FIRST-IN-FIRST-OUT IS VIOLATED IN REAL TRAFFIC

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ABSTRACT

The first-in-first-out (FIFO) principle is assumed in many traffic flow models and traffic assignment models but violated due to overtaking among vehicles on a multi-lane road. Thus it is important to know whether such FIFO violation is significant. In this study, based on a number of measures that can characterize the degree of FIFO violation, we analyze FIFO violation with vehicles' trajectories observed for real traffic. Systematic analysis yield results consistent with our driving experience and suggest that FIFO violation is significant, especially for congested traffic. That FIFO is violated in real traffic could have impacts on the validation of traffic flow models and definition of user equilibrium.

1. INTRODUCTION

In many studies of transportation networks, vehicular traffic has been assumed to follow the so-called First-In-First-Out (FIFO) principle, at least “on average” [1]. In queueing models of traffic flow [2], a network vehicular traffic system has been considered as a queueing system, where vehicles observe the FIFO principle on a link and, therefore, on a path. Different from the queueing models of traffic flow, many other well-studied traffic flow models usually assume implicit link FIFO. For example, vehicles’ relative orders can be maintained with respect to their trajectories [3], space positions [4], waiting times [5, 6], or queue orders [7]. Such FIFO principle is also observed in a model of mixed traffic [8]. In addition, the link FIFO principle has been an important assumption underlying many dynamic traffic assignment models. Actually, in a dynamic user equilibrium state, vehicles of the same origin-destination (O-D) but on different paths should also follow the O-D FIFO principle [9]. In the literature, there are extensive discussions on how to enforce link FIFO for different link performance functions or network loading models applied to solve dynamic traffic assignment problems [10, 11].

In reality, however, there is no doubt that link FIFO is violated absolutely, when a vehicle surpass another on a multi-lane road due to active pursuit of overtaking by aggressive drivers or oscillation in speeds on different lanes. It is yet not known whether link FIFO violation is significant (system-wide and persistent) or not (local and tentative). Our driving experience suggests that both scenarios are possible. For example, when an aggressive driver keeps overtaking slower vehicles, there is system-wide and persistent FIFO violation, increasing with the distance/time traveled. In contrast, when in congested traffic a vehicle just overtaken by another vehicle catches up the latter again, FIFO violation is local and tentative; i.e., FIFO violation should be close to zero in the long run. Then is FIFO violated in real traffic? More specifically, is FIFO violation significant in real traffic? It is important to look into this fundamental question, since its answer can significantly affect our understanding of some basic properties of vehicular traffic.

Compared with the many studies on sufficient and necessary conditions of FIFO principle, measures of FIFO violation are relatively new to the transportation community. In [12], both time- and space-based measures are defined to determine the aggregate FIFO violation among different groups of vehicles. These measures are able to capture the degree of mixture of two types of cars that are initially separated, and, with them, it was shown that the commodity-based kinematic wave model developed in [13] violates FIFO but converges to FIFO when the size of a cell diminishes. In [9], a measure of O-D FIFO violation among path traffic was defined with the assumption of link FIFO and used to derive a dynamical system model of the traffic assignment problem. In [14], FIFO violation is considered through the change in the orders of vehicles passing two locations on a road, and a temporal measure was developed to calculate FIFO violation among vehicles and applied to study FIFO violation in traffic simulated by a microscopic traffic simulator.

In this study, we further the study of FIFO violation by analyzing vehicles’ trajectories observed in real traffic. We use the data sets from the Federal Highway

Administration (FHWA)'s Next Generation Simulation (NGSIM) project [15], from which we compute the times for vehicles to pass a number of detectors. Then from the change in orders of vehicles passing two detectors, we compute a number of quantities characterizing the degree of FIFO violation. The concepts and definitions of this study are based on those of [14] but are introduced systematically and in details, so that this paper can be a stand-alone contribution to the literature. In addition, we apply another framework of definitions and introduce new concepts including FIFO violation of individual vehicles, FIFO violation of commodities, and FIFO violation among commodities.

The rest of the paper is organized as follows. In Section 2, we systematically introduce measures of FIFO violation. In Section 3, we present preliminary analysis of the data sets that we use. In Section 4, we systematically analyze FIFO violation in the data sets. Finally, in Section 5, we summarize our observations and discuss future research directions.

2. MEASURES OF FIFO VIOLATION

2.1 FIFO violation of individual vehicles

We consider a traffic stream of N vehicles, whose traveling direction is the same as that of x-axis. We place detector $j+1$ downstream to detector j; i.e., their coordinates satisfy $x_{j+1} > x_j$. For vehicle n ($n = 1, \cdots, N$), we denote its time to pass detector j at x_j by $t(n, x_j)$ and its order by $z(n, x_j)$. We assume that the passing order is a one-to-one function of n; i.e., two vehicles with the same passing times are assigned different passing orders. For two vehicles m and n, therefore, $z(n, x_j) < z(m, x_j)$ implies that $t(n, x_j) \le t(m, x_j)$. We denote the time for the zth vehicle to pass x_j by $t_z(z, x_j)$, which is a non-decreasing function in z and increasing function in x_j. Therefore, $t(n, x_j) \equiv t_z(z(n, x_j), x_j)$. The time for vehicle n to travel from detector x_1 to detector x_2 is given by

$$t(n; x_1, x_2) = t(n, x_2) - t(n, x_1) \tag{1}$$

The FIFO principle is violated, when the orders for vehicle n to pass two detectors 1 and 2 are different, or when the IDs of the zth vehicle passing detectors 1 and 2 are different. To measure the FIFO violation caused by vehicle n, we compare its passing times at two locations in the FIFO-violated traffic with those in the ideal FIFO traffic, which is generated by referring to the orders at either detector 1 or detector 2 as follows. If using detector 1 as a reference point, the ideal passing order at x_2 of vehicle n would be $z(n,x_1)$, and its ideal passing time $\bar{t}(n,x_2)=t_z(z(n,x_1),x_2)$. Similarly, if using detector 2 as a reference point, the ideal passing order at x_1 of vehicle n would be $z(n,x_2)$, and its ideal passing time $\bar{t}(n,x_1)=t_z(z(n,x_2),x_1)$. Here $\bar{t}(n,x_1)$ and $\bar{t}(n,x_2)$ can also be considered as the passing times for a phantom vehicle that switches order with vehicle n at detectors 1 and 2. Then we define the FIFO violation of vehicle n between detectors x_1 and x_2 by

$$v(n;x_1,x_2)=\frac{t(n,x_2)-\bar{t}(n,x_2)-t(n,x_1)+\bar{t}(n,x_1)}{2}. \tag{2}$$

If we denote the travel time of the phantom vehicle corresponding to vehicle n between detectors x_1 and x_2 by $\bar{t}(n;x_1,x_2)=\bar{t}(n,x_2)-\bar{t}(n,x_1)$, then the FIFO violation equals the difference in the travel times between vehicle n and its corresponding phantom vehicle; i.e., $v(n;x_1,x_2)=\frac{t(n;x_1,x_2)-\bar{t}(n;x_1,x_2)}{2}$.

From Equation 2, if vehicle n overtakes other vehicles; i.e., if $z(n,x_2)<z(n,x_1)$, its FIFO violation is non-positive. If it is overtaken, its FIFO violation is non-negative. Further, we have that $\sum_{n=1}^{N} v(n;x_1,x_2)=0$; i.e., the pursuit of FIFO violation of all vehicles can be considered as a zero-sum game [16].

2.2 FIFO violation among vehicles

At the aggregate level, FIFO violation among vehicles between detectors x_1 and x_2 defined in [14] can then be written as

$$V(x_1,x_2)=\frac{\sum_{n=1}^{N}\left|v(n;x_1,x_2)\right|}{N}=\frac{\left\|\vec{v}(x_1,x_2)\right\|_1}{N}, \tag{3}$$

where $\left\|\vec{v}(x_1,x_2)\right\|_1$ is the 1-norm of the vector $\vec{v}(x_1,x_2)$ with $v(n;x_1,x_2)$ as its nth ($n=1,\cdots,N$) element. The FIFO violation in Equation 3 is a meaningful measure, since it equals zero if and only if vehicles travel in a queueing fashion of FIFO, and it reaches maximum when vehicles travel in a stacking fashion of First-In-Last-Out

(FILO) [14]. Statistically, such a FIFO violation is similar to the standard deviation of FIFO violation of individual vehicles, $\sqrt{\frac{\sum_{n=1}^{N}\left|v(n;x_1,x_2)\right|^2}{N}}$. That is, the bigger FIFO violation, the more changes in vehicles' orders.

The average travel time from x_1 to x_2 is

$$T(x_1,x_2)=\frac{\sum_{n=1}^{N} t(n;x_1,x_2)}{N}. \tag{4}$$

It has been proved in [14] that $V(x_1,x_2)\le T(x_1,x_2)$, and a normalized FIFO violation can be defined as

$$\hat{V}(x_1,x_2)=\frac{V(x_1,x_2)}{T(x_1,x_2)}. \tag{5}$$

Statistically, when normalized FIFO violation is 0.3, then two vehicles departing at the same time are expected to have arriving times with difference of 18 minutes after one hour's travel.

2.3 Commodity FIFO violation

For a multi-commodity traffic stream, in which vehicles can be differentiated into a number of commodities according to their types, paths, or other criteria, there could exist FIFO violation among commodities. In [12], several measures are defined for FIFO violation among commodities for continuous traffic flow quantities. Here, we introduce a new measure of FIFO violation among commodities at the disaggregate and aggregate levels based on FIFO violation of individual vehicles.

Assuming that there are totally C commodities for N vehicles, and N_c vehicles in commodity c ($c=1,\cdots,C$), we have $N=\sum_{c=1}^{C} N_c$. Then the FIFO violation of commodity c can be defined by

$$v_c(x_1,x_2)=\sum_{n\in \text{commodity } c} v(n;x_1,x_2). \tag{6}$$

Therefore, FIFO violation of a commodity equals the sum of FIFO violation of individual vehicles belonging to the commodity, and commodity FIFO violation does not take into account FIFO violation among vehicles of the same commodity. If $v_c(x_1,x_2)<0$, then the commodity overtakes other commodities; if $v_c(x_1,x_2)>0$, the commodity is overtaken.

Moreover, we can define FIFO violation among commodities following Equation 3

$$V_C(x_1, x_2) = \frac{\sum_{c=1}^{C} |v_c(x_1, x_2)|}{N}. \quad (7)$$

We can see that FIFO violation among commodities is generally smaller than that among vehicles. However, if we consider each vehicle as a commodity, they are equivalent.

3. PRELIMINARY DATA ANALYSIS

In this study, we study FIFO violation in real traffic with data sets from FHWA's NGSIM project [15], which were transcribed from the video data of vehicles on a section in interstate 80 in Emeryville (San Francisco), California.

In our study, we consider five data sets [17, 18, 19, 20]. Data sets 1 to 3 contain the locations of each vehicle every tenth second on April 13, 2005 between 4pm and 4:15pm, between 5pm and 5:15pm, and between 5:15pm and 5:30pm, respectively; Data sets 4 and 5 contain locations of each vehicle every fifteenth second on December 3, 2003 between 2:35pm and 2:50pm and between 2:50pm and 3:05pm, respectively. Note that data sets 4 and 5 originally belong to the same data set and are split according to entrance times of vehicles.

For a vehicle at each time instant or frame, there are 18 describing quantities, such as ID of a vehicle, ID of a frame or time instant, total number of frames that a vehicle appears, global time since Jan 1, 1970, longitudinal distance from the entry edge of the study section, lateral distance from the left-most edge of the study section, and vehicle type.

3.1 Consistency of data

Before applying the data to analyze FIFO violation in real traffic, we first check the consistency of these data sets. Here we use data set 1 as an example. For each vehicle, we verify that the total number of frames in column 3 matches the number of different frame IDs in column 2. We also verify that the longitudinal distance from the entry edge of the study section in column 6 is not decreasing with respect to time for each vehicle, since vehicles are not allowed to travel backward.

The first frame is at 3:58:55pm on April 13, 2005 of California local time. Since California's time zone is UTC-7 (Coordinated Universal Time) on this day, the first frame corresponds to 10:58:55pm on April 13, 2005 of Greenwich Mean Time (GMT). The elapsed time for the first frame since January 1, 1970 equals $9 \cdot 366 + 26 \cdot 365 + (31 + 28 + 31 + 12) = 12886$ days plus 23 hours minus 65 seconds. Thus the first frame's global time is 1113433135000 ms. For example, the first frame that vehicle 1 appears is 12, and the global time is 1113433135000+1100=113433136100 ms. Therefore, the data in columns 2 and 4 are consistent.

We can obtain the linear relationship between local longitudinal coordinates (local y) and global longitudinal coordinates (global y) as

$$\text{global y}=2133073.377+0.9911\cdot\text{local y} \quad (8)$$

with R-square of 1.0000. Therefore, the linear approximation is very accurate, and the data in columns 6 and 8 are consistent with each other[2].

For data sets 4 and 5, the local longitudinal coordinates have a different origin from that for data sets 1 to 3, but the local and global longitudinal coordinates also follow a linear relationship. Here we use Equation 8 to compute the adjusted local longitudinal coordinates from the global longitudinal coordinates for data sets 4 and 5, so that they have the same local origin as data sets 1 to 3.

3.2 Variables and study area

In our study, we only use four variables from the data sets: vehicle ID, frame ID, local longitudinal coordinate, and vehicle type. For each data set, we set the first frame as time 0, and the unit of time is changed to second. We use the longitudinal direction as our x-axis and denote the position of a vehicle by its local longitudinal coordinate. Then from the data sets, we can obtain the locations of a vehicle at different time instants.

The most upstream positions of all vehicles in data set 1 are shown in Figure 1(a), from which we can clearly distinguish mainline and on-ramp vehicles: for mainline vehicles, the most upstream positions are smaller than 140 ft; for on-ramp vehicles, those are bigger than 260 ft. The most downstream positions of all vehicles in data set 1 are shown in Figure 1(b), from which we can see that all vehicles pass 1630 ft. From both figures, we can see that all mainline vehicles pass 150 ft and 1630 ft, and all on-ramp vehicles pass 400 ft and 1630 ft. Thus, our study area is set from 150 ft to 1630 ft. Along the section of road, we place seven main detectors at x_1=150, x_2=400, x_3=650, x_4=900, x_5=1150, x_6=1400, and x_7=1630 ft. Therefore, all mainline vehicles can be detected by seven main detectors and all on-ramp vehicles by detectors except the first one. The study area and the seven detectors are shown in Figure 2.

3.3 Computation of passing times

In the original data sets, we have the position of vehicle n at discrete time instant t_i as $x(n,t_i)$. In order to compute FIFO violation in a section, we need to know the time for it to pass a detector x_j, $t(n,x_j)$. In the data sets, vehicles may not be at x_j exactly at any time instants. That is, it is probable that $x(n,t_i) < x_j < x(n,t_{i+1})$. In this

[2] Note that we cannot obtain an accurate linear relationship between local and global lateral coordinates. However, since these variables are not used in our study, we do not check their consistency here.

case, we interpolate the section $\left(x(n,t_i), x(n,t_{i+1})\right)$ with a linear function $x = x(n,t_i) + s(x - x(n,t_i))$, where the slope $s = \frac{x(n,t_{i+1}) - x(n,t_i)}{\Delta t}$ with Δt as the time step. Then we can compute the time for vehicle n to pass detector x_j by

$$t(n,x_j) = t_i + \frac{x_j - x(n,t_i)}{s}, \tag{9}$$

from which we can obtain the time for a vehicle to pass any location.

4. ANALYSIS OF FIFO VIOLATION IN REAL TRAFFIC

The trajectories for the first three vehicles in data set 1 are shown in Figure 3, from which we can clearly see FIFO violation among vehicles: the red vehicle overtakes both blue and cyan vehicles; the blue vehicle first overtakes the cyan one and is then overtaken.

The relationships between FIFO violation and travel times of mainline vehicles running from detector 1 to detector j ($j = 2,\cdots,7$) are shown in Figure 4, from which we can observe an approximate linear relation between a vehicle's travel time and its FIFO violation. However, such a relation cannot be simply described by a function, since it is a multiple-value mapping.

4.1 Market penetration rate

In reality, we might only be able to obtain the trajectory data of a certain portion of vehicles with technologies such as vehicle re-identification [21, 22] and automatic vehicle identification [23]. We call the ratio between the vehicles that can be detected and all vehicles by market penetration rate, μ. Here we would like to check the influence of market penetration rate on the detection of FIFO violation among vehicles between detector 1 and 2 for data set 1. We expect similar results for other road sections.

Here we apply Monte Carlo simulation approach to studying the impact of market penetration rate [24]. In each Monte Carlo simulation run, we randomly select μ of all vehicles and compute the normalized FIFO violation among them, i.e., $\hat{V}(x_1, x_2)$. For market penetration rate of 50%, we repeat such Monte Carlo simulations for 100, 200, 400, 800, 1600 times respectively and compute the corresponding means and standard deviations of normalized FIFO violation among detected vehicles. As shown in Table 1, the Monte Carlo simulation results are consistent with each other for these repeating times, and the mean of $\hat{V}(x_1, x_2)$ is about 0.28.

Table 2 shows the impact of market penetration rates on the computation of FIFO violation among vehicles. The accurate normalized FIFO violation equals 0.2876. When μ=0.4; i.e., when only 40% vehicles' trajectories can be detected, we can still have an approximate normalized FIFO violation of 0.2707 with a relative error of about 6%. Therefore, when the market penetration rate is as low as 40%, we can still have a quite reasonable approximation of FIFO violation. Note that, however, such a good approximation is only possible for relatively dense traffic.

4.2 FIFO violation for commodity traffic

Still for data set 1, we first differentiate all mainline vehicles into three commodities according to their types. That is, we have motorcycle, auto, and truck commodities. Table 3 shows for each commodity between detector 1 and 2 the FIFO violation, $v_c(x_1, x_2)$, the number of vehicles, N_c, the average FIFO violation, $v_c(x_1, x_2)/N_c$, the average travel time, and the average speed. From the table, we can see that the motorcycle commodity has negative FIFO violation and, therefore, overtakes autos and trucks. From the average speeds of three commodities, we can see that motorcycles are much faster in congested traffic. This is consistent with our experience that motorcycles can still maintain a relatively high speed by traveling on lane lines when traffic is very congested. From the table, we can obtain the FIFO violation among commodities between detector 1 and 2 as 0.0778 s, which is much smaller than the FIFO violation among vehicles, 2.7876 s[3]. Moreover, we can compute the normalized FIFO violation among motorcycles, autos, and trucks as 0, 0.2882, and 0.0619 respectively. Thus, there is no overtaking among motorcycles and little among trucks, and the normalized FIFO violation among autos is very close to that among all vehicles, 0.2876. Such a difference is caused by the difference in the numbers of vehicles of difference commodities.

We can also differentiate all vehicles from detector 2 to 7 to on-ramp vehicles and mainline vehicles according to their origins. Table 4 shows the commodity FIFO violation and average travel times for mainline and on-ramp vehicles. From the table, we can see that mainline vehicles overtake on-ramp vehicles on average, and the difference between two commodities in terms of both FIFO violation and speed decreases as vehicles are more mixed along the road.

4.3 FIFO violation for different road sections and traffic conditions

In this subsection, we increase the number of detectors along the mainline freeway from 150 ft to 1600 ft, so that all road sections have the same length of 50 ft. Figure 5 shows the normalized FIFO violation among mainline vehicles of data set 1 for road sections from the starting point of the section, x_1, to detector x_j and for road sections

[3] The FIFO violation among vehicles equals the normalized FIFO violation, 0.2876, times the average travel time, 9.6928 s.

between two consecutive detectors x_{j-1} and x_j, respectively. We call the former global FIFO violation and the latter local FIFO violation. From the curve of local FIFO violation, we can see a significant increase of overtaking activities in the region following the on-ramp. This suggests that the merging traffic from on-ramp causes more lane-changes of mainline vehicles or larger vibrations in their speeds. However, the curve of global FIFO violation suggests that the disorder between vehicles gets mitigated along the road, even with the impact of merging traffic.

With all five data sets, we consider the impact of traffic condition on FIFO violation among vehicles. Figures 6(a)-(e) show both local (lines with diamonds) and global (lines with asterisks) FIFO violation for data set 4 (2:35-2:50pm, December 3, 2003), data set 5 (2:50-3:05pm, December 3, 2003), data set 1 (4:00-4:15pm, April 13, 2005), data set 2 (5:00-5:15pm, April 13, 2005), and data set 3 (5:15-5:30pm, April 13, 2005), respectively. Vehicles' average travel times in each section of 50 ft for the five data sets are shown in Figure 6(f), where the curves from the bottom to top are for data sets 4, 5, 1, 2, and 3 in order. From Figure 6(f), traffic is free-flowing and almost uniform in data set 4; traffic is still free-flowing in the upstream part, but gets congested in the downstream part in data set 5; traffic becomes more congested from data set 1 to data set 3. Comparing the curves of local FIFO violation in Figures 6(a)-(e), we can see that higher FIFO violation occurs for more congested traffic. From the curves of global FIFO violation in Figures 6(a) and 6(b), we can see that global FIFO violation keeps increasing with the distance in free flow. This is as expected, since faster vehicles can overtake slower ones without difficulty in free flow. However, from the curves of global FIFO violation in Figures 6(c)-(e), global FIFO violation keeps decreasing with the distance in congested traffic. This is also consistent in certain degree with the experience that a vehicle just overtaken by another vehicle catches up the latter again. Such FIFO violation could be caused by oscillation of speed on different lanes, and vehicles may not actively pursue FIFO violation. From all these figures, we can see that the global normalized FIFO violation for a section of 1450 ft is about 0.1 for free flow and can be as large as 0.5 for congested traffic.

5. CONCLUSION

In this paper, we introduced new definitions of FIFO violation of individual vehicles, FIFO violation among vehicles, and commodity FIFO violation based on times for vehicles to pass the boundaries of a road section. Through consistency test, we find that the five data sets of vehicle trajectories collected in 2003 and 2005 from FHWA NGSIM project are of very high quality for our analysis. We then analyzed the property of FIFO violation in real traffic for different market penetration rates, commodities, road sections, and traffic conditions. We have the following observations:

(i) FIFO violation occurs when vehicle trajectories cross each other, and FIFO violation of individual vehicles are related to their travel times or speeds but not in a functional form;

(ii) For congested traffic, we can have relatively accurate approximation of FIFO violation even when only a portion of vehicle trajectories are detected;

(iii) In congested traffic, motorcycles can constantly overtake autos and trucks, and mainline vehicles overtake vehicles from on-ramp in the merging area;

(iv) More serious FIFO violation occurs in more congested traffic. In free flow, faster vehicles keep overtaking slower ones, and normalized FIFO violation keeps increasing over distance; in congested flow, vehicles overtake and are overtaken constantly, and normalized FIFO violation keeps decreasing over distance. Such normalized FIFO violation in a road section of one third mile can be from 0.1 to 0.5.

Although we cannot obtain the FIFO violation over a longer section due to the availability of trajectory data, it is evident that there exists absolute FIFO violation in real traffic on a multi-lane roadway, and the degree of FIFO violation is significant, especially for congested traffic.

The observation of absolute violation of the FIFO principle means that many traffic flow models and dynamic traffic assignment models should be revised to incorporate such FIFO violation. For example, is it possible to model such FIFO violation in the framework of the LWR model [25, 26]? For dynamic traffic assignment, it is no longer reasonable to assume accurate O-D FIFO for the state of dynamic user equilibrium, since FIFO is even violated on links [9]. For example, with a normalized FIFO violation of 0.1 on a path of 60 minutes' travel, the difference in the arrival times of vehicles on the same path departing at the same time is about 6 minutes. In this case, it is not realistic to require that, in user equilibrium [27], vehicles departing at the same time on different paths arrive at the same time. How to adjust the definition of user equilibrium is subject to further investigation.

In the future, we will also be interested in studying the impact of road geometry, the number of lanes, and speed limit on FIFO violation. Other interesting topics include relationship between FIFO violation and the number of lane-changes, influence of oscillation of lane speeds on FIFO violation, and behavior interpretation behind FIFO violation.

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Table 1. The impact of number of Monte Carlo simulations on FIFO violation among vehicles for market penetration rate of 50%

Number of Monte Carlo simulations	100	200	400	800	1600
Mean of $\hat{V}(x_1, x_2)$	0.2770	0.2771	0.2785	0.2781	0.2779
Std. Dev. of $\hat{V}(x_1, x_2)$	0.0074	0.0081	0.0076	0.0073	0.0079

Table 2. FIFO violation vs market penetration rate

μ	1	0.75	0.5	0.4	0.2	0.1
Mean of $\hat{V}(x_1, x_2)$	0.2876	0.2852	0.2778	0.2707	0.2351	0.1788
Std. Dev. of $\hat{V}(x_1, x_2)$	0	0.0046	0.0079	0.0091	0.0170	0.0260

Table 3. Commodity FIFO violation for different types of vehicles

Commodity	Motorcycle	Auto	Truck
$v_c(x_1, x_2)$ (s)	-72.4241	51.4914	20.9327
N_c	14	1756	92
$v_c(x_1, x_2)/N_c$ (s)	-5.1731	0.0293	0.2275
Average travel time (s)	4.3027	9.7154	10.0818
Average speed (mph)	39.6157	17.5448	16.9072

Table 4. Commodity FIFO violation for mainline and on-ramp vehicles

Road sections	$[x_2, x_3]$	$[x_3, x_4]$	$[x_4, x_5]$	$[x_5, x_6]$	$[x_6, x_7]$
$v_c(x_1, x_2)$, mainline (s)	-371.1872	-358.8263	-63.0748	-61.5967	-99.3083
$v_c(x_1, x_2)$, on-ramp (s)	371.1872	358.8263	63.0748	61.5967	99.3083
Travel time, mainline (s)	10.7642	9.9842	9.5176	9.3560	8.6109
Travel time, on-ramp (s)	13.1198	12.1616	10.1877	9.9016	9.3136

Figure 1. The most upstream and downstream locations of all vehicles in order

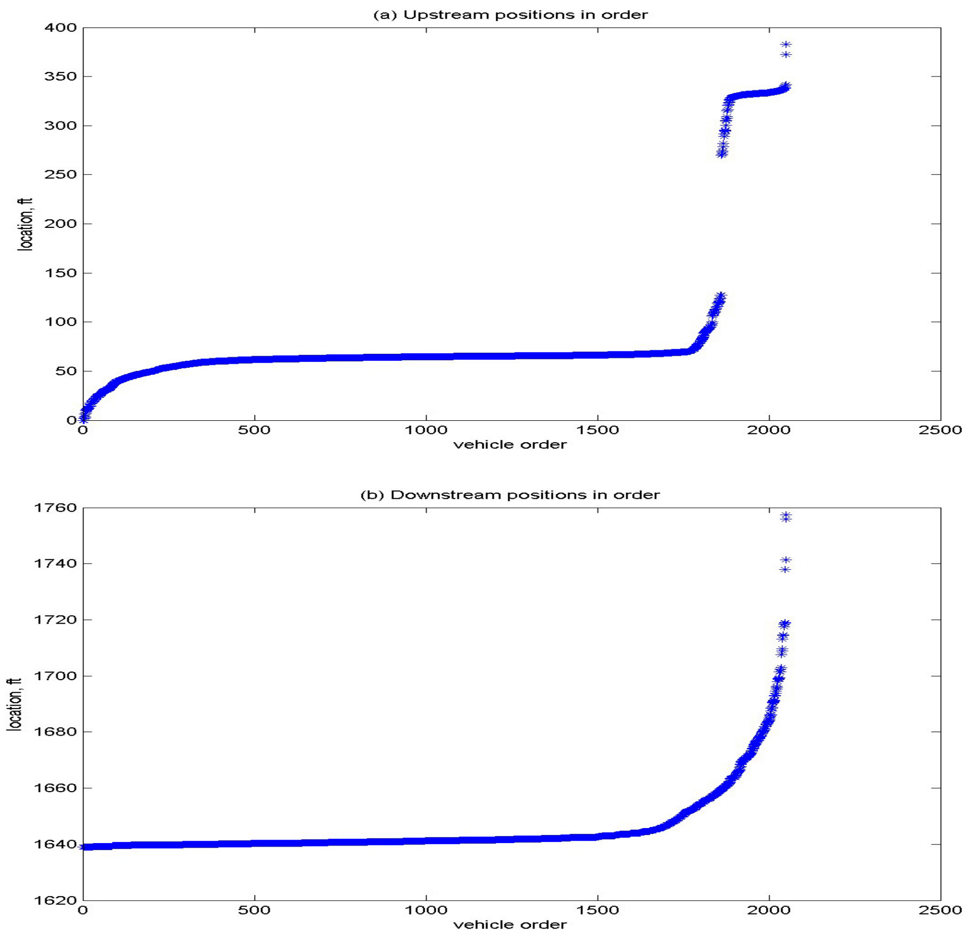

Figure 2. Study area and seven detectors

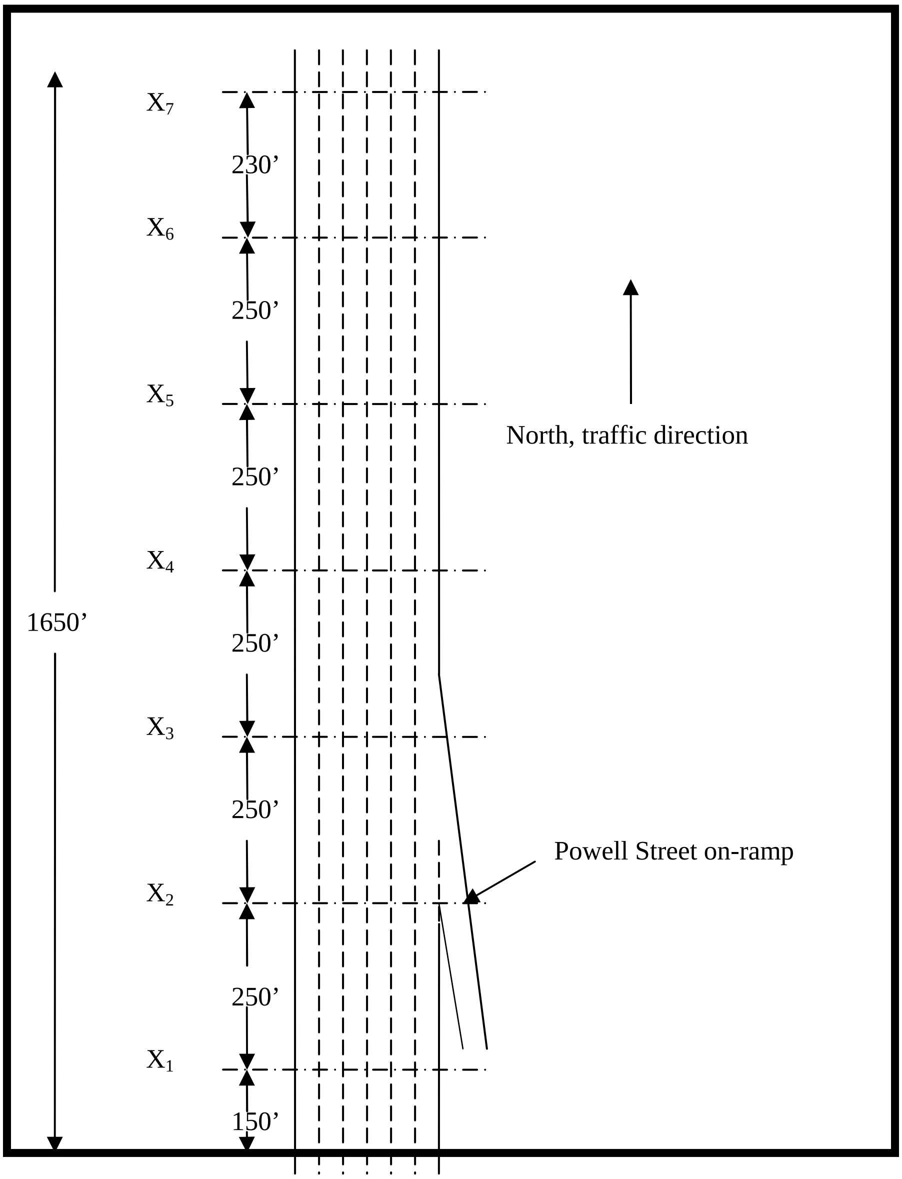

Figure 3. An example of FIFO violation among vehicles

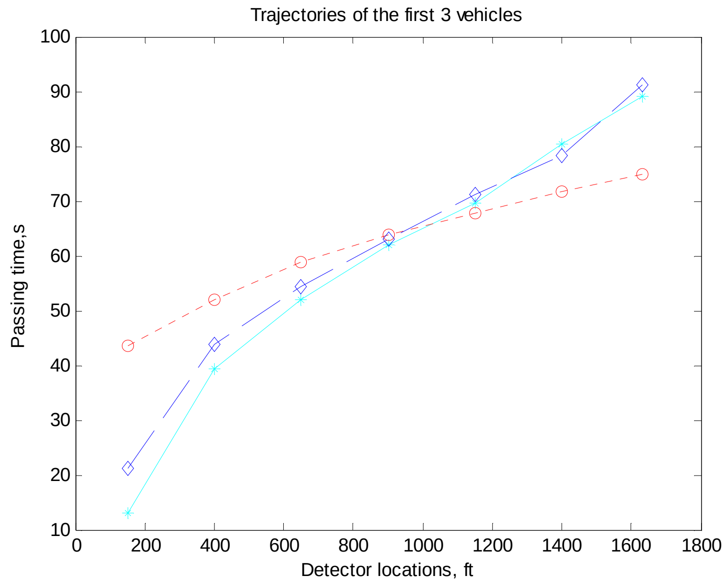

Figure 4. Individual FIFO violation vs travel time from detector 1 to detector j

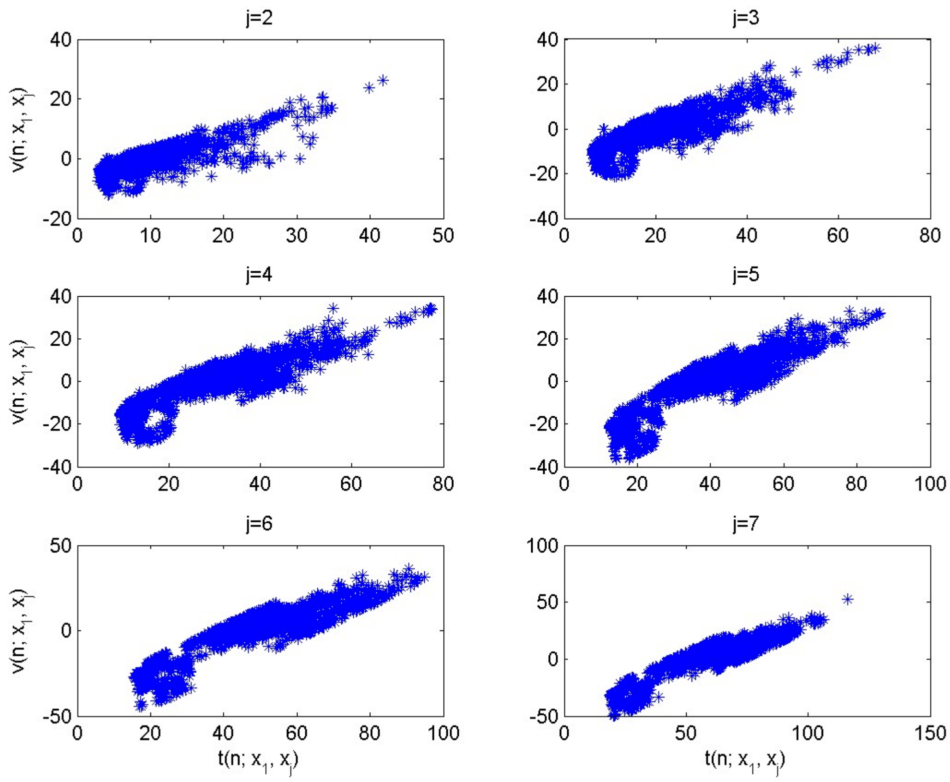

Figure 5. FIFO violation for different road sections

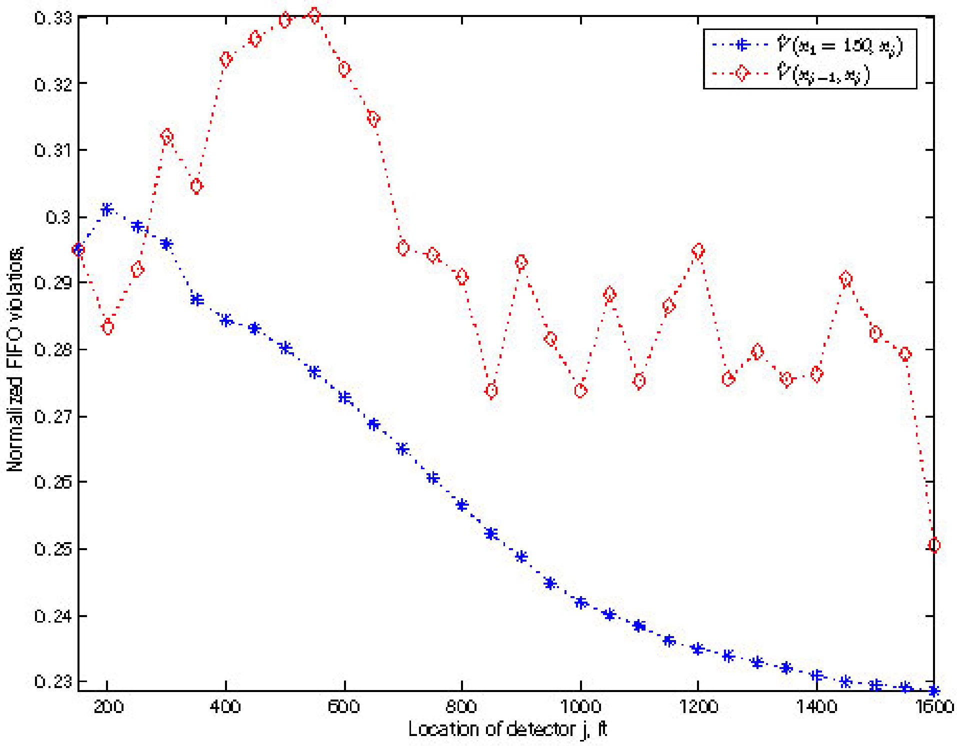

Figure 6. FIFO violation for different traffic conditions