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## **Driver Turn-Taking Behavior in Congested Freeway Merges**

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by

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## Driver Turn-Taking Behavior in Congested Freeway Merges

### ABSTRACT

Data from four merge locations in northern California and Toronto, Canada unveil a notable feature of driver turn taking. We have observed that queued vehicles from the on-ramp and freeway traffic streams enter a congested merge in some (nearly) fixed ratio, independent of the merge outflow. Drivers in competing traffic streams thus enter the merge by adopting some definite turn-taking behavior and this behavior is not influenced by the severity of the exogenous flow restriction from downstream. The findings validate part of an existing theory of merging traffic and should be considered when developing any new such theories.

### 1. INTRODUCTION

This paper concerns the manner in which two competing traffic streams enter a merge that is “fully congested;” i.e., a merge whereby an exogenous queue from downstream has spilled-over to both its approaches. Data were extracted from three such locations in California’s San Francisco Bay Area using video and from one site in Toronto, Canada using loop detectors. These data indicate that, at each site, drivers from the on-ramp and freeway merge together in what can reasonably be described as a definite ratio. And in each case, the ratio is approximately fixed, independent of the congested outflow from the merge. This means the turn-taking behavior that determines a merge ratio is unaffected by the severity of the exogenous flow restriction downstream of the merge (at least for data measured over time scales of 2 mins or more).

The findings are consistent with a theory of merging traffic proposed by *Daganzo (1995; 1996)*. The theory itself and our general approach to testing it are briefly described in the following section. The empirical evidence supporting the theory is provided in section 3. Practical implications of our findings and future research needs are discussed in section 4.

### 2. BACKGROUND

The need for theory to predict traffic conditions at merges is perhaps obvious, given that merges are such common freeway elements and given that the conditions they induce can widely affect freeway systems. What may be the best known and most rational merge theory is the one proposed by Daganzo (cited in the previous section). A brief description of it is given below.

A merge, like in Fig. 1(a), has a capacity,  $\mu$ , that can be realized when queues reside on one or both its approaches and there is no exogenous flow restriction from downstream. This maximum outflow is described with the “capacity line” in Fig. 1(b). The line indicates that merge capacity falls below  $\mu$  only when the demand from one approach (labeled “1” in the figure) is small and the other approach (the on-ramp labeled “2”) lacks sufficient capacity to keep the merge saturated.

There is evidence that the capacity of a merge is influenced by the traffic states on one or both its approaches in such way(s) that the simple form for the capacity line in Fig. 1(b) may not adequately describe the merge discharge mechanism (*Banks, 1990; Cassidy and Bertini, 1999*). This issue lies beyond the scope of our present work, however, and is

instead a subject of other studies (e.g. *Cassidy and Rudjanakanoknad, 2004; Papageorgiou and Kotsialos, 2002*).

The present study is concerned with the case when an exogenous queue from downstream engulfs the merge and spills-over to both its approaches. Both approaches thus have a reservoir of vehicles, such that drivers enter the merge at maximum rates (subject to the constraints from the downstream restriction). In this case, the theory assumes the approaches supply inflows to the merge in a definite ratio; i.e., drivers enter the merge by taking turns in some regular fashion. By specifying this ratio, delays and queue lengths can be predicted on both merge approaches. (The solution can be obtained by constructing separate queueing diagrams for each approach. The departure curves for these diagrams are constructed by specifying the merge ratio and by knowing the constrained outflow from the merge. Further discussion of this recipe is provided in *Daganzo*.)

The merge ratio is given by a line, like the one shown in Fig. 1(b). A straight “merge ratio line” has invariably been used given that, to now, there has been an absence of any data that might have suggested a different form. Thus, when queues reside on the approaches, the merge ratio is assumed to be independent of the merge outflow; i.e., the ratio is fixed, irrespective of the severity of the exogenous restriction. The same ratio is also presumed to occur when the approaches are queued and no exogenous restriction exists at all. The reader will note that the ratio’s value is given in Fig. 1(b) as  $\mu_2/\mu_1$ , where the numerator and denominator are the inflows that arise from queued approaches 2 and 1, respectively, when merge outflow is not restricted from downstream.

The data from our present study indicate that merge ratio is as described in the theory. These data were taken from four fully congested merges. All four sites are junctions formed by a freeway and an on-ramp, although each has a distinct geometry as will be described. None of the sites has a ramp meter or any other control devices to influence merging behavior.

Congested inflows to three merge locations in the San Francisco Bay Area were manually extracted from videos taken of the sites. Congested inflows from a merge in Toronto were collected from loop detectors installed there. In all cases, the analyses were performed only for those data collected from periods when the congested merge outflow was nearly stationary. (Description of the simple method used for distinguishing stationary outflows, and the rationale for sampling data in this manner, is saved for the following section.) A wide range of congested merge inflows and outflows was attained in this fashion.

Inspection of the resulting merge ratios indicates that on-ramp and freeway drivers merge in a reproducible manner. And each site can be described as having a fixed ratio. Presentation of these findings follows below.

### **3. EMPIRICAL FINDINGS**

Findings from the four study sites are presented in this section. We begin by discussing two merges formed along eastbound Interstate 80 by the on-ramps from Powell Street and from Ashby Avenue near San Francisco; these merges are highlighted with shading in Fig. 2. The upstream merge (at Powell) has five regular-use freeway travel lanes. The downstream merge (at Ashby) has four. Data from the High Occupancy Vehicle (HOV) lane were excluded from the analyses, since its traffic conditions were generally much

different from those in the adjacent lanes. (Vehicle maneuvers into and out of the HOV lane were rare near the merge locations.)

The freeway stretch is part of a “laboratory” whereby traffic is monitored using several video cameras mounted on the rooftop of a nearby 30-story building. The data used for our study of these two merges were manually extracted from videos.

Each afternoon rush, the queue from a downstream bottleneck engulfs these merges and spills-over to their approaches. Data were taken while merge approaches were queued to ensure that inflows to each merge occurred at maximum rates (subject to the downstream constraints), as this is a necessary condition for observing merge ratios. We next describe the data processing method used to verify the presence of these queues by applying the method to a portion of the data collected at the upstream-most merge at Powell Street.

Fig. 3(a) displays cumulative curves of freeway vehicle count vs time,  $t$ , at locations  $X_1$  and  $X_2$  (in Fig. 2). These cumulative curves were constructed from the counts collected over a 10-min portion of an afternoon rush (on Aug. 19, 2002). They display “virtual” departures at location  $X_2$ , such that the persistent vertical displacements between the curves verify that the freeway segment upstream of the Powell Street merge was queued. (The reader can refer to *Daganzo, 1997, pp 25-46*, for example, for further discussion on virtual departure curves.)

As a notable aside, the vertical displacements were made more visible to the naked eye by plotting the curves on an oblique coordinate system. Since they are actually presented here in orthogonal coordinates, the curves display the quantity  $O(t) = V(t) - q_0 \times (t - t_0)$ ; i.e., the virtual vehicle count to time  $t$ ,  $V(t)$ , minus a background reduction; the latter is some specified rate,  $q_0$ , multiplied by the interval extending from the curve’s start time,  $t_0$ , to  $t$ . (Further discussion on the construction of these O-curves can be found in a number of references, including *Cassidy and Windover, 1995* and *Munoz and Daganzo, 2002*).

O-curves for the Powell Street on-ramp are presented in Fig. 3(b). Their persistent vertical displacements illustrate that the ramp was queued during the period shown in the figure. Finally, the O-curves in Fig. 3(c) verify that a short freeway segment immediately downstream of the merge was queued; i.e., a queue from a downstream bottleneck restricted the outflows from our merge.

As previously noted, merge ratios were sampled only when outflows from the merge were nearly stationary. This sampling method was used to exclude data when disturbances interrupted turn taking. Generally speaking, we excluded only data from transition periods of a minute or so that often arose whenever merge outflows changed.

The near-stationary periods were distinguished by visually inspecting curves of cumulative vehicle count,  $N$ , measured in all (regular-use) freeway lanes just downstream of the merge. Near-linear portions of these N-curves marked periods of near-stationary outflows, since flows are equal to the slopes of piece-wise linear approximations to the N-curve. An N-curve was considered to have a near-linear trend when its deviations from a best-fit (straight) line never exceeded 25 vehicles. (A similar, albeit more involved method for identifying near-stationary traffic states is described in *Cassidy, 1998*.) This strategy for collecting data meant that sampling intervals were different for each data point. The intervals used in this work ranged from 2 to 20 mins.

Findings from our data analyses will now be presented separately for each site. The presentation begins with the data collected at the Powell Street merge.

### 3.1. Freeway 80 at Powell Street

We first focus attention on turn taking exhibited by drivers from the (Powell Street) on-ramp and those from the freeway's shoulder lane (only). Fig. 4(a) is used to this end. It is a scatter-plot of queued inflow from the shoulder lane vs queued on-ramp inflow. The ratios of these inflow streams are not what we have previously defined as the merge ratio, since they do not reflect turn taking by drivers in all (regular-use) travel lanes. The data in Fig. 4(a) are notable nonetheless, in that they were taken from the traffic streams that compete most directly for entry to the merge. These data will be used momentarily to verify that driver turn taking in these streams is not influenced by merge outflow and to distinguish this finding from the noisy data that can be created by factors exogenous to the merge.

Since the abscissa in Fig. 4(a) displays measurements taken only in the shoulder lane, each of its data points were extracted from a period marked by near-stationary outflows in that lane only. These periods were judged to arise whenever deviations between the shoulder lane's N-curve and its best-fit line never exceeded 10 vehicles. (Fig. 4(a) is the only scatter-plot we present that does not consider inflows and outflows from all regular-use freeway lanes.)

The unshaded data points in the figure were measured over a period spanning 50 mins during a typical (non-incident) afternoon rush period on Aug. 19, 2002. The blackened points were collected over a 30-min period on March 20, 2001 while a downstream incident created denser queueing at the merge.

The data in Fig. 4(a) exhibit a linear trend. A best-fit linear function (passing through the origin) generated a coefficient of determination,  $R^2$ , of 0.98, as annotated on the figure. (We explored the possibility of a non-linear merge ratio line by fitting the data with a power function of the form  $y = \alpha x^\beta$ . This, however, generated a slightly lower  $R^2$  and produced an estimate of  $\beta$  that was not significantly different from 1.) Also as annotated on the figure, the slope of the best-fit line through the data is very nearly 1 (1.14). The finding indicates that on-ramp and freeway shoulder lane drivers tend on average to take turns merging in what is very nearly a one-to-one alternating fashion. This kind of turn taking has been called the "zipper effect" (*Newman, 1986*).

(Scatter-plots measured at the other study sites also showed that on-ramp and shoulder lane drivers exhibit reproducible turn taking; the data in each plot exhibit a strictly linear trend with relatively little scatter. These particular plots are not presented here, however, since our study is less concerned with the interaction between on-ramp and shoulder lane traffic streams than with the merge ratios that arise when all regular-use freeway lanes are considered.)

Unfortunately, the reproducibility of turn-taking behavior at this specific site becomes less evident by plotting the inflows from all five regular-use freeway lanes against the on-ramp flows. Such plot is provided in Fig. 4(b). The data were sampled when merge outflows (in all regular-use lanes) were nearly stationary. The scatter in these data is greater than in the previous figure and the  $R^2$  for the best-fit linear function is lower as well (0.78).

Notably, the four encircled data points in Fig. 4(b) lie especially far from the best-fit line. One can visualize a straight line passing through the origin that fits the circled data points in the figure quite well. This indicates that the estimated merge ratio (the slope of the line) for these circled data would be (markedly) different from the ratio estimated for the other data in the figure. But this difference did not arise through an endogenous change in driver turn-taking. To the contrary, Fig. 4(a) previously verified that the ratio between the on-ramp's inflows and those from the freeway shoulder lane is approximately fixed over the entire range of measured conditions. It turns out that the data scatter in Fig. 4(b) is due to factors exogenous to the merge.

To advance this argument, we note first that the higher delays generated by the incident (on March 20, 2001) evidently motivated a number of drivers to divert from the freeway via the Ashby Avenue off-ramp; this off-ramp is located about 305 m downstream of the Powell Street merge, as shown in Fig. 2. While the incident was present, exit flows using this downstream ramp were nearly double those of the incident-free period; the average exit rates were about 820 and 460 vph, respectively. More revealing still, the percentage of merge outflow to have exited via that off-ramp jumped from 10 percent during the incident-free period to over 40 percent during the incident.

These higher exiting rates eased flow constraints in the shoulder lane upstream of the off-ramp. Consequently, the freeway queue was not first-in, first-out at our merge. Instead, the average shoulder lane flow (measured at  $X_3$ ) was about 750 vph during the incident, a rate that was generally about three times greater than the coinciding average flows measured in the freeway's four adjacent lanes. At this same time, vehicle speeds near the merge were observed to be higher in the shoulder lane as well.

These marked distinctions in the shoulder lane were observed only during the incident. Given these incident effects, on-ramp flows entering the merge became disproportionately high when measured relative to inflows from all regular-use freeway lanes. Consequently, all blackened data points in Fig. 4(b) lie above the best-fit line. Furthermore, the circled blackened points (that lie furthest from the line) were measured when the proportions of vehicles exiting the Ashby off-ramp were at their highest. The circled points were measured during a period when 45 percent of the outflow from the Powell Street merge exited via the Ashby off-ramp. In contrast, the other blackened points in the figure were measured when 37 percent of the outflow used this off-ramp.

Notably, the other sites used in this work did not have nearby downstream off-ramps. We find it no coincidence that these other sites yielded data without the kind of scatter we see in Fig. 4(b). Toward verifying this statement regarding scatter, we now turn our attention to the second of our four study sites.

### **3.2 Freeway 80 at Ashby Avenue**

The merge at Ashby Avenue is more isolated than its upstream counterpart, in that the nearest downstream off-ramp is located approximately 1,500 m away (see Fig. 2). As we describe below, this off-ramp had no noticeable effect on merge operations upstream.

Traffic data were collected from the Ashby merge for a 1-hour period of an afternoon rush (on March 20, 2001). Roughly half of this period was marked by typical, non-incident conditions. The other half was marked by a downstream incident. This incident created queues at the Ashby merge that were denser than usual. However, it evidently had rather little effect on the proportion of vehicles that discharged from the

merge via the shoulder lane. During the non-incident period, the shoulder lane outflow was approximately 10 percent greater than that of the average outflow in the three adjacent freeway lanes. During the incident, this difference grew to 15 percent, a modest increase.

In the absence of substantial exogenous effects of an off-ramp, the site's merge ratio was reproducible and fixed (approximately) for the entire range of conditions observed. Fig. 5 is a plot of queued inflow to the merge from the four regular-use freeway lanes vs queued inflow from the Ashby on-ramp. The blackened data points are from the incident period. The unshaded points are from the non-incident time.

These data clearly exhibit a linear trend. The best-fit line yields an  $R^2$  of 0.96. The slope of this line (the estimated merge ratio) is 0.38. This is an appreciably higher ratio than that estimated for the upstream merge at Powell Street (0.19, as annotated on Fig. 4(b)). The higher ratio is explained by the merge geometries.

As we already noted with the aid of Fig. 2, the Ashby merge has one less freeway travel lane than its upstream counterpart. This in itself is expected to produce a higher merge ratio at Ashby. Moreover, the Ashby on-ramp consists of two lanes upstream of the merge (also as shown in Fig. 2). We observed that numerous drivers in the ramp's left lane entered the freeway in advance of the merge; these drivers maneuvered into the freeway shoulder lane upstream of the merge gore. In effect then, the ramp very nearly served two lanes of inflowing traffic. This generated higher merge outflows in the freeway shoulder lane and increased the merge ratio.

The above finding is notable only in that it underscores that merge ratio is site specific. The ratio is no doubt influenced by a number of factors, not the least of which is merge geometry. Data from a third merge, with its own distinct geometry, are presented next.

### 3.3. State Route 24 at State Route 13

The next site is the segment of eastbound State Route (SR) 24 and the single-lane connector from SR 13 shown in Fig. 6(a). This merge also resides in the San Francisco Bay Area. It lies a short distance downstream of where SR 24 splits into two 2-lane freeway segments. (The two split sections eventually pass through separate bores of a downstream tunnel.) A video camera was set-up on a nearby hillside vantage point during two afternoon rush periods (on June 2 and 3, 2004) and the data were manually extracted from the videos.

The queue from a downstream bottleneck engulfs the merge. The observed range of congested inflows is not especially large at this site (since data were not obtained in the presence of any downstream incident, for example). The data that were collected there nonetheless suggest that the merge ratio can be described as fixed.

Fig. 6(b) is a scatter-plot of queued inflow from both freeway lanes vs queued on-ramp inflow. The data display a linear form. The merge ratio estimated for this site (the slope of the best-fit line in Fig. 6(b)) is 0.41.

As a minor side, it turns out this merge ratio is disproportionately high. Drivers in the on-ramp and freeway shoulder lane were observed, on average, to take turns in a nearly one-to-one fashion. (This was determined by constructing a scatter-plot like the one previously shown in Fig. 4(a)). Thus, the estimate of merge ratio exceeded 1/3 only because merge outflow was greater in the freeway shoulder lane than in the adjacent one.



The relatively small range of observed inflows is probably the more notable feature of this site, however. Happily, a larger range was obtained at our fourth and final merge location described next.

### **3.4. Westbound Gardiner Expressway at Spadina Avenue**

Finally, we examine the merge ratios measured at the Toronto site shown in Fig. 7(a). Unlike the other study sites, the merge has an acceleration lane. And unlike the other sites, the data from this merge were not obtained using video. Rather, the loop detectors shown in the figure sampled vehicle counts, speeds, and occupancies over 20-second intervals and furnished all of the data needed for the analyses at this site.

A scatter-plot of near-stationary, queued inflows is presented in Fig. 7(b). The data were taken over six hours spanning three afternoon rush periods (on March 19, 1997 and June 6 and 22, 1998). A wide range of inflows was observed, thanks to multiple bottlenecks downstream of the merge. Often, the queues at the merge created by one bottleneck were eventually over-run by denser queues from a more restrictive bottleneck further downstream.

The data in Fig. 7(b) exhibit a clear linear trend. The best-fit line yields an  $R^2$  of 0.95. The disproportionately high merge ratio of 0.36 is again the result of outflows in the shoulder lane that exceed those in any adjacent lane.

## **4. CONCLUSIONS**

The data from four study sites indicate that when both the on-ramp and freeway approaches are queued, inflows to a merge can be described with a ratio line of constant slope. Drivers evidently merge by taking turns in a definite fashion and, absent certain exogenous factors (e.g. due to a downstream off-ramp), the ratio is unaffected by merge outflow.

The findings mean that a congested merge can be modeled in a simple way. Namely, delays and queue lengths can be predicted for both approaches by specifying the merge ratio. (One must also specify traffic demands for the merge and the merge's constrained outflow, as described in *Daganzo*.) The merge ratio can be estimated at a site by jointly measuring inflows from its approaches as in our present work; i.e., when both approaches are queued. Since the ratio is evidently fixed, one need not collect samples over a wide range of flows to obtain an estimate (although the sampling interval should be long relative to any periods marked by non-stationary outflows brought by disturbances from downstream).

As noted earlier in section 2, predicting merge capacity (in the absence of an exogenous restriction) is an aspect of the theory still in need of further study. Empirical evidence (already cited in this manuscript) reveals that merge capacity is affected by the traffic states on its approaches. Further experiments are needed to understand this cause and effect relation more completely.

## **ACKNOWLEDGEMENT**

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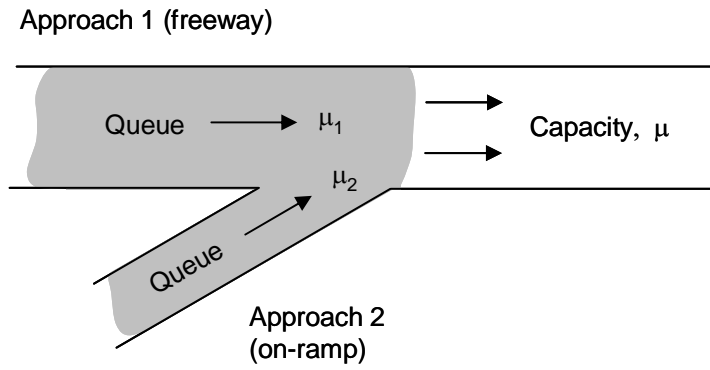
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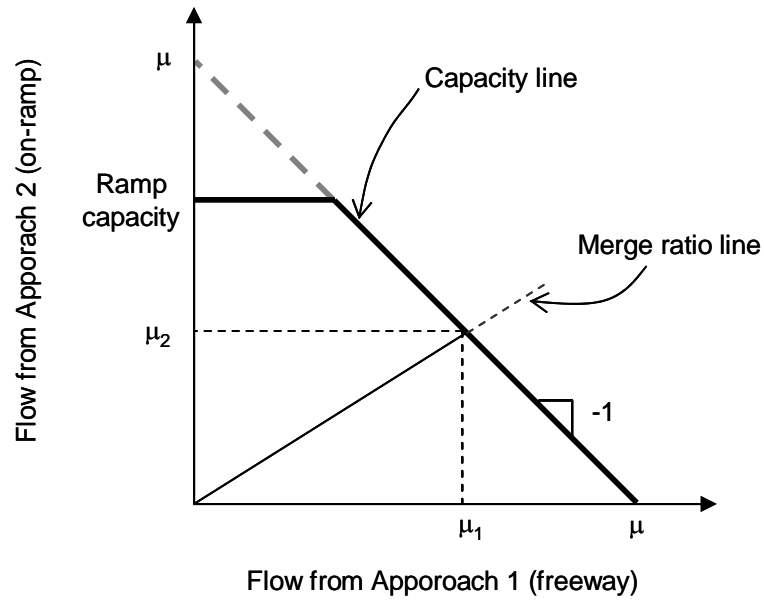
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(b) Inflows from all freeway lanes vs. inflows from Spadina Ave. on-ramp



(a)



(b)

Figure 1

(a) Hypothetical Merge

(b) Merge Theory

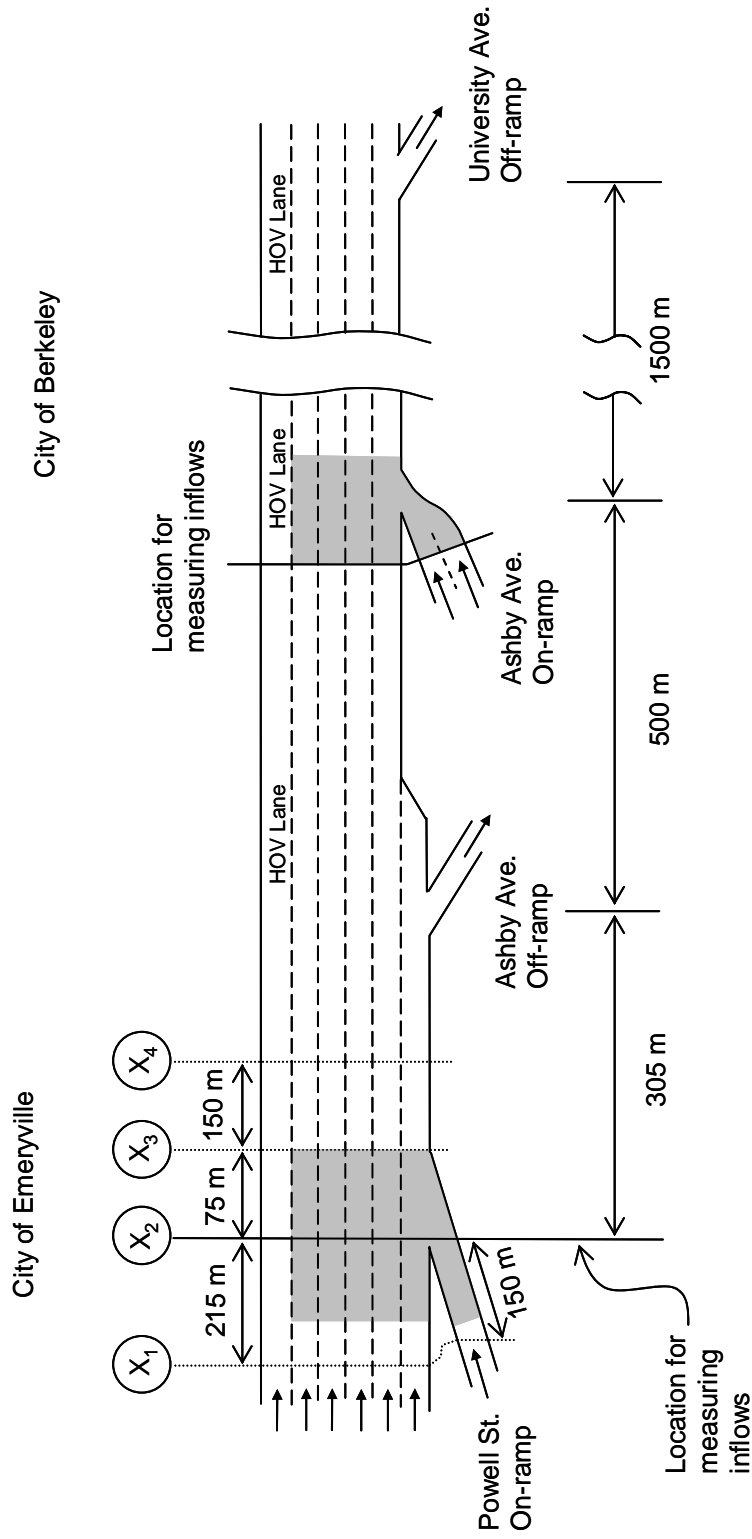
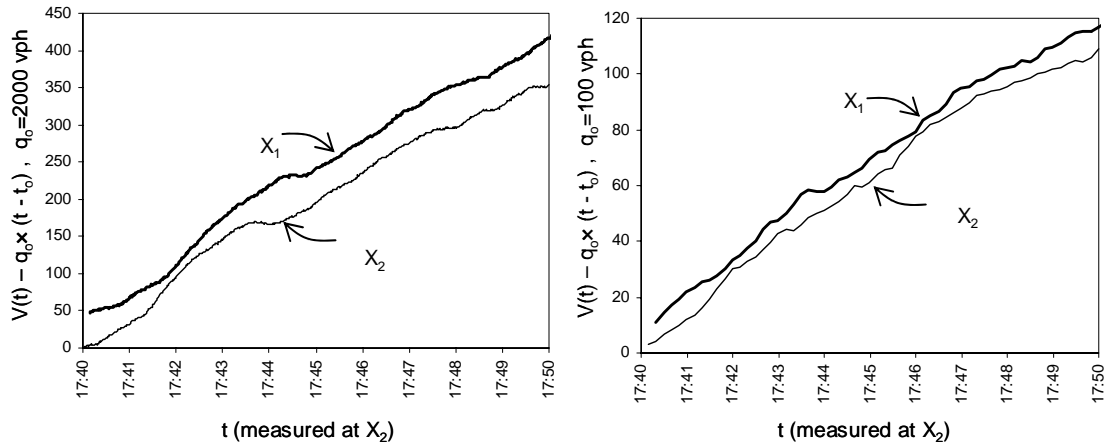
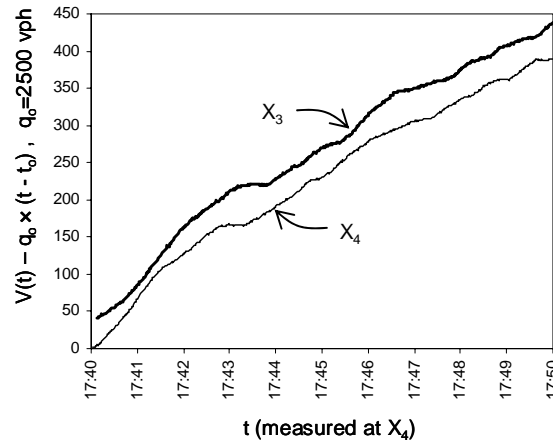


Figure 2: Eastbound Interstate 80



(a)

(b)



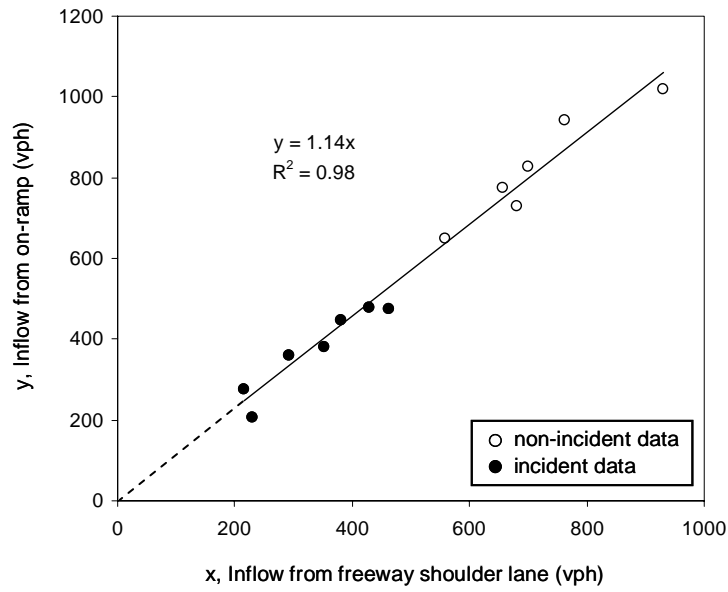
(c)

Figure 3

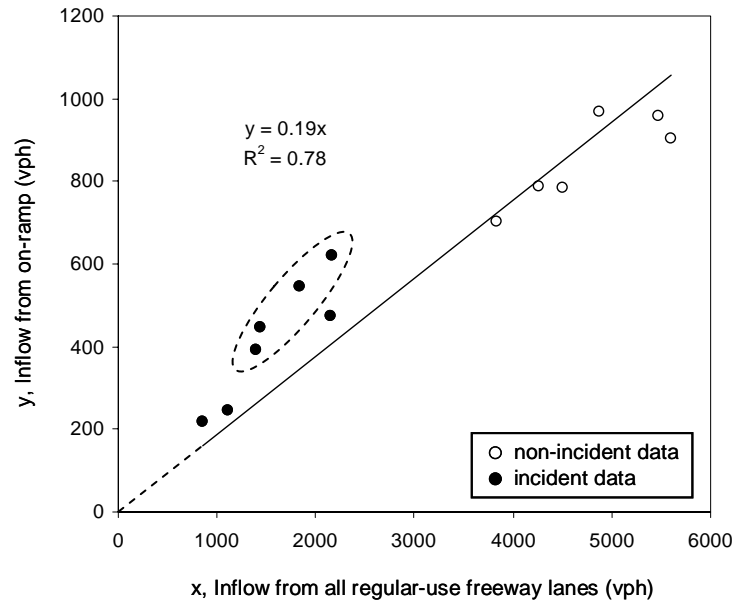
(a) O-curves for freeway approach at  $X_1$  and  $X_2$

(b) O-curves for on-ramp at  $X_1$  and  $X_2$

(c) O-curves at  $X_3$  and  $X_4$



(a)



(b)

Figure 4

- (a) Inflows from freeway shoulder lane vs. inflows from Powell St. on-ramp
- (b) Inflows from all regular-use freeway lanes and inflows from Powell St. on-ramp

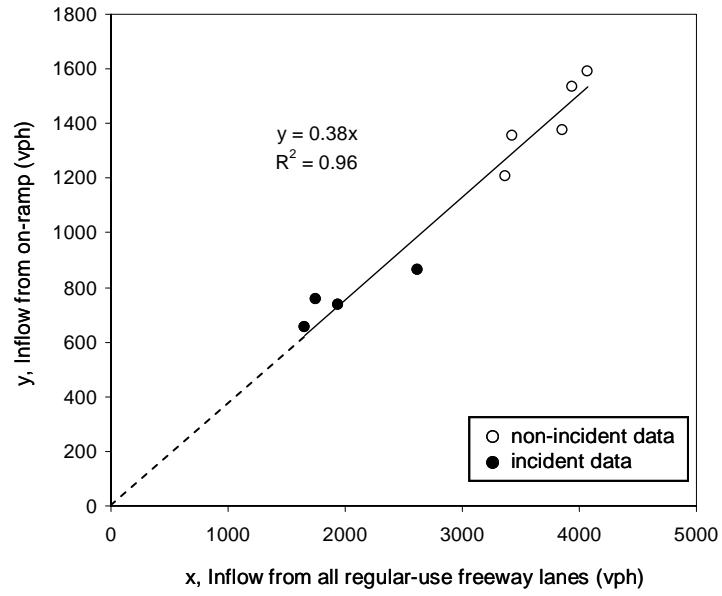


Figure 5: Inflows from all regular-use freeway lanes vs. inflows from Ashby Ave. on-ramp



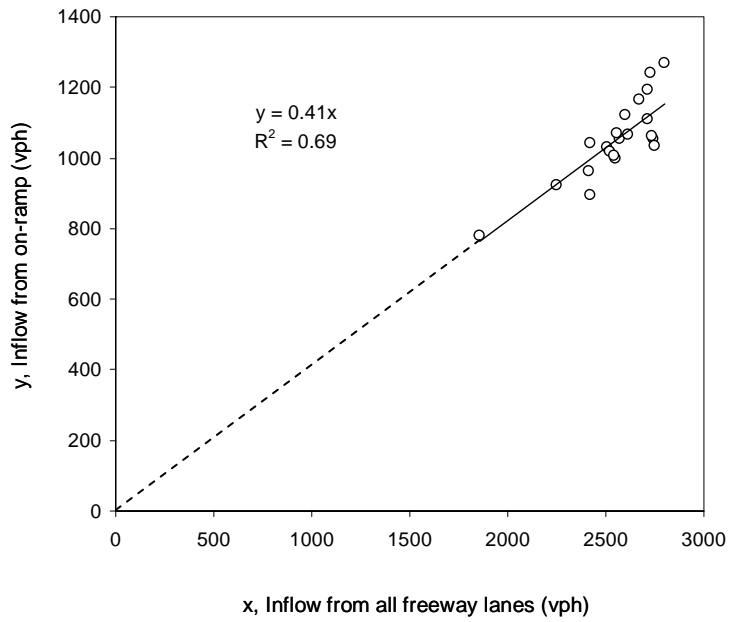
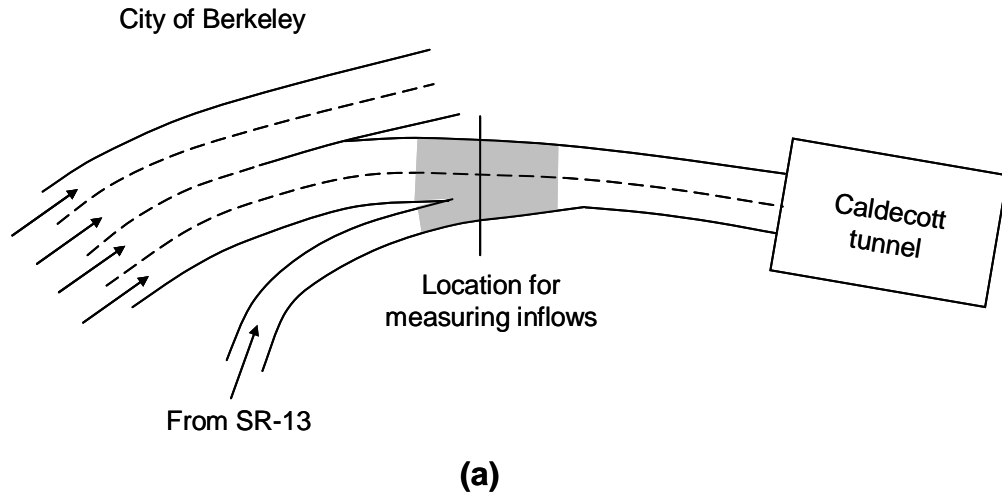
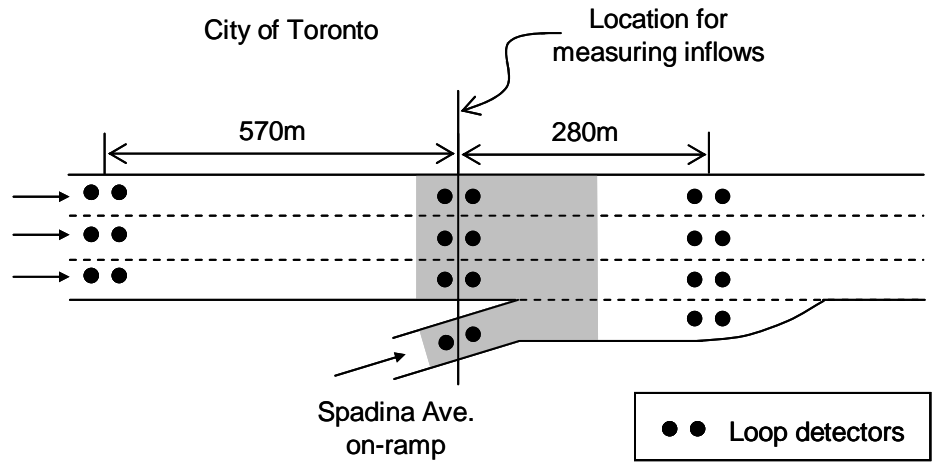
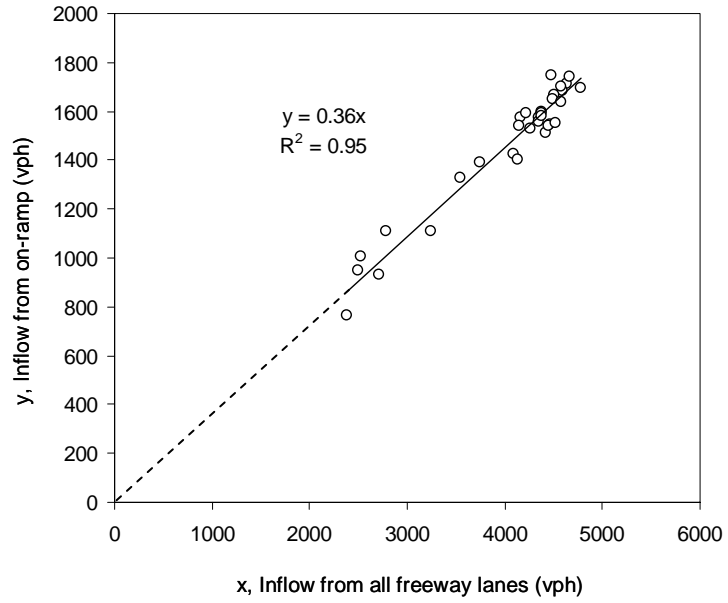


Figure 6

- (a) Eastbound State Route 24
- (b) Inflows from all freeway lanes vs. inflows from on-ramp



(a)



(b)

Figure 7

- (a) Westbound Gardiner Expressway, Toronto, Canada
- (b) Inflows from all freeway lanes vs. inflows from Spadina Ave. on-ramp