MEMORANDUM

TO:	Dr. Figliozzi
FROM:	Rohan Sirupa, Jaclyn Schaefer, Curt Petkus, Tinh Vo
DATE:	21March 2019
SUBJECT:	**Corridor Congestion Analysis: I-84 East/West, MP 4.25 – MP 6.70**

1. Background and Context of Study

The purpose of this report is to document and communicate the traffic analysis for Interstate 84 (I-84) eastbound (EB) and westbound (WB) between mileposts (MP) 4.25 and 6.70 in Portland, OR. The location being analyzed is shown in **Figure 1-1** and consists of four detector stations in the eastbound direction and five detector stations in the westbound direction, of which one is located on a ramp from NE Halsey St. The location and associated milepost of each station is shown in **Figure 1-2**. The speed limit in the area of study is 55 mph in both directions. The section of roadway being analyzed runs through the neighborhoods of North Tabor, Montavilla, Madison South, and Gateway, which consist primarily of single-family homes and light to medium density residential and commercial zoning. This report uses the data acquired from the detectors to derive traffic densities, flows, and speeds to compare the segments longitudinally and temporally as well as estimate congestion conditions, shockwave speeds, and travel times. These analyses have been compiled and presented in a graphic format.

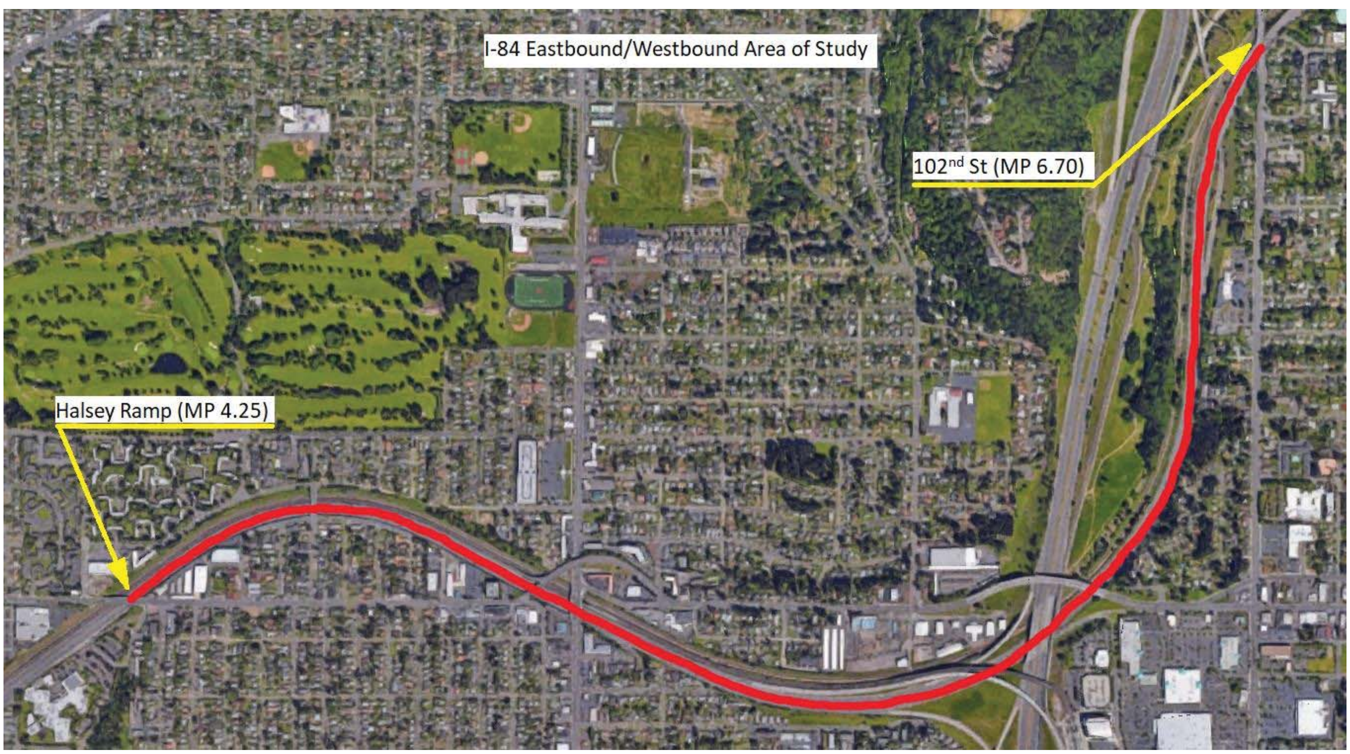

Figure 1-1: Aerial view of I-84 corridor between MP 4.25 and MP 6.70 *(adapted from Google, 2019)*.

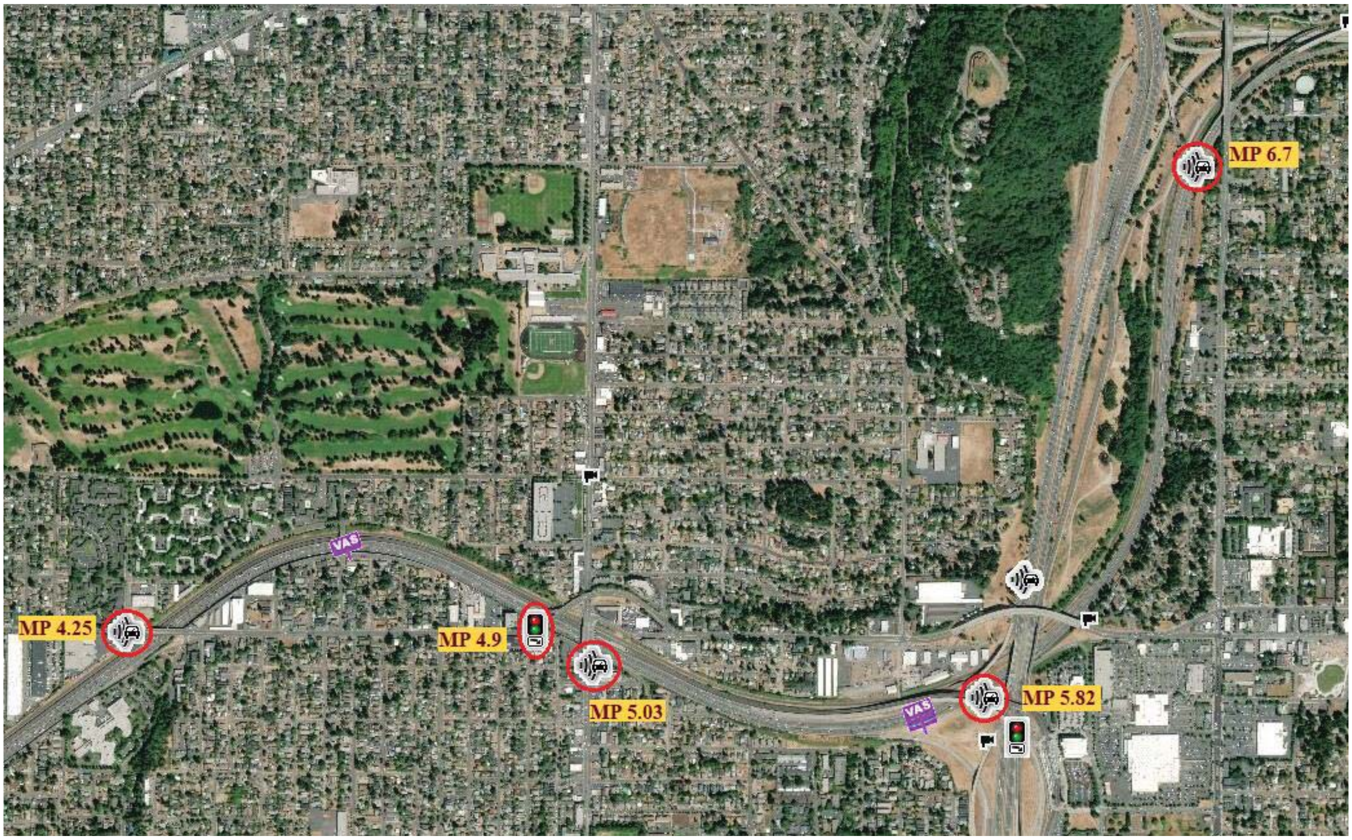

Figure 1-2: Detector locations *(adapted from ODOT, 2019).*

The geometry of the road under study consists of three 12’ lanes running EB, until the I-205 N exit ramp where it drops to two lanes, at approximately MP 6.3. In the WB direction, the road is primarily two 12’ lanes until approximately MP 5.2 where the ramp from I-205 NB joins I-84 WB and the road becomes three lanes. Both directions have a 9’ outside shoulder and a 2’ inside shoulder and are separated by a 4’ concrete jersey barrier. Running adjacent on the north side of I-84 is a MAX line, which crosses over near the I-205 SB/Gateway exit. There are no exit ramps and four entrance ramps in the westbound travel direction of the studied segment. Conversely, there are four exit ramps and no entrance ramps in the eastbound travel direction. These geometric considerations can be seen in the CAD drawing in **Figure 1-3**. Additionally, **Figure 1-4** shows a snapshot of an example of a detector location, utilizing Google Streetview *(Google, 2019).*

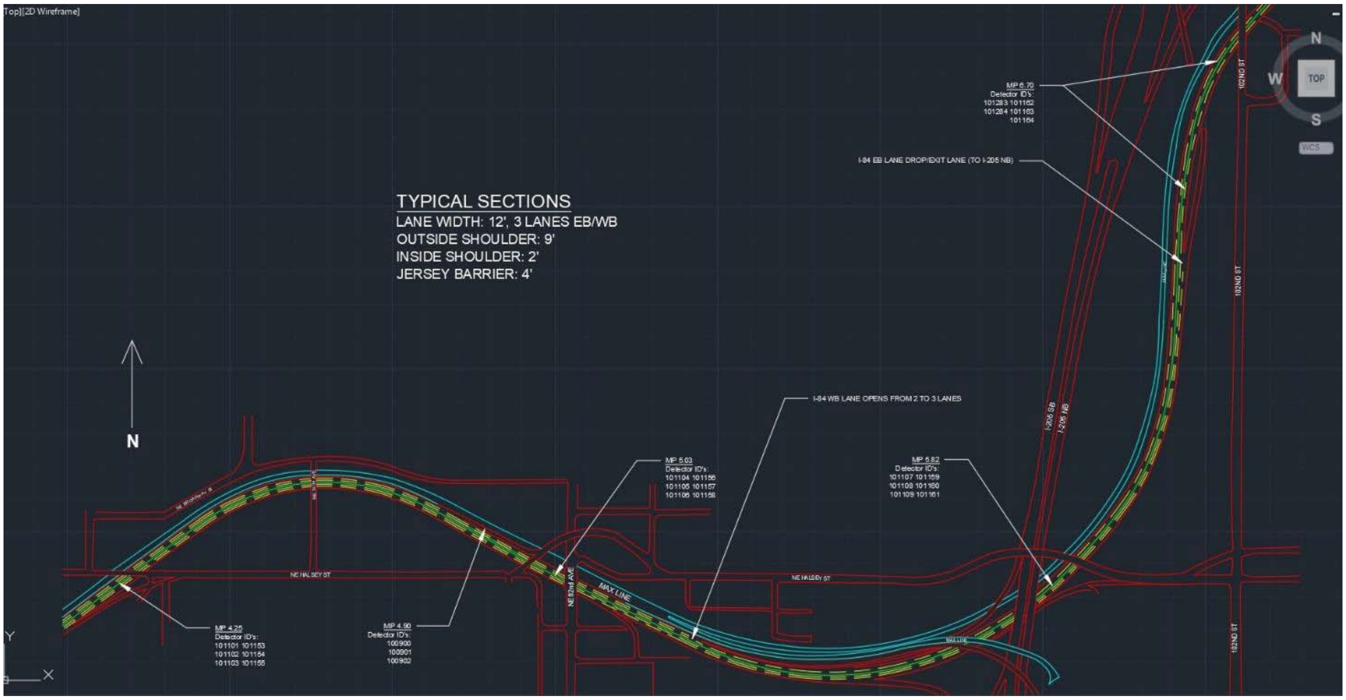

Figure 1-3: Geometric CAD design, marked with detector ID's and Locations

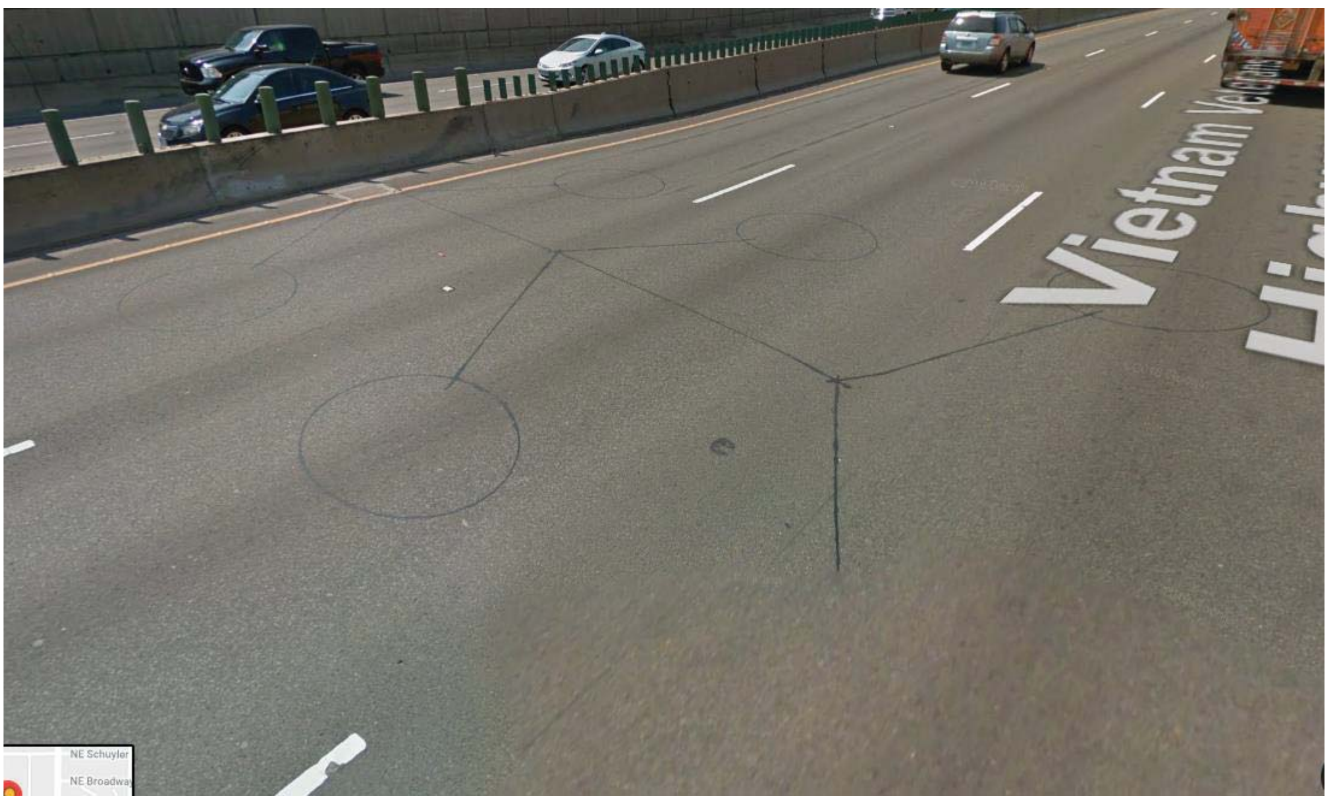

Figure 1-4: Google Streetview *(Google, 2019)* at WB I-84 Halsey Ramp, MP 5.82 (ID's: 101159-101161)

After inspecting and recording the geometric design of the road at locations where the detectors are present, traffic data obtained via Google Maps *(Google, 2019)* were analyzed to show a colored graphical representation of the typical traffic speeds during specific times of the day (**Figure 1-5** and **1-6**). According to Google, on a 55 mph road, green colors represent vehicle speeds greater than 50 mph, orange speeds range between 25 mph and 50 mph, and red represents speeds below 25 mph. The conditions are rated as low congestion, moderate congestion, and heavy congestion, respectively. Google Maps does not supply traffic data between the hours of 22:00 and 06:00. Additionally, Google Maps does not account for weather conditions nor the month of the year so the speeds shown in **Figures 1-5** and **1-6** are averages over a whole year. The colors presented represent the average speeds over the corridor under study (MP 4.25 to MP 6.70).

I-84 EB Traffic (MP 4.25 to MP 6.70)

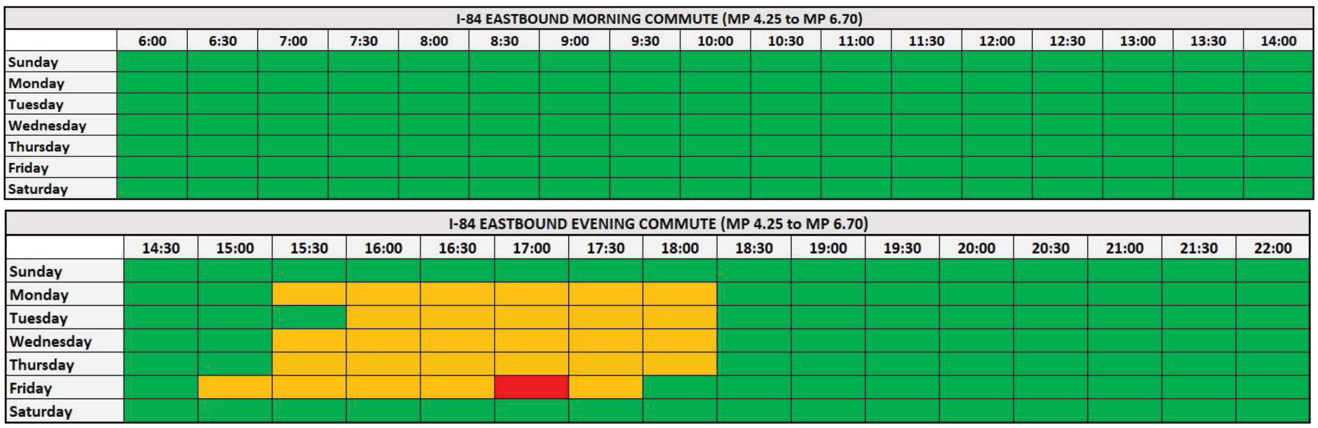

Figure 1-5: Morning and evening commute conditions traveling EB (Weekly, 0600-2200)

I-84 WB Traffic (MP 4.25 to MP 6.70)

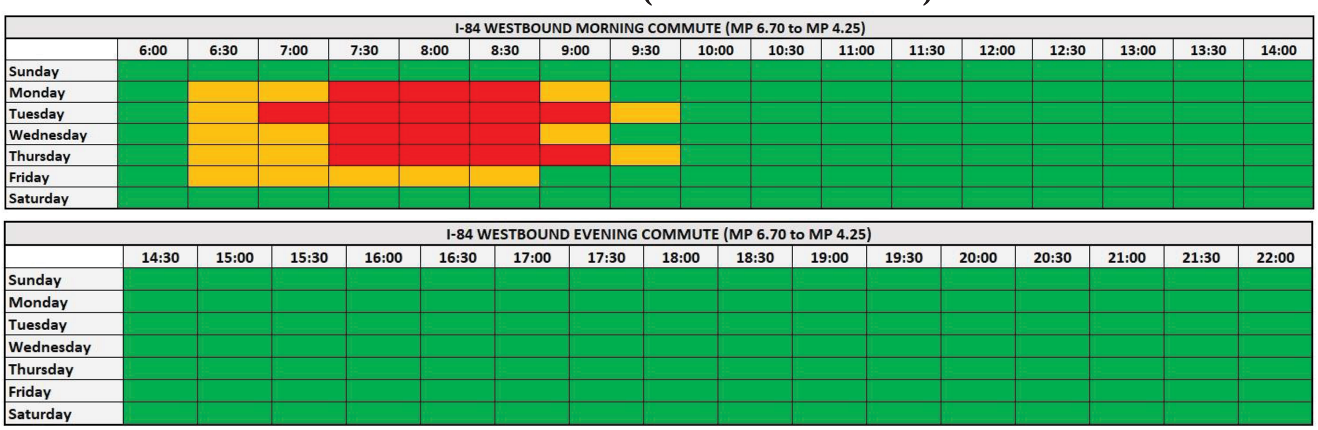

Figure 1-6: Morning and evening commute conditions traveling WB (Weekly, 0600-2200)

Inspection of Figures 1-5 and 1-6 show there is a stark difference in traffic conditions between the eastbound and westbound directions. The westbound traffic appears to experience heavy congestion conditions during the weekday morning peak hours from approximately 7am to 9am while the eastbound traffic experiences only moderate congestion during the evening peak hours from approximately 3:30pm to 6pm. These observations are congruent with expectations as the westbound direction leads into the city center and would see higher traffic volumes in the morning as commuters travel to work whereas the eastbound direction would see higher volumes in the evening as commuters return home. Additionally, it is intuitive that the congestion conditions would be worse in the westbound direction due to the four entrance ramps feeding traffic onto the freeway and zero exit ramps to release traffic as opposed to the eastbound direction's four exit ramps releasing traffic and zero entrance ramps.

2. Data Preparation

The raw data file provided contained 667,247 records and included vehicle count, detector occupancy, and average vehicle speed over 20 second intervals. The raw data was filtered to include only the stations relevant to the segment to be analyzed, of which there were 9. **Table 2-1** shows the stations with corresponding milepost and detector IDs. Flow (q) was calculated as

$$q = {}^{N}\!/_{T}$$

where N is the vehicle count in a given time interval and T is the length of the time interval. Density (k) was calculated as

$$k = \frac{o}{d + l}$$

where o is the detector occupancy, d is the detector length, and l is the vehicle length. For this calculation, we assumed an average detector plus vehicle length to be 22 ft.

Table 2-1: Relevant station and detector information for the segment under study.

Milepost	East Bound		West Bound	
	Station ID	Detectors	Station ID	Detectors
4.25	3131	101101, 101102, 101103	3132	101153, 101154, 101155
4.9	-	-	1059 (Ramp)	100900, 100901, 100902
5.03	3133	101104, 101105, 101106	3134	101156, 101157, 101158
5.82	3135	101107, 101108, 101109	3136	101159, 101160, 101161
6.7	3137	101283, 101284	3138	101162, 101163, 101164

The data cleaning in this project is primarily based on the concept of Minimum Occupancy which a vehicle needs to have when it travels at a certain speed. When a single vehicle passes over the detector at a specific speed, it has a fixed on-time and the ratio of this on-time to the time-period is considered as the Minimum Occupancy for that specific speed. The formula given below is used to calculate minimum occupancy.

$$Min.\ Occupancy = \frac{d + l}{v} * \frac{1}{T}$$

For this project, the time period of the data is 20 seconds and the average vehicle length plus detector width is assumed to be 22 ft. **Figure 2-1** shows the relation between the speed and minimum occupancy; all the data points which fall below or to the left of this red line are assumed to be outliers. The data cleaning using this concept of minimum occupancy also cleared the null recordings from the raw data, along with other abnormal recordings, such as the recordings where both the speed and density are less.

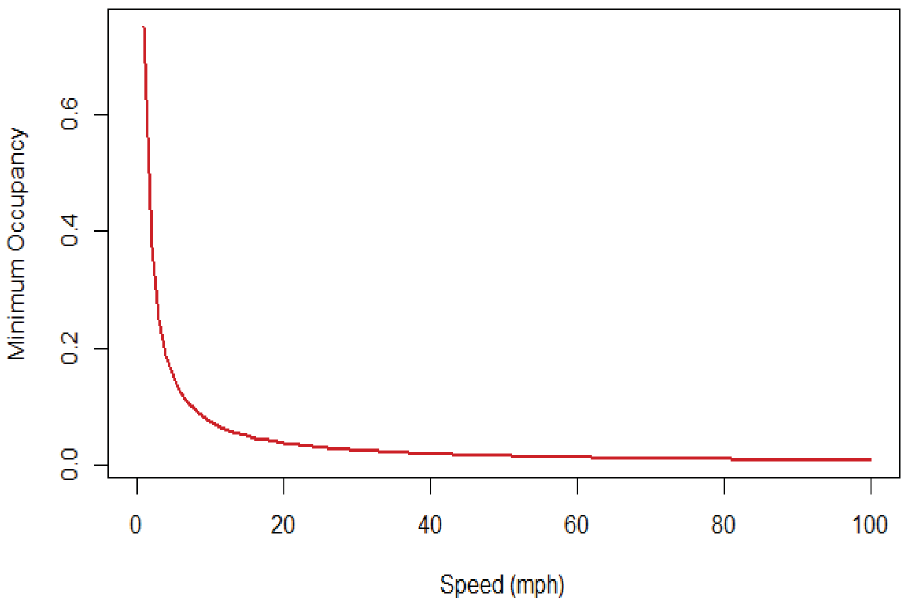

Figure 2-1: A plot of the function relating minimum occupancy to vehicle speed.

Once data points not meeting the preceding condition were eliminated, a speed threshold was set at 100 mph and all data points with speeds above 100 mph were also flagged for removal. The speed threshold was considered based on the corridor's speed limit and the number of high-speed data points. The clean data contained a total of 552,621 records. Approximately 17% of the raw data was eliminated from the analysis. It should be noted that one of the expected detectors in the eastbound direction (based on the metadata) was absent from the raw data, possibly due to construction interruption or service not yet initiated, and one of the detectors in the westbound direction contained nothing but null sets at a station where it appears there are only two lanes and the null-set detector would be a third. As such, all corresponding records were eliminated. Speed-density and flow-density plots of the raw data along with the eliminated data can be seen in **Figures 2-2** and **2-3**.

Once the outliers were removed, speed-density and flow density plots for each detector and station were created to compare differences between directions, stations, and lanes. **Figures 2-4** through **2-7** show examples of these plots on a station level with the left side corresponding to the left-most travel lane and are placed on the page such that the bottom plot is the upstream station to give a visual of how traffic conditions change in the direction of traffic flow.

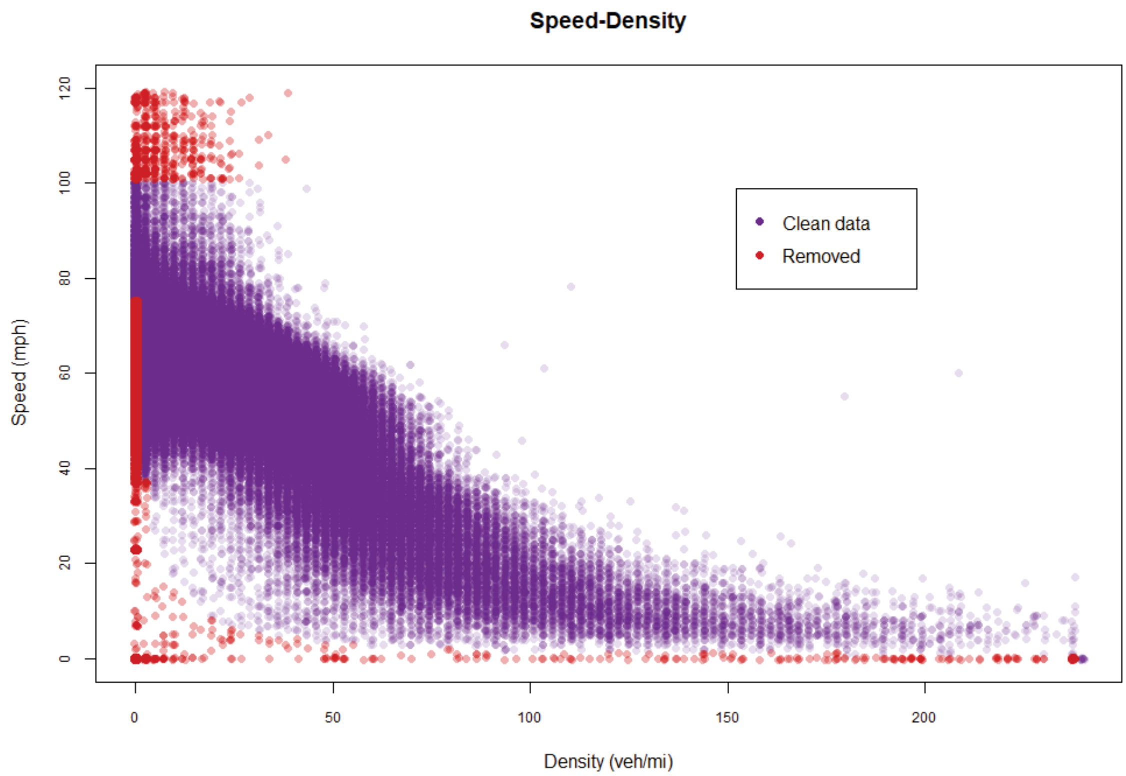

Figure 2-2: Speed-density plot of raw data showing eliminated outliers in red.

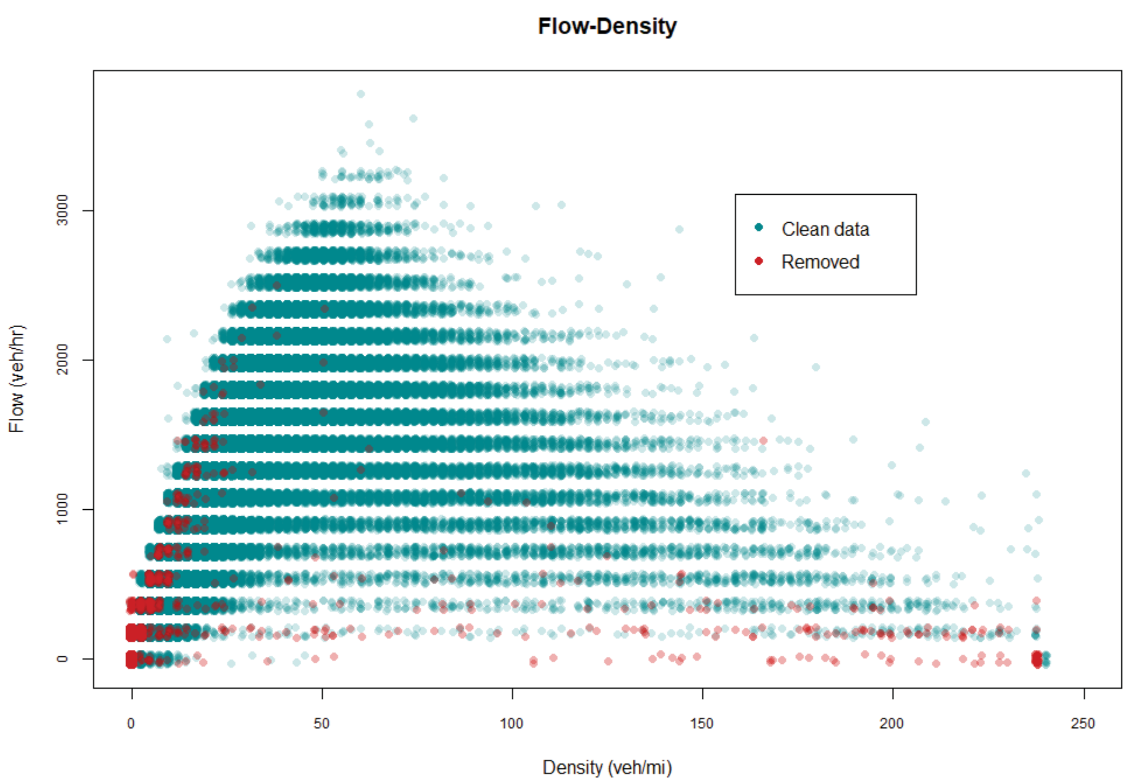

Figure 2-3: Flow-density plot of raw data showing outliers in red.

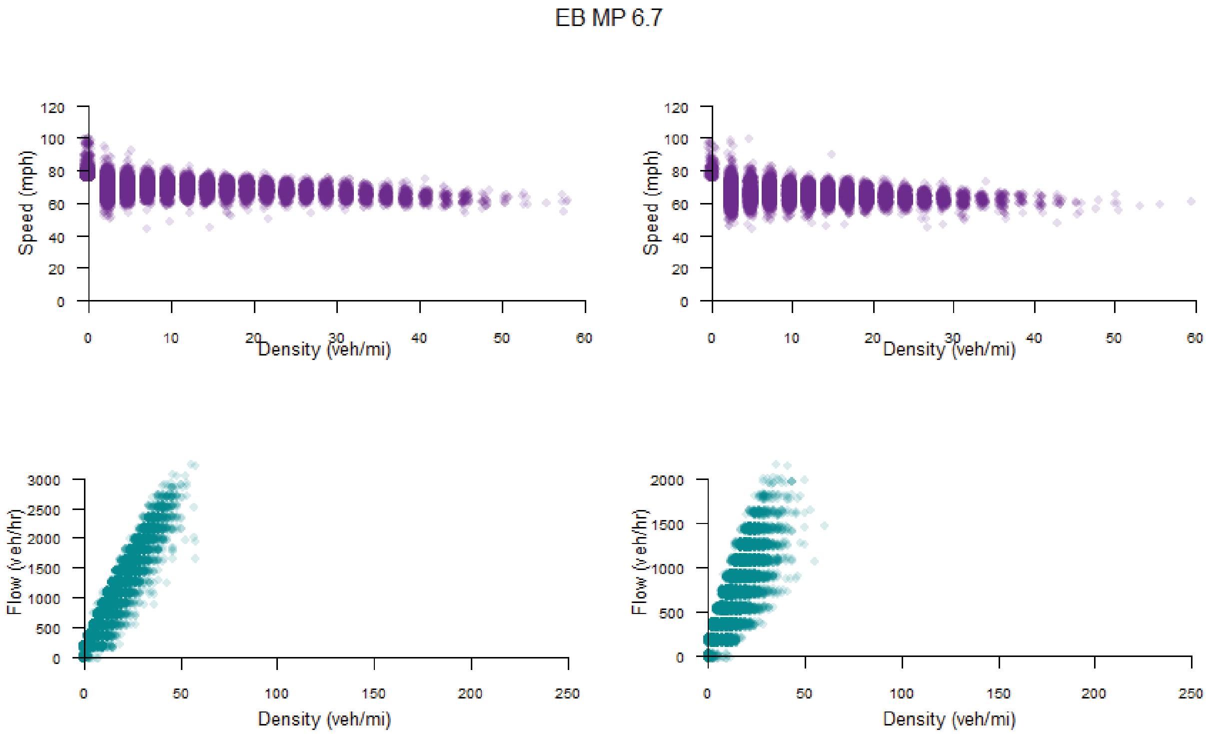

Figure 2-4: Speed-density and flow-density plots for MP 6.7 in the eastbound direction.

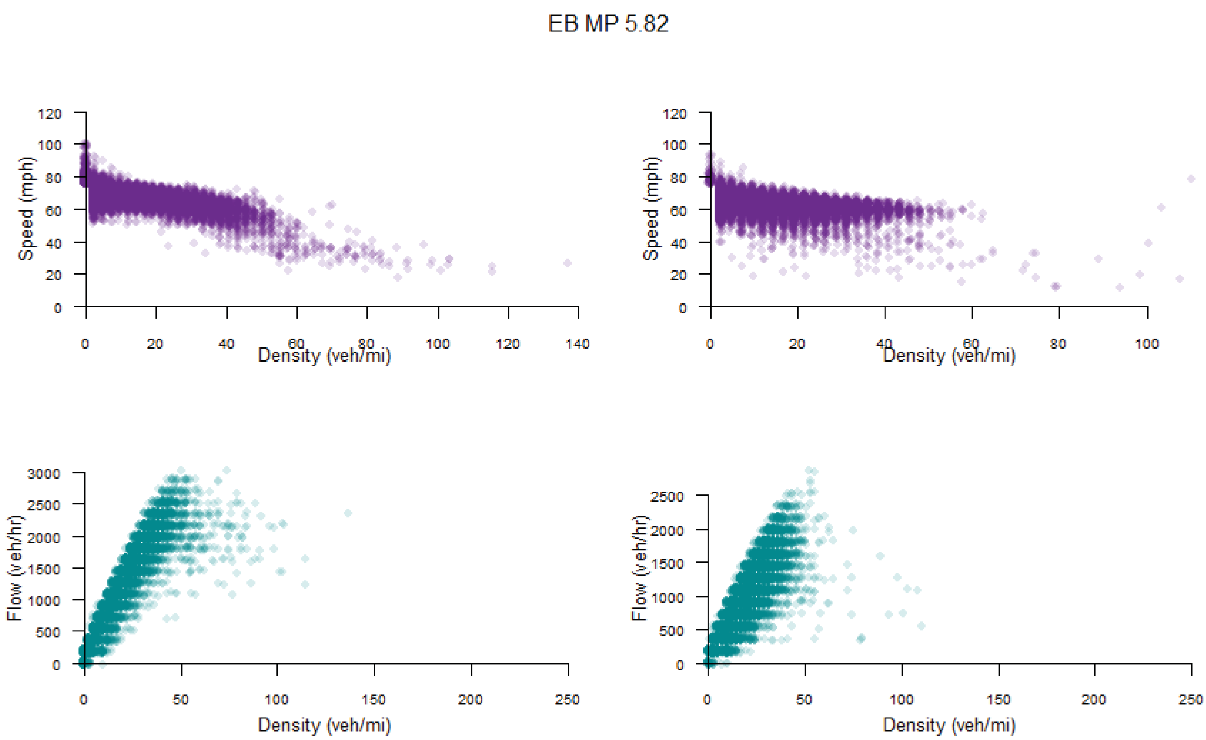

Figure 2-5: Speed-density and flow-density plots for MP 5.82 in the eastbound direction.

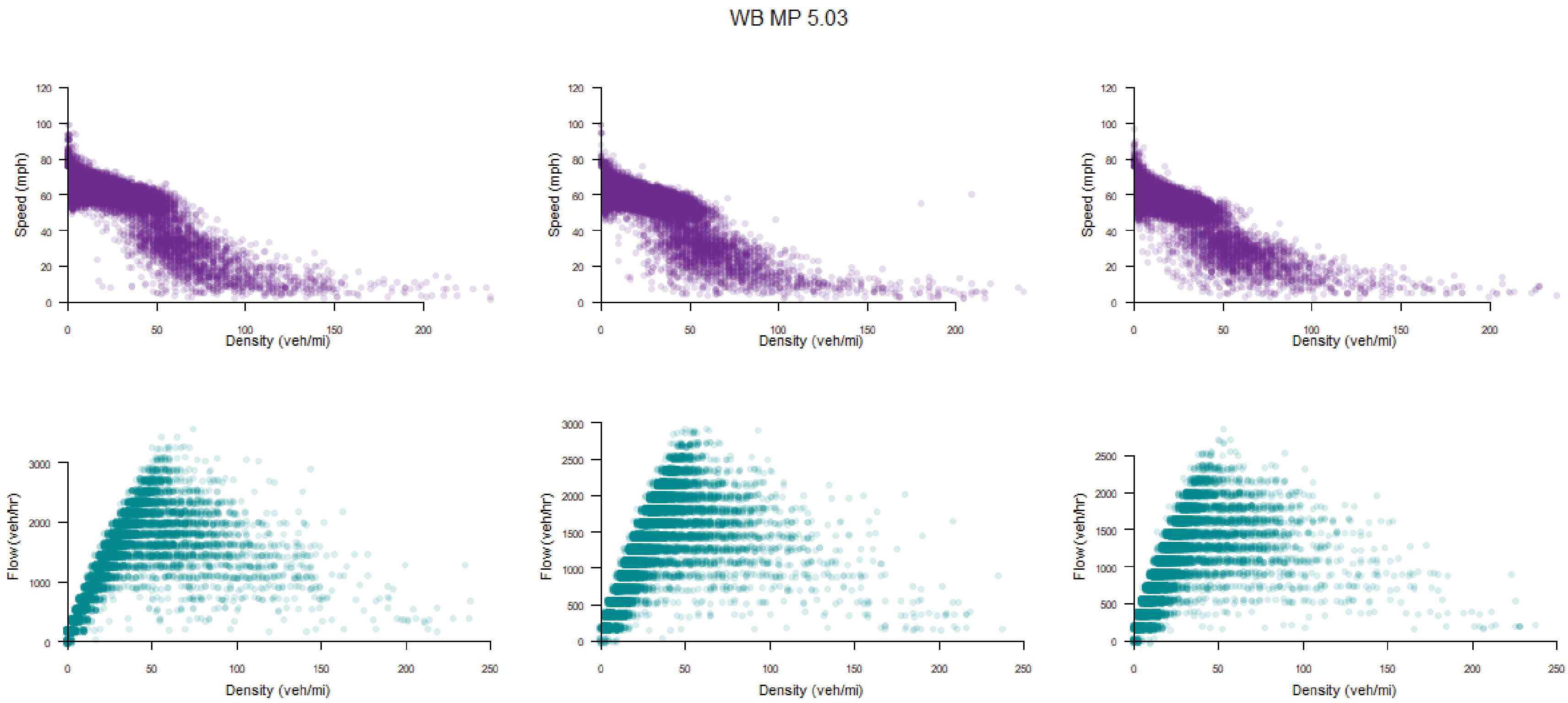

Figure 2-6: Speed-density and flow-density plots for MP 5.03 in the westbound direction.

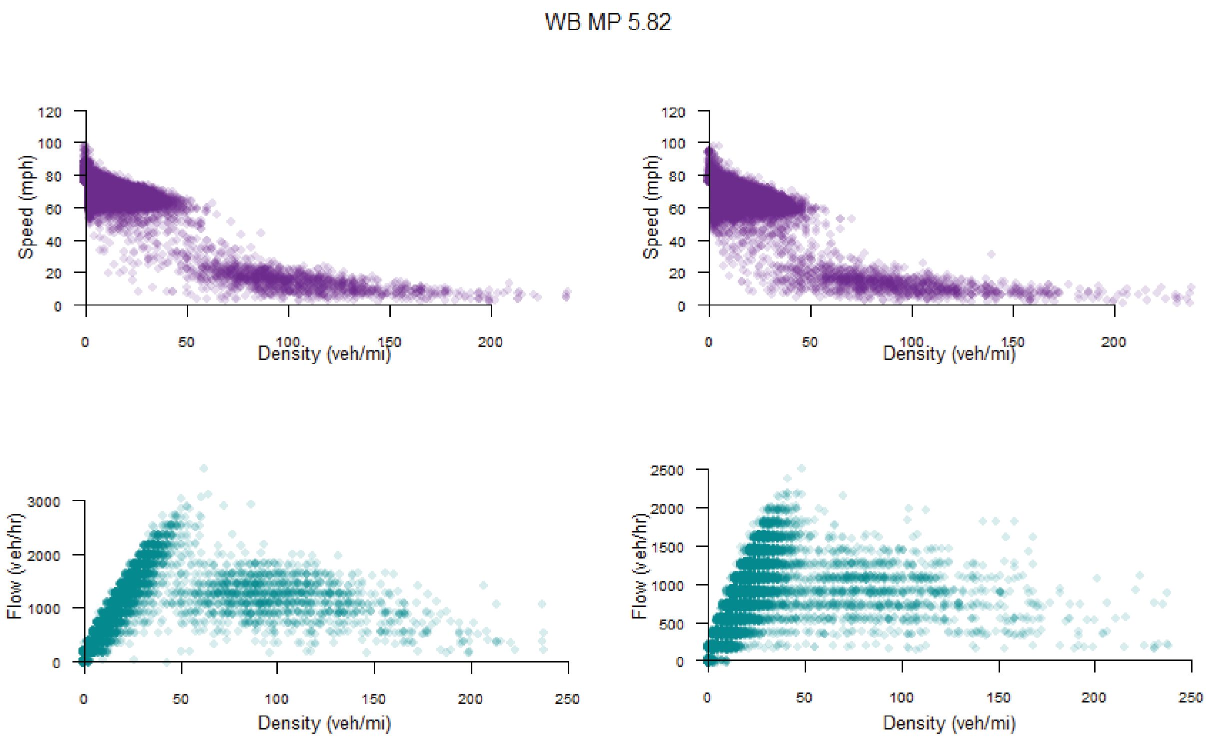

Figure 2-7: Speed-density and flow-density plots for MP 5.82 in the westbound direction.

From **Figures 2-4** and **2-5**, it can be seen that traffic density is decreasing as it moves in the downstream direction, and there is little to no indication of congestion occurring, particularly at MP 6.7. The left and right lane conditions appear to be fairly homogeneous with the left lane experiencing slightly higher densities, possibly due to the high number of vehicles exiting the freeway from the right lane.

Figures 2-6 and **2-7** show the traffic density is increasing as it moves in the downstream direction, and it can also be seen that congestion conditions worsen as traffic travels downstream. Again, this is likely due to the number of entrance ramps and lack of exit ramps in the westbound direction. Between these mileposts is an entrance ramp from I-205 NB that handles a high number of vehicles per day, so although a third lane is present at MP 5.03, it does not help reduce traffic density. The right lane appears to experience very slightly higher densities than the left-most lanes.

The observations made regarding **Figures 2-4** through **2-7** highlight the general trend in traffic density changes for the eastbound and westbound directions.

3. Fundamental Diagram

To estimate free-flow speeds and jam densities for each detector and location, the speed and flow variabilities were calculated and plotted as a function of density. The approximate density at which the first sudden increase in variability was seen was chosen as the critical density. Using this point and linear regression, triangular fundamental diagrams were constructed. Free flow speed was calculated as the slope of the uncongested regime's regression line and jam density was estimated as the maximum density where flow is equal to zero, theoretically corresponding to the x-intercept of the congested regime's regression line. **Figures 3-1** through **3-4** show examples of speed variance and flow variance plots for one detector of each the eastbound and westbound directions.

Figures 3-1 and **3-2** show a typical detector in the eastbound direction. There does not appear to be any evidence of congestion conditions occurring at this location based on these plots as there is relatively little variance in speed or flow. This was the general observation for all eastbound detectors.

Figures 3-3 and **3-4** show a typical westbound detector. From the plots it can be seen that the variance begins rapidly increasing just below a density of 50 veh/mi. This is the estimated critical density where a regime change occurs and congestion begins.

Figures 3-5 through **3-8** show examples of the triangular fundamental diagrams for one detector of each the eastbound and westbound directions**. Figures 3-5** and **3-6** show there is no congestion conditions for a typical eastbound detector. **Figures 3-7** and **3-8** show the approximate density where the regime change occurs for a typical westbound detector.

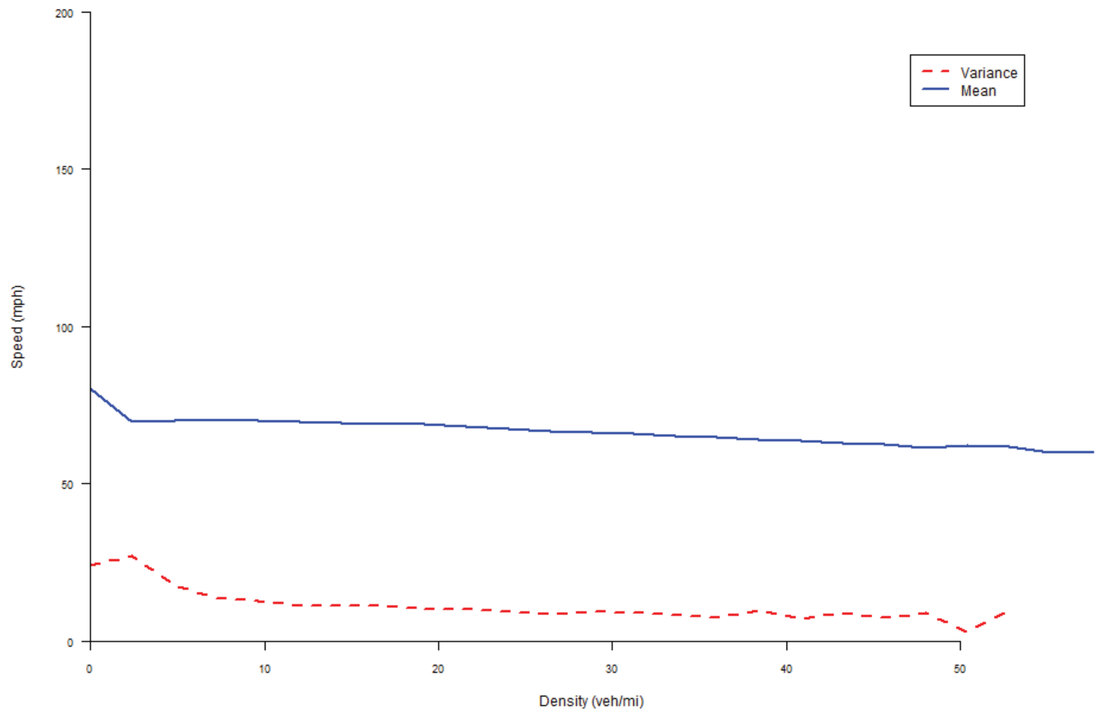

Figure 3-1: Speed variance as a function of density for a typical eastbound detector.

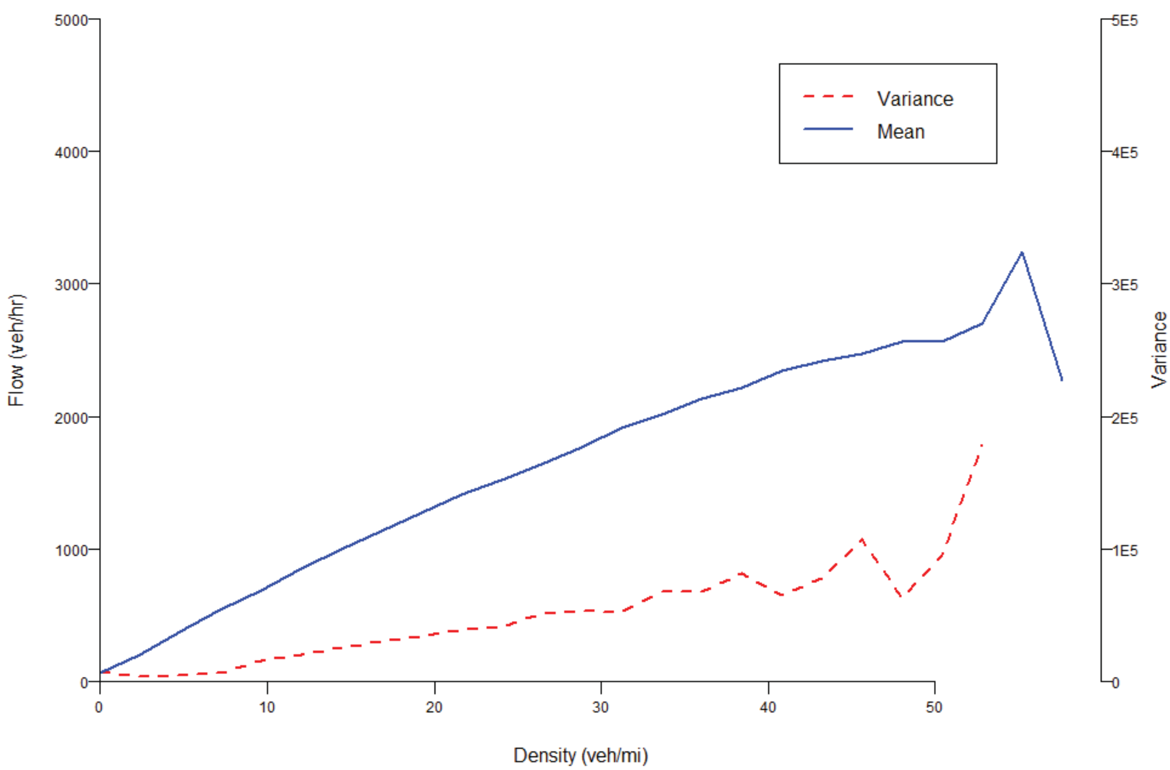

Figure 3-2: Flow variance as a function of density for a typical eastbound detector.

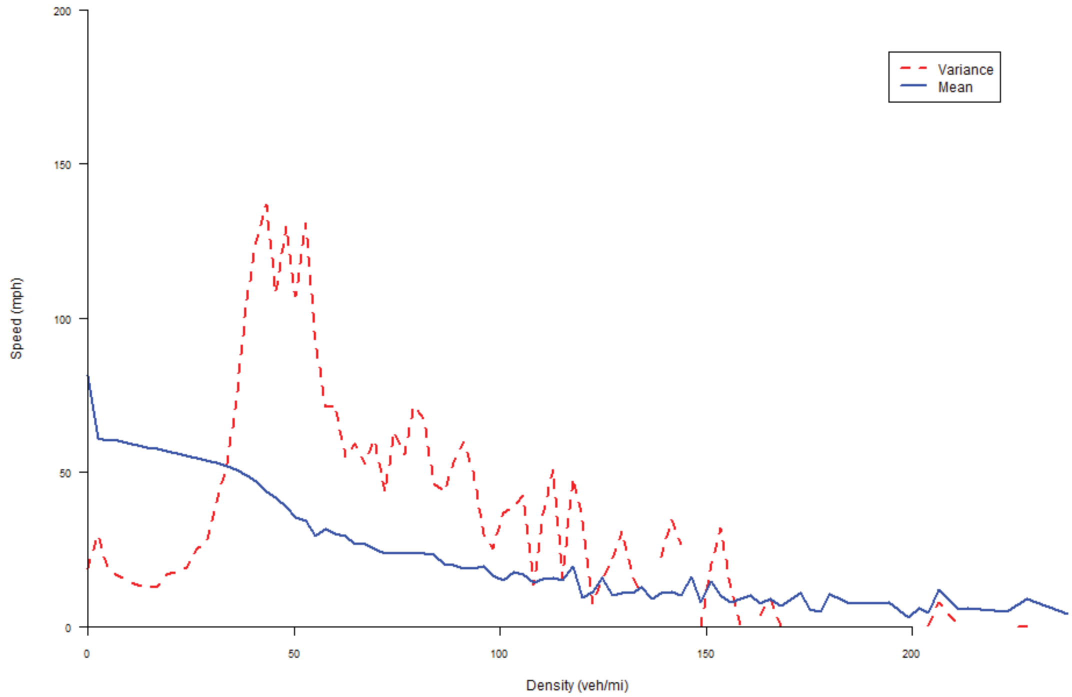

Figure 3-3: Speed variance as a function of density for a typical westbound detector.

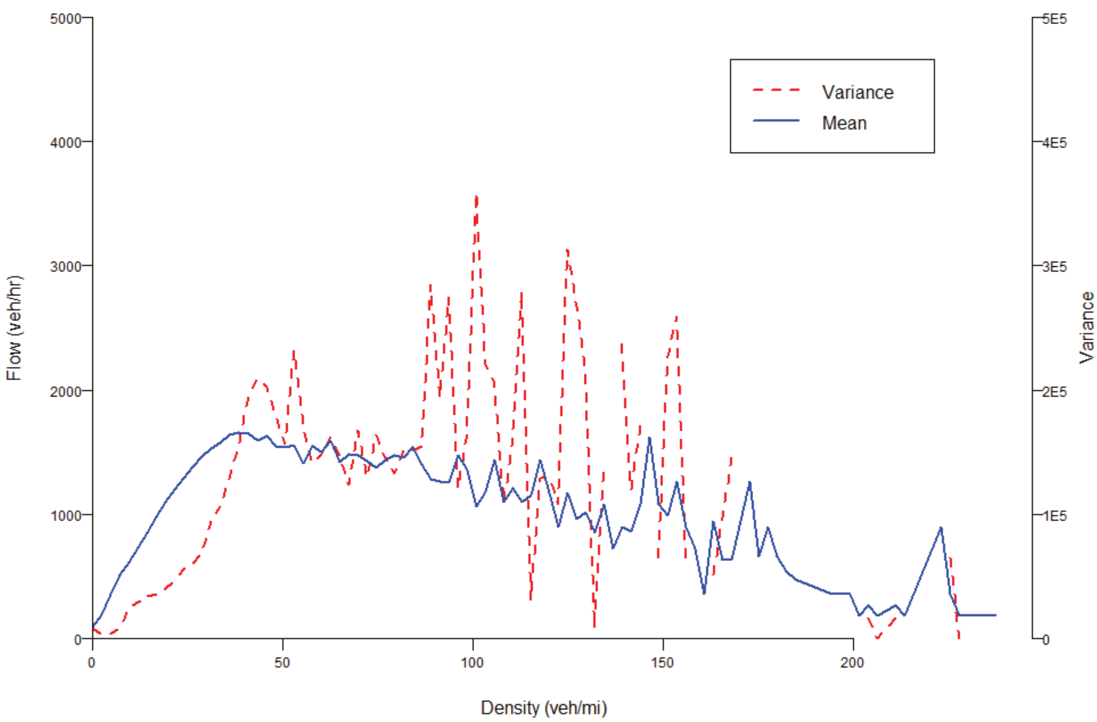

Figure 3-4: Flow variance as a function of density for a typical westbound detector.

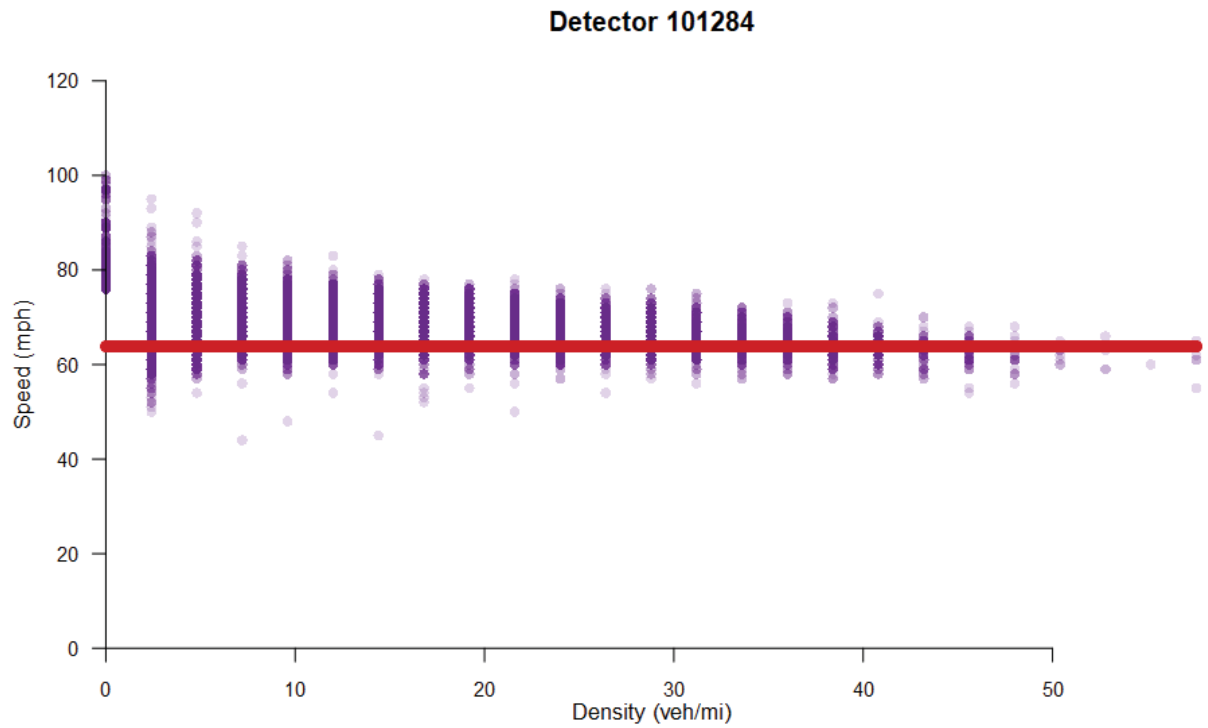

Figure 3-5: Speed fundamental diagram for a typical eastbound detector.

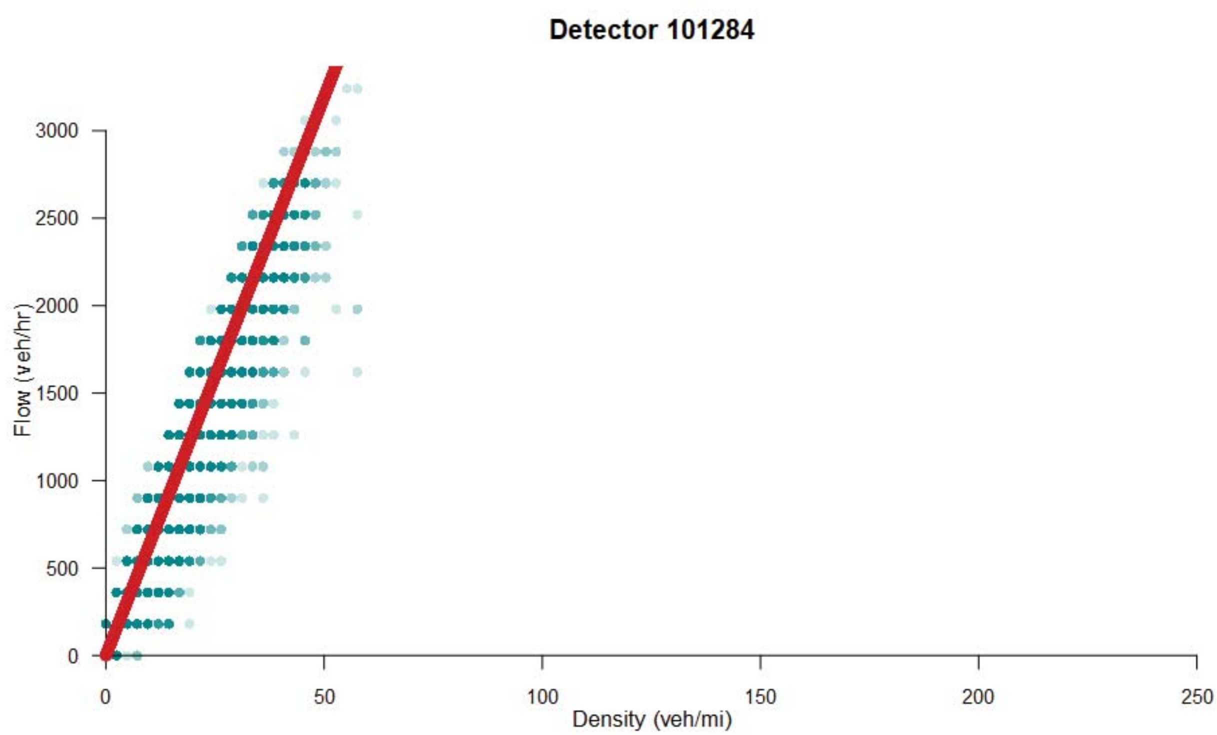

Figure 3-6: Flow fundamental diagram for a typical eastbound detector.

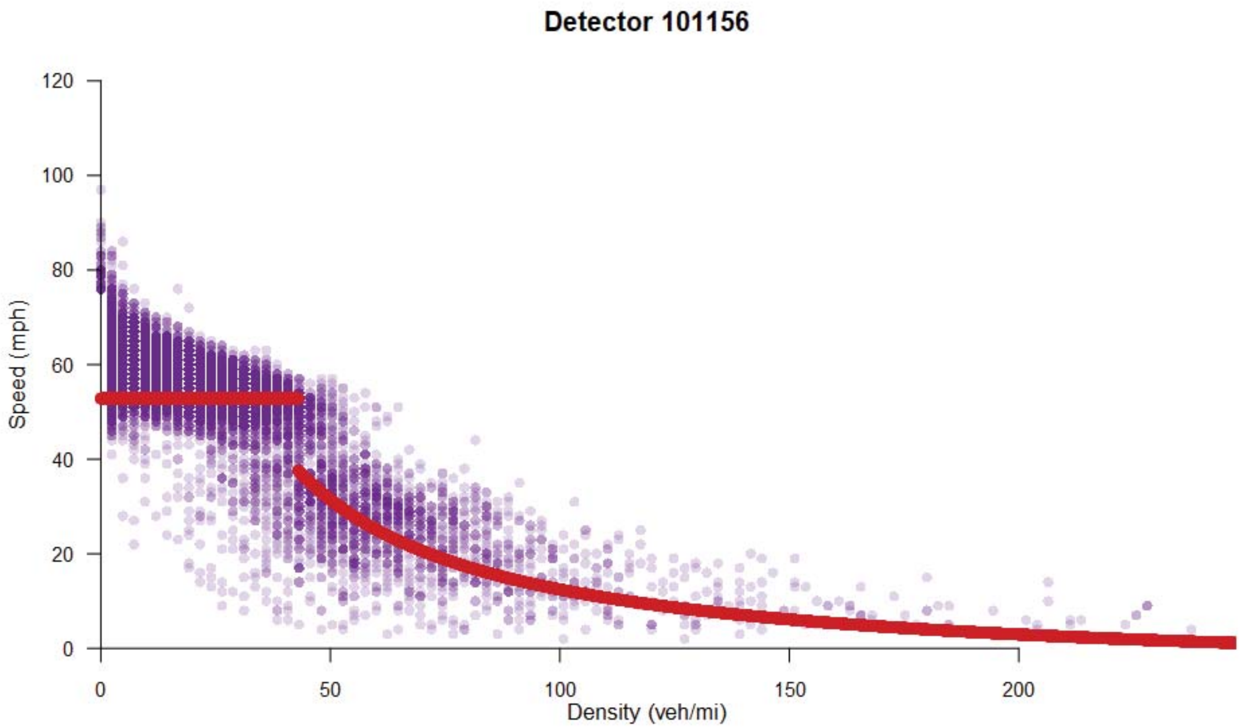

Figure 3-7: Speed fundamental diagram for a typical westbound detector.

Figure 3-8: Flow fundamental diagram for a typical westbound detector.

While the x-intercept of the congested regime's regression line should correspond to the jam density, we found that it did not represent our data well in most cases as the estimated jam densities were higher than the theoretical maximum of 240 veh/mi based on a vehicle plus detector length of 22 ft. Nevertheless, **Tables 3-1** and **3-2** show the estimated free-flow speeds as well as jam densities and theoretical shockwave speeds (if applicable) based on the results from the fundamental diagrams for each detector. The shockwave speed was calculated as the slope of the congested regime's regression line.

In the eastbound direction, no critical densities or shockwave speeds were calculated as there was no congestion. The estimated free-flow speeds range from approximately 43 mph to 64 mph. **Table 3-1** shows that free-flow speeds are higher in the left lanes and slowest in the right lanes. Additionally, the free-flow speeds increase moving from milepost to milepost in the downstream direction. In the westbound direction (shown in **Table 3-2**), it can be seen again that the left lanes typically have higher free-flow speeds than the right lanes. The free-flow speeds tend to decrease moving from milepost to milepost downstream. This corresponds to our previous observations regarding congestion increasing in the same direction.

Table 3-1: Estimated free-flow speeds and maximum densities reached for detectors in the eastbound direction.

Eastbound Detectors					
Detector ID	**Lane**	**Milepost**	**Free Flow Speed**	**Capacity Flow**	**Max Density**
101101	R	4.25	43.34	2496.43	156.00
101102	M	4.25	58.03	2506.84	175.20
101103	L	4.25	63.80	2603.24	127.20
101104	R	5.03	43.51	2715.01	170.40
101105	M	5.03	45.64	2628.95	124.80
101106	L	5.03	53.62	2831.30	86.40
101108	M	5.82	50.43	1936.33	110.40
101109	L	5.82	57.09	2603.27	136.80
101283	M	6.7	50.94	1467.05	60.00
101284	L	6.7	63.84	2298.29	57.60

Table 3-2: Estimated free-flow speeds, jam densities, and shockwave speeds for all detectors in the westbound direction.

Westbound Detectors

Detector ID	Lane	Milepost	Free Flow Speed	Capacity Flow	Jam Density	Congested Shockwave Speed	Flow at Regime Transition	Speed at Regime Transition	Capacity Density
101153	R	4.25	48.03	2257.34	299.22	-7.28	1836.12	39.07	47.00
101154	M	4.25	48.47	2665.79	280.67	-7.77	1754.35	31.90	55.00
101155	L	4.25	54.55	2673.18	252.34	-9.66	1963.91	40.08	49.00
101156	R	5.03	52.84	2272.27	290.25	-6.55	1618.48	37.64	43.00
101157	M	5.03	50.39	2670.42	260.90	-8.55	1777.16	33.53	53.00
101158	L	5.03	54.30	2877.90	259.65	-9.76	2017.93	38.07	53.00
101160	M	5.82	47.07	2118.20	387.41	-3.13	1070.77	23.79	45.00
101161	L	5.82	57.92	3069.59	328.34	-5.24	1441.63	27.20	53.00
100900	Ramp	4.90	60.63	2182.52	196.83	-10.51	1690.98	46.97	36.00
100901	Ramp	4.90	46.79	2807.20	215.82	-11.14	1736.30	28.94	60.00
100902	Ramp	4.90	60.46	2781.06	206.07	-13.31	2131.19	46.33	46.00
101162	R	6.7	55.71	1069.69	38.40*				
101163	M	6.7	47.04	1354.81	76.80*				
101164	L	6.7	62.20	1901.91	86.40*				

*Since congestion did not occur at these detectors, the maximum density reached is recorded instead of the jam density.

4. Congestion Analysis

To further analyze the congestion occurrences on this section of I-84, speed, flow, and density were plotted by time of day for each station. Data were aggregated for every 15 minutes for the time series plots. The time series plots were initially plotted at detector level, and it was found that the traffic trends in all lanes were similar across the station. Since all the lanes exhibit similar trends, further analysis was executed at station level. **Figures 4-1** and **4-2** show speed, flow, and density by time of day plots for a typical eastbound and westbound station, respectively.

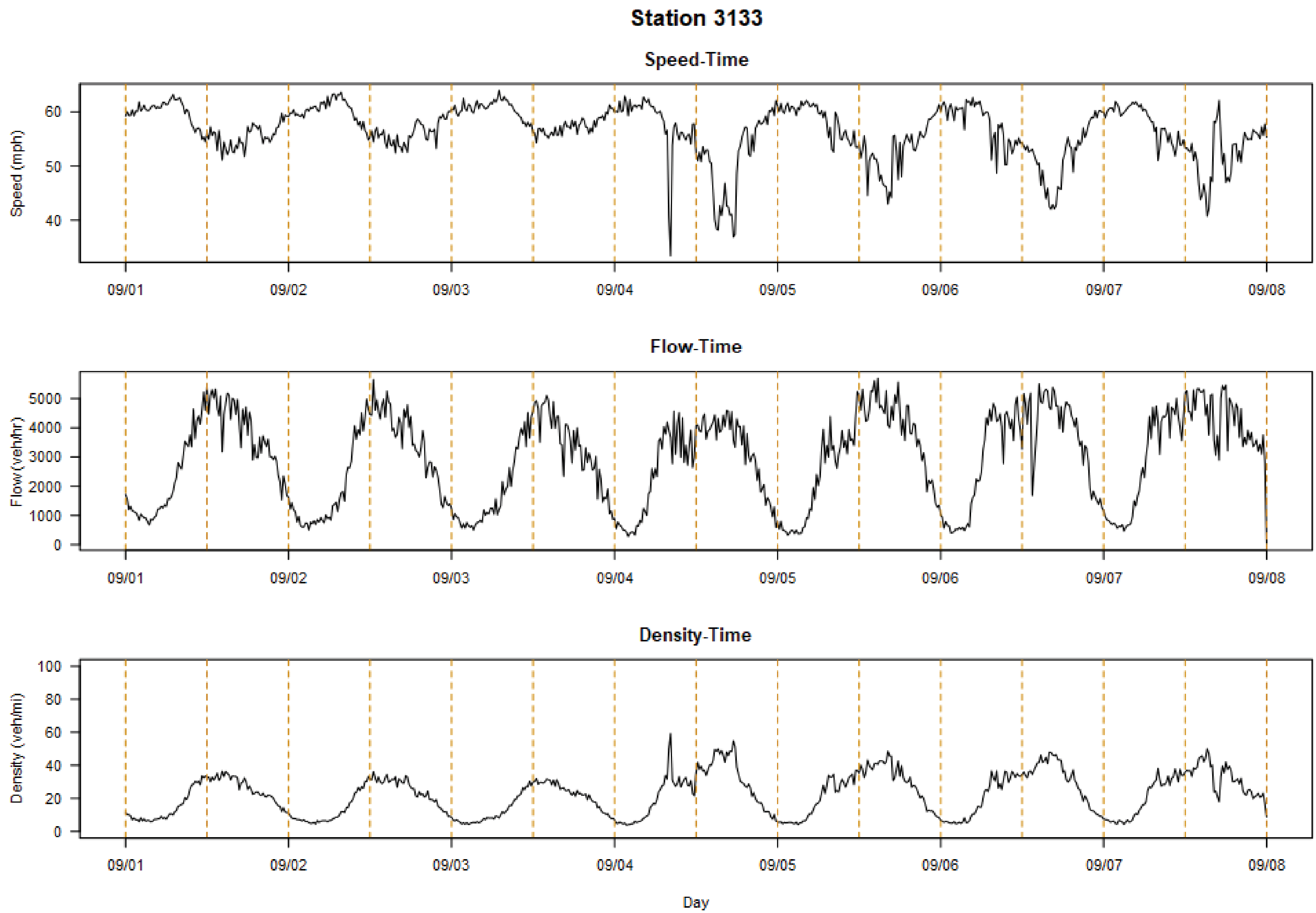

Figure 4-1: Speed, flow, and density by tiime of day for the eastbound station at MP 5.03.

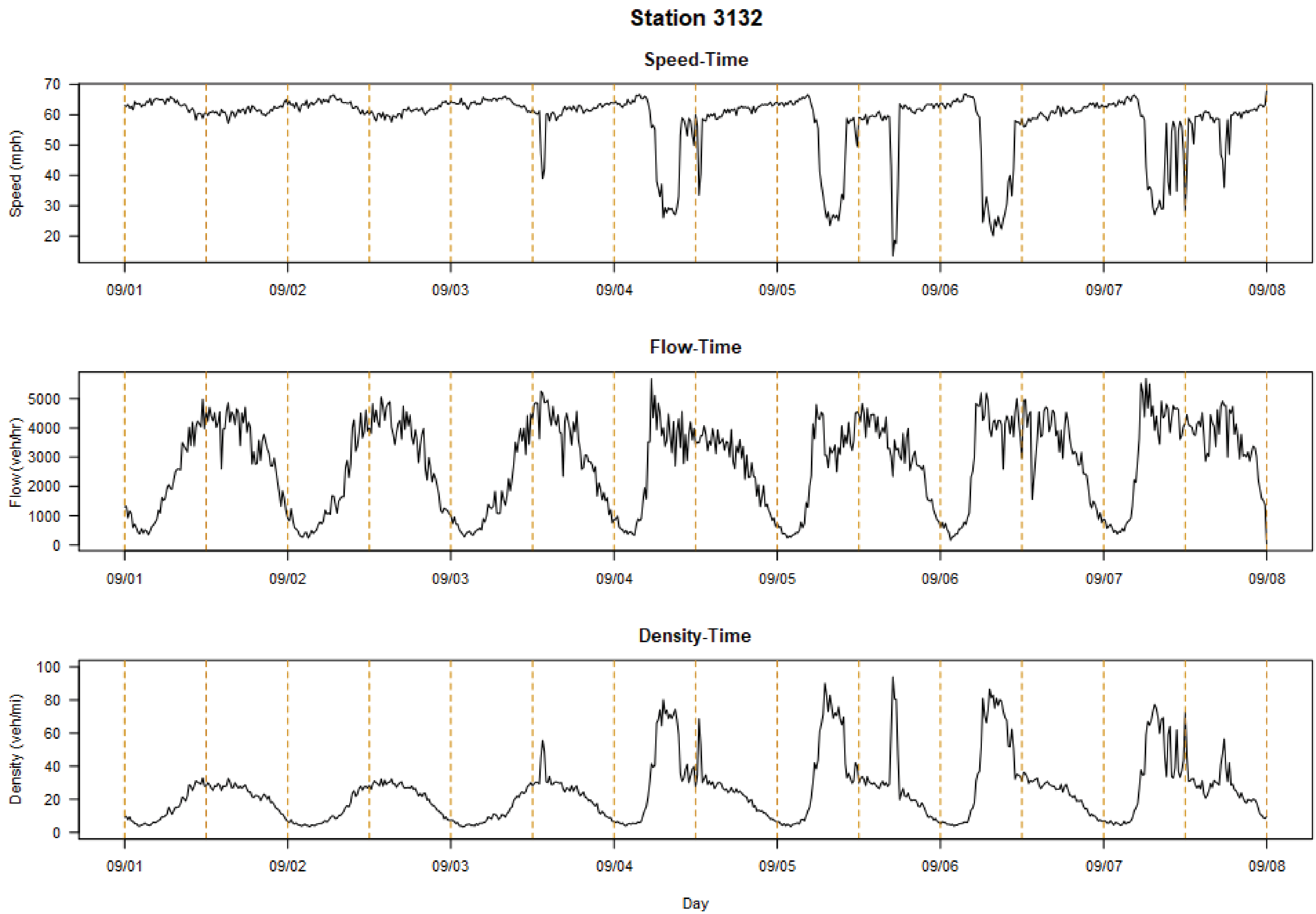

Figure 4-2: Speed, flow, and density by time of day for the westbound station at MP 4.25.

Figure 4-1 shows the flow and density of traffic typically increases in the second half of the day as would be expected for the eastbound direction. The maximum densities reached stay relatively low, indicating an absence of congestion. Densities are especially low from September 1st through September 3rd, corresponding to the Labor Day holiday weekend. An interesting observation in these plots is the spike in the morning of September 4th. Crash data from the Portland Police Bureau confirmed that a non-injury crash took place on easatbound I-84 on September 4th *(City of Portland, 2019).*

Figure 4-2 Shows the flow and density of traffic increases during the morning peak hours corresponding to an expected decrease in speed. Inspection of the flow plot in association with the speed and density plots indicates that congestion occurs during the morning peak hours. As in **Figure 4-1**, a spike can be seen during the afternoon of September 5th. Portland Police records *(City of Portland, 2019)* confirm that a crash occurred near SE 28th Ave on this day, which is further downstream from the limit of our westbound corridor. The crash likely caused the increase in flow and density seen in the plots.

Data from the time series plots were used to estimate congestion timings for relevant detectors. **Table 4-1** shows the estimated congestion times.

Table 4-1: Congestion timings.

Date	Milepost (WB)	Congestion Timings
4-Sep-18	4.25	6:00 to 9:30 & 12:15 to 12:45
	5.03	6:15 to 8:45
	5.82	6:30 to 8:15
5-Sep-18	4.25	6:00 to 9:45 & 16:30 to 17:45
	5.03	6:15 to 9:30
	5.82	6:15 to 8:30
6-Sep-18	4.25	6:00 to 10:45
	5.03	6:00 to 9:45
	5.82	6:15 to 9:00
7-Sep-18	4.25	6:15 to 9:00 & 11:45 to 12:15
	5.03	6:15 to 8:45
	5.82	6:15 to 6:45 & 7:15 to 8:00

To see if congestion at a location travels upstream and changes the conditions there, a simple shockwave analysis is performed. Following equation is used to calculate the shockwave speeds due to conditions changes.

$$\omega_{12} = \frac{q(k_2) - q(k_1)}{k_2 - k_1}$$

For calculation of shockwave speeds, the incoming and congestion traffic conditions are defined as following:

i. Congestion Traffic Conditions: The flow and density of these conditions is calculated as the average of flows and densities during the entire congestion.
ii. Incoming Traffic Conditions: The flow and density of these conditions is calculated as the average of flows and densities during the hour before congestion starts.

Consider the station at MP 4.25, on Thursday (date: 2018-09-06) the congestion starts at 6:00 AM and ends at 10:45. **Figures 4-3** and **4-4** shows the flows and densities respectively, at this station. The required shockwave conditions are calculated as the average of values between the red lines in these figures for this case.

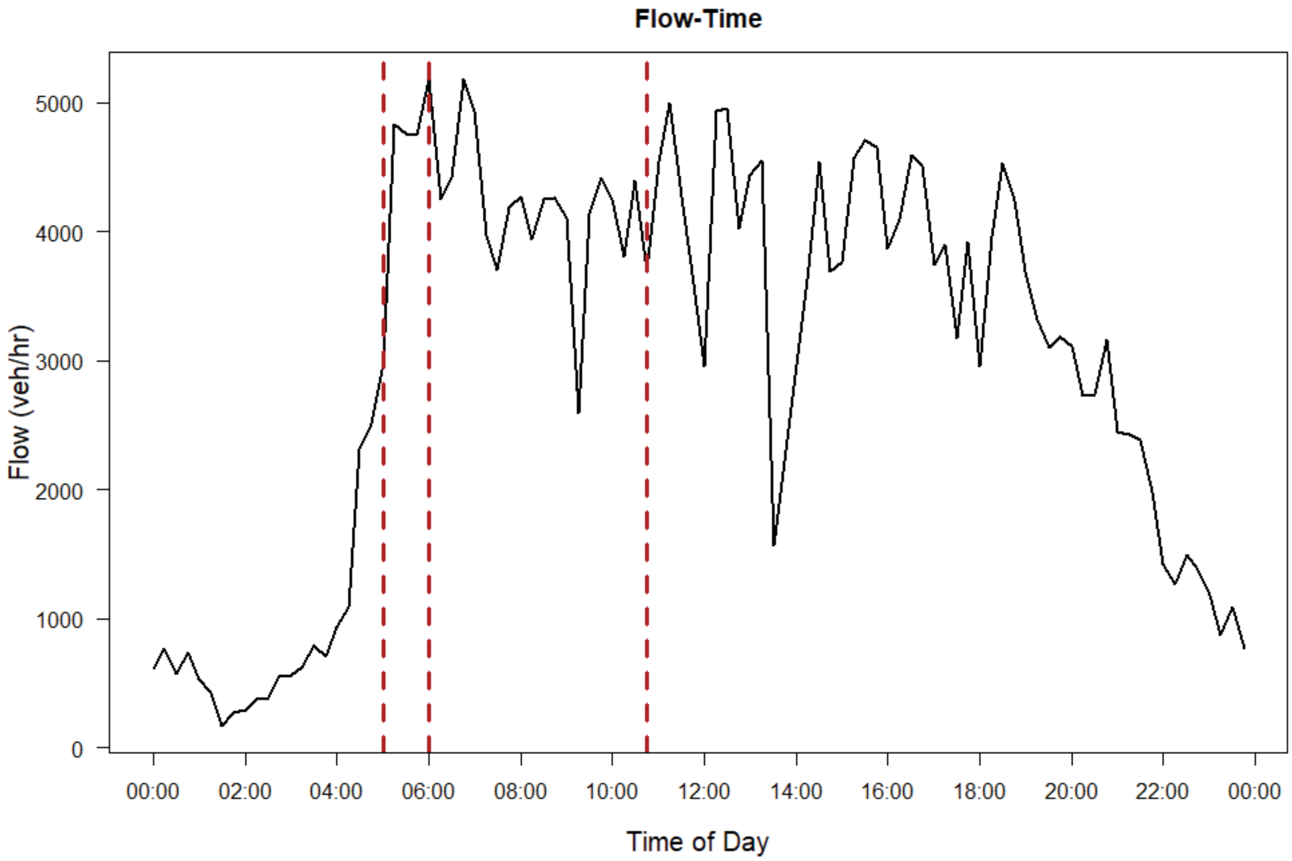

Figure 4-3: Flow vs time for station 3132 on Thursday.

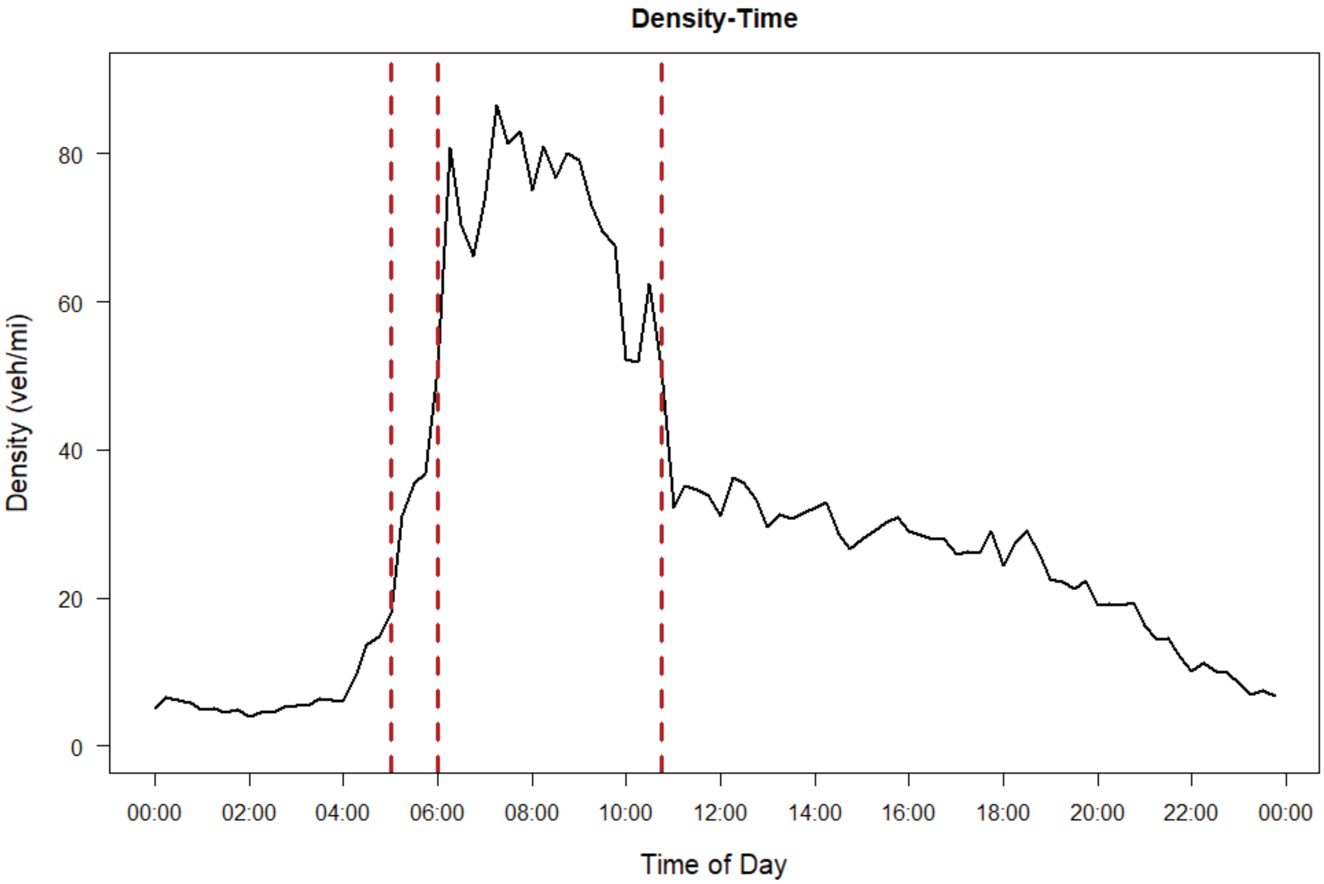

Figure 4-4: Density vs time for station 3132 on Thursday.

Since eastbound doesn't experience congestion, a shockwave couldn't travel upstream in this segment. **Table 4-2**, gives the incoming and congestion traffic conditions along with the shockwave speeds at each MP for different days. Also, this table has the values of minimum shockwave speeds, which is the minimum speed required by the shockwaves to reach an upstream location before the congestion starts there. Further, if congestion at a MP and at another MP upstream begins at the same time then such cases don't have a minimum shockwave speed.

Referring to **Table 4-2**, it is clear that all the minimum shockwave speeds are lower than the actual shockwave speeds. So, in all these cases the congestion in that location impacts the traffic conditions upstream.

Table 4-2: Shockwave speeds for westbound direction.

Date	Milepost	Initial Conditions		Congestion Conditions		Shockwave Speed (mph)	Min. Shockwave Speed (mph)
		q (Veh/hr)	k (Veh/mi)	q (Veh/hr)	k (Veh/mi)		
4-Sep-18	4.25	4435.20	34.84	3969.87	68.05	-14.01	-3.12
	5.03	4416.80	38.15	3765.09	66.82	-22.73	-3.16
	5.82	1867.20	33.57	1752.00	72.40	-2.97	-
5-Sep-18	4.25	3853.60	35.03	3489.00	71.13	-10.10	-3.12
	5.03	4080.00	40.21	3307.14	72.10	-24.23	-
	5.82	1662.40	24.21	1548.80	89.66	-1.74	-
6-Sep-18	4.25	4500.80	34.49	4199.00	70.63	-8.35	-
	5.03	4353.60	28.99	3884.50	69.96	-11.45	-3.16
	5.82	1868.00	27.12	1744.67	94.60	-1.83	-
7-Sep-18	4.25	4880.80	38.53	4519.67	66.31	-13.00	-
	5.03	4680.00	33.77	4258.18	65.31	-13.37	-
	5.82	1883.20	18.67	2157.33	68.04	5.55	-

5. Travel Time Analysis

Heat maps for the corridor over the period of one day were created to help visualize congestion conditions and can be seen in **Figures 5-1** and **5-2**. The color of the plot indicates the speed at that time and location. **Figure 5-1** shows that in the eastbound direction on September 4th, speeds are slower in the afternoon peak hours, congruent with previous analyses. Additionally, the effect of the crash in the morning can be seen.

Figure 5-2 shows the heat map for the westbound corridor for September 5th. The times and locations of the congested speeds reflect our previous observations and calculations. Congestion due to the other crash noted in Section 4 can be seen near the furthest downstream detector in the afternoon.

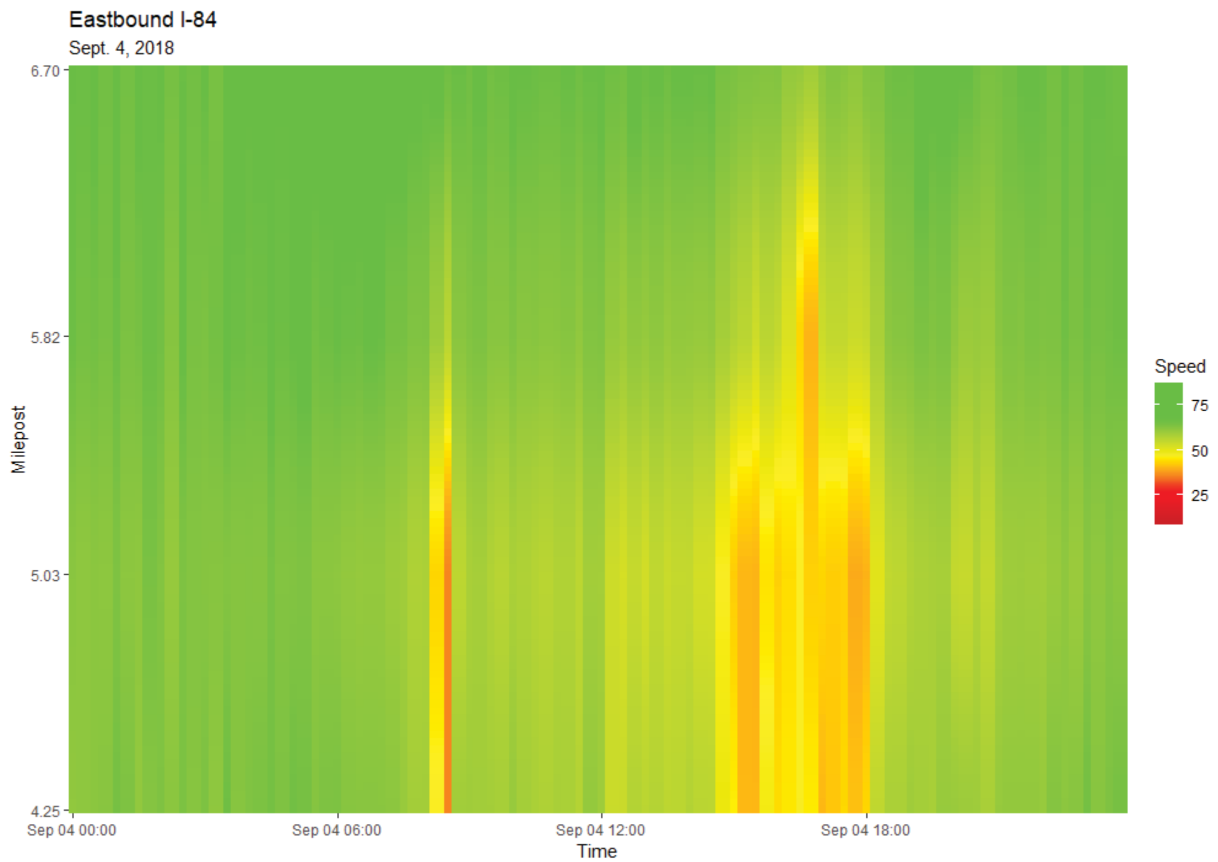

Figure 5-1: Heat map of the eastbound corridor for September 4th.

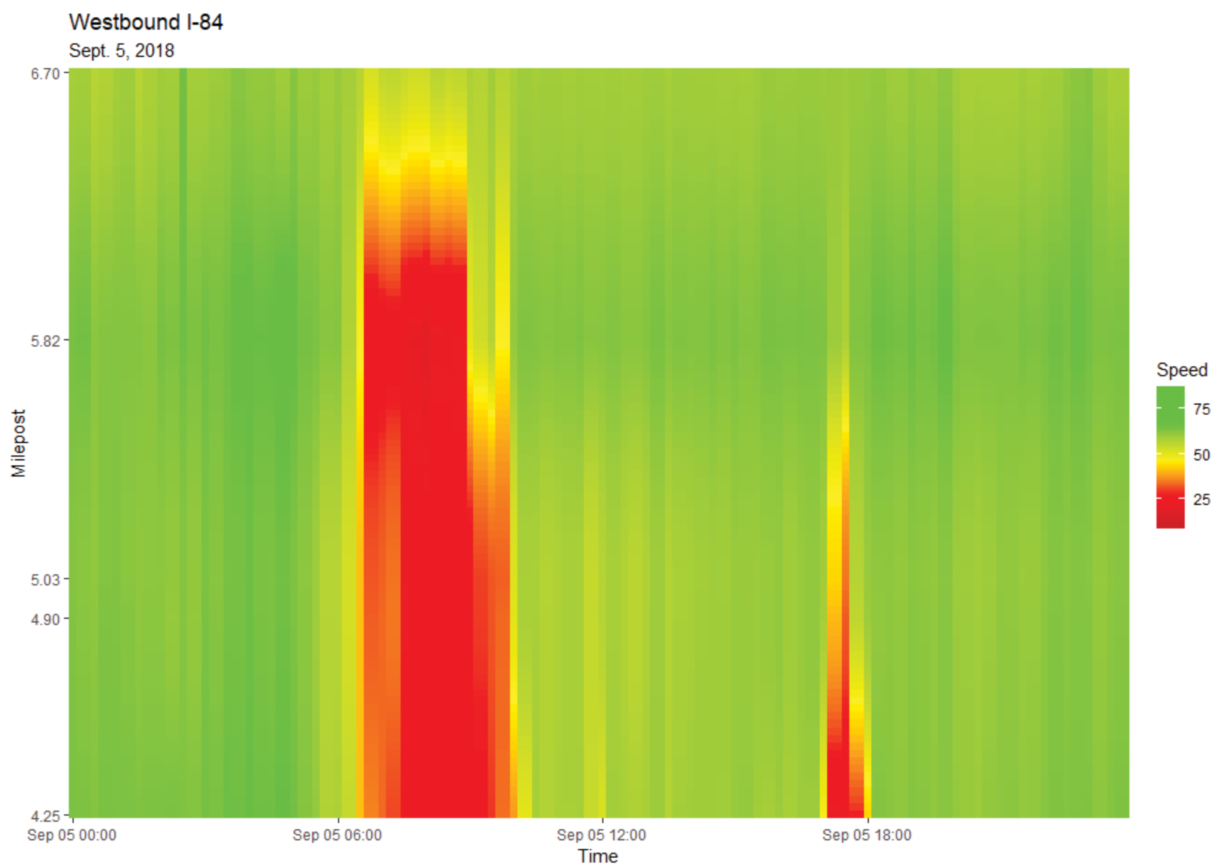

Figure 5-2: Heat map for the westbound corridor for September 5th.

Travel times for the corridor were estimated with speed averaged over a one-half hour interval and the travel distance of the corridor. **Figure 5-3** shows the estimated time it would take to travel between MP 4.25 and 6.7 for the week under study. Travel times for the eastbound corridor range between 2.2 minutes and 3.4 minutes and the travel times are highest in the afternoons. The morning spike on September 4th due to the crash can also be seen.

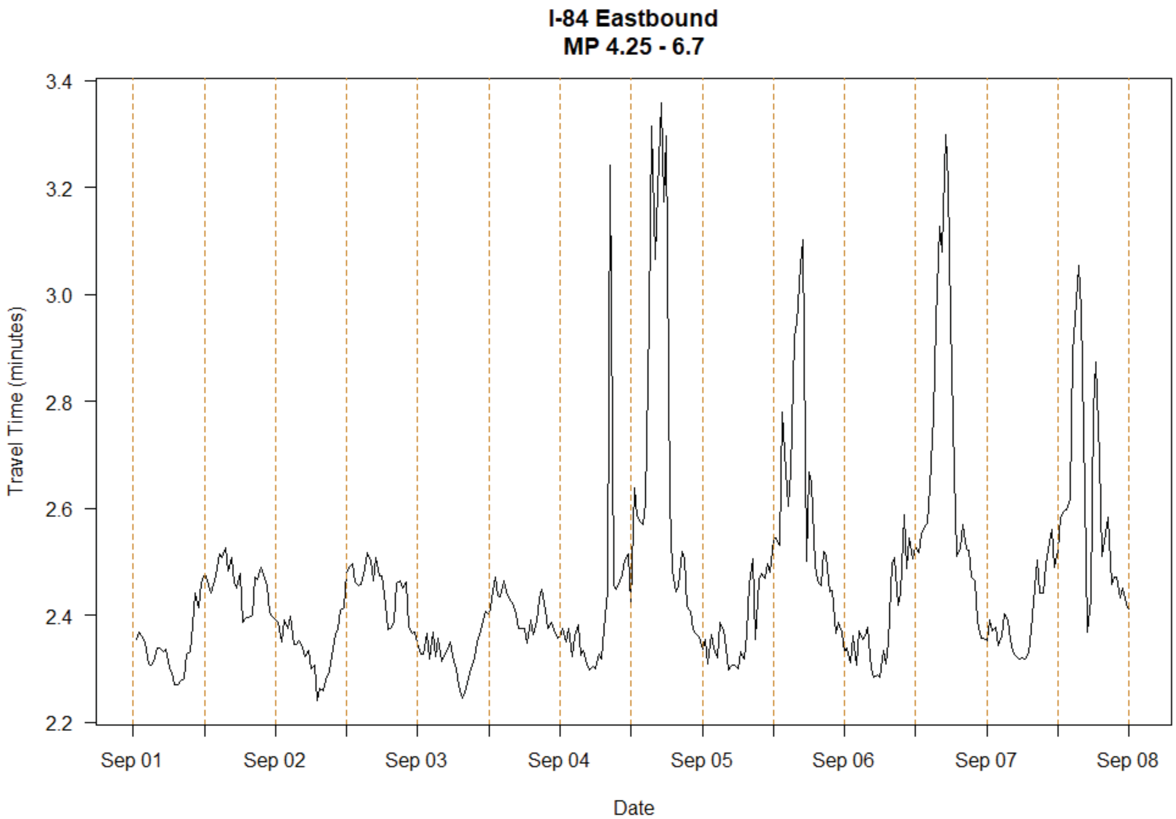

Figure 5-3: Estimated travel times for the eastbound corridor.

In **Figure 5-4**, the estimated time it would take to travel the westbound corridor from MP 6.7 to 4.25 can be seen. The travel time ranges from approximately two minutes during uncongested and off-peak hours to a maximum of approximately eight minutes during the morning peak hours.

These observations of travel time differences by time of day and direction of travel match up with all of our previous study and calculations.

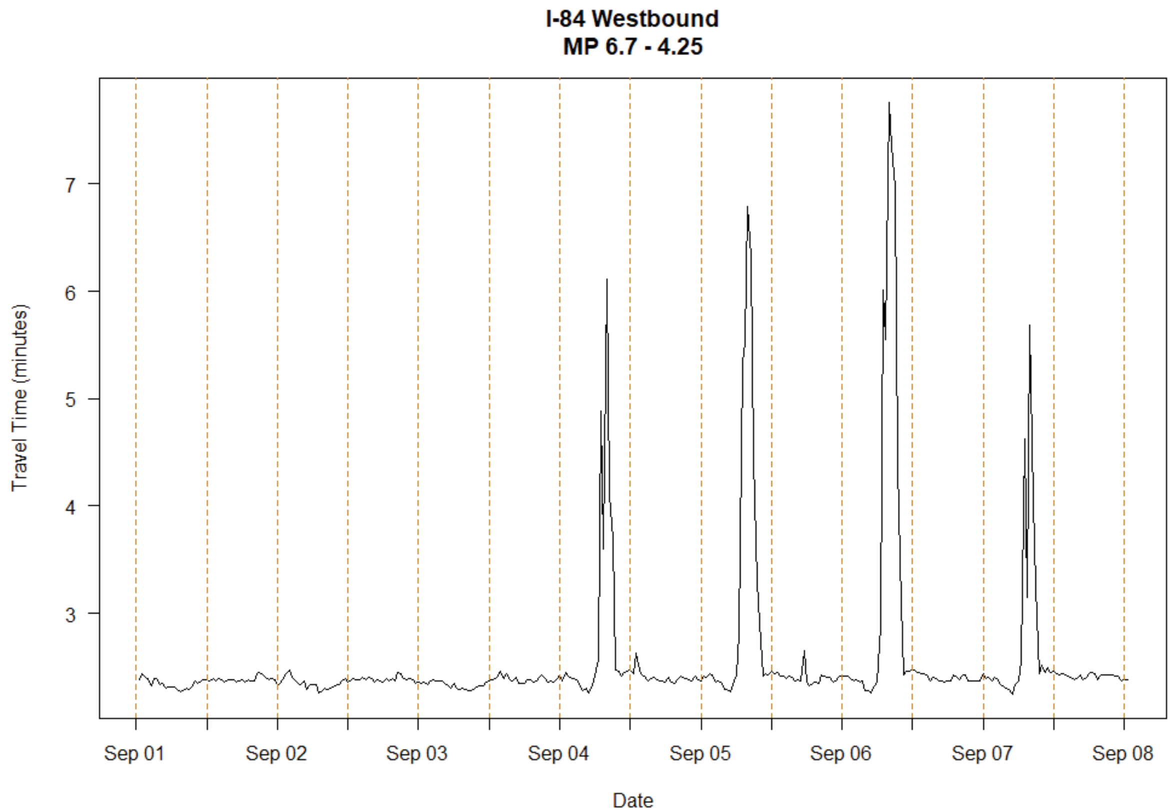

Figure 5-4: Estimated travel times for the westbound corridor.

6. Final Analysis

After the analysis of all the data, it is possible to hypothesize about the causes of congestion and possible solutions that might mitigate these problems. Heavy congestion occurs in the westbound direction at MP 4.25 during morning peak hours, Monday thru Thursday (the Friday morning commute traffic is lighter than other days). This is due to the several entrance ramps feeding traffic onto the freeway during the morning commute and the absence of exit ramps until MP 3.0 is reached. As the land is already well developed and right-of-way would be difficult and expensive to acquire, widening the freeway is not a logical option. Furthermore, there are doubts whether adding capacity would be a long-term solution.

The majority of the traffic takes either an exit for I-5 N or I-5 S at the terminus of I-84. Perhaps a redesign of this interchange would help alleviate some of the congestion, however, it may not make a large enough difference. Reducing the traffic flow on the freeway seems to be the most logical way of mitigating the issue, whether it be by redesigning the entrance ramps and spacing to eliminate some amount of access, introducing congestion pricing during the morning peak hours to deter single occupancy vehicle travel, or investing in bicycle and transit infrastructure to encourage commuters to choose an alternate mode.

7. References

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