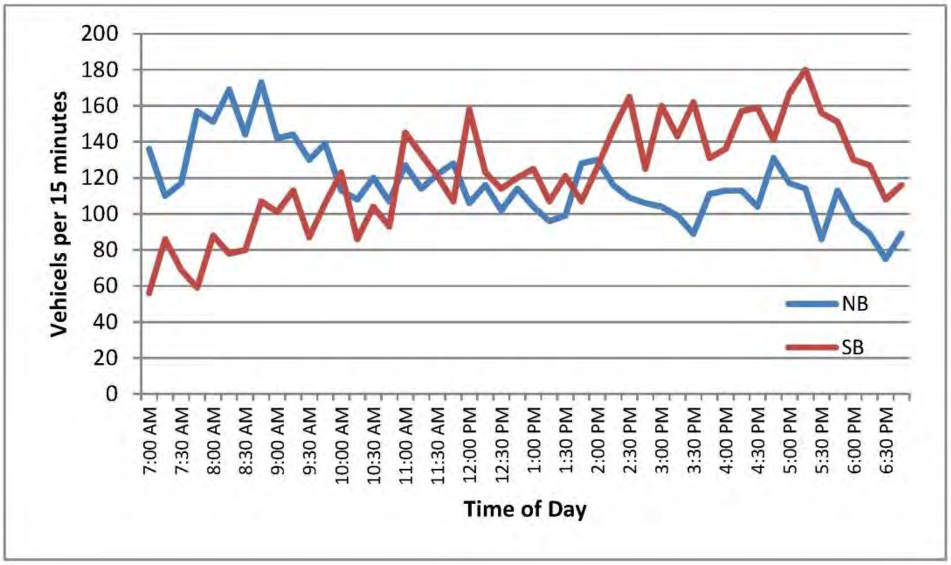


Exhibit C-9 La Jolla Boulevard Volume Profile, Graphical

The data in Exhibits C-8 and C-9 indicates that northbound volumes are highest during the weekday a.m. peak and gradually decrease throughout the day, whereas southbound volumes gradually increase throughout the day and are highest during the weekday p.m. peak. The weekday p.m. peak is relatively flat, as is common in areas with a mix of retail and residential development.

C.2.2. TRAVEL TIME

Travel time was recorded using both Bluetooth readers and GPS units in vehicles conducting floating car travel time runs

C.2.2.1. *Bluetooth*

Exhibits C-10 and C-11 provide a sample of the Bluetooth data taken along the northbound (right) and southbound (left) directions. The figure indicates that most of the Bluetooth data remained fairly consistent during daylight hours.

Exhibit C-10 Southbound Hour Bluetooth Travel Time Sample

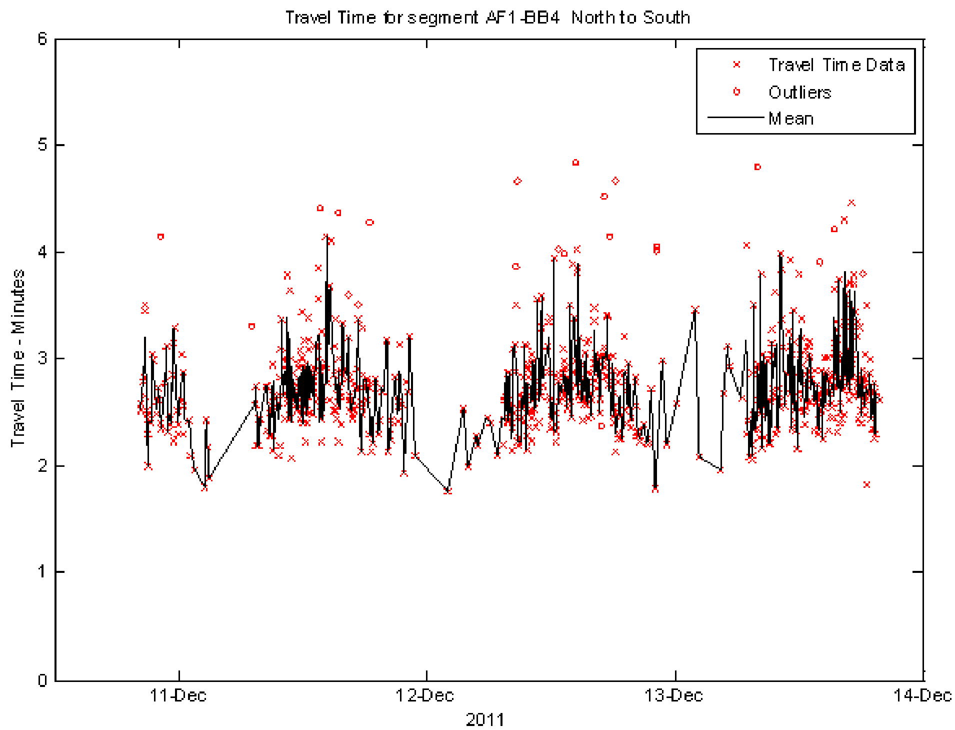
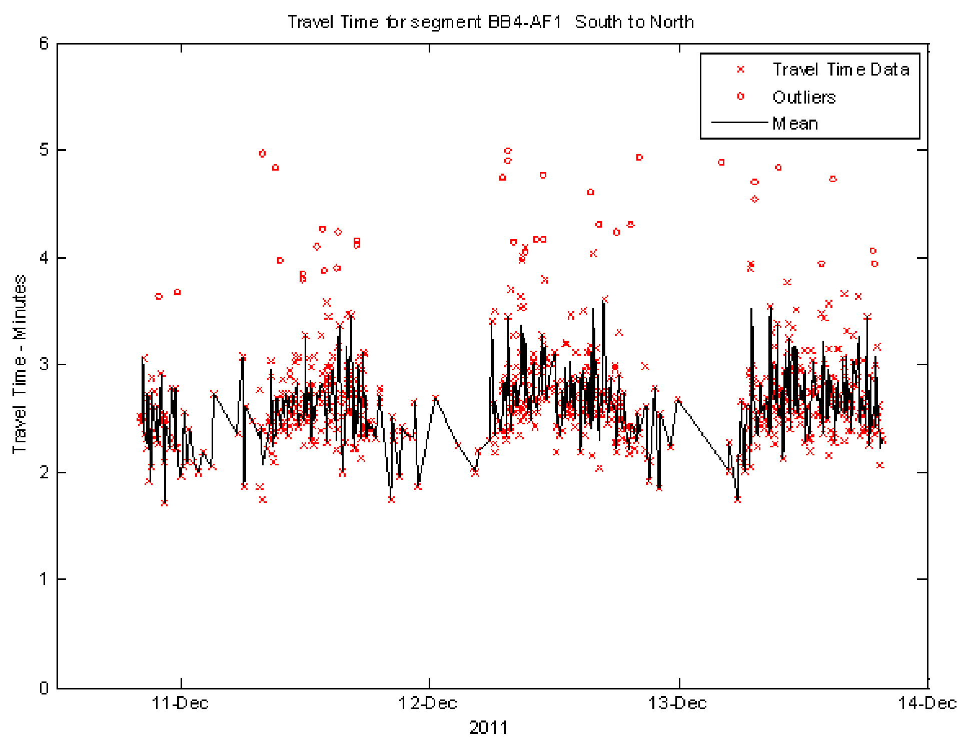


Exhibit C-11 Northbound Bluetooth Travel Time Sample



The travel time data were further processed to produce summary statistics and the level of service for the corridor during each hour of the day. Exhibits C-12 and C-13 display this summary. The average, minimum, and maximum travel

times recorded during each hour (aggregated over the 72-hour period) are recorded in the table, as well as the average speed and number of observations. The peak hours were identified as 8:00–9:00 a.m. and 5:00–6:00 p.m. and were further broken down into 15-minute intervals. Finally, the Level of Service (LOS) during each period was calculated based upon the Urban Streets procedure in the 2010 Highway Capacity Manual. In the Urban Streets procedure, LOS is determined based upon the ratio of travel speed to base free-flow speed. The specific LOS thresholds are provided in Exhibit 16-4 and 17-2. Bluetooth data provided measurement of these two speeds, enabling the research team to determine LOS by simply computing the ratio of the speeds rather than estimating them with the HCM's calculations. Free flow speed was assumed to be equal to the highest average speed observed during any hour of data collection. The results indicate that the corridor was generally uncongested.

Exhibit C-12 Northbound Bluetooth Travel Time and LOS

Start Hour	Average TT	Average Speed	S.D. TT	Min TT	Max TT	LOS	Sample Size
7:00	2.61	20.11	0.52	2.06	4.792	A	32
8:00	2.52	20.86	0.28	2.15	2.933	A	8
8:15	3.04	17.30	0.63	2.17	3.858	A	7
8:30	2.84	18.52	0.71	2.27	4.667	A	11
8:45	2.48	21.24	0.23	2.19	2.983	A	11
9:00	2.69	19.53	0.34	2.09	3.625	A	47
10:00	2.84	18.53	0.42	2.07	3.983	A	51
11:00	2.81	18.70	0.39	2.17	3.925	A	50
12:00	2.80	18.75	0.35	2.23	4.025	A	58
13:00	2.86	18.42	0.46	2.23	4.417	A	50
14:00	2.99	17.57	0.55	2.25	4.833	A	46
15:00	2.84	18.50	0.41	2.23	4.367	A	63
16:00	2.92	18.02	0.38	2.38	4.3	A	57
17:00	3.16	16.63	0.58	2.56	4.517	B	15
17:15	3.24	16.23	0.38	2.73	3.783	B	13
17:30	2.88	18.28	0.48	2.13	4.142	A	15
17:45	2.71	19.39	0.30	2.44	3.292	A	9
18:00	2.73	19.26	0.49	1.83	4.658	A	48
Night	2.58	20.40	0.44	1.77	4.142	A	128

Exhibit C-13 Southbound Bluetooth Travel Time and LOS

Start Hour	Average TT	Average Speed	S.D. TT	Min TT	Max TT	LOS	Sample Size
7:00	2.91	18.09	0.81	1.75	5.00	A	44
8:00	2.73	19.27	0.27	2.45	3.28	A	8
8:15	2.63	20.01	0.21	2.22	2.99	A	11
8:30	2.81	18.70	0.46	2.34	3.63	A	17
8:45	2.83	18.61	0.55	2.09	4.01	A	22
9:00	2.84	18.54	0.53	2.14	4.83	A	58
10:00	2.95	17.84	0.51	2.34	4.78	A	45
11:00	2.80	18.76	0.36	2.26	3.85	A	40
12:00	2.63	20.02	0.27	2.18	3.20	A	50
13:00	2.90	18.15	0.50	2.37	4.27	A	40
14:00	2.82	18.66	0.44	2.16	4.73	A	56
15:00	2.86	18.38	0.48	2.01	4.61	A	52
16:00	2.86	18.36	0.48	2.04	4.30	A	47
17:00	2.90	18.12	0.39	2.46	3.63	A	7
17:15	2.56	20.54	0.25	2.13	2.96	A	12
17:30	2.62	20.11	0.25	2.28	3.13	A	20
17:45	2.68	19.64	0.55	2.19	4.24	A	12
18:00	2.67	19.68	0.46	2.26	4.07	A	31
Night	2.52	20.87	0.55	1.72	4.93	A	136

C.2.2.2. *GPS Travel Time Runs*

Space-time trajectories and speed profiles for each of the six routes are located at the end of this appendix. Each diagram displays every travel time run that was conducted (including AM, PM, and off-peak runs).

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening." A vehicle stop is denoted by a purple dot. The vertical lines in the diagrams correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor, therefore, is an indication of the variability in the observed data. The distance along the x-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

The team isolated the free-flow travel time runs from the rest of the dataset. Exhibit C-14 summarizes these free-flow runs. Exhibit C-15 presents more

detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in mph, and all travel times are displayed in minutes. Using the free-flow data, the table shows HCM Urban Streets LOS and average roundabout LOS. The team determined Urban Street LOS for the GPS data the same way that they determined it for the Bluetooth data. Roundabout LOS was based upon average control delay in seconds and the LOS thresholds in the HCM2010.

Exhibit C-14 Free-flow Travel Time Runs

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)			
		Mean	Std Dev	Max	Min	Mean	Std Dev	Max	Min
1. South to North	10	21.4	0.6	22.4	20.5	0.8	0.0	0.9	0.8
2. North to South	6	19.7	1.6	21.4	17.2	2.6	0.2	3.0	2.4
3. East-to-South	9	23.7	0.5	24.6	23.0	2.3	0.0	2.3	2.2
4. South-to-West	11	22.8	0.6	24.1	22.0	2.3	0.1	2.4	2.2
5. West-to-North	10	19.8	1.7	22.7	17.9	2.0	0.2	2.2	1.7
6. North-to-East	10	21.6	1.4	23.9	19.2	1.1	0.1	1.3	1.0
Total	**56**	**21.6**	**1.8**	**24.6**	**17.2**	**1.8**	**0.7**	**3.0**	**0.8**

C.2.3. DELAY

Exhibit C-17 displays the impeded delay (equal to the difference between the average travel time and the unimpeded travel time) and total delay (equal to the difference between the average travel time and the free flow travel time) for each approach route. Each approach was split into the upstream and downstream segments, where the upstream segment extends from the yield bar to the upstream midblock point, and the downstream segment extends from the yield bar to the downstream midblock point.

Exhibit C-17 Summary of Field Travel Time and Delay

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT1-North Approach (Upstream)	**7.9**	**283**	**25.0**	**7.4**	**7.5**	**0.1**	**0.4**	**0.5**
AM	7.7	283	25.0	7.4	7.5	0.1	0.2	0.3
Off	8.1	283	25.0	7.4	7.5	0.1	0.6	0.6
PM	7.9	283	25.0	7.4	7.5	0.1	0.4	0.5
RBT1-North Approach (Downstream)	**14.3**	**585**	**34.0**	**11.7**	**13.5**	**1.8**	**0.8**	**2.5**
AM	14.0	585	34.0	11.7	13.5	1.8	0.5	2.3
Off	14.3	585	34.0	11.7	13.5	1.8	0.8	2.6
PM	14.4	585	34.0	11.7	13.5	1.8	0.9	2.7
RBT1-South Approach (Upstream)	**8.9**	**349**	**30.0**	**7.9**	**8.5**	**0.6**	**0.4**	**1.0**
AM	8.9	349	30.0	7.9	8.5	0.6	0.4	1.0
Off	8.9	349	30.0	7.9	8.5	0.6	0.4	1.0
PM	8.9	349	30.0	7.9	8.5	0.6	0.4	0.9
RBT1-South Approach (Downstream)	**11.4**	**384**	**25.0**	**10.2**	**11.0**	**0.8**	**0.4**	**1.2**
AM	11.3	384	25.0	10.2	11.0	0.8	0.3	1.1
Off	11.4	384	25.0	10.2	11.0	0.8	0.4	1.2
PM	11.5	384	25.0	10.2	11.0	0.8	0.5	1.4
RBT2-North Approach (Upstream)	**9.9**	**281**	**25.0**	**7.7**	**8.4**	**0.7**	**1.5**	**2.2**
AM	8.4	281	25.0	7.7	8.4	0.7	0.0	0.8
Off	10.5	281	25.0	7.7	8.4	0.7	2.1	2.8
PM	9.9	281	25.0	7.7	8.4	0.7	1.5	2.3
RBT2-North Approach (Downstream)	**12.4**	**410**	**25.0**	**10.6**	**11.0**	**0.4**	**1.4**	**1.8**
AM	11.5	410	25.0	10.6	11.0	0.4	0.5	0.9
Off	12.4	410	25.0	10.6	11.0	0.4	1.4	1.8
PM	13.1	410	25.0	10.6	11.0	0.4	2.1	2.5

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT2-South Approach (Upstream)	**10.3**	**285**	**25.0**	**7.8**	**8.0**	**0.2**	**2.3**	**2.5**
AM	9.6	285	25.0	7.8	8.0	0.2	1.6	1.9
Off	10.2	285	25.0	7.8	8.0	0.2	2.2	2.4
PM	11.2	285	25.0	7.8	8.0	0.2	3.2	3.5
RBT2-South Approach (Downstream)	**11.0**	**391**	**25.0**	**10.0**	**10.5**	**0.5**	**0.5**	**1.1**
AM	11.2	391	25.0	10.0	10.5	0.5	0.7	1.2
Off	10.7	391	25.0	10.0	10.5	0.5	0.2	0.7
PM	11.7	391	25.0	10.0	10.5	0.5	1.2	1.7
RBT3-North Approach (Upstream)	**11.9**	**336**	**25.0**	**9.2**	**10.0**	**0.8**	**1.9**	**2.7**
AM	10.5	336	25.0	9.2	10.0	0.8	0.5	1.3
Off	12.2	336	25.0	9.2	10.0	0.8	2.2	3.0
PM	12.6	336	25.0	9.2	10.0	0.8	2.6	3.5
RBT3-North Approach (Downstream)	**10.5**	**366**	**25.0**	**9.4**	**9.5**	**0.1**	**1.0**	**1.1**
AM	9.7	366	25.0	9.4	9.5	0.1	0.2	0.3
Off	10.9	366	25.0	9.4	9.5	0.1	1.4	1.5
PM	10.6	366	25.0	9.4	9.5	0.1	1.1	1.1
RBT3-South Approach (Upstream)	**8.9**	**267**	**25.0**	**7.3**	**7.5**	**0.2**	**1.4**	**1.6**
AM	9.4	267	25.0	7.3	7.5	0.2	1.9	2.1
Off	9.1	267	25.0	7.3	7.5	0.2	1.6	1.9
PM	7.9	267	25.0	7.3	7.5	0.2	0.4	0.6
RBT3-South Approach (Downstream)	**12.8**	**387**	**25.0**	**10.6**	**11.0**	**0.4**	**1.8**	**2.2**
AM	13.3	387	25.0	10.6	11.0	0.4	2.3	2.7
Off	13.1	387	25.0	10.6	11.0	0.4	2.1	2.5
PM	11.5	387	25.0	10.6	11.0	0.4	0.5	0.9

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT4-North Approach (Upstream)	**11.5**	**362**	**25.0**	**9.7**	**10.0**	**0.3**	**1.5**	**1.8**
AM	11.4	362	25.0	9.7	10.0	0.3	1.4	1.6
Off	11.7	362	25.0	9.7	10.0	0.3	1.7	1.9
PM	11.4	362	25.0	9.7	10.0	0.3	1.4	1.7
RBT4-North Approach (Downstream)	**14.5**	**429**	**25.0**	**10.4**	**10.5**	**0.1**	**4.0**	**4.1**
AM	10.8	429	25.0	10.4	10.5	0.1	0.3	0.5
Off	14.8	429	25.0	10.4	10.5	0.1	4.3	4.5
PM	17.0	429	25.0	10.4	10.5	0.1	6.5	6.6
RBT4-South Approach (Upstream)	**11.1**	**346**	**25.0**	**9.4**	**10.0**	**0.6**	**1.1**	**1.7**
AM	10.3	346	25.0	9.4	10.0	0.6	0.3	0.8
Off	11.6	346	25.0	9.4	10.0	0.6	1.6	2.1
PM	10.9	346	25.0	9.4	10.0	0.6	0.9	1.4
RBT4-South Approach (Downstream)	**12.4**	**452**	**25.0**	**11.7**	**11.8**	**0.1**	**0.6**	**0.7**
AM	12.1	452	25.0	11.7	11.8	0.1	0.3	0.4
Off	12.6	452	25.0	11.7	11.8	0.1	0.8	0.9
PM	12.4	452	25.0	11.7	11.8	0.1	0.6	0.7
RBT5-North Approach (Upstream)	**15.0**	**675**	**34.0**	**13.5**	**14.0**	**0.5**	**1.0**	**1.5**
AM	14.0	675	34.0	13.5	14.0	0.5	0.0	0.5
Off	14.6	675	34.0	13.5	14.0	0.5	0.6	1.0
PM	16.9	675	34.0	13.5	14.0	0.5	2.9	3.4
RBT5-North Approach (Downstream)	**14.1**	**469**	**25.0**	**12.8**	**13.0**	**0.2**	**1.1**	**1.3**
AM	13.3	469	25.0	12.8	13.0	0.2	0.3	0.5
Off	14.0	469	25.0	12.8	13.0	0.2	1.0	1.2
PM	15.2	469	25.0	12.8	13.0	0.2	2.2	2.4

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT5-South Approach (Upstream)	**12.2**	**389**	**25.0**	**10.6**	**11.0**	**0.4**	**1.2**	**1.6**
AM	11.7	389	25.0	10.6	11.0	0.4	0.7	1.1
Off	12.6	389	25.0	10.6	11.0	0.4	1.6	1.9
PM	11.9	389	25.0	10.6	11.0	0.4	0.9	1.3
RBT5-South Approach (Downstream)	**14.6**	**600**	**30.0**	**13.6**	**14.0**	**0.4**	**0.6**	**1.0**
AM	15.1	600	30.0	13.6	14.0	0.4	1.1	1.5
Off	14.6	600	30.0	13.6	14.0	0.4	0.6	1.0
PM	14.3	600	30.0	13.6	14.0	0.4	0.3	0.7

C.2.4. SPOT SPEEDS

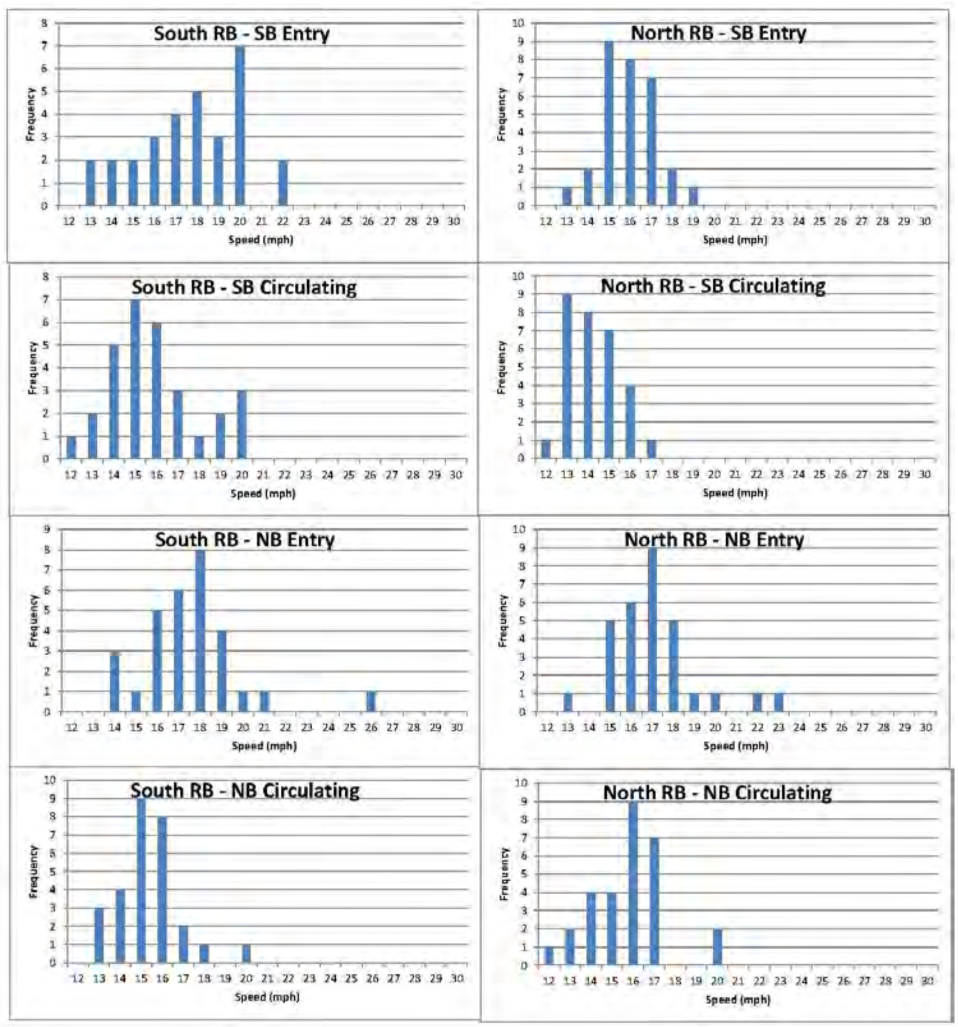
Spot speeds collected by the research team with a laser gun the endpoint roundabouts are shown below in Exhibit C-17. Thirty samples were recorded at each location.

Exhibit C-17 Spot Speeds from Laser Gun

RBT #	1 (South)				2 (North)			
Location	SB – Entry	SB – Circ	NB – Entry	NB - Circ	SB – Entry	SB – Circ	NB – Entry	NB - Circ
Mean Speed (mph)	17.7	15.9	17.5	15.1	15.9	14.2	17.0	15.4
St.Dev. (mph)	2.5	2.1	2.3	1.8	1.3	1.2	2.0	2.5

The speed measurements were also analyzed using histogram frequency distributions; all eight are displayed in Exhibit C-18. In this case the horizontal scales are kept the same to show the skew, but the vertical scales vary.

Exhibit C-18 Spot Speed Histogram



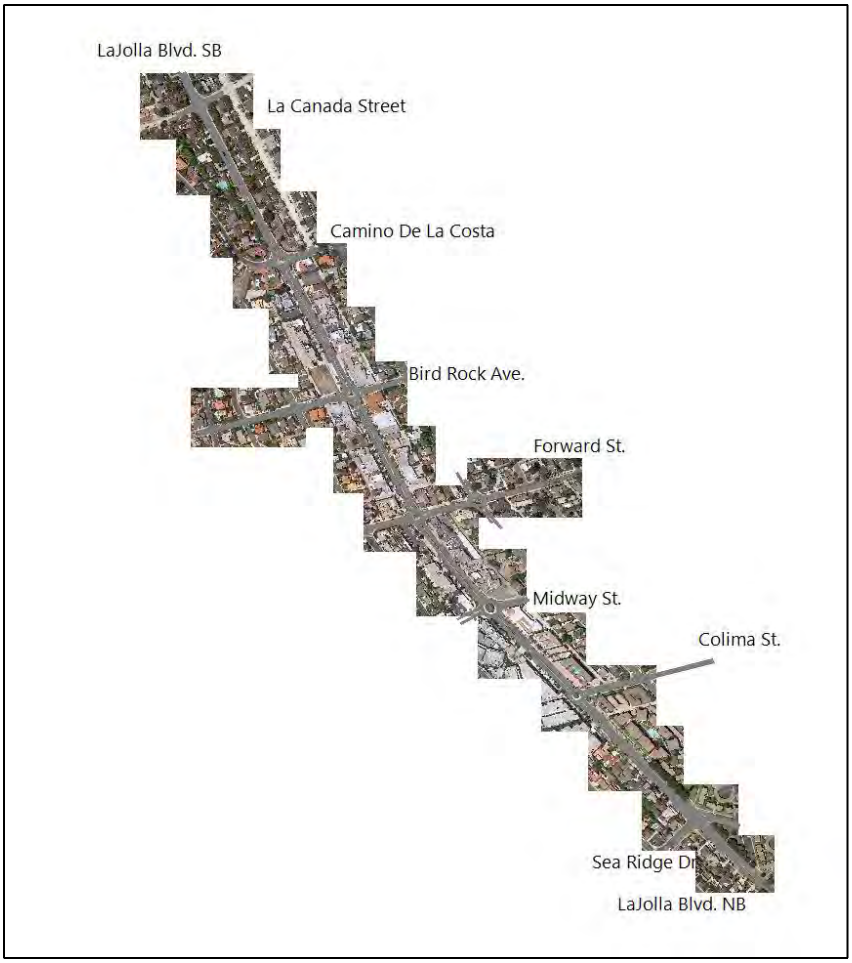
C.3. SIMULATION MODELING

The team modeled the La Jolla Boulevard corridor in the VISSIM microsimulation tool. The main objectives of the modeling were to 1) compare

the model results with field observations, and 2) compare the roundabout corridor performance with an equivalent signalized corridor. Details on the VISSIM modeling approach are described in Appendix C.

Exhibit C-19 shows a screenshot of the base model for the La Jolla corridor as coded in VISSIM. The model included the five subject roundabouts and extended through the adjacent signals, although signal operations at these intersections were not modeled. The model also included the adjacent roundabouts on the left-turn routes along Bird Rock Avenue and Forward Street.

Exhibit C-19 Screenshot of LaJolla Blvd. VISSIM Base-Model



The performance assessment in VISSIM included route-based measures (travel time and route delay), and node-based measures (control delay and other measures). Nodes were numbered from 1 to 5 going north to south, with the Camino De La Costa roundabout being node 1 and the Colima Street roundabout being node 5.

The route evaluation was performed for the north-to-south and south-to-north through routes, as well as four left-turn routes. The turnaround point for the north-to-east and east-to-south routes was at the eastern approach of Colima Street (Node 5); for the south-to-west and west-to-north routes the turnaround point was on the western approach of Bird Rock Avenue (Node 2).

Exhibit C-20 shows the average and standard deviation of travel times for all six routes for the weekday a.m. peak, weekday p.m. peak, and a weekday midday off-peak period. All results represent the average of 10 simulation runs.

Exhibit C-20 La Jolla Route Travel Times (sec)

Route		AM Peak		Midday		PM Peak	
		Mean	SD	Mean	SD	Mean	SD
Through Routes	North - South	156.7	1.0	159.8	0.8	163.7	1.1
	South - North	170.3	2.2	164.8	1.5	167.4	1.8
Left Turns	North - East	159.5	12.5	162.6	2.8	165.5	2.6
	East - South	60.3	2.0	58.0	5.5	58.4	1.7
	South - West	128.0	1.6	123.6	1.4	125.6	1.8
	West - North	75.0	8.1	75.1	5.5	77.1	12.4

The results in Exhibit C-20 show very similar travel times across time periods, generally suggesting low travel time variability across the day. A comparison of the two through routes suggests longer travel times in the south-to-north movement for all time periods. No patterns are apparent for the left-turn routes, other than differences attributable to different route lengths.

Exhibit C-21 offers a closer look at the variability by separating travel time from vehicle control delay experienced over the route. It is emphasized here that VISSIM does not include geometric delay (for example at roundabout entry) in its delay estimations.

Exhibit C-21 La Jolla Route Delay

Route		AM Peak		Midday		PM Peak	
		Mean	SD	Mean	SD	Mean	SD
Through Routes	North - South	12.0	0.8	15.5	0.8	19.5	0.9
	South - North	25.8	2.1	20.6	1.1	23.3	1.7
Left Turns	North - East	17.2	2.3	19.4	2.1	23.3	2.8
	East - South	5.9	1.8	3.1	1.0	3.7	1.4
	South - West	17.3	1.7	13.1	1.5	15.1	1.6
	West - North	8.4	1.3	8.6	2.6	10.6	2.9

The results in Exhibit C-21 show route delays above 20 seconds for the south-to-north route, and in the 10 to 20 second range for the north-to-south routes. Distributed across five roundabout nodes, this delay is considered to be quite low. Route delays for two of the left turns (north-to-east, and south-to-west) similarly in the 15 to 25 second range, with delays below 10 seconds for the shorter east-to-south and west-to-north routes. Exhibit C-22 separates the incurred vehicular delay for each of the five nodes. A detailed look at node movement delays is presented in a later section as a direct comparison to signalized intersection model results.

Exhibit C-22 La Jolla Node Delay

Node	AM Peak		Midday		PM Peak	
	#Veh.	Delay	#Veh.	Delay	#Veh.	Delay
1	255	4.2	270	4.4	305	5.3
2	258	3.4	261	3.1	299	3.9
3	268	5.6	264	4.0	289	4.8
4	268	5.6	249	3.4	286	4.2
5	228	3.8	215	2.8	255	3.3

The exhibit confirms the results from the route evaluation, showing very low average delays at all four roundabout nodes. Comparing the node delay to the HCM 2010 Levels of Service (LOS) categories for roundabouts, all of the roundabouts operate at LOS A (average delay less than 10 seconds).

C.3.1. COMPARISON TO FIELD DATA

This section compares the modeled roundabout corridor performance to the field-measured GPS travel time data and route delay as estimated from the GPS routes. These results correspond to the calibrated VISSIM model, although it should be emphasized that no iterative re-calibration was performed to achieve further improved performance. In other words, the team used field-measured volumes and speed observations to calibrate initial model inputs, but did not perform any additional calibration to improve the match between model and field data. This approach was deliberate, as the team wanted to avoid over-fitting a model to a specific observed roundabout corridor. Instead, the team believes that the results achieved are quite generalizable to other roundabout corridors, only requiring custom speed and volume observations as input. The team will be able to refine modeling guidance to include other simulation settings (for example entry gap acceptance), but for now all other parameters were left at the VISSIM defaults.

In the first comparison, Exhibit C-23 shows the comparison of route travel times. The data are presented as the absolute and percent difference of VISSIM roundabout performance minus GPS field data. A positive number therefore corresponds to VISSIM predicting higher travel times than the field; a negative number corresponds to a lower simulation estimates than the field observations. The actual GPS travel time is not shown, but can be estimated by combining results from this table with VISSIM travel time results in Exhibit C-20.

Route		AM Peak		Midday		PM Peak	
		Delta	% Diff	Delta	% Diff	Delta	% Diff
Through Routes	North - South	12.7	8.1%	-8.2	-5.1%	1.7	1.1%
	South - North	8.3	4.9%	2.8	1.7%	5.4	3.2%
Left Turns	North - East	-2.5	-1.6%	-5.4	-3.3%	-26.5	-16.0%
	East - South	0.3	0.5%	-2.0	-3.5%	4.4	7.6%
	South - West	2.0	1.5%	-2.4	-2.0%	-0.4	-0.3%
	West - North	-3.0	-4.0%	-2.9	-3.9%	5.1	6.6%

Exhibit C-23 Travel Time Comparison: VISSIM Minus GPS Field Data

The travel time comparison results show a very good match between VISSIM results to field-estimated travel times. For all but one of the route pairs, the percent difference is less than 10%, with only the north-east route in the PM peak showing a 16% difference. It should be noted that due to overall low delay at the roundabout nodes, it is expected to get a good calibration match as is shown above. The results give the team confidence that the speed inputs for these routes were calibrated well to match field data. However, care needs to be taken when using the underlying base model in close-to-capacity volume testing, as these conditions have not been directly calibrated from the field.

Exhibit C-24 shows the corresponding comparison for route control delay between VISSIM and the GPS field data.

Exhibit C-24 Route Delay Comparison: VISSIM Minus GPS Field Data

Route		AM Peak		Midday		PM Peak	
		Delta	% Diff	Delta	% Diff	Delta	% Diff
Through Routes	North - South	3.8	31.6%	-12.3	-79.8%	-5.5	-28.4%
	South - North	4.6	17.7%	-1.1	-5.5%	1.3	5.5%
Left-Turns	North - East	14.1	82.0%	8.0	41.4%	-11.8	-50.8%
	East - South	-3.3	-55.5%	-7.6	-244.6%	-1.3	-36.5%
	South - West	10.3	59.6%	5.6	42.6%	10.4	69.0%
	West - North	-3.2	-37.3%	-3.9	-45.9%	3.9	36.5%

The exhibit shows that VISSIM was able to match route delay reasonably well in terms of absolute difference, but shows some high percent differences, especially for routes with low base delay. For most of the longer routes (north-south, south-north, north-east, and south-west), VISSIM tended to overestimate the delay relative to the field (positive difference). Interestingly, for the shorter east-to-south and west-to-north routes, VISSIM underestimated the route delay. However, due to the relatively low base delay on these routes, not too much weight should be placed on the percent differences. It is emphasized here that there is a difference in the delay definition used in GPS analysis (route travel time versus free-flow travel time) versus VISSIM (actual speed versus desired speed, integrated over the route, and not accounting for geometric delay). The team will further investigate these delay definitions to assure consistency in reporting moving forward.

C.3.2. EQUIVILENT SIGNALIZED CORRIDOR COMPARISON

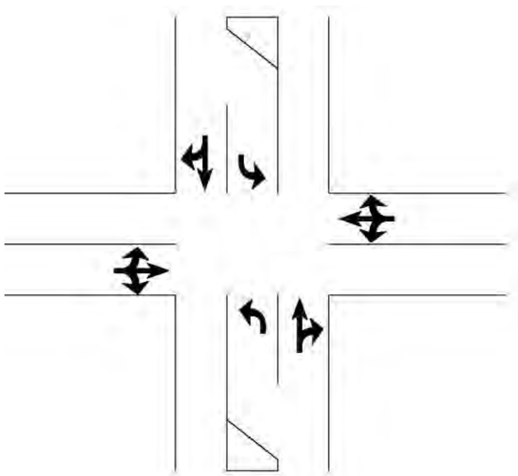
In this section, the performance of the roundabout corridors is compared to the performance of equivalent signalized corridors. The discussion initially describes how the comparison corridor was developed, followed by the modeling results.

C.3.2.1. *Developing Signalized Alternatives*

The research team developed lane configurations and traffic signal timings for a signalized equivalent to the La Jolla Boulevard roundabout corridor based on traffic volumes, functional classification, the surrounding road network, surrounding land uses, and the design of the roadway prior to the installation of roundabouts. Synchro software was used to assess lane configurations and develop timing plans.

The signalized La Jolla Boulevard corridor developed by the research team is a two-lane, divided roadway. Every intersection has left turn pockets on La Jolla Boulevard and no turn lanes on the side street. This design represents a signalized version of the road diet that was implemented by the City of San Diego as part of the roundabout installation. The intersection design is depicted below in Exhibit C-25.

Exhibit C-25 Design of Signalized and Stop-controlled Intersections on La Jolla Boulevard



Side-street volumes on La Jolla Boulevard for the time periods in which turning movement counts were conducted do not meet the MUTCD's peak hour signal warrant. However, it is possible that some intersections may meet other signal warrants. Therefore, the research team largely deferred to intersection controls which existed prior to the installation of roundabouts. The intersections at Roundabout #1 (Colima Street), Roundabout #2 (Midway Street), and Roundabout #5 (Camino De La Costa) were previously TWSC and modeled by the team as TWSC. Roundabout #4 (Bird Rock Avenue) was previously signalized and modeled by the team as a signal. Roundabout #3 (Forward Street) was previously AWSC, but with the road diet this intersection did not operate acceptably. The team chose to model Roundabout #3 as a signal.

The two signalized intersections operate with fixed time control. This method of control provides pedestrians with a protected crossing of La Jolla Boulevard each cycle, even when vehicles are not present on the side street. This is consistent

with the urban character of the corridor and the road diet. Each signal has two phases. The cycle length is 70 seconds in the weekday a.m. peak and midday time periods and 80 seconds in the weekday p.m. peak time period.

C.3.2.2. *Signals and Roundabouts Comparison*

The performance of the roundabout and partially signalized corridors is presented in terms of route travel time, route delay, and node delay performance. The route travel time results are shown in Exhibit C-26. The exhibit shows the absolute and percent difference of subtracting signalized performance from roundabout performance. A positive number therefore corresponds to higher travel times for the roundabouts; a negative number corresponds to lower travel times for roundabouts.

Exhibit C-26 Travel Time Comparison: Roundabouts Minus Signals

Route		AM Peak		Midday		PM Peak	
		Delta	% Diff	Delta	% Diff	Delta	% Diff
Through Routes	North - South	43.4	27.7%	43.4	27.1%	44.0	26.9%
	South - North	52.1	30.6%	48.3	29.3%	50.7	30.3%
Left-Turns	North - East	44.3	27.8%	45.7	28.1%	46.3	28.0%
	East - South	-85.2	-141.4%	-92.4	-159.4%	-107.3	-183.7%
	South - West	32.9	25.7%	27.3	22.1%	25.9	20.7%
	West - North	10.0	13.3%	9.3	12.4%	9.4	12.2%

The results show that the signalized corridor results in approximately 30% lower travel times for the signalized corridors compared to the roundabouts. This is explained by higher design speeds for the signals, which reduce the overall travel time. For the long left-turn routes (north-to-east and south-to-west), the travel time performance for signals is similar, with a 20% to 30% reduction relative to roundabout corridor travel times. A 12% to 13% reduction in travel time is evident for the west-to-north route for all time periods. The only route with the opposite trend is the short east-to-south route, and it is assumed that the explanation here is a high left-turn delay at the node 5 at the southern end of the corridor. This intersection was modeled with stop control at the side street, which appeared to result in high delays.

To further explore the performance differences, Exhibit C-27 shows the comparison of route control delay of roundabouts versus signals. Again, a negative number corresponds to lower delay for the roundabouts.

Route		AM Peak		Midday		PM Peak	
		Delta	% Diff	Delta	% Diff	Delta	% Diff
Through Routes	North – South	-1.7	-14.5%	-1.4	-8.8%	-0.5	-2.5%
	South – North	7.2	27.8%	3.7	17.9%	6.3	27.0%
Left-Turns	North – East	-2.8	-16.2%	-1.5	-7.6%	-0.6	-2.5%
	East – South	-27.8	-470.2%	-34.5	-1110%	-49.5	-1350%
	South – West	-2.9	-16.5%	-8.5	-64.8%	-9.6	-63.6%
	West – North	-10.3	-122.3%	-11.0	-128.4%	-10.9	-103.1%

Exhibit C-27 Route Delay Comparison: Roundabouts Minus Signals

The results in Exhibit C-27 show that the roundabouts actually outperformed signals in terms of delay for most of the routes. The exception is the south-to-north through route, which showed an 18% delay reduction in off-peak and a 27% to 28% in the peak periods. Good signal progression is likely the explanation for this difference. For the remaining routes, roundabout delays were on the order of 5 to 10 seconds lower for roundabouts, except for the previously-mentioned east-to-south route. Due to the apparent high left-turning delay, the stop-controlled side-street added between 25 and 50 seconds of delay to that route.

In the final comparison, Exhibit C-28 compares the total control delay at the node level for roundabouts and signals.

Node	AM Peak		Midday		PM Peak	
	Delta	% Diff	Delta	% Diff	Delta	% Diff
1	2.6	61.1%	-3.0	-68.9%	-8.0	-151.4%
2	-4.8	-140.4%	-1.6	-50.5%	-2.1	-54.3%
3	-4.5	-80.7%	-2.5	-62.4%	-4.1	-85.6%
4	-4.5	-80.7%	-2.2	-65.0%	-5.0	-118.7%
5	2.8	73.2%	-3.4	-121.1%	-4.5	-135.5%

Exhibit C-28 Node Delay Comparison: Roundabouts Minus Signals

The exhibit confirms an increase in node delay for signal- or stop-controlled control relative to roundabouts (negative number). The results correspond to total node delay, but it is expected that the majority of the delay is incurred by left-turning movements and side-street approaches, which are oftentimes at a disadvantage in a coordinated signal system. It is noted here that much of the route delay impact for the east-to-south route on node 5 is masked at the node level. This is explained by relatively low volumes on that side-street approach.

In an effort to investigate the node performance more, the team selected two nodes to show a movement-based comparison of delay. Exhibits C-29 and C-30 show average movement delay for nodes 3 and 5, respectively. Node 3 is the middle roundabout located at the intersection with Forward Street. This node has the highest pedestrian activity due to several coffee shops and restaurants being located in the vicinity of the intersection. Node 5 is the southern terminus roundabout at Colima Street and provides access to residential streets. It is also

node that suggested some high stop-controlled side-street delay in the route analysis.

The exhibits show the average control delay from ten simulation runs of the roundabout intersection versus signalized control. As before, a negative difference corresponds to lower delay for the roundabout. Data are shown for the PM peak hour and the midday off-peak period.

Exhibit C-31 Node 3 Movement Delay Comparison: Roundabouts Minus Signals

Movement		PM Peak				Off-Peak			
		RBTs	Sig.	Delta	% Diff	RBTs	Sig.	Delta	% Diff
East	RT	3.7	5.2	-1.5	-40%	3.6	2.7	0.9	25%
	T	3.7	2.0	1.7	46%	3.2	1.4	1.8	55%
	LT	3.9	2.6	1.2	32%	3.4	2.9	0.5	14%
North	RT	4.9	2.1	2.8	56%	3.9	1.9	2.1	53%
	T	4.6	10.4	-5.8	-126%	2.2	4.5	-2.3	-102%
	LT	7.2	8.5	-1.3	-18%	5.7	8.7	-3.0	-53%
South	RT	3.2	1.3	1.9	60%	2.1	2.1	0.0	-2%
	T	6.2	2.3	3.9	63%	5.3	2.7	2.6	49%
	LT	5.3	5.3	0.0	1%	3.7	4.0	-0.3	-7%
West	RT	5.6	10.6	-5.0	-88%	4.0	6.0	-2.0	-51%
	T	7.5	7.3	0.2	3%	4.9	4.1	0.8	17%
	LT	4.8	8.8	-4.0	-83%	4.9	5.6	-0.7	-15%
TOTAL	ALL	4.8	7.1	-2.4	-50%	4.0	6.4	-2.5	-62%

Exhibit C-32 shows generally low delays at node 3 for both roundabout and signal control. Overall, the roundabout results in 50% less delay than the signal in the PM peak, which is a volume-weighted average. However, the actual delay difference of only 2.4 seconds per vehicles is low.

Exhibit C-33 Node 5 Movement Delay Comparison: Roundabouts Minus Signals

Movement		PM Peak				Off-Peak			
		RBTs	Sig.	Delta	% Diff	RBTs	Sig.	Delta	% Diff
North	T	3.0	3.0	0.0	1%	2.4	4.5	-2.2	-91%
	LT	3.3	6.6	-3.3	-102%	2.6	3.0	-0.4	-13%
South	RT	1.1	8.4	-7.3	-681%	0.4	9.0	-8.6	-1968%
	T	3.8	7.1	-3.3	-88%	3.4	11.0	-7.7	-228%
East	RT	4.7	11.9	-7.2	-153%	3.4	6.8	-3.4	-100%
	LT	3.6	12.7	-9.1	-257%	2.9	7.7	-4.7	-160%
TOTAL	ALL	3.3	7.9	-4.5	-135%	2.8	6.2	-3.4	-121%

For Node 5, the delay benefits are greater in terms of the percent difference, on the order of 135% less delay for the roundabout at the node level. But again, the

absolute difference of only 4.5 seconds likely has little practical impact. Signalized intersection delays are highest for the east approach in the weekday p.m. peak hour, which is the stop-controlled movement discussed previously.

APPENDIX C1: AERIAL IMAGERY


CAMINO DE LA COSTA
(NO SCALE)
815'
BIRD ROCK AVE
745'
LA JOLLA BLVD
FORWARD ST
640'
MIDWAY ST
665'
COLIMA ST
©2010


N
1" = 100'
BIRD ROCK AVE
LA JOLLA BLVD


N
1" = 100'
CAMINO DE LA COSTA
LA JOLLA BLVD

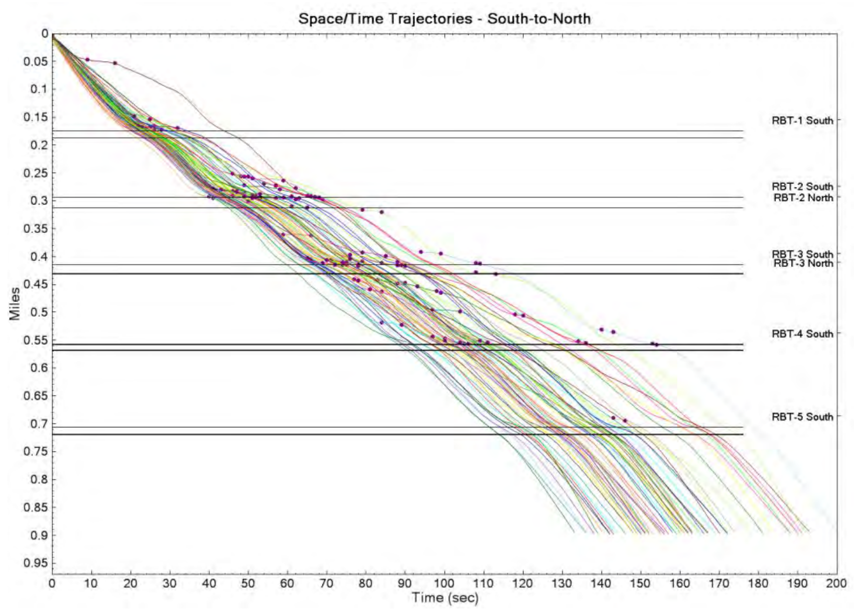

N
1" = 100'
COLIMA ST
LA JOLLA BLVD

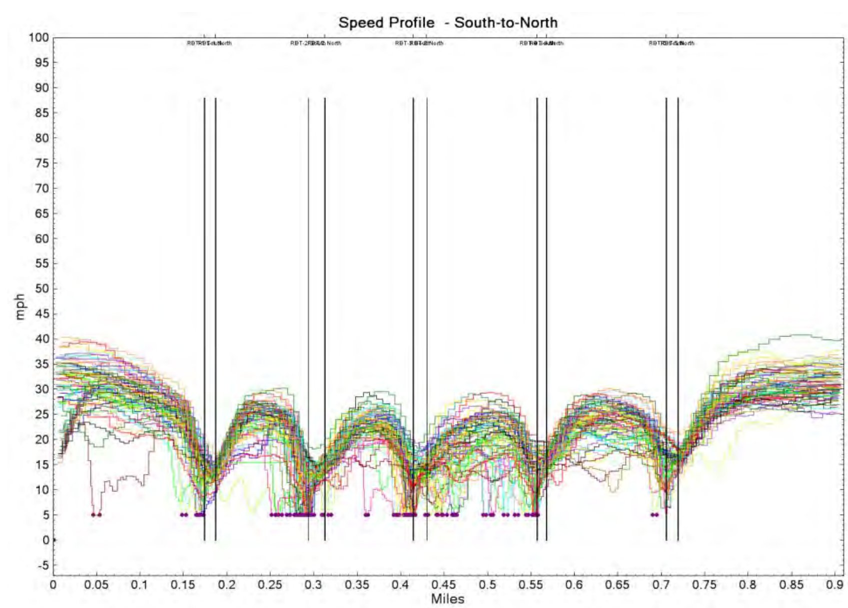

N
1" = 100'
FORWARD ST
LA JOLLA BLVD


MIDWAY ST
LA JOLLA BLVD
N

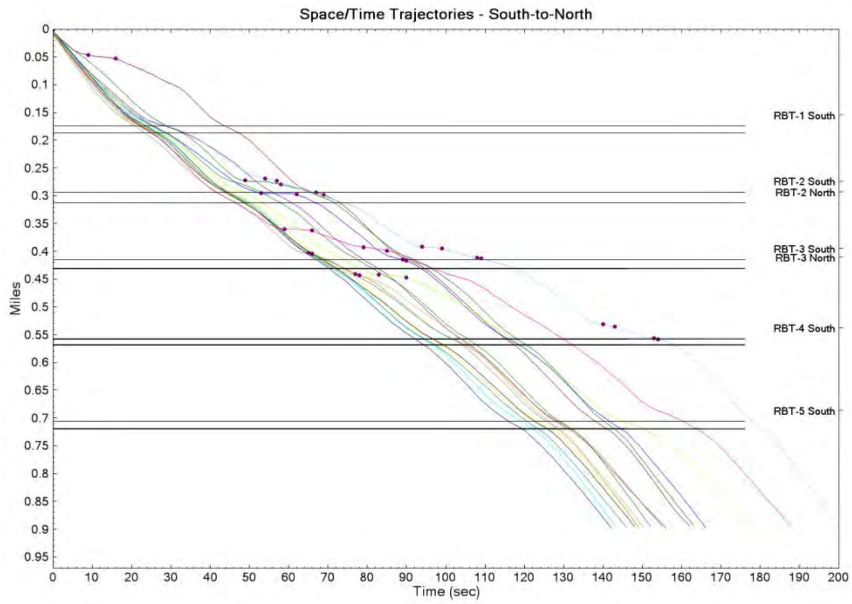
APPENDIX C2: SPEED PROFILES AND TRAVEL TIME TRAJECTORIES

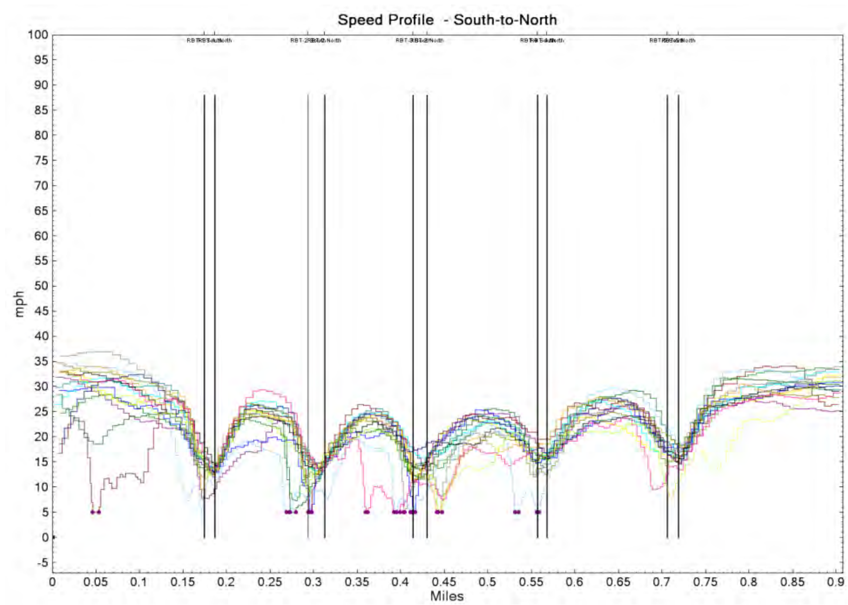
South-to-North All



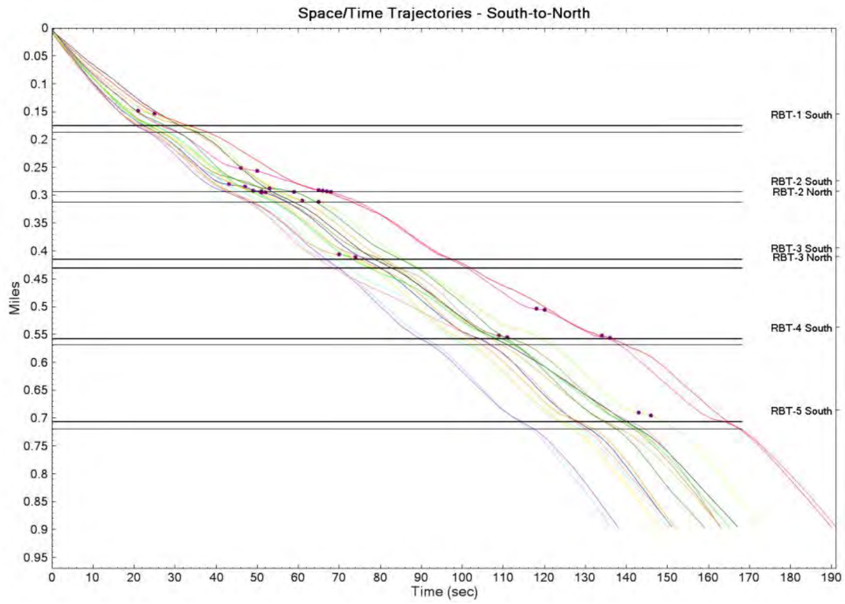


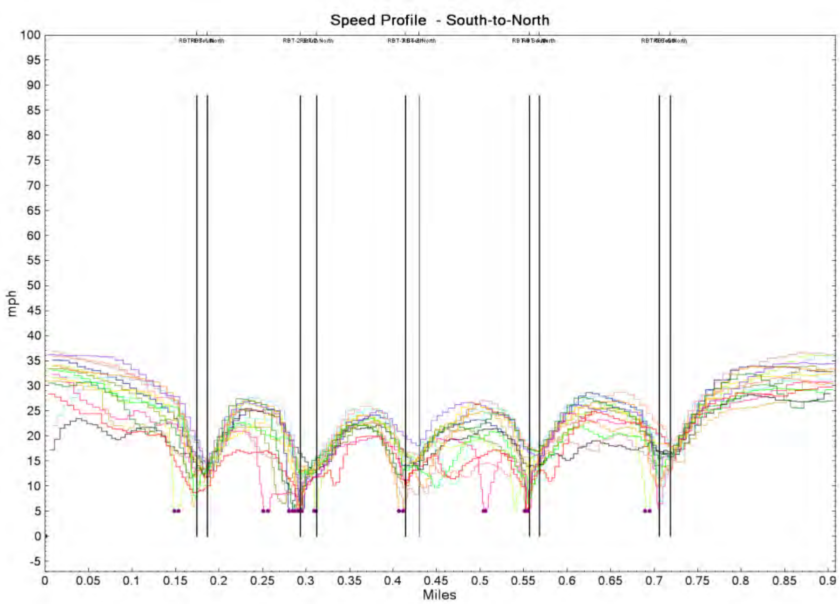
South-to-North AM (7-9)



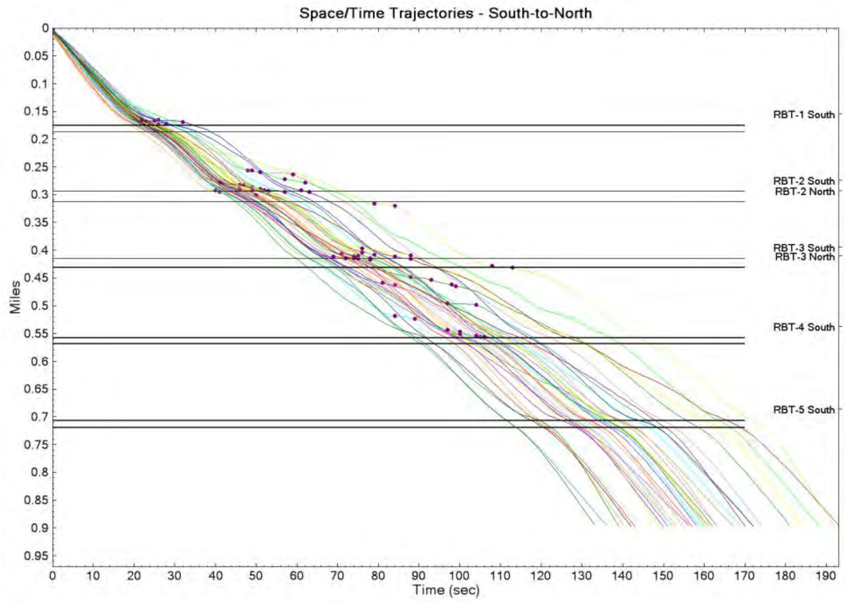


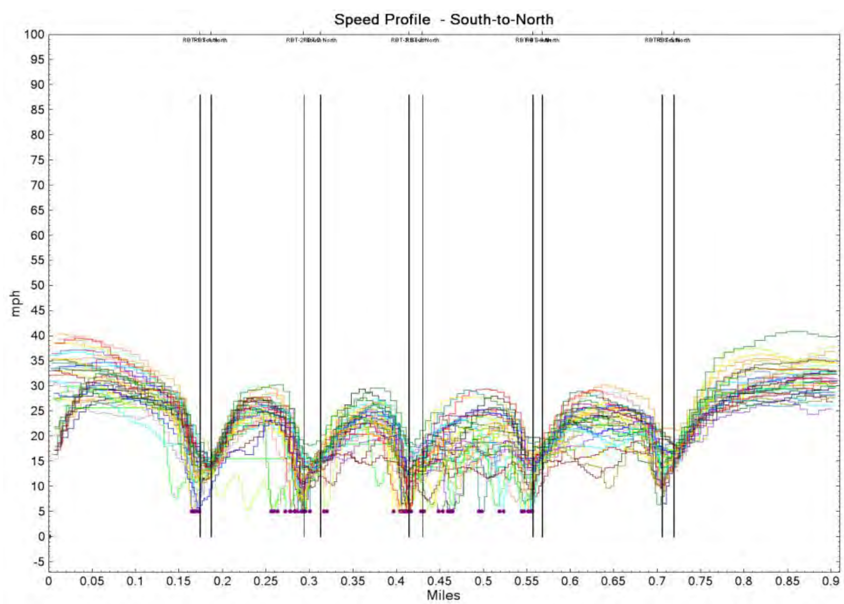
South-to-North PM (4-6)



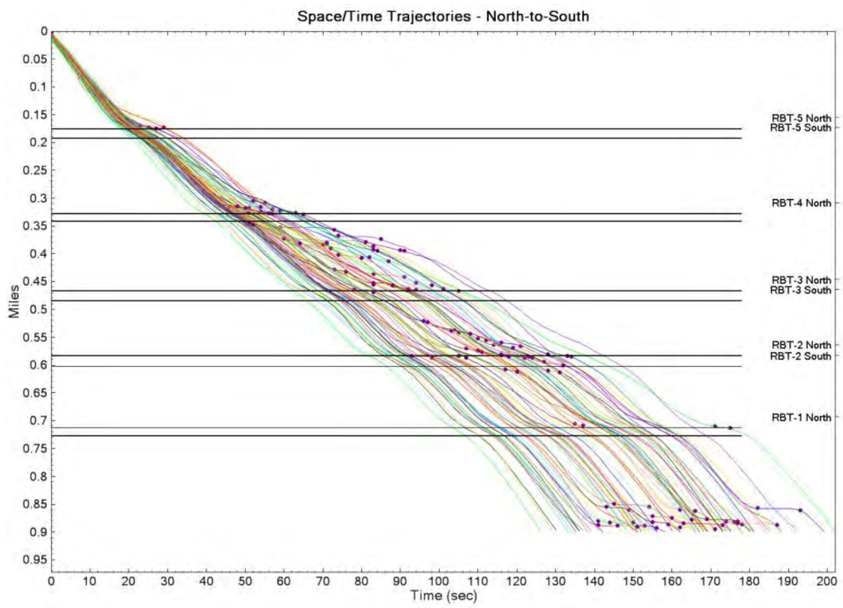


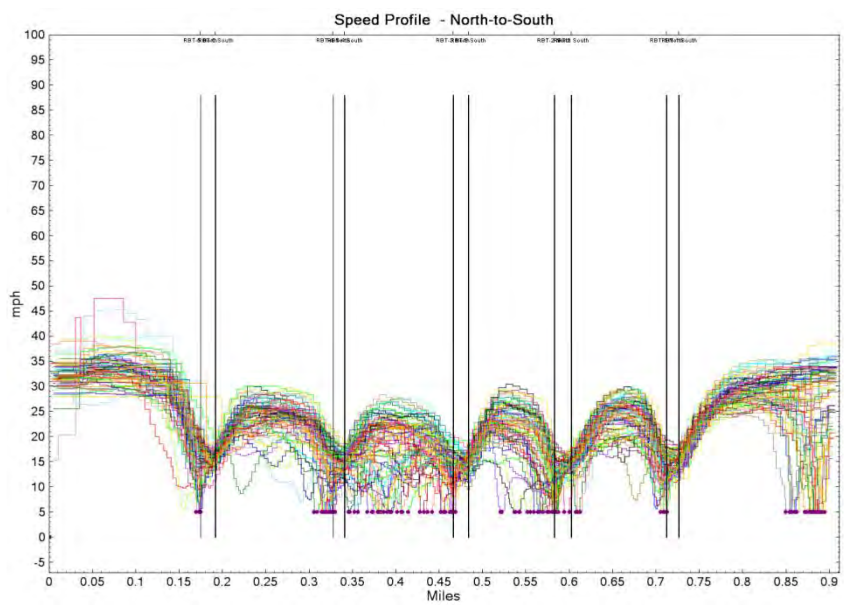
South-to-North Off



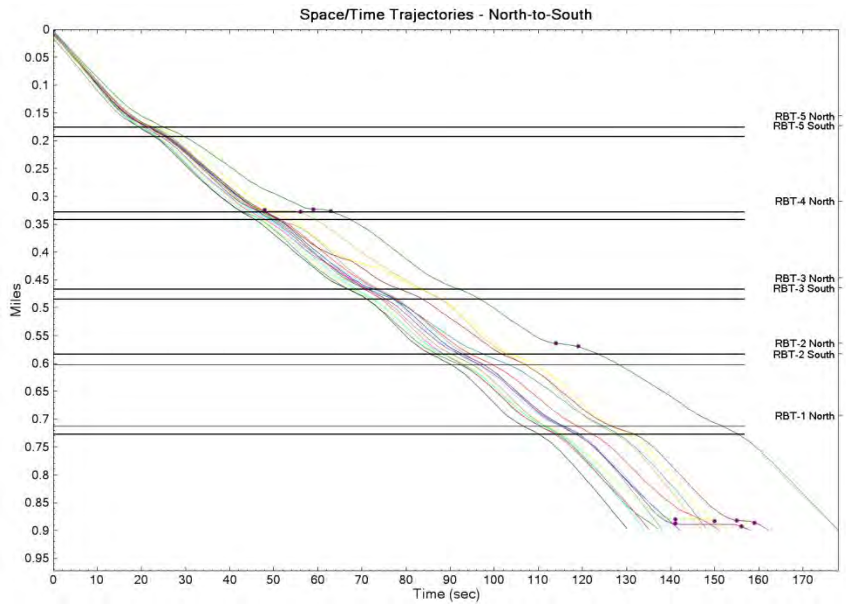


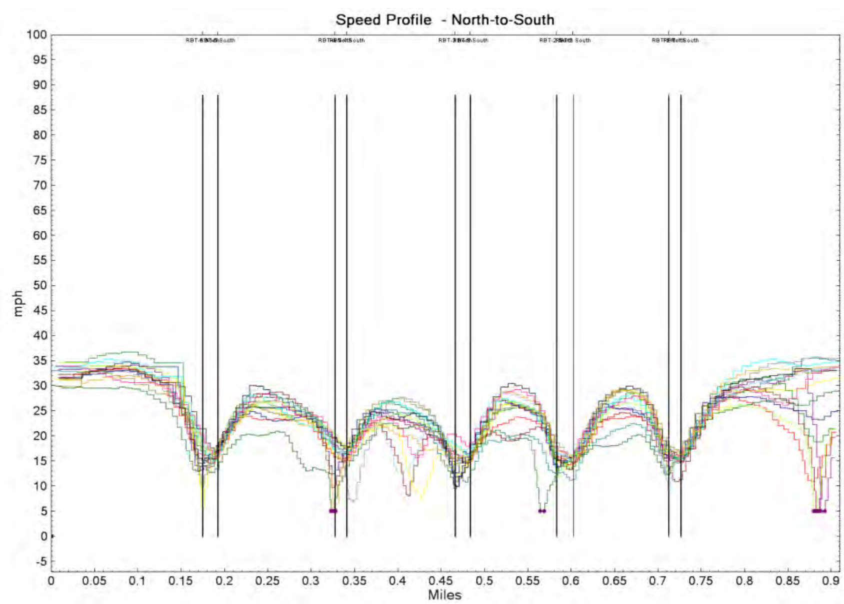
North-to-South All



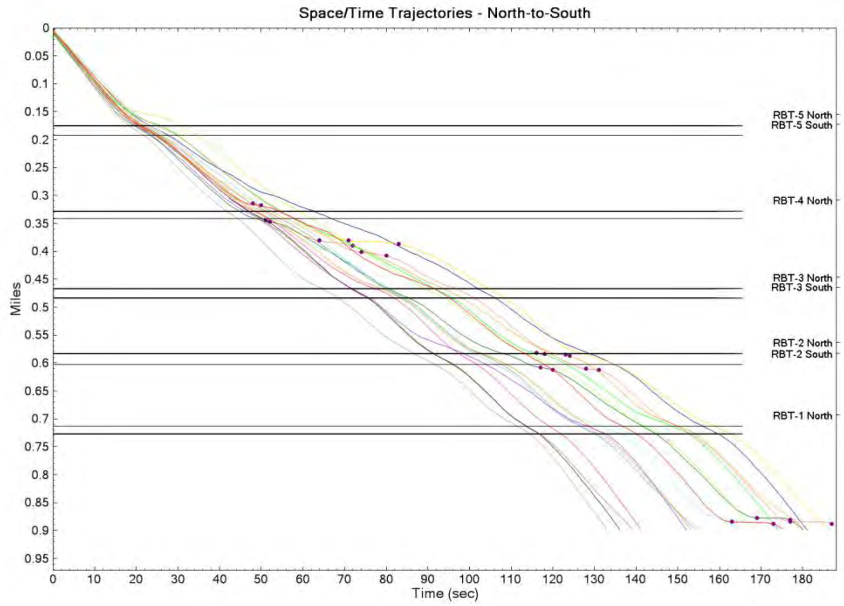


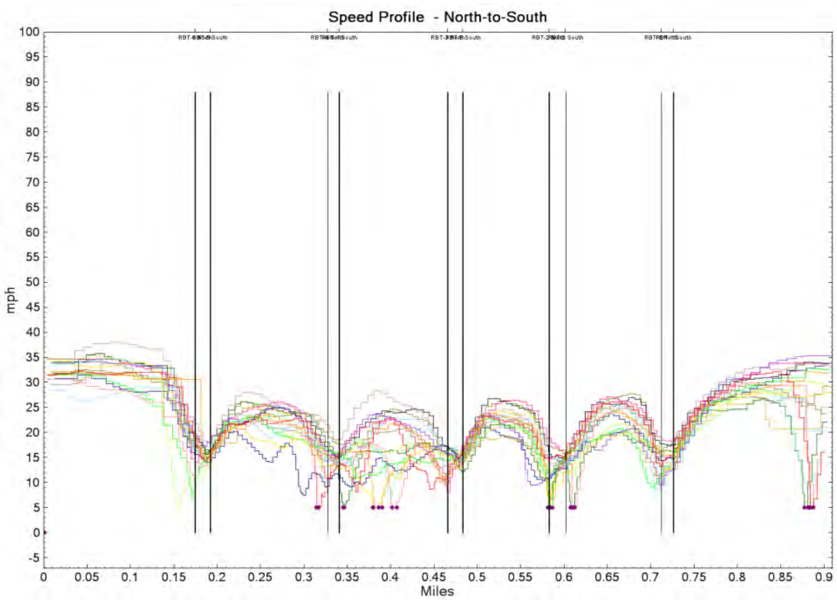
North-to-South AM (7-9)





North-to-South PM (4-6)





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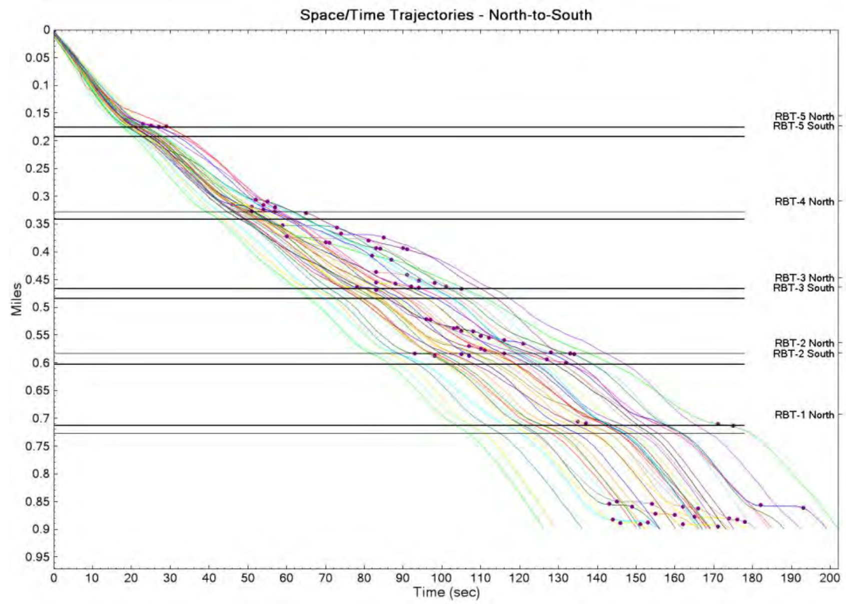
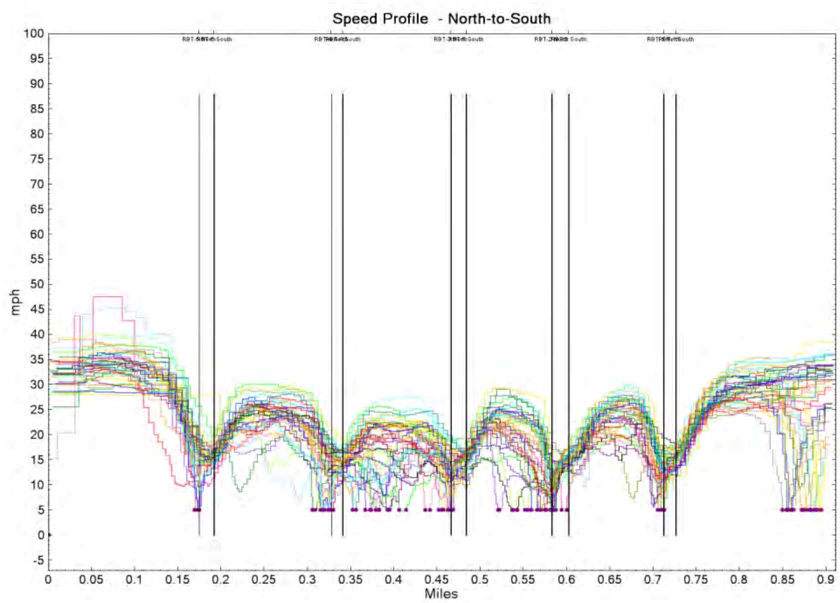
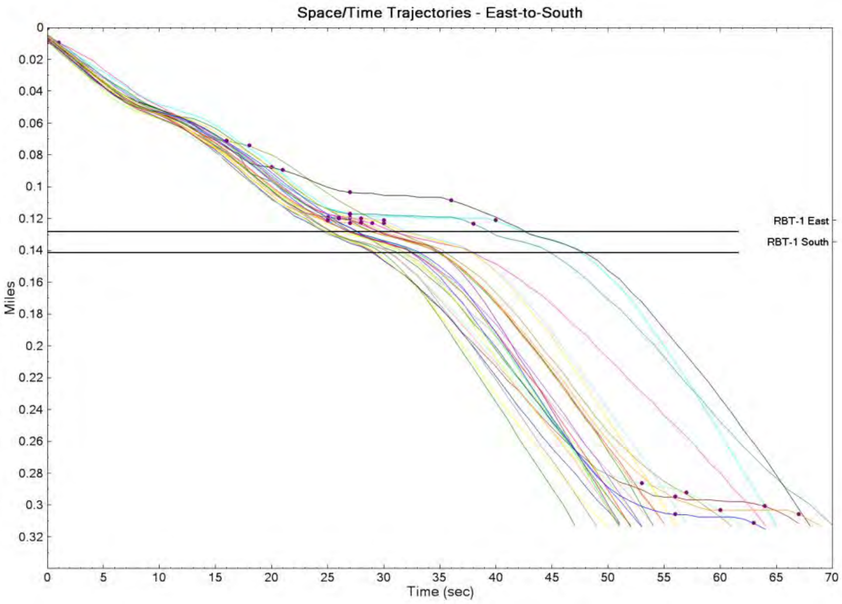
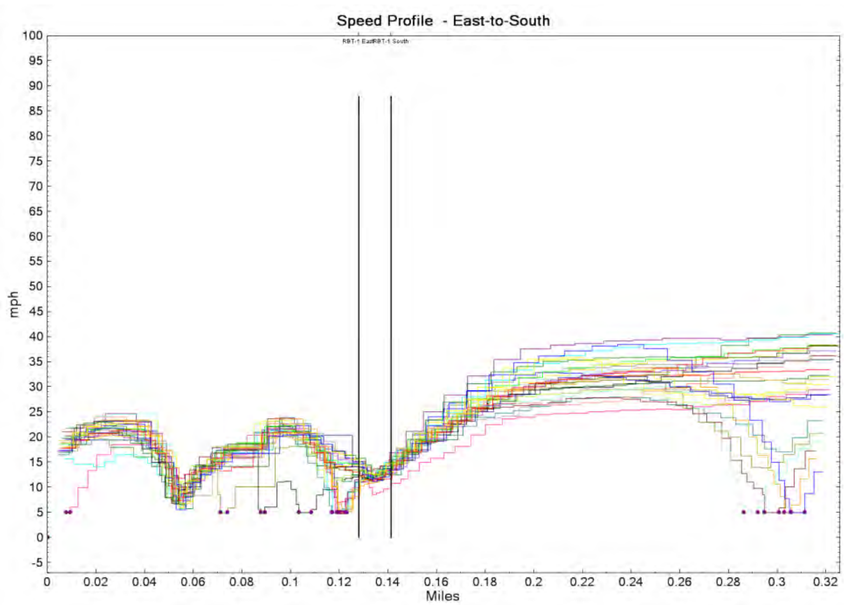


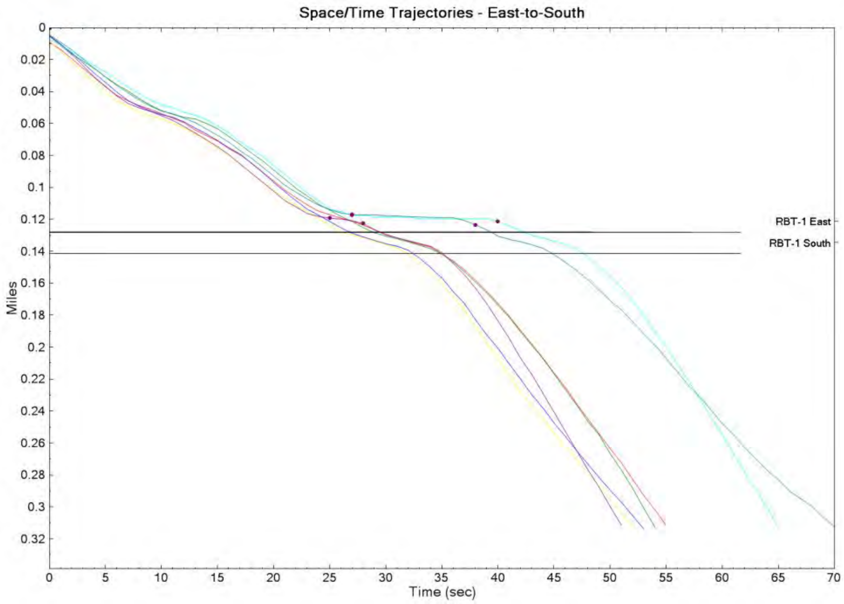


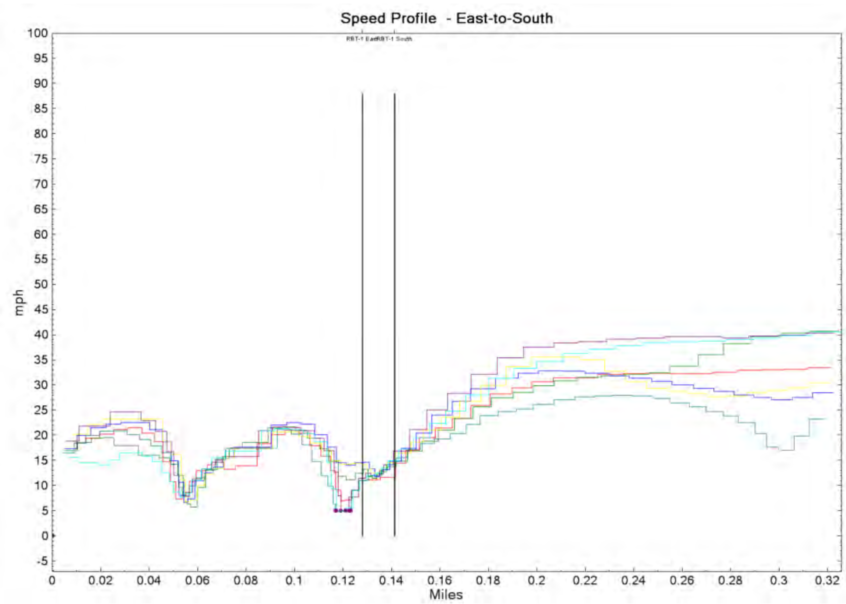
East-to-South All





East-to-South AM (7-9)





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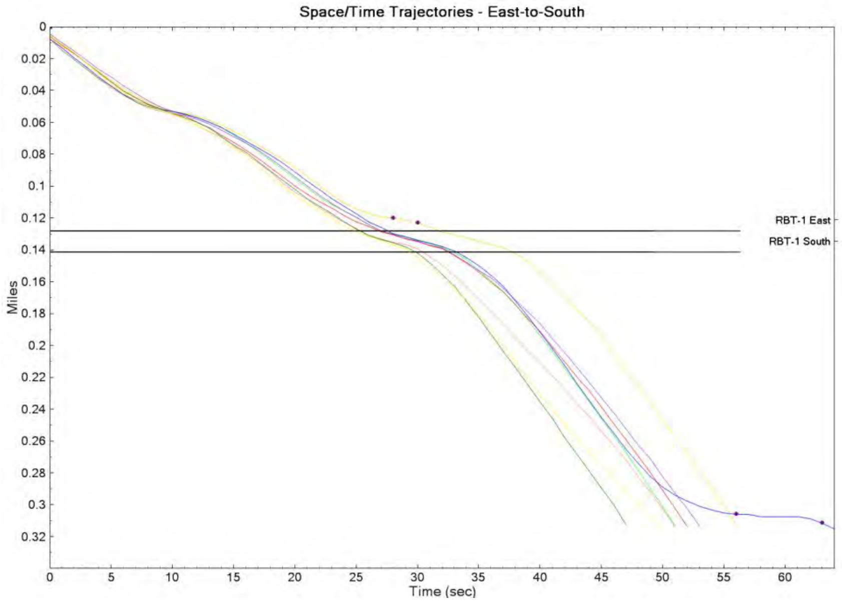

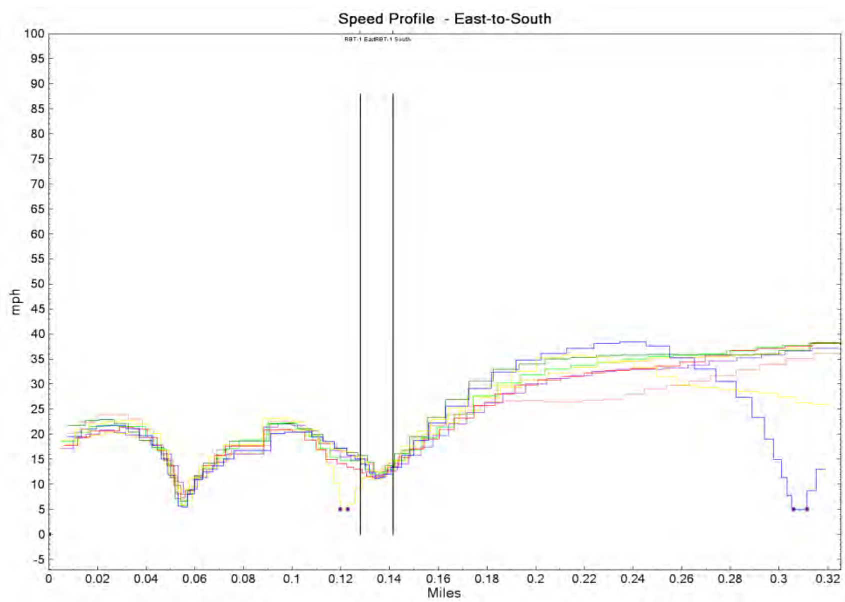

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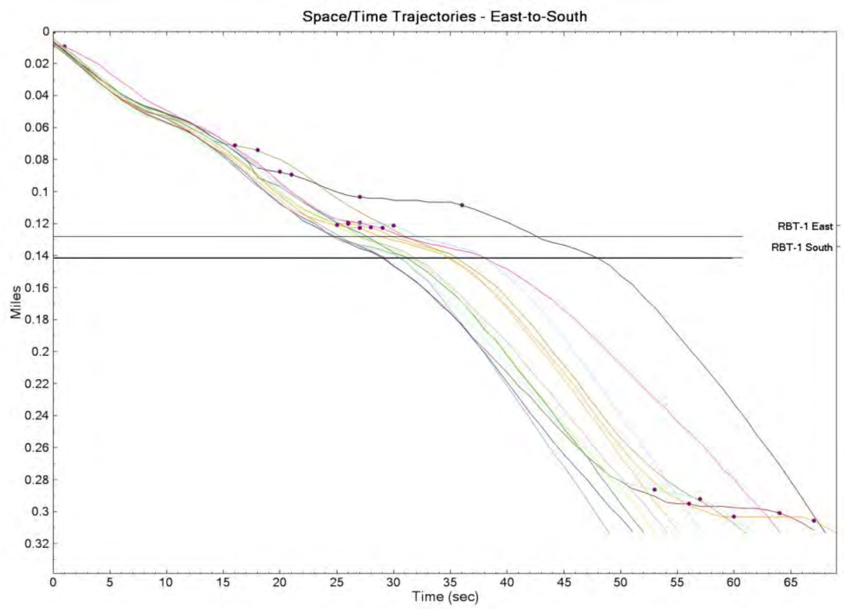
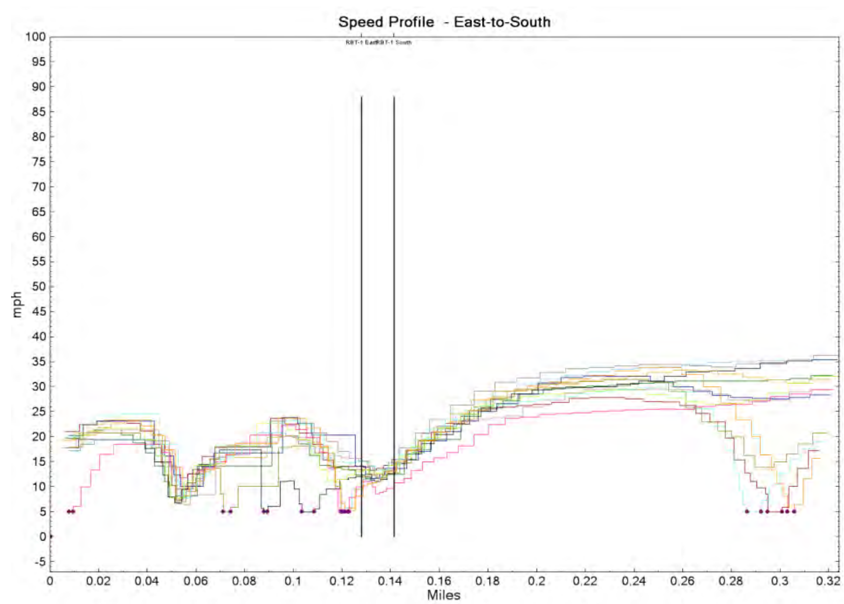
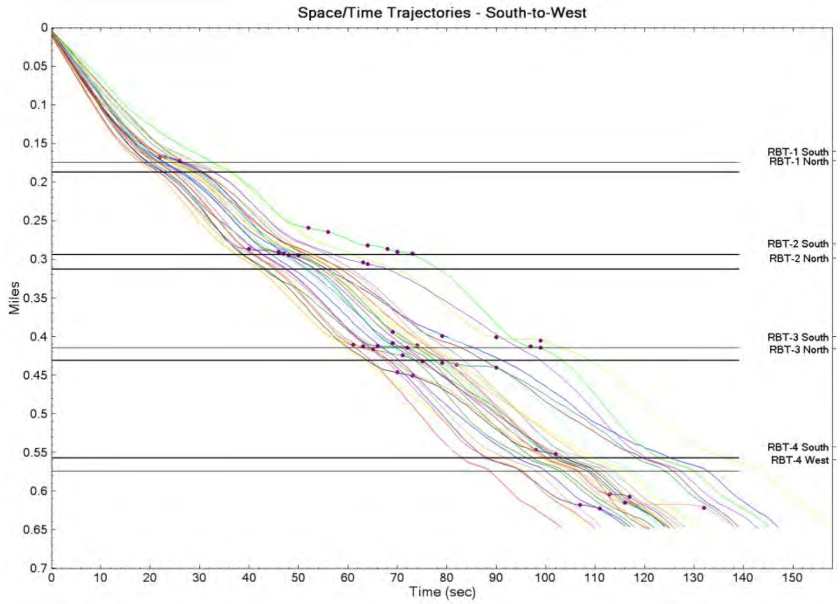
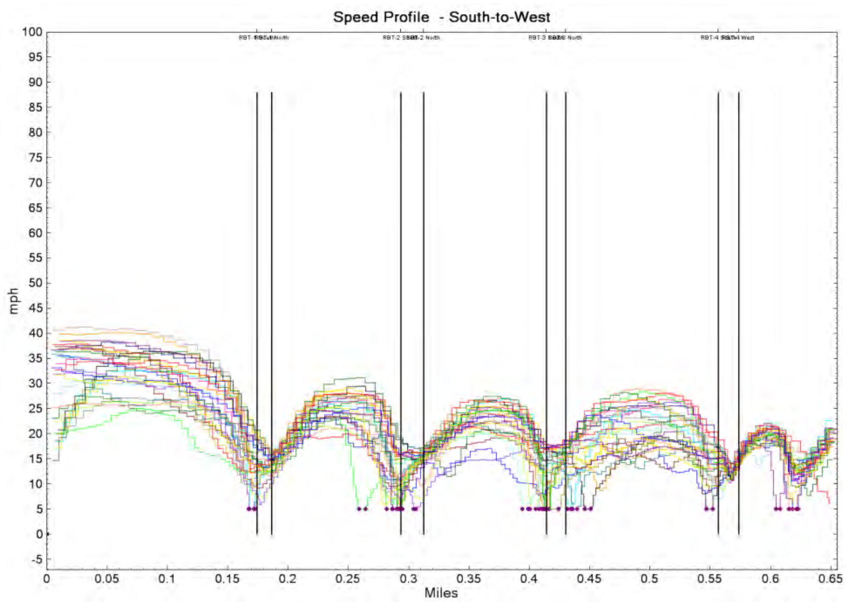




South-to-West All





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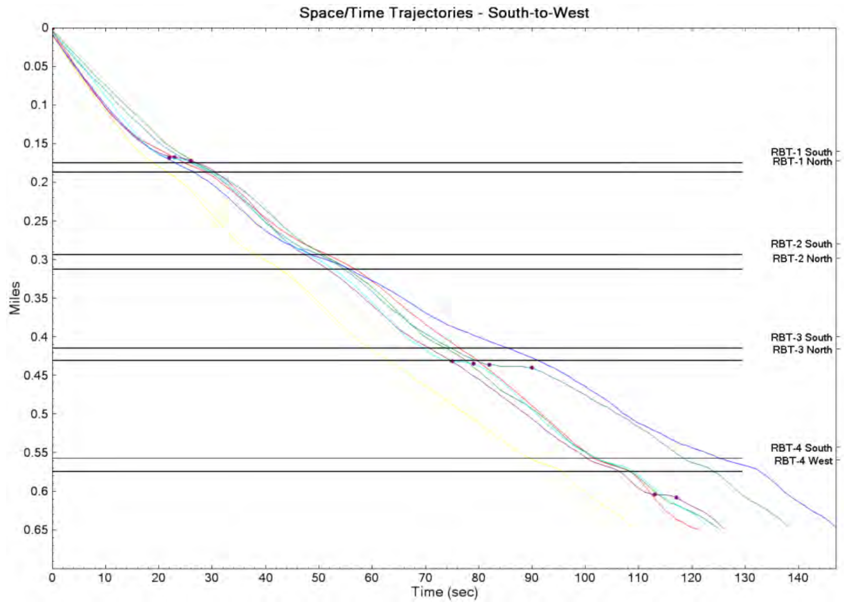

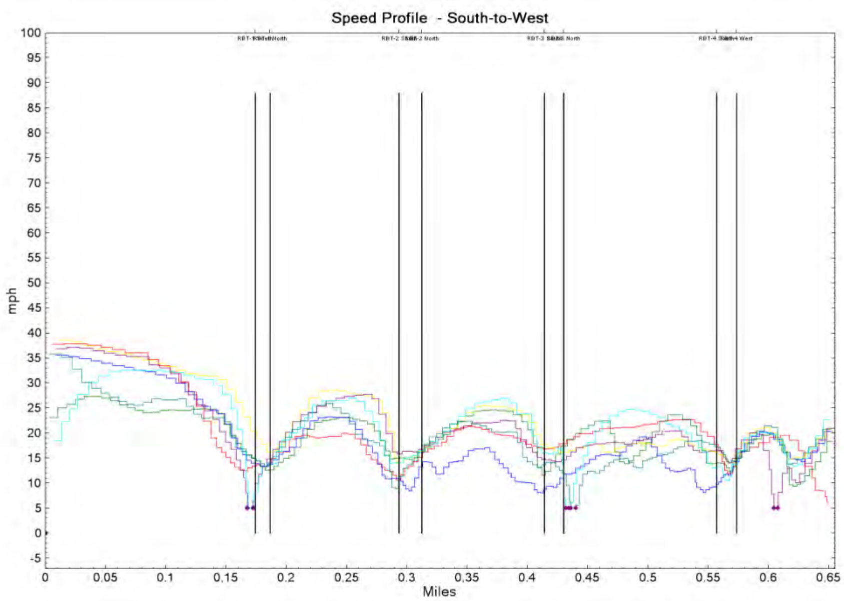

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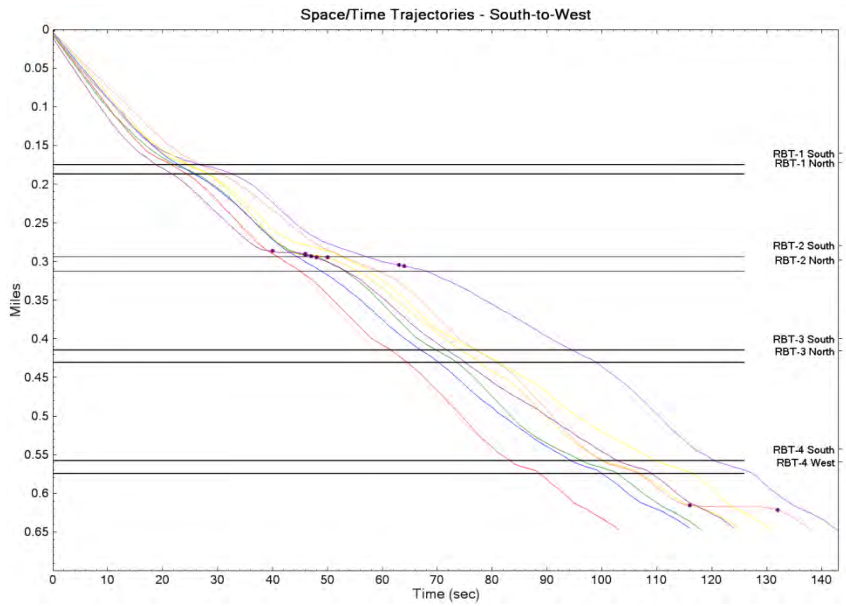

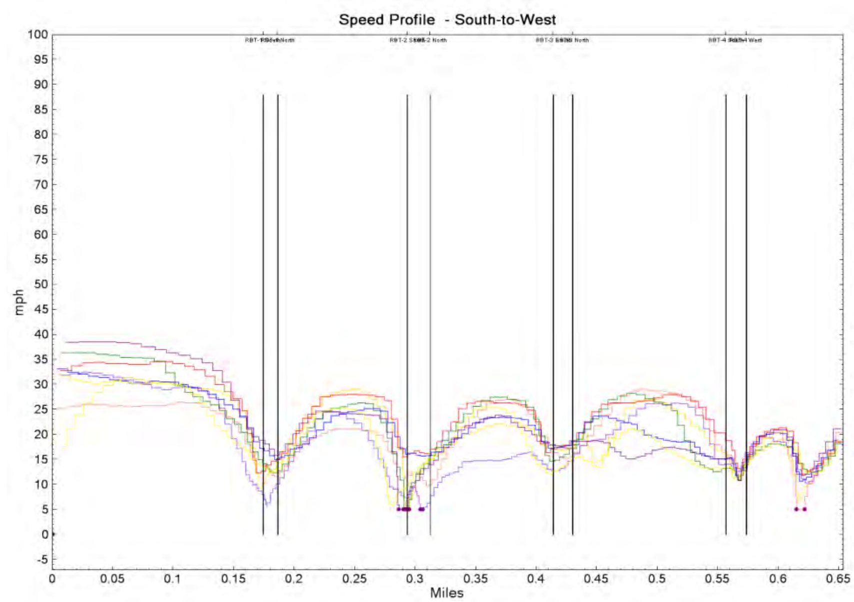

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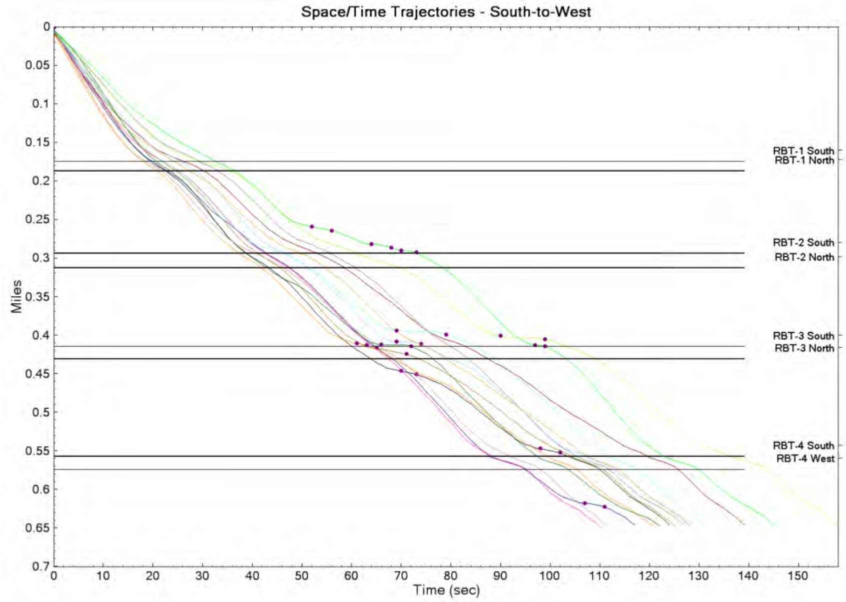
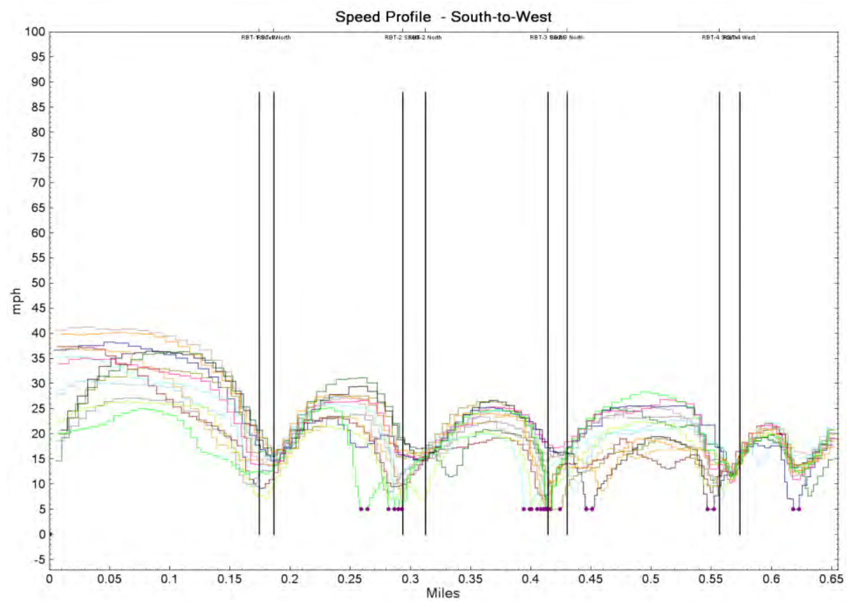
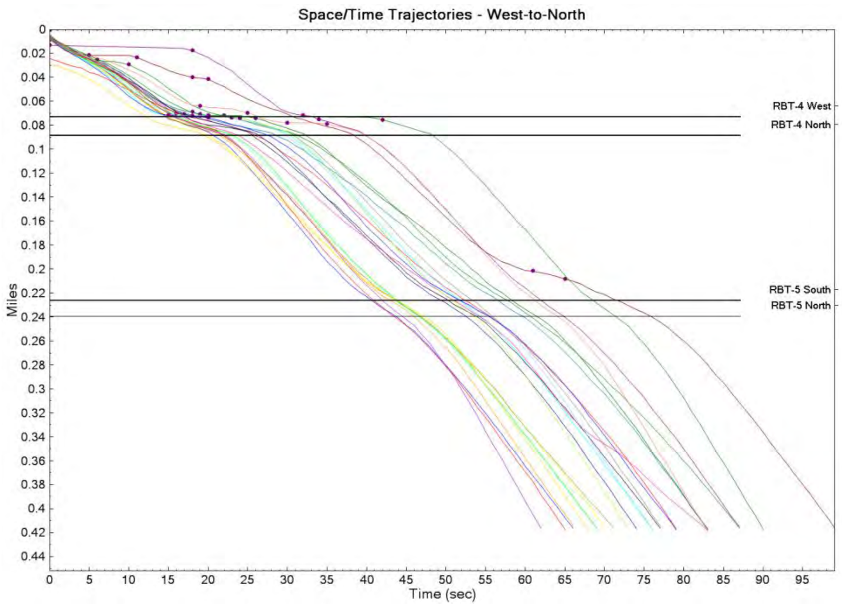
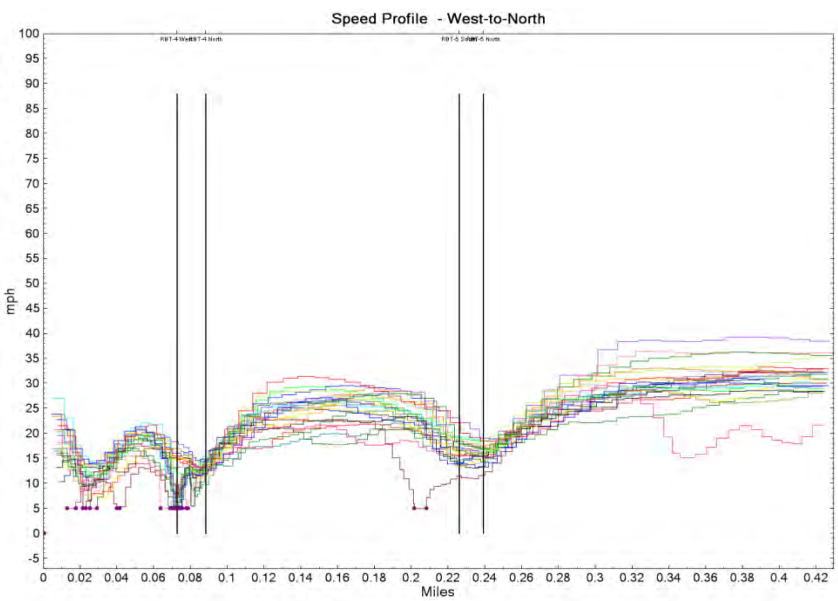


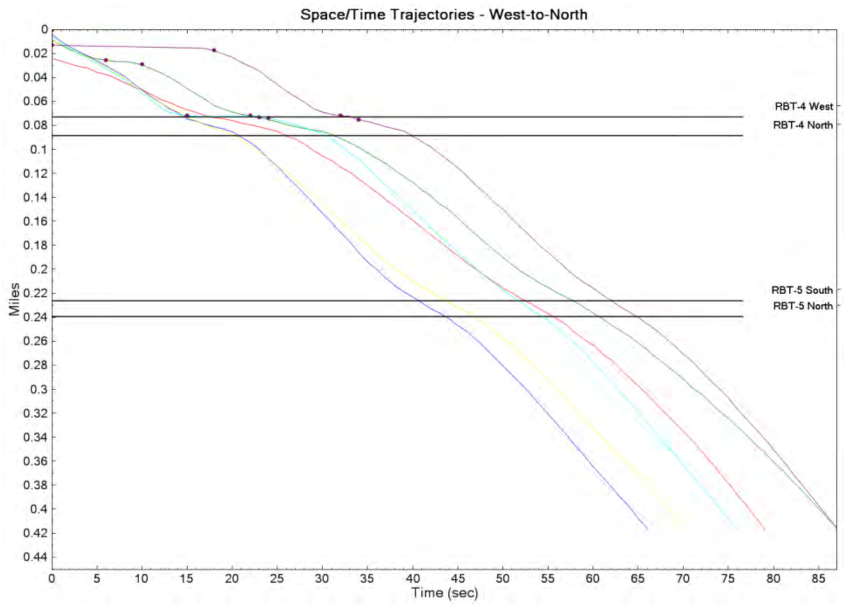


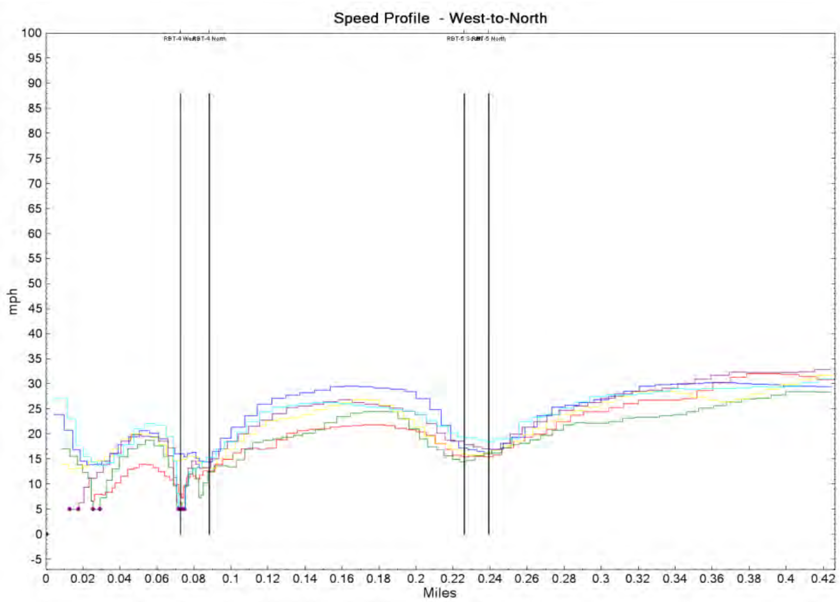
West-to-North All



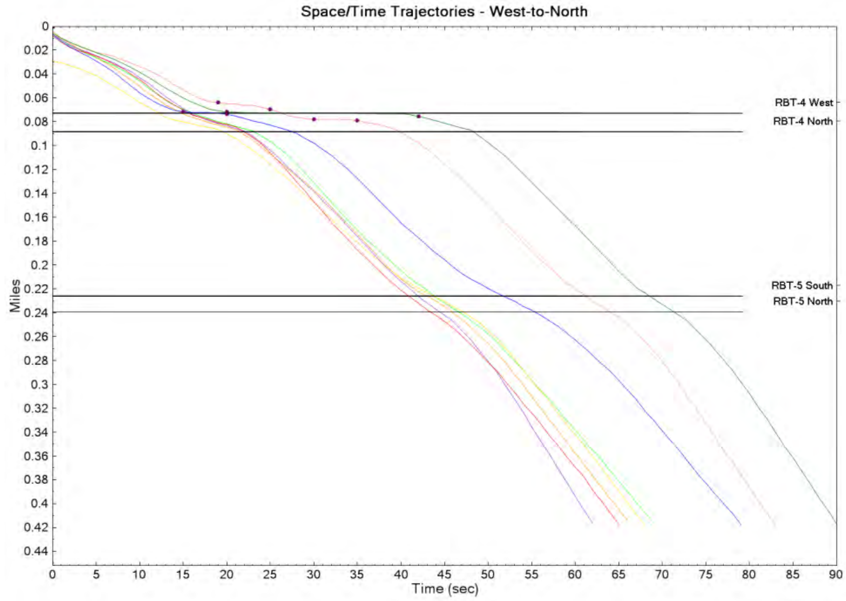


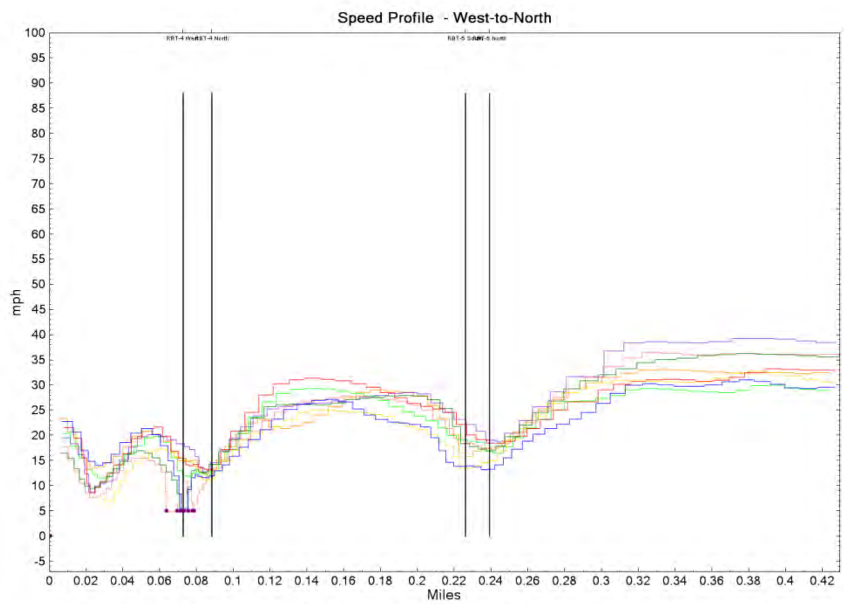
West-to-North AM (7-9)



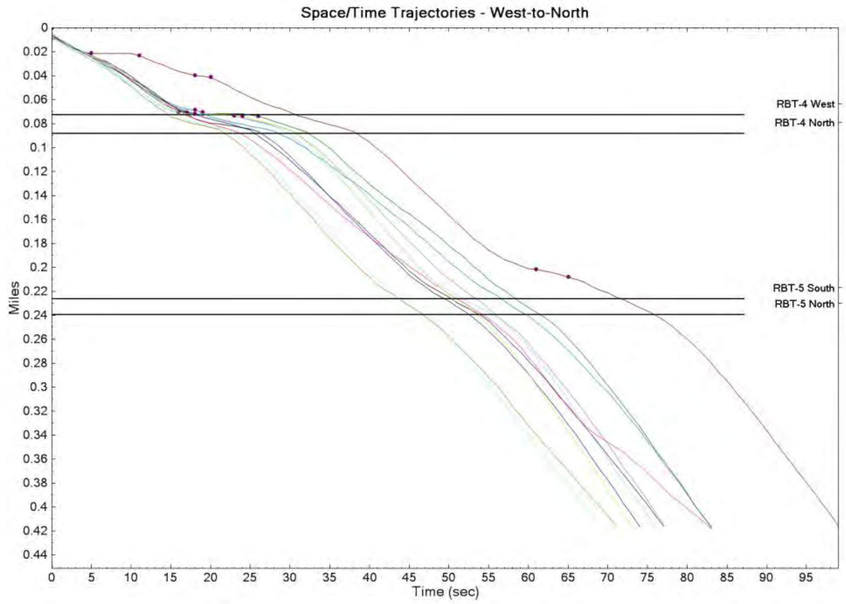


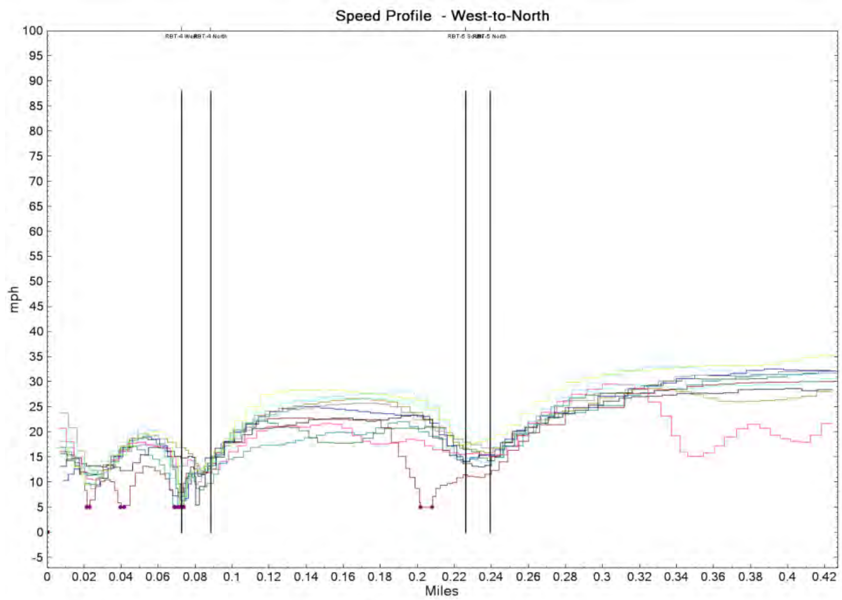
West-to-North PM (4-6)



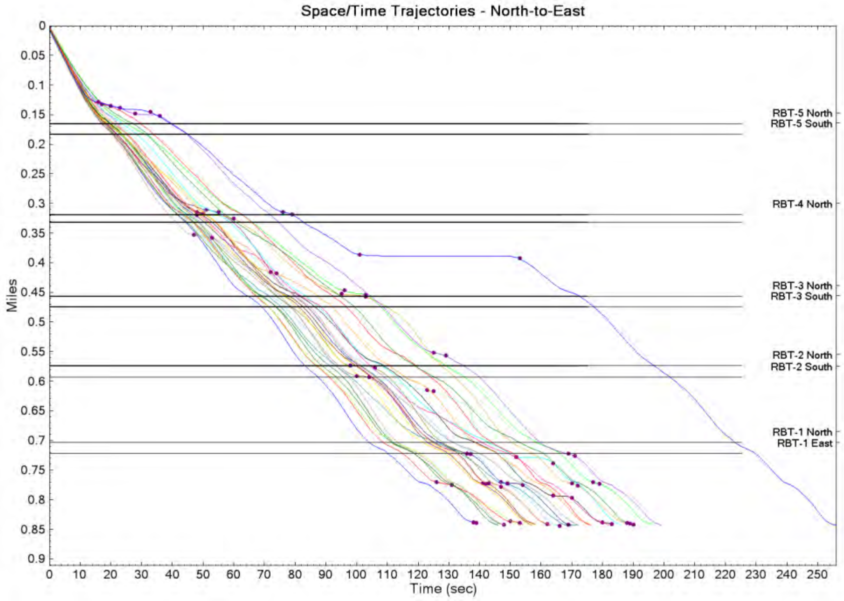


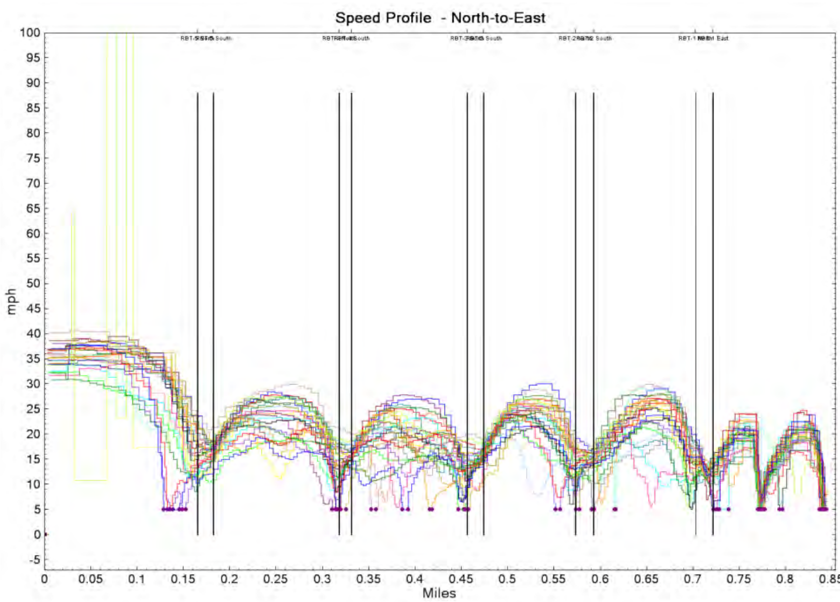
West-to-North Off



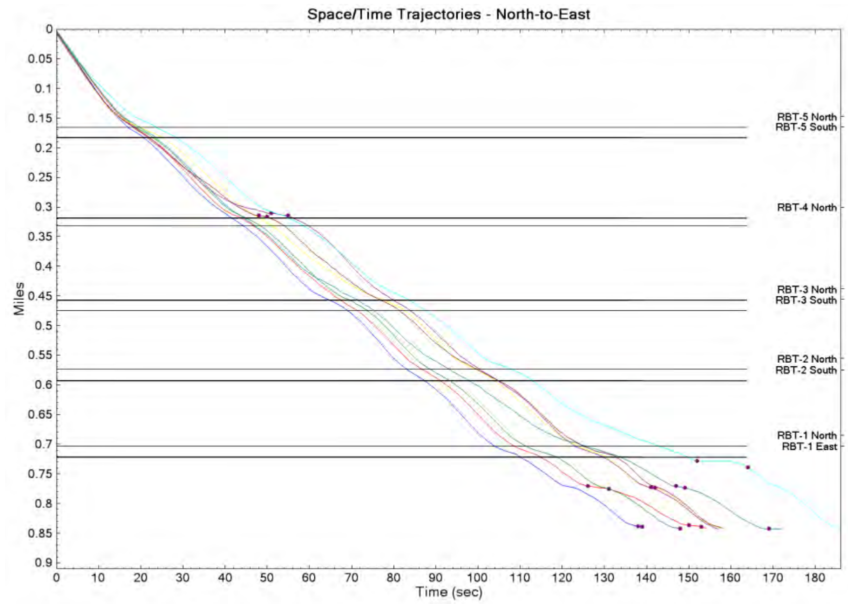


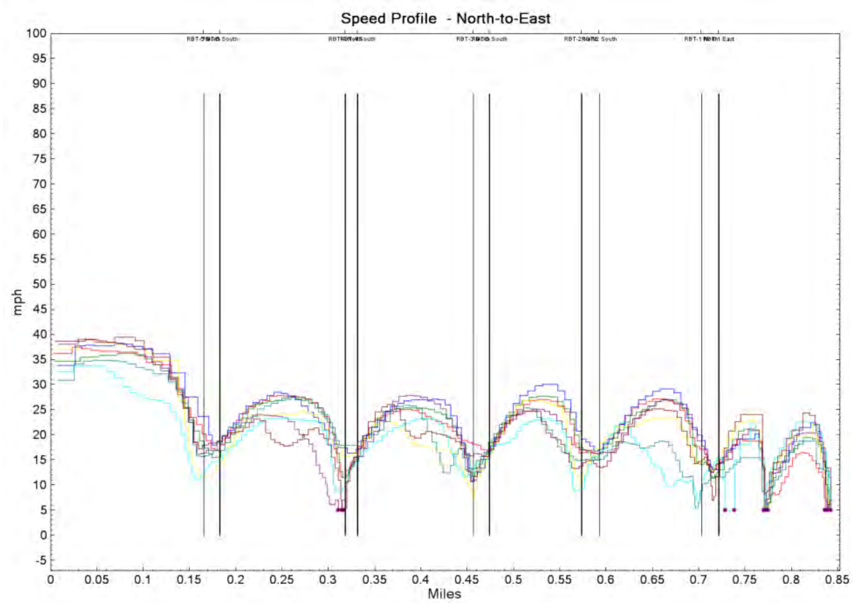
North-to-East All



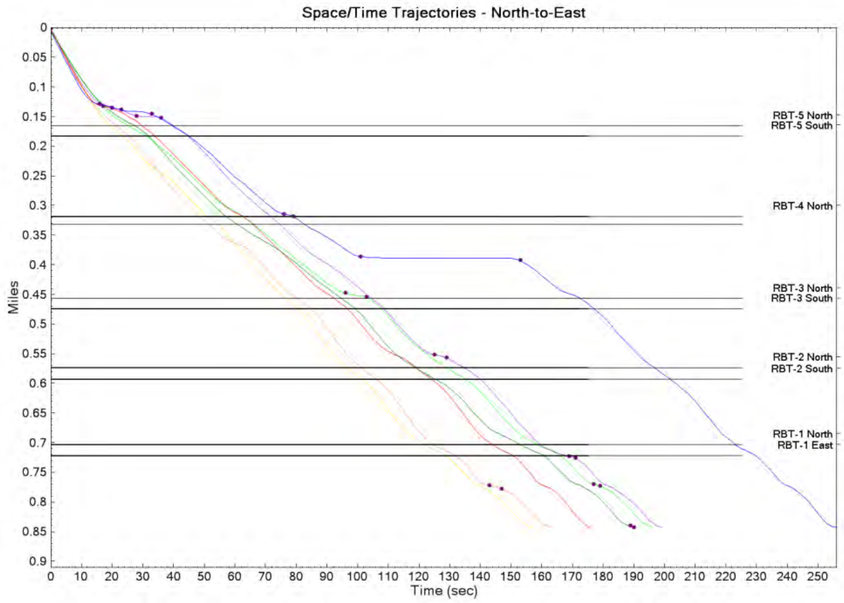


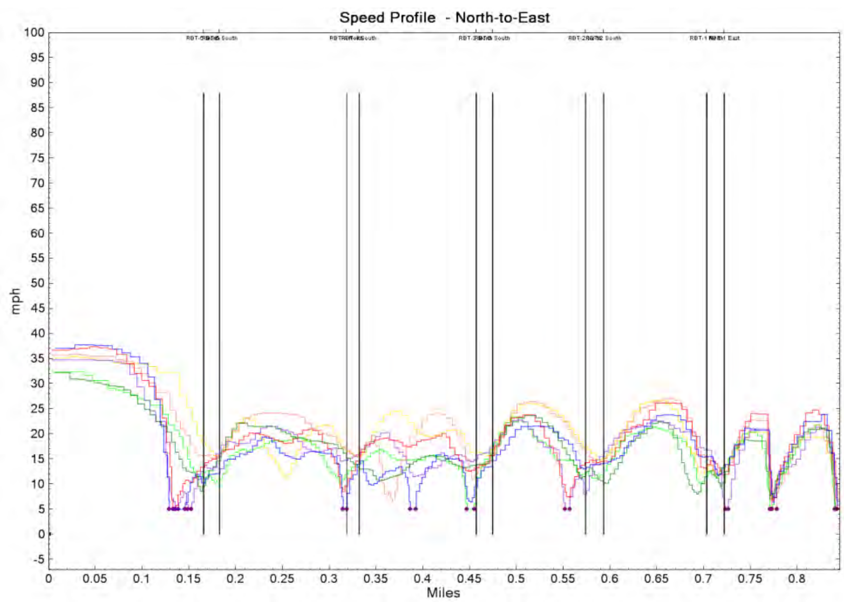
North-to-East AM (7-9)





East-to-North PM (4-6)





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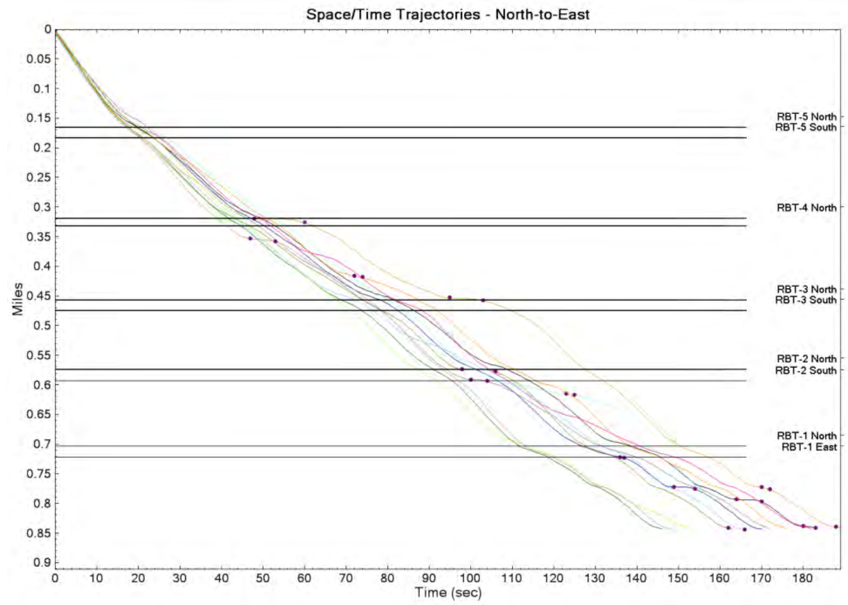

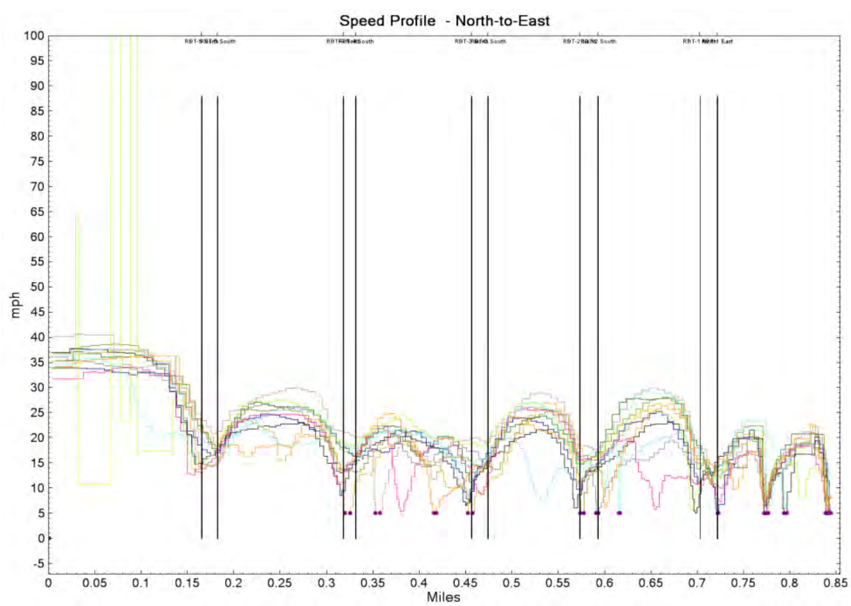

NCHRP 03-100

Appendix D

Carmel, Indiana
Old Meridian Street Field Data

Table of Contents

List of Tables

List of Figures

1. Introduction

This document describes the field data collected by the NCHRP 3-100 team at the Old Meridian Street roundabout corridor in Carmel, Indiana. Data collection and analysis follows the format described in the team's data collection plan.

The data collected at this roundabout corridor, which consisted of four roundabouts and one internal signalized intersection, included peak-hour and off-peak travel times and spot speed measurements. Travel times were recorded using vehicle-mounted GPS units. Additionally, video data were obtained through field-mounted cameras. Data were collected from May 14, 2012, to May 15, 2012.

This document provides an overview of the data collected and discusses the quality and size of the dataset, with comprehensive data provided in the appendix. Figure 1 displays a schematic of the corridor. The white numbers denote roundabouts.

The roundabout corridor on Old Meridian Street consists of four roundabouts over a distance of approximately 1.25 miles. A description of the four roundabout intersections is shown in Table 1. Old Meridian Street runs roughly southwest-to-northeast, though it will be referred to within this document as south-to-north.

Table 1: Description of Roundabout Intersections

Number	Cross Street	Legs	Remarks
1	Pennsylvania St.	4	Pennsylvania St. is the "major" road to the south, and Old Meridian is the "major" road to the north. The angle between Pennsylvania and Old Meridian is acute, and separate right-turn lanes facilitate movements in those quadrants. Northbound Pennsylvania has two approach lanes, but only one lane on the southbound approach.
2	Grand Blvd.	3	Single-lane westbound approach accommodates all traffic from Grand Blvd. Angle of intersection is approximately 90 degrees.
3	Main St.	4	Single-lane approaches in both directions on Main St., though a short dedicated right-turn lane is added between the crosswalk and the circulatory roadway. The right-turn lanes help to accommodate an acute angle of the intersection between Main and Old Meridian.
4	Guilford Rd.	4	The northbound approach on Guilford is aligned with a sharp turn to provide an angle of intersection close to 90 degrees. The approach on the west side of the roundabout is actually the entrance/exit to St. Vincent Hospital, as Guilford terminates at Old Meridian.

Figure 1. Aerial View of the Old Meridian Street Roundabout Corridor.

Surrounding development on Old Meridian Street is typically mixed commercial and professional offices, though some portions are single-family residential or undeveloped. Within the actual roundabout corridor, Old Meridian Street is a four-lane divided minor arterial, with periodic left-turn bays or two-way left-turn lanes for adjacent driveways. Between Pennsylvania Street and the south end of the corridor at Meridian Street, Old Meridian Street is a two-lane collector with driveways to medical and professional buildings and to a senior residential care facility. North of Guilford Road, Old Meridian Street widens to accommodate its eventual cross-section of two through lanes, two left-turn lanes, and one right-turn lane at the signalized intersection with US-31. The entire length of the corridor is has a posted speed limit of 40 miles per hour. In addition to the four roundabout intersections, there is a fifth major intersection at Carmel Drive, which is signalized. There are also T-intersections with three local streets in the mixed-use development on the east side of the corridor between Carmel Drive and Grand Boulevard, and a T-intersection with Smokey Row Rd. between Guilford Road and US-31.

All of the approaches to roundabouts on Old Meridian Street are two-lane approaches (with the exception of the northbound approach at Pennsylvania), and the circulatory roadways are built to be two lanes wide. To provide guidance to motorists, pavement markings were installed to delineate the appropriate driving paths for left-turn, through, and right-turn movements, and the approach geometries provide the necessary deflection and storage. However, while conducting the travel-time runs, team members observed a substantial number of vehicles that did not properly maintain their lane while traveling through the circulatory roadway, adopting somewhat of a "fastest path" trajectory. Indeed, during some travel-time runs, team members had to execute avoidance maneuvers (e.g., evasive braking/steering) and/or use the car horn to alert adjacent drivers to prevent collisions by encroaching vehicles. Inspection of the pavement markings within the circulatory roadways shows that many of them are worn away. It is unclear whether the pavement markings were worn away by "fastest path" drivers, or whether the current lack of markings is facilitating inadequate lane-keeping. The assumption is that many drivers on the Old Meridian corridor are familiar with roundabouts and should be accustomed to lane-keeping in general and to choosing the appropriate lane for their destination at these specific intersections. Formal documentation of this behavior may be available after the video recordings are reduced.

Congestion was not commonly found on the Old Meridian Street corridor. There were periods of heavier traffic during the morning and evening peaks, but they typically dissipated within one round trip on the team's travel time runs. Traffic was particularly heavy at the Guilford Road roundabout in the afternoon/evening peak, due to school-related traffic followed by the typical increase in traffic at the end of the workday. However, much of the congestion effects from that traffic were observed between the Guilford Road roundabout and the signalized intersection at US-31. Indeed, team members had some difficulty turning around north of Guilford Road to begin southbound travel-time runs during this period; however, operations at the roundabouts remained fairly smooth, with minimal queues in general.

2. Traffic Counts

The research team obtained the traffic counts and turning-movement counts for each of the intersections along the corridor. Table 1 displays the turning-movement counts during the a.m. and p.m. peak periods for each intersection. Because of its diagonal alignment, Old Meridian

Street comprises the east- and westbound directions for the Pennsylvania Street roundabout, but it comprises the north- and southbound directions for the other three roundabouts.

Table 2: Turning Movement Counts

Intersection		AM				PM			
#	Name	Approach	Left	Through	Right	Approach	Left	Through	Right
1	Pennsylvania St	NB	20	166	134	NB	28	314	744
		SB	2	504	10	SB	0	254	10
		EB	14	112	24	EB	24	226	40
		WB	604	22	4	WB	170	16	10
2	Grand Blvd	NB	0	162	28	NB	0	764	62
		SB	14	560	0	SB	28	278	0
		WB	76	0	12	WB	56	0	22
3	Main St	NB	20	96	56	NB	36	584	252
		SB	62	366	90	SB	56	174	22
		EB	12	66	4	EB	90	172	2
		WB	246	134	32	WB	152	64	34
4	Guilford Rd	NB	12	54	0	NB	6	728	2
		SB	332	496	158	SB	284	188	34
		EB	14	10	30	EB	104	18	14
		WB	2	30	158	WB	4	4	508

Figure 2 displays the 12-hour volume profiles taken between roundabouts 2 and 3. The peak hour was identified to be between 4:30 p.m. and 5:30 p.m.

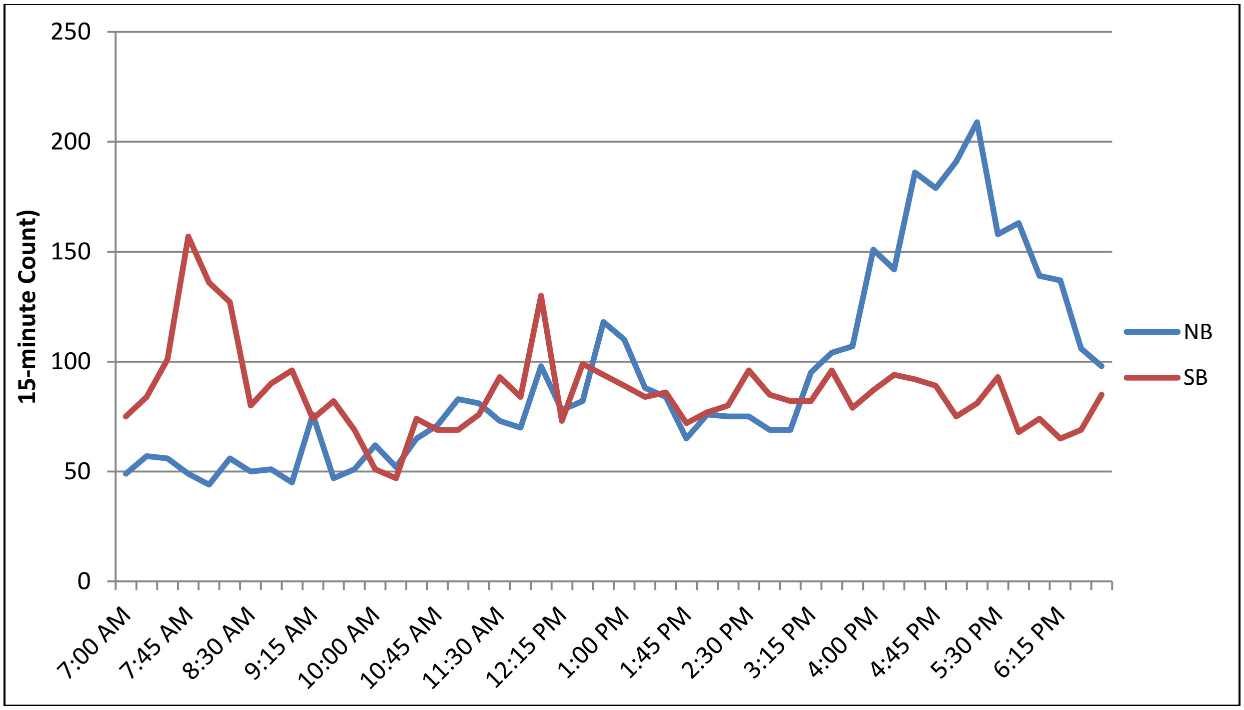

Figure 2: 12-hour Volume Profile

3. Field-Observed Data

In addition to an inventory of the site characteristics and geometry of the roundabouts, the team recorded GPS travel times and spot-speed data along the corridor. These data are presented in the following sections.

3.1. GPS Travel Times

The travel time through the corridor was also measured using vehicle-mounted GPS units. A total of six routes were used to conduct the study:

1. Northbound through the entire corridor;
2. Southbound through the entire corridor;
3. Starting from the south end, then turning left through roundabout 1 (Pennsylvania Street);
4. Starting from west of roundabout 3 (Main Street), then turning left through the roundabout and proceeding to the north end;
5. Starting from the north end, then turning left through roundabout 2 (Grand Boulevard); and
6. Starting east of roundabout 2 (Grand Boulevard), then turning left through the roundabout and proceeding to the south end.

The last four routes were used to capture left-turns through the two roundabouts that the team deemed the most congested. Figures 3A through 3F display the space-time trajectories from each of the six routes. Each diagram displays every travel time run that was conducted (including a.m., p.m., and off-peak runs). Note that the horizontal and vertical scales vary from route to route. The corresponding speed profiles are displayed in Appendix D2.

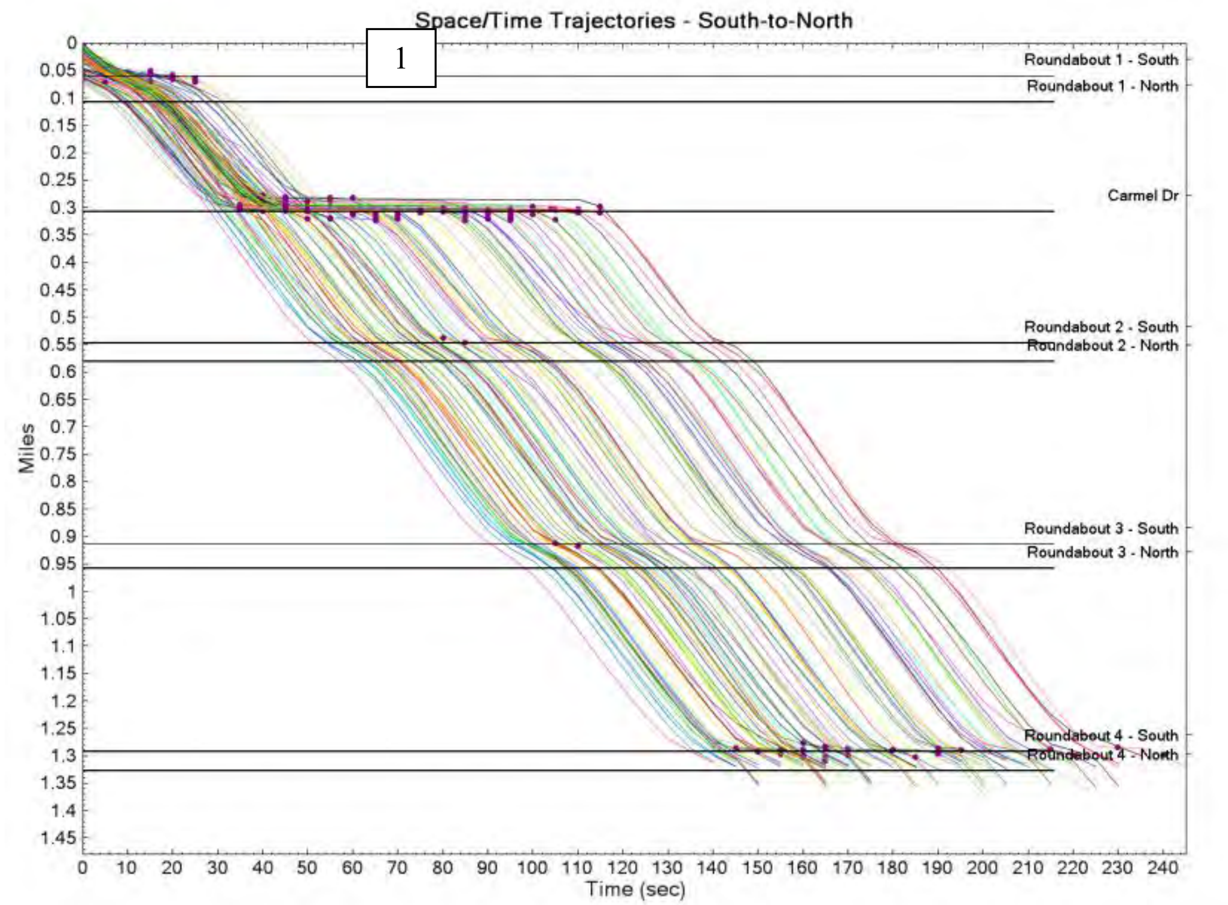

Figure 3A. Space-Time Trajectories for Route 1 (Northbound Through the Entire Corridor)

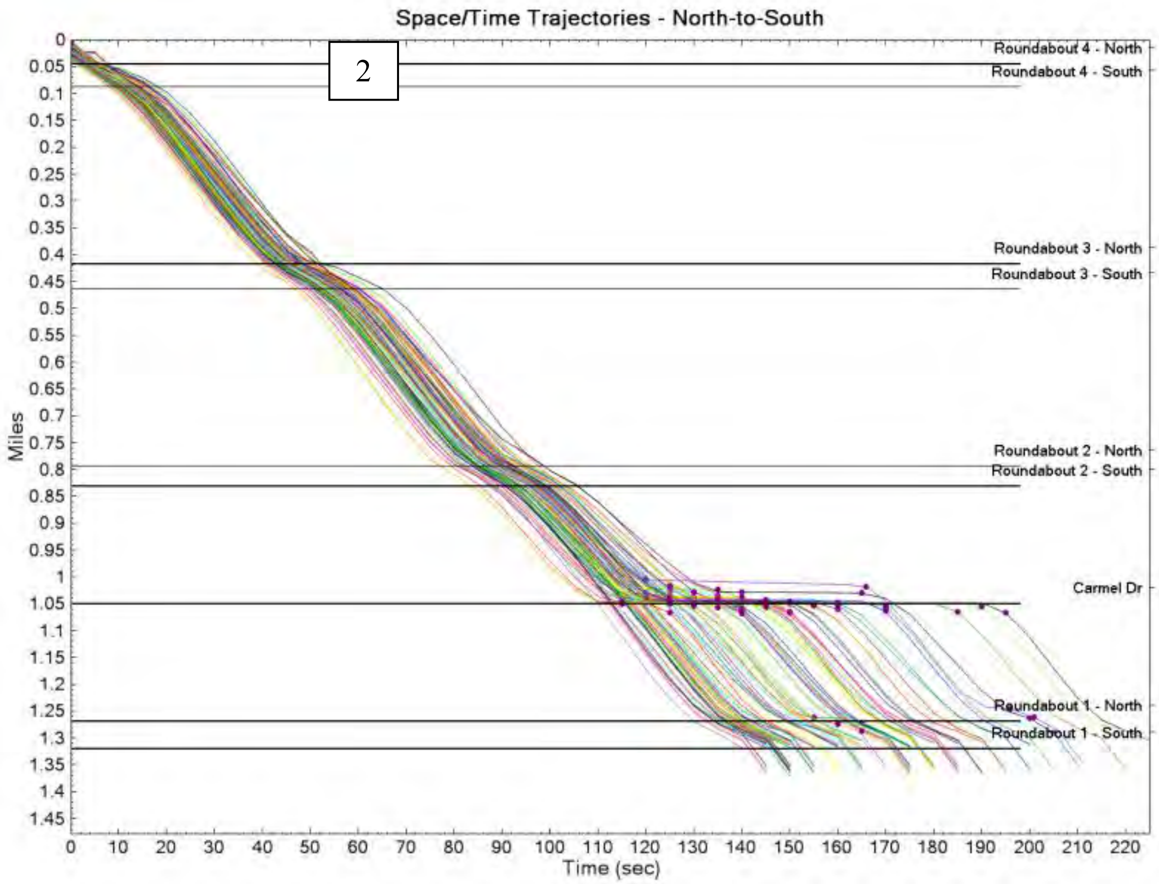

Figure 3B. Space-Time Trajectories for Route 2 (Southbound Through the Entire Corridor)

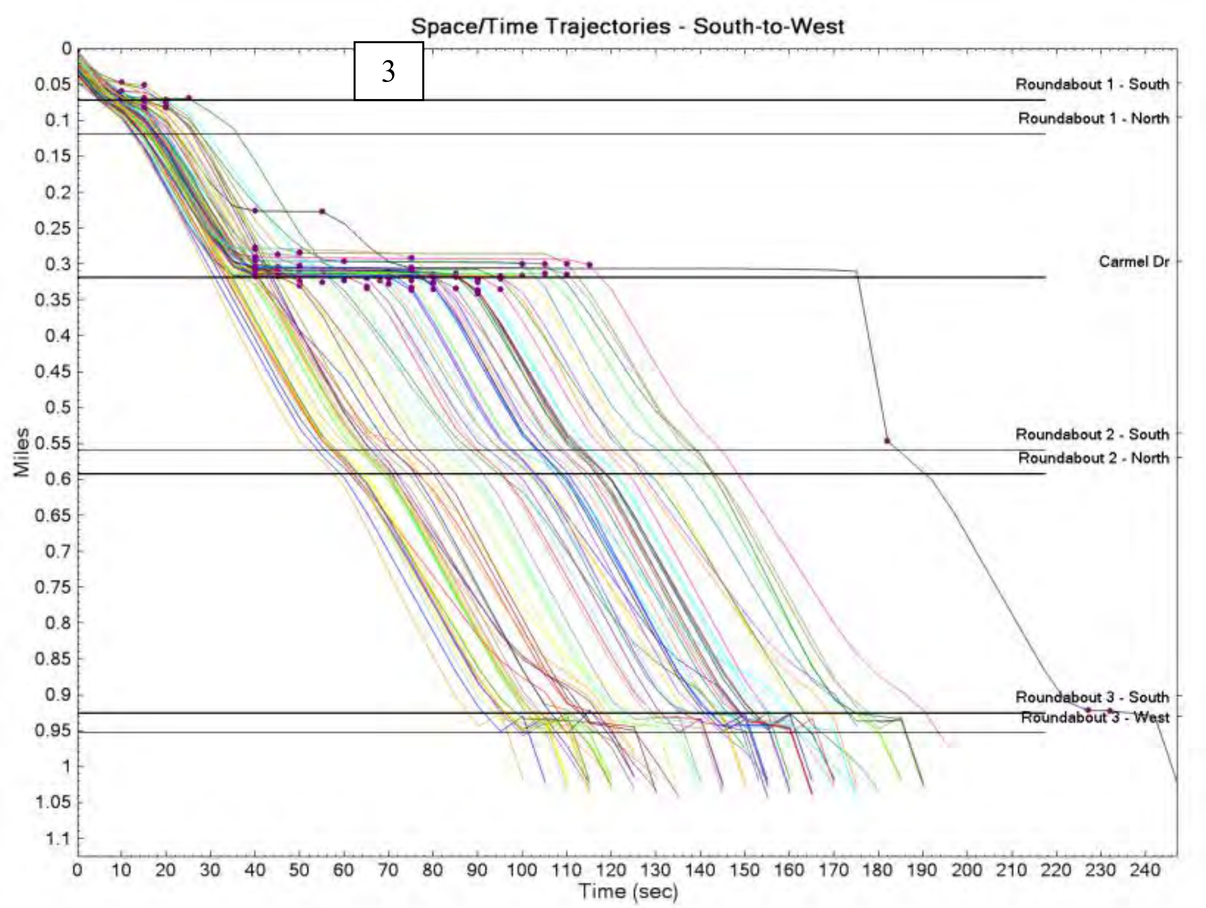

Figure 3C. Space-Time Trajectories for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 1)

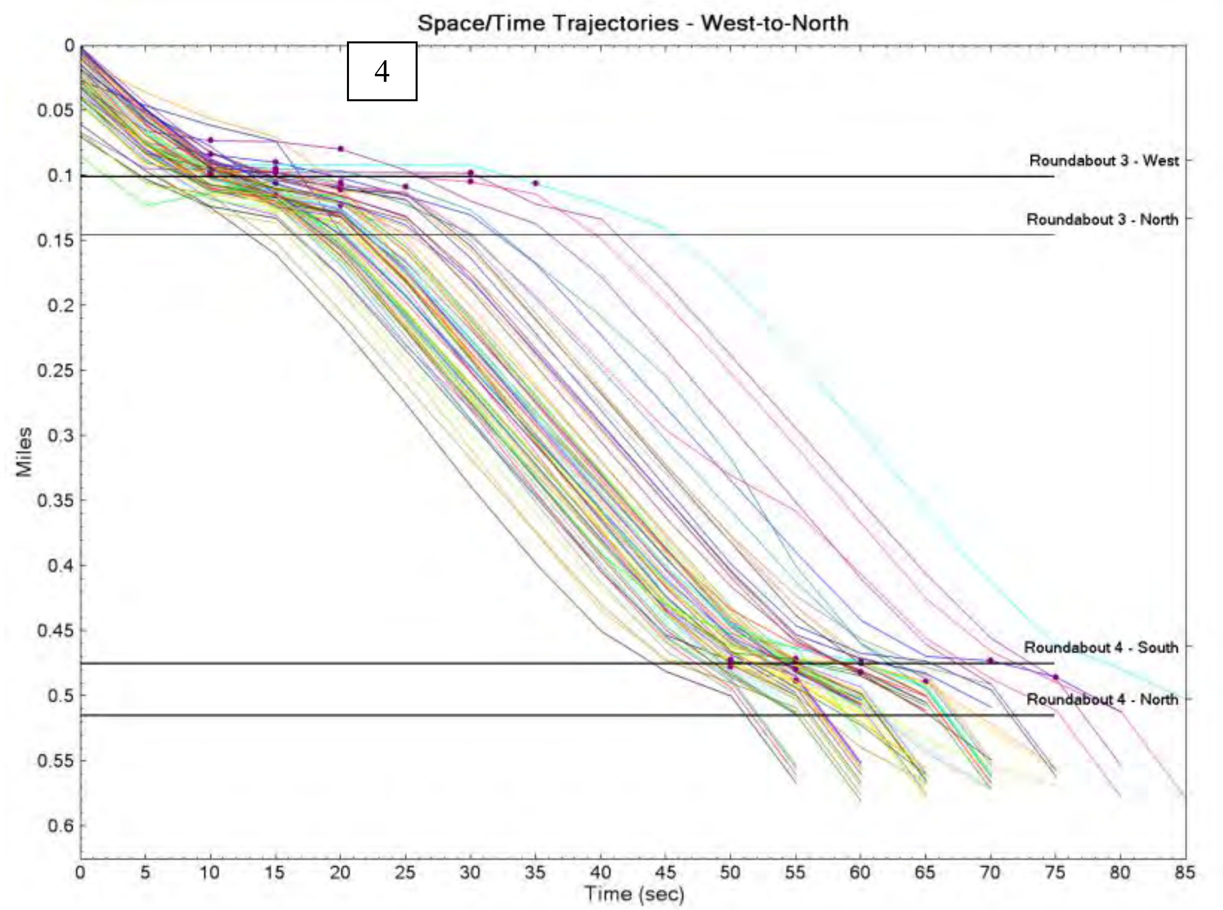

Figure 3D. Space-Time Trajectories for Route 4 (Starting from West of Roundabout 3, then Turning Left at Roundabout 3)

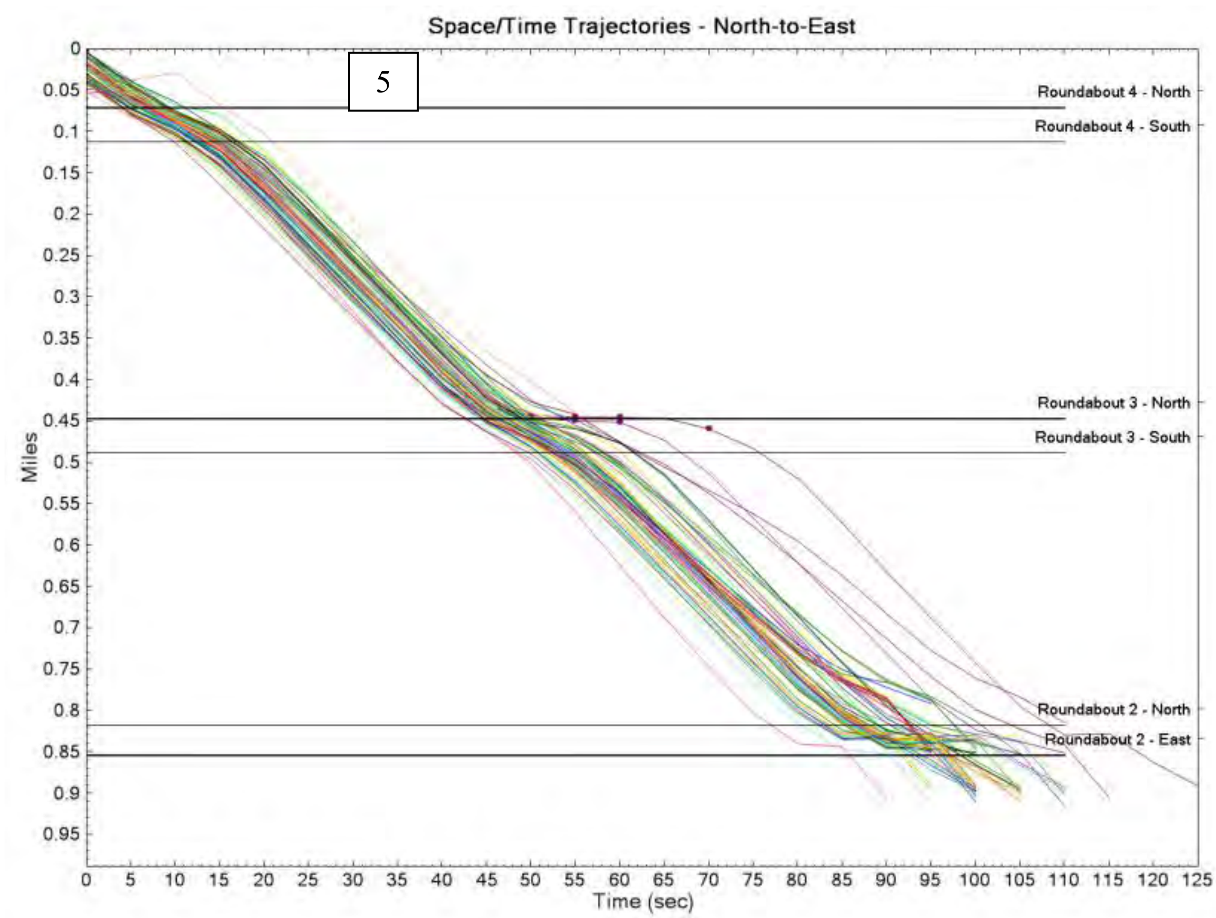

Figure 3E. Space-Time Trajectories for Route 5 (Starting from North of Roundabout 4, then Turning Left at Roundabout 2)

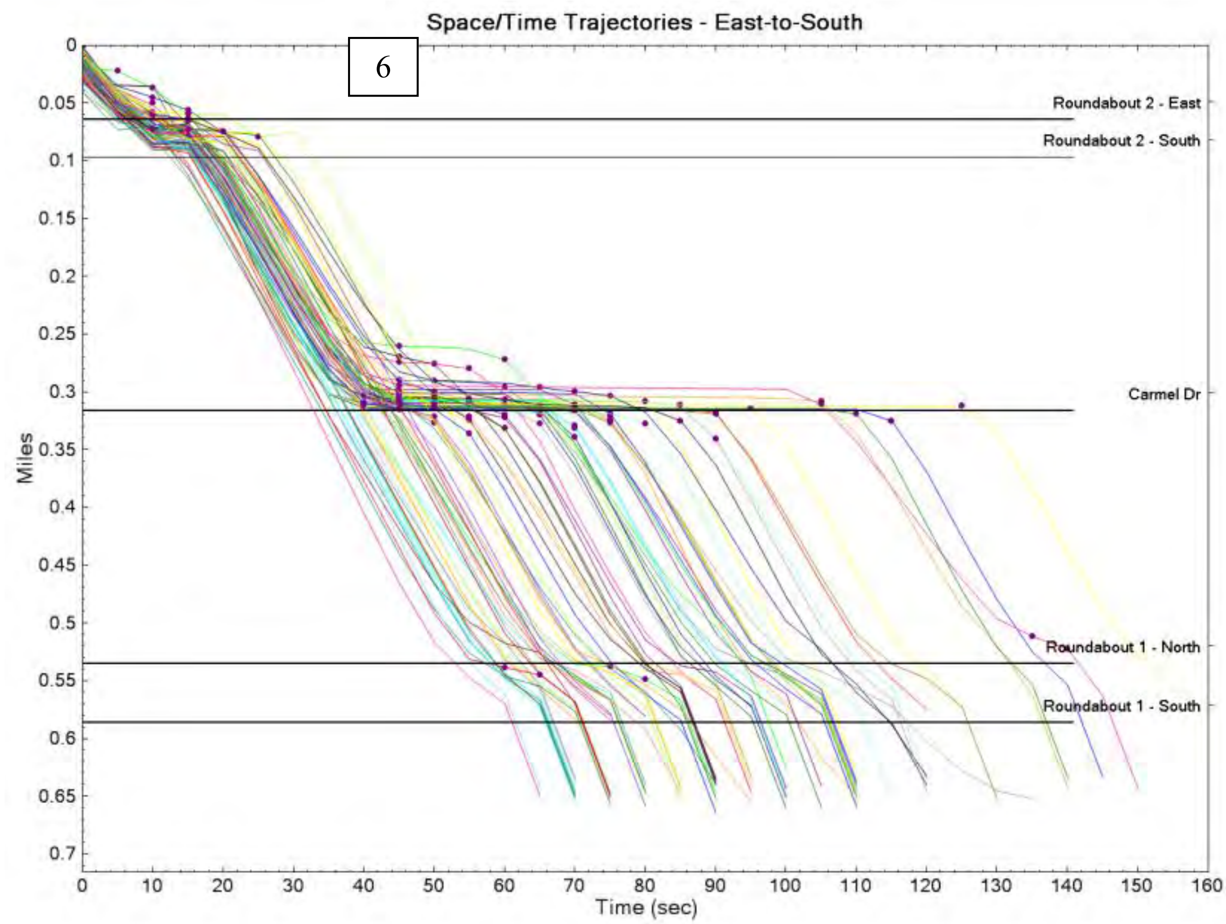

Figure 3F. Space-Time Trajectories for Route 6 (Starting from East of Roundabout 2, then Turning Left at Roundabout 2)

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening." A vehicle stop is denoted by a purple dot. The horizontal lines in the diagrams correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor is an indication of the variability in the observed data. The distance along the y-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed travel times. Note that most of the delay as well as variability in the observed travel times can be attributed to the signalized intersection at Carmel Drive (routes 1, 2, 3, and 6).

Table 3 presents more-detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in miles per hour, and all travel times are displayed in minutes. Using free-flow and unimpeded travel times, the table shows HCM Urban Streets Level of Service (based on % FFS) and average roundabout LOS (based on average control delay in seconds). The table shows how the difference in calculating these two levels of service can affect the results. The table indicates

that the LOS assigned to each route may vary using either method; the urban streets LOS tends to be lower than the roundabout LOS

Table 3: Summary of a.m., p.m., and Off-peak Travel Times

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)				Free-Flow Speed (mph)	% FFS	Urban Street LOS	Free-Flow TT (min)	Avg. RBT Geometric Delay (sec)	Travel Time Impeded Only by Geometric Delay (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min								
1. South-to-North	**86**	**26.4**	**3.4**	**32.6**	**19.3**	**3.03**	**0.43**	**4.08**	**2.33**	**40.2**	**65.7%**	**C**	**1.96**	**12.8**	**2.54**	**5.9**	**A**
AM	13	26.5	3.3	32.6	21.5	3.01	0.40	3.75	2.33		65.9%	C		12.6		5.7	A
Off	55	26.8	3.4	32.6	19.6	2.98	0.40	4.00	2.33		66.7%	C		12.2		5.3	A
PM	18	25.2	3.6	31.4	19.4	3.20	0.48	4.08	2.50		62.7%	C		14.9		8.0	A
2. North-to-South	**81**	**28.7**	**3.7**	**45.6**	**20.6**	**2.79**	**0.37**	**3.75**	**1.75**	**38.3**	**74.9%**	**B**	**2.07**	**8.6**	**2.49**	**3.6**	**A**
AM	12	31.6	6.2	45.6	25.6	2.71	0.39	3.17	1.75		82.5%	B		7.7		2.6	A
Off	51	28.8	3.0	34.2	22.6	2.77	0.32	3.52	2.33		75.2%	B		8.4		3.3	A
PM	18	27.6	3.8	32.4	20.6	2.93	0.45	3.75	2.42		72.1%	B		10.3		5.3	A
3. South-to-West	**76**	**26.0**	**4.8**	**34.9**	**14.6**	**2.44**	**0.47**	**4.12**	**1.67**	**40.2**	**64.7%**	**C**	**1.54**	**10.8**	**1.81**	**7.5**	**A**
AM	19	27.3	4.8	34.9	21.1	2.30	0.41	2.92	1.67		67.9%	B		9.1		5.8	A
Off	40	25.8	4.6	33.6	18.8	2.44	0.41	3.17	1.75		64.2%	C		10.8		7.5	A
PM	17	24.9	5.2	33.4	14.6	2.60	0.60	4.12	1.83		61.9%	C		12.7		9.4	A
4. West-to-North	**76**	**29.6**	**3.0**	**35.1**	**20.7**	**1.08**	**0.13**	**1.42**	**0.83**	**40.2**	**73.6%**	**B**	**0.79**	**3.5**	**0.97**	**1.3**	**A**
AM	18	29.7	4.3	35.1	20.7	1.08	0.16	1.42	0.83		73.9%	B		3.5		1.3	A
Off	42	30.0	2.4	34.8	23.0	1.05	0.10	1.42	0.92		74.6%	B		3.1		1.0	A
PM	16	28.4	2.6	33.2	24.3	1.14	0.12	1.33	0.92		70.6%	B		4.2		2.1	A
5. North-to-East	**80**	**31.6**	**1.5**	**35.0**	**26.8**	**1.67**	**0.10**	**2.08**	**1.50**	**38.3**	**82.5%**	**B**	**1.38**	**3.5**	**1.61**	**0.7**	**A**
AM	19	31.4	1.9	35.0	26.8	1.68	0.14	2.08	1.50		82.0%	B		3.6		0.9	A
Off	42	31.7	1.2	33.5	28.6	1.67	0.08	1.83	1.58		82.8%	B		3.5		0.7	A
PM	19	31.6	1.7	33.7	27.4	1.67	0.11	1.92	1.50		82.5%	B		3.5		0.7	A

Table 3 Continued

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)				Free-Flow Speed (mph)	% FFS	Urban Street LOS	Free-Flow TT (min)	Avg. RBT Geometric Delay (sec)	Travel Time Impeded Only by Geometric Delay (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min								
6. East-to-South	**78**	**24.2**	**5.0**	**34.4**	**13.5**	**1.60**	**0.36**	**2.67**	**1.08**	**38.3**	**63.2%**	**C**	**0.96**	**7.7**	**1.21**	**4.7**	**A**
AM	19	23.8	4.9	34.3	14.7	1.58	0.34	2.42	1.08		62.1%	C		7.4		4.5	A
Off	42	25.1	4.6	32.2	15.6	1.54	0.32	2.33	1.17		65.5%	C		7.0		4.0	A
PM	17	22.5	5.8	34.4	13.5	1.75	0.46	2.67	1.08		58.7%	C		9.5		6.5	A

Notes: FFS = free-flow speed, Rbt = roundabout, LOS = Level of Service, TT = travel time

3.2. **Spot Speed Profiles**

In addition to the travel time data, the team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at the end roundabouts (roundabouts 1 and 4), as well as in a midblock portion of the corridor (between roundabouts 2 and 3). These speeds were collected using a laser speed gun. These speed profiles will primarily be used to calibrate a geometric delay prediction model of the roundabout corridor, but they also provide an indication of the safety and performance of the roundabouts. Finally, these speeds provide a more realistic estimation of operating speeds at the roundabouts than the GPS travel time runs, which were conducted by engineers using the floating car technique. Summary statistics are displayed in Table 4. The spot speed measurements were broken down into 2-hour intervals to explore time of day trends. Each speed is measured either at the midblock between roundabouts, the circulating lane, the entry to the roundabout (near the yield line), or at the roundabout exit.

Table 4: Spot-Speed Summary Statistics

Point		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	Sample Size at Each Point
RBT #		2-3	2-3	1	1	1	4	4	4	
Location		SB – midblock	NB – midblock	NB – circulating	NB - exit	NB - entry	SB - circulating	SB - exit	SB - entry	
9-11am	Mean Speed (mph)	39.3	39.3	18.9	25.6	24.1	19.5	24.8	21.5	30
	StdDev. (mph)	3.7	4.1	2.4	3.1	3.2	2.0	3.7	3.0	
11am-1pm	Mean Speed (mph)	38.0	40.6	19.2	23.4	23.7	19.0	24.8	20.7	30
	StdDev. (mph)	3.3	3.9	1.6	2.1	2.4	2.5	3.9	2.7	
1-3pm	Mean Speed (mph)	37.7	39.8	17.4	24.9	27.5	19.9	25.3	21.3	30
	StdDev. (mph)	4.2	3.4	4.1	2.0	2.9	2.4	3.5	2.6	
3-5pm	Mean Speed (mph)	38.2	40.7	18.9	24.4	24.2	19.3	25.7	19.9	60
	StdDev. (mph)	3.6	3.7	2.0	2.6	3.7	2.2	3.0	2.8	
Combined	Mean Speed (mph)	38.3	40.2	18.7	24.6	24.7	19.4	25.2	20.7	150
	StdDev. (mph)	3.7	3.8	2.6	2.6	3.5	2.3	3.4	2.8	

The speed measurements from the combined dataset were also analyzed using histogram frequency distributions—all eight are displayed in Figure 4. These histograms indicate the variance and skew of each speed profile.

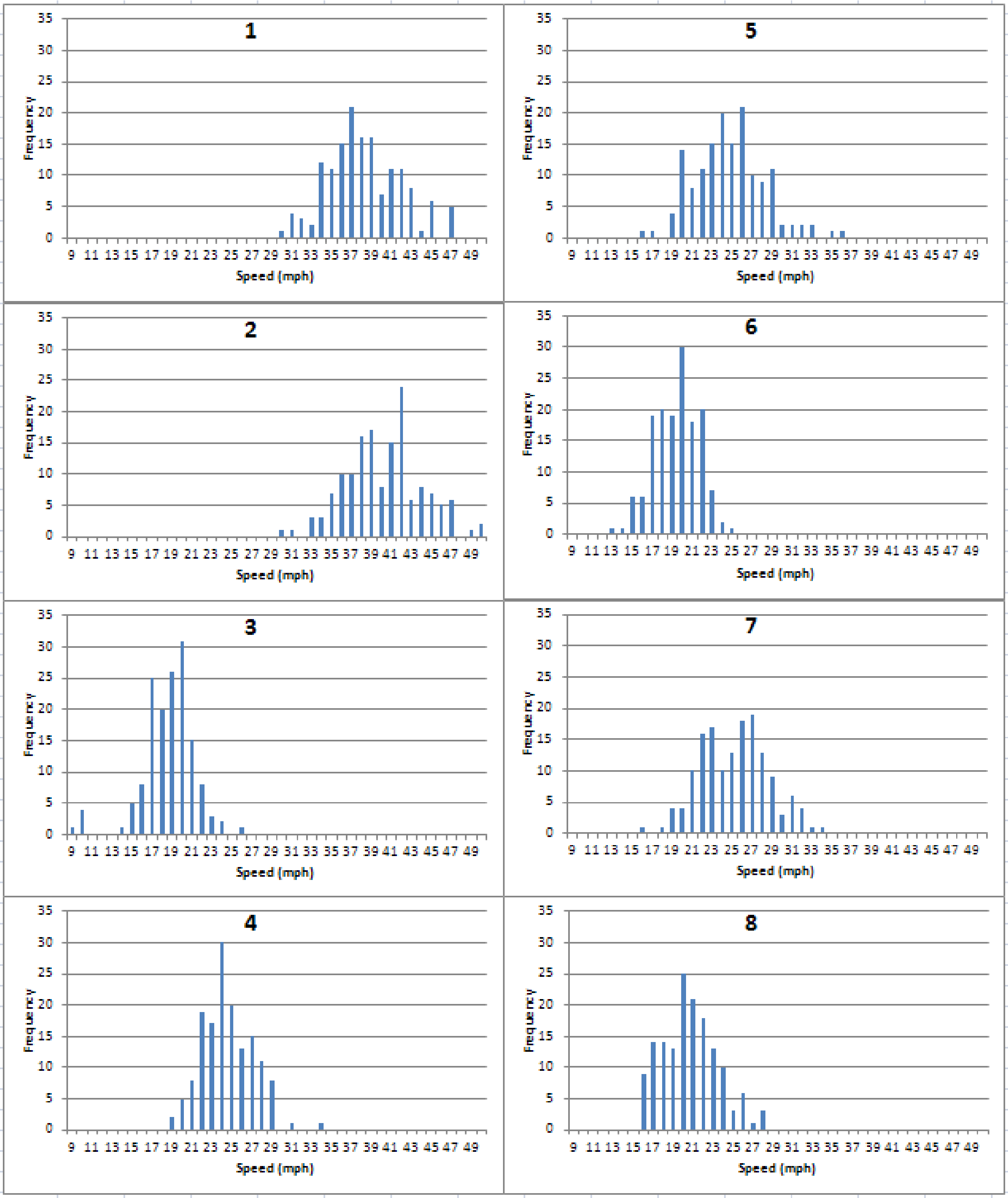

Figure 3: Spot-Speed Histograms

4. Appendix

4.1. Appendix D1: Aerial Imagery

Figure B1. Old Meridian St at Pennsylvania St

Figure B2. Old Meridian St at Carmel Dr (Signalized)

Figure B3. Old Meridian St at Grand Blvd

Figure B4. Old Meridian St at Main St

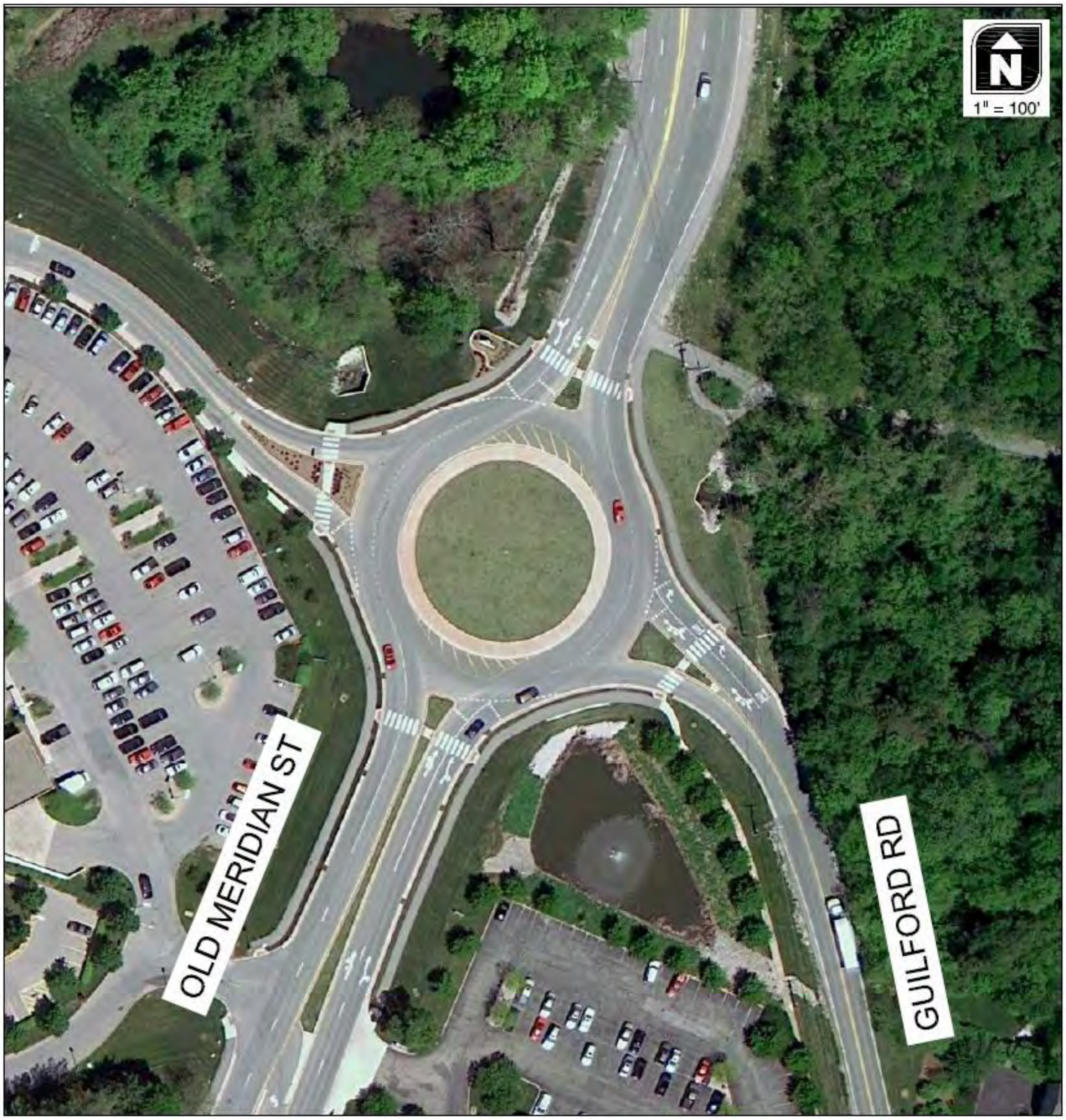

Figure B5. Old Meridian St at Guilford Rd

4.2. **Appendix D2: Speed Profiles**

The speed profiles below correspond to the space-time trajectories for each of the six routes in Figures 3A through 3F.

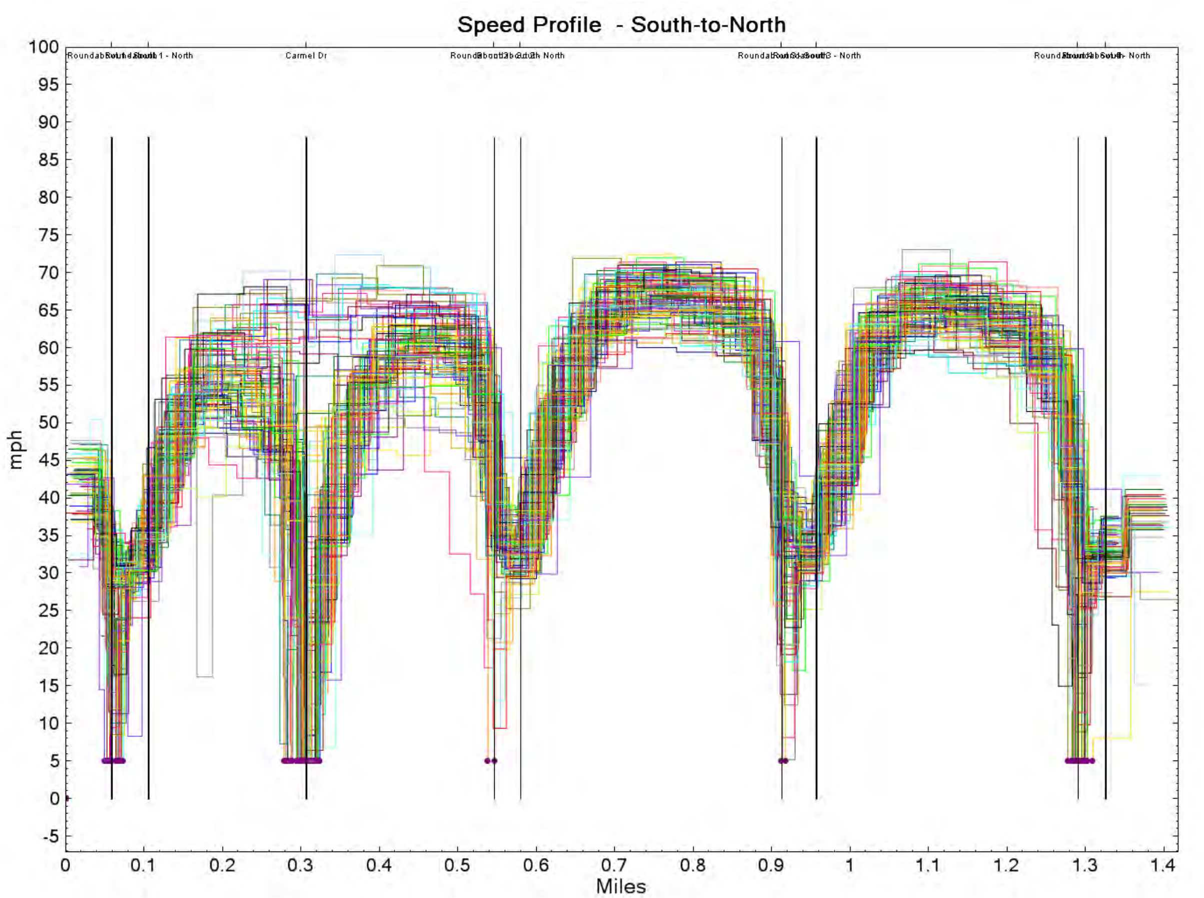

Figure B1. Speed Profile for Route 1 (Northbound Through the Entire Corridor)

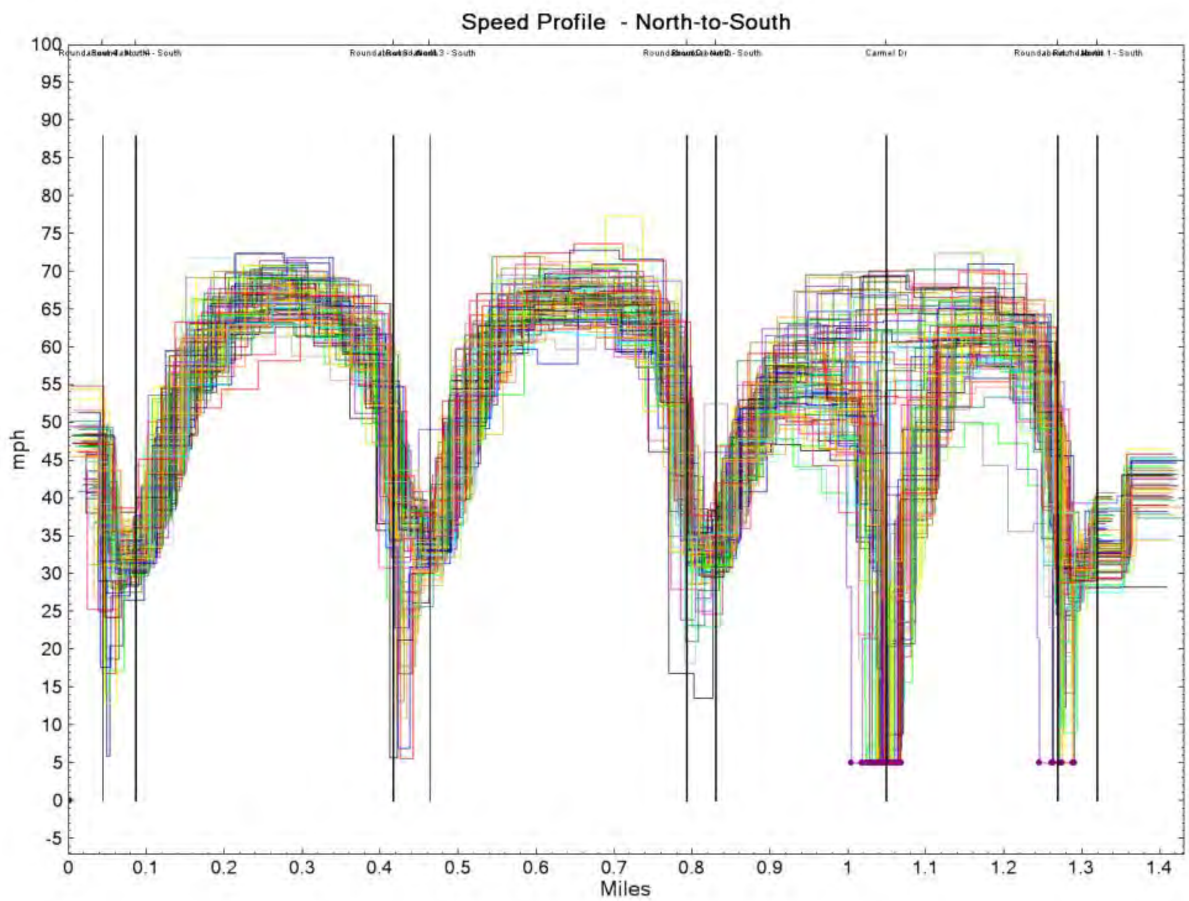

Figure B2. Speed Profile for Route 2 (Southbound Through the Entire Corridor)

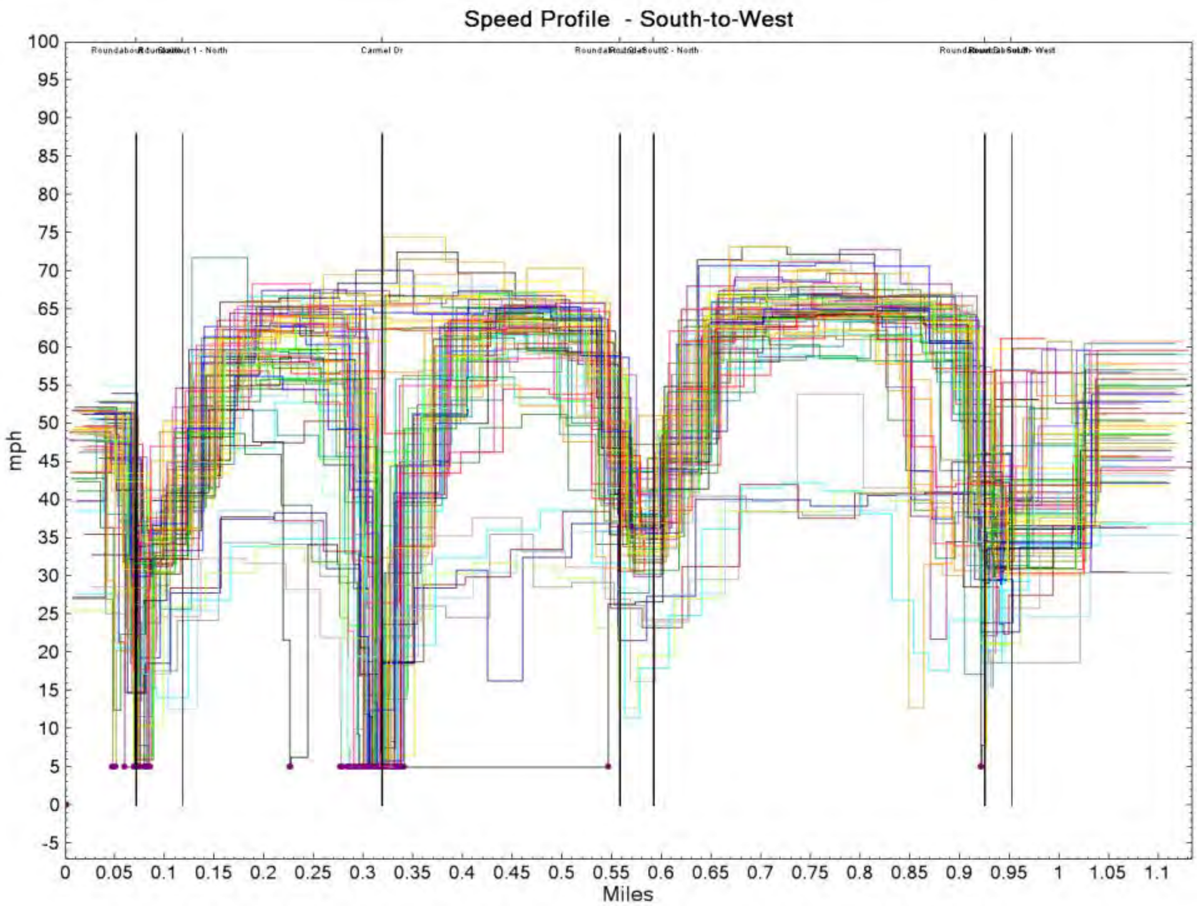

Figure B3. Speed Profile for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 1)

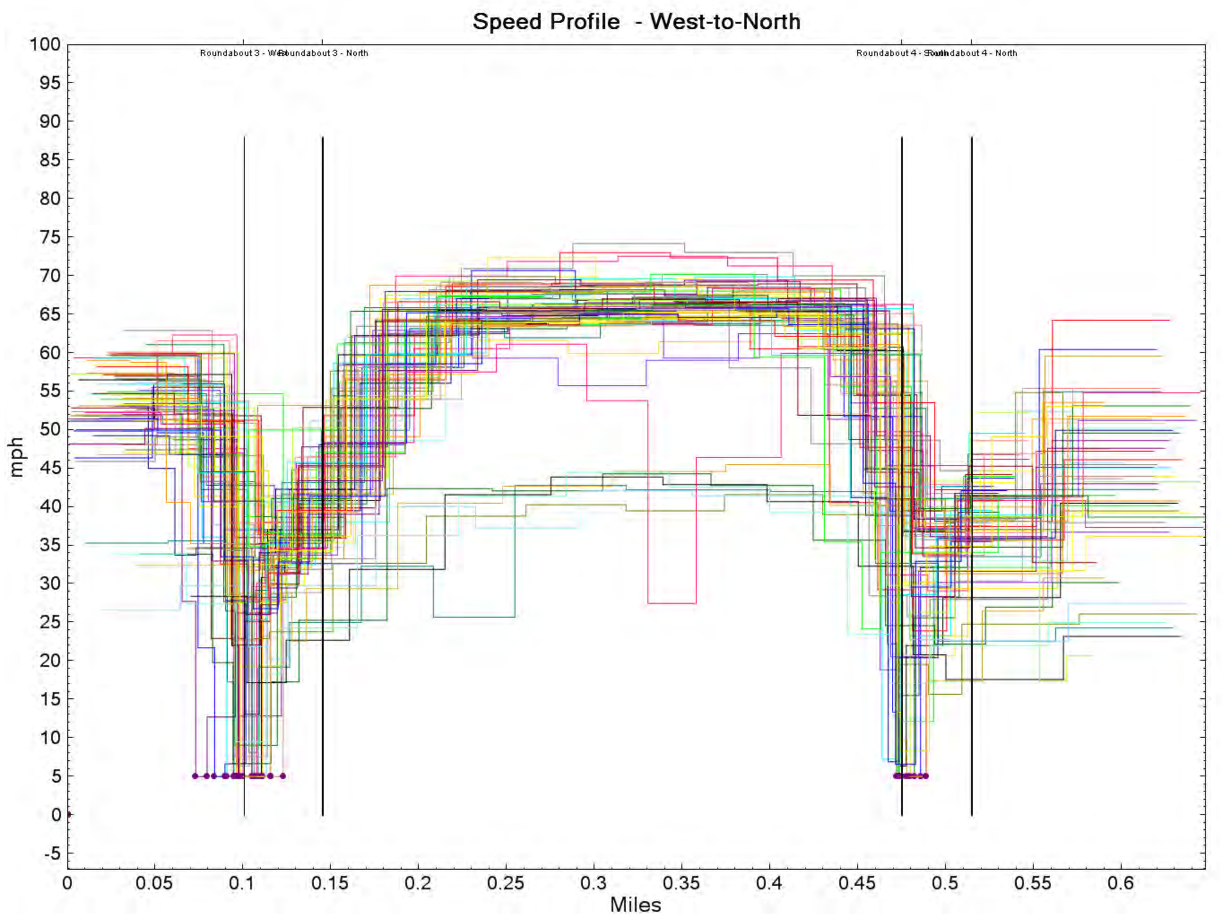

Figure B4. Speed Profile for Route 4 (Starting from West of Roundabout 3, then Turning Left at Roundabout 3)

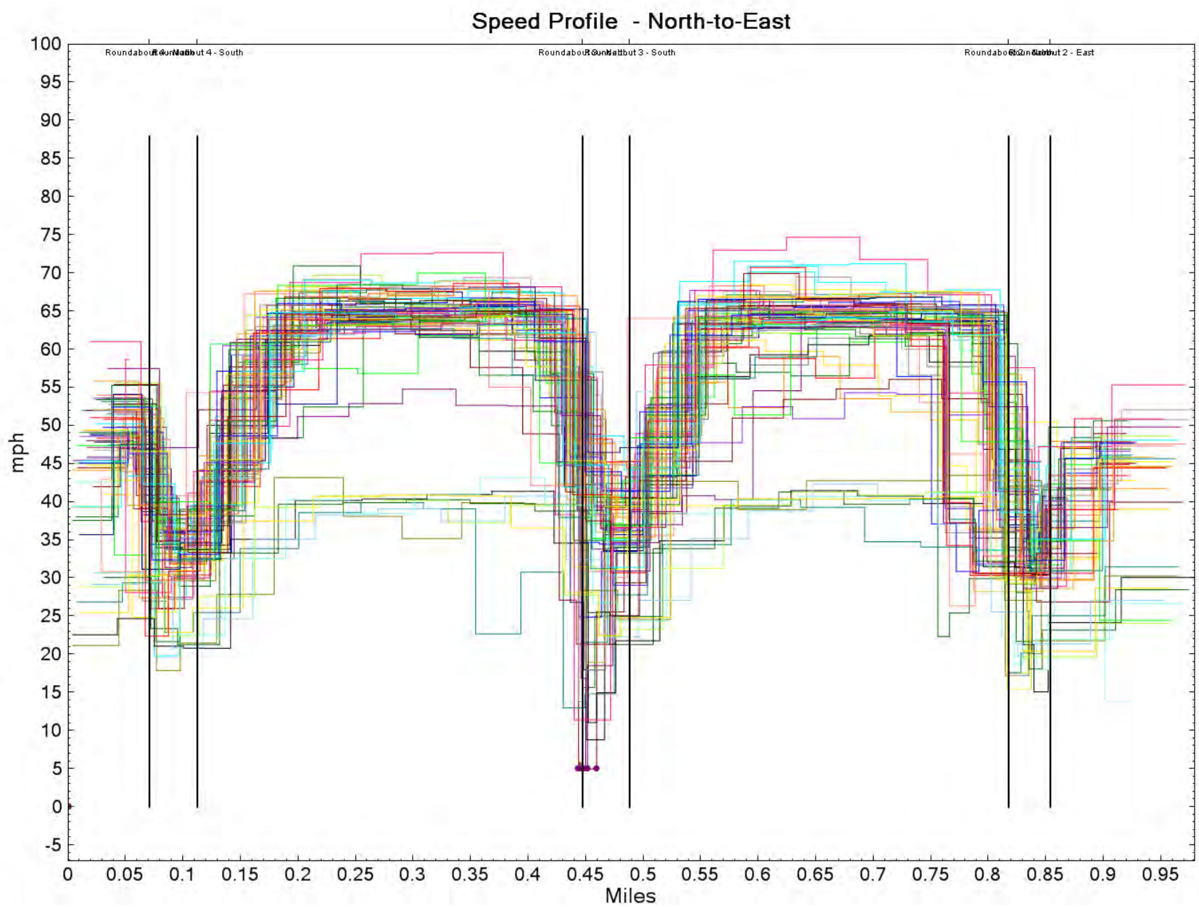

Figure B5. Speed Profile for Route 5 (Starting from North of Roundabout 4, then Turning Left at Roundabout 2)

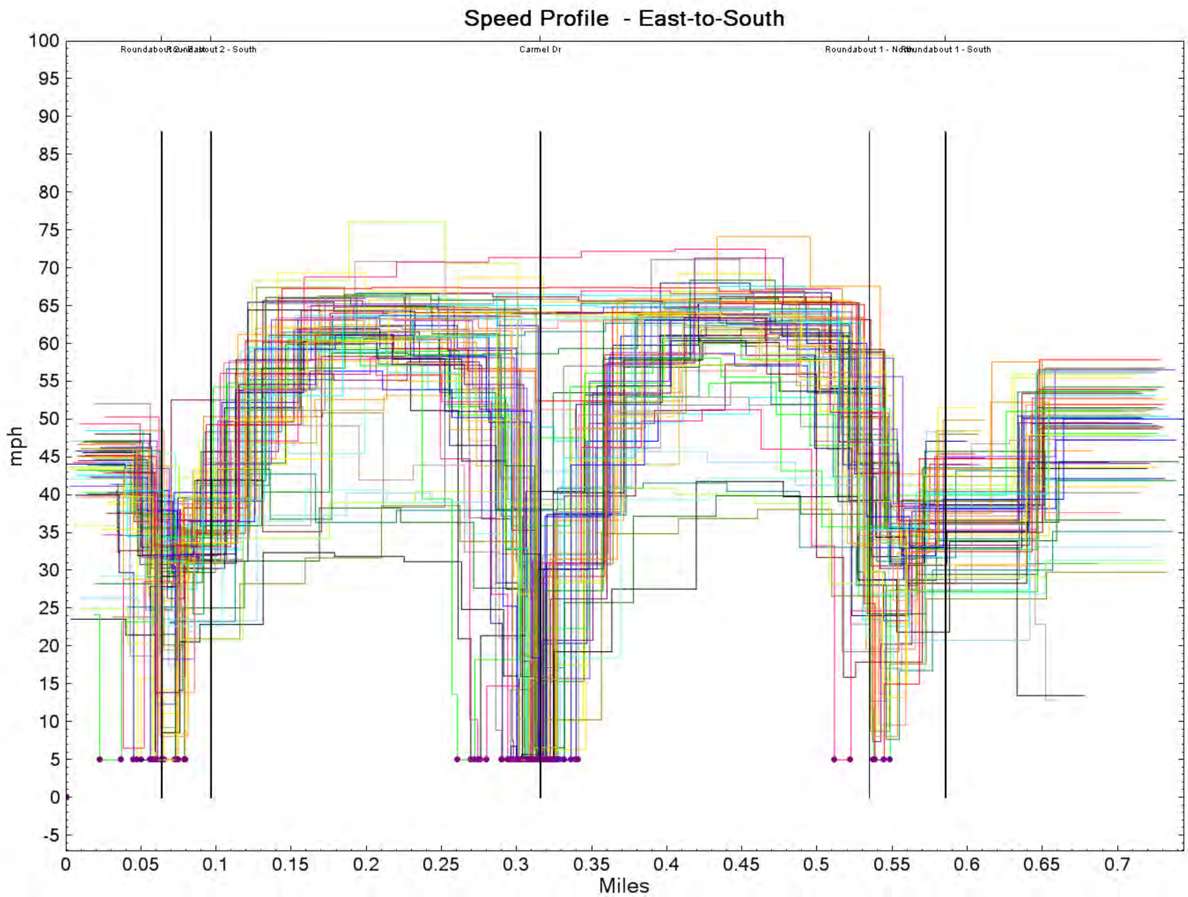

Figure B6. Speed Profile for Route 6 (Starting from East of Roundabout 2, then Turning Left at Roundabout 2)

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NCHRP 03-100

Appendix E

Carmel, Indiana
Spring Mill Road Field Data

Table of Contents

List of Tables

List of Figures

1. Introduction

This document describes the field data collected by the NCHRP 03-100 team at the Spring Mill Road roundabout corridor in Carmel, Indiana. Data collection and analysis follows the format described in the team's data collection plan.

The data collected at this roundabout corridor, which consisted of seven roundabouts in series, included peak-hour and off-peak travel times and spot speed measurements. Travel times were recorded using vehicle-mounted GPS units. Additionally, video data were obtained through field-mounted cameras. Data were collected between May 15, 2012, and May 17, 2012.

This document provides an overview of the data collected and discusses the quality and size of the dataset, with comprehensive data provided in the appendix. Figure 1 displays a split-screen schematic of the corridor. The white numbers denote roundabouts.

The roundabout corridor on Spring Mill Road consists of seven roundabouts over a distance of approximately 4.5 miles. A description of the seven roundabout intersections is shown in Table 1. The corridor runs approximately the entire length of the Carmel city limits, with Indianapolis on the south beginning around 96th Street and the community of Westfield north of 146th Street. As shown in Figure 1, Spring Mill Road runs essentially in a straight line south-to-north; all of the crossing streets intersect at angles of roughly 90 degrees.

Table 1: Description of Roundabout Intersections

Number	Cross Street	Legs	Remarks
1	96th St.	4	96th St. is a major arterial at this location and is the major road at this intersection, with two approach lanes from both the east and west legs.
2	106th St.	4	Single-lane approaches on all legs. Traffic volumes are fairly low, though there is increased traffic during the AM and PM peak periods.
3	116th St.	4	116th St. is a major arterial at this location and is the major road at this intersection. The westbound approach has two lanes, one of which is separated into a dedicated right-turn lane. Traffic seemed steady at this intersection, particularly from the westbound approach, with noticeable AM and PM peak volumes.
4	Dorset Blvd.	4	A small roundabout that serves entrances to residential developments. Typically very little crossing traffic at this intersection.
5	Main St.	4	The only roundabout in the corridor where Spring Mill has two approach lanes, and those are only on the northbound approach (left-turn only and shared through/right). The westbound approach on Main also has two approach lanes (shared left/through and a right-turn only lane). The intersection has some level of traffic throughout the day, both from crossing vehicles and from ped/bike traffic.
6	136th St.	4	Like Main St., 136th St. is a minor arterial with commensurate levels of traffic, with increased volumes during the AM and PM peaks and ped/bike traffic periodically throughout the day
7	141st St.	3	Serves a residential neighborhood to the west. Low traffic volumes, though increased activity could be seen leaving the neighborhood in the morning and returning in the evening.

Surrounding development on Spring Mill Road is a mix of single-family residential, agricultural, and undeveloped. Spring Mill Road is a two-lane minor arterial, with a divided cross-section south of Main Street and a raised median north of Main Street. The portion of the corridor near Dorset Boulevard is somewhat of a transition area from the more rural surroundings on the south end of the corridor (with narrower lanes, little to no shoulder, and numerous trees close to the roadside) to the suburban fringe environment on the north end (with wide lanes, curb-and-gutter treatment, and wide multi-use paths separated from the roadway with grass buffers). In addition to the seven roundabout intersections, there are numerous residential driveways as well as three-leg and four-leg intersections with minor roads that are stop-controlled on the minor roads.

Figure 1. Aerial View of the Spring Mill Road Roundabout Corridor.

Only two roundabouts on the Spring Mill Road corridor had two-lane approaches (Main Street and 96th Street), although the generous cross-section at 96th St. seemed to make lane-keeping less problematic than at Main Street. Northbound Spring Mill Road drivers at Main Street frequently straddled the solid lane line on the approach, and the pavement markings in the circulatory roadways at both Main St. and 96th St. were very worn and barely visible in some places. Congestion on Spring Mill Road was also not common, though the presence of only a single lane on Spring Mill Road contributed to longer queues than if there were two approach lanes. Southbound traffic traveling toward Indianapolis in the morning showed some queues at 136th St., Main Street, and 116th Street in particular, and northbound queues were observed in the evening at 96th Street, 116th Street, Main Street, and 136th Street for short periods on selected days. Some eastbound and westbound queues also developed at these locations. However, the queues typically had dissipated within one round-trip on the travel-time runs.

2. Traffic Counts

The research team has obtained the traffic counts and turning movement counts for each of the intersections along the corridor. Table 2 displays the turning movement counts during the a.m. and p.m. peak periods for each intersection. Spring Mill Road comprises the north- and southbound directions of each roundabout.

Table 2: Turning Movement Counts

Intersection		AM				PM			
#	Name	Approach	Left	Through	Right	Approach	Left	Through	Right
1	96th St	NB	10	182	88	NB	48	328	92
		SB	278	498	82	SB	148	422	124
		EB	150	558	56	EB	44	430	68
		WB	24	380	114	WB	96	598	352
2	106th St	NB	22	216	98	NB	88	592	26
		SB	332	794	32	SB	74	546	94
		EB	24	388	54	EB	32	364	60
		WB	52	236	58	WB	36	480	156
3	116th St	NB	32	84	194	NB	78	562	106
		SB	116	774	18	SB	50	378	72
		EB	16	360	170	EB	68	410	134
		WB	278	246	24	WB	214	588	202
4	Dorset Blvd.	NB	6	96	22	NB	34	816	32
		SB	26	786	0	SB	16	322	14
		EB	26	156	52	EB	8	48	16
		WB	18	20	4	WB	136	74	96
5	131st St/ Main St	NB	2	84	46	NB	128	720	64
		SB	564	792	68	SB	134	296	72
		EB	8	336	12	EB	150	284	36
		WB	6	180	80	WB	24	302	390
6	136th St	NB	30	154	20	NB	80	1,030	66
		SB	110	1,190	52	SB	92	390	28
		EB	24	136	144	EB	46	116	46
		WB	46	110	76	WB	40	182	134
7	141st St	NB	64	214	0	NB	164	950	0
		SB	0	1,054	76	SB	0	384	58
		EB	122	0	188	EB	104	0	102

Figure 2 displays the 12-hour volume profiles for the corridor between 131st Street and 136th Street. The peak hour was identified to be between 4:45 p.m. and 5:45 p.m.

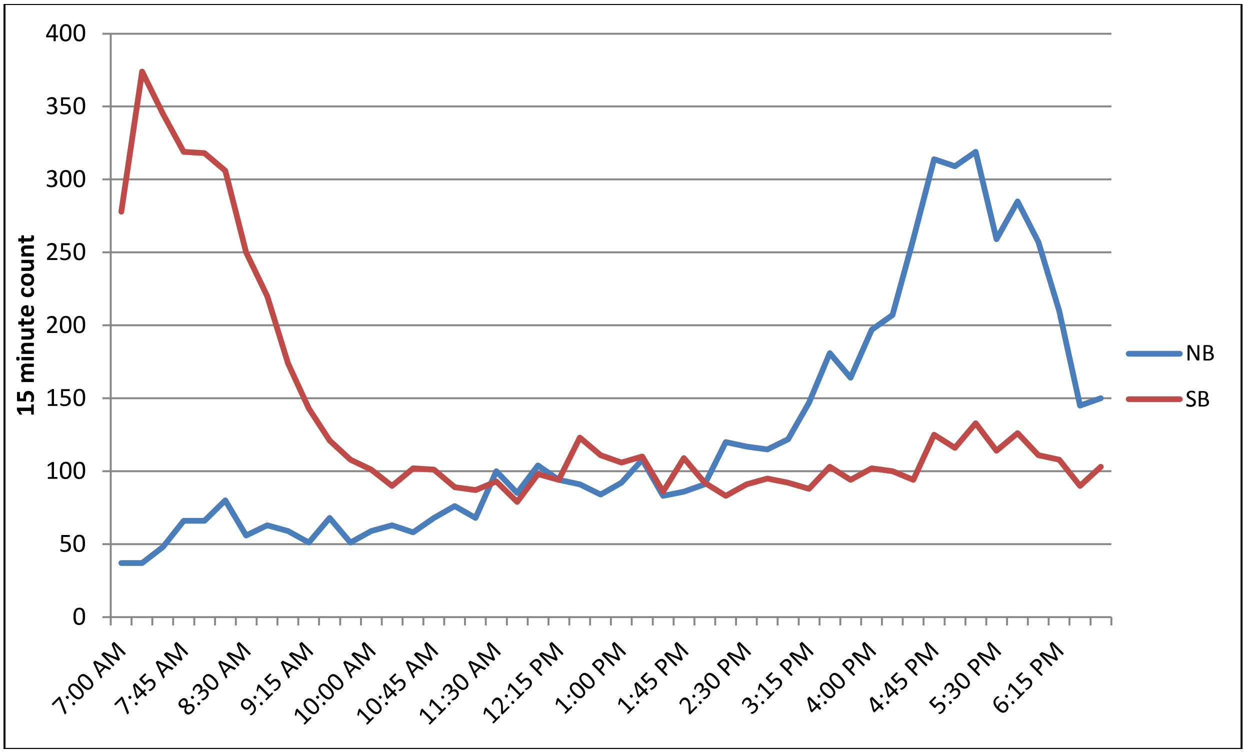

Figure 2:12-hour Volume Profile

3. Field-Observed Data

GPS travel times and spot-speed data were collected along the corridor.

3.1. GPS Travel Times

The travel time through the corridor was also measured using vehicle-mounted GPS units. A total of six routes were used to conduct the study:

1. Northbound through the entire corridor;
2. Southbound through the entire corridor;
3. Starting from the south end, then turning left through roundabout 6 (136th Street);
4. Starting from west of roundabout 6, (136th Street) then turning left through the roundabout and proceeding to the north end;
5. Starting from the north end, then turning left through roundabout 5 (131st Street); and
6. Starting east of roundabout 5 (131st Street), then turning left through the roundabout and proceeding to the south end.

The last four routes were used to capture left-turns through the two roundabouts that the team deemed the most congested. Figures 3A through 3F display the space-time trajectories from each of the six routes. Each diagram displays every travel time run that was conducted (including a.m., p.m., and off-peak runs). Note that the scale varies from route to route. The corresponding speed profiles are displayed in Appendix E2.

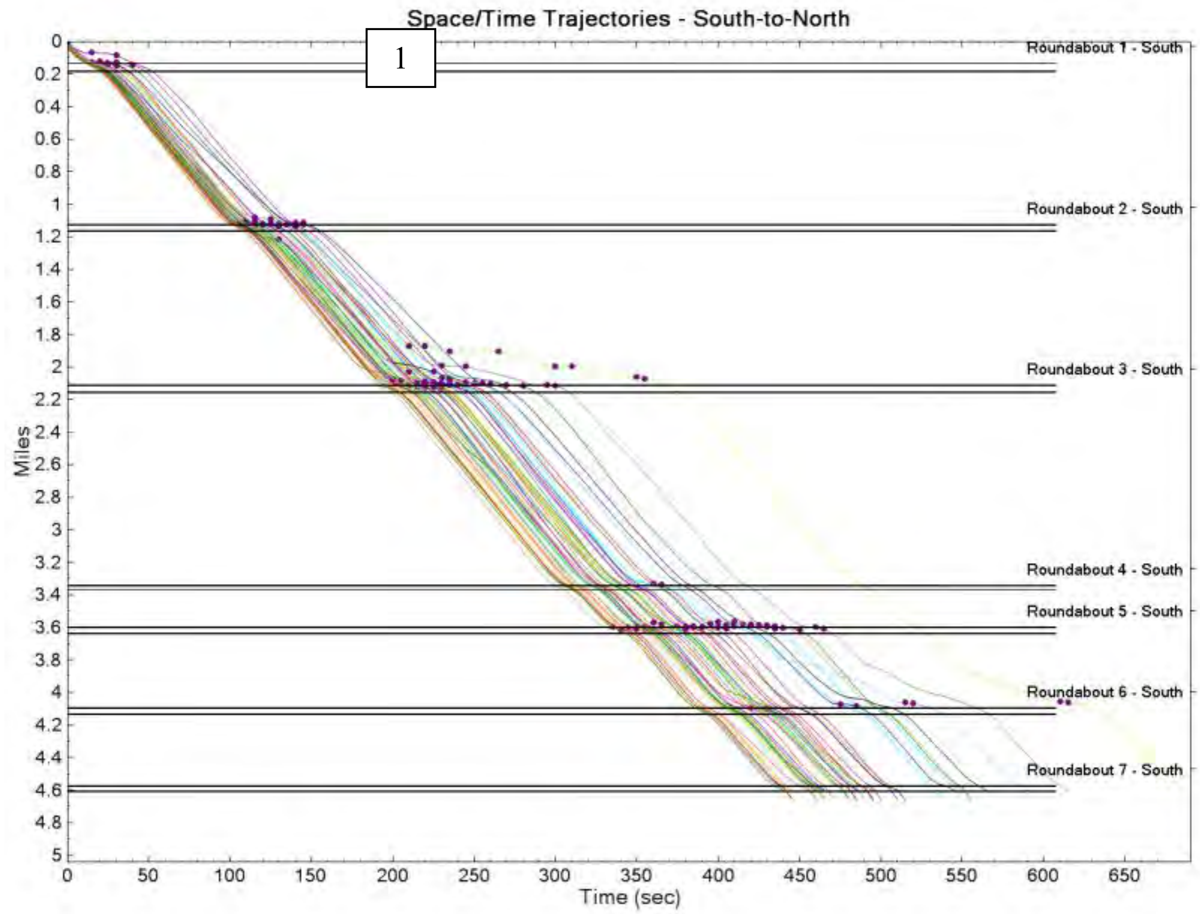

Figure 3A. Space-Time Trajectories for Route 1 (Northbound Through the Entire Corridor)

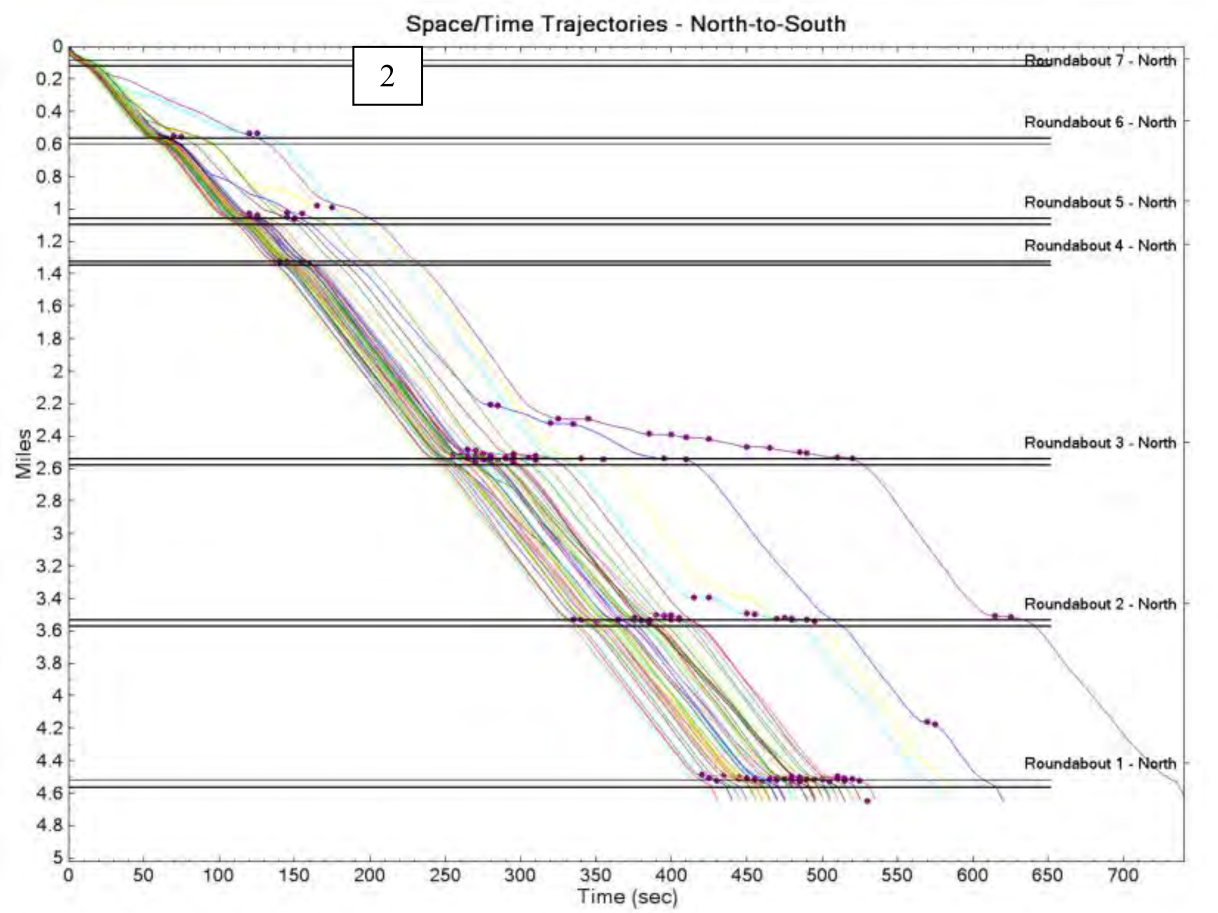

Figure 3B. Space-Time Trajectories for Route 2 (Southbound Through the Entire Corridor)

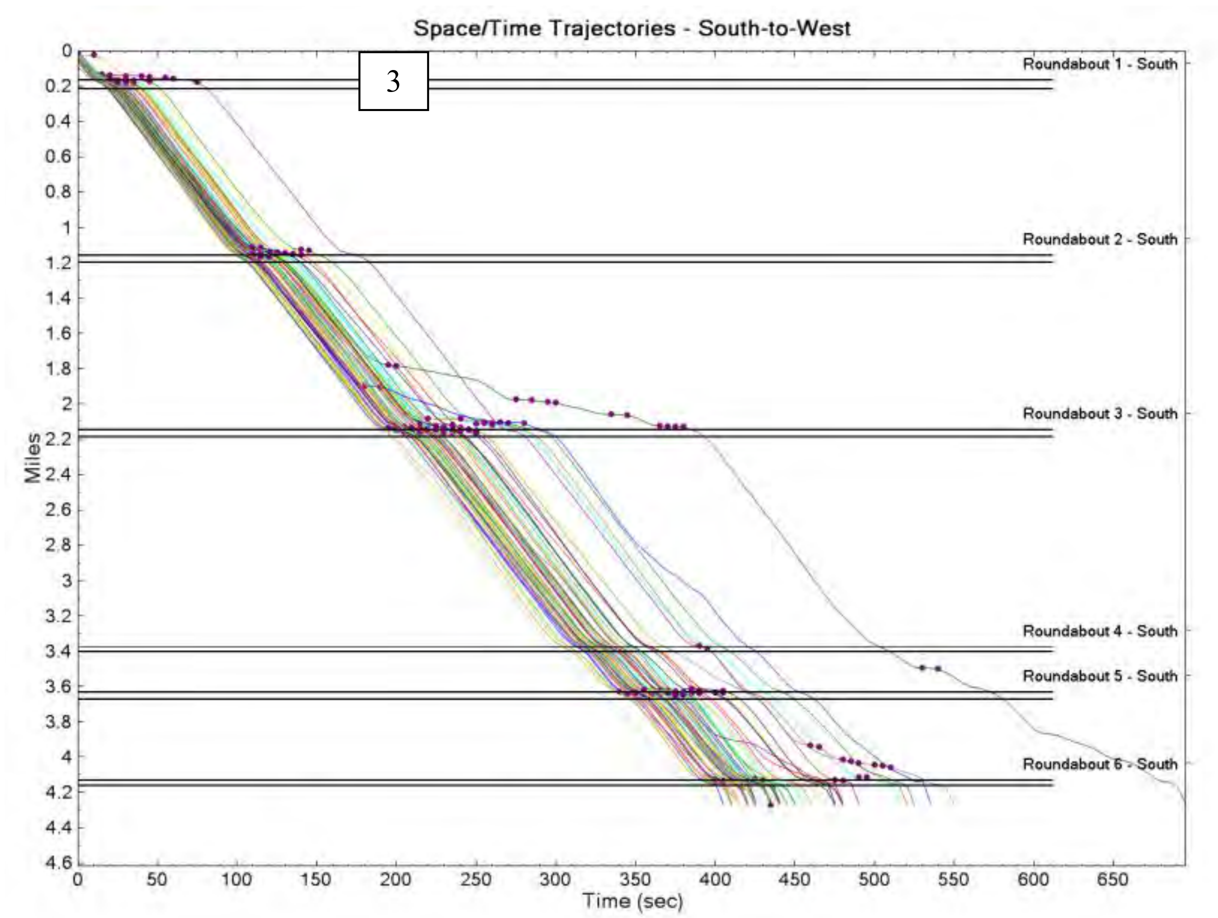

Figure 3C. Space-Time Trajectories for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 6)

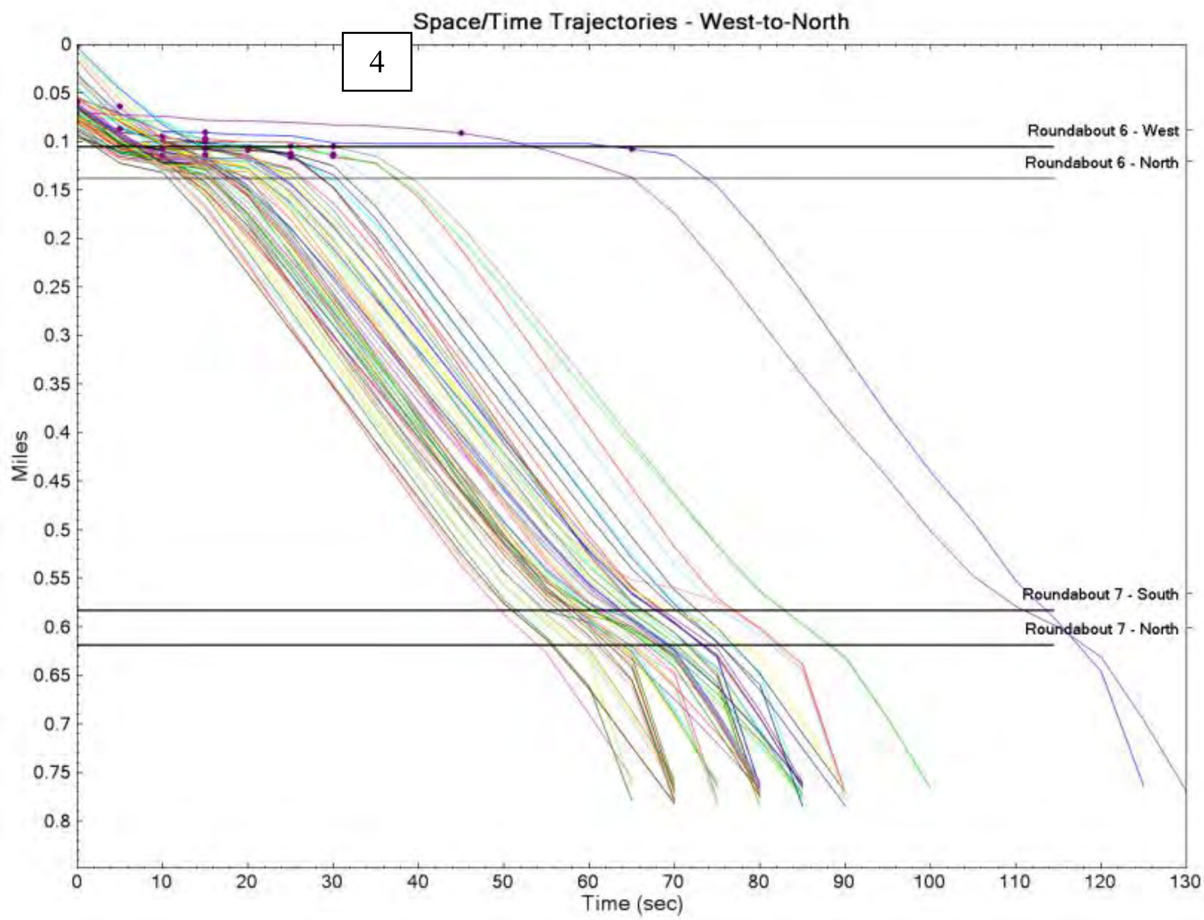

Figure 3D. Space-Time Trajectories for Route 4 (Starting from West of Roundabout 6, then Turning Left at Roundabout 6)

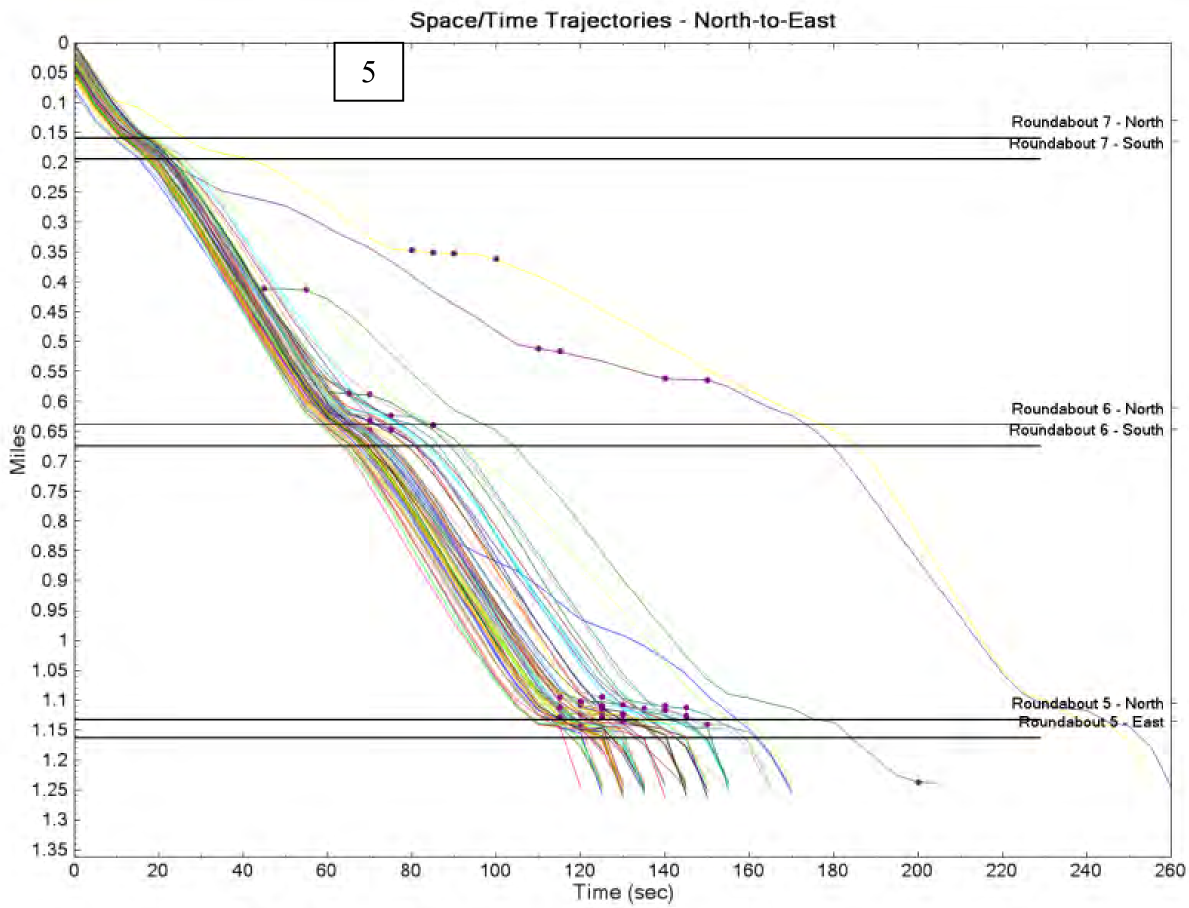

Figure 3E. Space-Time Trajectories for Route 5 (Starting from North of Roundabout 7, then Turning Left at Roundabout 5)

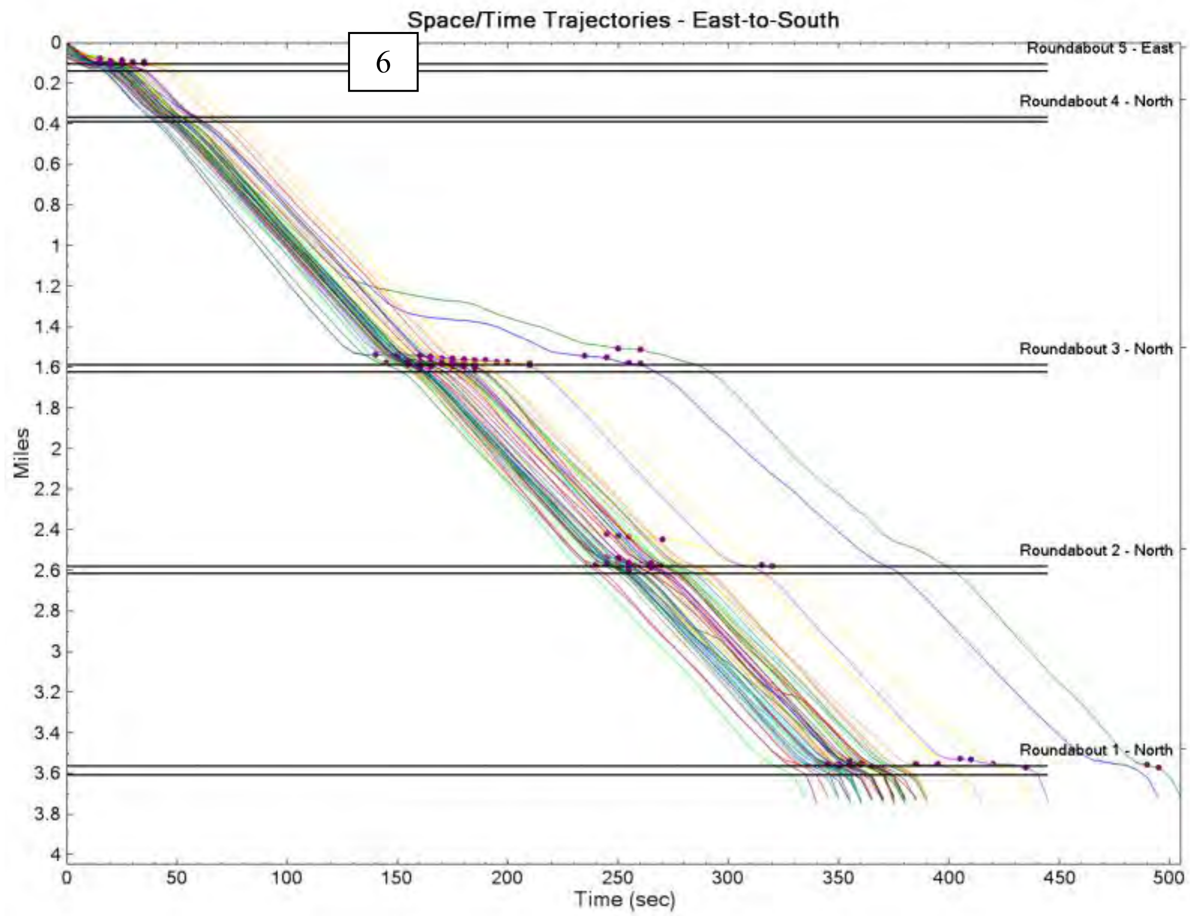

Figure 3F. Space-Time Trajectories for Route 6 (Starting from East of Roundabout 5, then Turning Left at Roundabout 5)

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening." A vehicle stop is denoted by a purple dot. The horizontal in the diagrams correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor therefore is an indication of the variability in the observed data. The distance along the y-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

Table 3 presents more-detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in miles per hour, and all travel times are displayed in minutes. Using free-flow and unimpeded travel times, the table shows HCM Urban Streets Level of Service (based on % FFS) and average roundabout Level of service (based on average control delay in seconds). The table indicates that the LOS assigned to each route may vary using either method; the urban streets LOS tends to be lower than the roundabout LOS.

Table 3: Summary of AM, PM, and Off-peak Travel Time

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)				Free-Flow Speed (mph)	% FFS	Urban Street LOS	Free-Flow TT (min)	Avg. RBT Geometric Delay (sec)	TT Impeded Only by Roundabout Geometry (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min								
1. South-to-North	**50**	**33.9**	**2.9**	**37.5**	**24.1**	**8.21**	**0.82**	**11.50**	**7.33**	**42.4**	**80.0%**	**B**	**6.51**	**20.4**	**7.59**	**7.4**	**A**
AM	11	33.5	2.1	36.0	29.9	8.29	0.54	9.25	7.67		79.0%	B		21.4		8.4	A
Off	30	35.2	1.7	37.5	30.9	7.86	0.40	9.00	7.33		83.0%	B		16.2		3.2	A
PM	9	30.1	3.7	35.6	24.1	9.28	1.18	11.50	7.75		71.0%	B		33.2		20.2	C
2. North-to-South	**51**	**34.1**	**3.0**	**38.8**	**22.1**	**8.13**	**0.88**	**12.33**	**7.08**	**41.3**	**82.6%**	**B**	**6.64**	**17.9**	**7.48**	**7.8**	**A**
AM	13	31.1	3.9	35.9	22.1	8.97	1.29	12.33	7.67		75.3%	B		28.0		17.9	C
Off	29	35.5	1.6	38.8	32.5	7.75	0.35	8.42	7.08		86.0%	A		13.3		3.2	A
PM	9	33.8	1.9	36.2	30.8	8.17	0.51	8.92	7.58		81.8%	B		18.4		8.3	A
3. South-to-West	**67**	**34.1**	**2.7**	**37.9**	**21.9**	**7.44**	**0.74**	**11.58**	**6.58**	**42.4**	**80.4%**	**B**	**5.94**	**18.0**	**6.97**	**5.7**	**A**
AM	15	34.8	1.7	37.2	30.9	7.25	0.38	8.17	6.75		82.1%	B		15.7		3.4	A
Off	39	35.2	1.2	37.9	31.6	7.17	0.27	7.92	6.58		83.0%	B		14.8		2.4	A
PM	13	30.1	3.2	34.7	21.9	8.48	1.09	11.58	7.25		71.0%	B		30.5		18.2	C
4. West-to-North	**65**	**30.6**	**3.4**	**37.0**	**18.8**	**1.35**	**0.19**	**2.17**	**1.08**	**42.4**	**72.2%**	**B**	**0.96**	**4.7**	**1.19**	**2.0**	**A**
AM	14	28.0	4.7	35.8	18.8	1.50	0.30	2.17	1.08		66.0%	C		6.5		3.8	A
Off	39	31.6	2.6	37.0	24.5	1.29	0.12	1.67	1.08		74.5%	B		4.0		1.2	A
PM	12	30.6	2.3	33.2	25.4	1.35	0.10	1.50	1.17		72.2%	B		4.7		2.0	A
5. North-to-East	**70**	**30.7**	**3.7**	**35.5**	**16.7**	**2.40**	**0.41**	**4.33**	**2.00**	**41.3**	**74.3%**	**B**	**1.76**	**7.7**	**2.17**	**2.7**	**A**
AM	17	27.1	4.8	33.6	16.7	2.78	0.64	4.33	2.17		65.6%	C		12.2		7.3	A
Off	40	32.3	1.9	35.5	28.1	2.23	0.14	2.58	2.00		78.2%	B		5.6		0.7	A
PM	13	30.4	3.1	34.1	25.5	2.42	0.23	2.83	2.17		73.6%	B		7.9		3.0	A
6. East-to-South	**58**	**35.3**	**2.5**	**39.6**	**26.3**	**6.29**	**0.52**	**8.42**	**5.58**	**41.3**	**85.5%**	**A**	**5.35**	**11.3**	**5.94**	**4.2**	**A**
AM	14	34.0	3.4	38.1	26.3	6.57	0.78	8.42	5.83		82.3%	B		14.6		7.6	A
Off	33	36.2	1.3	39.6	34.1	6.10	0.23	6.50	5.58		87.7%	A		9.0		2.0	A
PM	11	34.2	2.6	37.8	29.4	6.50	0.51	7.42	5.83		82.8%	B		13.8		6.8	A

3.2. **Spot Speed Profiles**

In addition to the travel time data, the team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at the easternmost and westernmost roundabouts (Figure 1). These speeds were collected using a laser speed gun. These speed profiles will primarily be used to calibrate a running speed prediction model for the roundabout corridor, but they also provide an indication of the safety and performance of the roundabouts. Finally, these speeds provide a more realistic estimation of operating speeds at the roundabouts than the GPS travel time runs, which were conducted by engineers using the floating car technique. Summary statistics are displayed in Table 4. The spot speed measurements were broken down into 2-hour intervals to explore time of day trends.

Table 4: Spot Speed Summary Statistics

Point		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	Sample Size at Each Point
RBT #		3-4	3-4	7	7	7	1	1	1	
Location		SB - midblock	NB - midblock	NB - circ	NB - exit	SB - entry	SB - circ	SB - exit	NB - entry	
9-11am	Mean Speed (mph)	40.5	41.5	19.0	26.9	26.1	19.4	28.6	24.1	30
	StdDev. (mph)	3.9	4.0	2.3	3.7	3.1	2.3	2.6	3.3	
11am-1pm	Mean Speed (mph)	41.7	43.3	21.5	25.4	25.0	19.4	28.6	22.6	30
	StdDev. (mph)	3.6	3.7	3.5	2.8	3.1	1.9	3.1	2.4	
1-3pm	Mean Speed (mph)	41.8	41.3	20.3	26.0	27.2	18.5	27.5	23.8	30
	StdDev. (mph)	3.3	2.1	3.3	1.9	2.9	2.5	1.7	3.3	
3-5pm	Mean Speed (mph)	41.2	43.0	20.0	26.0	22.0	20.2	30.3	22.9	60
	StdDev. (mph)	3.9	3.2	3.2	2.2	4.0	2.2	3.8	3.0	
Combined	Mean Speed (mph)	41.3	42.4	20.2	26.1	24.5	19.5	29.4	23.3	150
	StdDev. (mph)	3.7	3.4	3.2	2.7	4.1	2.3	3.4	3.0	

Figure 4 displays a histogram of the combined spot speed measurements at each point.

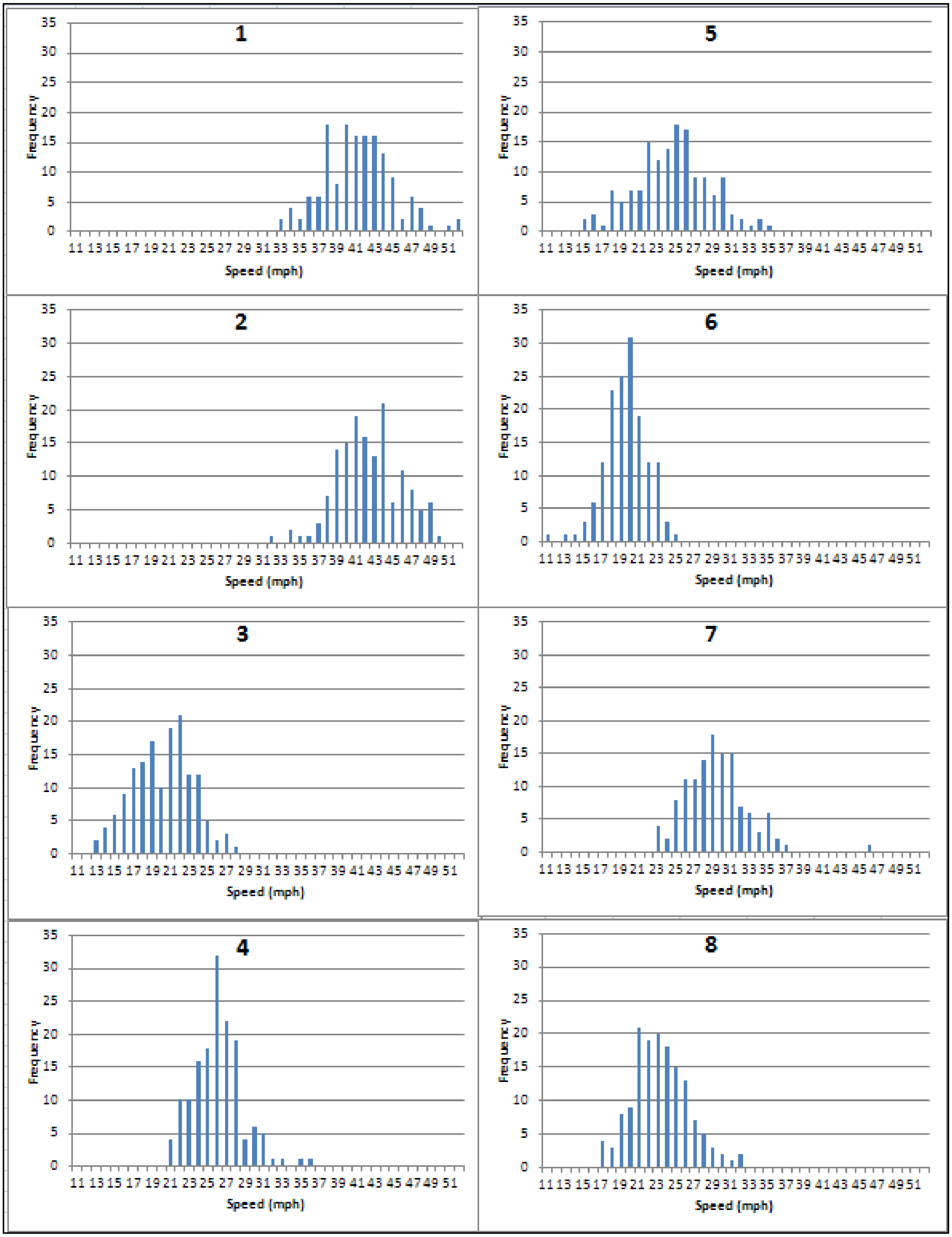

Figure 3: Spot Speed Histograms

4. Appendix

4.1. Appendix E1: Aerial Imagery

Figure B1. Spring Mill Rd at 96th St

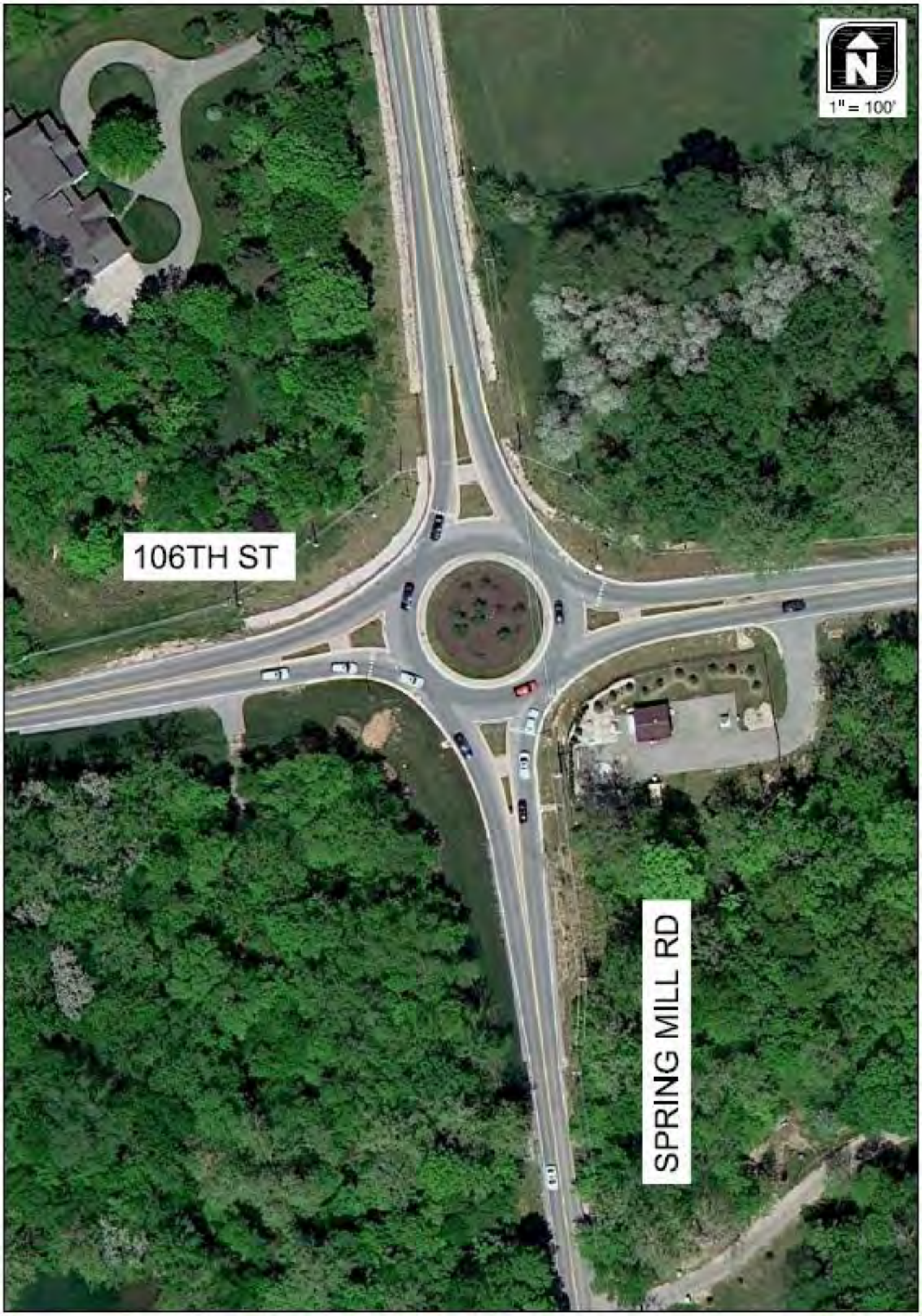
N
1" = 100'
106TH ST
SPRING MILL RD

Figure B2. Spring Mill Rd at 106th St

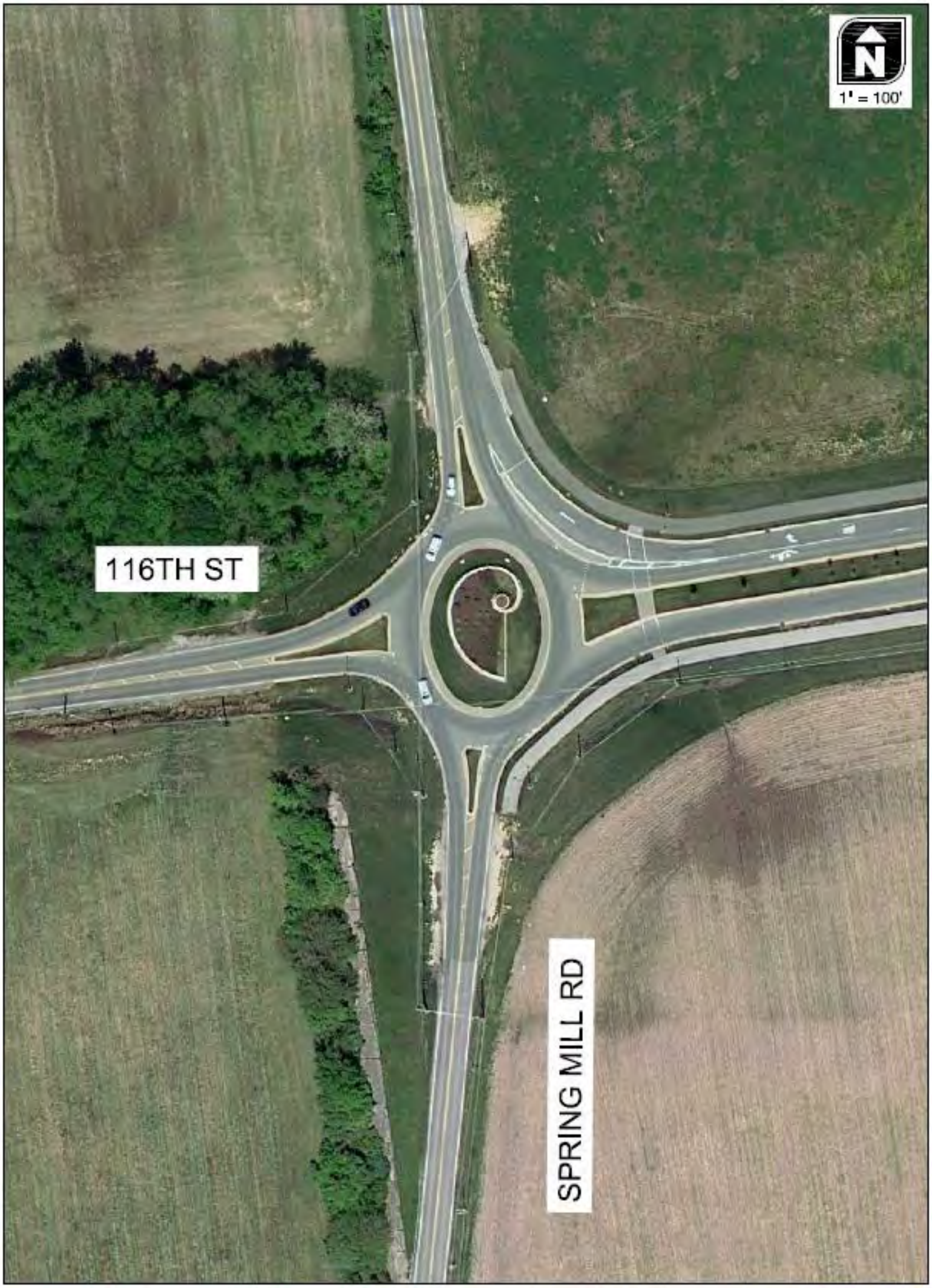

Figure B3. Spring Mill Rd at 116th St

Figure B4. Spring Mill Rd at Dorset Blvd

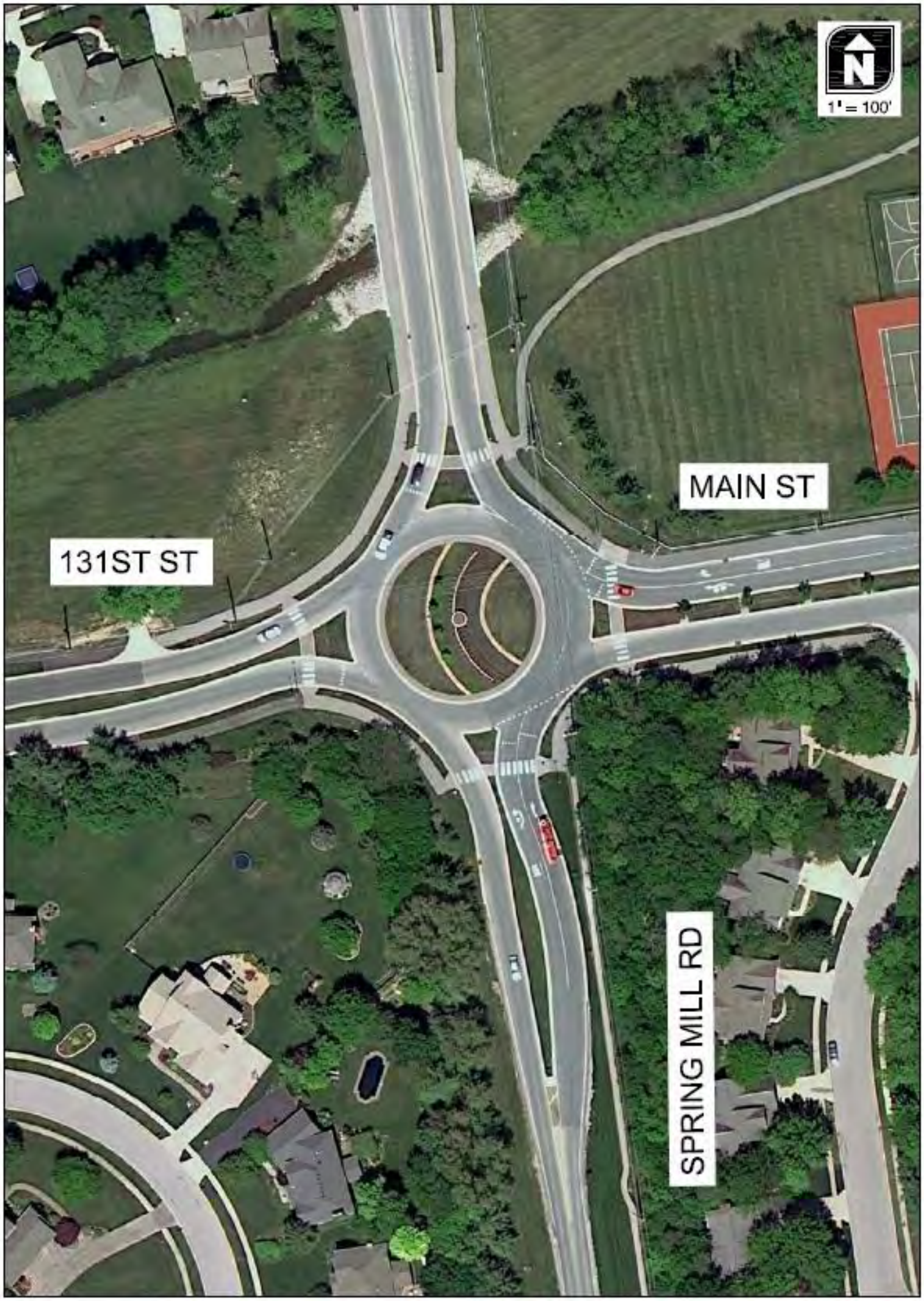

Figure B5. Spring Mill Rd at 131st St / Main St

Figure B6. Spring Mill Rd at 136th St

Figure B7. Spring Mill Rd at 141st St

4.2. **Appendix E2: Speed Profiles**

The speed profiles below correspond to the space-time trajectories for each of the six routes in Figure 3A through 3F.

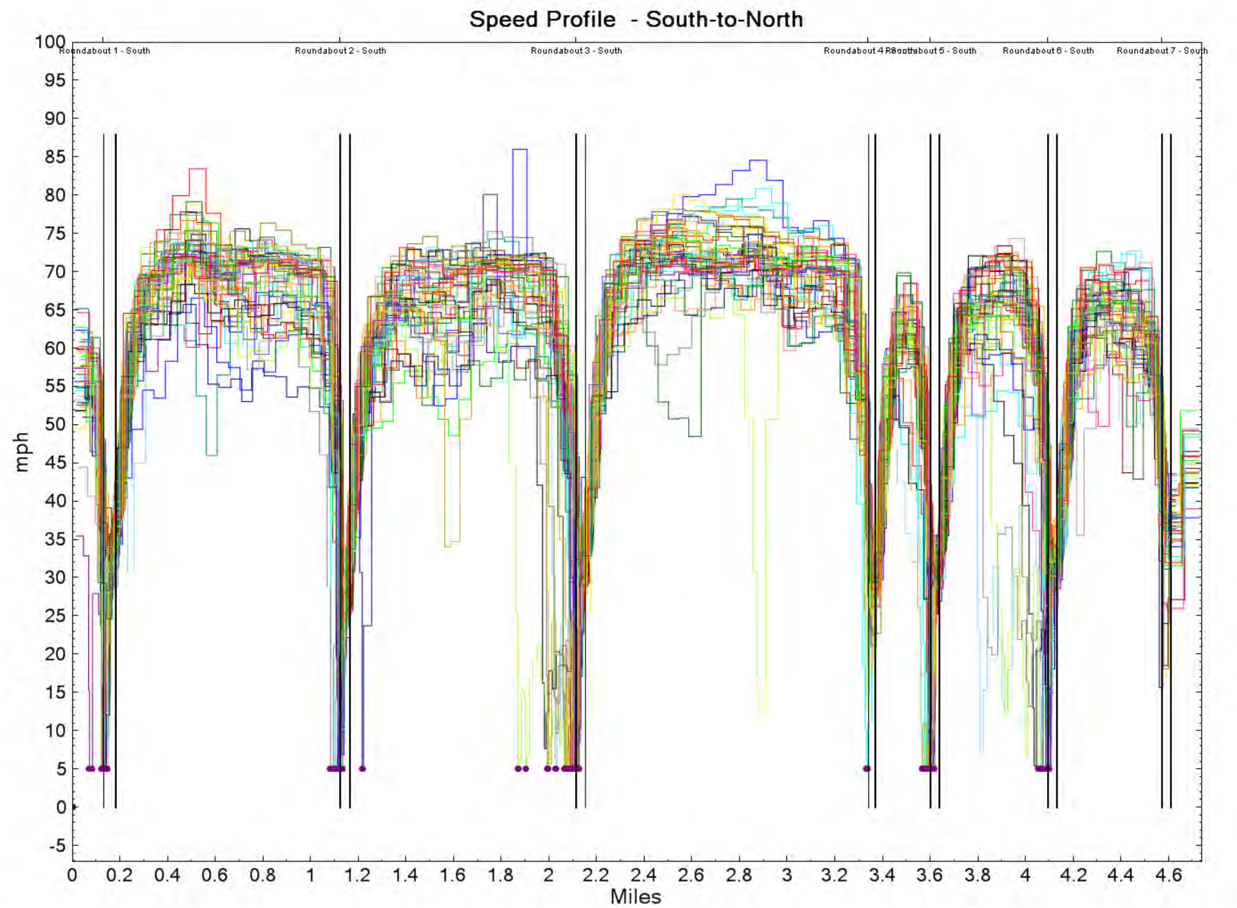

Figure 3A. Speed Profile for Route 1 (Northbound Through the Entire Corridor)

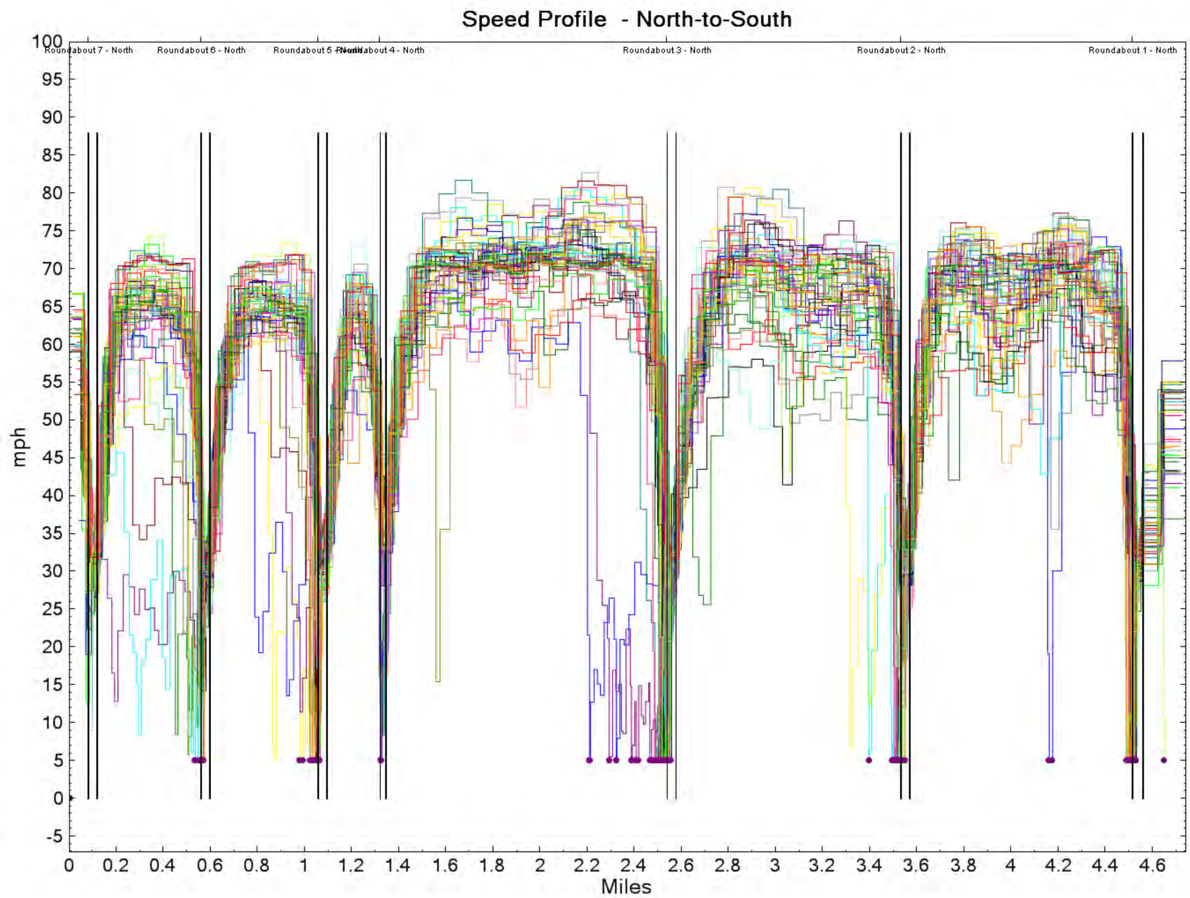

Figure 3B. Speed Profile for Route 2 (Southbound Through the Entire Corridor)

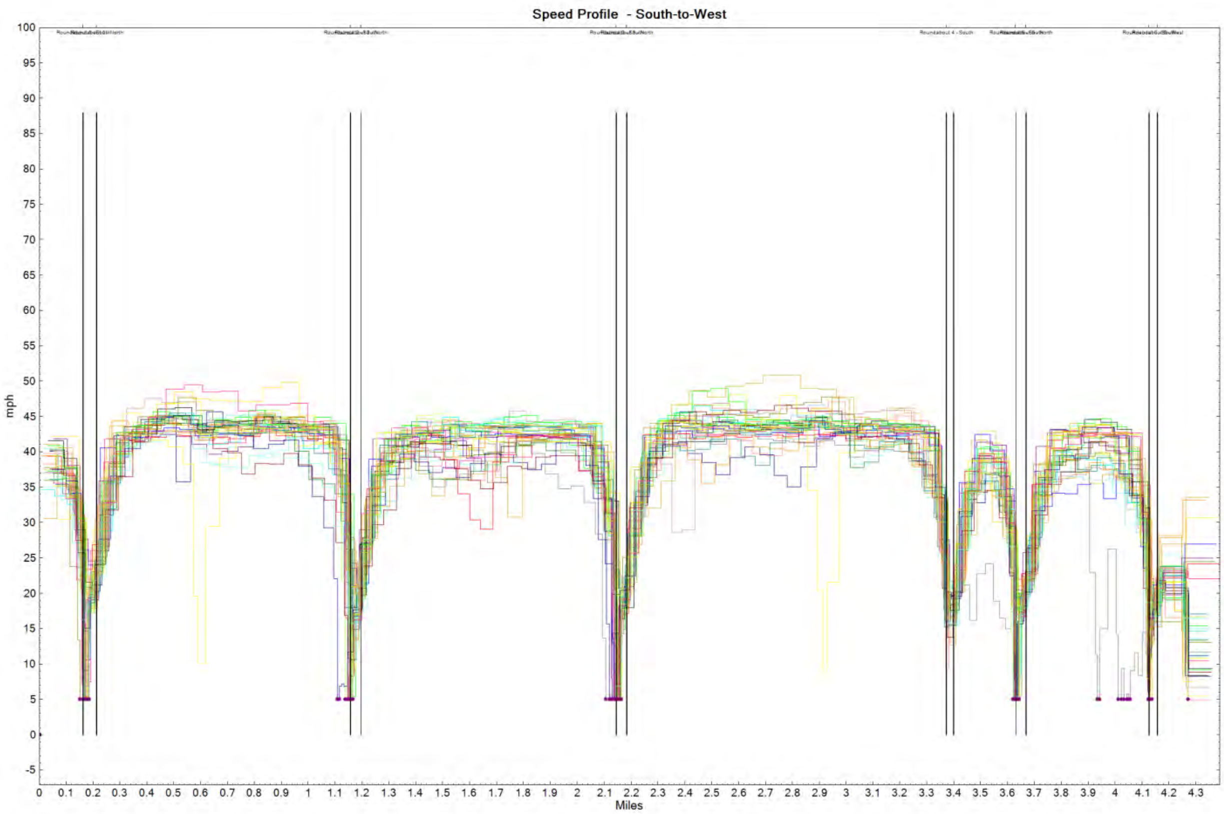

Figure 3C. Speed Profile for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 6)

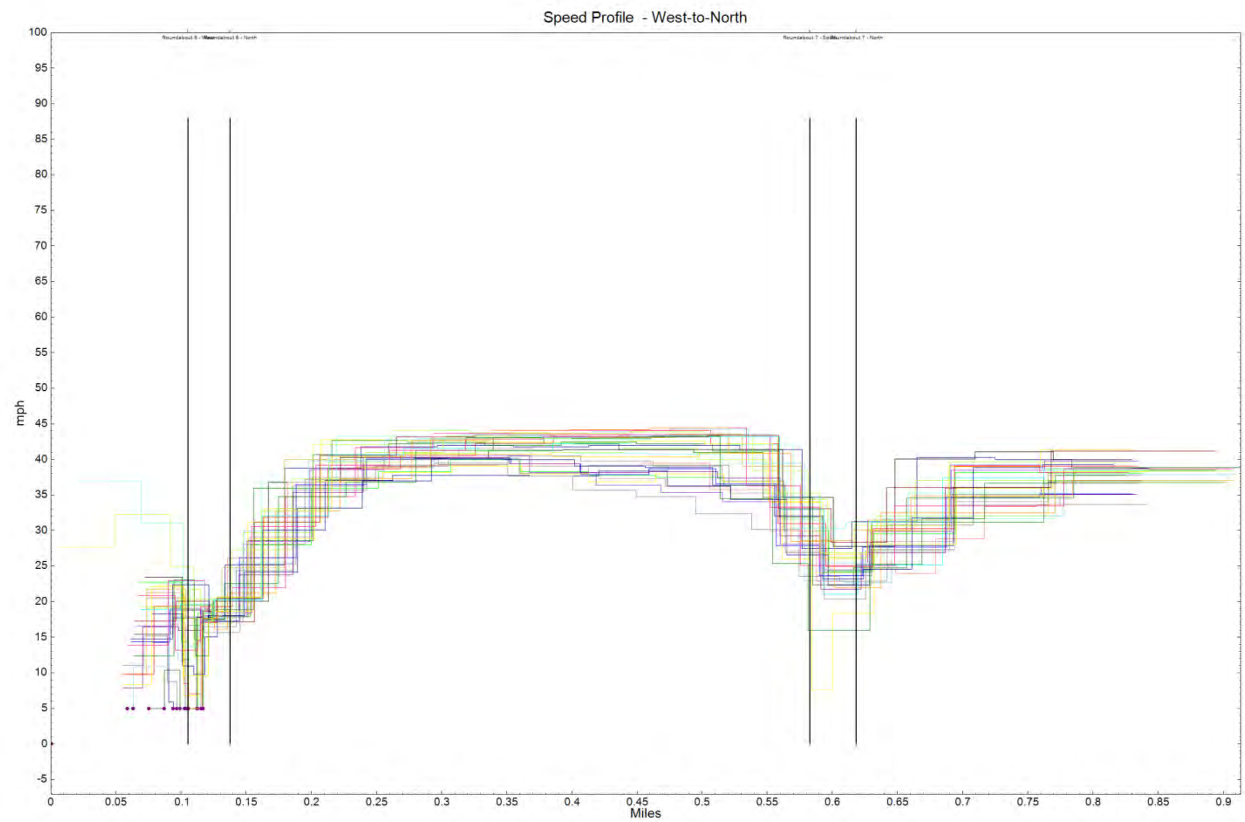

Figure 3D. Speed Profile for Route 4 (Starting from West of Roundabout 6, then Turning Left at Roundabout 6)

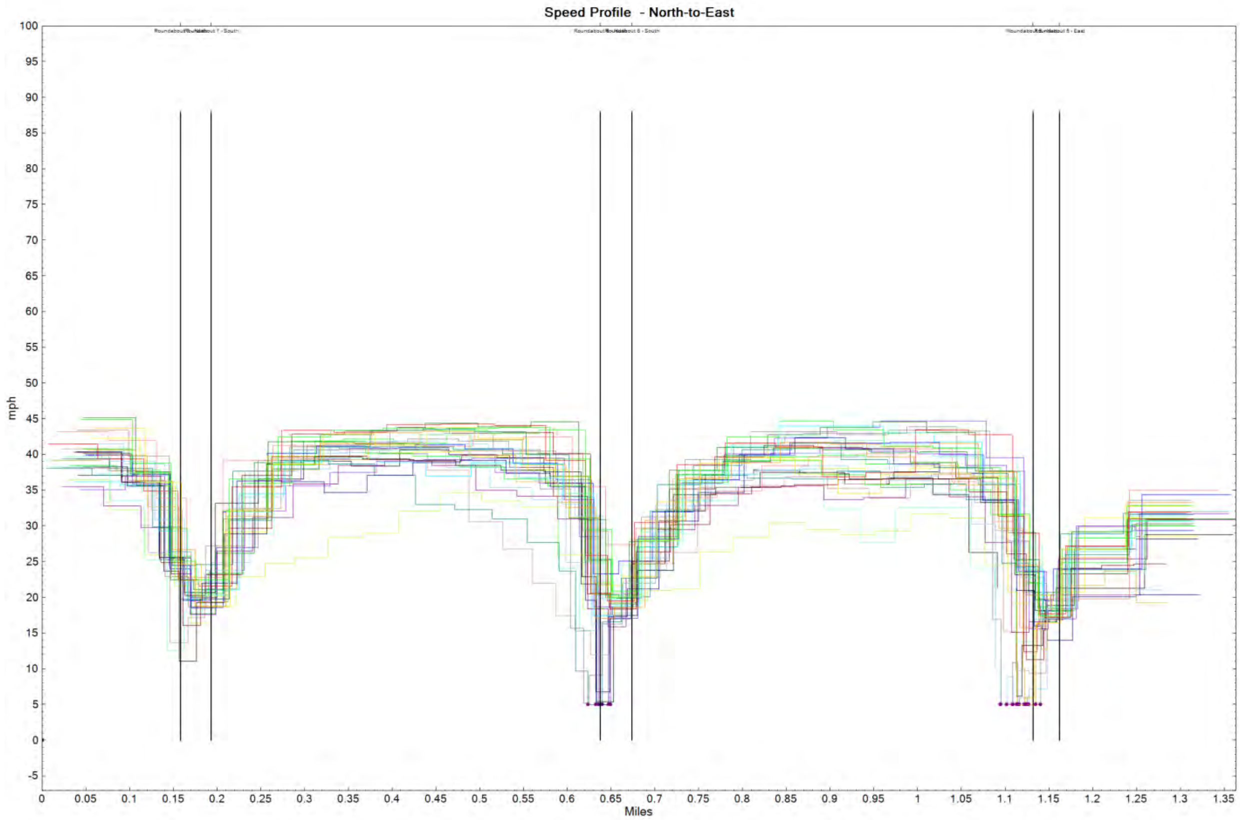

Figure 3E. Speed Profile for Route 5 (Starting from North of Roundabout 7, then Turning Left at Roundabout 5)

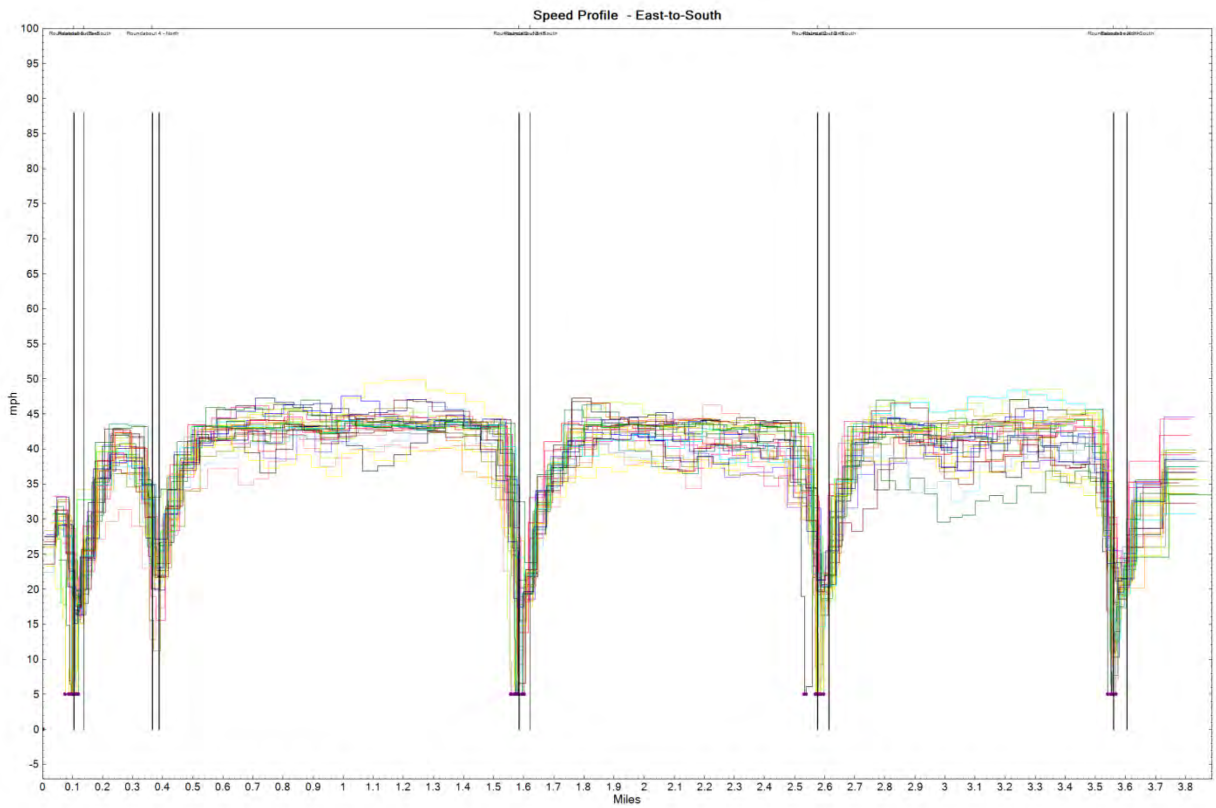

Figure 3F. Speed Profile for Route 6 (Starting from East of Roundabout 5, then Turning Left at Roundabout 5)

NCHRP 03-100

Appendix F

Gig Harbor, Washington
Borgen Boulevard Field Data

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1. Introduction

This document describes the field data collected by the NCHRP 3-100 team at the Borgen Boulevard roundabout corridor in Gig Harbor, Washington. The data collection and analysis efforts follow the format described in the team's data-collection plan.

The data collected at this roundabout corridor, which consisted of five roundabouts, included peak-hour and off-peak travel times and spot-speed measurements. Travel times were recorded using vehicle-mounted GPS units. Additionally, video data were obtained through field-mounted cameras. Data were collected during the period of May 31-June 2, 2012.

This document provides an overview of the data collected and discusses the quality and size of the dataset. Figure 1 displays a schematic of the corridor.

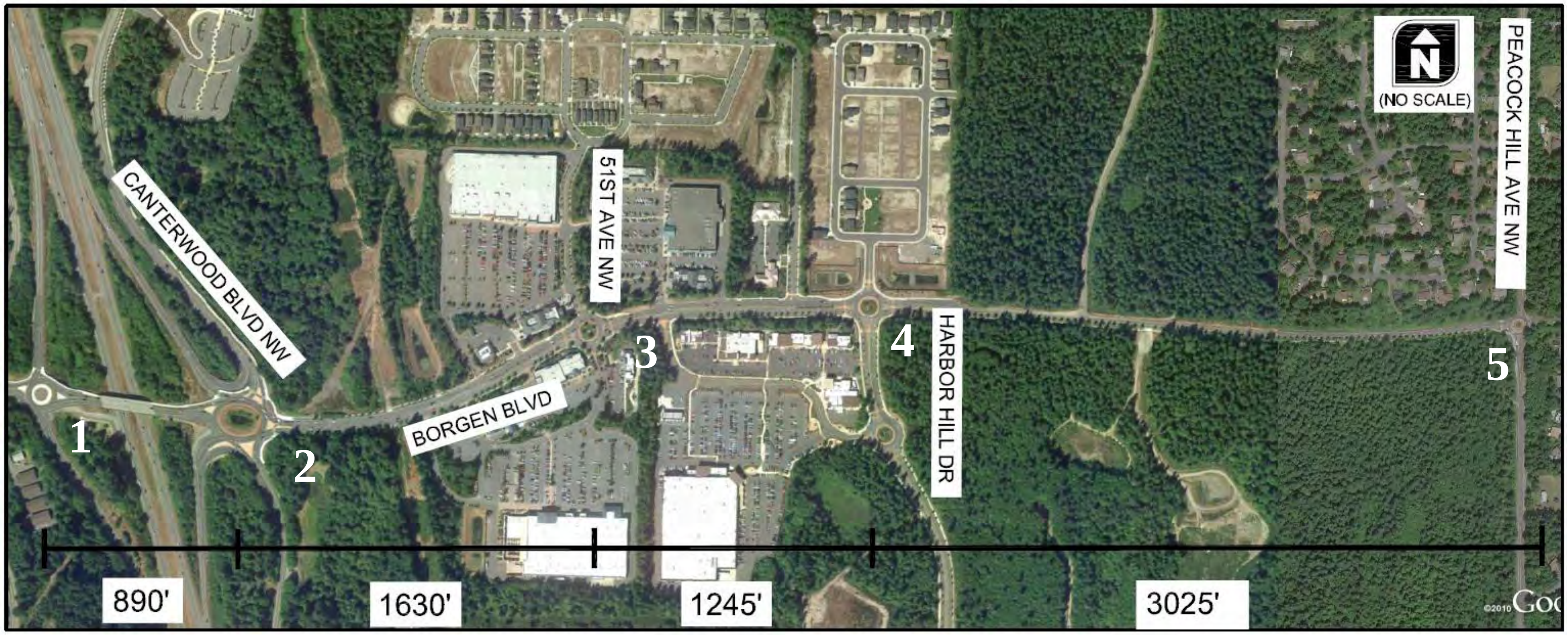

Figure 1: Aerial View of the Borgen Boulevard Roundabout Corridor

2. Traffic Counts

The research team has obtained the traffic counts and turning-movement counts for the four westernmost intersections along the corridor. Table 1 displays the turning-movement counts during the PM peak period, which was determined to occur from 5:00 p.m. to 6:00 p.m. Borgen Boulevard comprises the east- and westbound approaches of each roundabout. The NB SR 16/Burnham / Canterwood roundabout has five entry legs and five exit legs and is listed separately.

Table 1: Turning Movement Counts (5:00 to 6:00 p.m.)

Intersection #	Intersection Name	Direction	L	T	R		
1	SB SR 16	SB	406	2	84		
		EB		292	106		
		WB	586	328			
Intersection #	**Intersection Name**	**Direction**	**To WB Borgen**	**To SB Burnham**	**To EB Borgen**	**To NB Canterwood**	**To NB WA-16**
2	NB SR 16 / Burnham / Canterwood	NB from WA-16	124	56	576	278	6
		NB from Burnham	60		156	38	88
		SB Canterwood	180	48	96		38
		EB Borgen		106	470	36	96
		WB Borgen	548	66		124	444
Intersection #	**Intersection Name**	**Direction**	**L**	**T**	**R**		
3	51st	NB	130	18	108		
		SB	106	16	150		
		EB	146	906	38		
		WB	108	724	80		
4	Harbor Hill	NB	490	4	156		
		SB	2	2	10		
		EB	48	388	208		
		WB	84	212	2		

Figure 2 displays the 12-hour volume profile taken between the NB SR 16/Burnham/Canterwood roundabout and the 51st Avenue roundabout. The peak 30-minutes were identified to occur between 5:15 p.m. and 5:45 p.m.

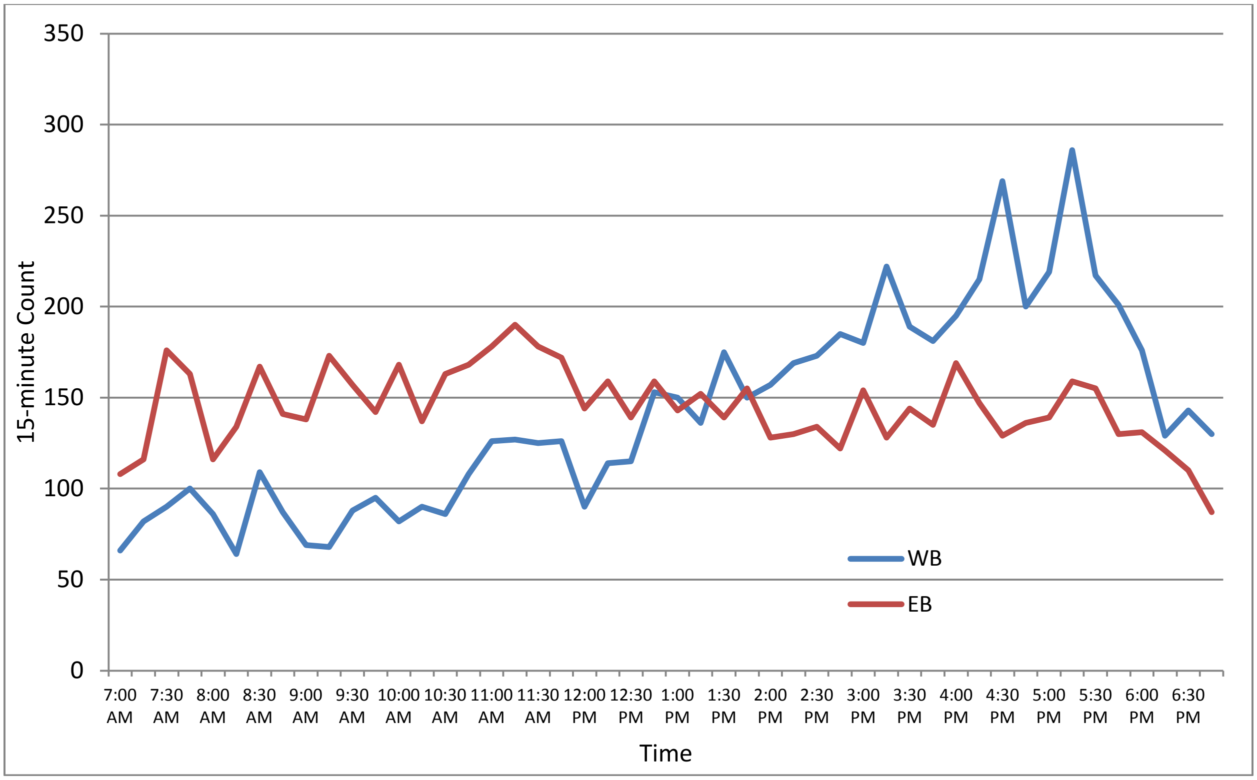

Figure 2: 12-hour Volume Profile

3. Field-Observed Data

GPS travel times and spot-speed data were collected along the corridor.

3.1. GPS Travel Times

The travel time through the corridor was also measured using vehicle-mounted GPS units. A total of six routes were used to conduct the study:

1. Westbound through the entire corridor;
2. Eastbound through the entire corridor;
3. Beginning east of roundabout 5 (Peacock Hill Avenue), then turning left at roundabout 3 (51st Avenue);
4. Beginning south of roundabout 3 (51st Avenue), then turning left at roundabout 3 and proceeding to the west end of the corridor;
5. Beginning west of roundabout 1 (SR 16), then turning left at roundabout 3 (51st Avenue); and
6. Beginning north of roundabout 3 (51st Avenue), then turning left at roundabout 3 and proceeding to the east end of the corridor.

Figures 3A through 3F display the space-time trajectories from each of the six routes. Each diagram displays every travel time run that was conducted (including a.m., p.m., and off-peak

runs). Note that the scale varies from route to route. The corresponding speed profiles are located in Appendix F2.

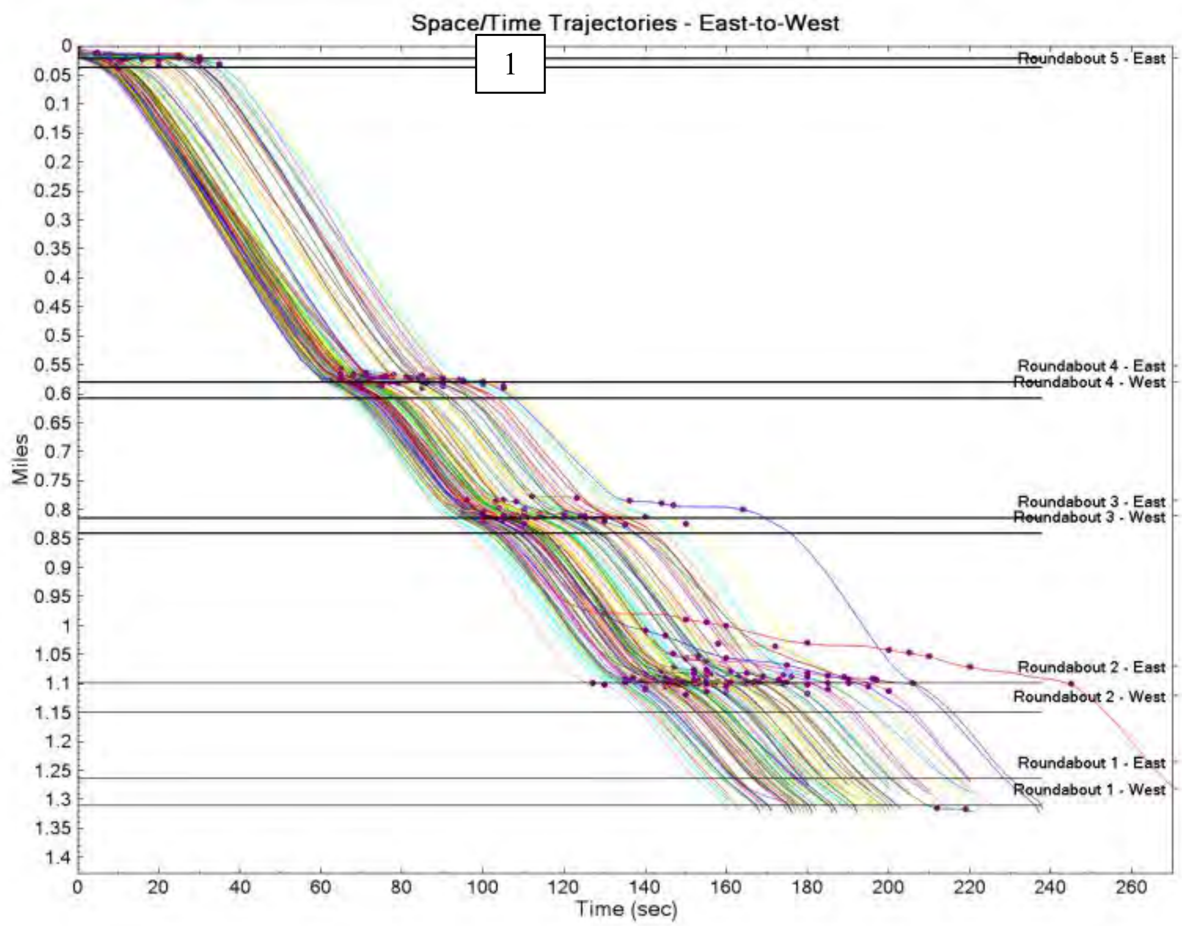

Figure 3A. Space/Time Trajectories for Route 1 (Westbound Through the Entire Corridor)

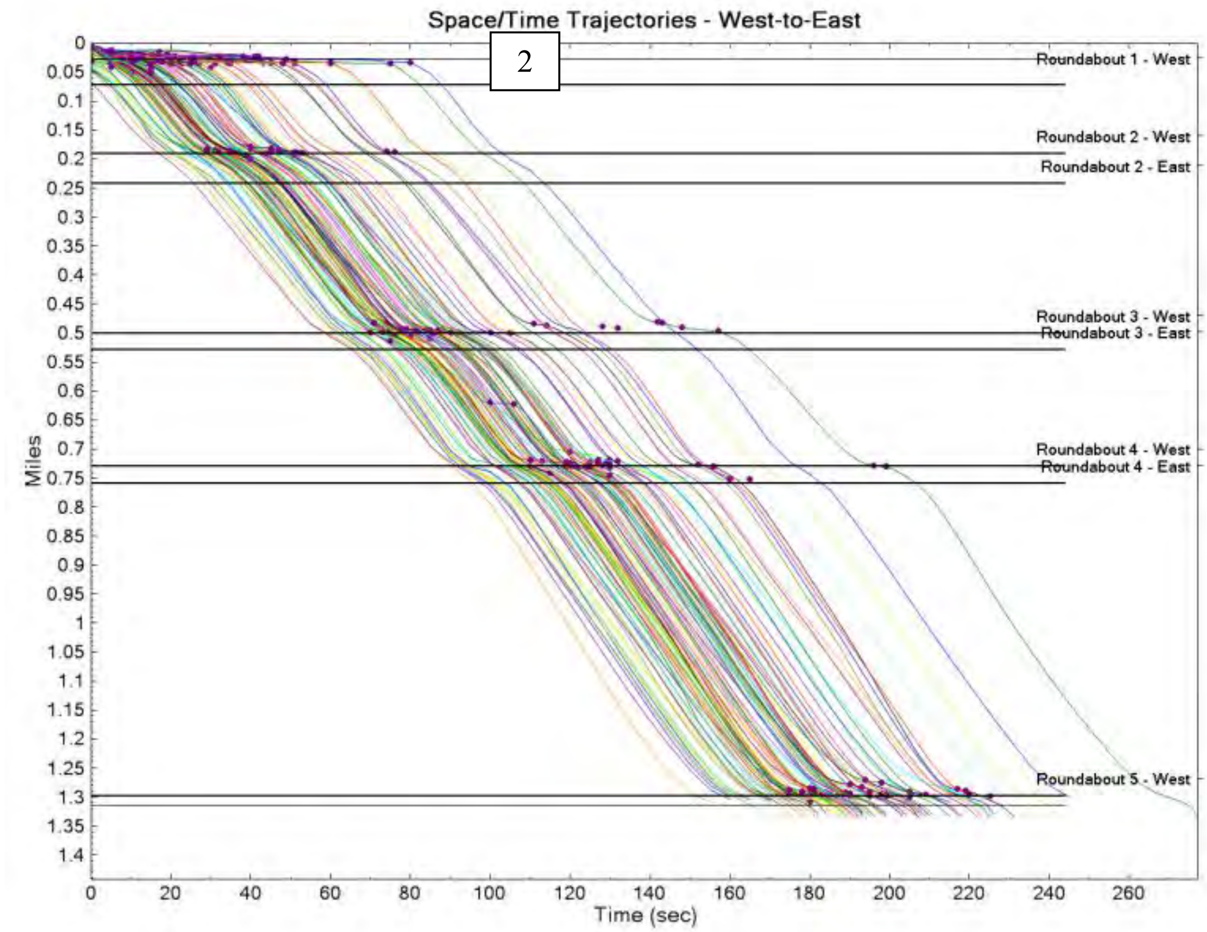

Figure 3B. Space/Time Trajectories for Route 2 (Eastbound Through the Entire Corridor)

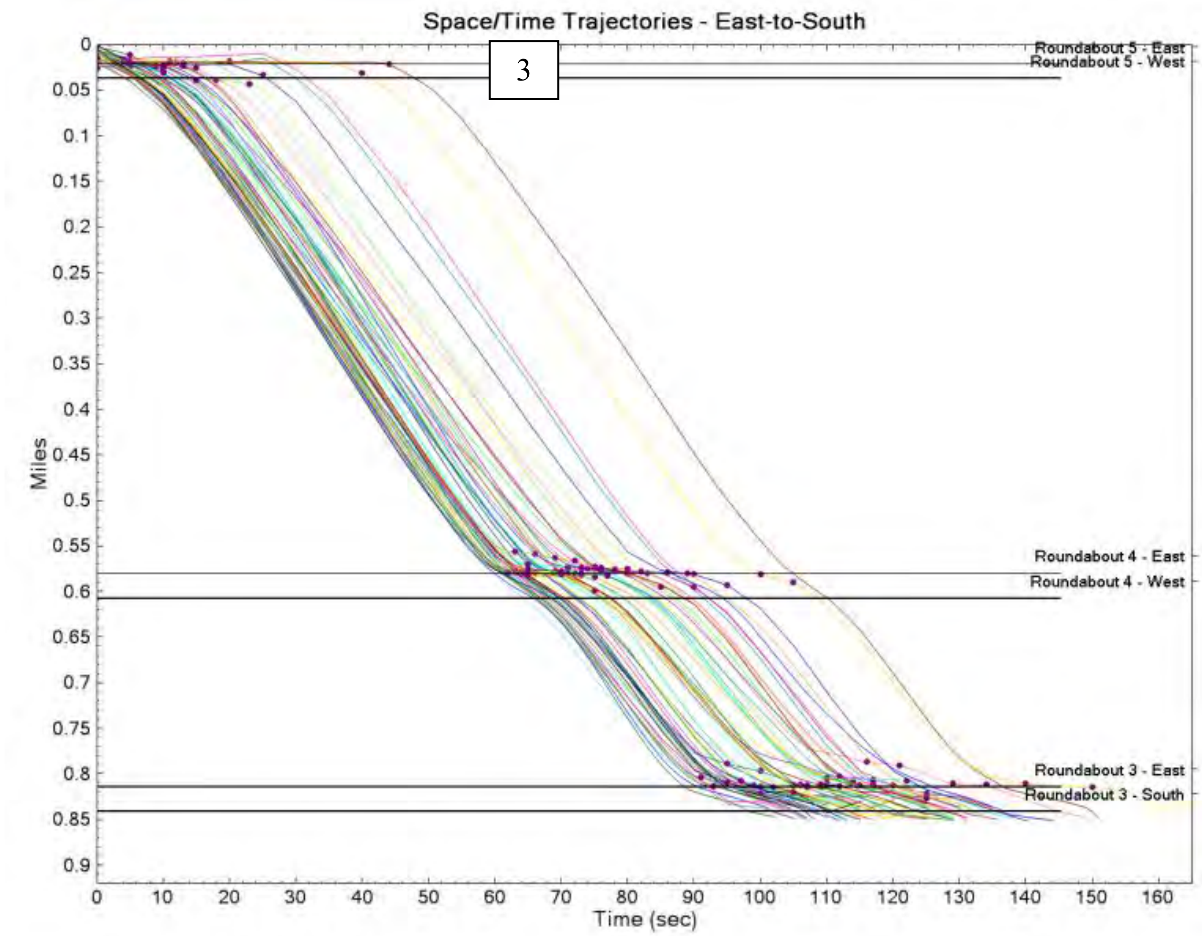

Figure 3C. Space/Time Trajectories for Route 3 (Beginning East of Roundabout 5, then Turning Left at Roundabout 3)

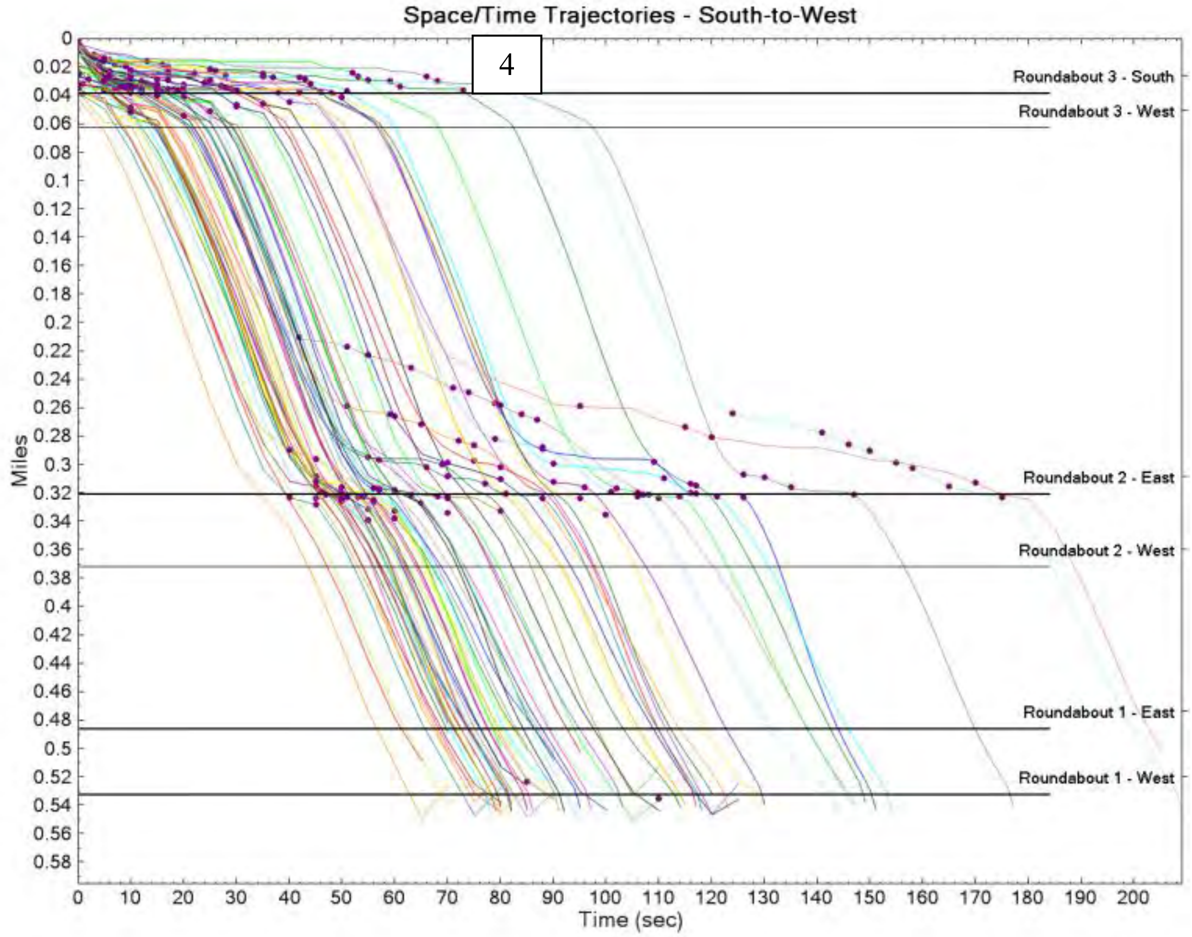

Figure 3D. Space/Time Trajectories for Route 4 (Beginning South of Roundabout 3, then Turning Left at Roundabout 3)

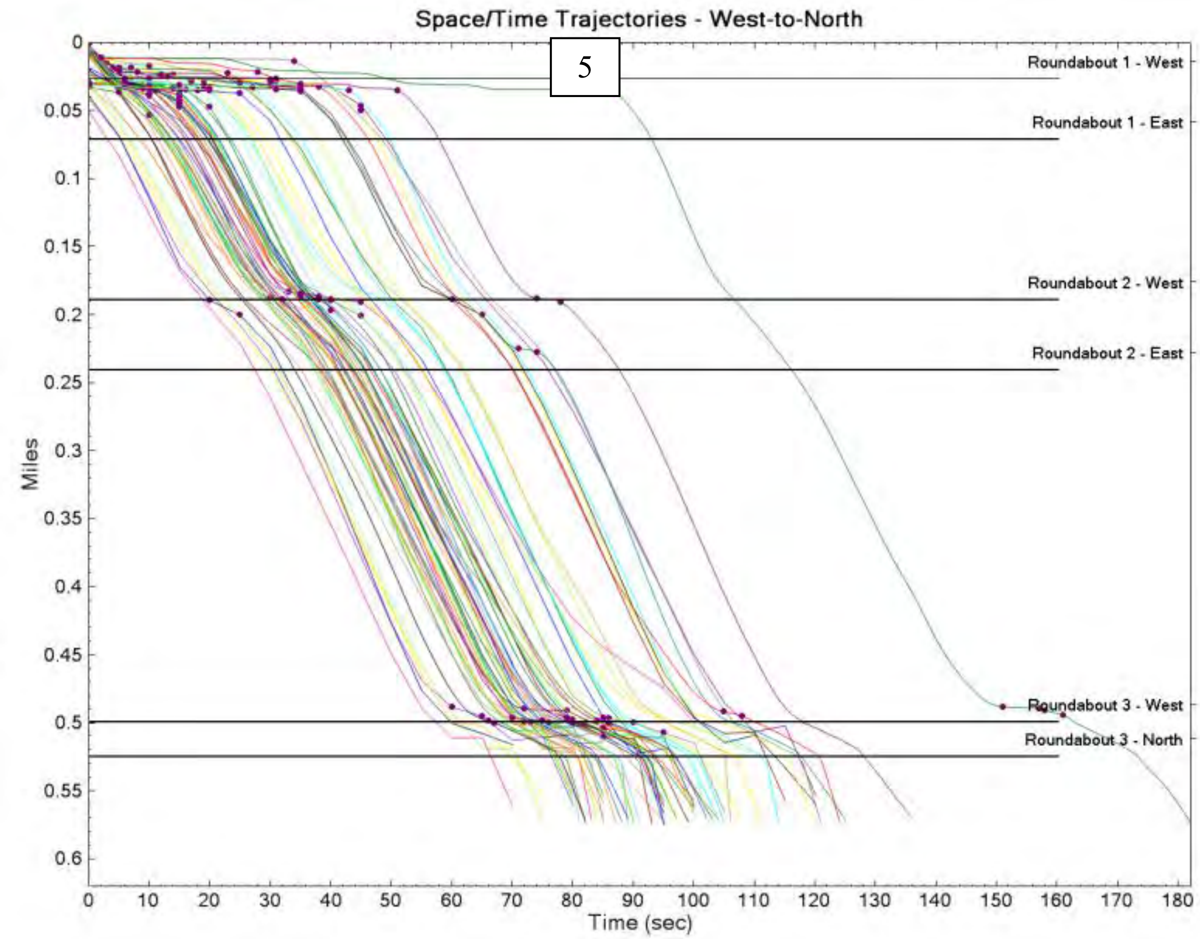

Figure 3E. Space/Time Trajectories for Route 5 (Beginning West of Roundabout 1, then Turning Left at Roundabout 3)

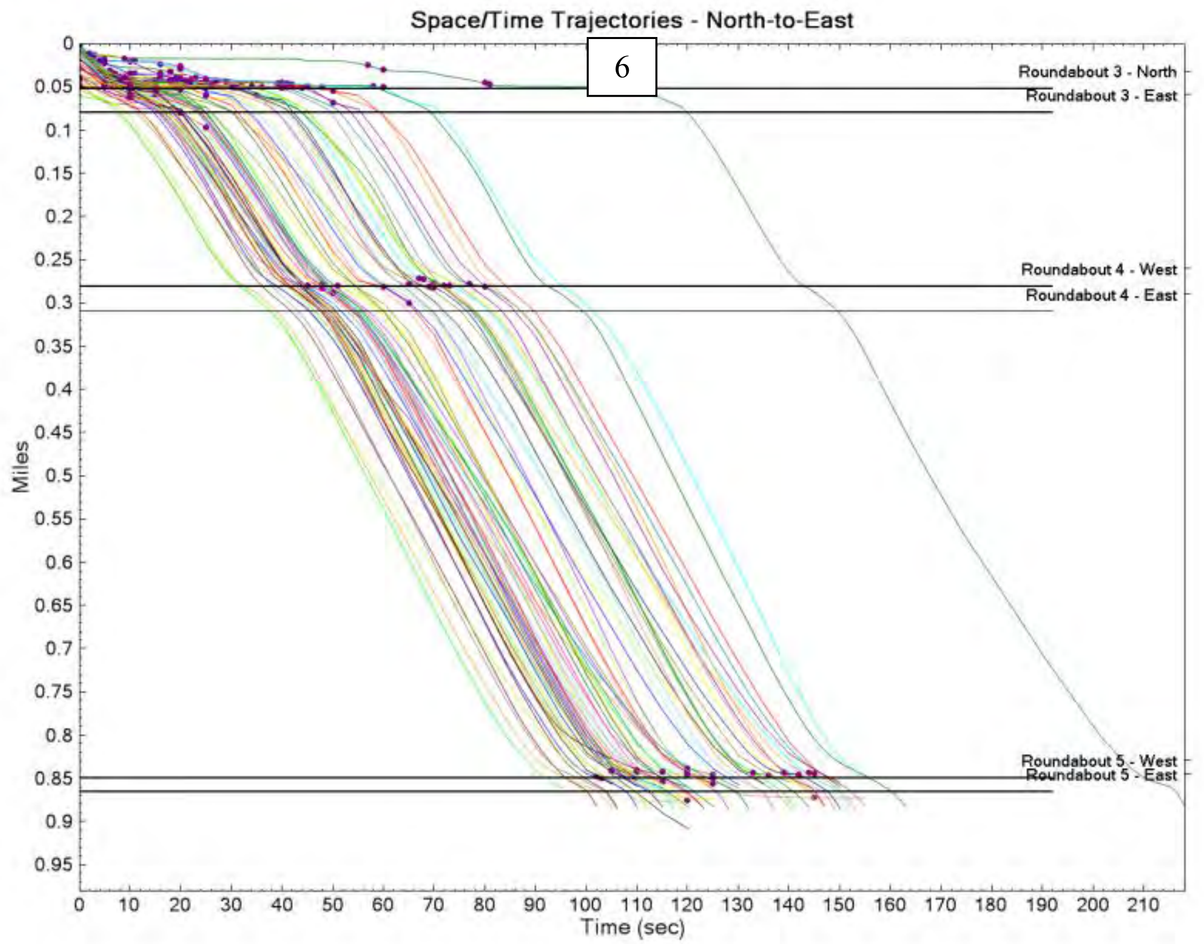

Figure 3F. Space/Time Trajectories for Route 6 (Beginning North of Roundabout 3, then Turning Left at Roundabout 3)

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening." A vehicle stop is denoted by a purple dot. The horizontal line in the diagrams corresponds to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor reflects the variability in the observed data. The distance along the y-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

Table 2 presents more-detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel-time runs, which are grouped into peak hour and off-peak times. All speeds are displayed in miles per hour, and all travel-times are displayed in minutes. Using the free-flow travel time, the table shows HCM Urban Streets LOS (based on % FFS aggregated over the entire route). The table indicates that the LOS assigned to each route may vary using either method; the urban streets LOS tends to be lower than the roundabout LOS

Table 2: Summary of a.m., p.m., and Off-peak Travel Time

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)				Free-Flow Speed (mph)	% FFS	Urban Street LOS	Travel Distance (mi)	Free-Flow TT (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min							
East to South	**61**	**26.2**	**2.5**	**31.3**	**19.1**	**2.03**	**0.21**	**2.75**	**1.70**	**37.0**	**70.7%**	**B**	**0.88**	**1.43**	**7.3**	**A**
AM	11	26.5	2.5	29.4	20.6	1.98	0.22	2.52	1.78		71.7%	B			6.7	A
Off	37	26.4	2.4	31.3	21.4	2.02	0.20	2.48	1.70		71.4%	B			7.1	A
PM	13	25.1	2.6	28.2	19.1	2.12	0.24	2.75	1.87		67.9%	B			8.3	A
East to West	**103**	**25.7**	**2.3**	**29.9**	**17.1**	**3.12**	**0.32**	**4.50**	**2.67**	**37.0**	**69.4%**	**B**	**1.33**	**2.16**	**11.6**	**B**
AM	16	27.6	1.0	28.9	25.8	2.87	0.12	3.10	2.67		74.5%	B			8.6	A
Off	63	25.7	1.9	29.9	20.3	3.12	0.26	3.95	2.67		69.4%	B			11.5	B
PM	24	24.4	2.9	29.3	17.1	3.31	0.43	4.50	2.72		66.0%	C			13.8	B
North to East	**70**	**25.3**	**3.2**	**31.1**	**14.8**	**2.11**	**0.33**	**3.63**	**1.58**	**37.4**	**67.7%**	**B**	**0.88**	**1.41**	**8.4**	**A**
AM	14	27.1	1.7	30.4	23.0	1.95	0.13	2.25	1.70		72.5%	B			6.4	A
Off	40	25.4	3.4	31.1	14.8	2.11	0.38	3.63	1.58		67.9%	B			8.4	A
PM	16	23.5	2.5	28.9	20.2	2.27	0.24	2.58	1.67		62.9%	C			10.3	B
South to West	**69**	**20.8**	**4.5**	**27.7**	**9.2**	**1.70**	**0.51**	**3.48**	**1.08**	**37.0**	**56.3%**	**C**	**0.6**	**0.89**	**9.7**	**A**
AM	14	24.2	1.8	27.7	20.8	1.32	0.12	1.52	1.08		65.3%	C			5.2	A
Off	41	20.6	4.3	27.6	11.5	1.71	0.42	2.95	1.17		55.8%	C			9.9	A
PM	14	18.0	5.0	24.7	9.2	2.02	0.71	3.48	1.33		48.6%	D			13.6	B
West to East	**104**	**25.1**	**2.3**	**29.7**	**17.5**	**3.21**	**0.35**	**4.62**	**2.58**	**37.4**	**67.1%**	**B**	**1.33**	**2.13**	**12.9**	**B**
AM	17	25.6	1.9	28.6	21.9	3.14	0.27	3.70	2.67		68.5%	B			12.1	B
Off	63	25.1	2.4	29.7	17.5	3.21	0.38	4.62	2.58		67.0%	C			12.9	B
PM	24	24.8	2.2	28.0	19.3	3.24	0.33	4.08	2.83		66.4%	C			13.3	B
West to North	**70**	**21.6**	**2.9**	**26.3**	**12.1**	**1.60**	**0.30**	**3.03**	**1.17**	**37.4**	**57.8%**	**C**	**0.56**	**0.90**	**8.4**	**A**
AM	16	21.7	2.7	25.6	16.5	1.57	0.23	2.02	1.25		57.9%	C			8.0	A
Off	40	21.9	3.0	26.3	12.1	1.58	0.34	3.03	1.17		58.6%	C			8.2	A
PM	14	20.7	2.5	23.9	16.8	1.69	0.20	2.07	1.45		55.2%	C			9.6	A

Notes: FFS = free-flow speed, Rbt = roundabout, LOS = Level of Service

3.2. Geometric and Approach Delay from GPS

The team also examined the approach delay at each roundabout while considering the geometric delay incurred by the roundabouts themselves. Table 4 presents a summary of this analysis. For each approach and time of day, the free-flow travel time was estimated by isolating the unimpeded trajectories from the rest of the data set and then measuring the peak midblock speed from the trajectories. Although the true free-flow speed may not be observable in this manner (it may be higher than the observed speeds due to friction / driver behavior along the corridor), the team believed that this method was advantageous in that it provided a much greater sample size (including more sample locations) than the midblock speed study (Section 3.3). Additionally, the travel distance used to compute the free-flow travel time was taken as the centerline distance between each pair of roundabouts so that the geometric delay caused by the additional travel distance to navigate the roundabouts did not affect the estimate of the free-flow travel time.

Table 3 shows the distances used for estimating free-flow travel time, relative to the actual travel distance through the roundabout. Each segment is assumed to start about half-way between two roundabouts and to end at (approximately) the downstream crosswalk at a roundabout. Note that the sum of all segments does NOT equal the total travel distance, as the distance between the downstream crosswalk and the next segment start is not accounted for. For the complete route analysis, the reader should refer to the analysis in the previous section. The table also shows the field-estimated FFS for each segment, along with the posted speed limit.

Table 3: Summary of Segment Distances

Direction	Route Segment	Free-Flow Distance (feet)	Trajectory Distance (feet)	Segment FFS (mph)	Speed Limit (mph)
Eastbound	RBT1-East Approach	581	581	34.0	35
	RBT2-East Approach	1083	1,108	39.9	35
	RBT3-East Approach	869	898	37.0	35
	RBT4-East Approach	1840	1,848	44.6	35
	RBT5-East Approach	361	370	44.6	35
Westbound	RBT1-West Approach	412	722	33.0	35
	RBT2-West Approach	786	792	33.0	35
	RBT3-West Approach	984	1,003	39.1	35
	RBT4-West Approach	785	792	37.4	35
	RBT5-West Approach	1,334	1,426	42.1	35

Note: RBT = roundabout, FFS = free-flow speed

Table 4 displays the impeded delay (equal to the difference between the average travel time and the unimpeded travel time) and total delay (equal to the difference between the average travel time and the free flow travel time) for each approach route. Each approach was split into the upstream and downstream segments, where the upstream segment extends from the yield bar to the upstream midblock point, and the downstream segment extends from the yield bar to the downstream midblock point.

Table 4: Summary of Geometric and Approach Delay

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Unimpeded Travel Time (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT1-East Approach (Upstream)	**7.6**	**365**	**37**	**6.7**	**7.5**	**0.8**	**0.1**	**0.9**
AM	**7.7**	365	37	6.7	7.5	0.8	0.2	1.0
Off	**7.6**	365	37	6.7	7.5	0.8	0.1	0.9
PM	**7.6**	365	37	6.7	7.5	0.8	0.1	0.9
RBT1-East Approach (Downstream)	**7.3**	**308**	**30**	**6.6**	**6.6**	**0.0**	**0.7**	**0.7**
AM	**6.8**	308	30	6.6	6.6	0.0	0.2	0.3
Off	**7.1**	308	30	6.6	6.6	0.0	0.5	0.5
PM	**8.1**	308	30	6.6	6.6	0.0	1.5	1.5
RBT1-West Approach (Upstream)	**15.3**	**140**	**30**	**2.9**	**3.7**	**0.8**	**11.5**	**12.3**
AM	**12.1**	140	30	2.9	3.7	0.8	8.4	9.2
Off	**16.4**	140	30	2.9	3.7	0.8	12.7	13.5
PM	**15.6**	140	30	2.9	3.7	0.8	11.8	12.6
RBT1-West Approach (Downstream)	**10.9**	**506**	**35**	**9.4**	**10.5**	**1.1**	**0.4**	**1.5**
AM	**11.3**	506	35	9.4	10.5	1.1	0.8	1.9
Off	**10.8**	506	35	9.4	10.5	1.1	0.3	1.4
PM	**10.9**	506	35	9.4	10.5	1.1	0.4	1.5
RBT2-East Approach (Upstream)	**23.7**	**725**	**35**	**14.1**	**18.0**	**3.9**	**5.7**	**9.6**
AM	**19.6**	725	35	14.1	18.0	3.9	1.6	5.5
Off	**21.5**	725	35	14.1	18.0	3.9	3.5	7.4
PM	**31.2**	725	35	14.1	18.0	3.9	13.2	17.1
RBT2-East Approach (Downstream)	**13.4**	**596**	**35**	**10.7**	**13.0**	**2.3**	**0.4**	**2.7**
AM	**13.8**	596	35	10.7	13.0	2.3	0.8	3.1
Off	**13.2**	596	35	10.7	13.0	2.3	0.2	2.5
PM	**13.6**	596	35	10.7	13.0	2.3	0.6	2.8
RBT2-West Approach (Upstream)	**10.3**	**349**	**35**	**6.6**	**9.0**	**2.4**	**1.3**	**3.7**
AM	**10.3**	349	35	6.6	9.0	2.4	1.3	3.7
Off	**9.9**	349	35	6.6	9.0	2.4	0.9	3.3
PM	**11.2**	349	35	6.6	9.0	2.4	2.2	4.6

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Unimpeded Travel Time (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT2-West Approach (Downstream)	**23.3**	**1000**	**35**	**19.1**	**22.5**	**3.4**	**0.8**	**4.2**
AM	**23.8**	1000	35	19.1	22.5	3.4	1.3	4.6
Off	**23.4**	1000	35	19.1	22.5	3.4	0.9	4.2
PM	**22.9**	1000	35	19.1	22.5	3.4	0.4	3.7
RBT3-East Approach (Upstream)	**17.9**	**561**	**35**	**10.9**	**13.5**	**2.6**	**4.4**	**7.0**
AM	**13.9**	561	35	10.9	13.5	2.6	0.4	2.9
Off	**19.5**	561	35	10.9	13.5	2.6	6.0	8.6
PM	**18.1**	561	35	10.9	13.5	2.6	4.6	7.2
RBT3-East Approach (Downstream)	**17.0**	**870**	**37**	**15.7**	**16.5**	**0.8**	**0.5**	**1.3**
AM	**16.6**	870	37	15.7	16.5	0.8	0.1	1.0
Off	**17.0**	870	37	15.7	16.5	0.8	0.5	1.3
PM	**17.4**	870	37	15.7	16.5	0.8	0.9	1.7
RBT3-West Approach (Upstream)	**17.1**	**729**	**37**	**13.4**	**15.0**	**1.6**	**2.1**	**3.6**
AM	**15.5**	729	37	13.4	15.0	1.6	0.5	2.0
Off	**17.6**	729	37	13.4	15.0	1.6	2.6	4.1
PM	**17.3**	729	37	13.4	15.0	1.6	2.3	3.9
RBT3-West Approach (Downstream)	**15.1**	**676**	**41**	**11.1**	**14.5**	**3.4**	**0.6**	**4.0**
AM	**14.9**	676	41	11.1	14.5	3.4	0.4	3.8
Off	**15.2**	676	41	11.1	14.5	3.4	0.7	4.2
PM	**14.8**	676	41	11.1	14.5	3.4	0.3	3.8
RBT4-East Approach (Upstream)	**33.6**	**1446**	**35**	**28.2**	**29.3**	**1.1**	**4.3**	**5.5**
AM	**30.1**	1446	35	28.2	29.3	1.1	0.8	1.9
Off	**35.4**	1446	35	28.2	29.3	1.1	6.1	7.2
PM	**32.7**	1446	35	28.2	29.3	1.1	3.4	4.5
RBT4-East Approach (Downstream)	**15.0**	**713**	**35**	**13.4**	**14.5**	**1.1**	**0.5**	**1.5**
AM	**14.7**	713	35	13.4	14.5	1.1	0.2	1.2
Off	**15.1**	713	35	13.4	14.5	1.1	0.6	1.7
PM	**15.0**	713	35	13.4	14.5	1.1	0.5	1.6

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Unimpeded Travel Time (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT4-West Approach (Upstream)	**13.5**	**559**	**41**	**9.3**	**12.0**	**2.7**	**1.5**	**4.2**
AM	**12.1**	559	41	9.3	12.0	2.7	0.1	2.8
Off	**14.2**	559	41	9.3	12.0	2.7	2.2	4.9
PM	**13.4**	559	41	9.3	12.0	2.7	1.4	4.1
RBT4-West Approach (Downstream)	**32.7**	**1594**	**41**	**26.3**	**32.0**	**5.7**	**0.7**	**6.3**
AM	**33.0**	1594	41	26.3	32.0	5.7	1.0	6.7
Off	**32.8**	1594	41	26.3	32.0	5.7	0.8	6.5
PM	**32.1**	1594	41	26.3	32.0	5.7	0.1	5.7
RBT5-East Approach (Upstream)	**6.2**	**161**	**42**	**2.6**	**4.0**	**1.3**	**2.3**	**3.6**
AM	**7.6**	161	42	2.6	4.0	1.3	3.7	5.0
Off	**5.0**	161	42	2.6	4.0	1.3	1.1	2.4
PM	**7.5**	161	42	2.6	4.0	1.3	3.6	4.9
RBT5-East Approach (Downstream)	**27.2**	**1553**	**42**	**25.0**	**27.0**	**2.0**	**0.2**	**2.3**
AM	**27.5**	1553	42	25.0	27.0	2.0	0.5	2.6
Off	**27.1**	1553	42	25.0	27.0	2.0	0.1	2.2
PM	**27.2**	1553	42	25.0	27.0	2.0	0.2	2.3
RBT5-West Approach (Upstream)	**30.5**	**1449**	**40**	**24.7**	**27.5**	**2.8**	**3.0**	**5.8**
AM	**29.9**	1449	40	24.7	27.5	2.8	2.4	5.2
Off	**30.3**	1449	40	24.7	27.5	2.8	2.8	5.6
PM	**31.4**	1449	40	24.7	27.5	2.8	3.9	6.7
RBT5-West Approach (Downstream)	**8.8**	**303**	**40**	**4.7**	**8.5**	**3.8**	**0.3**	**4.1**
AM	**8.9**	303	40	4.7	8.5	3.8	0.4	4.2
Off	**8.9**	303	40	4.7	8.5	3.8	0.4	4.2
PM	**8.5**	303	40	4.7	8.5	3.8	0.0	3.8

3.3. Spot-Speed Profiles

In addition to the travel time data, the team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at two of the internal roundabouts (3 and 4). These data were collected with a laser speed gun. Finally, these speeds provide a more realistic estimation of operating speeds at the roundabouts than do the GPS travel-time runs, which were conducted by engineers using the floating car technique. Summary statistics are displayed in Table 4. Each speed was sampled a total of 30 times.

Table 5: Spot Speed Summary Statistics

Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
RBT #	3	3	3	3-4	3-4	4	4	4
Location	EB – entry	WB – exit	EB – circ	EB – midblock	WB – midblock	WB – circ	EB – exit	WB – entry
Mean Speed (mph)	19.8	22.8	15.0	31.8	32.7	15.9	18.0	16.2
StdDev (mph)	1.9	2.5	1.6	3.2	3.7	1.3	1.7	1.7

The table indicates that the average east- and westbound midblock speeds were 31.8 and 32.7 mph, respectively. These speeds are slightly lower than the free-flow speeds measured from the GPS trajectories in Table 4, which were estimated to be 37.4 and 37.0 mph, respectively. This indicates that the pilot vehicles may have been traveling above the true free-flow speed, or it may indicate that the speeds measured in the field were below the true free-flow speed. The speed measurements from the combined dataset were also analyzed using histogram frequency distributions—all eight are displayed in Figure 4.

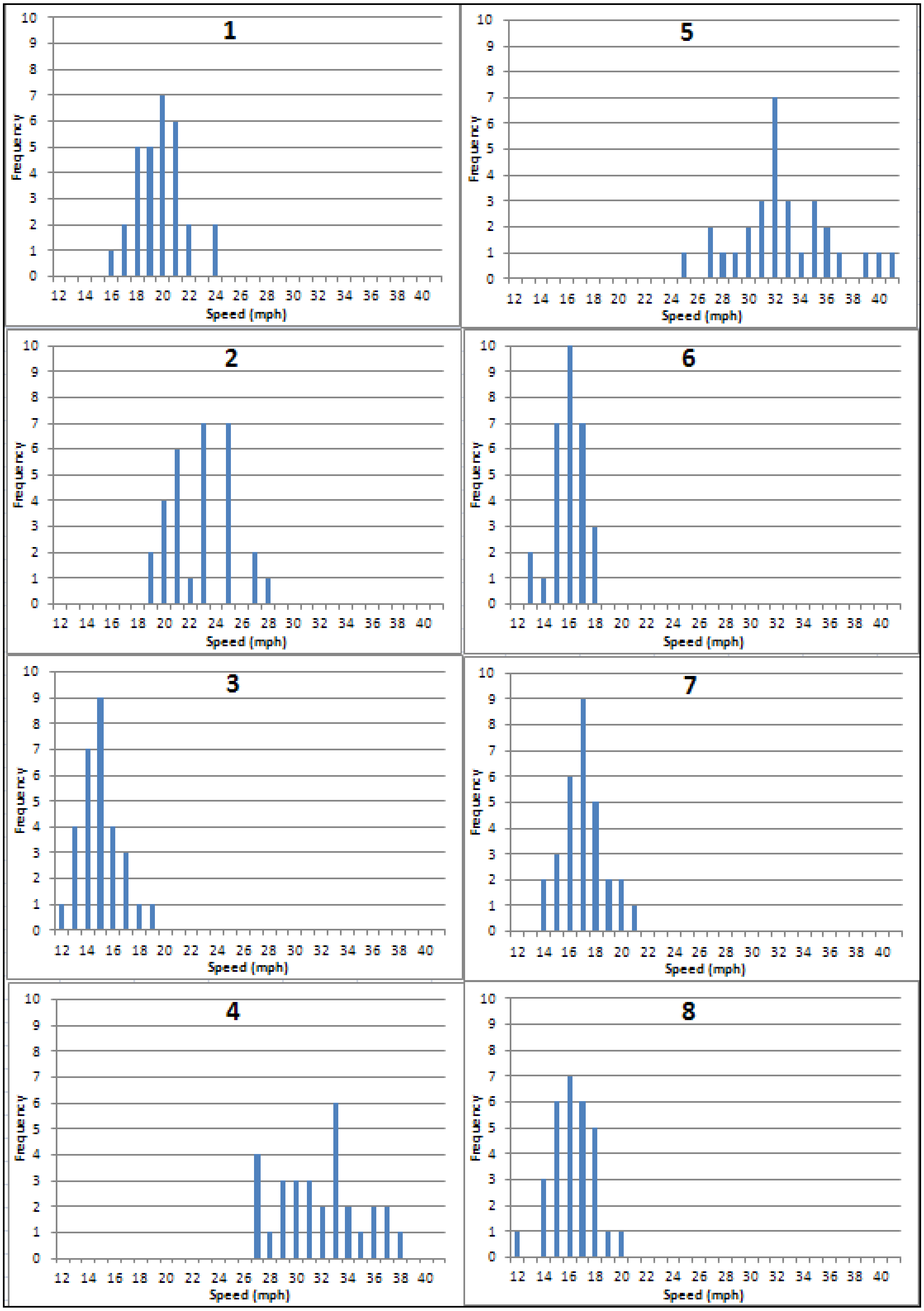

Figure 3: Spot Speed Histograms

4. Appendix

4.1. Appendix F1: Aerial Imagery

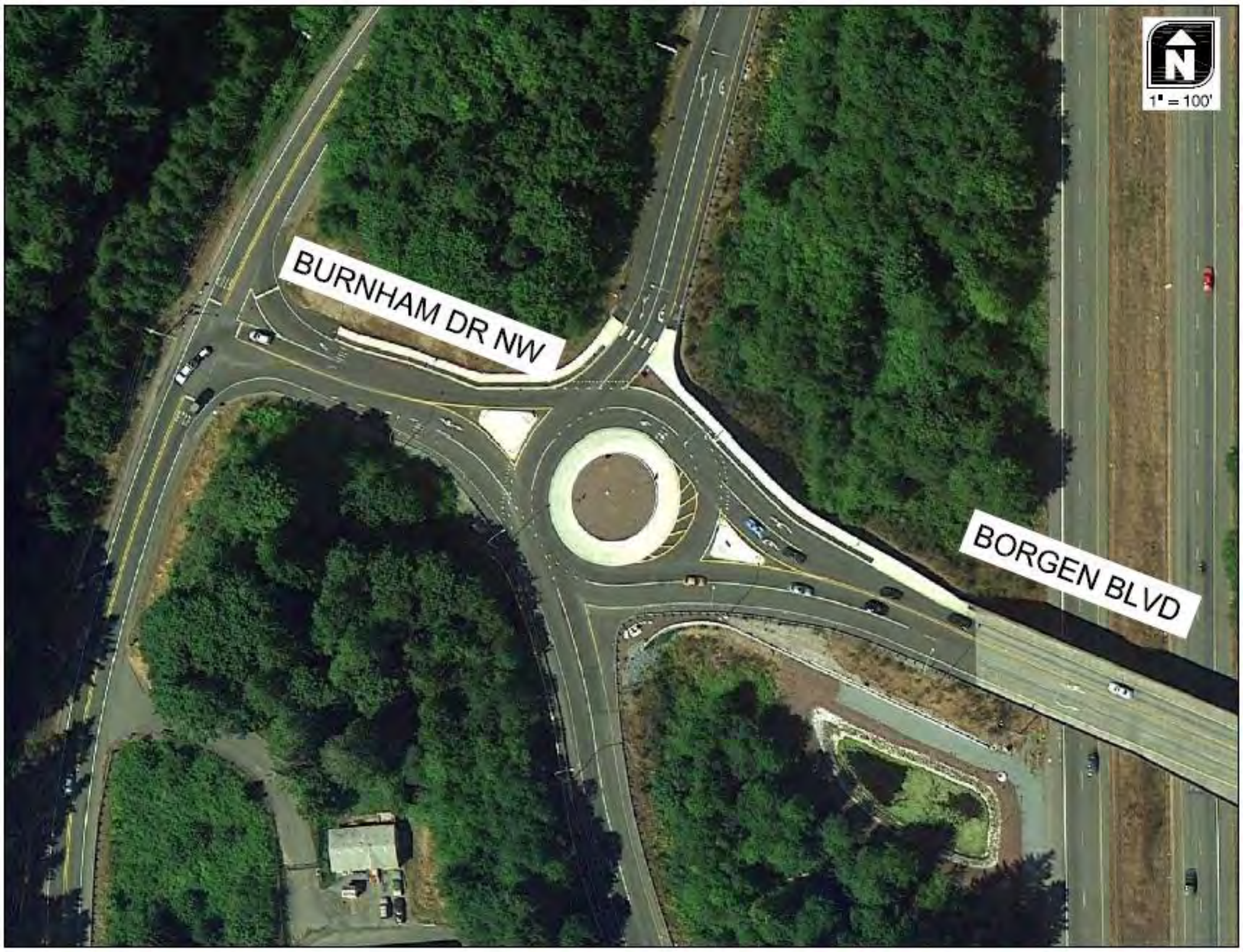

Figure 1. Burnham Dr/Borgen Blvd at SR 16 SB

Figure 2. Borgen Blvd at SR 16 NB/Burham Dr/Canterwood Blvd

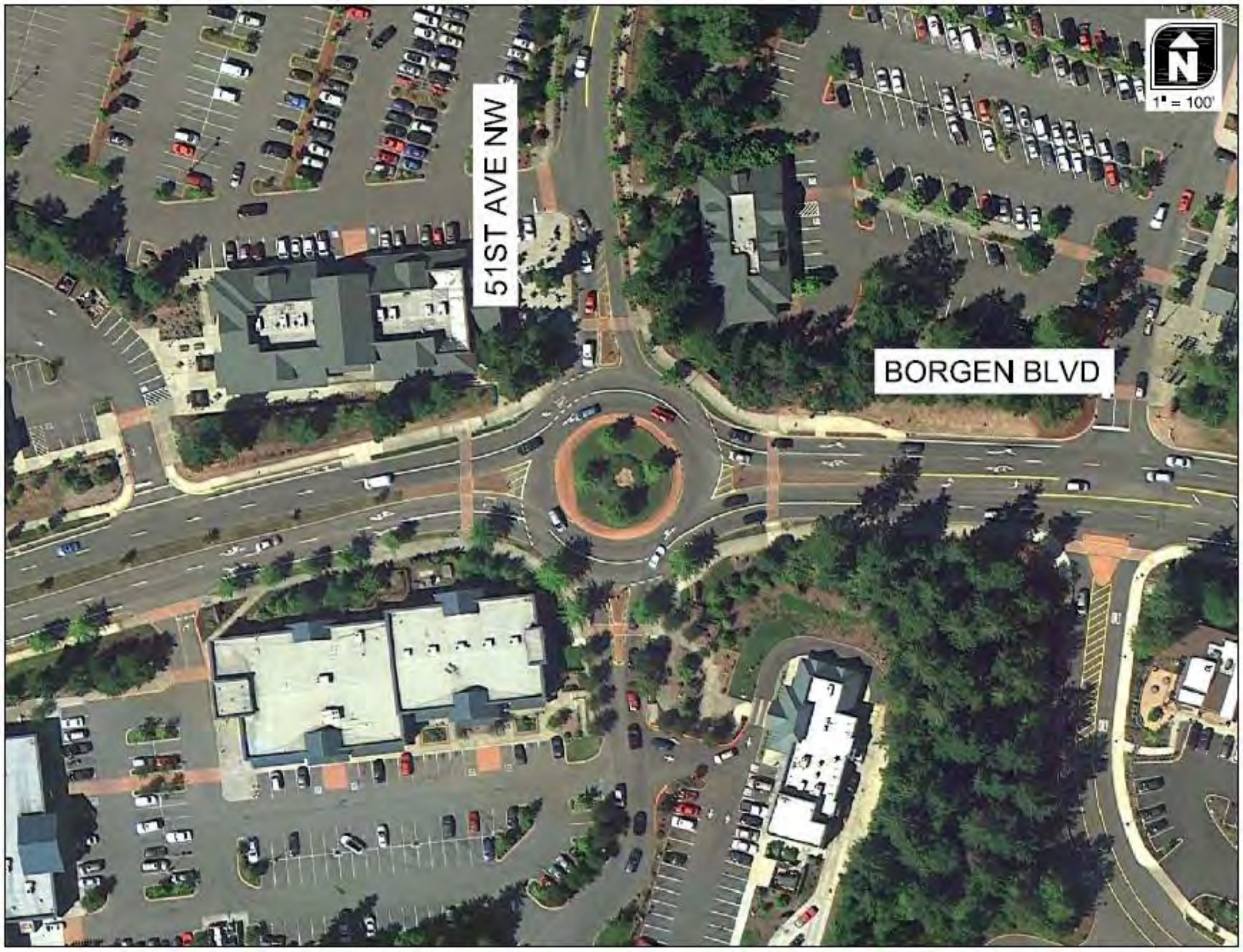

Figure 3. Borgen Blvd at 51st Ave

Figure 4. Borgen Blvd at Harbor Hill Dr

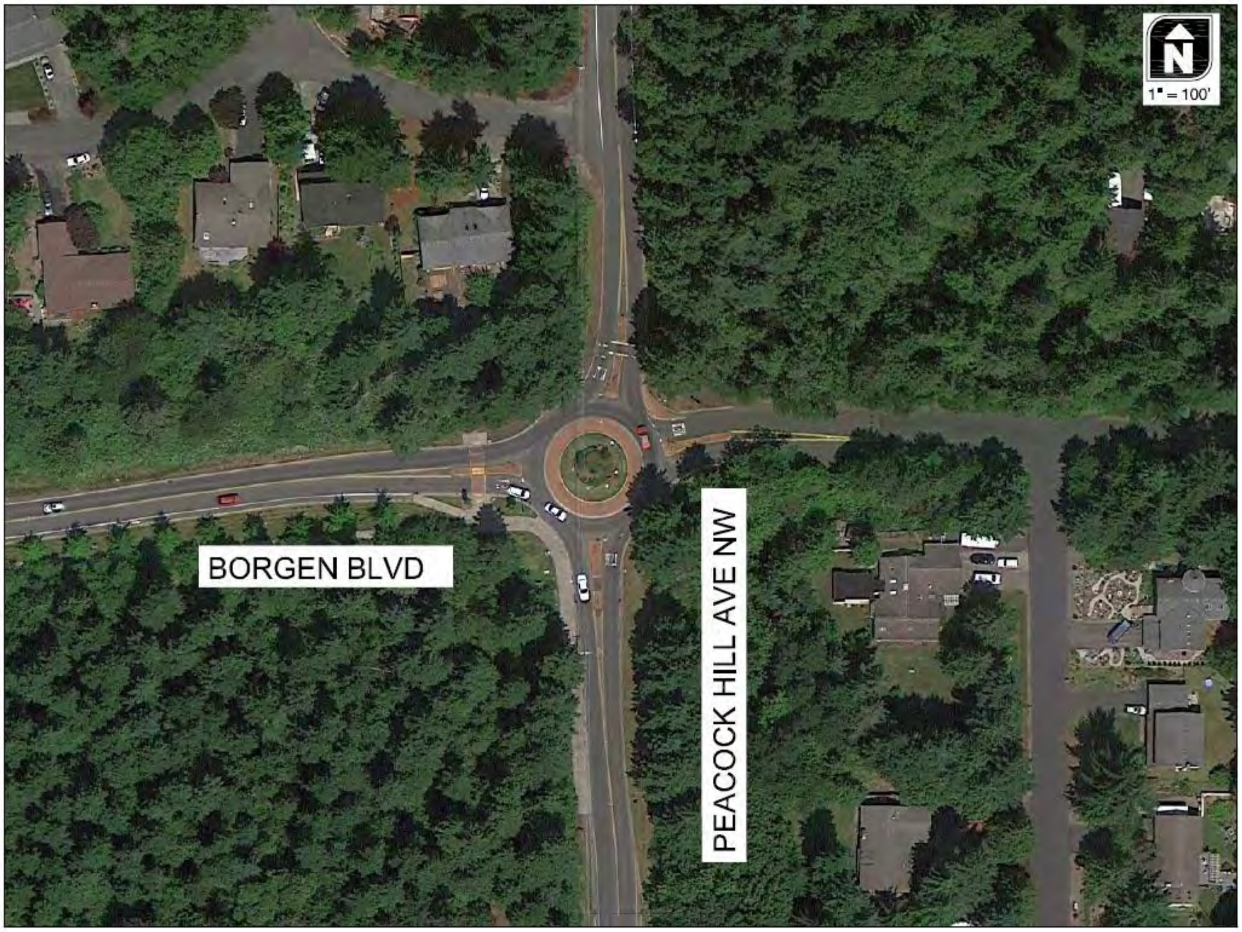

Figure 5. Borgen Blvd at Peacock Hill Ave NW

4.2. **Appendix F2: Speed Profiles**

The speed profiles below correspond to the space-time trajectories for each of the six routes in Figures 3A through 3F.

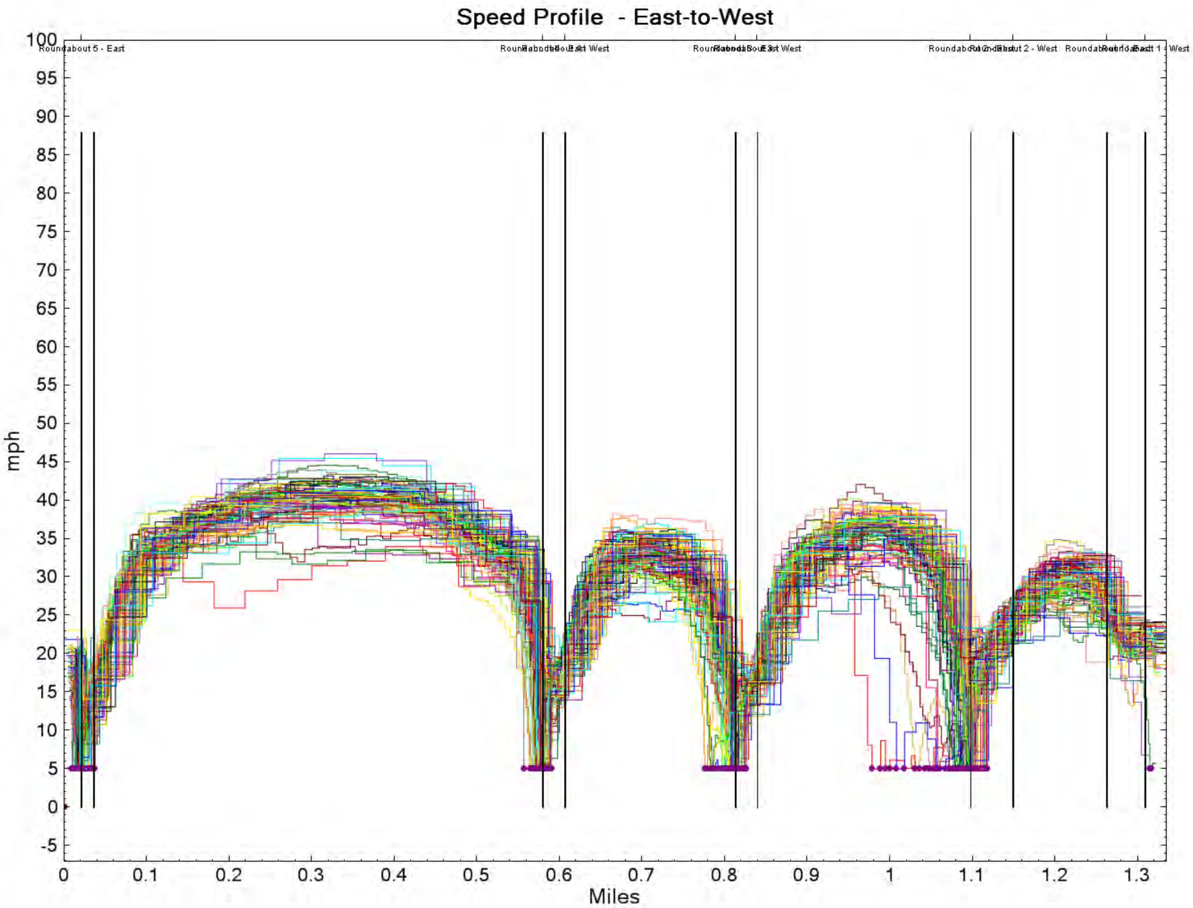

Figure B1. Speed Profile for Route 1 (Westbound Through the Entire Corridor)

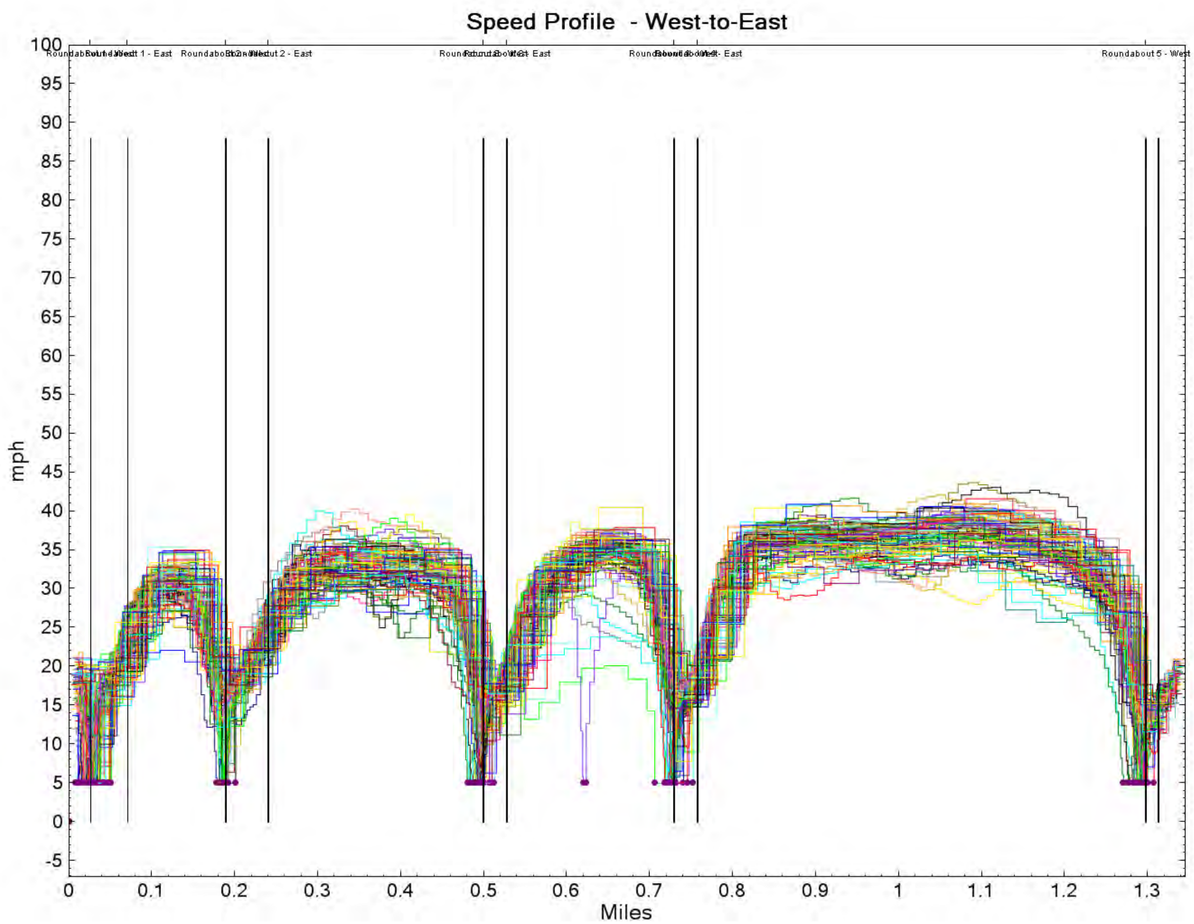

Figure B2. Speed Profile for Route 2 (Eastbound Through the Entire Corridor)

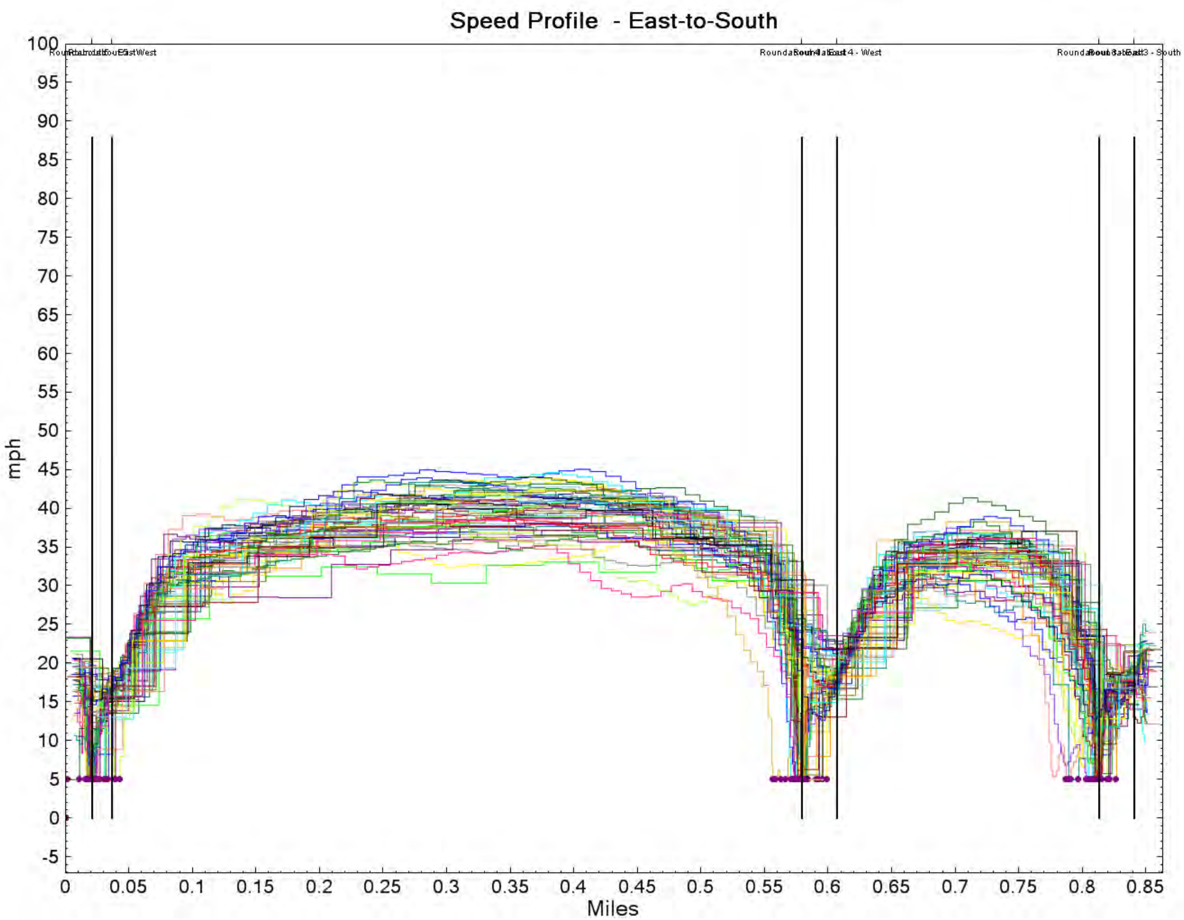

Figure B3. Speed Profile for Route 3 (Beginning East of Roundabout 5, then Turning Left at Roundabout 3)

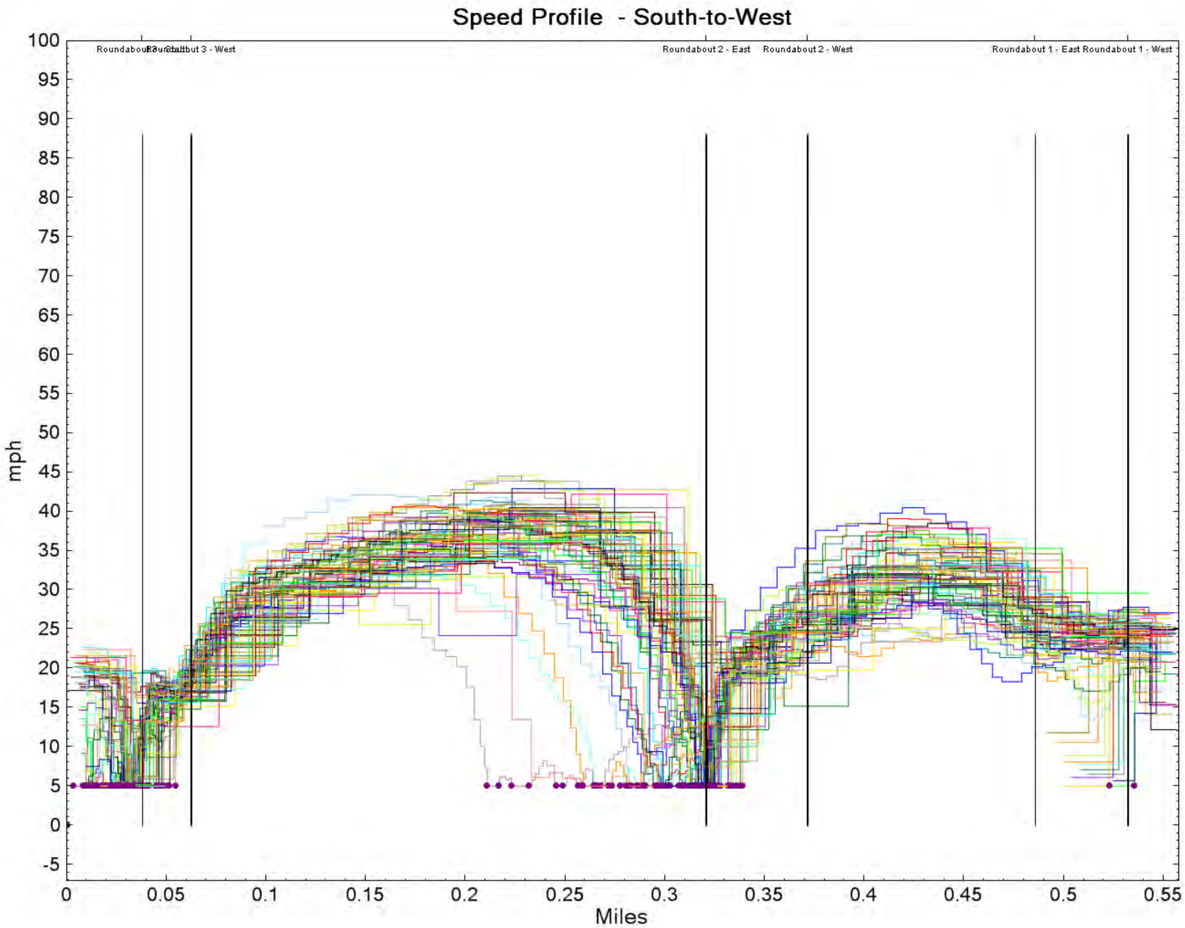

Figure B4. Speed Profile for Route 4 (Beginning South of Roundabout 3, then Turning Left at Roundabout 3)

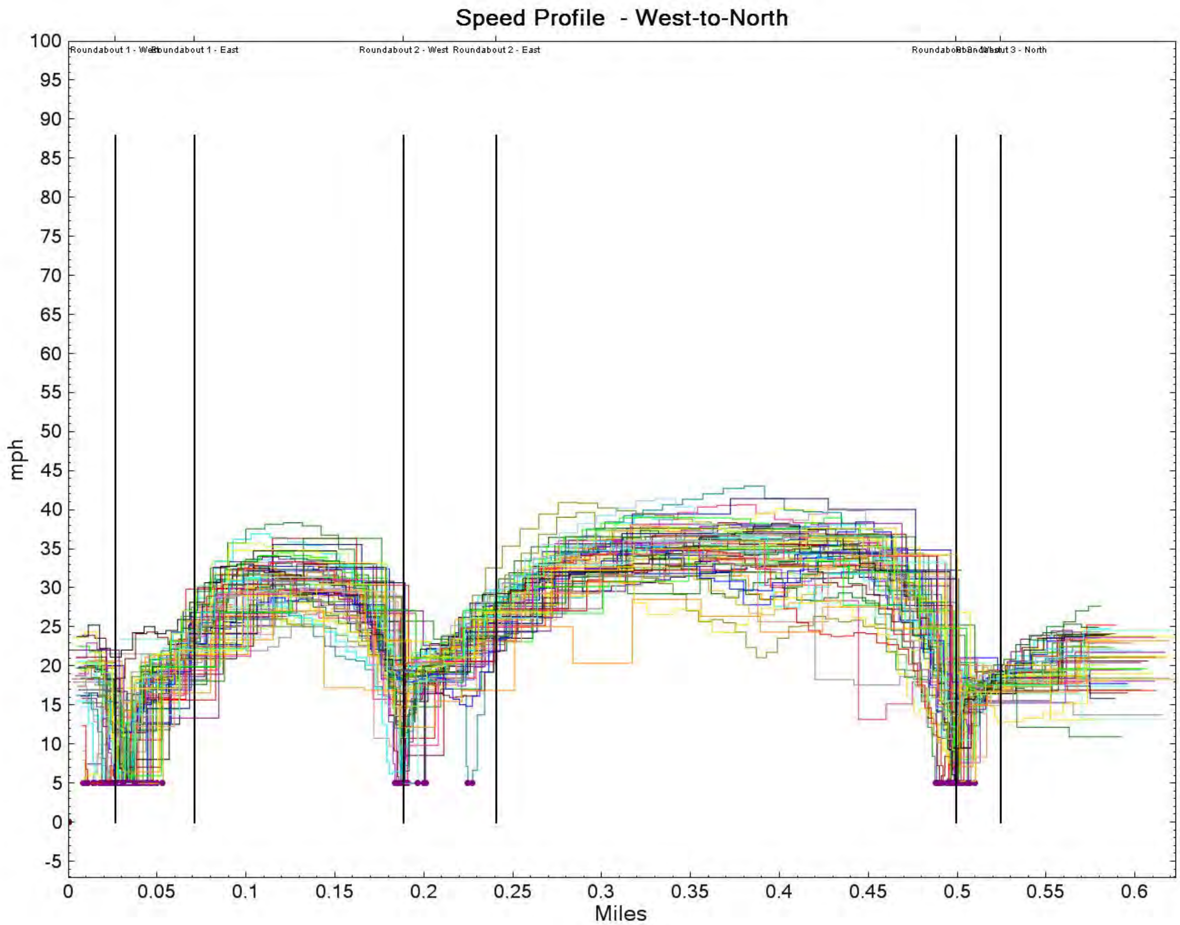

Figure B5. Speed Profile for Route 5 (Beginning West of Roundabout 1, then Turning Left at Roundabout 3)

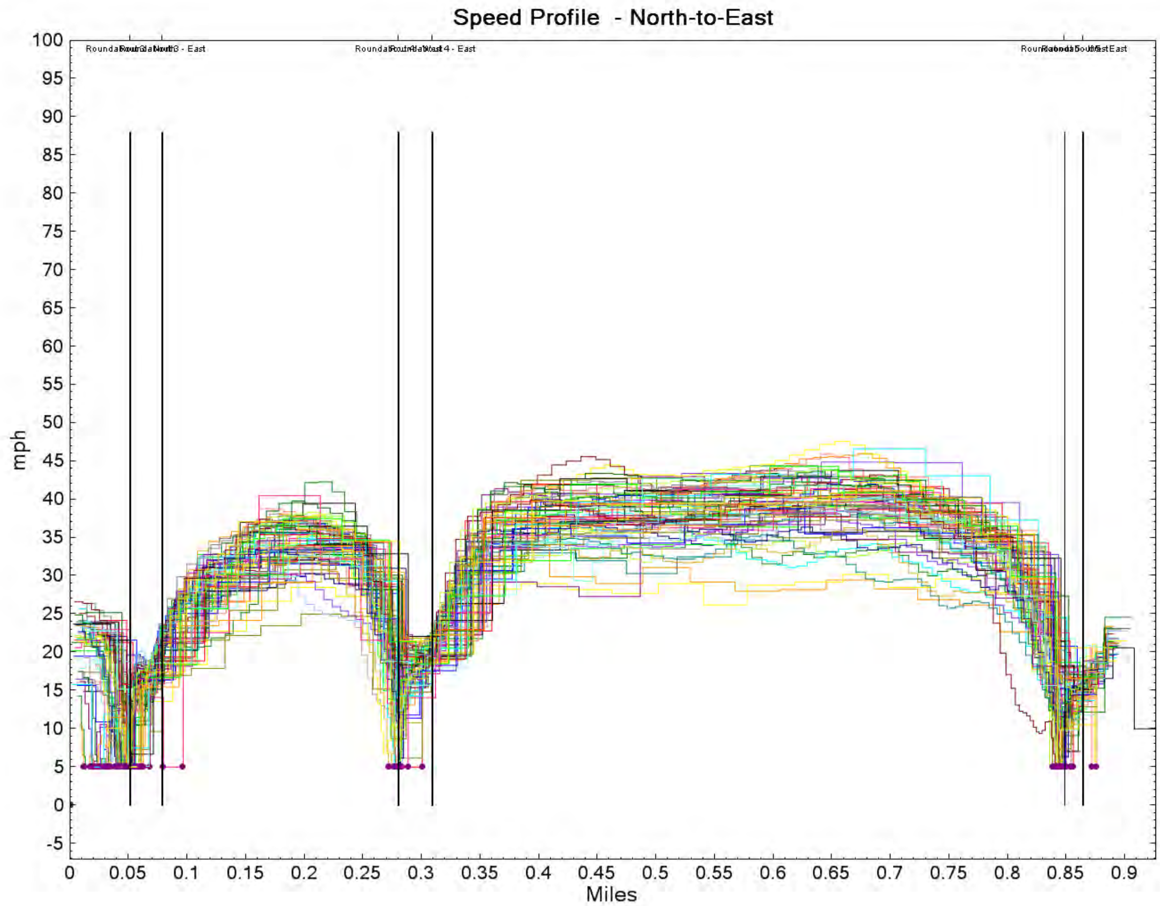

Figure B6. Speed Profile for Route 6 (Beginning North of Roundabout 3, then Turning Left at Roundabout 3)

NCHRP 03-100

Appendix G

Whatcom County, Washington
SR 539 Field Data

Table of Contents

List of Tables

List of Figures

1. Introduction

This document describes the field data collected by the NCHRP 3-100 team at the Washington State Route 539/Guide Meridian Road roundabout corridor in Whatcom County, Washington. The data collection and analysis efforts follow the format described in the team's data collection plan.

The data collected at this roundabout corridor, which consisted of four roundabouts and one internal signalized intersection, included peak-hour and off-peak travel times as well as spot speed measurements. Travel times were recorded using vehicle-mounted GPS units. Additionally, video data were obtained through field-mounted cameras. Data were collected from May 31, 2012, to June 2, 2012.

This document provides an overview of the data collected and discusses the quality and size of the dataset. Figure 1 displays a split-screen schematic of the corridor. The white numbers denote roundabouts.

Figure 1. Aerial View of the SR 539 Roundabout Corridor. ©Google, Inc.

2. Traffic Counts

The research team obtained traffic counts along the corridor. Table 1 displays the turning-movement counts that were collected during the peak hour (5:15 p.m. to 6:15 p.m.).

Table 1: Turning Movement Counts (5:15 p.m. to 6:15 p.m.)

Intersection		Movement	L	T	R
#	Name				
1	Ten Mile Rd	Northbound	0	468	17
		Southbound	14	265	0
		Eastbound	0	0	1
		Westbound	3	0	4
2	E Pole Rd	Northbound	34	340	85
		Southbound	73	200	45
		Eastbound	34	28	26
		Westbound	41	24	48
3	Wiser Lake Rd	Northbound	19	395	19
		Southbound	42	292	23
		Eastbound	25	2	3
		Westbound	8	3	19
4	River Rd	Northbound	8	442	
		Southbound		347	2
		Eastbound	3		3

Figure 2 displays the 12-hour volume profile taken between the Pole Road roundabout and the Wiser Lake Road roundabout. The peak 30-minute period was identified to occur between 5:00 p.m. and 5:30 p.m.

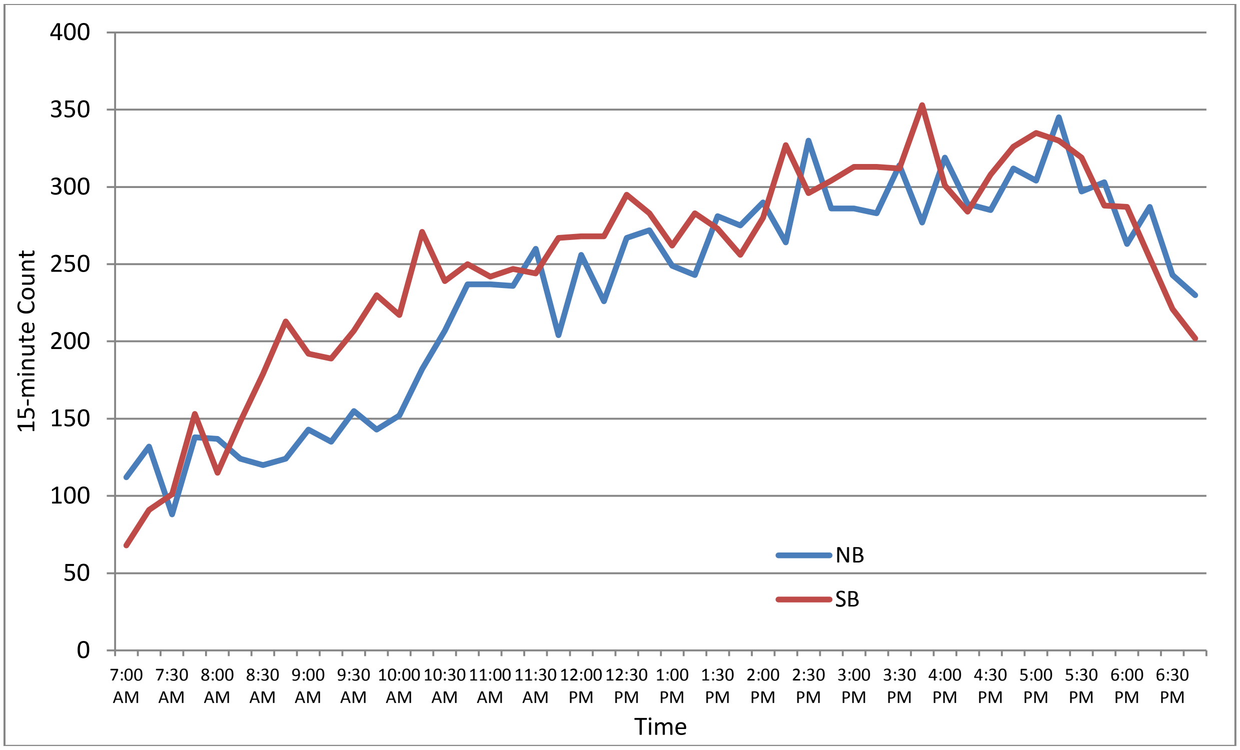

Figure 2: 12-hour Volume Profile

3. Field-Observed Data

GPS travel times and spot-speed data were collected along the corridor.

3.1. GPS Travel Times

The travel time through the corridor was measured using vehicle-mounted GPS units. A total of six routes were used to conduct the study:

1. Northbound through the entire corridor;
2. Southbound through the entire corridor;
3. Beginning at the southern end of the corridor and turning left through roundabout 2 (Pole Road);
4. Beginning west of roundabout 2 (Pole Road) and turning left, proceeding to the northern end of the corridor;
5. Beginning at the northern end of the corridor and turning left through roundabout 3 (Wiser Lake Road); and
6. Beginning east of roundabout 3 (Wiser Lake Road) and turning left, proceeding to the southern end of the corridor.

Figure 2 displays the space-time trajectories from each of the six routes. Each diagram displays every travel-time run that was conducted (including a.m., p.m., and off-peak runs). Note that the scale varies from route to route. The corresponding speed profiles are displayed in Appendix G2.

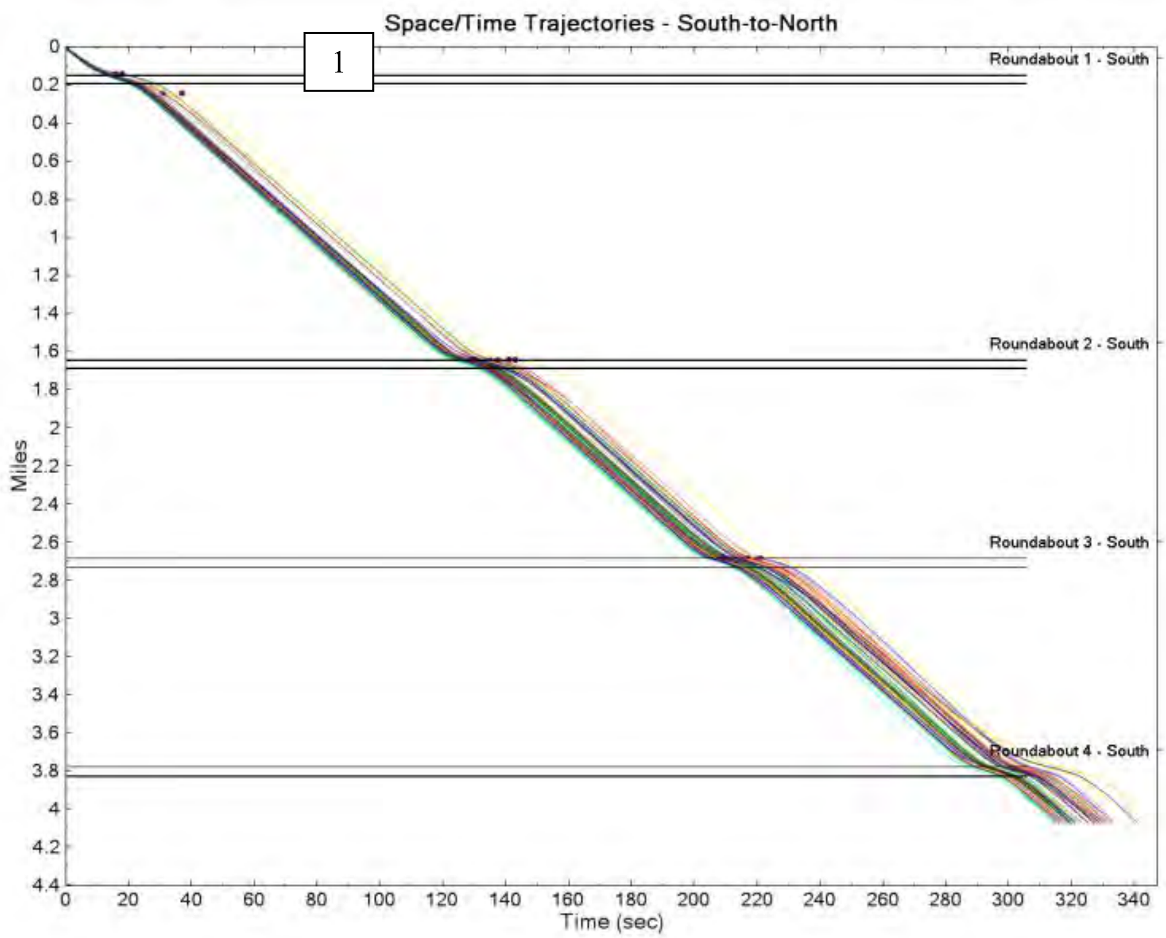

Figure B1. Space/Time Trajectories for Route 1 (Northbound Through the Entire Corridor)

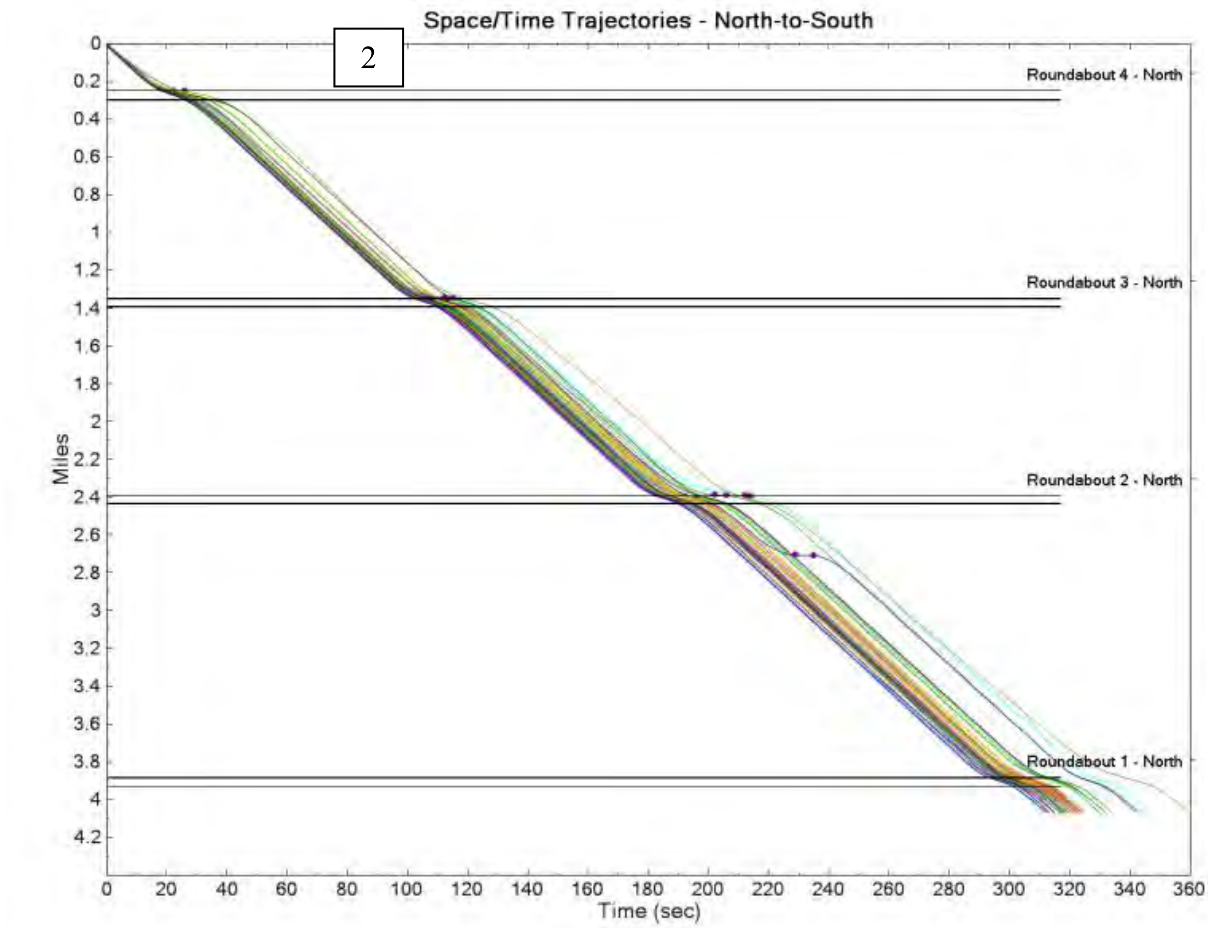

Figure B2. Space/Time Trajectories for Route 2 (Southbound Through the Entire Corridor)

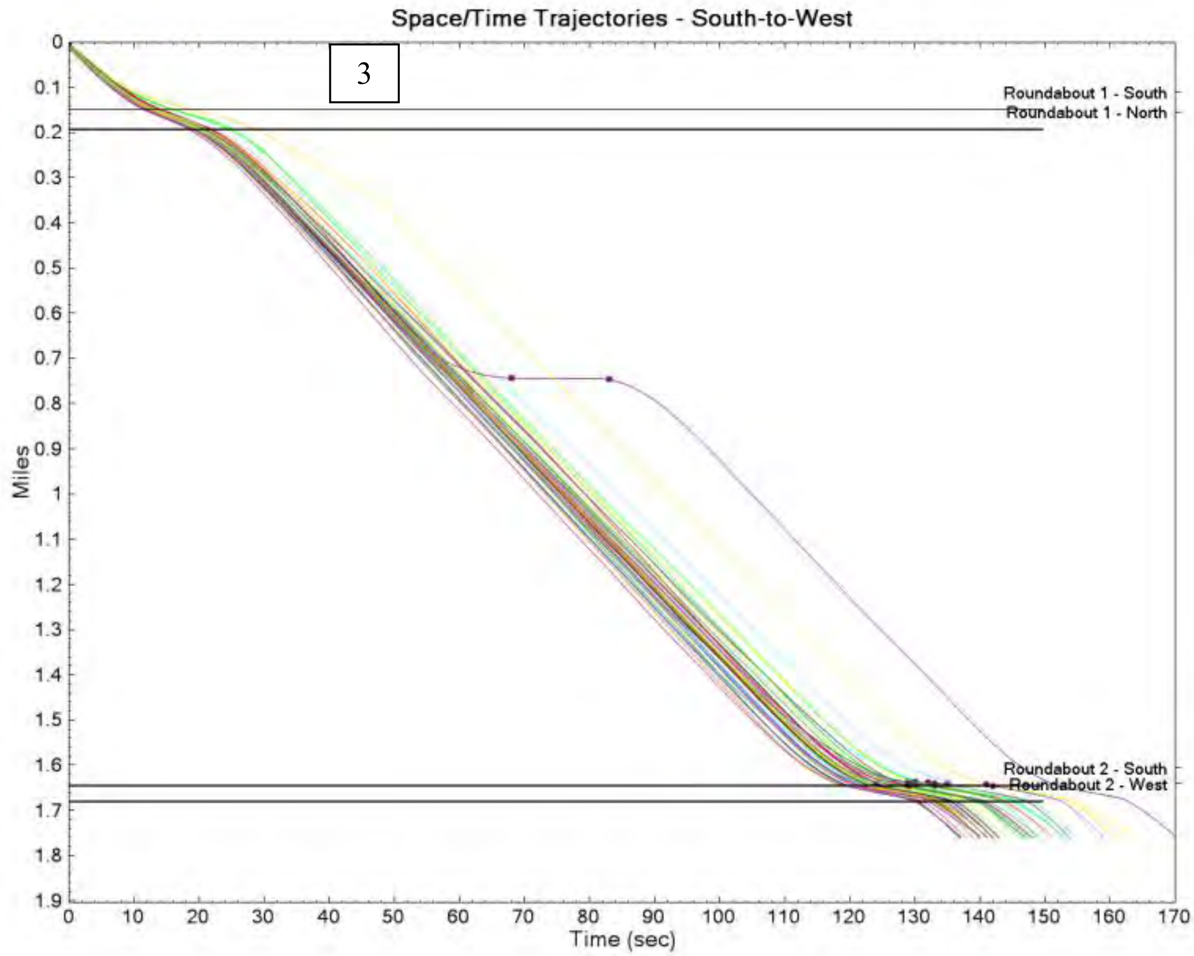

Figure B3. Space/Time Trajectories for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 2)

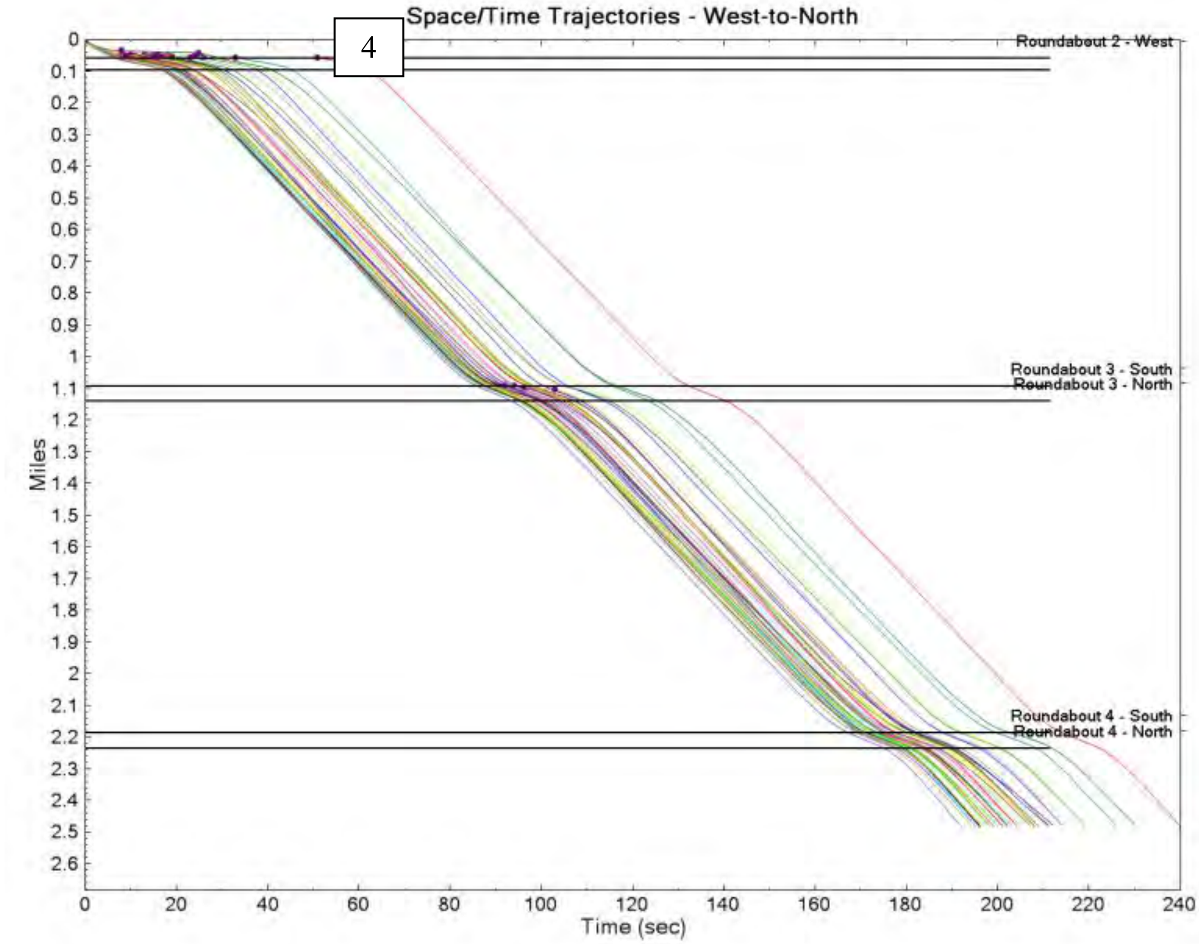

Figure B4. Space/Time Trajectories for Route 4 (Starting from West of Roundabout 2, then Turning Left at Roundabout 2)

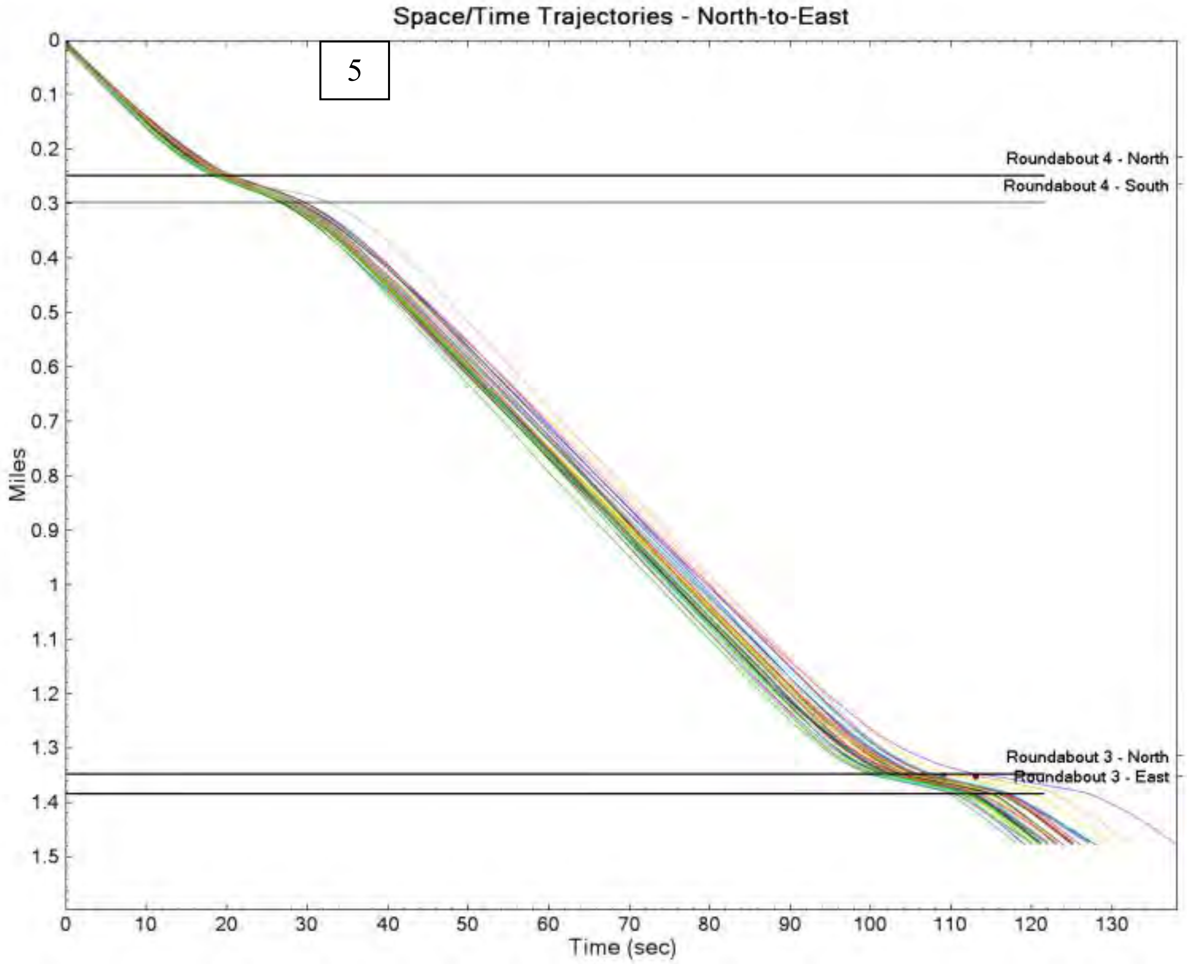

Figure B5. Space/Time Trajectories for Route 5 (Starting from North of Roundabout 4, then Turning Left at Roundabout 3)

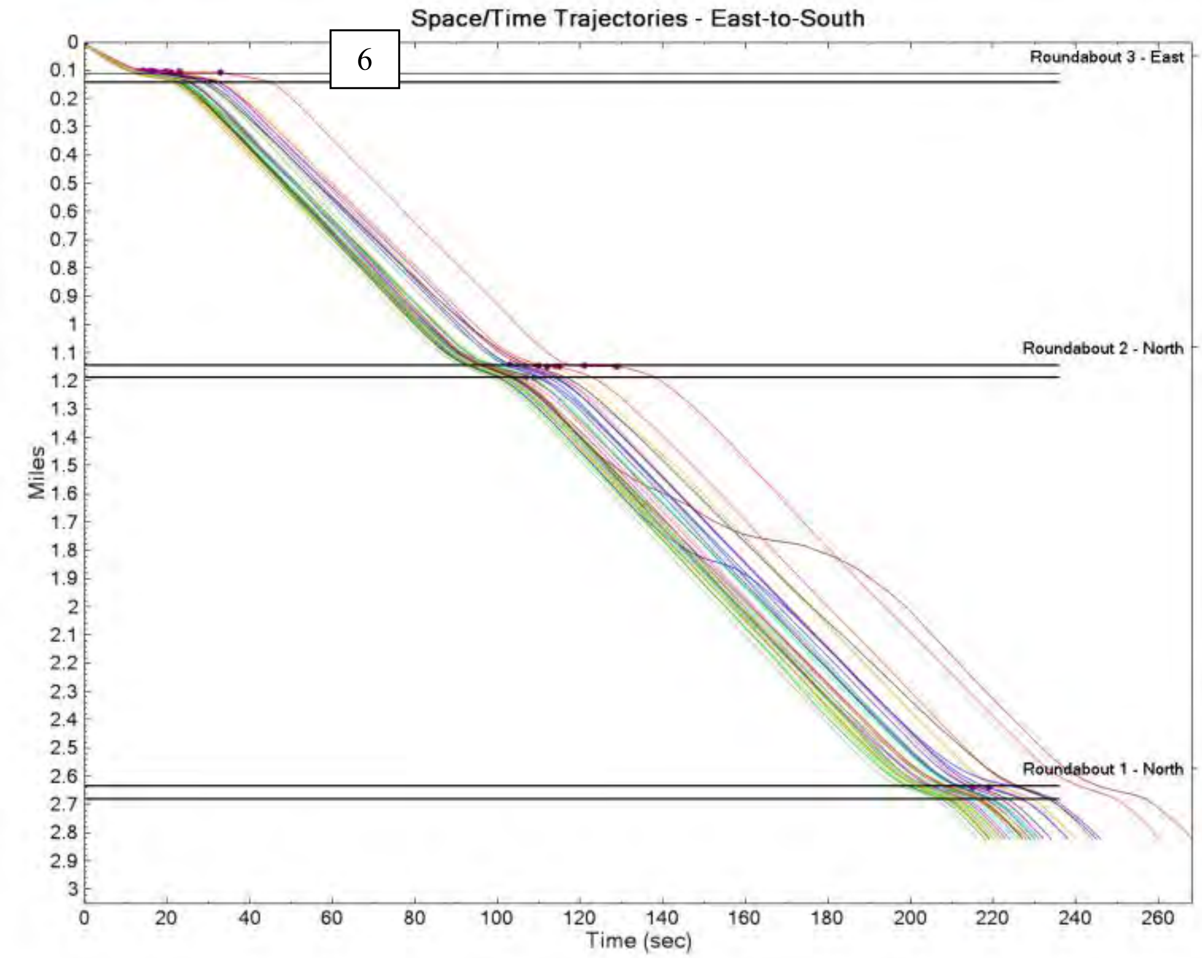

Figure B6. Space/Time Trajectories for Route 6 (Starting from East of Roundabout 3, then Turning Left at Roundabout 3)

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening." A vehicle stop is denoted by a purple dot. The horizontal lines in the diagrams correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor reflects the variability in the observed data. The distance along the y-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

Table 2 presents more detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in mph, and all travel times are displayed in minutes. Using the free-flow travel time, the table shows HCM Urban Streets LOS (based on % FFS aggregated over all roundabouts along the route) and the average HCM Roundabout LOS. . The table indicates that the LOS assigned to each route may vary using either method; the urban streets LOS tends to be lower than the roundabout LOS.

Table 2: Summary of a.m., p.m., and Off-peak Travel Times

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)				Free-Flow Speed (mph)	% FFS	Urban Street LOS	Travel Distance (mi)	Free-Flow TT (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min							
East-to-South	**41**	**44.8**	**1.7**	**47.3**	**39.5**	**3.81**	**0.16**	**4.33**	**3.60**	**56.4**	**79.4%**	**B**	**2.84**	**3.02**	**9.5**	**A**
AM	9	44.7	1.5	46.4	41.8	3.82	0.13	4.07	3.67		79.2%	B			9.5	A
Off	24	44.8	1.9	47.3	39.5	3.81	0.17	4.33	3.60		79.5%	B			9.4	A
PM	8	44.8	1.7	46.7	41.5	3.80	0.15	4.10	3.65		79.4%	B			9.4	A
North-to-East	**45**	**43.4**	**1.2**	**45.0**	**38.8**	**2.06**	**0.06**	**2.30**	**1.97**	**56.4**	**77.0%**	**B**	**1.49**	**1.59**	**5.7**	**A**
AM	10	43.3	0.7	44.1	42.3	2.07	0.04	2.12	2.03		76.7%	B			5.8	A
Off	26	43.2	1.4	44.8	38.8	2.06	0.08	2.30	1.98		76.7%	B			5.8	A
PM	9	44.1	0.8	45.0	42.3	2.02	0.04	2.12	1.97		78.1%	B			5.2	A
South-to-West	**46**	**44.4**	**1.9**	**46.8**	**39.0**	**2.40**	**0.11**	**2.73**	**2.28**	**58**	**76.5%**	**B**	**1.78**	**1.84**	**6.8**	**A**
AM	10	44.3	1.3	45.8	41.7	2.40	0.07	2.55	2.32		76.5%	B			6.7	A
Off	26	44.2	2.2	46.8	39.0	2.42	0.13	2.73	2.28		76.2%	B			6.9	A
PM	10	44.8	1.8	46.8	41.2	2.38	0.10	2.57	2.28		77.2%	B			6.5	A
West-to-North	**47**	**44.0**	**2.0**	**46.7**	**37.3**	**3.41**	**0.17**	**4.00**	**3.20**	**58**	**75.8%**	**B**	**2.5**	**2.58**	**10.0**	**A**
AM	9	42.9	2.5	45.7	37.3	3.50	0.22	4.00	3.27		73.9%	B			11.1	B
Off	29	44.5	1.5	46.7	41.0	3.37	0.11	3.65	3.20		76.7%	B			9.5	A
PM	9	43.5	2.6	45.9	39.1	3.45	0.22	3.83	3.25		75.0%	B			10.5	B
North-to-South	**58**	**45.4**	**1.2**	**47.1**	**40.6**	**5.37**	**0.15**	**6.00**	**5.18**	**56.4**	**80.6%**	**B**	**4.06**	**4.32**	**12.6**	**B**
AM	12	44.4	1.7	45.9	40.6	5.51	0.22	6.00	5.32		78.7%	B			14.2	B
Off	32	45.9	0.7	47.1	43.8	5.31	0.09	5.57	5.18		81.4%	B			11.9	B
PM	14	45.3	1.0	46.3	42.9	5.38	0.12	5.70	5.25		80.4%	B			12.8	B
South-to-North	**57**	**45.3**	**0.9**	**46.6**	**42.2**	**5.39**	**0.11**	**5.78**	**5.23**	**58**	**78.0%**	**B**	**4.07**	**4.21**	**14.2**	**B**
AM	11	45.1	0.8	46.3	44.2	5.41	0.09	5.52	5.27		77.8%	B			14.4	B
Off	33	45.5	0.7	46.5	44.0	5.36	0.08	5.55	5.25		78.5%	B			13.8	B
PM	13	44.8	1.4	46.6	42.2	5.45	0.17	5.78	5.23		77.2%	B			14.9	B

Notes: FFS = free-flow speed, Rbt = roundabout, LOS = Level of Service

3.2. Geometric and Approach Delay from GPS

The team also examined the approach delay at each roundabout while considering the geometric delay incurred by the roundabouts themselves. Table 4 presents a summary of this analysis. For each approach and time of day, the free-flow travel time was estimated by isolating the unimpeded trajectories from the rest of the data set and by measuring the peak midblock speed from the trajectories. Although the true free-flow speed may not be observable in this manner (it may be higher than the observed speeds due to friction/driver behavior along the corridor), but the team believed that this method was advantageous in that it provided a much greater sample size (in a greater number of locations) than the midblock speed study (Section 3.3). Additionally, the travel distance used to compute the free-flow travel time was taken as the centerline distance between each pair of roundabouts so that the geometric delay caused by the additional travel distance to navigate the roundabouts did not affect the estimate of the free-flow travel time.

Table 3 shows the distances used for estimating free-flow travel time, relative to the actual travel distance through the roundabout. Each segment is assumed to start about half-way between two roundabouts and to end at (approximately) the downstream crosswalk at a roundabout. Note that the sum of all segments does not equal the total travel distance because the distance between the downstream crosswalk and the next segment start is not accounted for. For the complete route analysis, the reader should refer to the analysis in the previous section. The table also shows the field-estimated FFS for each segment, as well as the posted speed limit.

Table 3: Summary of Segment Distances

Direction	Route Segment	Free-Flow Distance (feet)	Trajectory Distance (feet)	Segment FFS (mph)	Speed Limit (mph)
Northbound	RBT1- North Approach	4,134	4,435	54.1	50
	RBT2- North Approach	2,880	2,904	54.9	50
	RBT3- North Approach	1,508	1,584	58.0	50
	RBT4- North Approach	1,955	2,006	55.0	50
Southbound	RBT1- South Approach	1,113	1,584	50.8	50
	RBT2- South Approach	3,425	4,118	56.4	50
	RBT3- South Approach	2,660	2,798	55.7	50
	RBT4- South Approach	2,347	2,347	58.2	50

Note: RBT = roundabout, FFS = free-flow speed

Table 4 displays the impeded delay (equal to the difference between the average travel time and the unimpeded travel time) and total delay (equal to the difference between the average travel time and the free-flow travel time) for each approach route.

Table 4: Summary of Geometric and Approach Delay

Approach / Time of Day	Average Travel Time (s)	Travel Distance (mi)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT1-North Approach	**64.7**	**0.78**	**54.1**	**52.1**	**62.7**	**10.6**	**2.0**	**12.6**
AM	65.7	0.78	54.1	52.1	62.7	10.6	3.0	13.6
Off	64.3	0.78	54.1	52.1	62.7	10.6	1.6	12.2
PM	64.7	0.78	54.1	52.1	62.7	10.6	2.0	12.6
RBT1-South Approach	**30.0**	**0.21**	**50.8**	**14.9**	**28.1**	**13.1**	**2.0**	**15.1**
AM	30.5	0.21	50.8	14.9	28.1	13.1	2.5	15.6
Off	29.9	0.21	50.8	14.9	28.1	13.1	1.8	15.0
PM	29.9	0.21	50.8	14.9	28.1	13.1	1.8	14.9
RBT2-North Approach	**46.3**	**0.55**	**54.9**	**35.8**	**43.7**	**7.9**	**2.6**	**10.5**
AM	49.5	0.55	54.9	35.8	43.7	7.9	5.8	13.7
Off	45.3	0.55	54.9	35.8	43.7	7.9	1.6	9.6
PM	45.6	0.55	54.9	35.8	43.7	7.9	2.0	9.9
RBT2-South Approach	**63.4**	**0.65**	**56.4**	**41.4**	**60.4**	**19.0**	**3.0**	**22.0**
AM	64.3	0.65	56.4	41.4	60.4	19.0	3.9	22.8
Off	63.1	0.65	56.4	41.4	60.4	19.0	2.7	21.7
PM	63.5	0.65	56.4	41.4	60.4	19.0	3.1	22.1
RBT2-West Approach	**33.0**	**0.15**	**38.2**	**14.6**	**25.8**	**11.2**	**7.2**	**18.4**
AM	38.0	0.15	38.2	14.6	25.8	11.2	12.2	23.4
Off	30.7	0.15	38.2	14.6	25.8	11.2	4.9	16.1
PM	34.5	0.15	38.2	14.6	25.8	11.2	8.7	19.9
RBT3-East Approach	**37.7**	**0.19**	**37.8**	**17.9**	**34.1**	**16.2**	**3.6**	**19.8**
AM	37.8	0.19	37.8	17.9	34.1	16.2	3.7	19.9
Off	37.8	0.19	37.8	17.9	34.1	16.2	3.7	19.9
PM	37.5	0.19	37.8	17.9	34.1	16.2	3.4	19.6

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (mi)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT3-North Approach	**28.8**	**0.29**	**58.0**	**17.7**	**25.9**	**8.1**	**2.9**	**11.0**
AM	31.1	0.29	58.0	17.7	25.9	8.1	5.2	13.3
Off	27.3	0.29	58.0	17.7	25.9	8.1	1.5	9.6
PM	30.3	0.29	58.0	17.7	25.9	8.1	4.5	12.6
RBT3-South Approach	**44.6**	**0.50**	**55.7**	**32.6**	**42.2**	**9.7**	**2.3**	**12.0**
AM	44.2	0.50	55.7	32.6	42.2	9.7	2.0	11.6
Off	44.2	0.50	55.7	32.6	42.2	9.7	1.9	11.6
PM	45.8	0.50	55.7	32.6	42.2	9.7	3.6	13.3
RBT4-North Approach	**33.1**	**0.37**	**55.0**	**24.2**	**31.3**	**7.1**	**1.8**	**8.9**
AM	34.1	0.37	55.0	24.2	31.3	7.1	2.8	9.9
Off	33.3	0.37	55.0	24.2	31.3	7.1	2.0	9.1
PM	31.9	0.37	55.0	24.2	31.3	7.1	0.6	7.6
RBT4-South Approach	**46.4**	**0.44**	**58.2**	**27.5**	**44.2**	**16.7**	**2.2**	**18.9**
AM	46.4	0.44	58.2	27.5	44.2	16.7	2.1	18.9
Off	45.8	0.44	58.2	27.5	44.2	16.7	1.6	18.3
PM	48.0	0.44	58.2	27.5	44.2	16.7	3.8	20.6

The data in the table indicate that the geometric delays tended to be much higher than the impeded delays. This indicates that the corridor was likely uncongested, and much of the total corridor delay can be attributed to deceleration associated with the roundabouts.

3.3. Spot Speed Profiles

In addition to the travel time data, the team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at a few selected roundabouts (Figure 1). These were collected using a laser speed gun. These speeds may provide a more-realistic estimation of operating speeds at the roundabouts than the GPS travel time runs, which were conducted by engineers using the floating car technique. Summary statistics are displayed in Table 5.

Table 5: Spot-Speed Summary Statistics

Point	**1**	**2**	**3**	**4**	**5**	**6**	**8**	**9**	**10**	**11**
RBT #	1	1	1	2-3	2-3	3	3	4	4	4
Location	NB – entry	SB – exit	NB – circ	NB – midblock	SB – midblock	SB – circ	SB – entry	SB – circ	NB – exit	SB – entry
Mean Speed (mph)	22.6	27.7	19.5	50.2	51.7	19.4	23.0	20.2	26.1	22.9
StdDev (mph)	2.6	2.5	1.9	3.4	3.5	1.6	3.3	2.0	2.5	2.9
Sample Size	30	30	30	30	30	30	30	30	30	30

The table indicates that the mean midblock northbound and southbound speeds measured between roundabouts 2 and 3 were 50.2 and 51.7 mph, respectively. This compares to 54.9 and 55.7 mph from the mid-segment trajectories (Table 4). The speed measurements from the combined dataset were also analyzed using histogram frequency distributions—all eight are displayed in Figure 4.

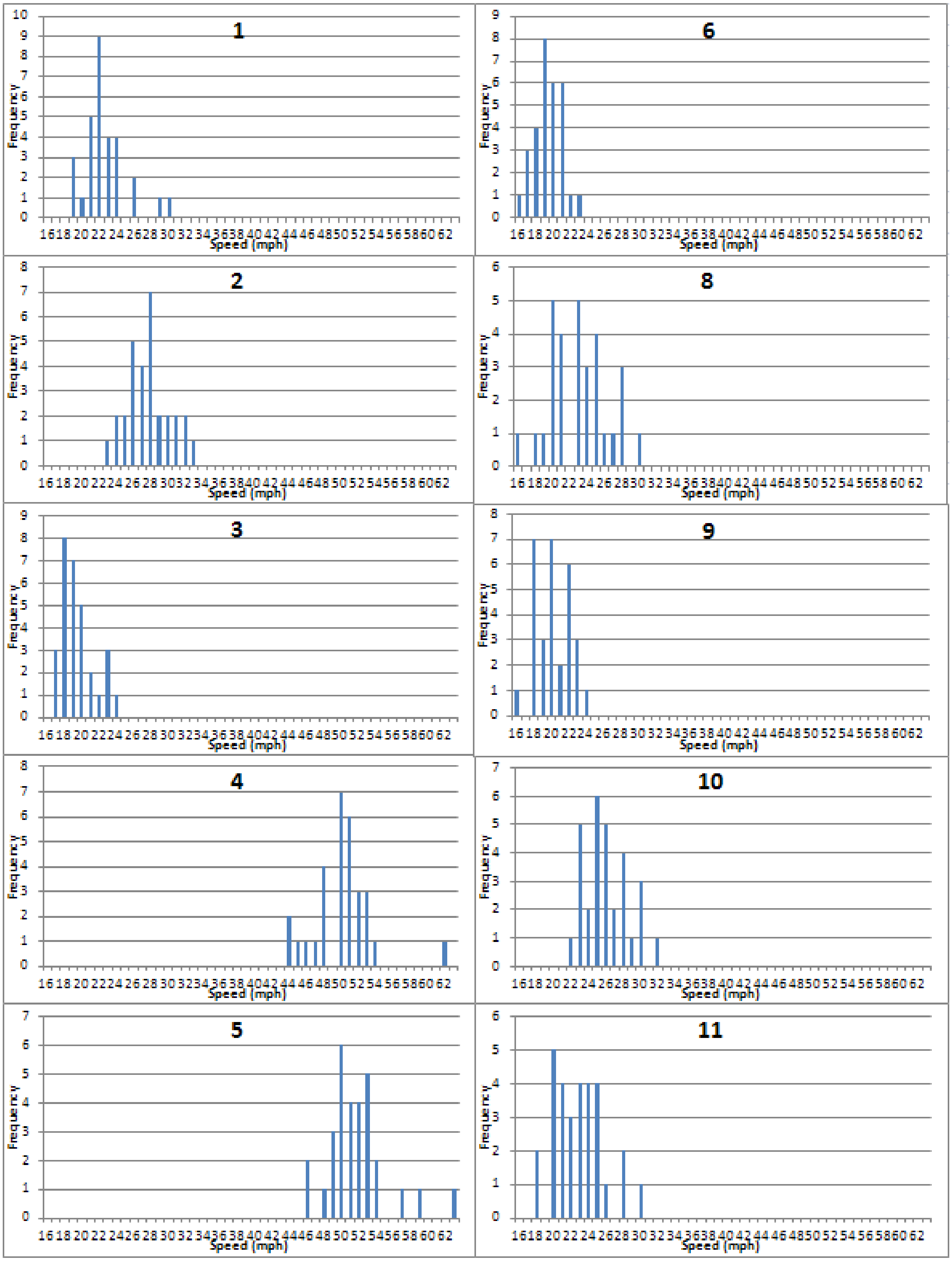

Figure 3: Spot-Speed Histograms

4. Appendix

4.1. Appendix G1: Aerial Imagery

Figure 1. WA-539 at River Rd

Figure 2. WA-539 at Wiser Lake Rd

Figure 3. WA-539 at Pole Rd

Figure 4. WA-539 at Ten Mile Rd

4.2. **Appendix G2: Speed Profiles**

The speed profiles below correspond to the space-time trajectories for each of the six routes in Figures 3A through 3F.

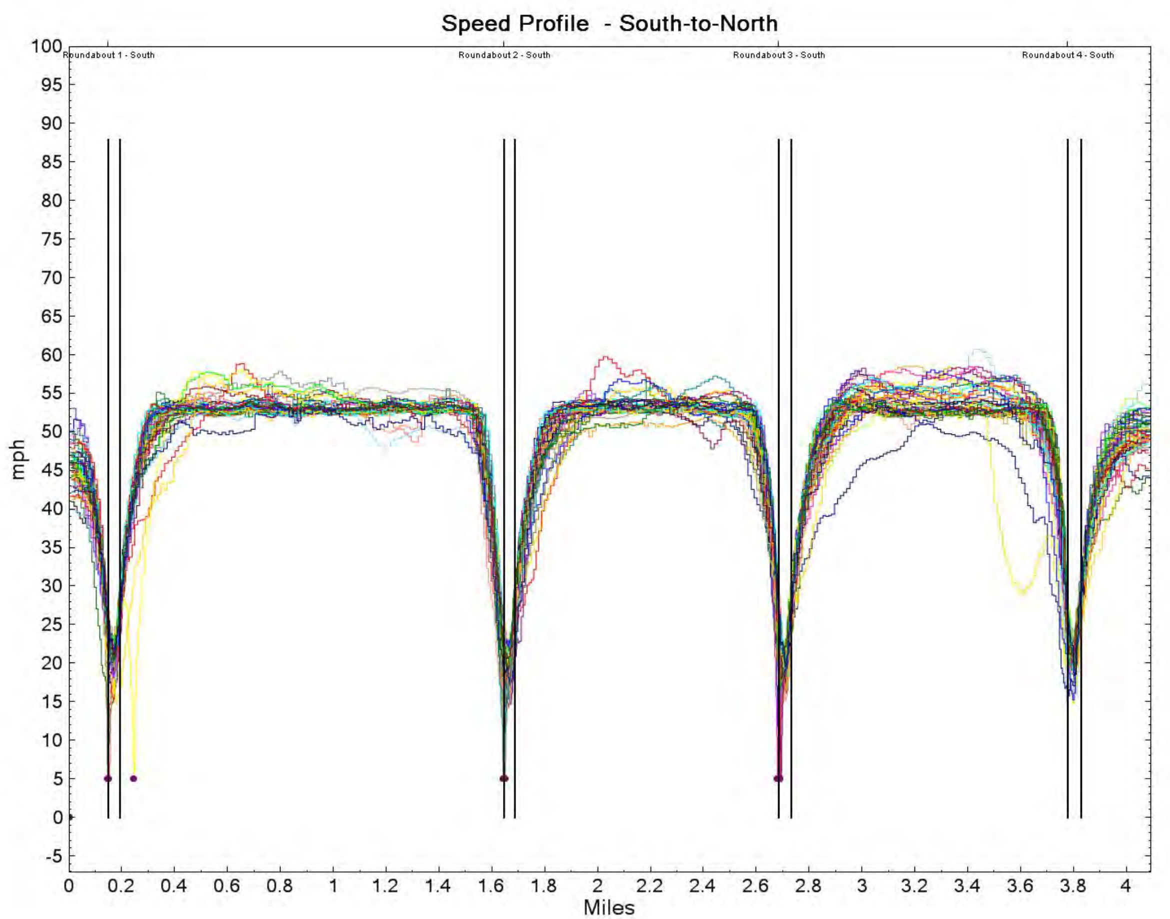

Figure B1. Speed Profile for Route 1 (Northbound Through the Entire Corridor)

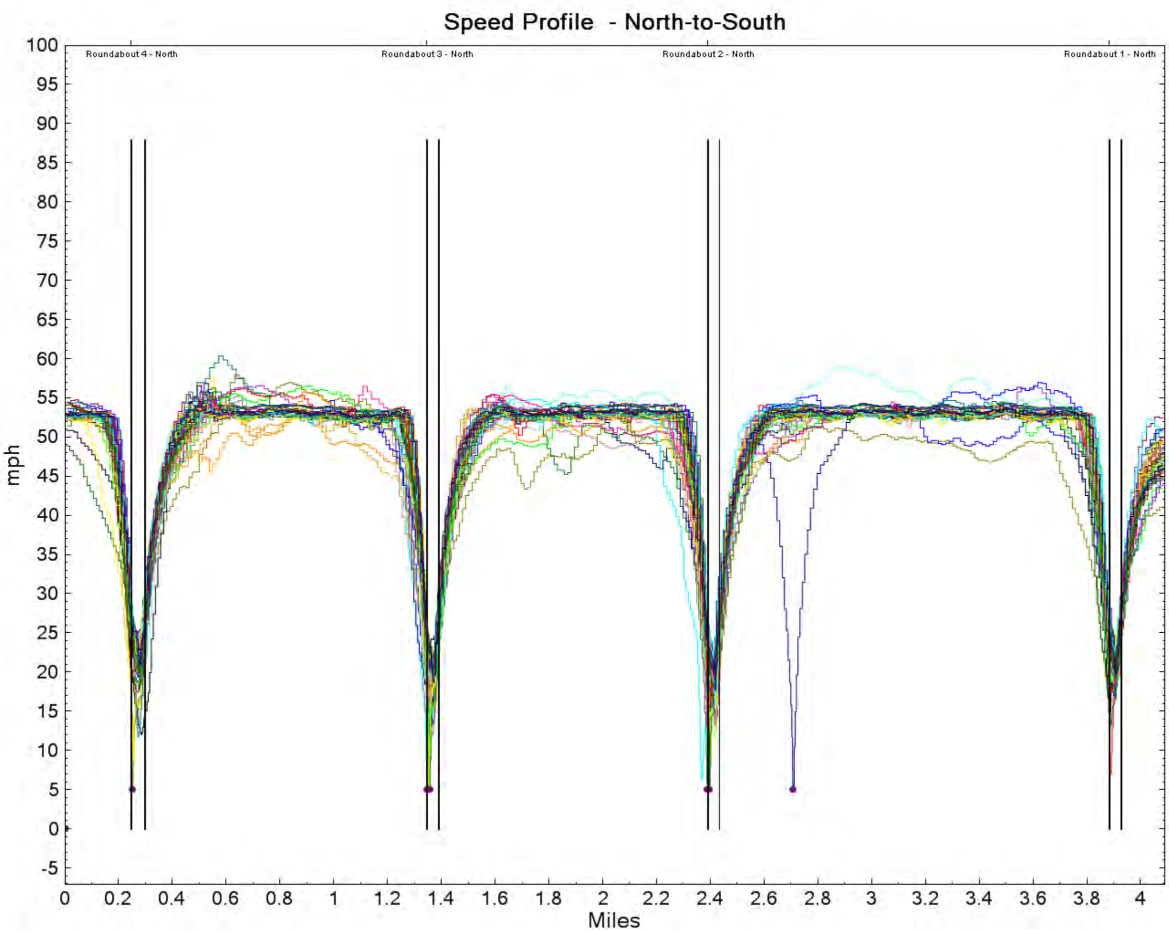

Figure B2. Speed Profile for Route 2 (Southbound Through the Entire Corridor)

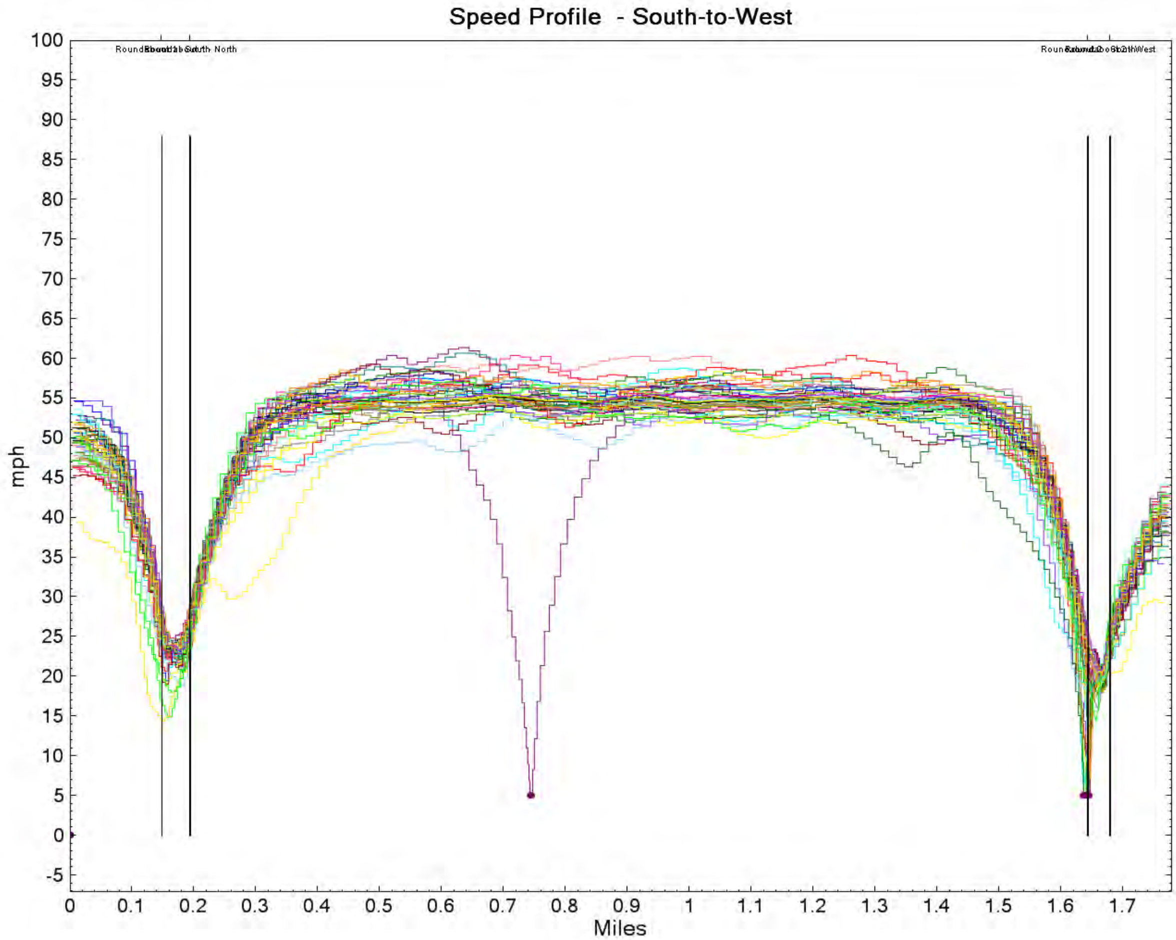

Figure B3. Speed Profile for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 2)

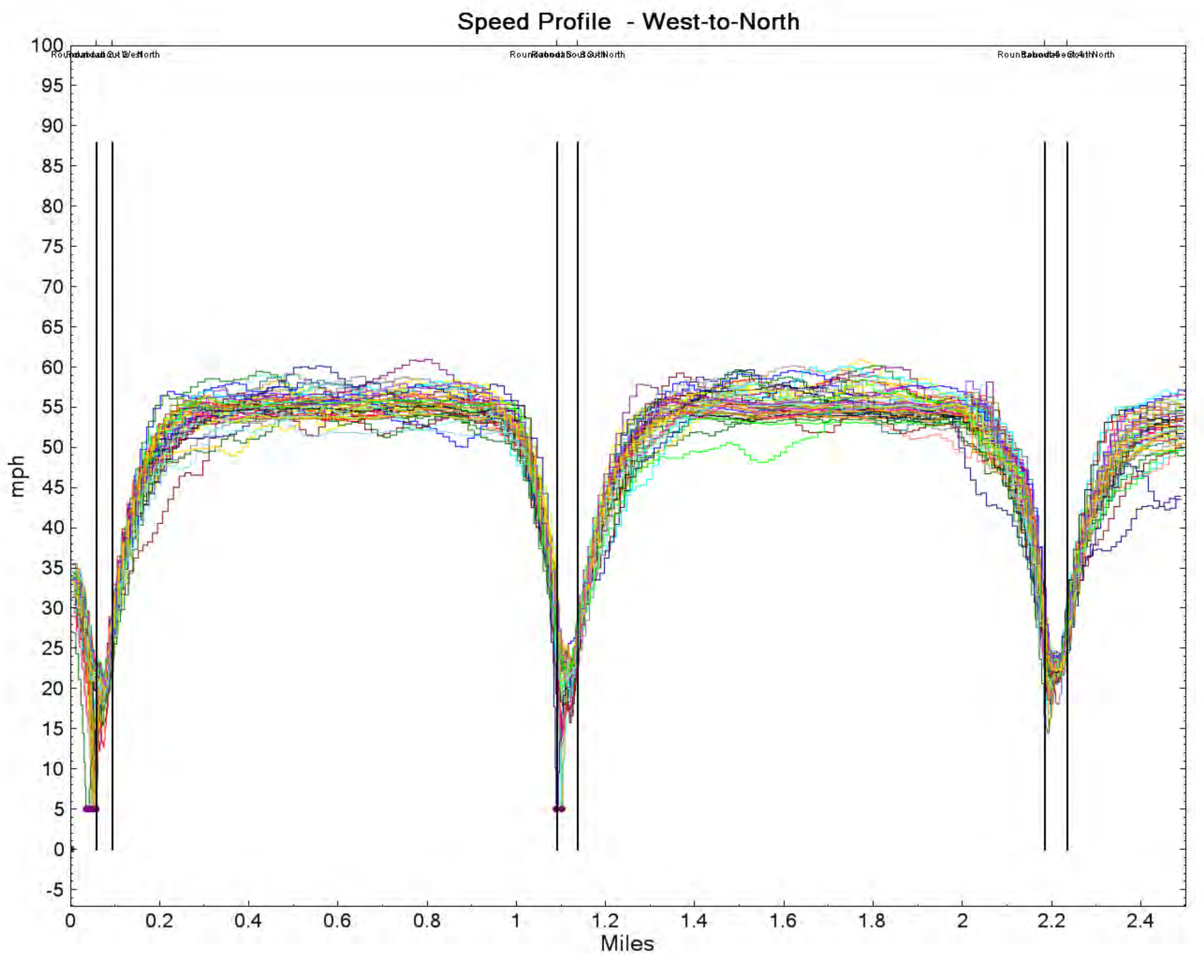

Figure B4. Speed Profile for Route 4 (Starting from West of Roundabout 2, then Turning Left at Roundabout 2)

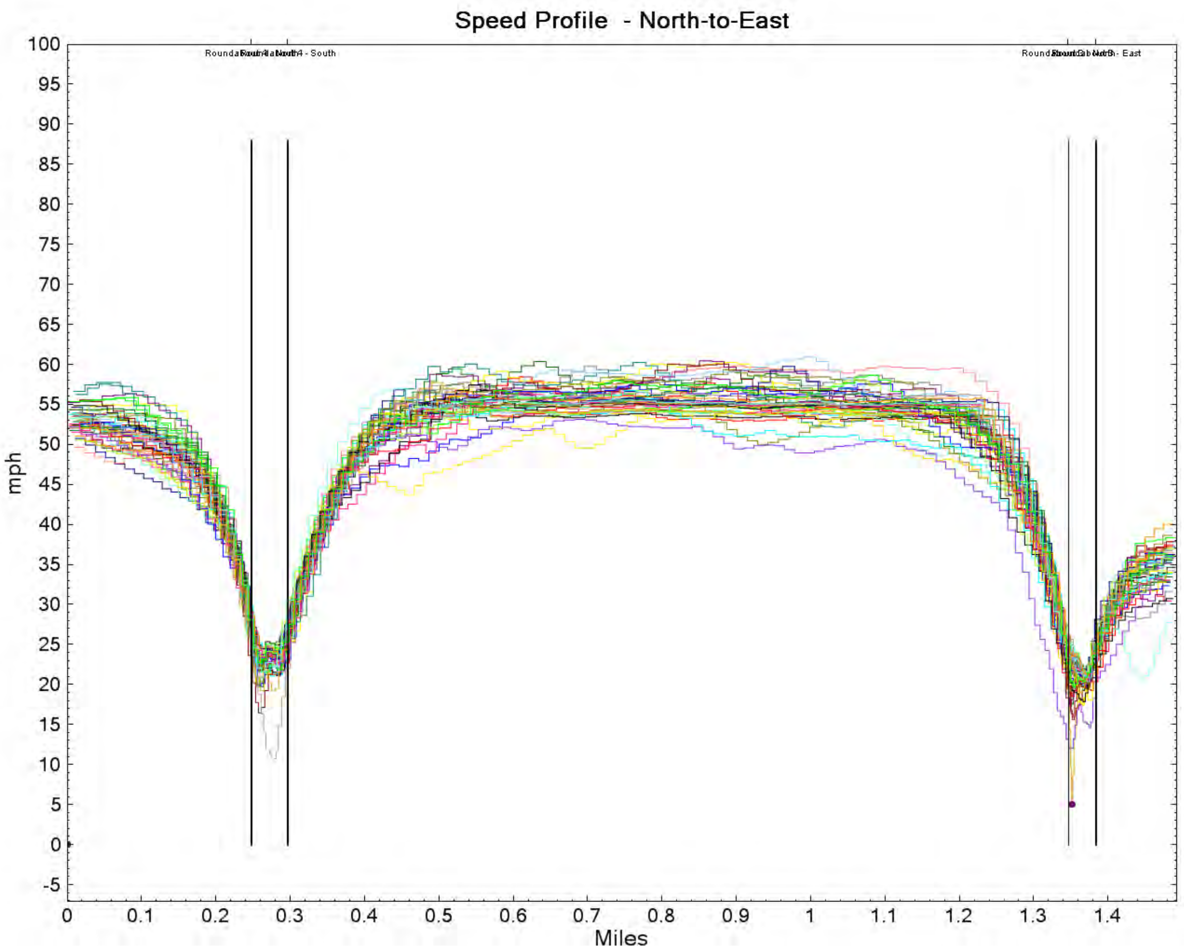

Figure B5. Speed Profile for Route 5 (Starting from North of Roundabout 4, then Turning Left at Roundabout 3)

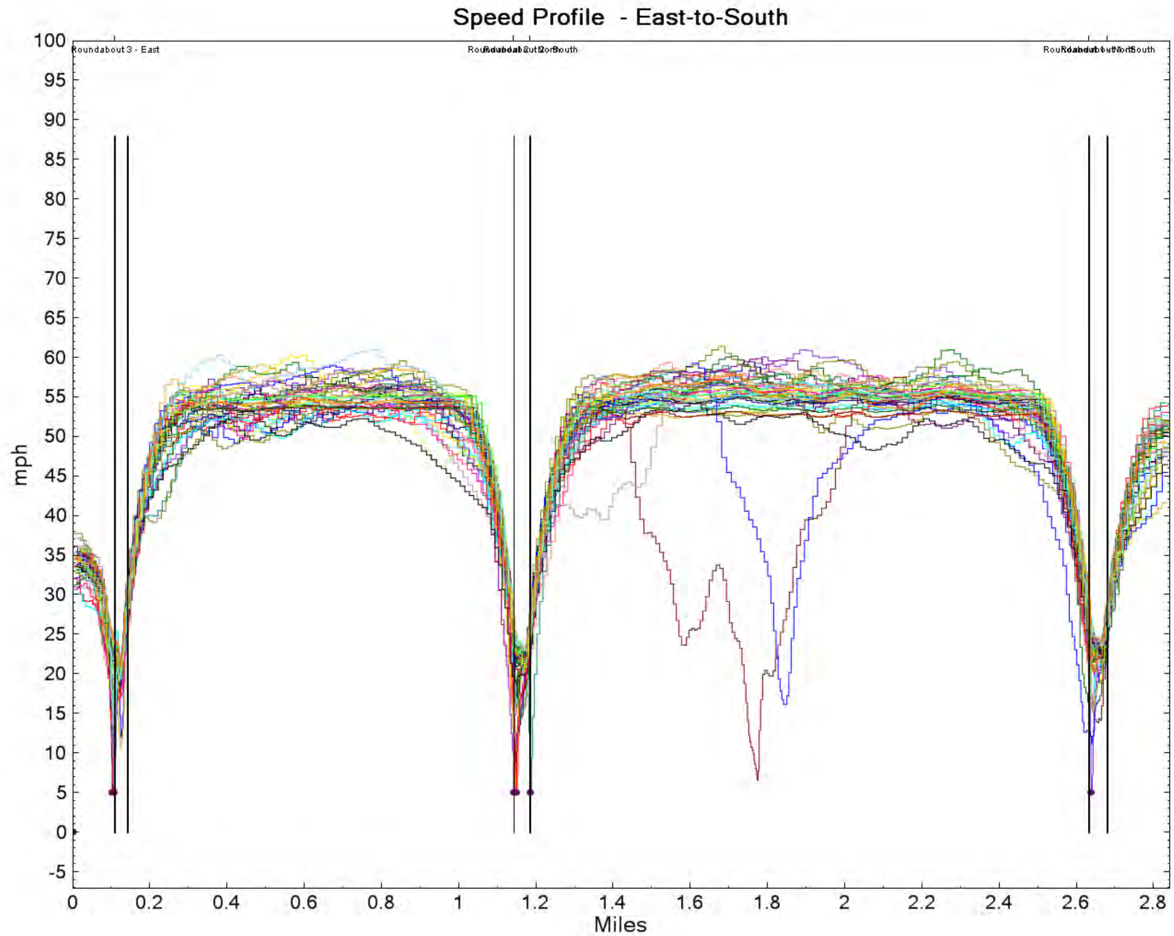

Figure B6. Speed Profile for Route 6 (Starting from East of Roundabout 3, then Turning Left at Roundabout 3)

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NCHRP 03-100

Appendix H

Golden, Colorado
Golden Road Field Data

Table of Contents

List of Tables

List of Figures

1. Introduction

This document describes the field data collected by the NCHRP 3-100 team at the Golden Road roundabout corridor in Golden, Colorado. The data collection and analysis efforts follow the format described in the team's data-collection plan.

The data collected at this roundabout corridor, which consisted of five roundabouts, included peak-hour and off-peak travel times as well as spot-speed measurements. Travel times were recorded using vehicle-mounted GPS units. Additionally, video data were obtained through field-mounted cameras. Data were collected from July 30 through August 1, 2012.

This document provides an overview of the data collected and discusses the quality and size of the dataset. Figure 1 displays a schematic of the corridor. The white numbers denote roundabouts.

Figure 1: Aerial View of the Golden Roundabout Corridor.

2. Traffic Counts

The research team obtained the traffic counts and turning movement counts for each of the intersections along the corridor. Table 1 displays the turning-movement counts during the 12:00 to 1:00 p.m. peak period for each intersection (all counts are in vehicles per hour). Golden Road comprises the north- and southbound approaches of each roundabout.

Table 1: Turning-Movement Counts (12:00 to 1:00 p.m.)

Intersection		Approach	L	T	R
#	Name				
1	Ulysses St	NB Golden Rd	24	390	30
		SB Golden Rd	64	456	112
		NB Ulysses St	86	60	46
		SB Ulysses St	72	62	66
2	Utah St	NB Golden Rd	20	588	48
		SB Golden Rd	46	698	26
		NB Utah St	2	0	4
		SB Utah St	26	0	24
3	Lunnonhaus St	NB Golden Rd	54	578	0
		SB Golden Rd	18	688	22
		NB Lunnonhaus St	22	0	22
		SB Lunnonhaus St	6	4	12
4	Johnson Rd/ 16th Ave	NB Golden Rd	114	448	10
		SB Golden Rd	16	472	232
		NB Johnson Rd	192	12	176
		WB 16th Ave	10	10	28
5	Jackson St	NB Golden Rd	10	622	8
		SB Jackson St	8	672	4
		NB Parking Lot	2	0	12
		SB Parking Lot	6	0	0

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Figure 2 displays the 12-hour volume profile taken between Utah Street and Ulysses Street (roundabouts 1 and 2). The peak 30 minutes was identified to occur between 12:30 p.m. and 1:00 p.m.

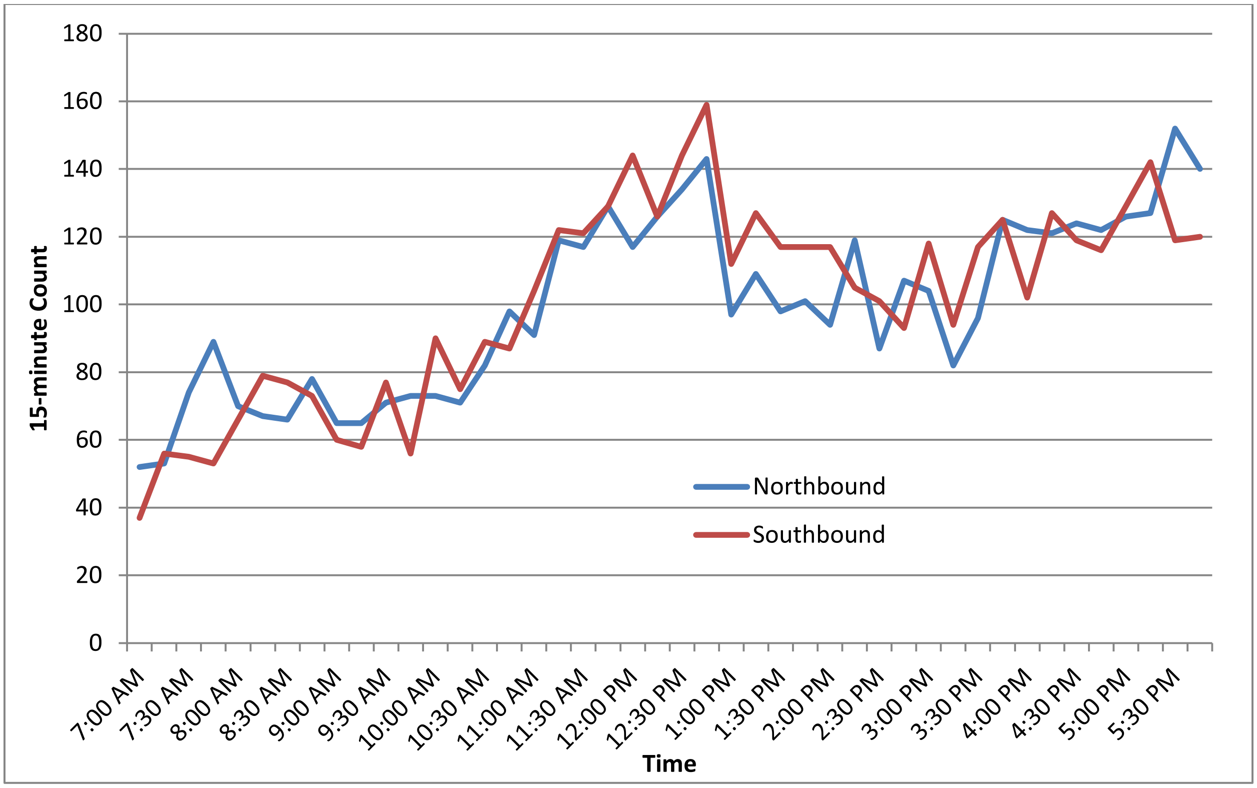

Figure 2: 12-hour Volume Profile

3. Field-Observed Data

GPS travel times and spot-speed data were collected along the corridor.

3.1. GPS Travel Times

The travel time through the corridor was also measured using vehicle-mounted GPS units. A total of six routes were used to conduct the study:

1. Northbound through the entire corridor;
2. Southbound through the entire corridor;
3. Beginning from the south end of the corridor, then turning left at roundabout 4 (Johnson Road/16th Avenue);
4. Beginning from west of roundabout 4 (Johnson Road/16th Avenue), then turning left at roundabout 4 and proceeding to the north end of the corridor;
5. Beginning from the north end of the corridor, then turning left at roundabout 4 (Johnson Road/16th Avenue); and
6. Beginning from east of roundabout 4 (Johnson Road/16th Avenue), then turning left at roundabout 4 and proceeding to the south end of the corridor.

Figures 3A through 3F display the space-time trajectories from each of the six routes. Each diagram displays every travel-time run that was conducted (including a.m., p.m., and off-peak runs). Note that the scale varies from route to route. The corresponding speed profiles are displayed in Appendix H2.

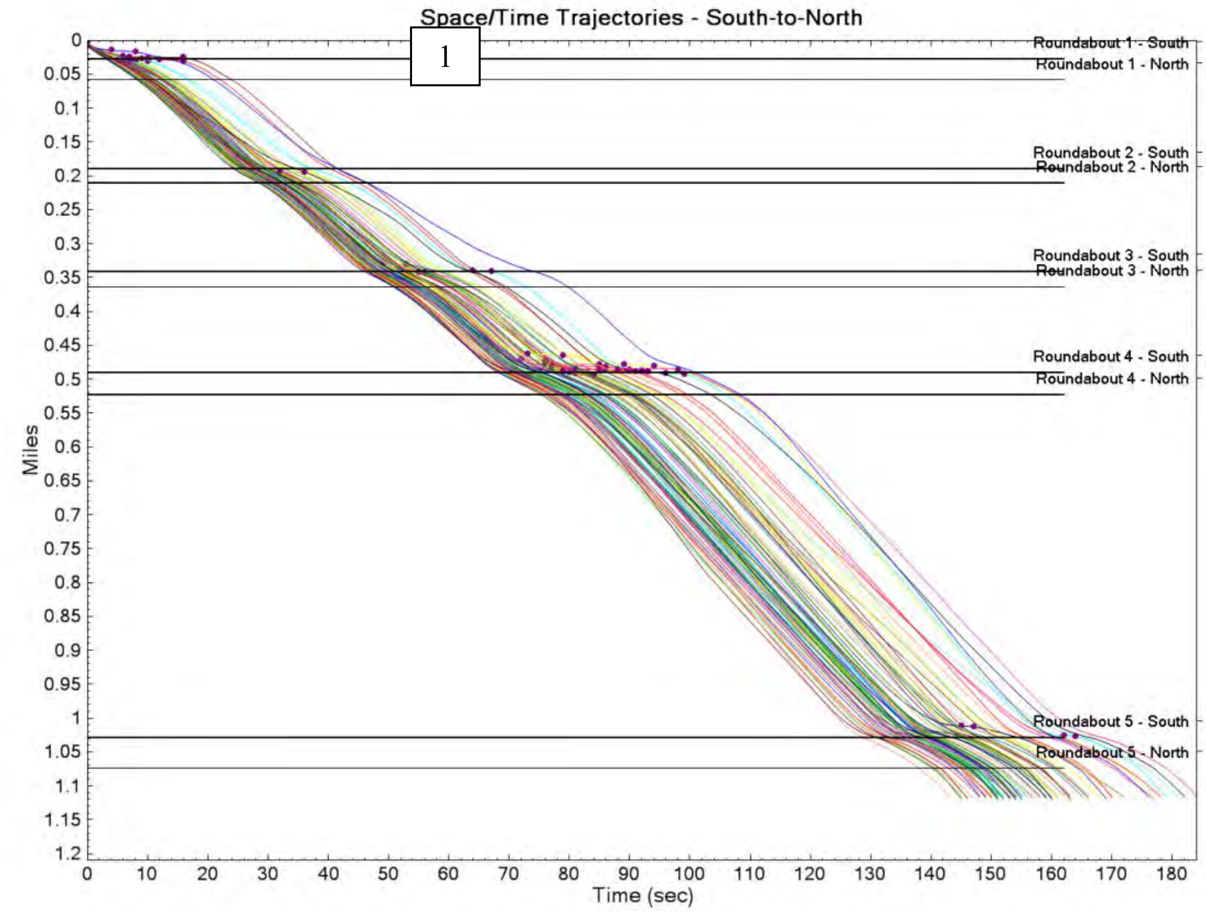

Figure 3A. Space/Time Trajectories for Route 1 (Northbound Through the Entire Corridor)

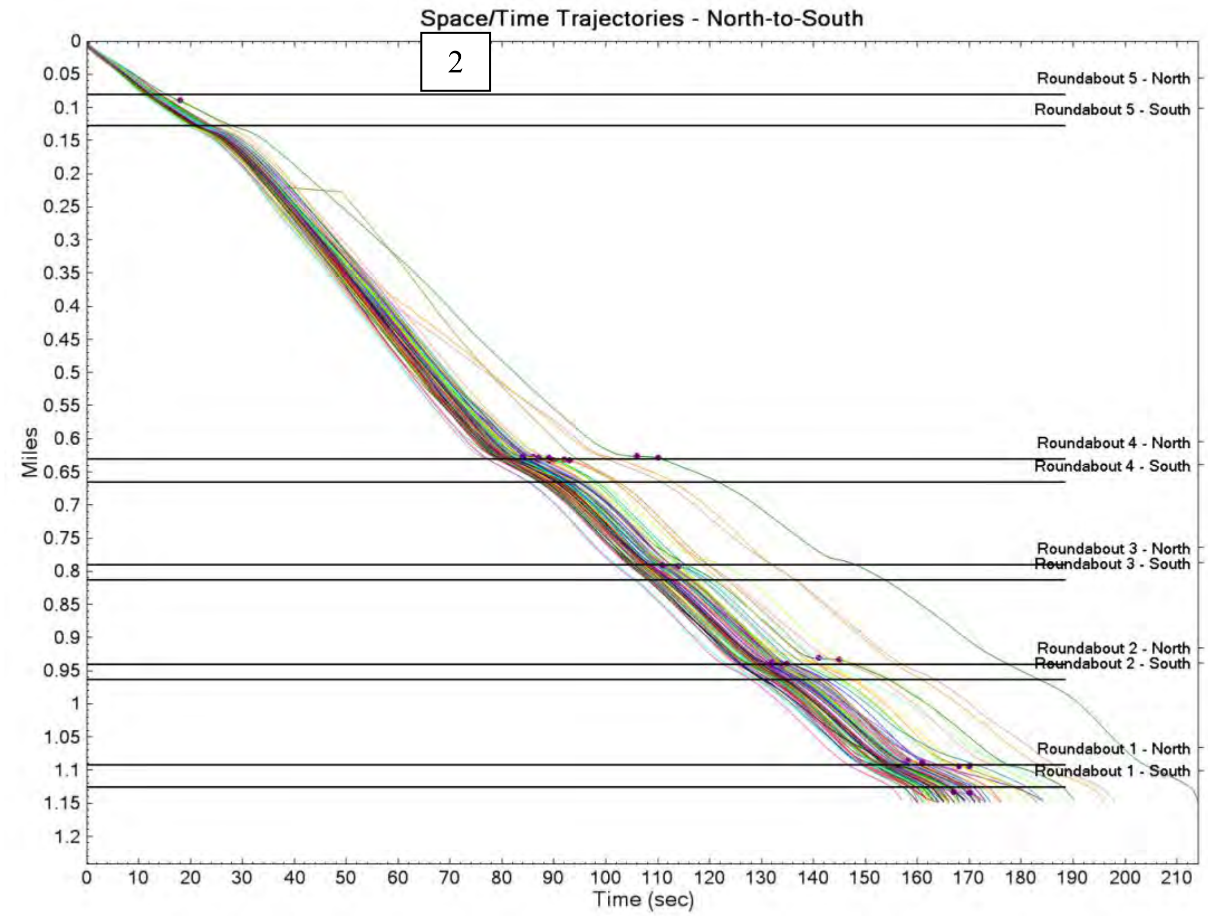

Figure 3B. Space/Time Trajectories for Route 2 (Southbound Through the Entire Corridor)

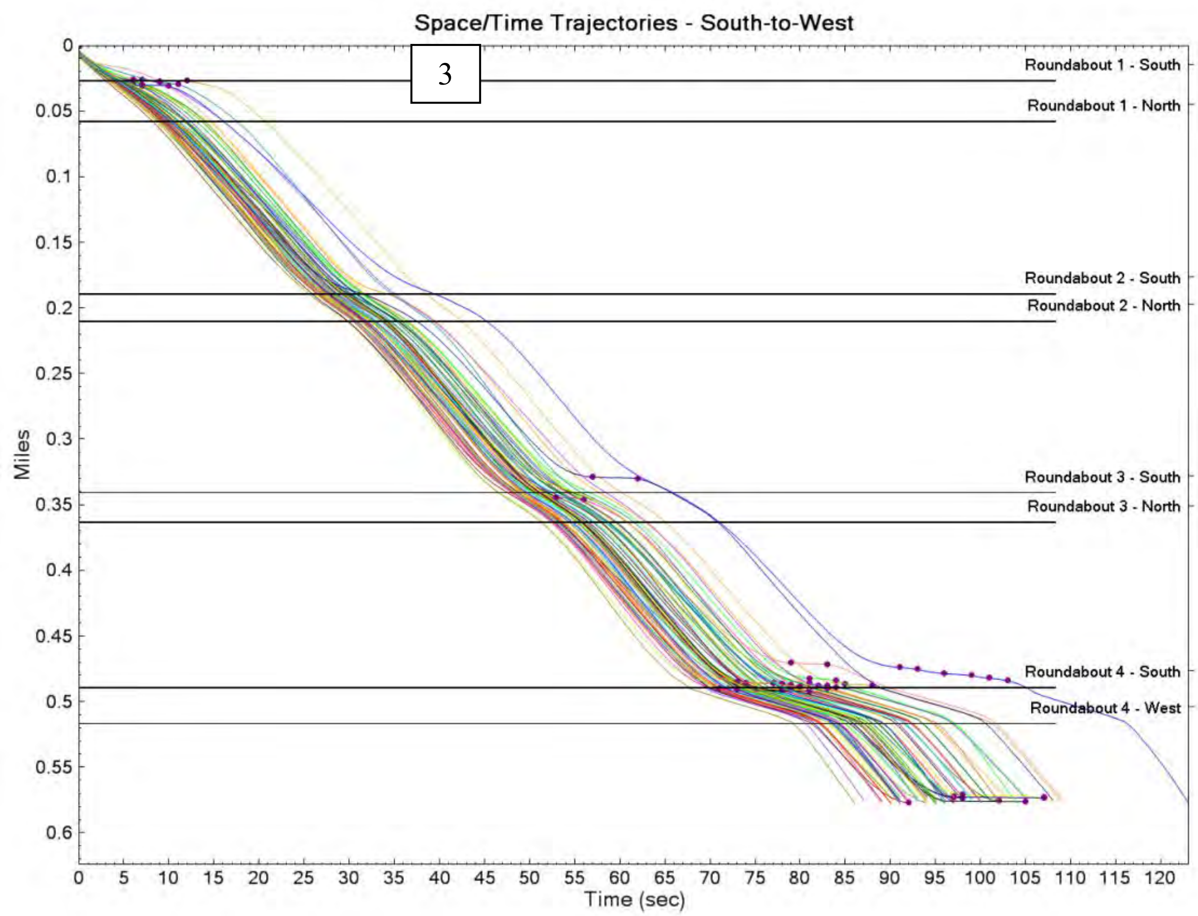

Figure 3C. Space-Time Trajectories for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 4)

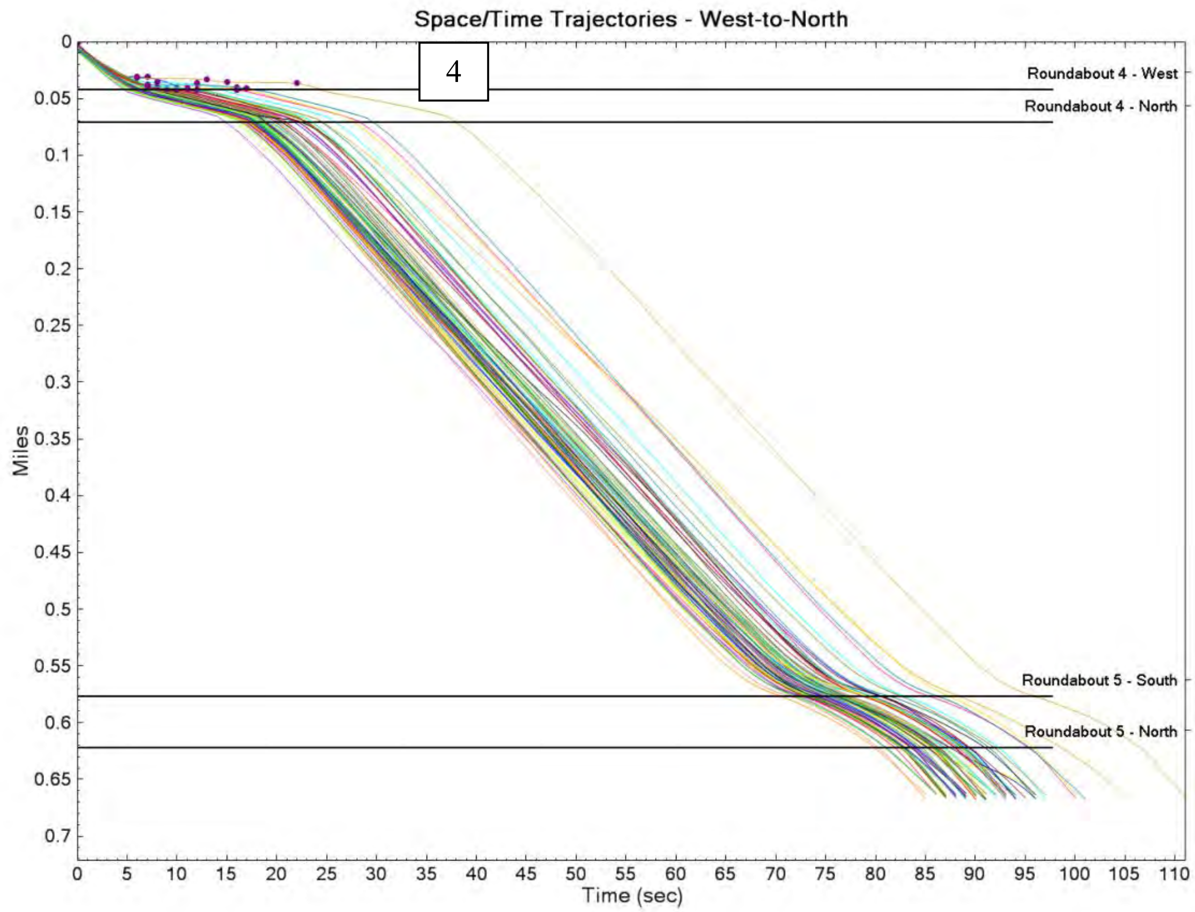

Figure 3D. Space-Time Trajectories for Route 4 (Starting from West of Roundabout 4, then Turning Left at Roundabout 4)

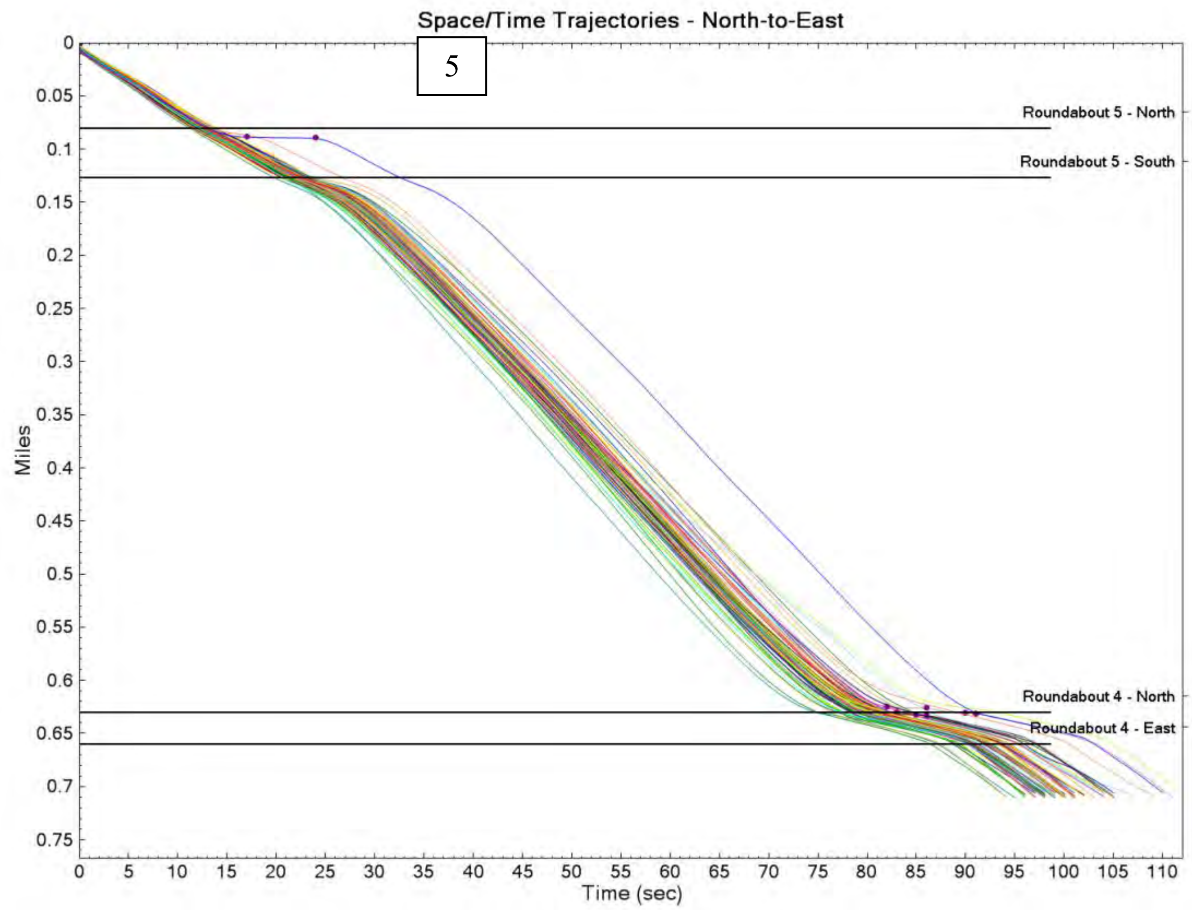

Figure 3E. Space-Time Trajectories for Route 5 (Starting from North of Roundabout 5, then Turning Left at Roundabout 4)

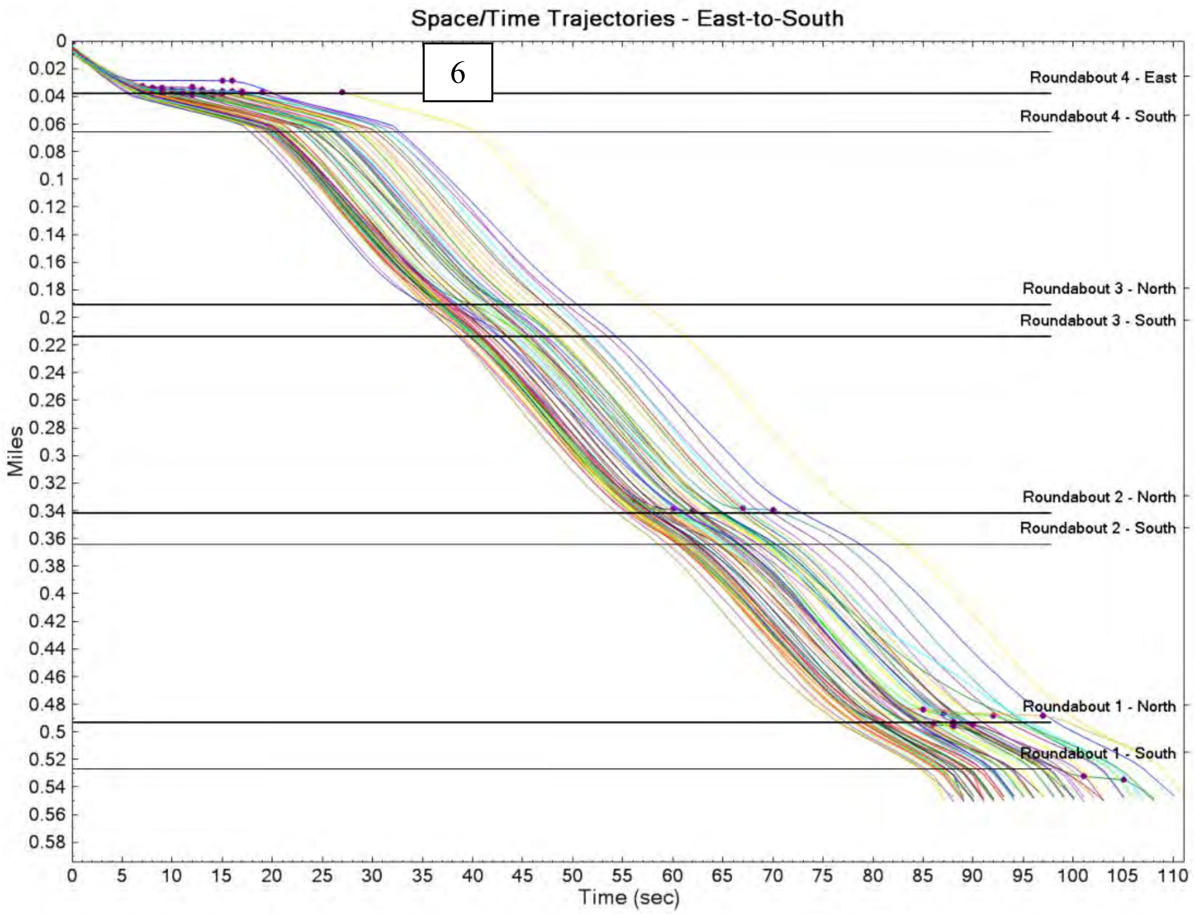

Figure 3F. Space-Time Trajectories for Route 6 (Starting from East of Roundabout 4, then Turning Left at Roundabout 4)

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening." A vehicle stop is denoted by a purple dot. The horizontal lines in the diagrams correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor reflects the variability in the observed data. The distance along the y-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

Table 2 presents more detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in mph, and all travel times are displayed in minutes. Using the free-flow travel time, the table shows HCM Urban Streets LOS (based on % FFS aggregated over the entire route) and the average HCM Roundabout LOS. The table indicates that the LOS assigned to each route may vary using either method; the urban streets LOS tends to be lower than the roundabout LOS

Table 2: Summary of a.m., p.m., and Off-peak Travel Time

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)				Free-Flow Speed (mph)	% FFS	Urban Street LOS	Route Distance (mi)	Free-Flow TT (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min							
East-to-South	**90**	**22.0**	**1.6**	**27.1**	**18.5**	**1.58**	**0.11**	**1.85**	**1.28**	**30.7**	71.5%	**B**	**0.58**	**1.13**	**5.4**	**A**
AM	22	22.6	0.9	23.9	20.3	1.54	0.06	1.70	1.45		73.5%	B			4.8	A
Off	52	22.0	1.8	27.1	18.6	1.58	0.12	1.80	1.28		71.7%	B			5.4	A
PM	16	21.0	1.5	23.1	18.5	1.65	0.13	1.85	1.48		68.4%	B			6.2	A
North-to-East	**89**	**27.3**	**3.3**	**49.1**	**17.4**	**1.65**	**0.16**	**2.58**	**0.92**	**30.7**	88.9%	**A**	**0.75**	**1.47**	**2.3**	**A**
AM	22	26.7	0.6	27.5	25.1	1.67	0.04	1.78	1.62		87.0%	A			2.5	A
Off	52	27.7	4.2	49.1	17.4	1.64	0.20	2.58	0.92		90.3%	A			2.1	A
PM	15	26.7	1.0	28.1	24.5	1.68	0.06	1.82	1.58		86.8%	A			2.5	A
North-to-South	**101**	**24.9**	**1.3**	**27.9**	**19.6**	**2.82**	**0.16**	**3.57**	**2.48**	**30.7**	80.9%	**B**	**1.17**	**2.29**	**6.4**	**A**
AM	21	25.1	1.0	26.4	22.9	2.78	0.12	3.07	2.53		81.9%	B			6.0	A
Off	61	24.7	1.4	27.9	19.6	2.84	0.18	3.57	2.52		80.5%	B			6.7	A
PM	19	25.0	1.1	26.9	22.8	2.79	0.14	3.02	2.48		81.4%	B			6.0	A
South-to-North	**100**	**25.4**	**1.6**	**28.8**	**20.0**	**2.65**	**0.18**	**3.37**	**2.33**	**29.9**	85.1%	**A**	**1.1**	**2.25**	**4.8**	**A**
AM	19	26.0	1.4	27.8	22.3	2.59	0.16	3.02	2.42		87.0%	A			4.1	A
Off	62	25.5	1.6	28.8	20.0	2.64	0.18	3.37	2.33		85.3%	A			4.8	A
PM	19	24.7	1.6	27.1	21.8	2.72	0.18	3.07	2.48		82.6%	B			5.7	A
South-to-West	**91**	**22.3**	**1.6**	**26.9**	**17.0**	**1.59**	**0.11**	**2.05**	**1.32**	**29.9**	74.4%	**B**	**0.59**	**1.18**	**4.9**	**A**
AM	22	22.7	0.9	23.8	20.2	1.56	0.06	1.75	1.48		75.7%	B			4.6	A
Off	54	22.3	1.6	26.9	19.1	1.59	0.11	1.85	1.32		74.5%	B			4.9	A
PM	15	21.6	2.1	24.5	17.0	1.64	0.16	2.05	1.43		72.1%	B			5.5	A
West-to-North	**91**	**27.2**	**1.5**	**31.8**	**22.4**	**1.52**	**0.09**	**1.85**	**1.28**	**29.9**	91.0%	**A**	**0.68**	**1.36**	**1.8**	**A**
AM	23	27.2	0.8	28.4	25.8	1.51	0.04	1.60	1.45		91.0%	A			1.8	A
Off	52	27.2	1.7	31.8	22.4	1.52	0.10	1.85	1.28		90.8%	A			1.9	A
PM	16	27.3	1.6	29.2	24.5	1.52	0.09	1.68	1.42		91.3%	A			1.8	A

Notes: FFS = free-flow speed, Rbt = roundabout, LOS = Level of Service

3.2. Geometric and Approach Delay from GPS

The team also examined the approach delay at each roundabout while considering the geometric delay incurred by the roundabouts themselves. Table 3 presents a summary of this analysis. For each approach and time of day, the free-flow travel time was estimated by isolating the unimpeded trajectories from the rest of the data set and then measuring the peak midblock speed from the trajectories. Although the true free-flow speed may not be observable in this manner (it may be higher than the observed speeds due to friction/driver behavior along the corridor), but the team believed that this method was advantageous in that it provided a much greater sample size (in a greater number of locations) than the midblock speed study (Section 3.3). Additionally, the travel distance used to compute the free-flow travel time was taken as the centerline distance between each pair of roundabouts so that the geometric delay caused by the additional travel distance to navigate the roundabouts did not affect the estimate of the free flow travel time.

Table 3 shows the distances used for estimating free-flow travel time, relative to the actual travel distance through the roundabout. For the complete route analysis, the reader should refer to the analysis in the previous section. The table also shows the field-estimated FFS for each segment, as well as the posted speed limit.

Table 3: Summary of Segment Distances

Direction	Route Segment	Free-Flow Distance (feet)	Trajectory Distance (feet)	Segment FFS (mph)	Speed Limit (mph)
Northbound	RBT1- North Approach	615	634	29.9	25
	RBT2- North Approach	550	739	30.7	25
	RBT3- North Approach	512	528	31.9	25
	RBT4- North Approach	1,879	1,901	39.3	25
	RBT5- North Approach	709	686	27.4	35
Southbound	RBT1- South Approach	352	422	29.9	25
	RBT2- South Approach	600	581	32.6	25
	RBT3- South Approach	524	581	29.8	25
	RBT4- South Approach	624	686	32.7	25
	RBT5- South Approach	1,581	1,637	41.8	35

Table 4 displays the impeded delay (equal to the difference between the average travel time and the unimpeded travel time) and total delay (equal to the difference between the average travel time and the free-flow travel time) for each approach route. Each approach was split into the upstream and downstream segments, where the upstream segment extends from the yield bar to the upstream midblock point, and the downstream segment extends from the yield bar to the downstream midblock point.

Table 4: Summary of Geometric and Approach Delay

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free Flow Speed (mph)	Free Flow Travel Time (s)	Unimpeded Travel Time (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT1-North Approach (Upstream)	**9.4**	**351**	**26**	**9.2**	**9.2**	**0.0**	**0.2**	**0.2**
AM	9.3	351	26.0	9.2	9.2	0.0	0.1	0.1
Off	9.4	351	26	9.2	9.2	0.0	0.2	0.2
PM	9.4	351	26	9.2	9.2	0.0	0.2	0.2
RBT1-North Approach (Downstream)	**10.0**	**311**	**26**	**8.2**	**9.5**	**1.3**	**0.5**	**1.8**
AM	10.1	311	26.0	8.2	9.5	1.3	0.6	2.0
Off	9.9	311	26	8.2	9.5	1.3	0.4	1.8
PM	10.0	311	26	8.2	9.5	1.3	0.5	1.8
RBT1-South Approach (Upstream)	**5.4**	**173**	**30**	**3.9**	**4.0**	**0.1**	**1.4**	**1.5**
AM	4.8	173	30.0	3.9	4.0	0.1	0.8	0.9
Off	5.2	173	30	3.9	4.0	0.1	1.2	1.3
PM	6.6	173	30	3.9	4.0	0.1	2.6	2.7
RBT1-South Approach (Downstream)	**12.4**	**506**	**30**	**11.1**	**11.5**	**0.4**	**0.9**	**1.3**
AM	12.2	506	30.0	11.1	11.5	0.4	0.7	1.1
Off	12.0	506	30	11.1	11.5	0.4	0.5	0.9
PM	13.4	506	30	11.1	11.5	0.4	1.9	2.3
RBT2-North Approach (Upstream)	**9.8**	**356**	**29**	**8.4**	**8.5**	**0.1**	**1.3**	**1.4**
AM	9.2	356	29.0	8.4	8.5	0.1	0.7	0.8
Off	9.8	356	29	8.4	8.5	0.1	1.3	1.4
PM	10.3	356	29	8.4	8.5	0.1	1.8	1.9
RBT2-North Approach (Downstream)	**13.0**	**459**	**26**	**11.9**	**12.0**	**0.1**	**1.0**	**1.2**
AM	13.2	459	26.0	11.9	12.0	0.1	1.2	1.3
Off	13.1	459	26	11.9	12.0	0.1	1.1	1.2
PM	12.7	459	26	11.9	12.0	0.1	0.7	0.8

Table 4 continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free Flow Speed (mph)	Free Flow Travel Time (s)	Unimpeded Travel Time (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT2-South Approach (Upstream)	**8.9**	**361**	**30**	**8.2**	**8.5**	**0.3**	**0.7**	86
AM	8.6	361	30.0	8.2	8.5	0.3	0.4	19
Off	8.8	361	30	8.2	8.5	0.3	0.6	48
PM	9.3	361	30	8.2	8.5	0.3	1.1	19
RBT2-South Approach (Downstream)	**10.1**	**440**	**30**	**9.5**	**10.0**	**0.5**	**0.6**	87
AM	10.1	440	30.0	9.5	10.0	0.5	0.6	20
Off	10.0	440	30	9.5	10.0	0.5	0.5	48
PM	10.4	440	30	9.5	10.0	0.5	0.8	19
RBT3-North Approach (Upstream)	**9.1**	**361**	**29**	**8.5**	**8.5**	**0.0**	**0.6**	87
AM	8.7	361	29.0	8.5	8.5	0.0	0.2	20
Off	9.3	361	29	8.5	8.5	0.0	0.8	48
PM	9.1	361	29	8.5	8.5	0.0	0.6	19
RBT3-North Approach (Downstream)	**11.0**	**460**	**29**	**10.3**	**10.5**	**0.2**	**0.8**	87
AM	11.1	460	29.0	10.3	10.5	0.2	0.8	20
Off	11.0	460	29	10.3	10.5	0.2	0.7	48
PM	11.0	460	29	10.3	10.5	0.2	0.7	19
RBT3-South Approach (Upstream)	**10.1**	**384**	**30**	**8.7**	**9.0**	**0.3**	**1.3**	87
AM	9.5	384	30.0	8.7	9.0	0.3	0.8	20
Off	10.3	384	30	8.7	9.0	0.3	1.6	48
PM	10.0	384	30	8.7	9.0	0.3	1.3	19
RBT3-South Approach (Downstream)	**9.9**	**453**	**30**	**9.4**	**9.5**	**0.1**	**0.5**	87
AM	10.3	453	30.0	9.4	9.5	0.1	0.9	20
Off	9.8	453	30	9.4	9.5	0.1	0.4	48
PM	9.8	453	30	9.4	9.5	0.1	0.4	19

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free Flow Speed (mph)	Free Flow Travel Time (s)	Unimpeded Travel Time (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT4-North Approach (Upstream)	**28.4**	**1394**	**37**	**24.4**	**27.5**	**3.1**	**0.9**	**4.0**
AM	28.5	1394	37.0	24.4	27.5	3.1	1.0	4.1
Off	28.6	1394	37	24.4	27.5	3.1	1.0	4.1
PM	27.9	1394	37	24.4	27.5	3.1	0.4	3.4
RBT4-North Approach (Downstream)	**13.7**	**516**	**29**	**11.4**	**13.0**	**1.6**	**0.7**	**2.3**
AM	13.4	516	29.0	11.4	13.0	1.6	0.4	2.0
Off	13.9	516	29	11.4	13.0	1.6	0.9	2.5
PM	13.4	516	29	11.4	13.0	1.6	0.4	2.0
RBT4-South Approach (Upstream)	**10.6**	**376**	**30**	**8.5**	**8.5**	**0.0**	**2.1**	**2.0**
AM	8.8	376	30.0	8.5	8.5	0.0	0.3	0.2
Off	10.6	376	30	8.5	8.5	0.0	2.1	2.0
PM	12.5	376	30	8.5	8.5	0.0	4.0	4.0
RBT4-South Approach (Downstream)	**31.3**	**1476**	**37**	**27.2**	**31.0**	**3.8**	**0.3**	**4.1**
AM	31.9	1476	37.0	27.2	31.0	3.8	0.9	4.7
Off	31.2	1476	37	27.2	31.0	3.8	0.1	4.0
PM	31.1	1476	37	27.2	31.0	3.8	0.1	3.9
RBT5-North Approach (Upstream)	**15.7**	**627**	**37**	**11.6**	**15.0**	**3.4**	**0.7**	**4.1**
AM	15.5	627	37.0	11.6	15.0	3.4	0.5	3.9
Off	15.8	627	37	11.6	15.0	3.4	0.8	4.2
PM	15.6	627	37	11.6	15.0	3.4	0.6	4.1
RBT5-North Approach (Downstream)	**37.0**	**1595**	**37**	**29.4**	**36.0**	**6.6**	**1.0**	**7.6**
AM	36.4	1595	37.0	29.4	36.0	6.6	0.4	7.0
Off	37.2	1595	37	29.4	36.0	6.6	1.2	7.8
PM	36.9	1595	37	29.4	36.0	6.6	0.9	7.5

Table 4 continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free Flow Speed (mph)	Free Flow Travel Time (s)	Unimpeded Travel Time (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT5-South Approach (Upstream)	**29.2**	**1395**	**37**	**25.7**	**29.0**	**3.3**	**0.2**	**3.5**
AM	29.0	1395	37.0	25.7	29.0	3.3	0.0	3.3
Off	29.0	1395	37	25.7	29.0	3.3	0.0	3.3
PM	29.7	1395	37	25.7	29.0	3.3	0.7	4.0
RBT5-South Approach (Downstream)	**14.9**	**576**	**37**	**10.6**	**14.5**	**3.9**	**0.4**	**4.3**
AM	14.9	576	37.0	10.6	14.5	3.9	0.4	4.2
Off	15.0	576	37	10.6	14.5	3.9	0.5	4.3
PM	14.7	576	37	10.6	14.5	3.9	0.2	4.0

3.3. Spot-Speed Profiles

In addition to the travel time data, the team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at a few selected roundabouts (Figure 1). These data were collected using a laser speed gun. These speed profiles will primarily be used to calibrate a geometric delay model for the roundabout corridor, but they also provide an indication of the safety and performance of the roundabouts. Finally, these speeds provide a more-realistic estimation of operating speeds at the roundabouts than do the GPS travel time runs, which were conducted by engineers using the floating car technique. Summary statistics are displayed in Table 5.

Table 5: Spot Speed Summary Statistics

Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
RBT #	3-4	1	1	1	3-4	5	5	5
Location	SB - midblock	NB - entry	NB - circ	NB - exit	NB - midblock	SB – entry	SB – circ	SB – exit
Mean Speed (mph)	29.2	20.1	18.2	30.7	28.5	16.4	17.7	32.9
StdDev (mph)	3.7	2.7	2.8	3.4	4.1	3.1	2.9	2.4
Sample Size	90	90	90	90	90	80	80	80

The midblock speeds measured between roundabouts 3 and 4 were compared to the free flow speeds estimated from the GPS trajectories. The northbound field-observed and GPS-estimated speeds were 28.5 and 29.8 mph, respectively, and the corresponding southbound speeds were 29.2 and 39.9 mph, respectively. The speed measurements from the combined dataset were also analyzed using histogram frequency distributions; all eight are displayed in Figure 4.

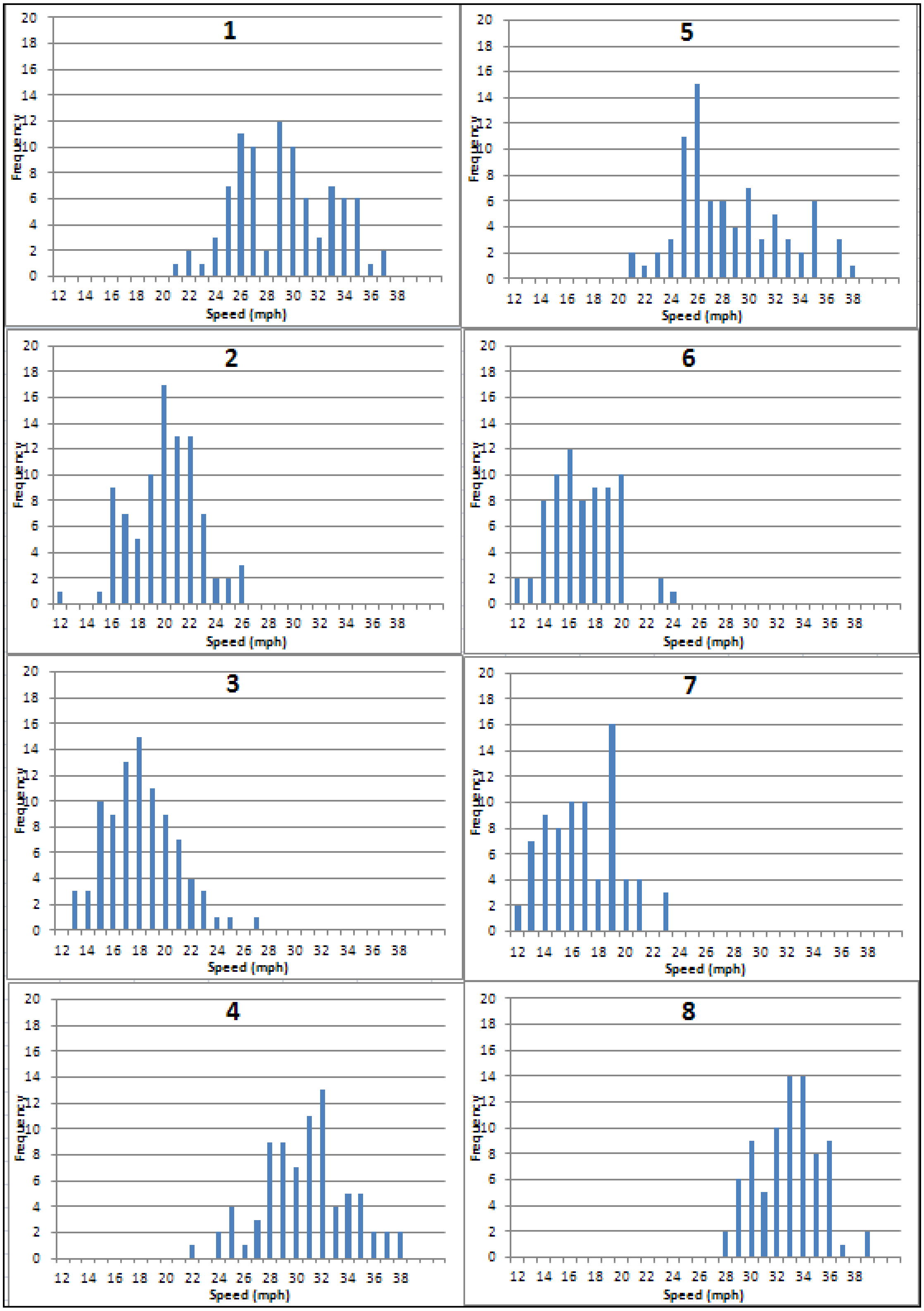

Figure 3: Spot-Speed Histograms

4. Appendix

4.1. Appendix H1: Aerial Imagery

Figure B1. Golden Road at Jackson Street / Ford Street

Figure B2. Golden Road at Johnson Road

Figure B3. Golden Road at Lunnonhaus Street

Figure B4. Golden Road at Utah Street

Figure B5. Golden Road at Ulysses Street

4.2. **Appendix H2: Speed Profiles**

These speed profiles correspond to the space-time trajectories for each of the six routes in Figures 3A through 3F.

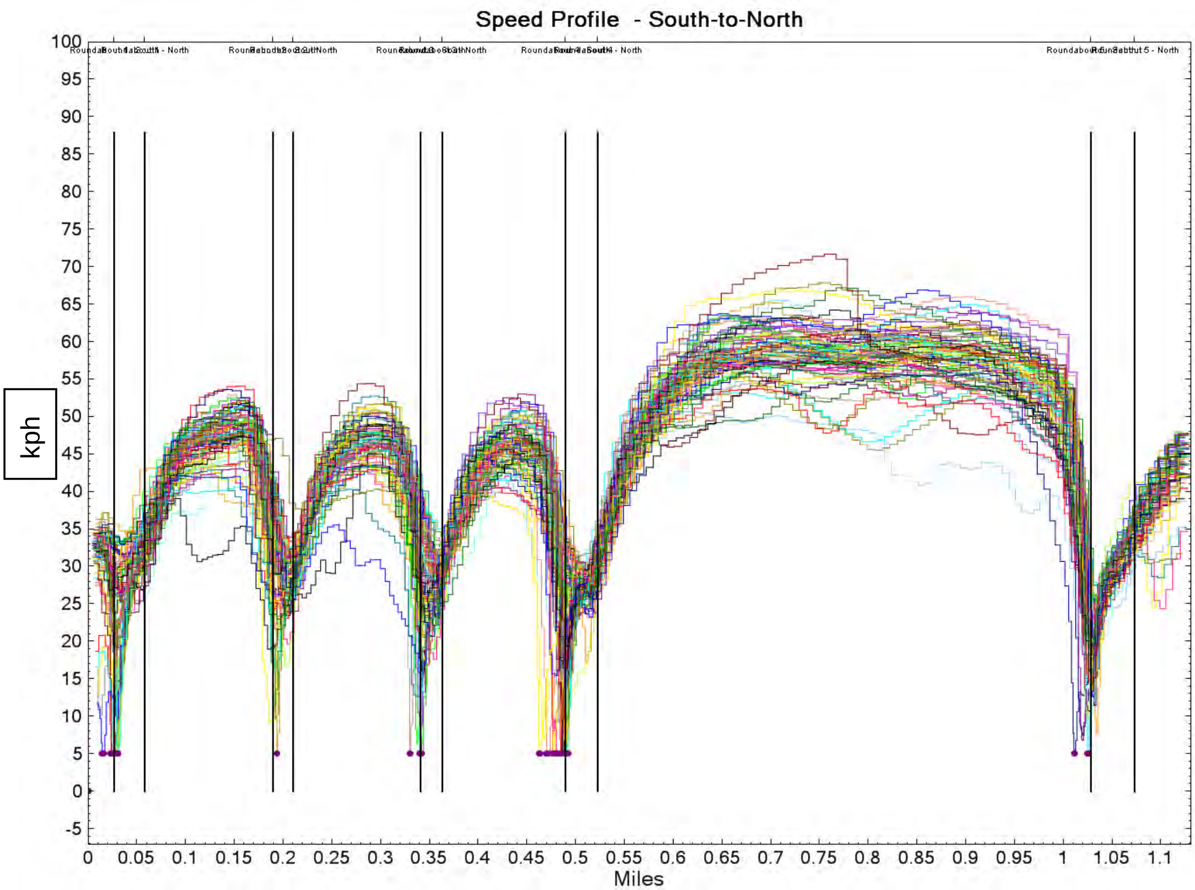

Figure B1. Speed Profile for Route 1 (Northbound Through the Entire Corridor)

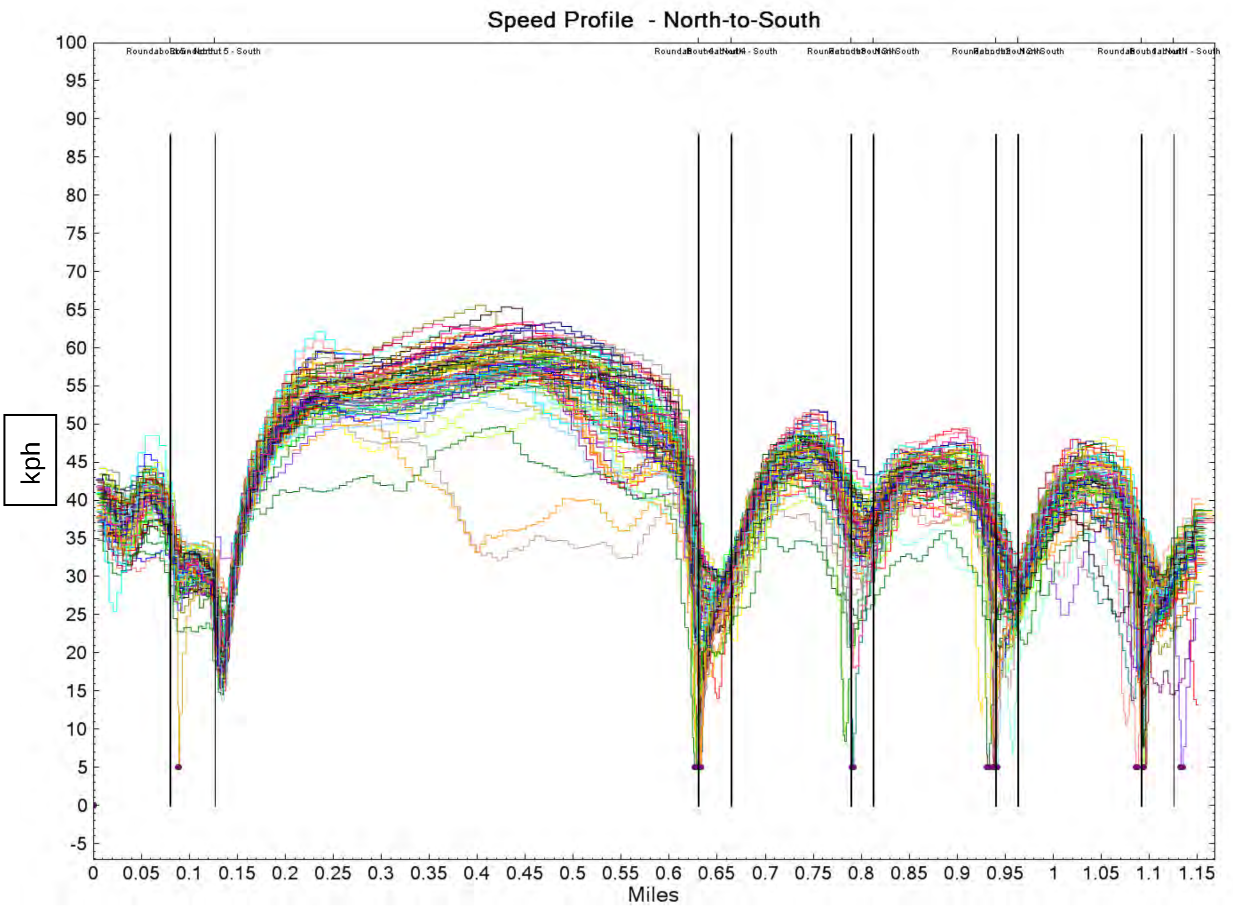

Figure B2. Speed Profile for Route 2 (Southbound Through the Entire Corridor)

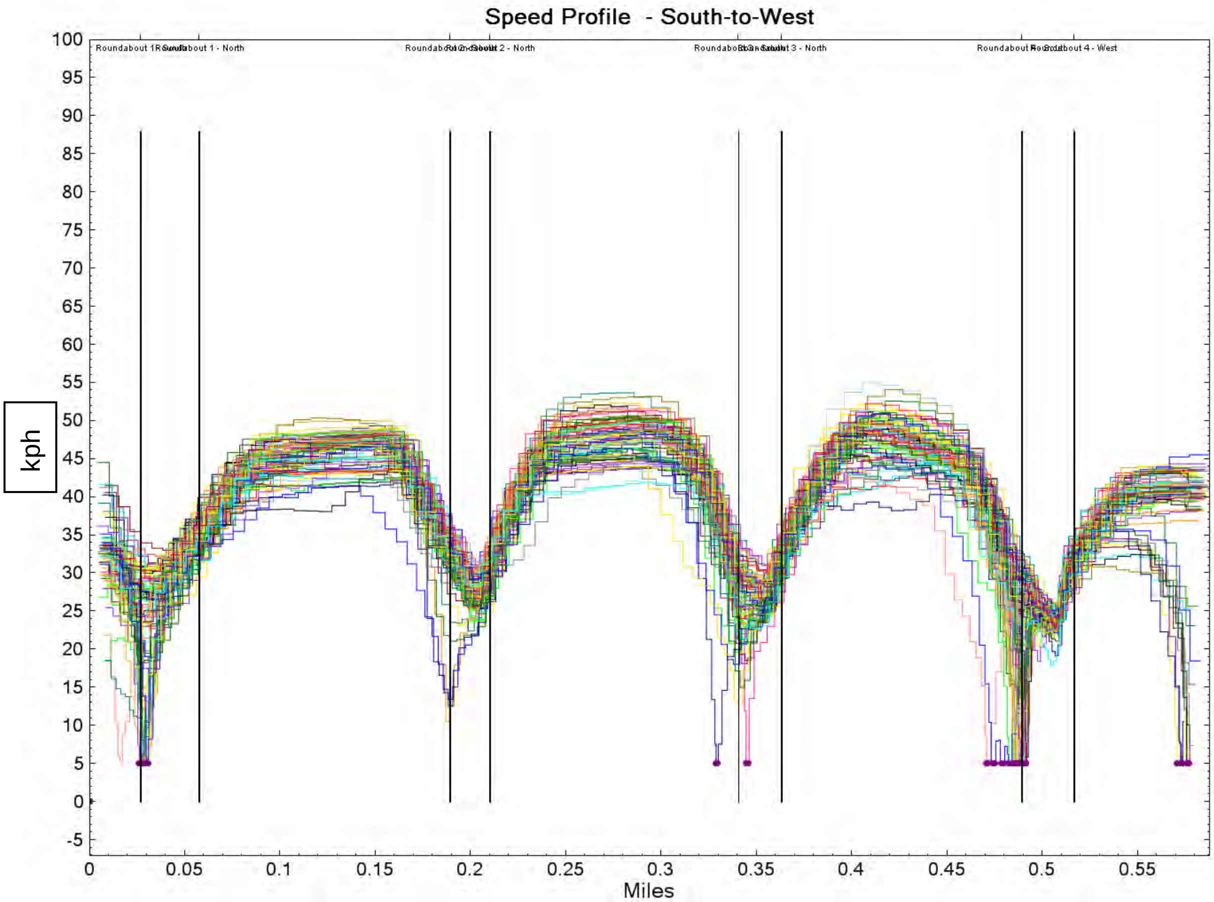

Figure B3. Speed Profile for Route 3 (Starting from South of Roundabout 1, then Turning Left at Roundabout 4)

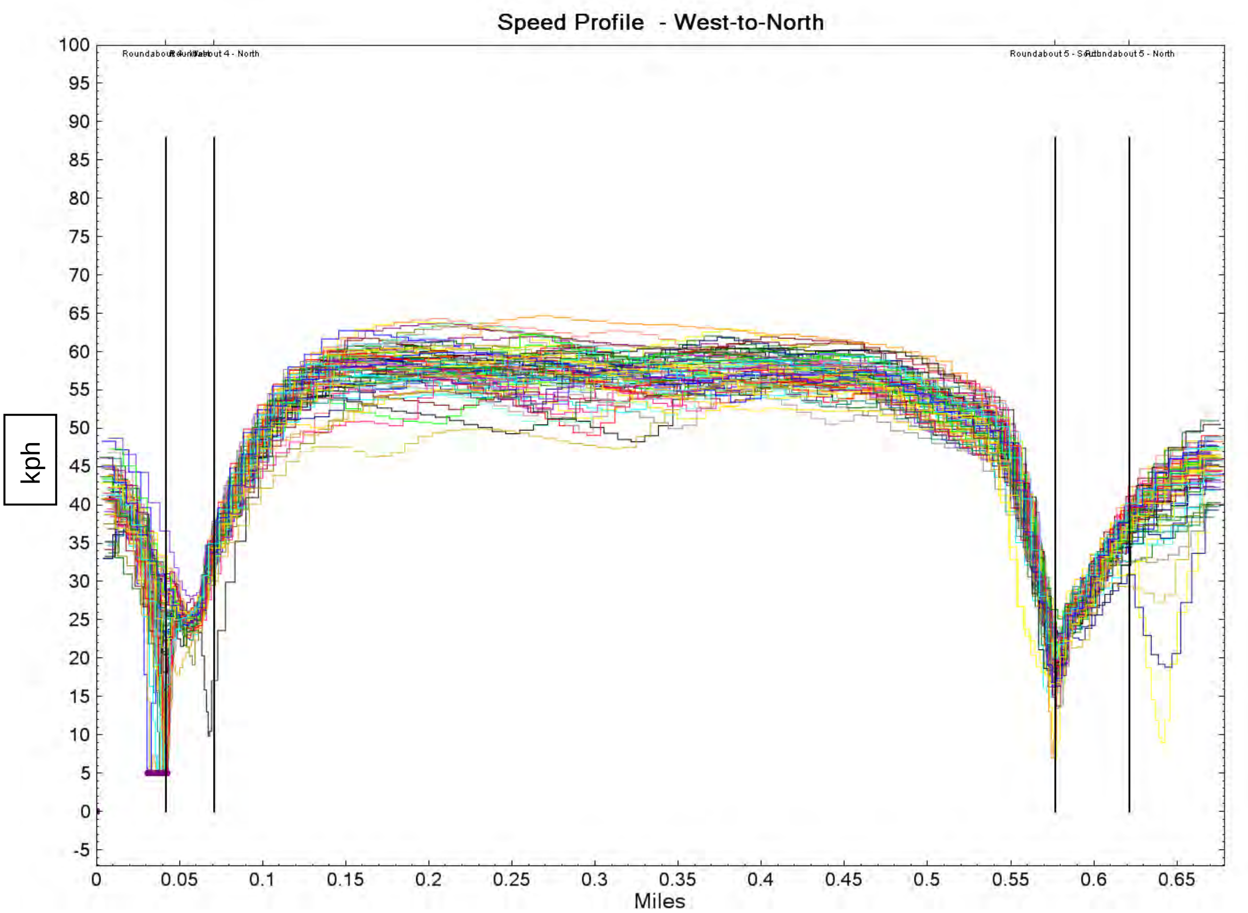

Figure B4. Speed Profile for Route 4 (Starting from West of Roundabout 4, then Turning Left at Roundabout 4)

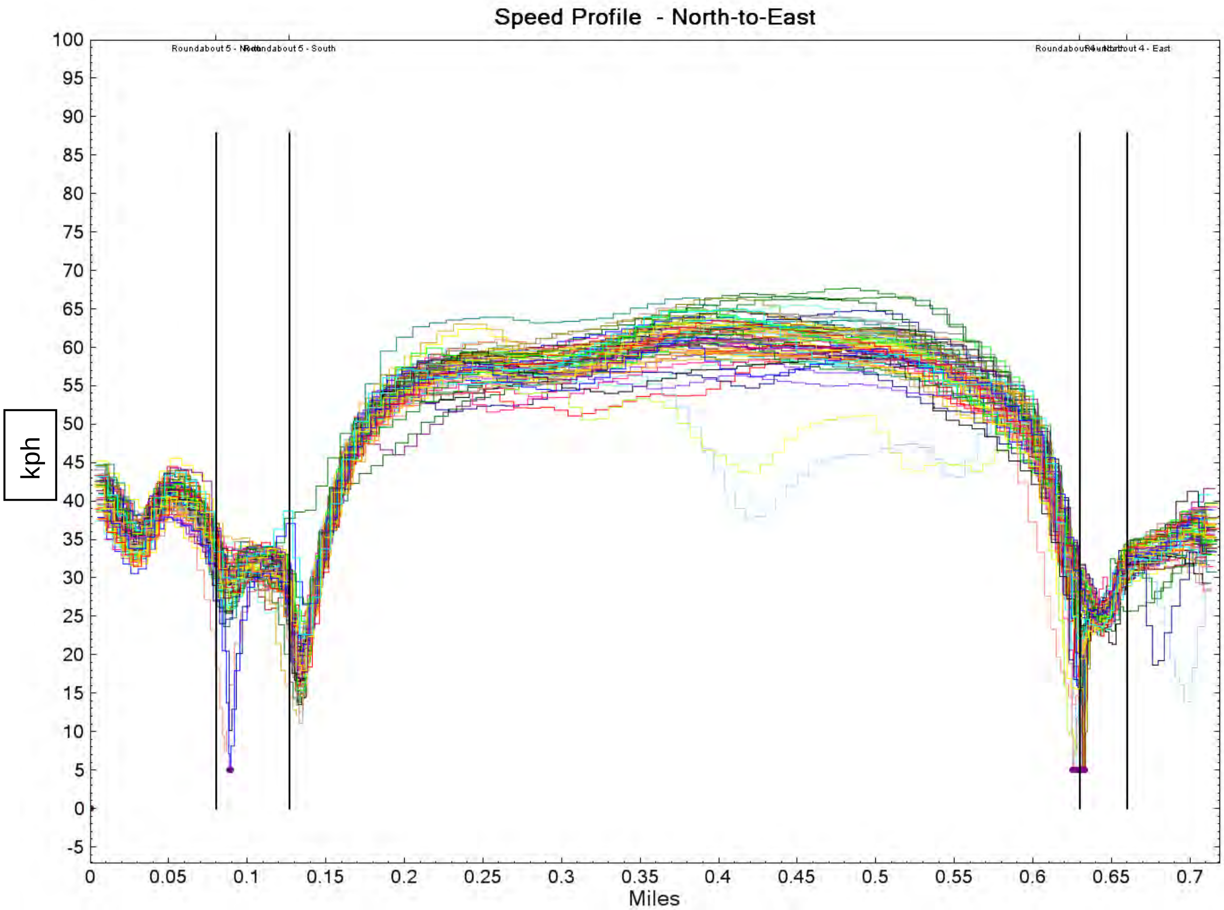

Figure B5. Speed Profile for Route 5 (Starting from North of Roundabout 5, then Turning Left at Roundabout 4)

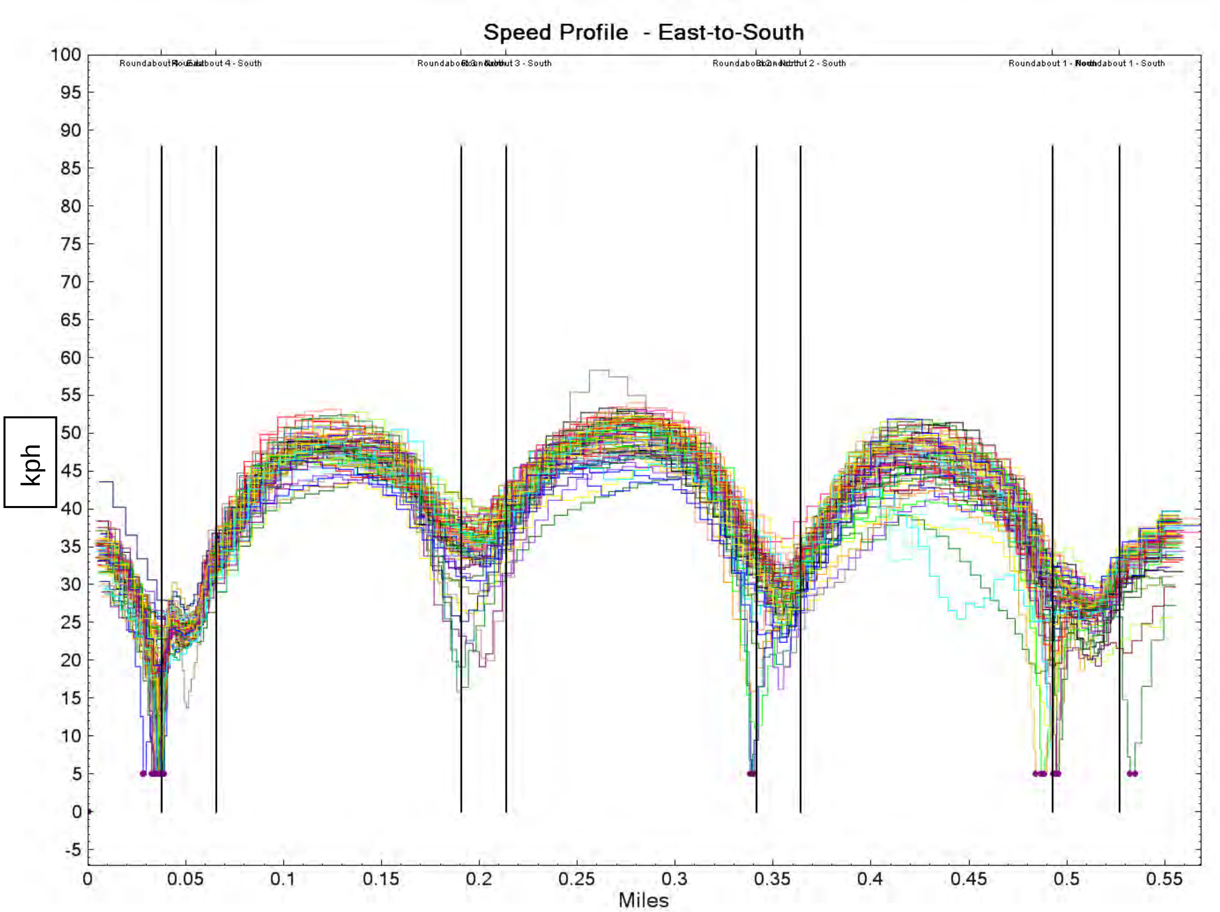

Figure B6. Speed Profile for Route 6 (Starting from East of Roundabout 4, then Turning Left at Roundabout 4)

NCHRP 03-100

Appendix I

Avon, Colorado
Avon Road Field Data

Table of Contents

List of Tables

List of Figures

1. Introduction

This document describes the field data collected by the NCHRP 3-100 team at the Avon Road roundabout corridor in Avon, Colorado. The data collection and analysis efforts follow the format described in the team's data-collection plan.

The data collected at this roundabout corridor, which consisted of four roundabouts and one internal signalized intersection, included peak-hour and off-peak travel times and spot-speed measurements. Travel times were recorded using vehicle-mounted GPS units. Additionally, video data were obtained through field-mounted cameras. Data were collected from August 1 through August 3, 2012.

This document provides an overview of the data collected and discusses the quality and size of the dataset. Figure 1 displays a schematic of the corridor. The white numbers denote roundabouts.

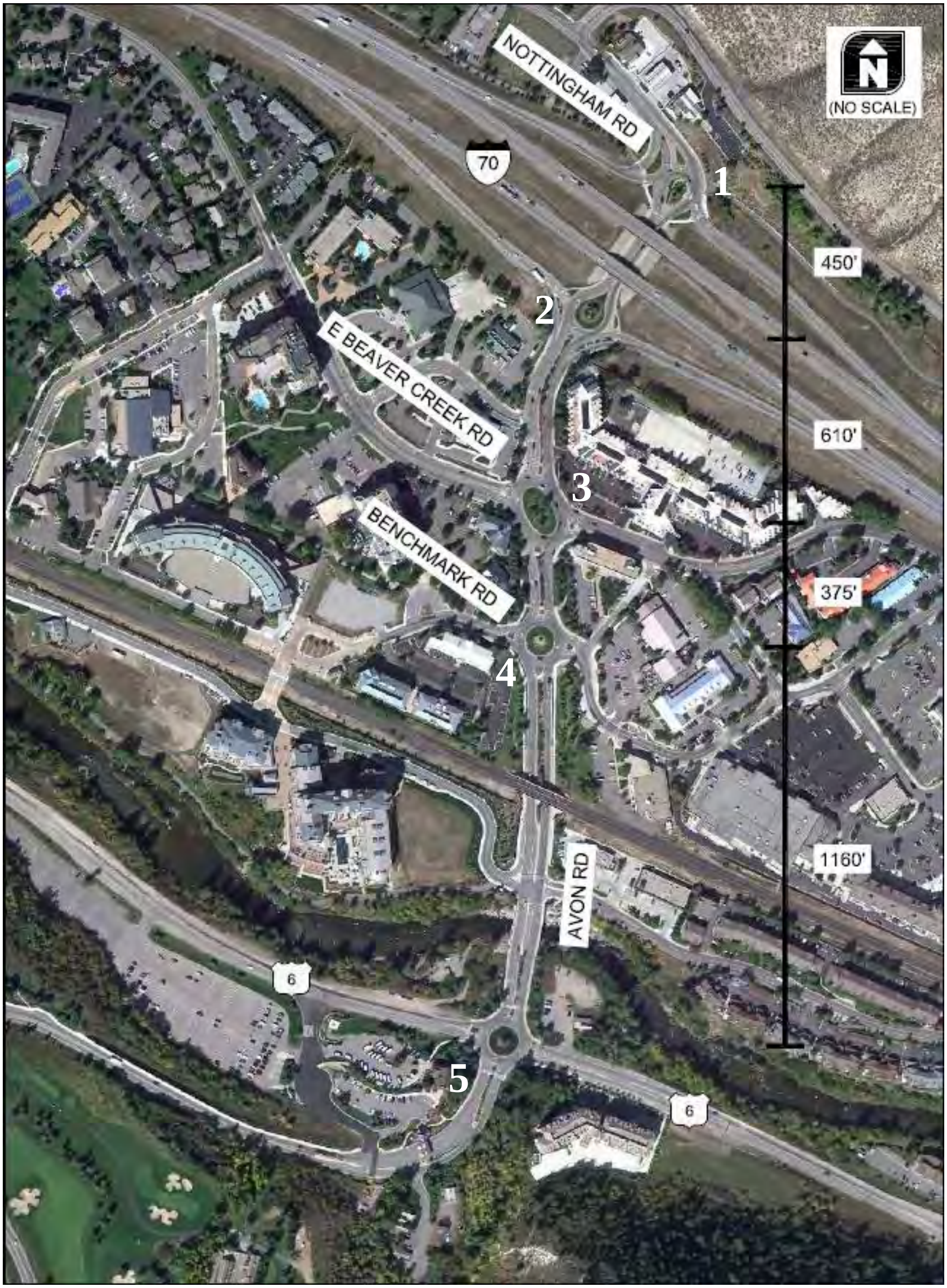

Figure 1. Aerial View of the Avon Road Roundabout Corridor.

2. Traffic Counts

The research team has obtained the traffic counts and turning-movement counts for each of the intersections along the corridor. Table 1 displays the turning-movement counts for the corridor. The peak hour was identified to occur between 5:00 p.m. and 6:00 p.m. All counts are measured in vehicles per hour. Avon Road comprises the north- and southbound approaches of each roundabout.

Table 1: Turning-Movement Counts (5:00 to 6:00 p.m.)

Intersection		Approach	Left	Through	Right
#	Name				
1	I-70 WB	Northbound	416	368	0
		Southbound	0	358	150
		Westbound	428	2	120
2	I-70 EB	Northbound	0	680	310
		Southbound	148	660	0
		Eastbound	86	0	242
3	Beaver Creek Blvd	Northbound	148	448	64
		Southbound	286	400	200
		Eastbound	200	126	140
		Westbound	52	82	280
4	Benchmark Rd	Northbound	90	488	326
		Southbound	82	452	46
		Eastbound	100	30	74
		Westbound	222	16	82
5	Village Rd	Northbound	8	378	130
		Southbound	174	268	294
		Eastbound	242	212	12
		Westbound	38	276	184

Figure 2 displays the 12-hour volume profile taken between Beaver Creek Road and eastbound I-70 (roundabouts 4 and 5). The peak 30-minutes were identified to occur between 5:00 p.m. and 5:30 p.m.

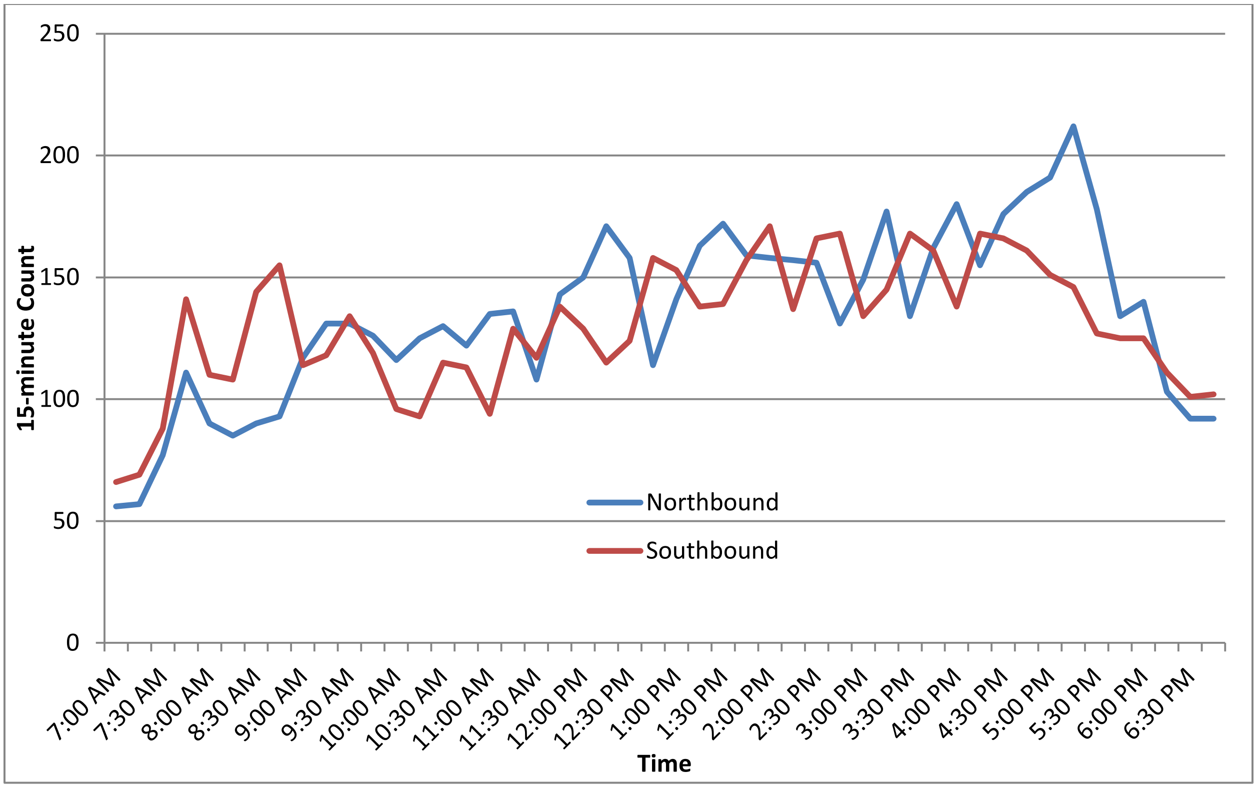

Figure 2: 12-hour Volume Profile

3. Field-Observed Data

GPS travel times and spot-speed data were collected along the corridor.

3.1. GPS Travel Times

The travel time through the corridor was also measured using vehicle-mounted GPS units. A total of six routes were used to conduct the study:

1. Northbound through the entire corridor;
2. Southbound through the entire corridor;
3. Starting from south of roundabout 5 (US 6), then turning left at roundabout 3 (Beaver Creek Road);
4. Starting from west of roundabout 3 (Beaver Creek Road), then turning left at roundabout 3 and continuing to the north end of the corridor;
5. Starting from north of roundabout 1 (I-70 westbound ramps), then turning left at roundabout 4 (Benchmark Road); and
6. Starting from east of roundabout 4 (Benchmark Road), then turning left at roundabout 4 and continuing to the south end of the corridor.

Figures 3A through 3F display the space-time trajectories from each of the six routes. Each diagram displays every travel time run that was conducted (including a.m., p.m., and off-peak runs). Note that the scale varies from route to route. The corresponding speed profiles are displayed in Appendix I2.

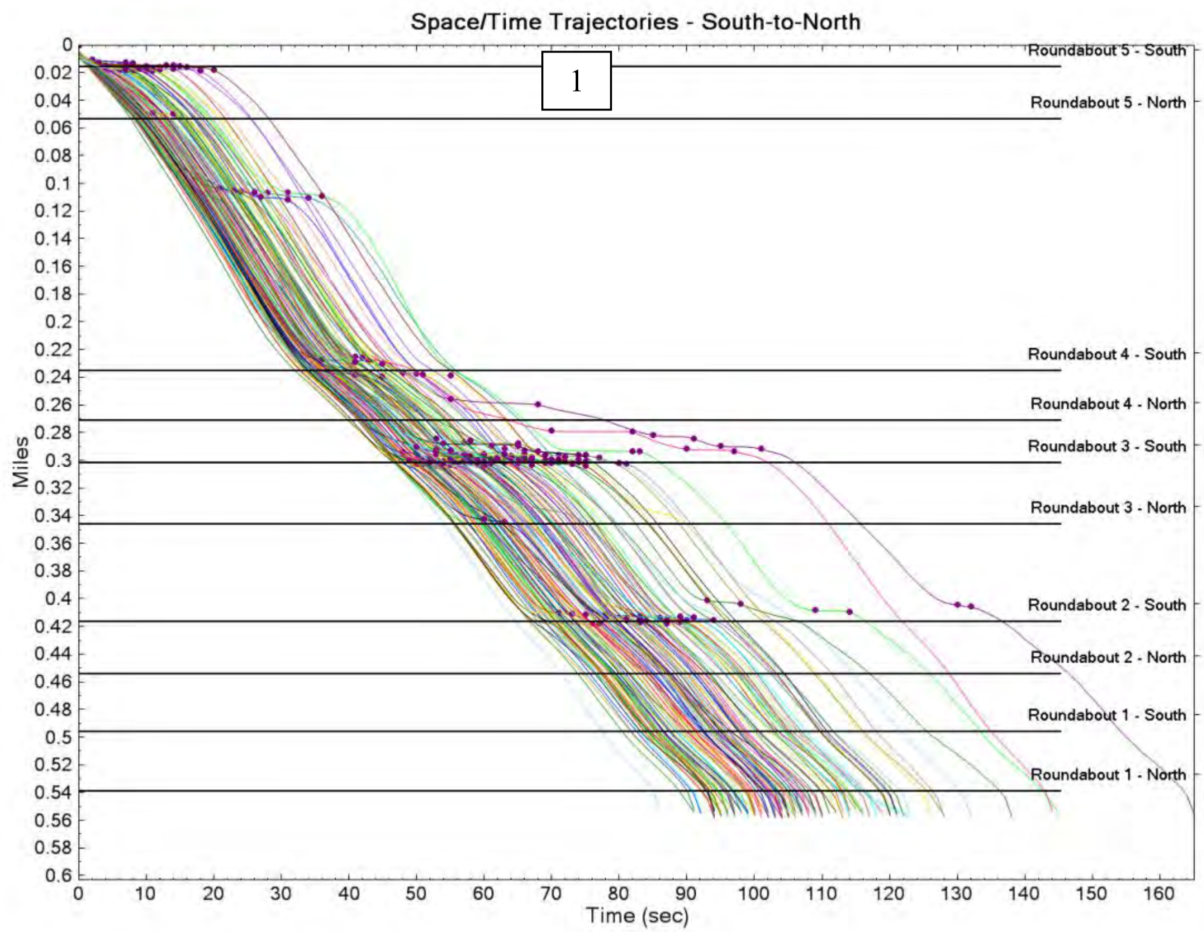

Figure 3A. Space/Time Trajectories for Route 1 (Northbound Through the Entire Corridor)

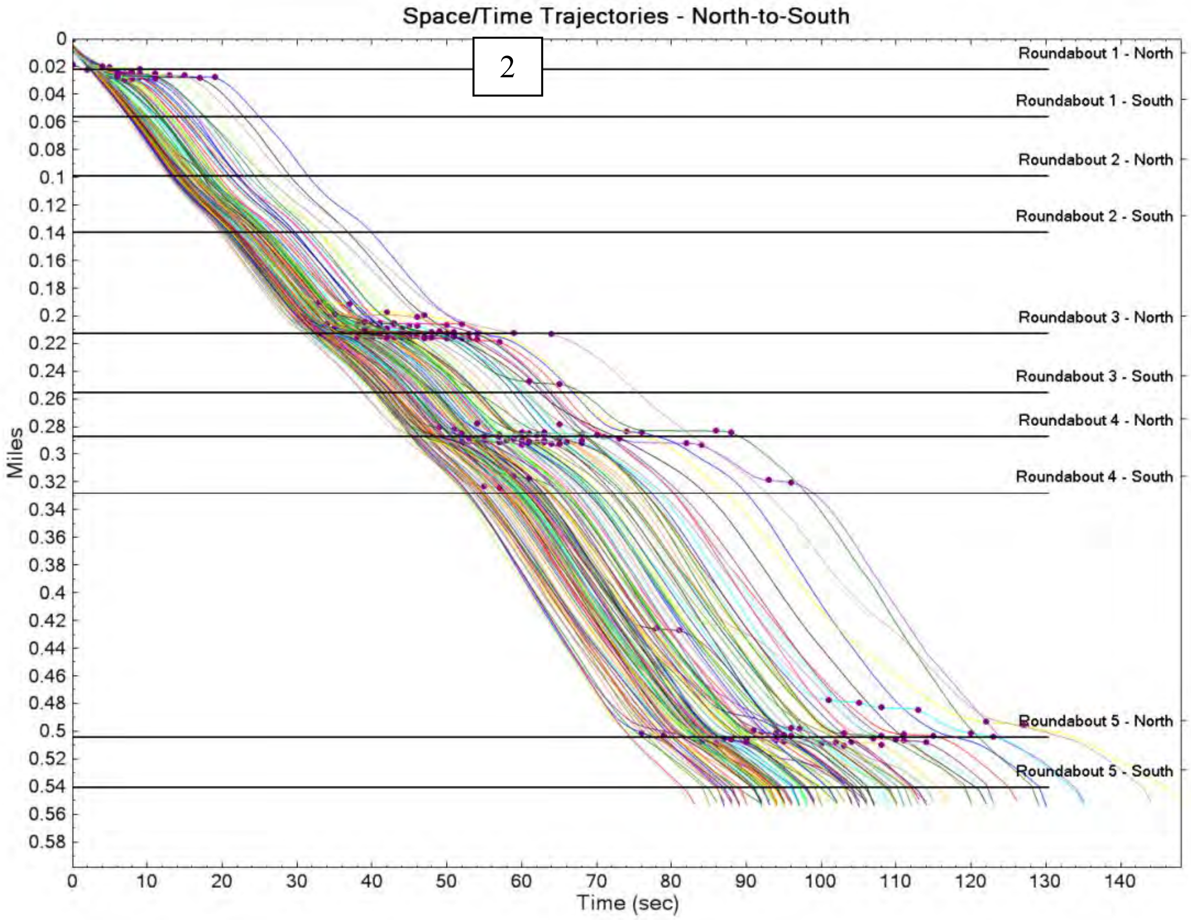

Figure 3B. Space/Time Trajectories for Route 2 (Southbound Through the Entire Corridor)

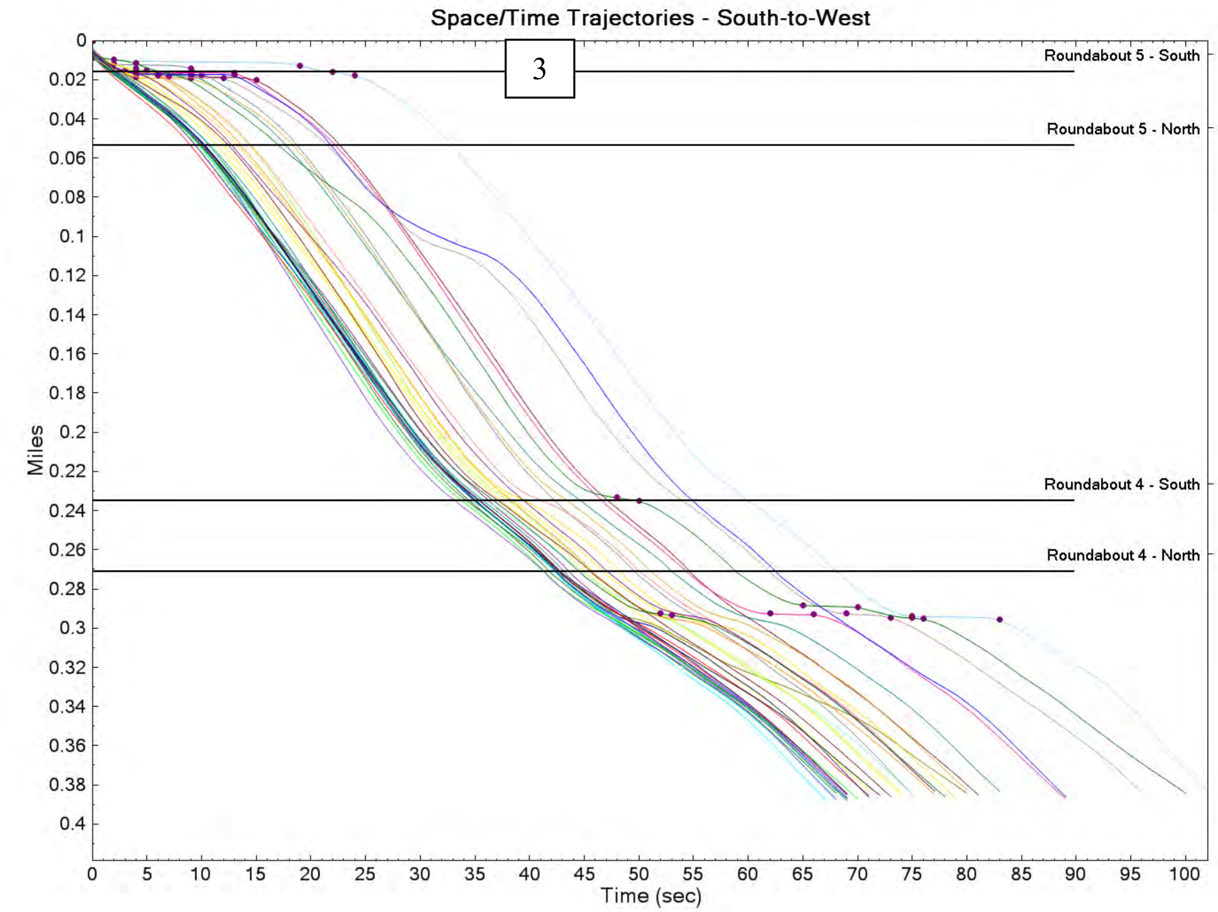

Figure 3C. Space-Time Trajectories for Route 3 (Starting from South of Roundabout 5, then Turning Left at Roundabout 3)

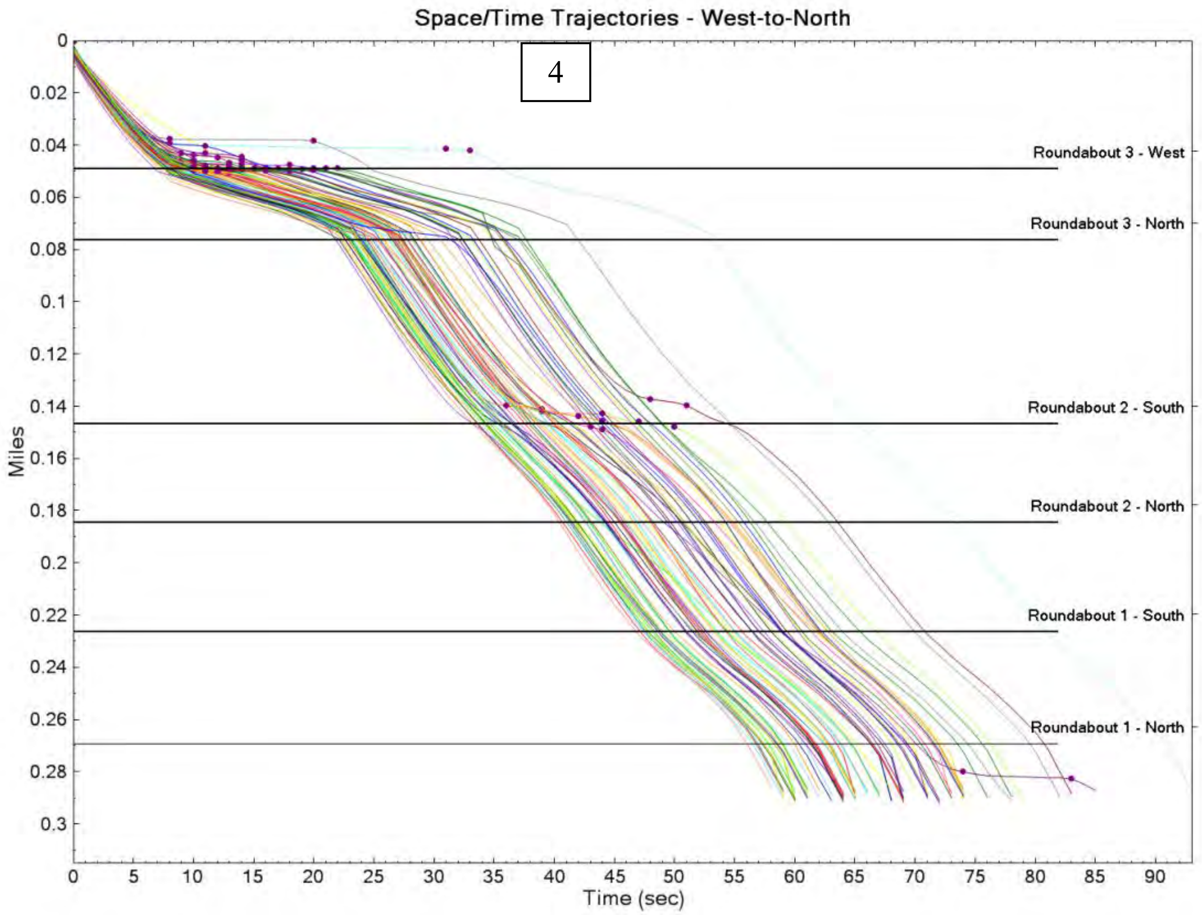

Figure 3D. Space-Time Trajectories for Route 4 (Starting from West of Roundabout 3, then Turning Left at Roundabout 3)

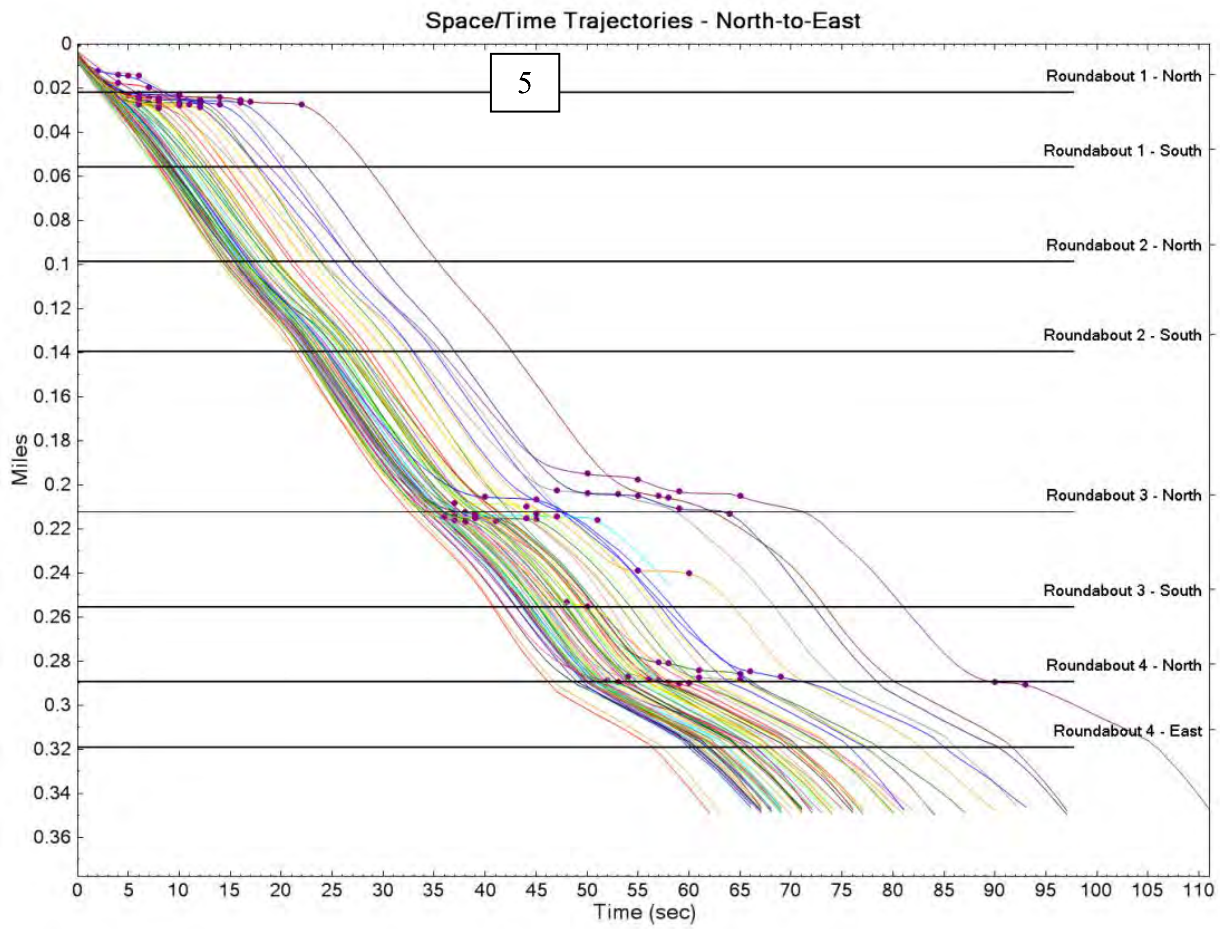

Figure 3E. Space-Time Trajectories for Route 5 (Starting from North of Roundabout 1, then Turning Left at Roundabout 4)

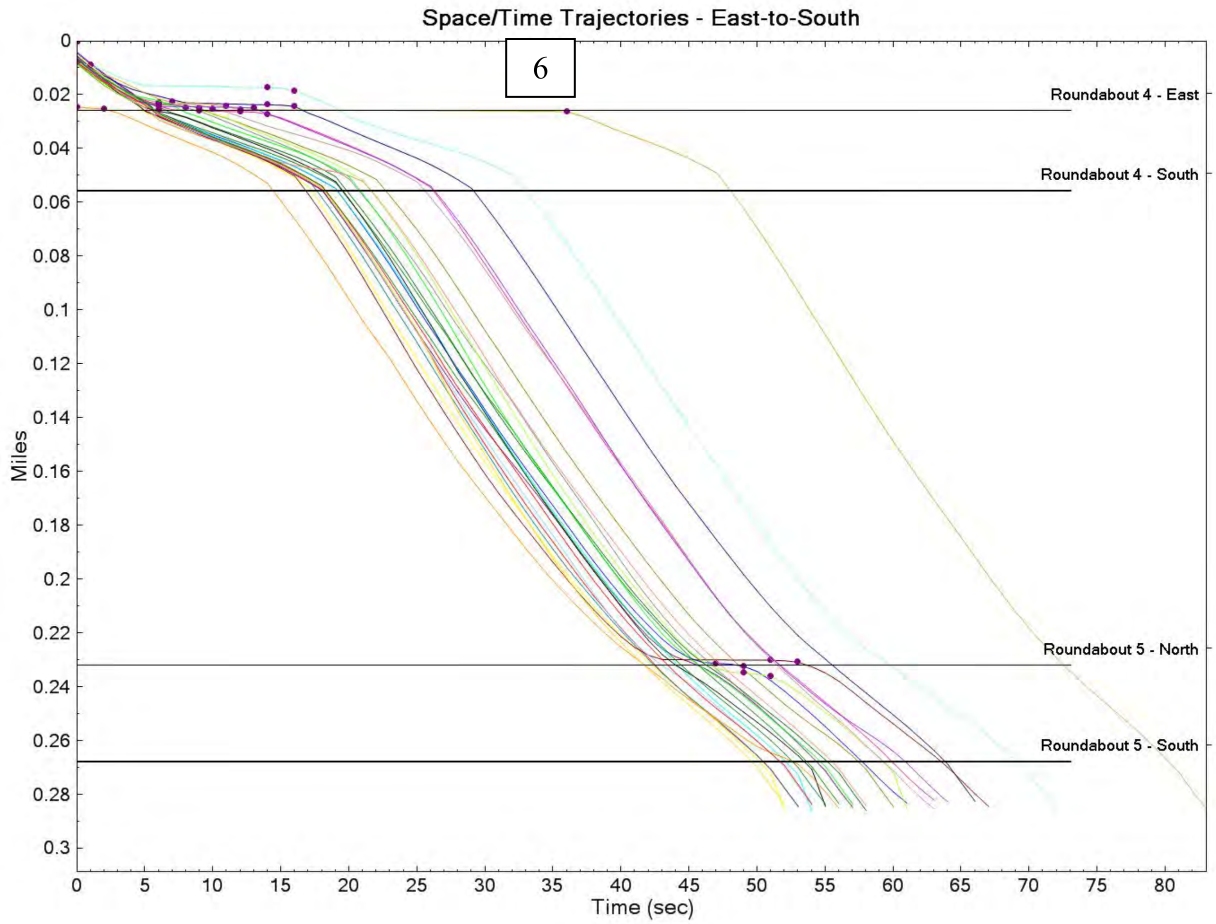

Figure 3F. Space-Time Trajectories for Route 6 (Starting from East of Roundabout 4, then Turning Left at Roundabout 4)

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening". A vehicle stop is denoted by a purple dot. The horizontal lines in the diagrams correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor reflects the variability in the observed data. The distance along the y-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

Table 2 presents more detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in mph, and all travel times are displayed in minutes. Using the free-flow travel time, the table shows HCM Urban Streets LOS (based on % FFS aggregated over the entire route) and the average HCM Roundabout LOS. The table indicates that the LOS assigned to each route may vary using either method; the urban streets LOS tends to be lower than the roundabout LOS.

Table 2: Summary of a.m., p.m., and Off-peak Travel Time

Route	# Obs	Avg. Travel Speed (mph)				Avg. Travel Time (minutes)				FFS (mph)	% FFS	Urban Street LOS	Route Distance (mi)	Free-Flow TT (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min							
East-to-South	**32**	**19.5**	**3.7**	**29.6**	**12.7**	**0.98**	**0.17**	**1.47**	**0.63**	**30.3**	**64.2%**	**C**	**0.31**	**0.61**	**4.3**	**A**
AM	8	23.4	4.6	29.6	16.6	0.82	0.17	1.12	0.63		77.4%	B			2.5	A
Off	20	18.2	2.2	21.1	12.7	1.02	0.15	1.47	0.87		60.1%	C			4.9	A
PM	4	17.7	1.2	18.5	15.9	1.04	0.10	1.17	0.93		58.4%	C			5.1	A
North-to-East	**91**	**20.1**	**6.4**	**44.0**	**9.8**	**1.18**	**0.30**	**2.25**	**0.50**	**30.3**	**66.2%**	**C**	**0.37**	**0.73**	**5.4**	**A**
AM	28	23.2	8.1	44.0	13.1	1.05	0.31	1.70	0.50		76.5%	B			3.9	A
Off	47	18.8	4.4	40.6	13.6	1.22	0.18	1.63	0.55		61.9%	C			5.8	A
PM	16	18.4	6.8	37.9	9.8	1.32	0.46	2.25	0.58		60.8%	C			7.0	A
South-to-West	**27**	**25.4**	**13.7**	**54.0**	**14.7**	**1.19**	**0.37**	**1.68**	**0.48**	**30.9**	**82.1%**	**A**	**0.41**	**0.80**	**3.5**	**A**
AM	Data unavailable														Data unavailable	
Off	20	20.8	5.7	43.5	14.4	1.24	0.22	1.70	0.57		67.2%	B			5.4	A
PM	7	30.0	21.7	64.4	14.9	1.14	0.52	1.65	0.38		97.0%	A			4.1	A
West-to-North	**92**	**16.8**	**5.1**	**28.1**	**4.4**	**1.52**	**1.07**	**4.68**	**0.72**	**30.9**	**54.4%**	**C**	**0.3**	**0.66**	**10.3**	**B**
AM	28	13.9	7.1	28.1	4.4	2.17	1.53	4.65	0.72		45.1%	D			18.2	C
Off	49	17.9	3.3	21.2	4.4	1.26	0.69	4.68	0.97		58.0%	C			7.2	A
PM	15	18.3	3.7	23.5	7.5	1.20	0.45	2.75	0.87		59.4%	C			6.4	A
South-to-North	**160**	**19.1**	**2.1**	**23.4**	**12.4**	**1.79**	**0.22**	**2.75**	**1.43**	**30.9**	**61.9%**	**C**	**0.56**	**1.09**	**8.5**	**A**
AM	47	20.2	1.3	23.4	17.4	1.68	0.11	1.95	1.43		65.5%	C			7.2	A
Off	86	19.1	1.7	22.1	14.1	1.79	0.17	2.42	1.52		61.8%	C			8.4	A
PM	27	17.2	2.7	23.4	12.4	2.01	0.32	2.75	1.43		55.7%	C			11.1	B
North-to-South	**160**	**19.9**	**2.2**	**25.2**	**13.5**	**1.69**	**0.21**	**2.47**	**1.33**	**30.3**	**65.8%**	**C**	**0.56**	**1.11**	**6.9**	**A**
AM	47	21.0	1.3	24.2	18.5	1.58	0.11	1.80	1.35		69.4%	B			5.7	A
Off	85	19.7	2.4	25.2	13.9	1.71	0.23	2.40	1.33		64.9%	C			7.2	A
PM	28	18.9	2.3	24.6	13.5	1.79	0.22	2.47	1.37		62.5%	C			8.1	A

Notes: FFS = free-flow speed, Rbt = roundabout, LOS = Level of Service

3.2. Geometric and Approach Delay from GPS

The team also examined the approach delay at each roundabout while considering the geometric delay incurred by the roundabouts themselves. Table 4 presents a summary of this analysis. For each approach and time of day, the free-flow travel time was estimated by isolating the unimpeded trajectories from the rest of the data set and by measuring the peak midblock speed from the trajectories. Although the true free-flow speed may not be observable in this manner (it may be higher than the observed speeds due to friction/driver behavior along the corridor), the team believed that this method was advantageous in that it provided a much greater sample size (in a greater number of locations) than the midblock speed study (Section 3.3). Additionally, the travel distance used to compute the free-flow travel time was taken as the centerline distance between each pair of roundabouts so that the geometric delay caused by the additional travel distance to navigate the roundabouts did not affect the estimate of the free-flow travel time.

Table 3 shows the distances used for estimating free-flow travel time, relative to the actual travel distance through the roundabout. For the complete route analysis, the reader should refer to the analysis in the previous section. The table also shows the field-estimated FFS for each segment, as well as the posted speed limit.

Table 3: Summary of Segment Distances

Direction	Route Segment	Free-Flow Distance (feet)	Trajectory Distance (feet)	Segment FFS (mph)	Speed Limit (mph)
Northbound	RBT1- North Approach	292	317	23.1	25
	RBT2- North Approach	412	422	29.1	25
	RBT3- North Approach	460	475	26.7	25
	RBT4- North Approach	290	317	25.4	25
	RBT5- North Approach	750	792	32.7	25
Southbound	RBT1- South Approach	355	370	25.8	25
	RBT2- South Approach	414	422	26.8	25
	RBT3- South Approach	347	370	22.1	25
	RBT4- South Approach	640	686	33.3	25
	RBT5- South Approach	310	317	21.6	25

Note: RBT = roundabout, FFS = free-flow speed

Table 4 displays the impeded delay (equal to the difference between the average travel time and the unimpeded travel time) and total delay (equal to the difference between the average travel time and the free flow travel time) for each approach route. Each approach was split into the upstream and downstream segments, where the upstream segment extends from the yield bar to the upstream midblock point, and the downstream segment extends from the yield bar to the downstream midblock point.

Table 4: Summary of Geometric and Approach Delay

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT1-North Approach (Upstream)	**4.6**	**153**	**27.3**	**3.8**	**4.0**	**0.2**	**0.6**	**0.7**
AM	4.2	153	27.3	3.8	4.0	0.2	0.2	0.4
Off	4.6	153	27.3	3.8	4.0	0.2	0.6	0.8
PM	5.3	153	27.3	3.8	4.0	0.2	1.3	1.5
RBT1-North Approach (Downstream)	**7.7**	**276**	**27.3**	**6.7**	**7.0**	**0.3**	**0.7**	**1.0**
AM	7.4	276	27.3	6.7	7.0	0.3	0.4	0.7
Off	7.8	276	27.3	6.7	7.0	0.3	0.8	1.1
PM	7.7	276	27.3	6.7	7.0	0.3	0.7	1.0
RBT1-South Approach (Upstream)	**4.7**	**151**	**24.9**	**4.1**	**4.2**	**0.1**	**0.5**	**0.5**
AM	4.9	151	24.9	4.1	4.2	0.1	0.7	0.8
Off	4.6	151	24.9	4.1	4.2	0.1	0.4	0.5
PM	4.4	151	24.9	4.1	4.2	0.1	0.2	0.3
RBT1-South Approach (Downstream)	**8.8**	**285**	**24.9**	**7.8**	**8.5**	**0.7**	**0.3**	**1.0**
AM	8.8	285	24.9	7.8	8.5	0.7	0.3	1.0
Off	8.8	285	24.9	7.8	8.5	0.7	0.3	1.0
PM	9.3	285	24.9	7.8	8.5	0.7	0.8	1.5
RBT2-North Approach (Upstream)	**3.9**	**123**	**27.3**	**3.1**	**3.5**	**0.4**	**0.4**	**0.8**
AM	3.9	123	27.3	3.1	3.5	0.4	0.4	0.8
Off	3.8	123	27.3	3.1	3.5	0.4	0.3	0.7
PM	4.1	123	27.3	3.1	3.5	0.4	0.6	1.0
RBT2-North Approach (Downstream)	**10.2**	**362**	**24.9**	**9.9**	**9.9**	**0.0**	**0.3**	**0.2**
AM	10.3	362	24.9	9.9	9.9	0.0	0.4	0.4
Off	10.1	362	24.9	9.9	9.9	0.0	0.2	0.2
PM	10.0	362	24.9	9.9	9.9	0.0	0.1	0.0

Table 4 continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT2-South Approach (Upstream)	**6.6**	**205**	**24.9**	**5.5**	**6.0**	**0.5**	**0.6**	**1.0**
AM	6.6	205	24.9	5.5	6.0	0.5	0.6	1.1
Off	6.4	205	24.9	5.5	6.0	0.5	0.4	0.9
PM	7.2	205	24.9	5.5	6.0	0.5	1.2	1.7
RBT2-South Approach (Downstream)	**9.1**	**298**	**24.9**	**8.2**	**8.5**	**0.3**	**0.6**	**0.9**
AM	8.9	298	24.9	8.2	8.5	0.3	0.4	0.7
Off	9.2	298	24.9	8.2	8.5	0.3	0.7	1.0
PM	9.1	298	24.9	8.2	8.5	0.3	0.6	0.9
RBT3-North Approach (Upstream)	**8.3**	**316**	**24.9**	**6.4**	**6.5**	**0.1**	**1.8**	**1.9**
AM	6.7	316	24.9	6.4	6.5	0.1	0.2	0.4
Off	8.5	316	24.9	6.4	6.5	0.1	2.0	2.1
PM	11.6	316	24.9	6.4	6.5	0.1	5.1	5.2
RBT3-North Approach (Downstream)	**8.3**	**320**	**23.6**	**7.9**	**8.0**	**0.1**	**0.3**	**0.4**
AM	8.1	320	23.6	7.9	8.0	0.1	0.1	0.2
Off	8.4	320	23.6	7.9	8.0	0.1	0.4	0.5
PM	8.5	320	23.6	7.9	8.0	0.1	0.5	0.6
RBT3-South Approach (Upstream)	**5.7**	**95**	**19.9**	**3.3**	**3.5**	**0.2**	**2.2**	**2.5**
AM	3.9	95	19.9	3.3	3.5	0.2	0.4	0.6
Off	5.6	95	19.9	3.3	3.5	0.2	2.1	2.3
PM	11.7	95	19.9	3.3	3.5	0.2	8.2	8.5
RBT3-South Approach (Downstream)	**12.7**	**442**	**24.9**	**11.9**	**12.0**	**0.1**	**0.7**	**0.9**
AM	12.3	442	24.9	11.9	12.0	0.1	0.3	0.4
Off	13.0	442	24.9	11.9	12.0	0.1	1.0	1.1
PM	12.8	442	24.9	11.9	12.0	0.1	0.8	0.9

Table 4 continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT4-North Approach (Upstream)	**5.2**	**126**	**23.6**	**3.6**	**4.0**	**0.4**	**1.2**	**1.5**
AM	4.4	126	23.6	3.6	4.0	0.4	0.4	0.8
Off	5.5	126	23.6	3.6	4.0	0.4	1.5	1.9
PM	5.8	126	23.6	3.6	4.0	0.4	1.8	2.2
RBT4-North Approach (Downstream)	**15.3**	**672**	**30.4**	**13.5**	**14.5**	**1.0**	**0.8**	**1.8**
AM	14.7	672	30.4	13.5	14.5	1.0	0.2	1.1
Off	15.7	672	30.4	13.5	14.5	1.0	1.2	2.1
PM	15.5	672	30.4	13.5	14.5	1.0	1.0	2.0
RBT4-South Approach (Upstream)	**13.4**	**508**	**30.4**	**11.2**	**12.5**	**1.3**	**0.9**	**2.2**
AM	12.7	508	30.4	11.2	12.5	1.3	0.2	1.6
Off	13.5	508	30.4	11.2	12.5	1.3	1.0	2.3
PM	14.9	508	30.4	11.2	12.5	1.3	2.4	3.7
RBT4-South Approach (Downstream)	**9.1**	**266**	**19.9**	**8.2**	**8.3**	**0.1**	**0.8**	**0.9**
AM	8.4	266	19.9	8.2	8.3	0.1	0.1	0.2
Off	8.8	266	19.9	8.2	8.3	0.1	0.5	0.6
PM	12.2	266	19.9	8.2	8.3	0.1	3.9	4.0
RBT5-North Approach (Upstream)	**15.6**	**526**	**30.4**	**11.8**	**14.0**	**2.2**	**1.6**	**3.8**
AM	14.8	526	30.4	11.8	14.0	2.2	0.8	3.0
Off	15.9	526	30.4	11.8	14.0	2.2	1.9	4.1
PM	16.1	526	30.4	11.8	14.0	2.2	2.1	4.3
RBT5-North Approach (Downstream)	**7.3**	**240**	**30.4**	**5.4**	**7.0**	**1.6**	**0.3**	**2.0**
AM	7.4	240	30.4	5.4	7.0	1.6	0.4	2.0
Off	7.3	240	30.4	5.4	7.0	1.6	0.3	1.9
PM	7.5	240	30.4	5.4	7.0	1.6	0.5	2.1

Table 4 continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free-Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT5-South Approach (Upstream)	**4.7**	**119**	**30.4**	**2.7**	**3.0**	**0.3**	**1.7**	**2.0**
AM	3.8	119	30.4	2.7	3.0	0.3	0.8	1.1
Off	5.0	119	30.4	2.7	3.0	0.3	2.0	2.3
PM	5.7	119	30.4	2.7	3.0	0.3	2.7	3.1
RBT5-South Approach (Downstream)	**17.9**	**688**	**30.4**	**15.2**	**17.0**	**1.8**	**0.9**	**2.8**
AM	17.3	688	30.4	15.2	17.0	1.8	0.3	2.2
Off	18.3	688	30.4	15.2	17.0	1.8	1.3	3.1
PM	17.9	688	30.4	15.2	17.0	1.8	0.9	2.8

3.3. Spot-Speed Profiles

In addition to the travel time data, the team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at a few selected roundabouts along the corridor (Figure 1). These data were collected using a laser speed gun. These speeds provide a more realistic estimation of operating speeds at the roundabouts than do the GPS travel-time runs, which were conducted by engineers using the floating car technique. Summary statistics are displayed in Table 5.

Table 5: Spot-Speed Summary Statistics

Point	**1**	**2**	**3**	**4**	**5**
RBT #	1-2	2	4-5	4-5	3
Location	SB - midblock	SB – circulating	SB – midblock	NB – midblock	NB – circulating
Mean Speed (mph)	22.9	16.8	30.3	30.9	14.7
StdDev (mph)	2.3	2.3	3.1	3.5	2.0
Sample Size	90	90	90	90	90

Note that the midblock speeds in Table 5 indicate an estimated free flow speed of 30.9 mph in the northbound direction and 30.3 mph in the southbound direction. This compares to estimated free flow speeds of 33.3 mph and 32.7 mph from the GPS trajectories, respectively. The speed measurements from the combined dataset were also analyzed using histogram frequency distributions—all eight are displayed in Figure 4.

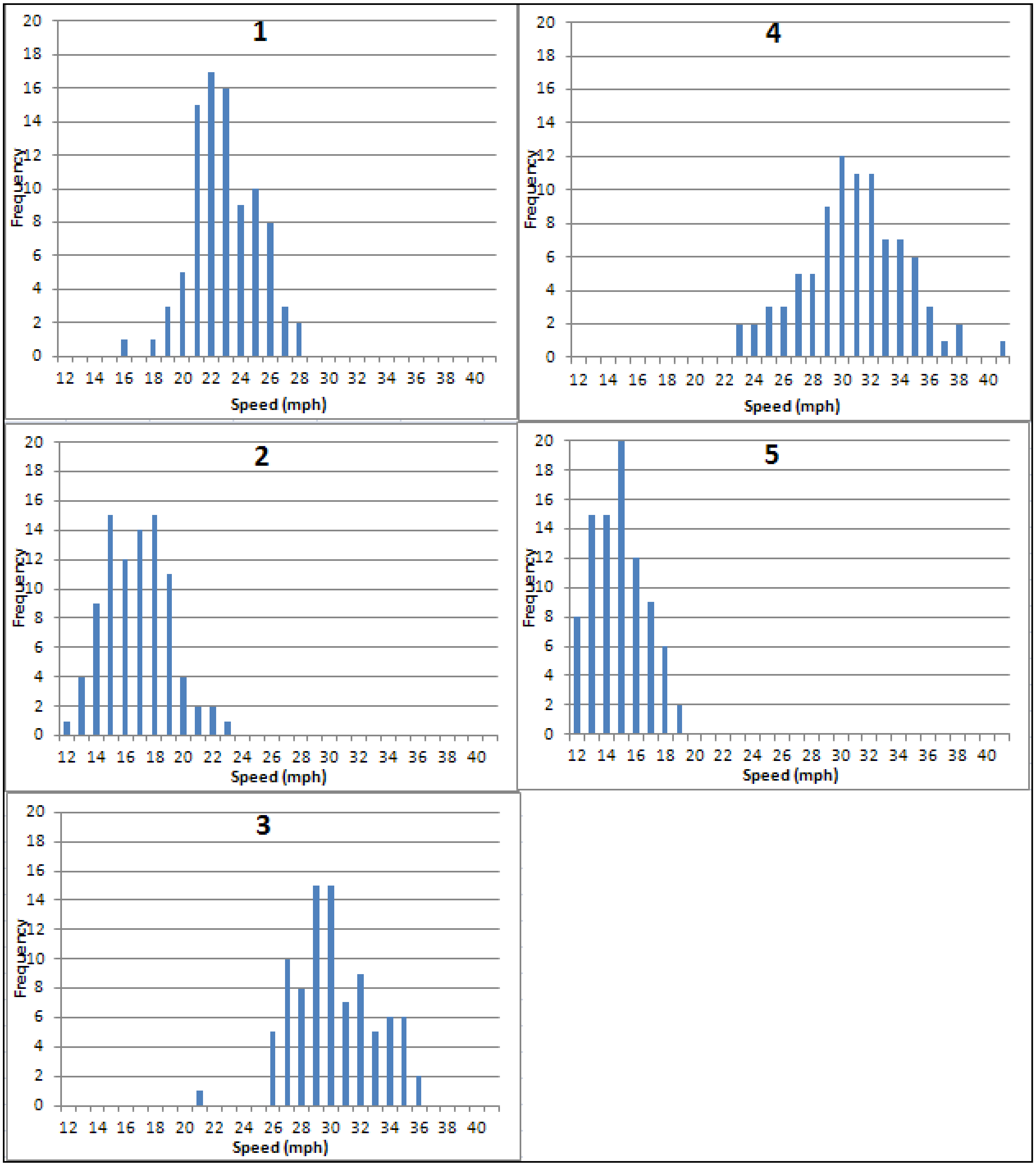

Figure 3: Spot-Speed Histograms

4. Appendix

4.1. Appendix I1: Aerial Imagery

Figure A1. Avon Road at US-6 (Roundabout 5)

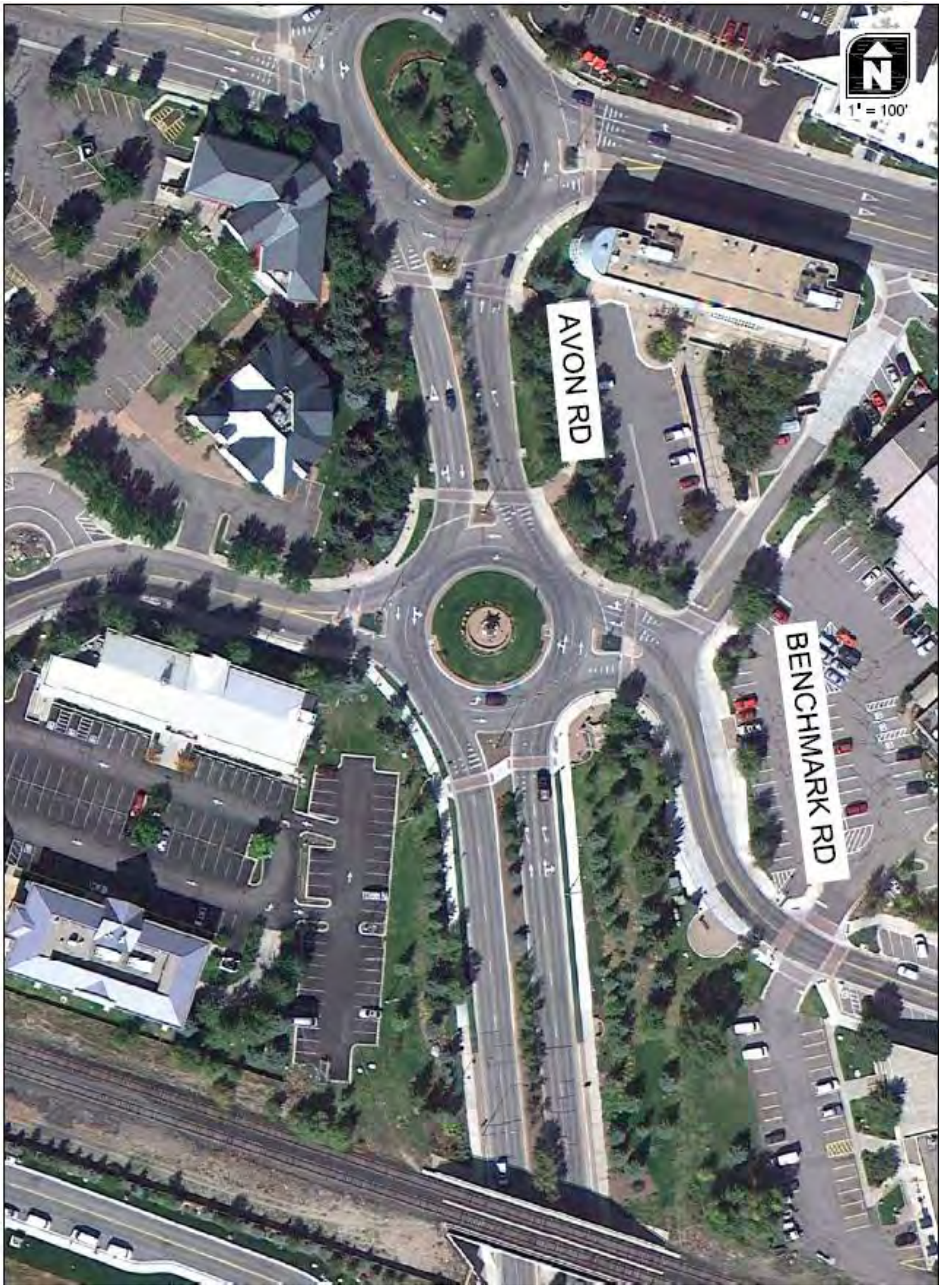

Figure A2. Avon Road at Benchmark Rd (Roundabout 4)

Figure A3. Avon Road at Beaver Creek Blvd (Roundabout 3)

Figure A4. Avon Road at I-70 EB (Roundabout 2)

Figure A5. Avon Road / Nottingham Road at I-70 WB (Roundabout 1)

4.2. Appendix I2: Speed Profiles

The speed profiles presented below correspond to the space-time trajectories presented in Figures 3A through 3F.

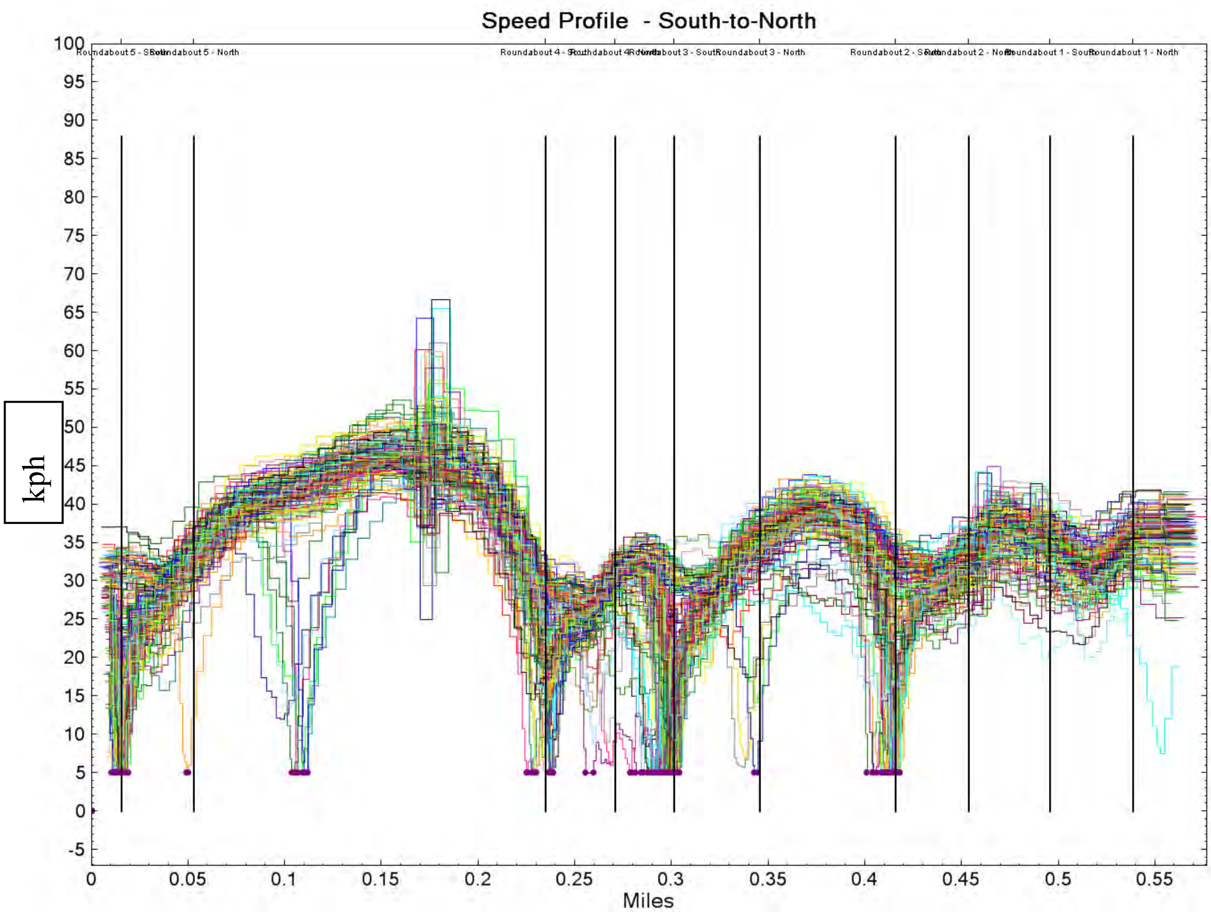

Figure B1. Speed Profile for Route 1 (Northbound Through the Entire Corridor)

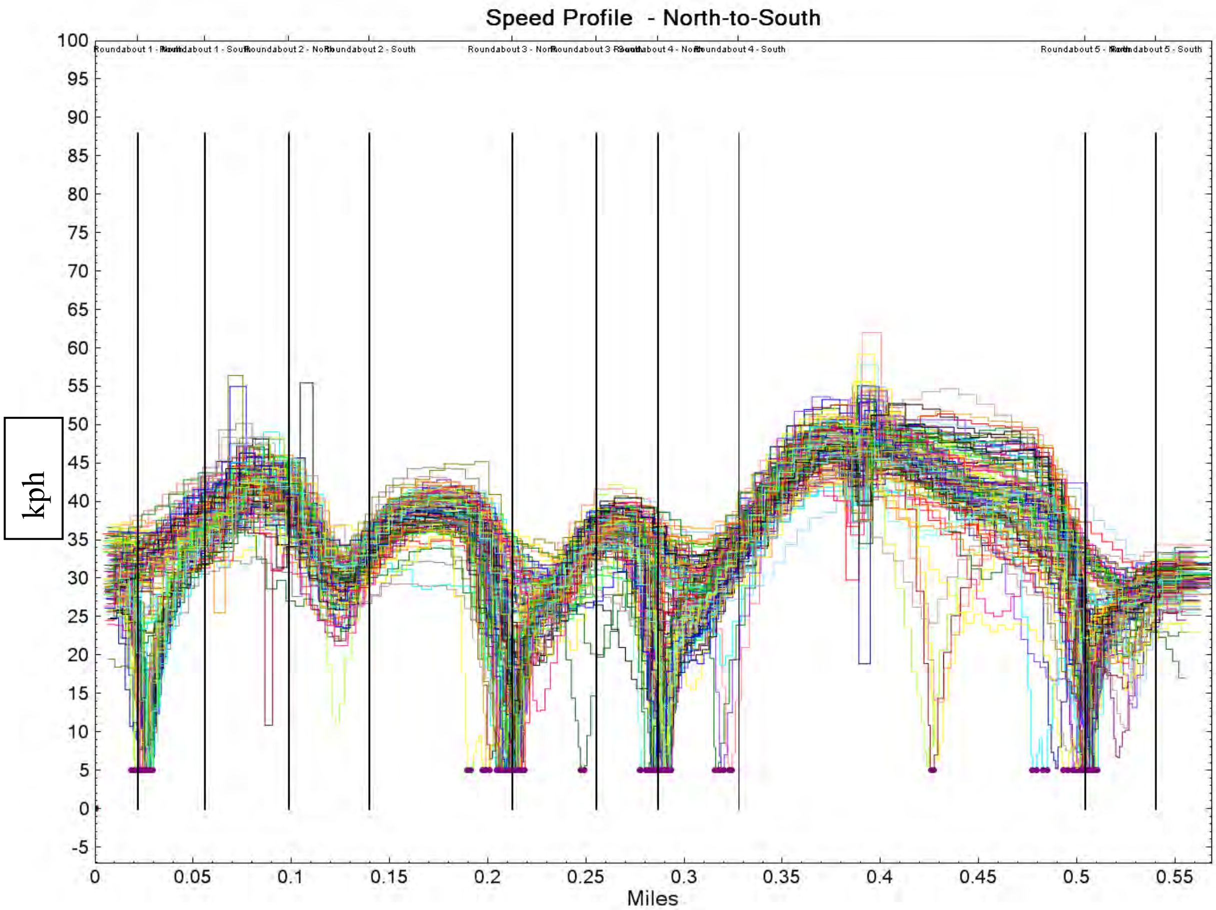

Figure B2. Speed Profile for Route 2 (Southbound Through the Entire Corridor)

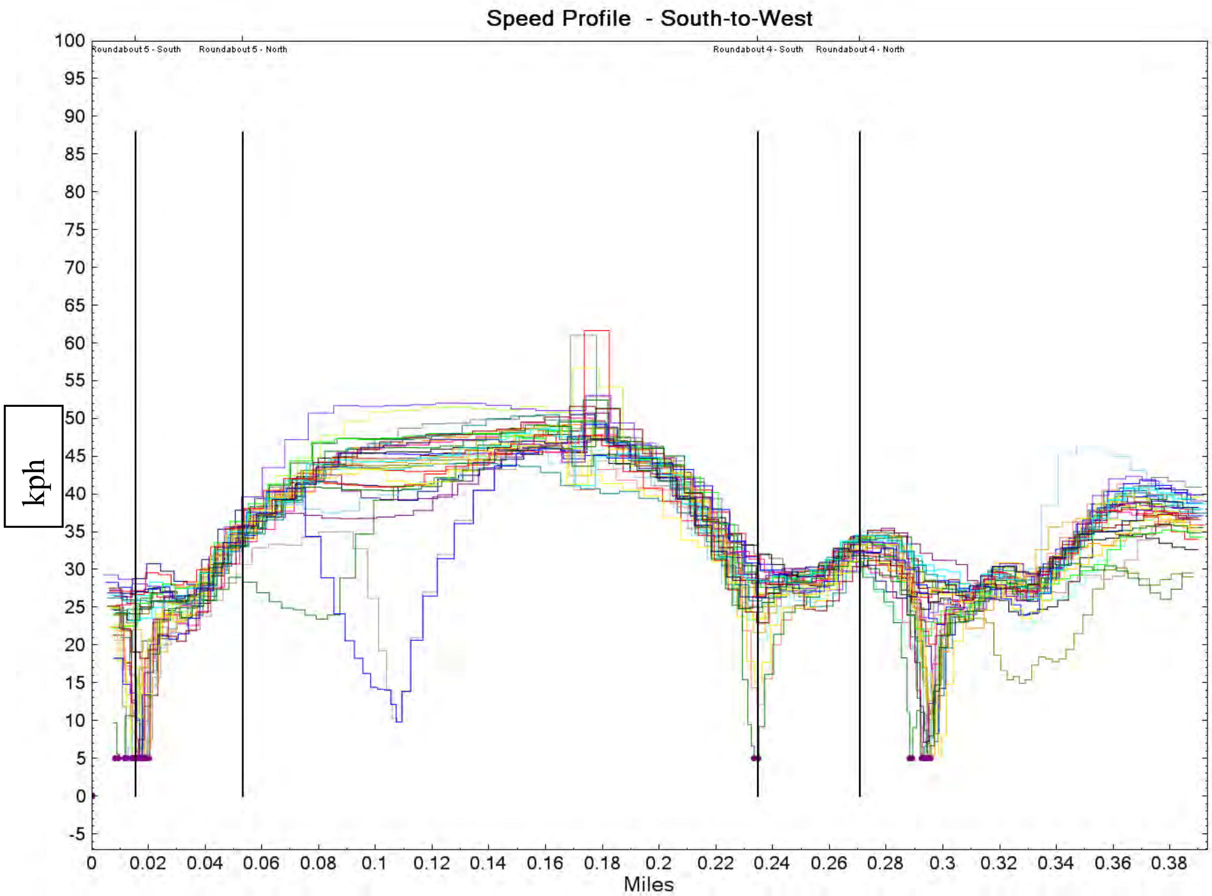

Figure B3. Speed Profile for Route 3 (Starting from South of Roundabout 5, then Turning Left at Roundabout 3)

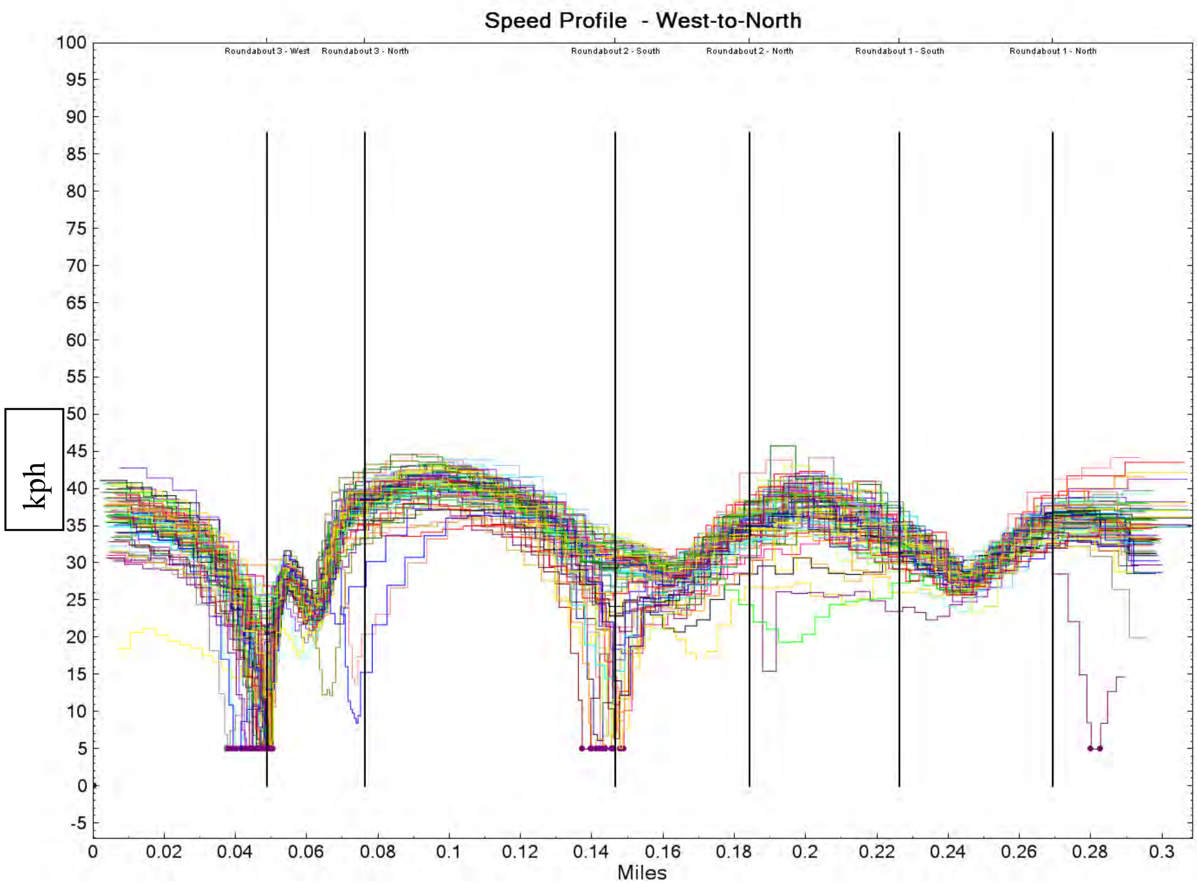

Figure B4. Speed Profile for Route 4 (Starting from West of Roundabout 3, then Turning Left at Roundabout 3)

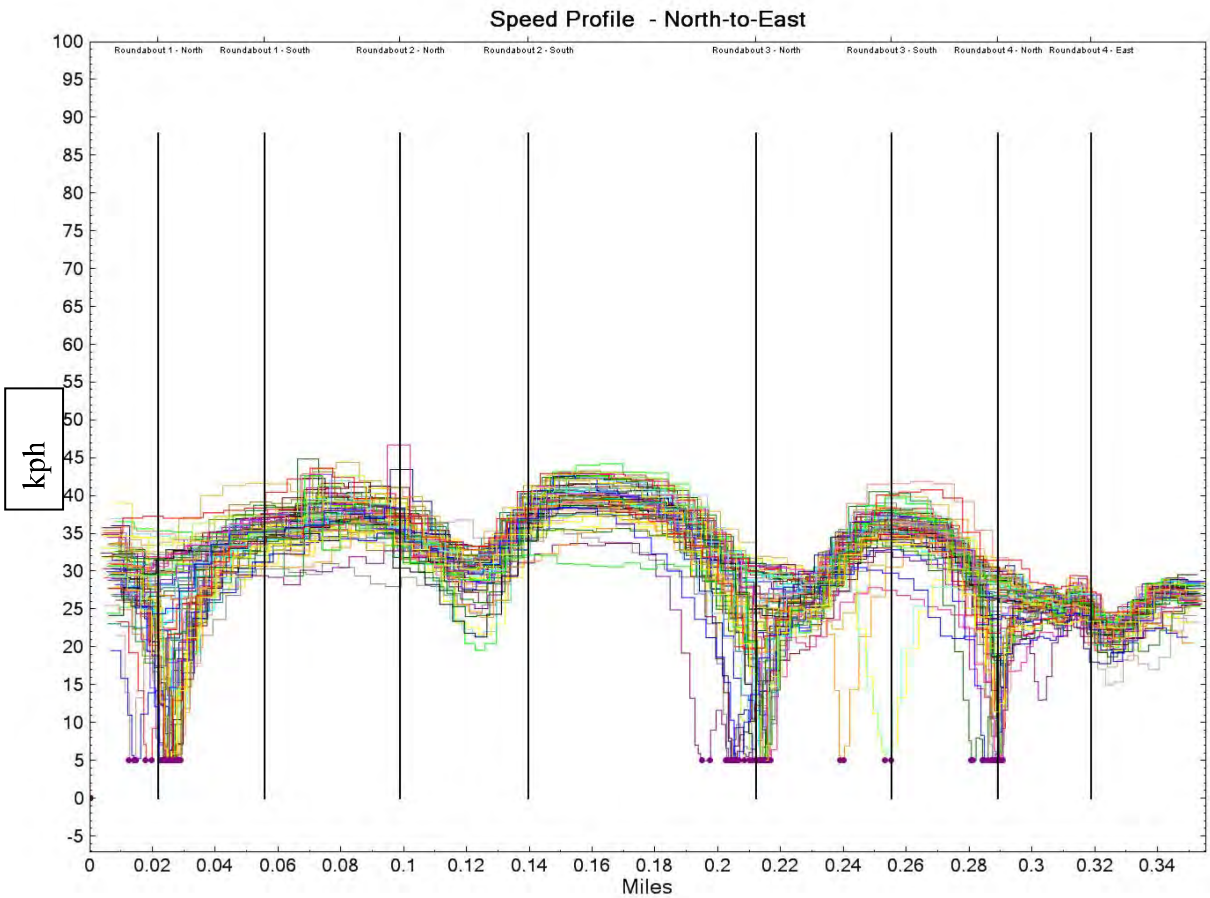

Figure B5. Speed Profile for Route 5 (Starting from North of Roundabout 1, then Turning Left at Roundabout 4)

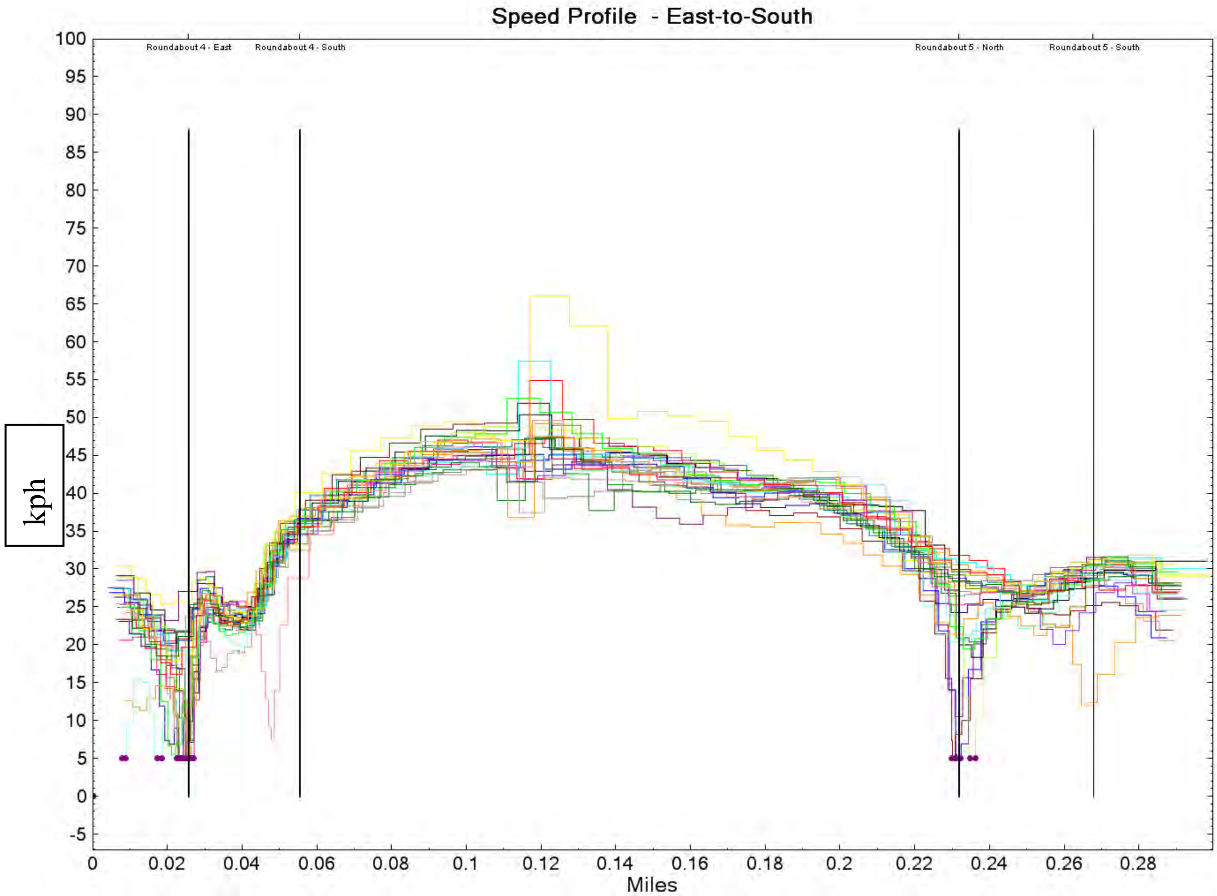

Figure B6. Speed Profile for Route 6 (Starting from East of Roundabout 4, then Turning Left at Roundabout 4)

NCHRP 03-100

Appendix J

Malta, New York

SR 67/Dunning Street Field Data

Table of Contents

List of Tables

List of Figures

1. Introduction

This document describes the field data collected by the NCHRP 3-100 team at the SR 67/ Dunning Street roundabout corridor in Malta, New York. The data collection and analysis efforts follow the format described in the team's data collection plan.

The data collected at this roundabout corridor, which consisted of seven roundabouts in series, included peak-hour and off-peak travel times and spot speed measurements. Travel times were recorded using vehicle-mounted GPS units. Additionally, video data were obtained through field-mounted cameras. Data were collected from August 6 through August 8, 2012.

This document provides an overview of the data collected and discusses the quality and size of the dataset. Figure 1 displays a schematic of the corridor. The white numbers denote roundabouts.

Figure 1: Schematic Illustration of the NY-67 / Dunning Street Roundabout Corridor

2. Traffic Counts

The research team obtained the traffic counts and turning movement counts for the two easternmost roundabouts along the corridor. Table 1 displays the turning movement counts for each intersection along the corridor. The volumes (in vehicles per hour) are displayed for the peak hour, which was determined to occur between 5:00 p.m. and 6:00 p.m. With the exception of the last intersection (Plains/Hermes), SR 67/Dunning Street comprises the east- and westbound approaches to each intersection.

Table 1: Turning Movement Counts (5:00 to 6:00 p.m.)

Intersection		Direction	L	T	R
#	Name				
1	State Farm Blvd East	Northbound	45	0	183
		Eastbound	0	430	3
		Westbound	22	440	0
2	I-87 SB	Southbound	78	0	103
		Eastbound	0	375	250
		Westbound	172	354	0
3	I-87 NB	Northbound	199	1	258
		Eastbound	186	261	0
		Westbound	0	320	124
4	Kelch Dr	Northbound	85	0	40
		Southbound	1	0	0
		Eastbound	1	457	63
		Westbound	21	358	0
5	US 9	Northbound	119	274	57
		Southbound	78	180	93
		Eastbound	208	183	113
		Westbound	49	142	76
6	Partridge Drum / Fox Wander	Northbound	28	1	0
		Southbound	2	0	38
		Eastbound	70	242	42
		Westbound	3	213	2
7	Plains Rd / Hermes Rd	Eastbound Dunning	185	0	22
		Westbound Plains	5	0	101
		Westbound Hermes	105	0	31

Figure 2 displays the 12-hour volume profile for SR 67 between Kelch Drive and US-9 (roundabouts 4 and 5). 5:00 p.m. to 5:30 p.m. was identified as the peak 30 minutes in both directions.

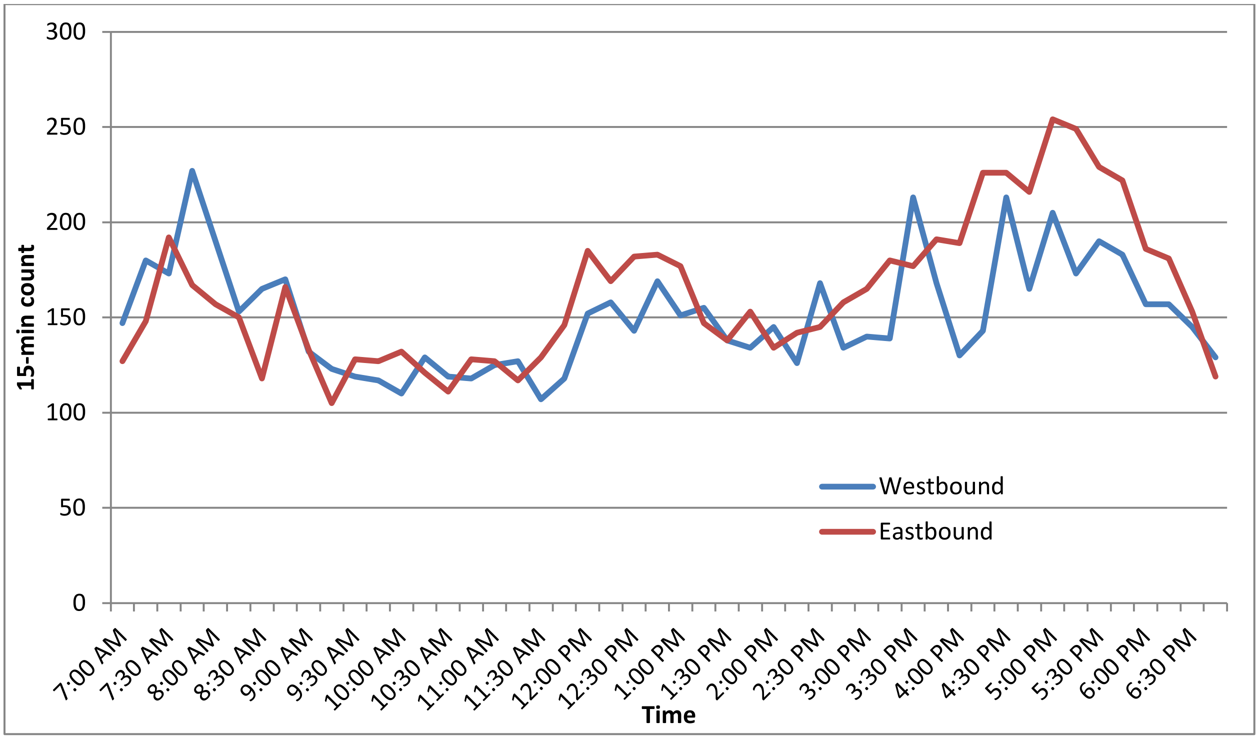

Figure 2: 12-hour Volume Profile

3. Field-Observed Data

Several data elements were collected in the field during the data collection period. This includes GPS travel times and spot-speed measurements along the corridor.

3.1. **GPS Travel Times**

The travel time through the corridor was also measured using vehicle-mounted GPS units. A total of six routes were used to conduct the study:

1. Eastbound through the entire corridor;
2. Westbound through the entire corridor;
3. Starting from the east end, then turning left through roundabout 5 (US 9);
4. Starting from south of roundabout 5 (US 9), then turning left through the roundabout and proceeding to the west end;
5. Starting from the west end, then turning left through roundabout 5 (US 9); and
6. Starting from north of roundabout 5 (US 9, then turning left through the roundabout and proceeding to the east end.

The last four routes were used to capture left-turns through the US 9 roundabout, which the team considered to be the most congested of the corridor.

Figures 3A through 3F display the space-time trajectories from each of the six routes. Each diagram displays every travel time run that was conducted (including a.m., p.m., and off-peak runs). Note that the scale varies from route to route. Corresponding speed profiles are displayed in Appendix J2.

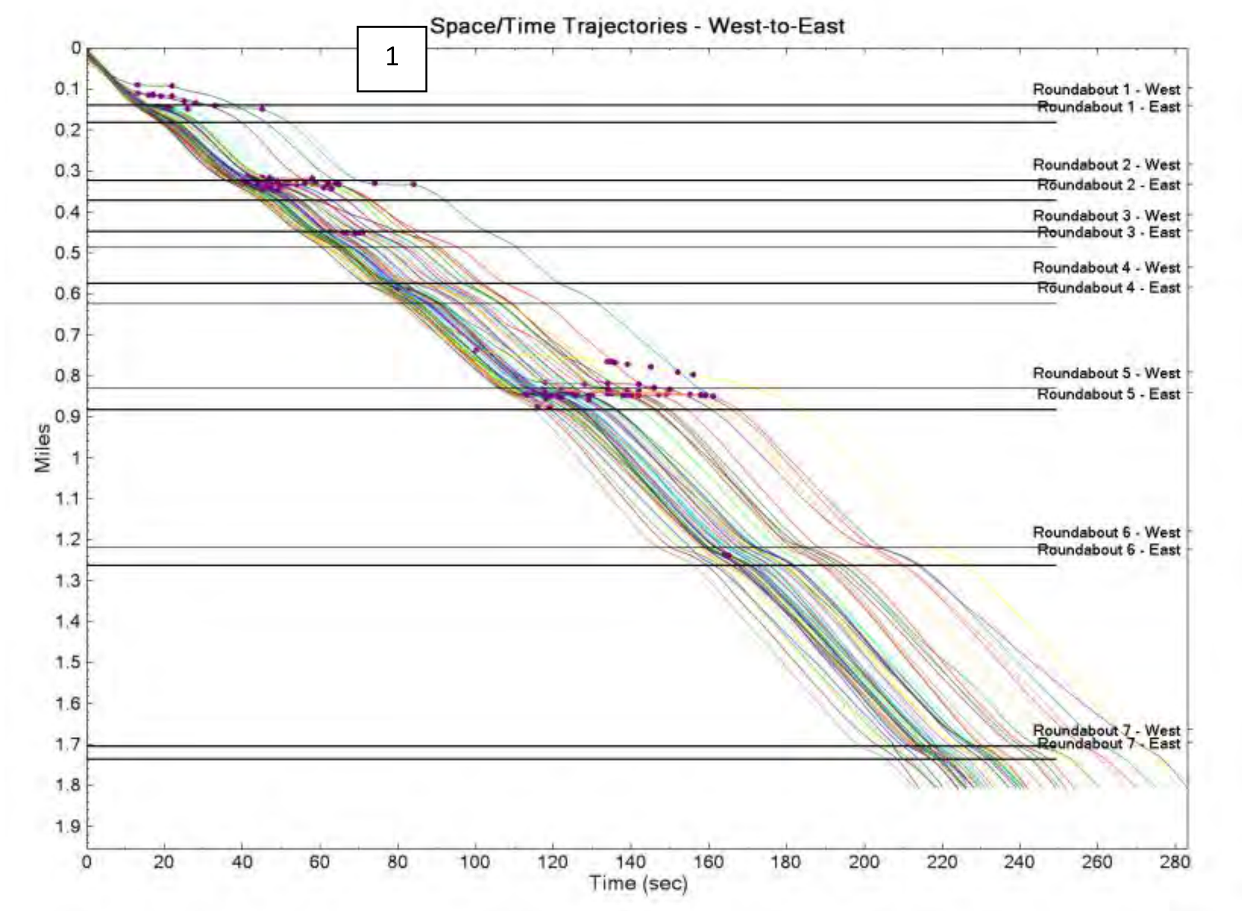

Figure 3A. Space/Time Trajectories for Route 1 (Eastbound Through the Entire Corridor)

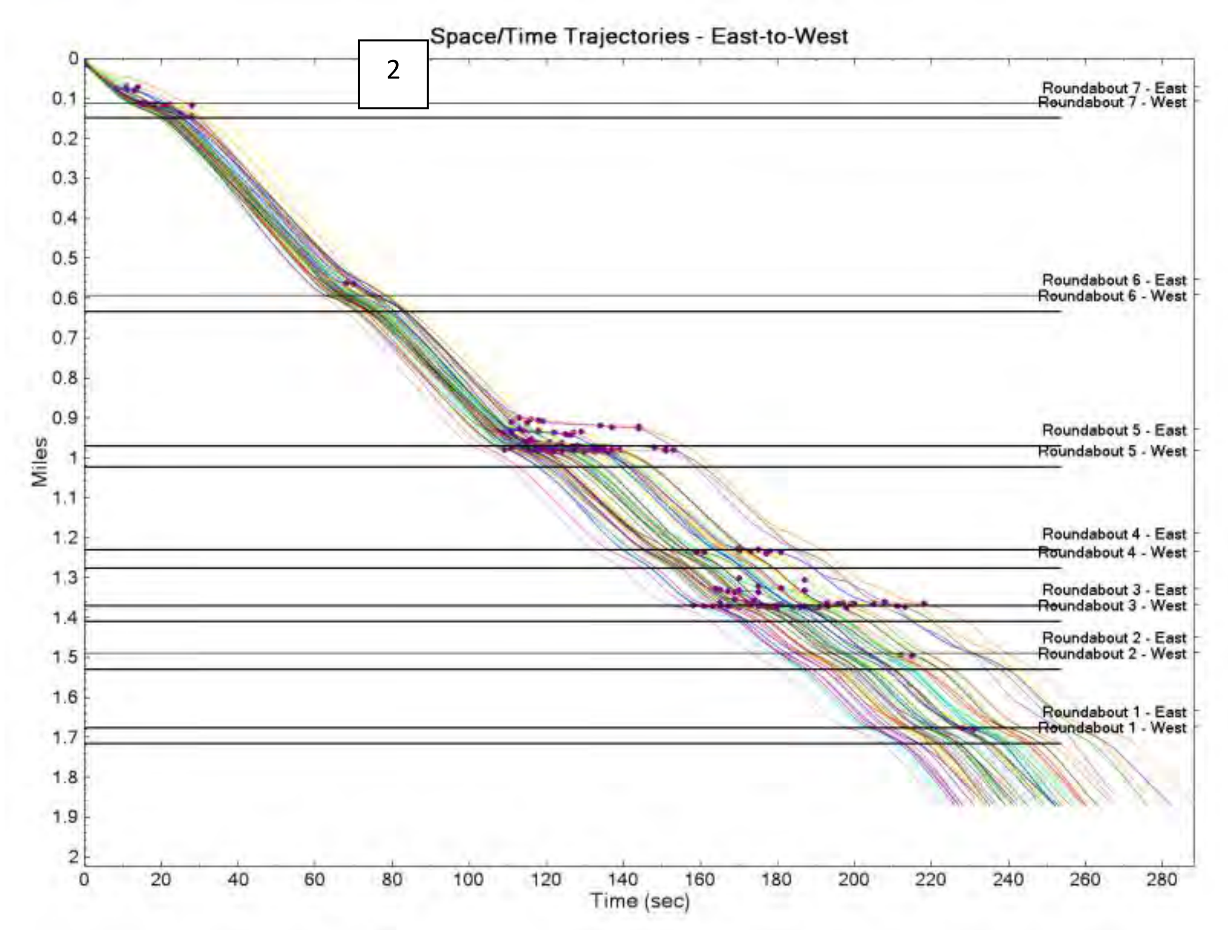

Figure 3B. Space/Time Trajectories for Route 2 (Westbound Through the Entire Corridor)

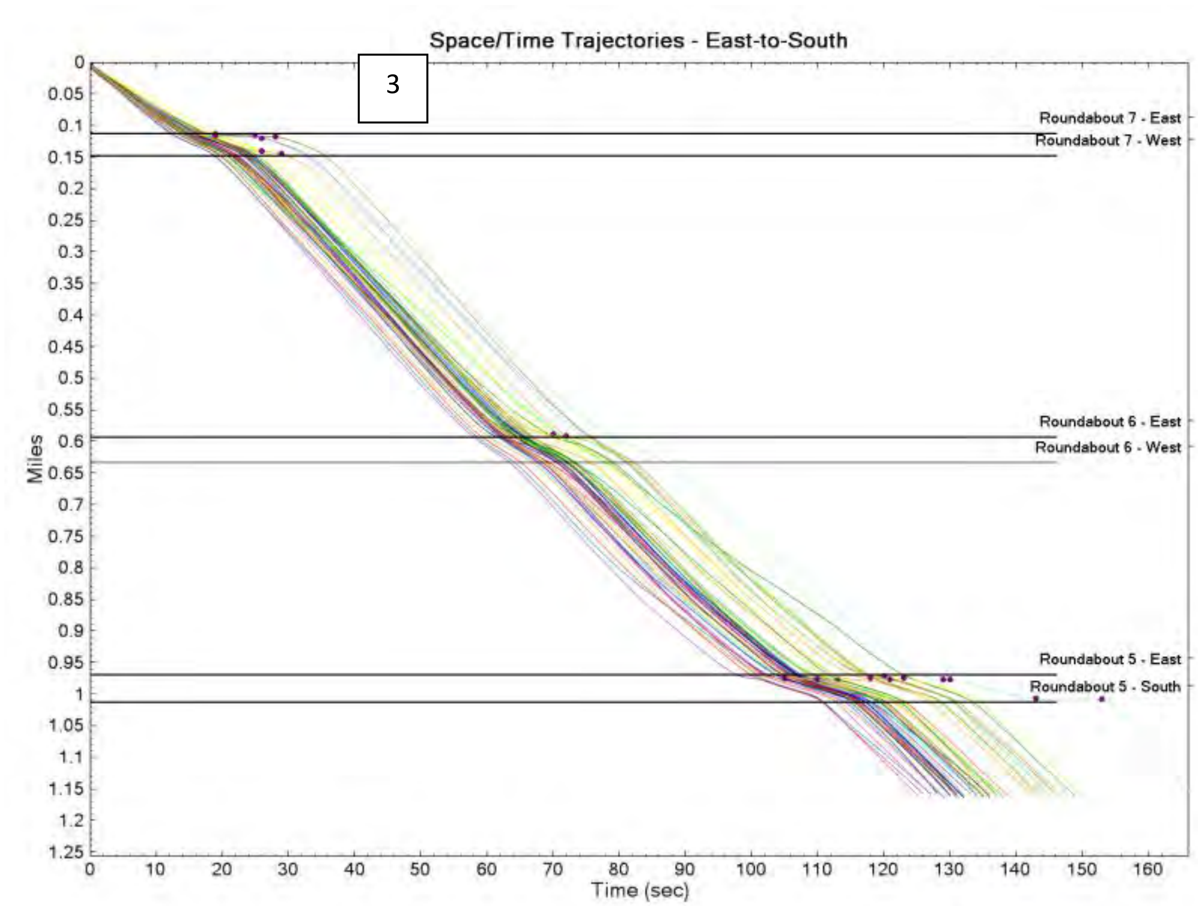

Figure 3C. Space/Time Trajectories for Route 3 (Beginning East of Roundabout 7, then Turning Left at Roundabout 5)

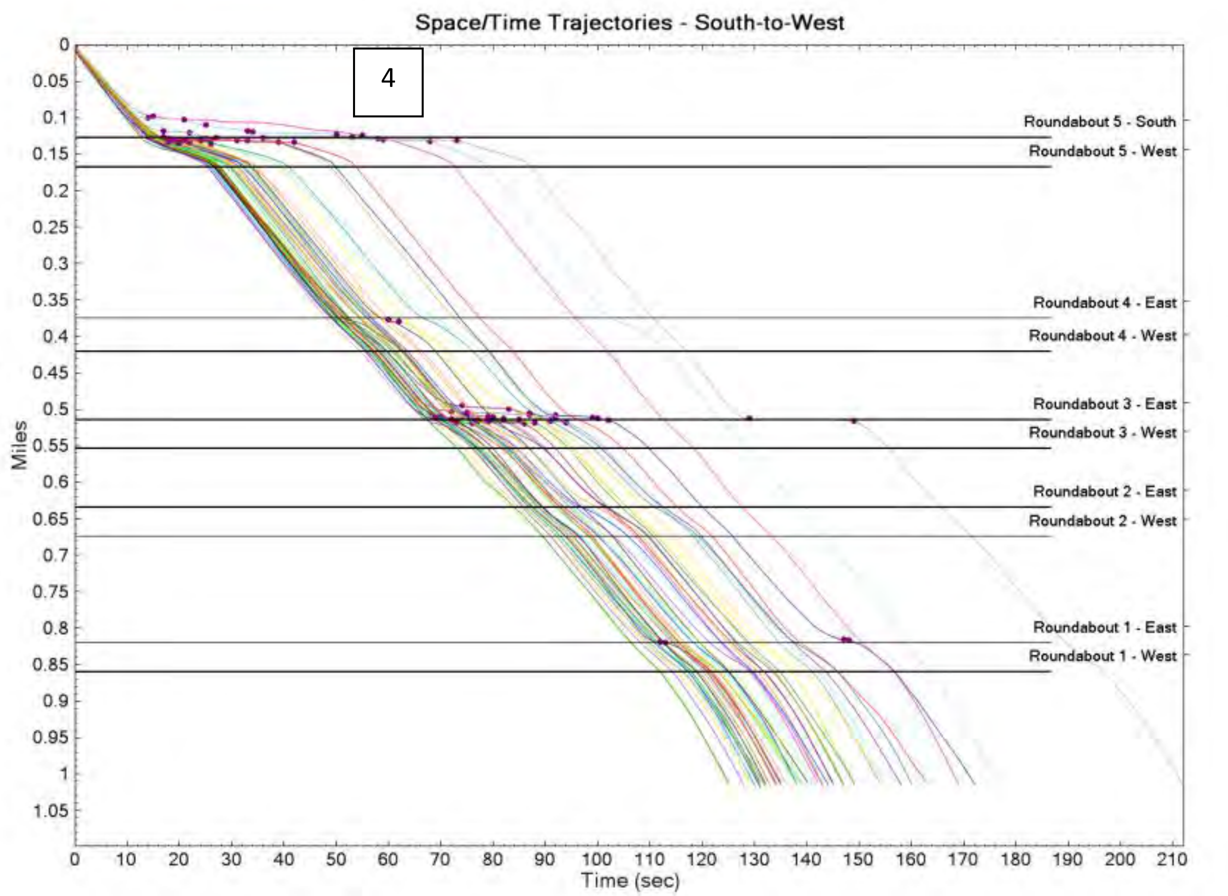

Figure 3D. Space/Time Trajectories for Route 4 (Beginning South of Roundabout 5, then Turning Left at Roundabout 5)

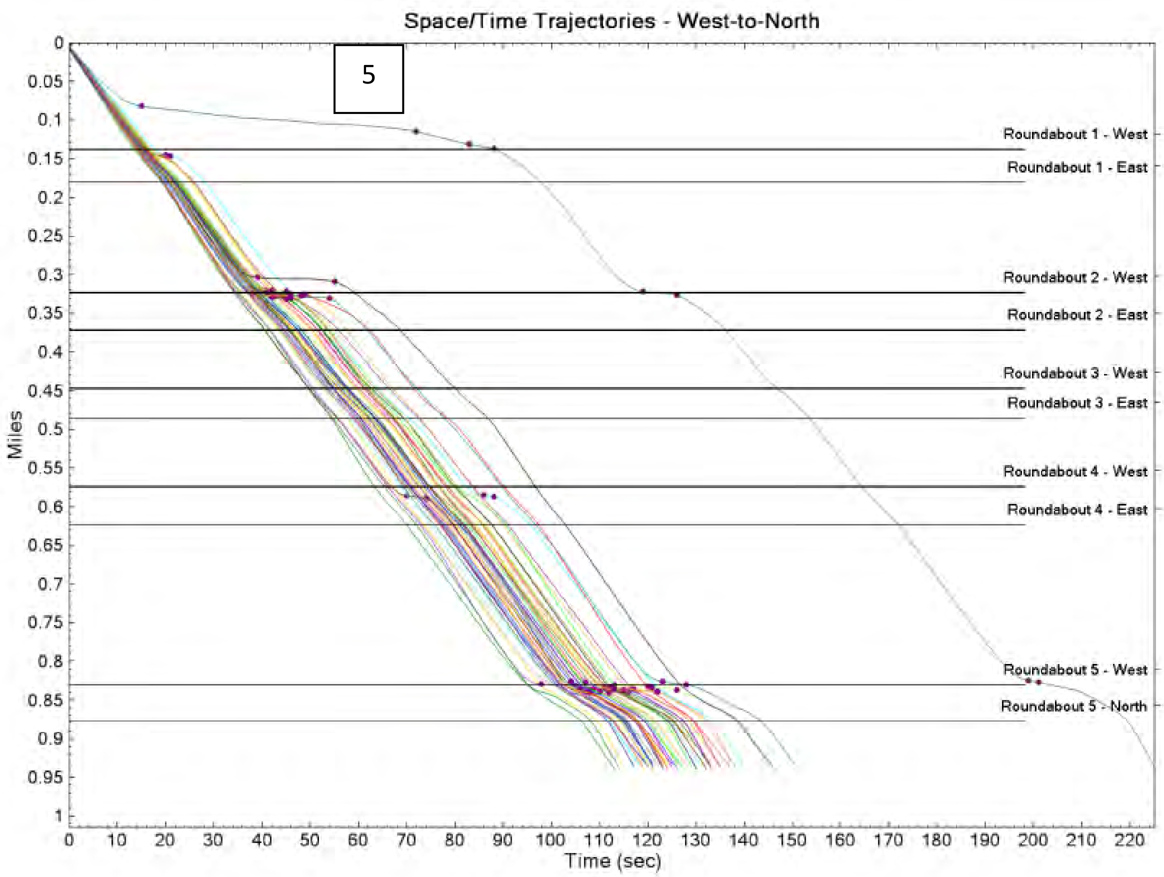

Figure 3E. Space/Time Trajectories for Route 5 (Beginning West of Roundabout 1, then Turning Left at Roundabout 5)

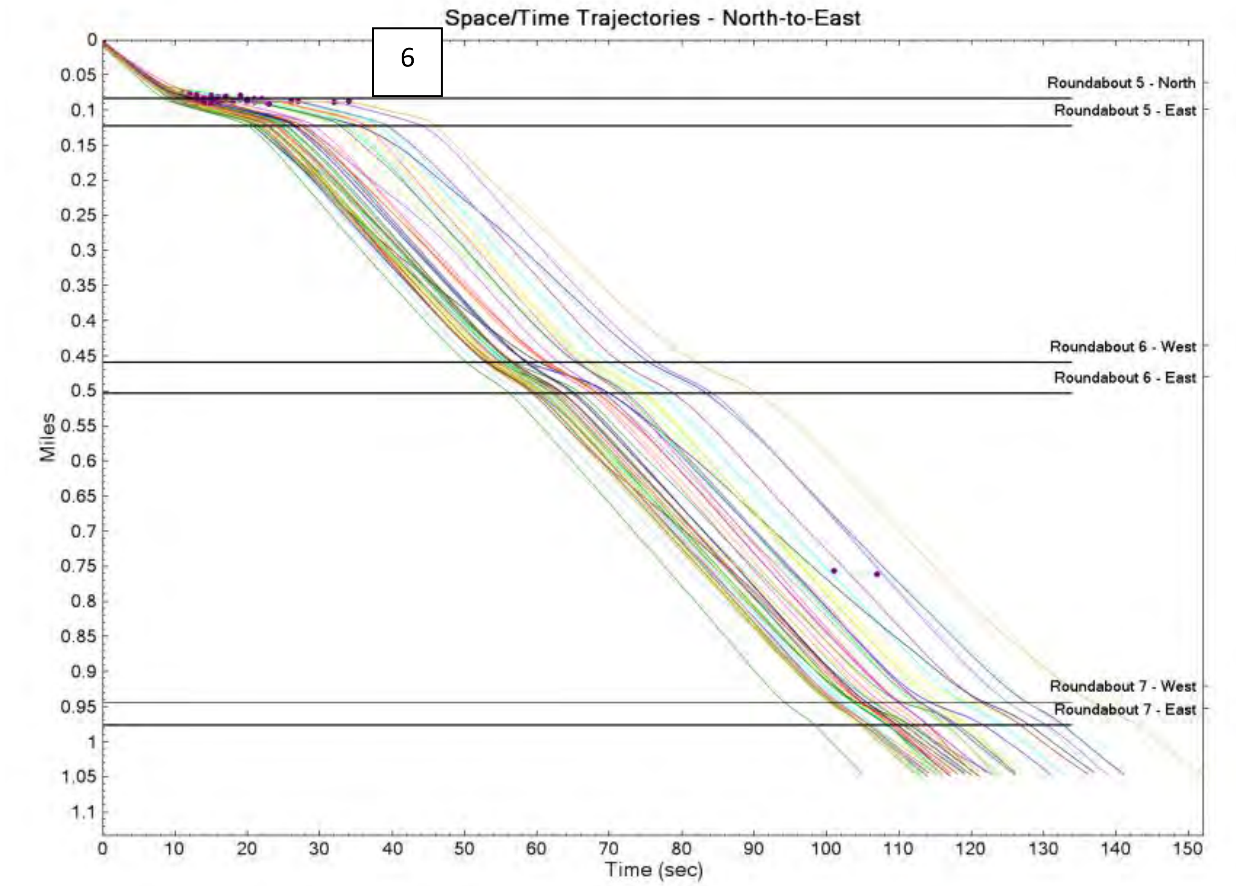

Figure 3F. Space/Time Trajectories for Route 6 (Beginning North of Roundabout 5, then Turning Left at Roundabout 5)

The space-time diagrams give a sense of the average travel speed along the corridor, which corresponds to the slope of the trajectory line. The diagrams also show delays incurred during individual runs, which is evident by the trajectory line "flattening." A vehicle stop is denoted by a purple dot. The horizontal lines correspond to the entry and exit points of the various roundabouts traversed during the route. It should be noted that all routes are shown to emerge from a common origin. The "spreading" of different routes as vehicles travel through the corridor reflects the variability in the observed data. The distance along the x-axis between the steepest (fastest) and flattest (slowest) trajectory corresponds to the range of observed data.

Table 2 presents more detailed statistics regarding the GPS travel time data. It displays the summary statistics for all travel time runs, grouped into peak hour and off-peak. All speeds are displayed in mph, and all travel times are displayed in minutes. Using the free-flow travel time, the table shows HCM Urban Streets LOS (based on % FFS aggregated over the entire route) and the average HCM Roundabout LOS. The table indicates that the LOS assigned to each route may vary using either method.

Table 2: Summary of a.m., p.m., and Off-peak Travel Times

Route	Sample Size	Average Travel Speed (mph)				Average Travel Time (minutes)				Free-Flow Speed (mph)	% FFS	Urban Street LOS	Travel Distance (mi)	Free-Flow TT (min)	Avg. Rbt Control Delay (sec)	Avg HCM Rbt LOS
		Mean	StdDev	Max	Min	Mean	StdDev	Max	Min							
East-to-South	**50**	**31.3**	**1.6**	**33.7**	**25.5**	**2.26**	**0.13**	**2.77**	**2.08**	**36.7**	85.2%	**A**	**1.18**	**1.93**	**4.0**	**A**
AM	15	31.4	1.3	32.8	28.4	2.25	0.10	2.48	2.15		85.7%	A			3.8	A
Off	23	31.5	1.4	33.7	28.2	2.25	0.10	2.50	2.08		85.7%	A			3.8	A
PM	12	30.7	2.3	33.2	25.5	2.31	0.19	2.77	2.12		83.6%	B			4.6	A
North-to-East	**50**	**31.6**	**2.3**	**36.5**	**25.4**	**2.04**	**0.16**	**2.53**	**1.75**	**36.3**	87.2%	**A**	**1.07**	**1.77**	**3.3**	**A**
AM	15	31.5	2.2	34.2	28.1	2.05	0.15	2.28	1.88		86.9%	A			3.3	A
Off	23	31.9	2.1	36.5	27.3	2.02	0.14	2.35	1.75		87.9%	A			3.0	A
PM	12	31.3	2.9	34.4	25.4	2.07	0.21	2.53	1.87		86.3%	A			3.6	A
South-to-West	**49**	**26.5**	**2.5**	**30.1**	**17.8**	**2.38**	**0.26**	**3.53**	**2.08**	**36.7**	72.1%	**B**	**1.04**	**1.70**	**8.2**	**A**
AM	15	27.0	1.6	28.7	23.7	2.32	0.15	2.63	2.17		73.6%	B			7.4	A
Off	22	26.9	2.0	30.1	23.0	2.33	0.18	2.72	2.08		73.3%	B			7.6	A
PM	12	25.0	3.6	28.8	17.8	2.55	0.41	3.53	2.18		68.0%	B			10.2	B
West-to-North	**51**	**27.0**	**2.4**	**30.5**	**15.2**	**2.15**	**0.27**	**3.75**	**1.88**	**36.3**	74.2%	**B**	**1.0**	**1.57**	**6.9**	**A**
AM	17	26.0	3.2	29.1	15.2	2.25	0.41	3.75	1.97		71.7%	B			8.1	A
Off	22	27.7	1.9	30.5	22.7	2.08	0.15	2.52	1.88		76.2%	B			6.1	A
PM	12	27.0	1.5	28.9	23.8	2.13	0.13	2.43	2.00		74.3%	B			6.7	A
West-to-East	**60**	**27.7**	**1.7**	**30.5**	**23.0**	**3.93**	**0.27**	**4.72**	**3.55**	**36.3**	76.3%	**B**	**1.81**	**2.99**	**11.2**	**B**
AM	20	26.9	1.8	29.7	23.0	4.05	0.29	4.72	3.63		74.1%	B			12.7	B
Off	25	28.2	1.3	30.5	25.5	3.86	0.17	4.23	3.55		77.6%	B			10.4	B
PM	15	27.9	2.0	30.3	23.2	3.89	0.32	4.68	3.57		76.9%	B			10.8	B
East-to-West	**59**	**27.3**	**1.7**	**30.6**	**23.5**	**4.13**	**0.26**	**4.80**	**3.68**	**36.7**	74.3%	**B**	**1.87**	**3.06**	**12.9**	**B**
AM	19	28.3	1.4	30.6	26.0	3.98	0.20	4.33	3.68		77.1%	B			11.1	B
Off	25	26.9	1.6	29.9	24.0	4.20	0.26	4.70	3.77		73.3%	B			13.7	B
PM	15	26.6	1.5	29.1	23.5	4.22	0.25	4.80	3.85		72.5%	B			14.0	B

Notes: FFS = free-flow speed, Rbt = roundabout, LOS = Level of Service

3.2. Geometric and Approach Delay from GPS

The team also examined the approach delay at each roundabout while considering the geometric delay incurred by the roundabouts themselves. Table 4 presents a summary of this analysis. For each approach and time of day, the free-flow travel time was estimated by isolating the unimpeded trajectories from the rest of the data set and by measuring the peak midblock speed from the trajectories. Although the true free-flow speed may not be observable in this manner (it may be higher than the observed speeds due to friction/driver behavior along the corridor), the team believed that this method was advantageous in that it provided a greater sample size (in a greater number of locations) than the midblock speed study (Section 3.3). Additionally, the travel distance used to compute the free-flow travel time was taken as the centerline distance between each pair of roundabouts so that the geometric delay caused by the additional travel distance required to navigate the roundabouts did not affect the estimate of the free flow travel time.

Table 3 shows the distances used for estimating free-flow travel time, relative to the actual travel distance through the roundabout. Each segment is assumed to start about half-way between two roundabouts and to end at (approximately) the downstream crosswalk at a roundabout. The table also provides the field-estimated FFS for each segment, along with the posted speed limit.

Table 3: Summary of Segment Distances

Direction	Route Segment	Free-Flow Distance (feet)	Trajectory Distance (feet)	Segment FFS (mph)	Speed Limit (mph)
Eastbound	RBT1-East Approach	669	686	38.4	35
	RBT2-East Approach	455	528	32.8	35
	RBT3-East Approach	520	528	36.3	35
	RBT4-East Approach	825	898	38.4	35
	RBT5-East Approach	1,152	1,162	40.9	35
	RBT6-East Approach	1,467	1,531	44.4	45
	RBT7-East Approach	756	792	39.0	45
Westbound	RBT1-West Approach	968	1,056	44.6	35
	RBT2-West Approach	589	686	37.5	35
	RBT3-West Approach	485	528	34.1	35
	RBT4-West Approach	589	634	36.7	35
	RBT5-West Approach	829	898	36.8	35
	RBT6-West Approach	1,093	1,162	40.0	45
	RBT7-West Approach	1,160	1,162	43.4	45

Note: RBT = roundabout, FFS = free-flow speed

Table 4 displays the impeded delay (equal to the difference between the average travel time and the unimpeded travel time) and total delay (equal to the difference between the average travel time and the free flow travel time) for each approach route. Each approach was split into the upstream and downstream segments, where the upstream segment extends from the yield bar to the upstream midblock point, and the downstream segment extends from the yield bar to the downstream midblock point.

Table 4: Summary of Geometric and Approach Delay

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT1-East Approach (Upstream)	10.1	415	33	8.6	9.0	0.4	1.1	1.5
AM	10.0	415	33	8.6	9.0	0.4	1.0	1.4
Off	10.3	415	33	8.6	9.0	0.4	1.3	1.7
PM	9.4	415	33	8.6	9.0	0.4	0.4	0.8
RBT1-East Approach (Downstream)	17.0	822	40	14.0	15.5	1.5	1.5	3.0
AM	17.2	822	40	14.0	15.5	1.5	1.7	3.2
Off	17.0	822	40	14.0	15.5	1.5	1.5	3.0
PM	16.0	822	40	14.0	15.5	1.5	0.5	1.9
RBT1-West Approach (Upstream)	15.2	740	40	12.6	12.6	0.0	2.6	2.6
AM	17.9	740	40	12.6	12.6	0.0	5.3	5.3
Off	13.6	740	40	12.6	12.6	0.0	1.0	1.0
PM	12.8	740	40	12.6	12.6	0.0	0.2	0.2
RBT1-West Approach (Downstream)	12.4	587	33	11.4	12.0	0.6	0.4	1.0
AM	12.4	587	33	11.4	12.0	0.6	0.4	1.1
Off	12.4	587	33	11.4	12.0	0.6	0.4	1.0
PM	12.5	587	33	11.4	12.0	0.6	0.5	1.2
RBT2-East Approach (Upstream)	5.3	242	33	5.0	4.5	-0.5	0.8	0.3
AM	5.4	242	33	5.0	4.5	-0.5	0.9	0.4
Off	5.4	242	33	5.0	4.5	-0.5	0.9	0.4
PM	4.7	242	33	5.0	4.5	-0.5	0.2	-0.3
RBT2-East Approach (Downstream)	13.0	580	33	11.9	12.0	0.1	1.0	1.1
AM	13.2	580	33	11.9	12.0	0.1	1.2	1.3
Off	13.0	580	33	11.9	12.0	0.1	1.0	1.1
PM	12.1	580	33	11.9	12.0	0.1	0.1	0.2

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT2-West Approach (Upstream)	12.9	428	33	8.8	10.0	1.2	2.9	4.1
AM	14.8	428	33	8.8	10.0	1.2	4.8	5.9
Off	12.0	428	33	8.8	10.0	1.2	2.0	3.2
PM	10.4	428	33	8.8	10.0	1.2	0.4	1.6
RBT2-West Approach (Downstream)	9.4	423	33	8.1	9.0	0.9	0.4	1.3
AM	9.3	423	33	8.1	9.0	0.9	0.3	1.2
Off	9.6	423	33	8.1	9.0	0.9	0.6	1.4
PM	9.0	423	33	8.1	9.0	0.9	0.0	0.9
RBT3-East Approach (Upstream)	9.4	285	33	5.9	7.0	1.1	2.4	3.5
AM	8.3	285	33	5.9	7.0	1.1	1.3	2.4
Off	10.1	285	33	5.9	7.0	1.1	3.1	4.2
PM	9.8	285	33	5.9	7.0	1.1	2.8	4.0
RBT3-East Approach (Downstream)	9.4	423	33	8.0	9.0	1.0	0.4	1.5
AM	9.6	423	33	8.0	9.0	1.0	0.6	1.6
Off	9.4	423	33	8.0	9.0	1.0	0.4	1.4
PM	9.0	423	33	8.0	9.0	1.0	0.0	1.0
RBT3-West Approach (Upstream)	5.7	250	33	5.2	5.3	0.1	0.4	0.6
AM	5.7	250	33	5.2	5.3	0.1	0.4	0.5
Off	5.8	250	33	5.2	5.3	0.1	0.5	0.7
PM	5.4	250	33	5.2	5.3	0.1	0.1	0.2
RBT3-West Approach (Downstream)	9.1	431	33	8.4	9.0	0.6	0.1	0.7
AM	9.1	431	33	8.4	9.0	0.6	0.1	0.7
Off	9.0	431	33	8.4	9.0	0.6	0.0	0.7
PM	9.0	431	33	8.4	9.0	0.6	0.0	0.6

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT4-East Approach (Upstream)	14.3	643	33	13.3	13.0	-0.3	1.3	1.0
AM	13.4	643	33	13.3	13.0	-0.3	0.4	0.1
Off	14.9	643	33	13.3	13.0	-0.3	1.9	1.6
PM	14.4	643	33	13.3	13.0	-0.3	1.4	1.1
RBT4-East Approach (Downstream)	9.5	421	33	8.6	9.0	0.4	0.5	0.9
AM	9.3	421	33	8.6	9.0	0.4	0.3	0.7
Off	9.5	421	33	8.6	9.0	0.4	0.5	0.9
PM	9.7	421	33	8.6	9.0	0.4	0.7	1.1
RBT4-West Approach (Upstream)	6.5	292	33	6.0	6.0	0.0	0.5	0.5
AM	6.6	292	33	6.0	6.0	0.0	0.6	0.5
Off	6.5	292	33	6.0	6.0	0.0	0.5	0.4
PM	6.4	292	33	6.0	6.0	0.0	0.4	0.3
RBT4-West Approach (Downstream)	18.5	811	33	16.8	18.0	1.2	0.5	1.8
AM	18.5	811	33	16.8	18.0	1.2	0.5	1.8
Off	18.4	811	33	16.8	18.0	1.2	0.4	1.7
PM	19.3	811	33	16.8	18.0	1.2	1.3	2.6
RBT5-East Approach (Upstream)	21.2	794	40	13.5	16.0	2.5	5.2	7.7
AM	17.1	794	40	13.5	16.0	2.5	1.1	3.5
Off	22.9	794	40	13.5	16.0	2.5	6.9	9.4
PM	27.7	794	40	13.5	16.0	2.5	11.7	14.2
RBT5-East Approach (Downstream)	16.2	777	33	14.9	15.5	0.6	0.7	1.4
AM	16.2	777	33	14.9	15.5	0.6	0.7	1.4
Off	16.3	777	33	14.9	15.5	0.6	0.8	1.5
PM	15.8	777	33	14.9	15.5	0.6	0.3	1.0

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT5-West Approach (Upstream)	18.9	577	33	11.9	14.5	2.6	4.4	7.0
AM	18.8	577	33	11.9	14.5	2.6	4.3	6.8
Off	17.4	577	33	11.9	14.5	2.6	2.9	5.4
PM	27.2	577	33	11.9	14.5	2.6	12.7	15.3
RBT5-West Approach (Downstream)	22.8	1130	40	19.3	22.0	2.7	0.8	3.5
AM	22.3	1130	40	19.3	22.0	2.7	0.3	3.1
Off	23.3	1130	40	19.3	22.0	2.7	1.3	4.0
PM	22.1	1130	40	19.3	22.0	2.7	0.1	2.8
RBT6-East Approach (Upstream)	25.8	1352	40	23.0	25.5	2.5	0.3	2.7
AM	25.6	1352	40	23.0	25.5	2.5	0.1	2.5
Off	26.0	1352	40	23.0	25.5	2.5	0.5	2.9
PM	25.7	1352	40	23.0	25.5	2.5	0.2	2.6
RBT6-East Approach (Downstream)	19.3	971	40	16.6	19.0	2.4	0.3	2.7
AM	19.5	971	40	16.6	19.0	2.4	0.5	2.9
Off	19.1	971	40	16.6	19.0	2.4	0.1	2.6
PM	19.6	971	40	16.6	19.0	2.4	0.6	3.0
RBT6-West Approach (Upstream)	18.3	905	40	15.4	17.5	2.1	0.8	2.8
AM	18.5	905	40	15.4	17.5	2.1	1.0	3.1
Off	18.2	905	40	15.4	17.5	2.1	0.7	2.7
PM	17.8	905	40	15.4	17.5	2.1	0.3	2.4
RBT6-West Approach (Downstream)	27.2	1422	40	24.2	26.5	2.3	0.7	2.9
AM	27.5	1422	40	24.2	26.5	2.3	1.0	3.2
Off	26.9	1422	40	24.2	26.5	2.3	0.4	2.7
PM	27.3	1422	40	24.2	26.5	2.3	0.8	3.1

Table 4 Continued

Approach / Time of Day	Average Travel Time (s)	Travel Distance (feet)	Free-Flow Speed (mph)	Free Flow Travel Time (s)	Travel Time Impeded Only by Roundabout Geometry (s)	Geometric Delay (s)	Impeded Delay (s)	Total Delay (s)
RBT7-East Approach (Upstream)	16.3	722	40	12.3	15.0	2.7	1.3	4.0
AM	15.7	722	40	12.3	15.0	2.7	0.7	3.4
Off	16.1	722	40	12.3	15.0	2.7	1.1	3.8
PM	19.2	722	40	12.3	15.0	2.7	4.2	6.9
RBT7-East Approach (Downstream)	24.9	1205	40	20.5	24.5	4.0	0.4	4.3
AM	25.0	1205	40	20.5	24.5	4.0	0.5	4.4
Off	24.8	1205	40	20.5	24.5	4.0	0.3	4.3
PM	25.0	1205	40	20.5	24.5	4.0	0.5	4.4
RBT7-West Approach (Upstream)	21.9	1123	40	19.1	21.0	1.9	0.9	2.8
AM	22.6	1123	40	19.1	21.0	1.9	1.6	3.5
Off	21.6	1123	40	19.1	21.0	1.9	0.6	2.5
PM	21.0	1123	40	19.1	21.0	1.9	0.0	1.9
RBT7-West Approach (Downstream)	12.3	631	40	10.8	11.5	0.7	0.8	1.5
AM	12.7	631	40	10.8	11.5	0.7	1.2	2.0
Off	12.1	631	40	10.8	11.5	0.7	0.6	1.3
PM	11.9	631	40	10.8	11.5	0.7	0.4	1.1

3.3. **Spot-Speed Profiles**

In addition to the travel time data, the team collected cross-sectional speed profiles for the entering and circulating traffic in each direction at roundabouts 1, 5, and 6 (Figure 1). These data were collected using a radar speed gun. These speed profiles will primarily be used to calibrate a midblock running speed model for the roundabout corridor, but they also provide an indication of the safety and performance of the roundabouts. Finally, these speeds provide a more realistic estimation of operating speeds at the roundabouts than do the GPS travel time runs, which were conducted by engineers using the floating car technique. Summary statistics are displayed in Table 4. A total of 30 spot speed measurements were taken at each point. The table also displays a comparison of the midblock speeds with the free flow speeds estimated from the GPS trajectories in Table 4.

Table 5: Spot Speed Summary Statistics

Roundabout	1 - State Farm Blvd							
Point	1	2	3	4	5	6	7	8
Location	EB – exit	EB – circ	EB – enter	EB - midblock	WB – circ	WB - exit	WB - midblock	WB - enter
Average Speed (mph)	27.5	24.1	25.2	40.8	22.1	26.8	37.8	21.5
StdDev (mph)	4.7	4.0	5.1	3.0	3.5	4.5	2.9	3.1
Speed from GPS (Table 4)				44.6			38.4	
Roundabout	5 – US 9							
Point	1	2	3	4	5	6	7	8
Location	WB – exit	WB – circ	WB - midblock	EB - enter	EB - midblock	EB - circ	EB – exit	WB - enter
Average Speed (mph)	23.1	18.6	32.3	18.3	31.4	18.5	25.6	18.3
StdDev (mph)	2.5	2.2	3.2	2.7	4.2	3.1	2.3	3.3
Speed from GPS (Table 4)			38.4		36.8			
Roundabout	6 - Partridge Drum / Fox Wander Rd							
Location	WB – midblock	EB – midblock	WB – exit	WB – circ	WB – enter	EB – circ	EB – exit	EB - enter
Point	1	2	3	4	5	6	7	8
Average Speed (mph)	36.6	37.7	27.2	21.9	19.7	19.4	25.7	19.9
StdDev (mph)	4.5	4.3	3.7	4.5	2.7	3.2	3.4	2.6
Speed from GPS (Table 4)	40.9	40.0						

The speed measurements were also analyzed using histogram frequency distributions—they are displayed in Figures 4, 5, and 6.

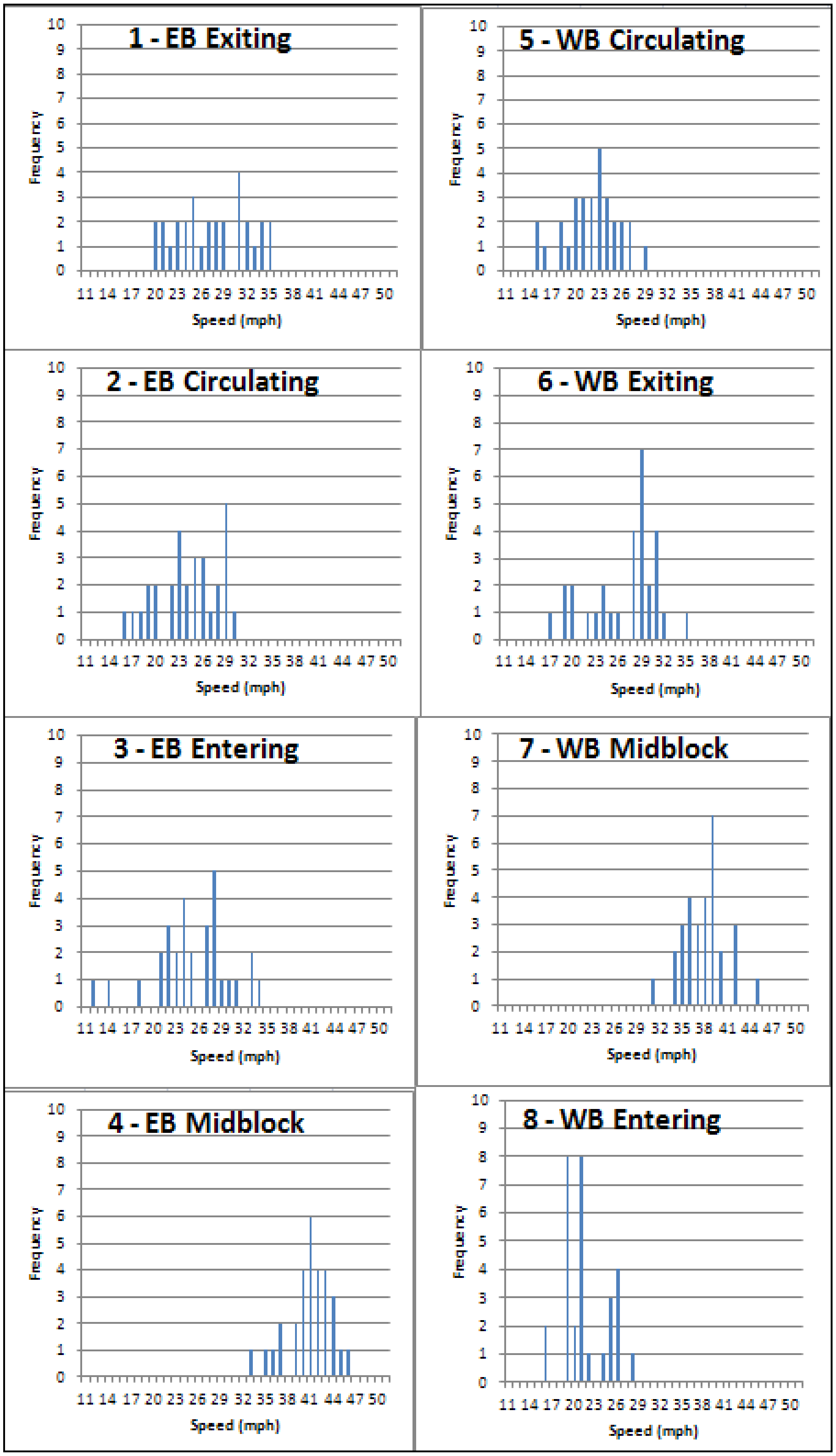

Figure 3: Spot-Speed Histograms for Roundabout 1

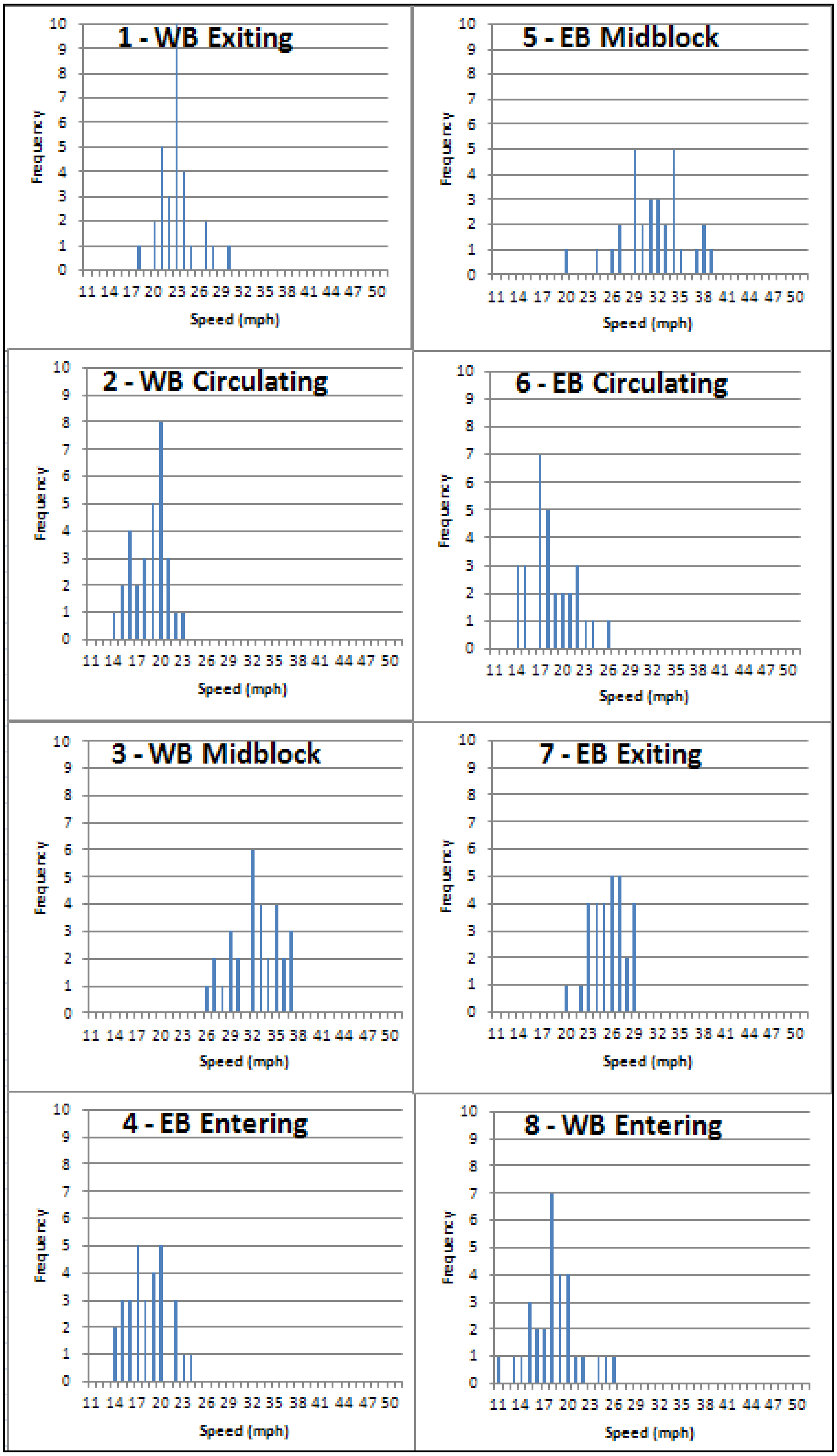

Figure 4: Spot-Speed Histograms for Roundabout 5

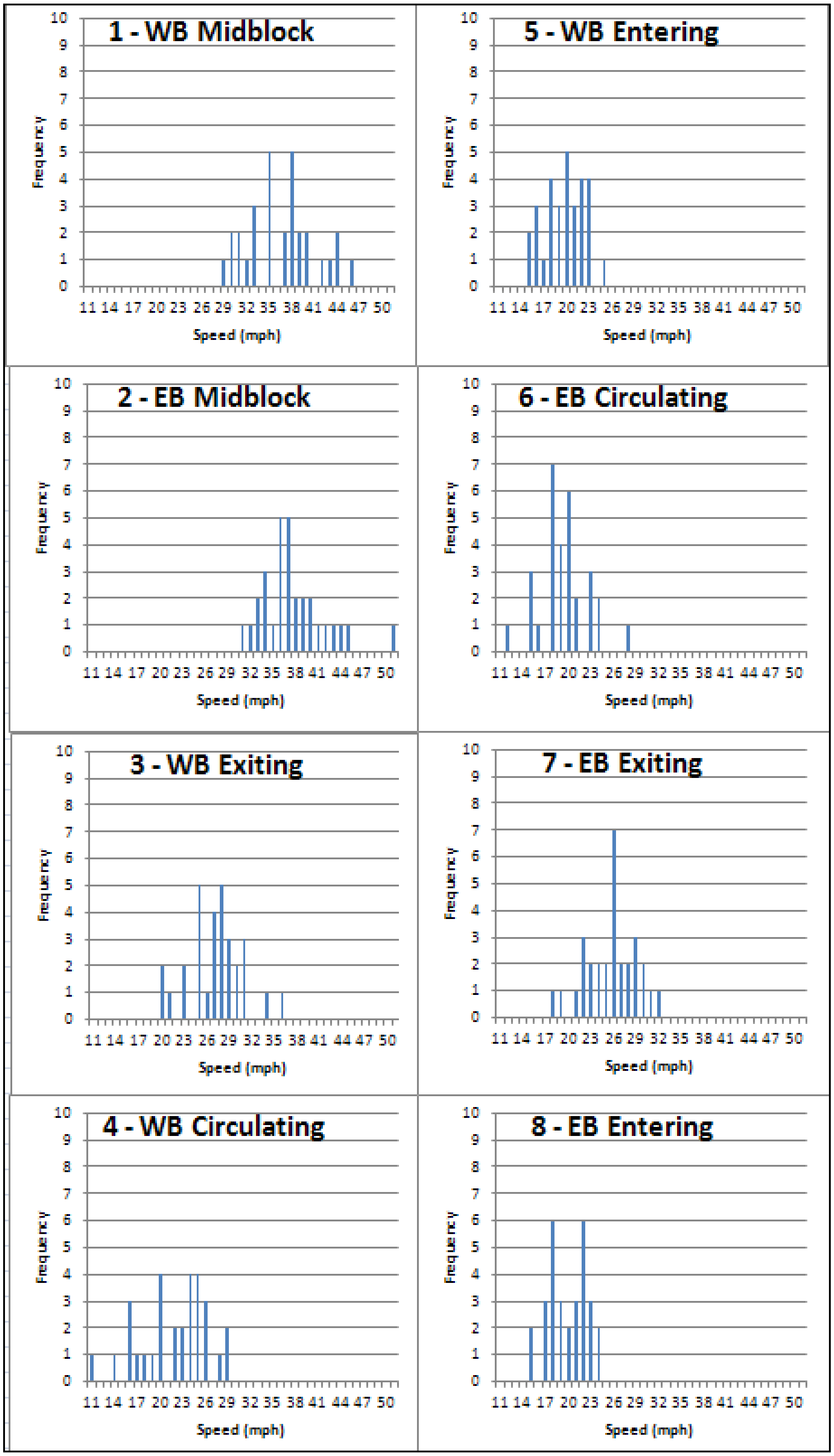

Figure 5: Spot-Speed Histograms for Roundabout 6

4. Appendix

4.1. Appendix J1: Aerial Imagery

Figure B1. SR 67 at State Farm Blvd

Figure B2. SR 67 at I-87 SB

Figure B3. SR 67 at I-87 NB

Figure B4. SR 67 at Kelch Dr

Figure B5. SR 67 at US 9

Figure B6. Dunning St at Partridge Drum

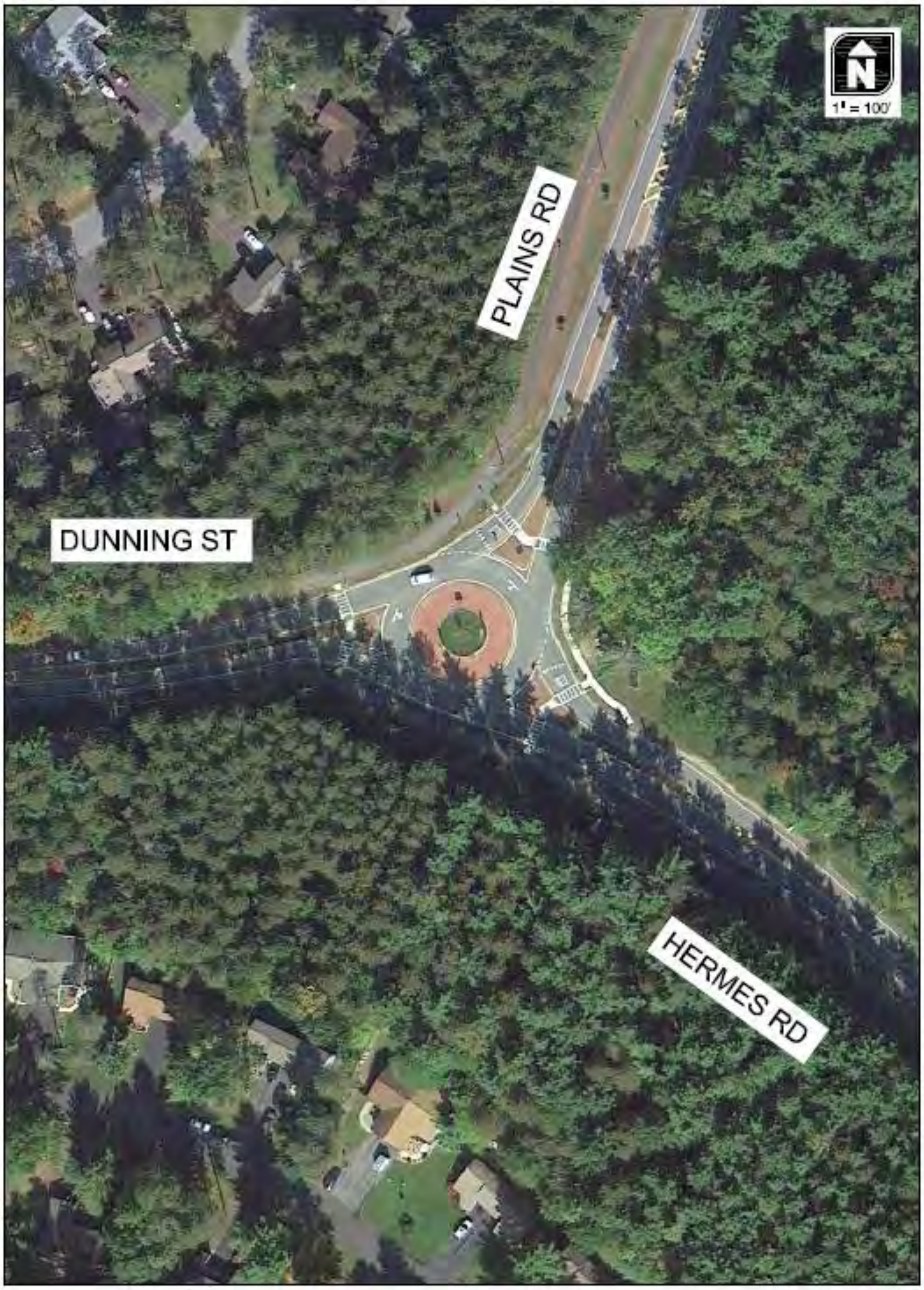

Figure B7. Dunning St at Plains Dr / Hermes Rd

4.2. **Appendix J2: Speed Profiles**

The speed profiles below correspond to the space-time trajectories for each of the six routes in Figures 3A through 3F.

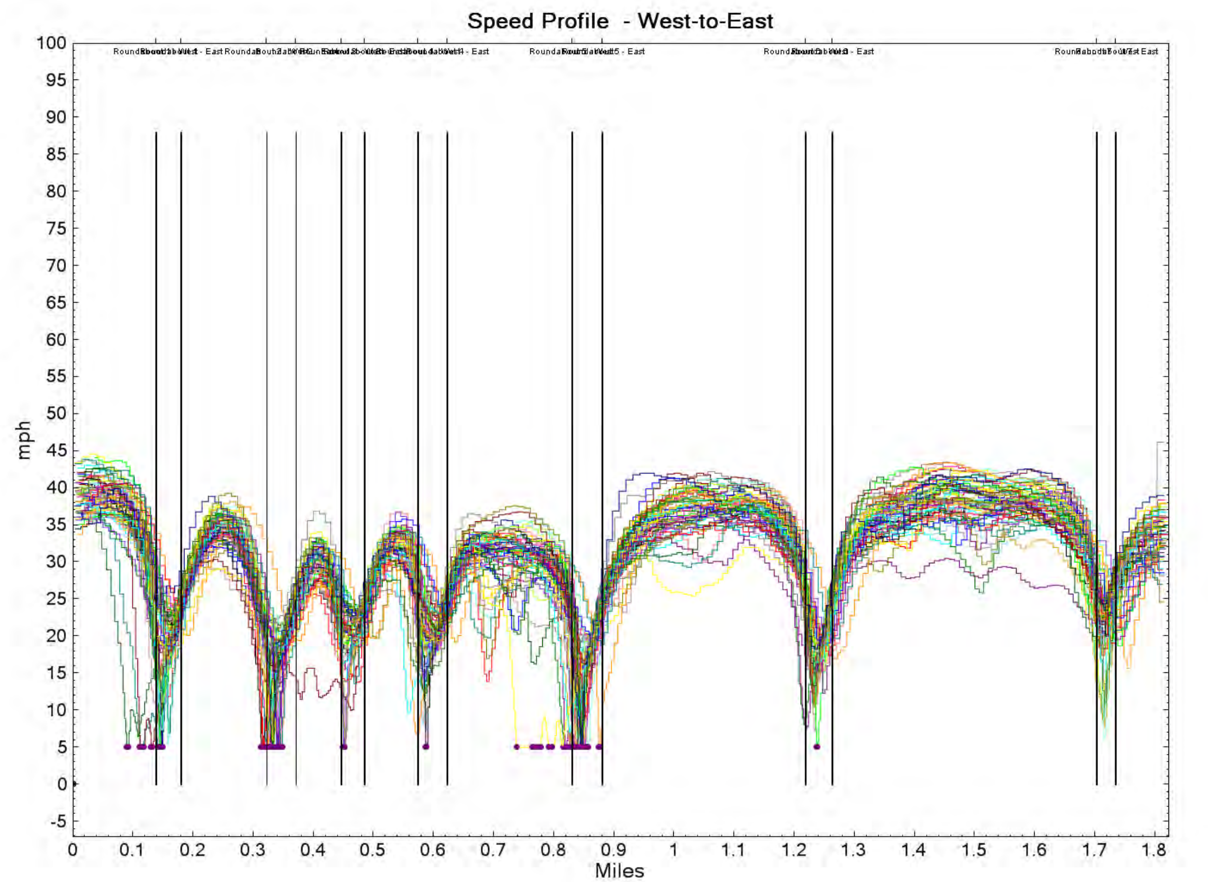

Figure B1. Speed Profile for Route 1 (Eastbound Through the Entire Corridor)

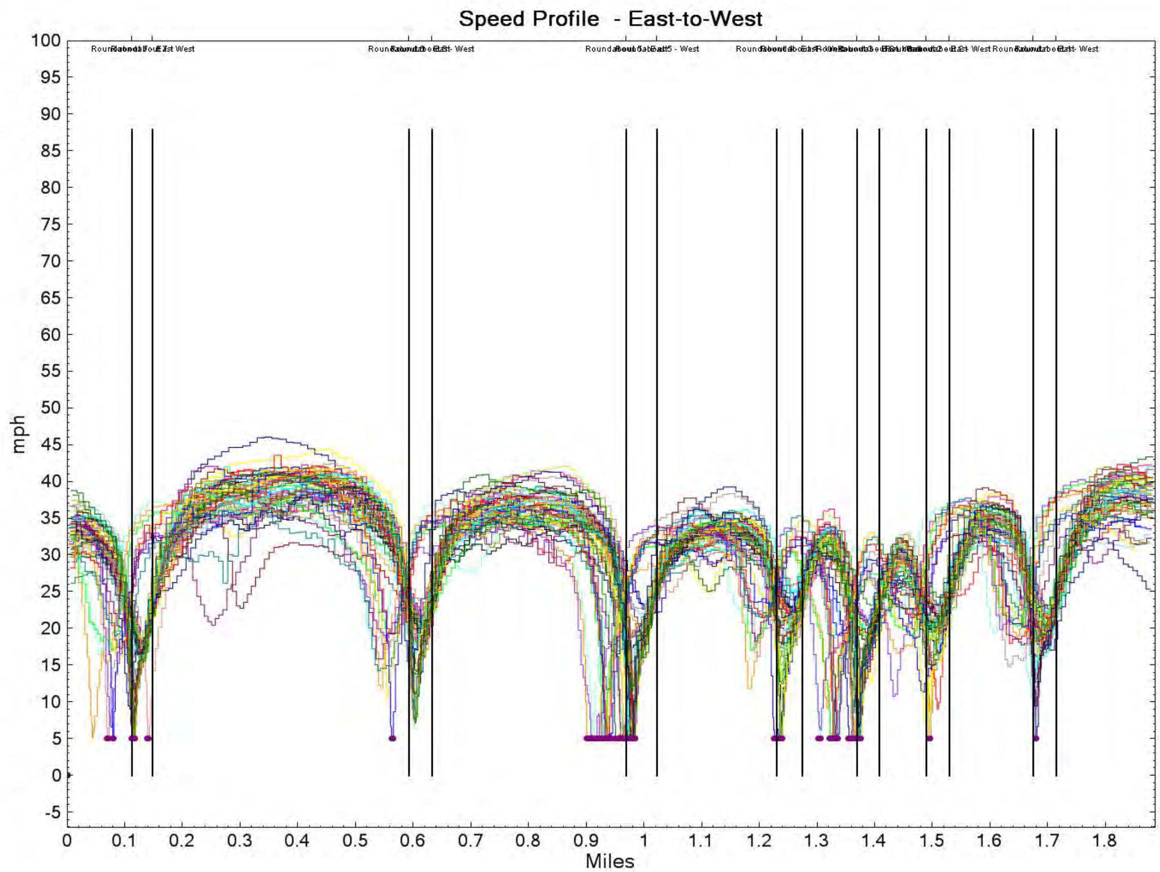

Figure B2. Speed Profile for Route 2 (Westbound Through the Entire Corridor)

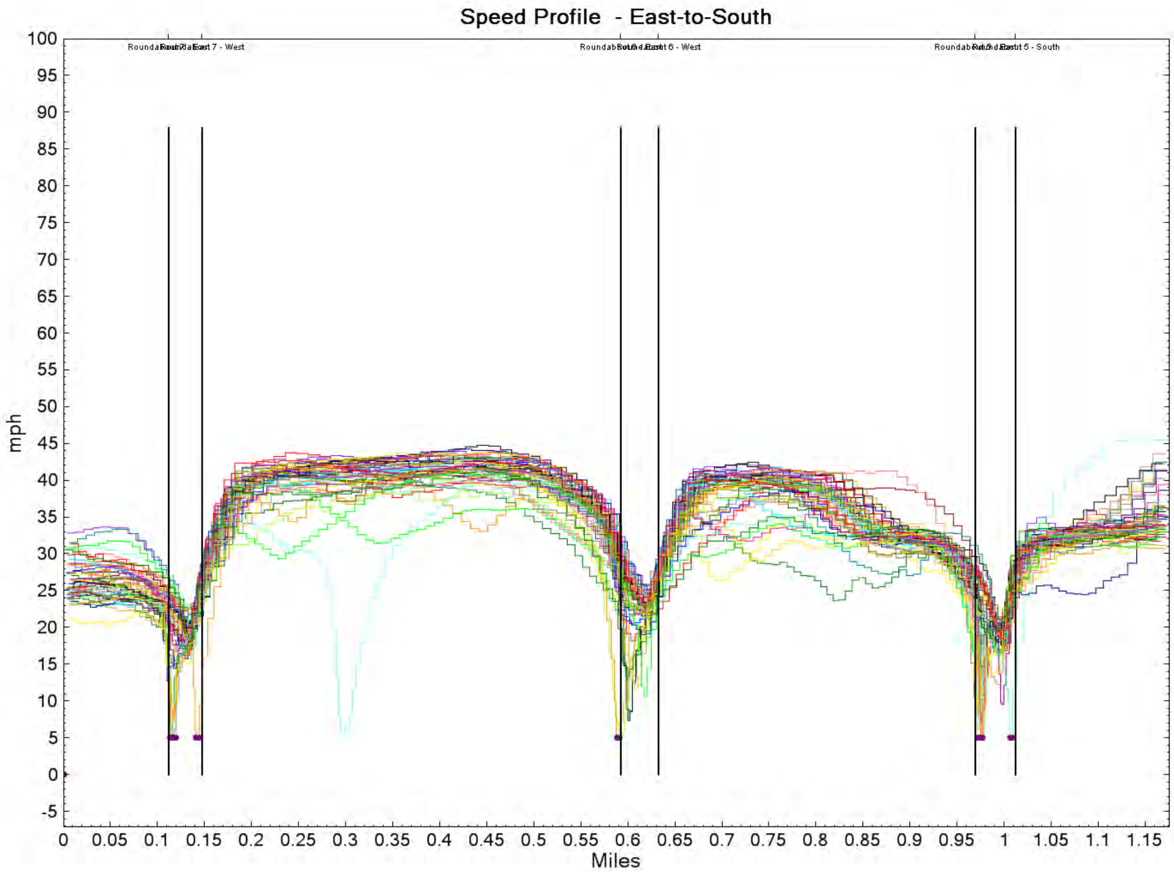

Figure B3. Speed Profile for Route 3 (Beginning East of Roundabout 7, then Turning Left at Roundabout 5)

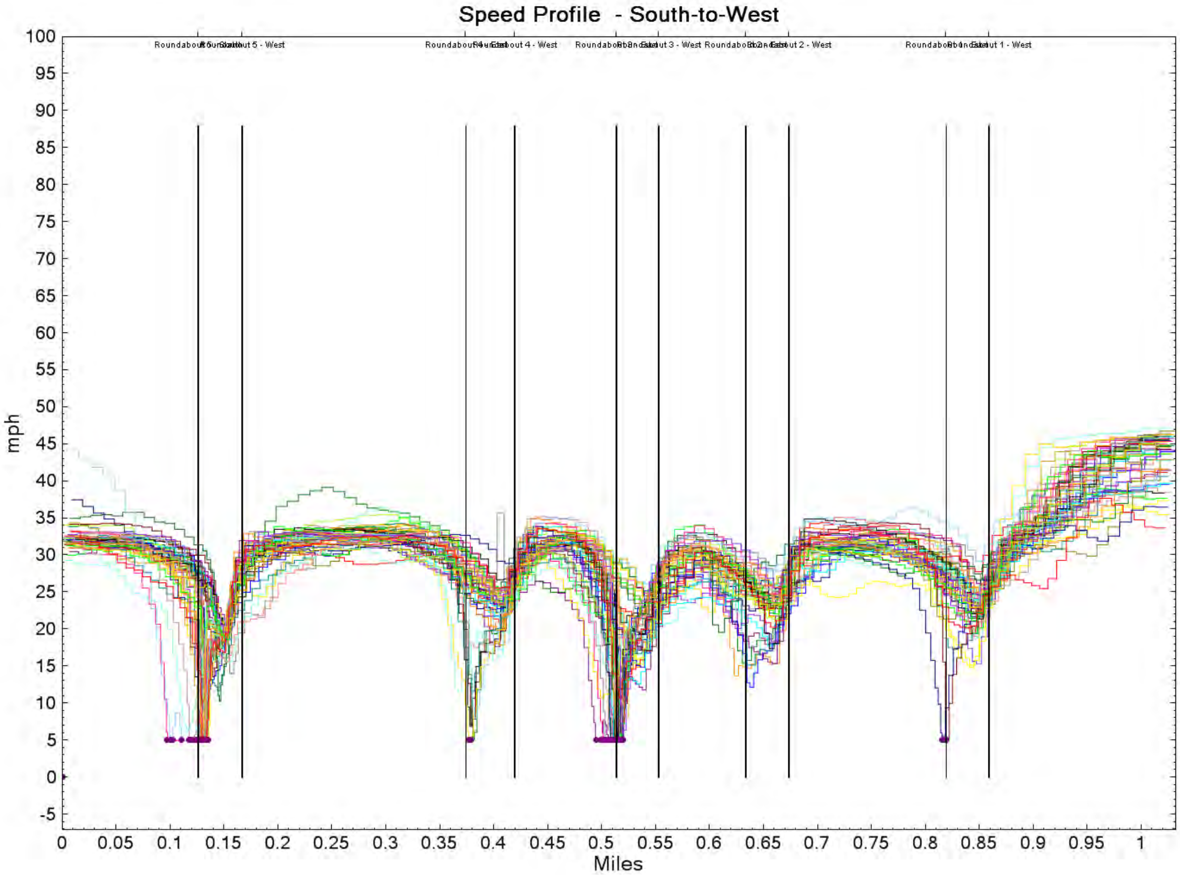

Figure B4. Speed Profile for Route 4 (Beginning South of Roundabout 5, then Turning Left at Roundabout 5)

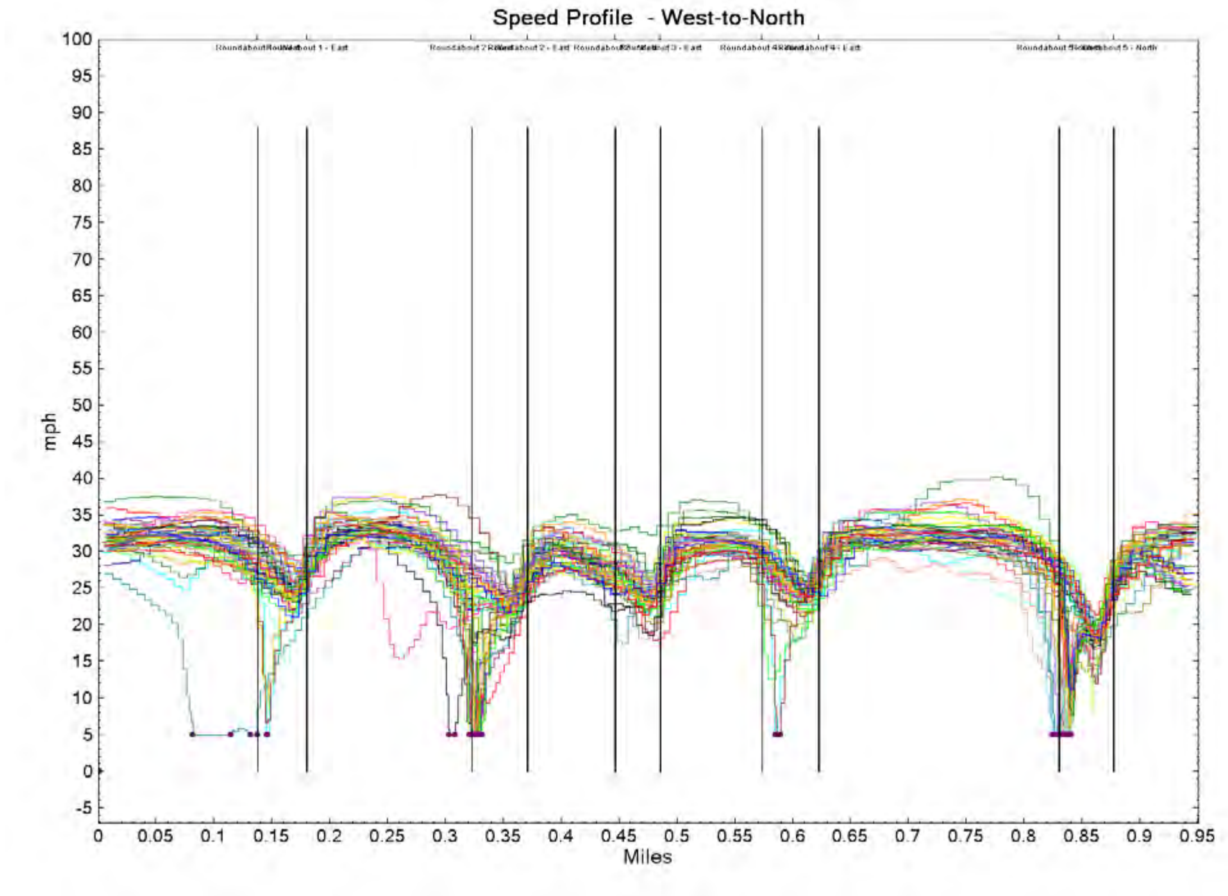

Figure B5. Speed Profile for Route 5 (Beginning West of Roundabout 1, then Turning Left at Roundabout 5)

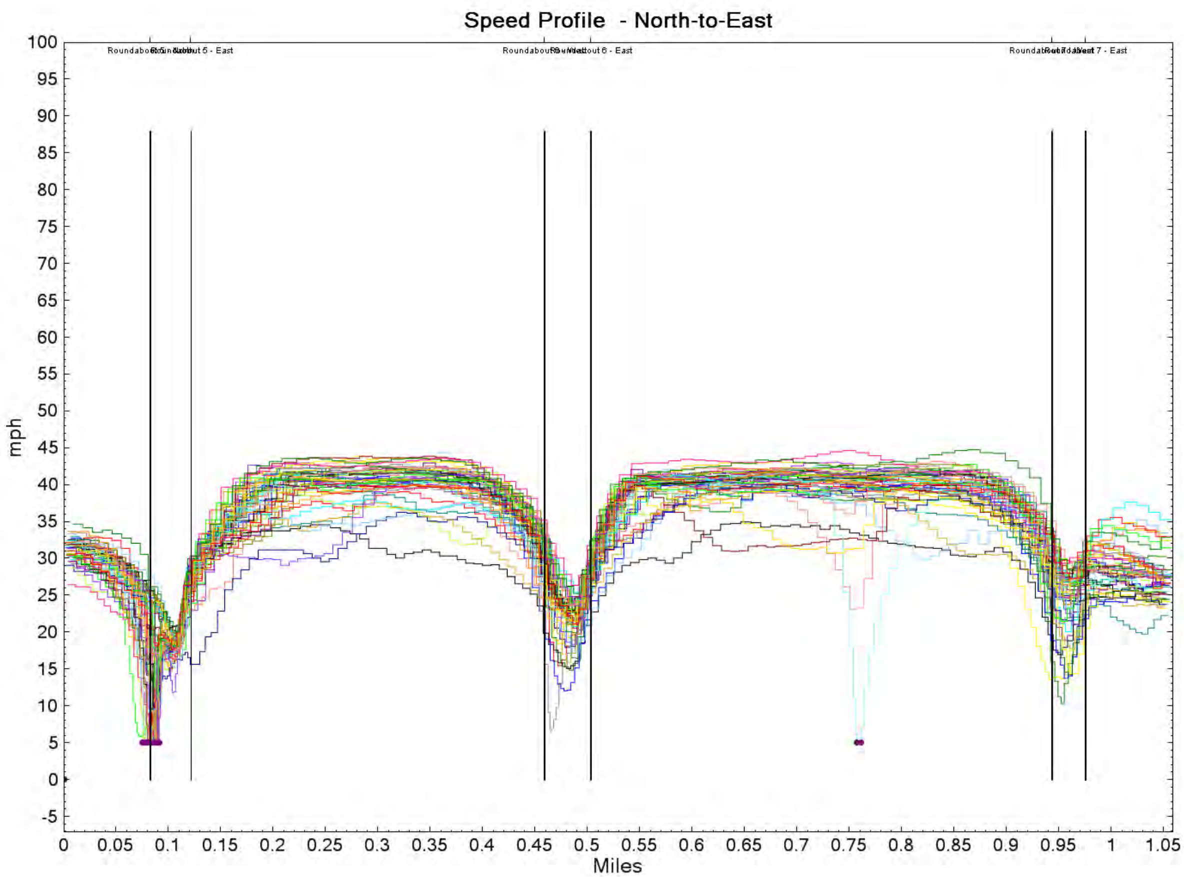

Figure B6. Speed Profile for Route 6 (Beginning North of Roundabout 5, then Turning Left at Roundabout 5)