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## **Empirical Study of Ramp Metering and Capacity**

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<p><b>16. Abstract</b></p> <p>Traffic data near the junction of a single-lane on-ramp (with a ramp meter) and a three-lane freeway were measured for six weekdays during the rush and studied. On each of these days, the merge became a bottleneck with queue discharge rates that were substantially lower than the flows that had passed the merge prior to the bottleneck's activation. On some days, these earlier high flows persisted for many minutes.</p> <p>The bottleneck always occurred when inflows from the on-ramp surged in the presence of high flows arriving from the freeway. Often, the on-ramp surges persisted for no longer than a minute or two and a wide range of these surges was observed. The data show strong correlation between the magnitudes of the on-ramp surges and the merge area's outflows that were measured during the final minutes before the bottleneck activations. These short-run outflows were markedly higher on days when surges from the on-ramp were low. This implies on-ramp metering can be an effective means of postponing this bottleneck's activation, thereby prolonging higher outflows from the merge.</p> <p>Further study of the data indicates that vehicles often maneuvered from the shoulder lane to the center lane at locations just downstream of the merge. It appears that bursts in this lane-changing activity were what triggered the bottleneck's daily activations and that these bursts coincided with surges in inflow from the on-ramp. (These lane changes were evidently negotiated by drivers who had just originated from the on-ramp and/or by other drivers overtaking them). Thus, the benefits of metering inflows at this on-ramp seem to stem from the effects this has on limiting disruptive lane changing downstream.</p>			
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## **IMPLEMENTATION STATEMENT**

- Copies of this report will be distributed to districts of the California Department of Transportation and to selected persons in the headquarters office of that agency.
- This report is published in the effort to assist traffic engineers, transportation planners and highway designers in the area of freeway operations.

## **DISCLOSURE STATEMENT**

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## 1. INTRODUCTION

This manuscript reports on certain traffic details measured at a freeway merge before and after it became a bottleneck on each of six observation days. The findings indicate that flows departing this merge can be made substantially higher by metering the on-ramp to restrict the rate its vehicles enter the freeway. Evidently this is because restricting inflows from the on-ramp will limit disruptive vehicle lane-changing maneuvers just downstream. It follows that a metering scheme can reduce the total delay at this merge (collectively incurred by all vehicles arriving from the freeway and the ramp), even absent any changes in commuter travel patterns in response to the scheme.

These findings came to light by collecting high resolution data (including individual vehicle arrival times) at strategic locations near the merge and then processing and analyzing these data in careful ways. These painstaking procedures verified, among other things, that during each afternoon rush the site became an *active* bottleneck; i.e., queues formed near the merge, but traffic remained freely flowing at locations just downstream of this (*Daganzo, 1997*). During its active periods, measured flows departing the bottleneck were therefore not impeded by any queues emanating from further downstream.

The freeway site itself, and the kinds of traffic data extracted there, are described in section 2 of the manuscript. Verification that the site became an active bottleneck and that this activation diminished outflows (i.e., capacities) is provided in section 3. In section 4, we show that the on-ramp inflows that accompanied the bottleneck's activation each day were negatively correlated with the short-run outflows measured just prior to these activations. This finding indicates that ramp meters can postpone the bottleneck's activation. Presentations in section 5 offer an explanation for this. The data provided there indicate that the bottleneck was triggered each day by bursts in the vehicle lane-changing activity just downstream of the merge and that these bursts were evidently motivated by surges in inflow from the on-ramp. We show in section 6 that on-ramp metering served to increase queue discharge flows even after the bottleneck had activated. Certain implications of these findings are summarized in the conclusions.

## 2. STUDY SITE AND ITS DATA

Figure 1 is a sketch of the study site, a stretch of eastbound Freeway 22 and its junction with the Fairview Avenue on-ramp in Orange County, California. Data were collected during the afternoon rush hours on six days spanning the period of November 8, 2000 to March 28, 2002.

As shown in the figure, loop detectors are located in each lane at MilePosts (MPs) 8.7 and 9.0. These recorded, among other things, vehicle counts over 30-sec intervals.<sup>1</sup> But as will be made clear in the following sections, data from these loop detectors played a minor role in the study. Instead, analyses were primarily performed on the individual vehicle arrival times at MPs 9.1, through 9.4 (as labeled on the figure). Vehicle trip times between some of these MPs were measured as well. These data were manually extracted from videotapes that were recorded by cameras placed on the freeway over-crossing just downstream of the merge.

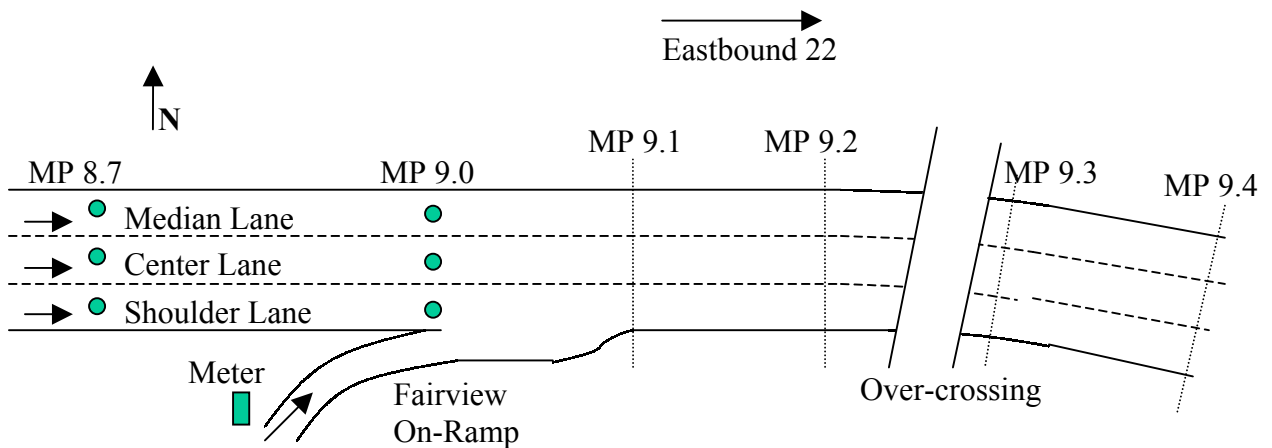


Figure 1  
Study Site. Eastbound Freeway 22, Orange County, California

One of these cameras provided measurements of on-ramp vehicles passing MP 9.0 and merging onto the freeway. The meter at this ramp reportedly restricts on-ramp traffic at a fixed rate of 1,200 vph. A wide range of ramp inflows was nonetheless observed to accompany the bottleneck's activations over the six days studied here. On

<sup>1</sup> During one of the days studied here (November 8, 2000), only the detectors at MP 8.7 functioned while those downstream at MP 9.0 did not record data. On three other days, the opposite occurred; i.e., the detectors at MP 9.0 were the only ones to function.

several days, for example, lower demands at the on-ramp kept these inflows from reaching 1,200 vph. On one such occasion, the ramp surge that accompanied the bottleneck activation was only 960 vph. On another day, the meter was not in operation and on-ramp inflow surged to 1,440 vph.

Weather conditions were good on each of the observation days. Analyses of the data and the findings are described in the following three sections of the manuscript.

### **3. THE BOTTLENECK AND ITS FLOWS**

In this section, we demonstrate the use of specially transformed cumulative count curves for identifying the bottleneck and the outflows that occurred each day before and after this bottleneck became active. To this end, Figures 2(a) and (b) show curves of cumulative vehicle count,  $N$ , vs time,  $t$ , that were measured across all freeway lanes at certain MPs during a rush (on March 15, 2001). These curves have been transformed as explained below.

First, the curves in each figure were measured from the passage of an imaginary reference vehicle so that each set of curves was constructed from the same collection of vehicles. Secondly, each  $N$ -curve was shifted forward by the average free flow vehicle trip time from its respective MP to the downstream-most MP shown in its figure. The vertical separations between any two curves (of the same figure) are thus the excess vehicle accumulations between the respective MPs due to freeway traffic delays.

The  $N$ -curves were transformed in one final way to render these separations and certain other of their features more visible. Namely, an oblique coordinate system was used in each figure to plot  $N - q_0 \times (t - t_0)$  vs  $t$  for each curve's starting time,  $t_0$ , and some choice of background flow,  $q_0$ ; a fixed  $q_0$  was used for the entire collection of curves shown in a given figure and its value was selected so that the range of  $N - q_0 \times (t - t_0)$  was small as compared with the  $N$  itself. This coordinate system reduced the vehicle count actually displayed on each figure's ordinate. This, in turn, amplified the curves' vertical separations and made them more visible to the naked eye.

The curves' changes in slopes were amplified as well, such that flow changes at a MP are made evident by taking piece-wise linear interpolations of the curves themselves.

Examples of piece-wise interpolations are provided in Figures 2(a) and (b) and will be provided in other figures as well.

Further discussion on the construction and interpretation of oblique N-curves is available from a number of sources, including Cassidy and Windover (1995). It suffices for now to direct the discussion to Figure 2(a). It presents curves at the four MPs downstream of the on-ramp during a certain 14-min period of the rush. It is clear from the figure that traffic was nearly freely flowing during the early minutes of this period; i.e., these curve portions remained nearly (although not entirely) superimposed, even as flows departing the merge climbed to well above 7,000 vph. But by  $t = 13:30$ , the curves at MPs 9.1 and 9.2 diverged from their two downstream counterparts (indicating the presence of excess vehicle accumulations), while the curves at downstream MPs 9.3 and 9.4 remained superimposed. The freeway segment between MPs 9.2 and 9.3 was thus identified as the initial location of an active bottleneck; i.e., the head of a queue first resided somewhere between these MPs.

But Figure 2(a) also shows that queueing downstream of MP 9.1 all but disappeared by  $t = 13:34$ . By this time, its N-curves were again nearly superimposed and only occasionally displayed (rather small) vertical displacements thereafter.

Figure 2(b) shows, however, that the head of the queue had merely moved backward (against the flow of traffic) and that delays and excess vehicle accumulations persisted upstream of the merge. Shown in this second figure are oblique N-curves at MPs 9.0 and 9.1. These were constructed from the counts of vehicles that had arrived to the merge from the freeway. Vehicles from the on-ramp were excluded from this figure since these did not pass the location described by the upstream curve (i.e., at MP 9.0)<sup>2</sup>. The figure clearly indicates that queueing between MPs 9.0 and 9.1 continued well beyond  $t = 13:34$ .

Figures 2(a) and (b) collectively verify that, beyond  $t = 13:30$  (and prior to the bottleneck's de-activation some time later), flows measured downstream of the on-ramp

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<sup>2</sup> The N-curve at MP 9.0 was constructed from (30-sec) counts measured by loop detectors that were likely subject to small errors. But the finding that queueing persisted between MPs 9.0 and 9.1 rests upon large vertical separations between the respective N-curves, such that small errors in the detector counts would not change this diagnosis.



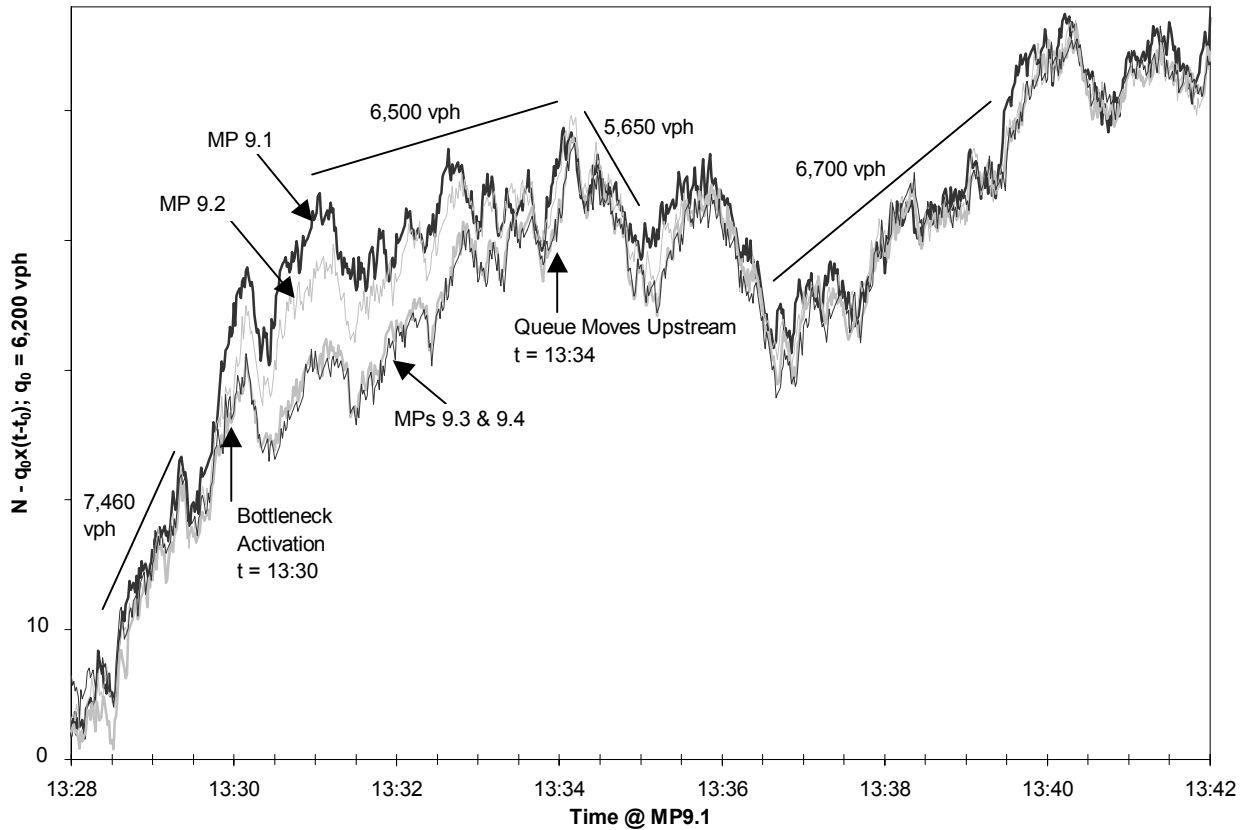


Figure 2(a)  
Oblique N-curves at MPs 9.1 through 9.4 (March 15, 2001)

(e.g. at MP 9.3) were queue discharge rates. These were the maximum rates that could depart the active bottleneck.

It is notable that, following the activation, the N-curves in Figure 2(a) display obvious changes in slopes, indicating changes in the queue discharge flows. These changes are evident both in the short-run (as wiggles on the curves) and in the longer-run (as exemplified by the linear approximations that accompany some extended portions of the N-curves). Longer-run trends in the curves also show that flows departing the merge diminished following the bottleneck's activation.

An explanation for these changes in flow is offered in a later section of this manuscript. We now conclude the current section with a second demonstration of the changes in outflow that accompanied an activation of this bottleneck.

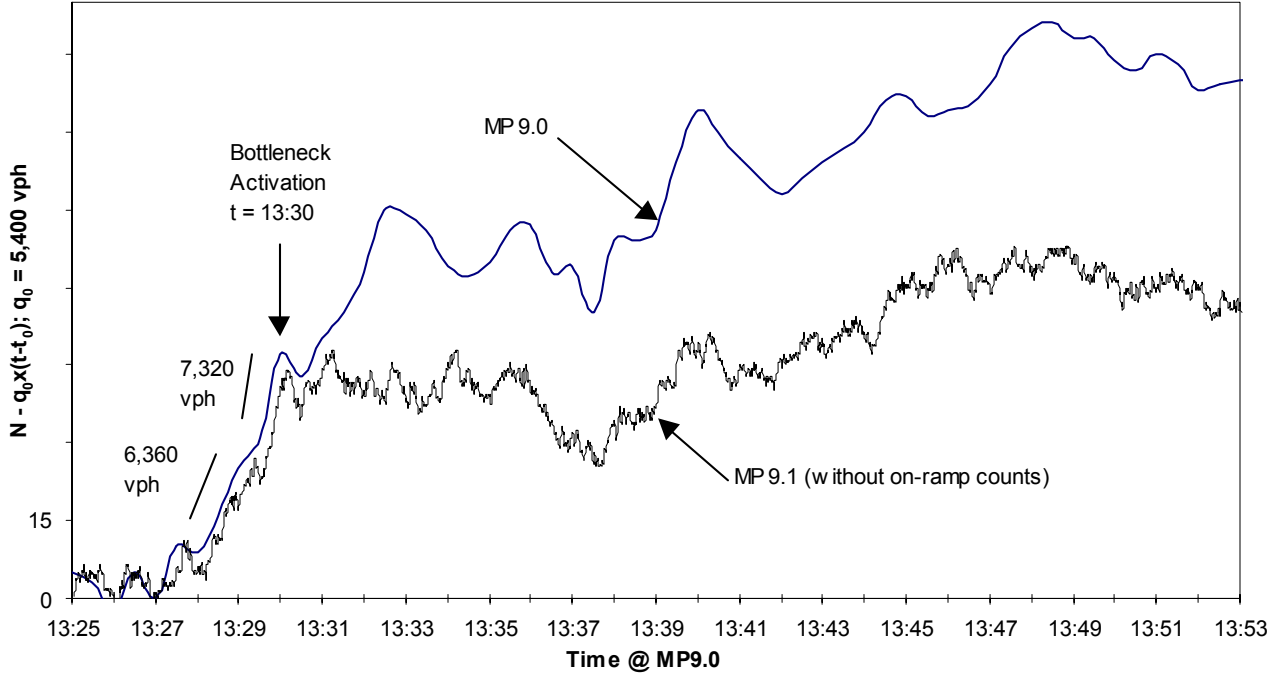


Figure 2(b)  
Oblique N-curves of freeway traffic at MPs 9.0 and 9.1 (without on-ramps) (March 15, 2001)

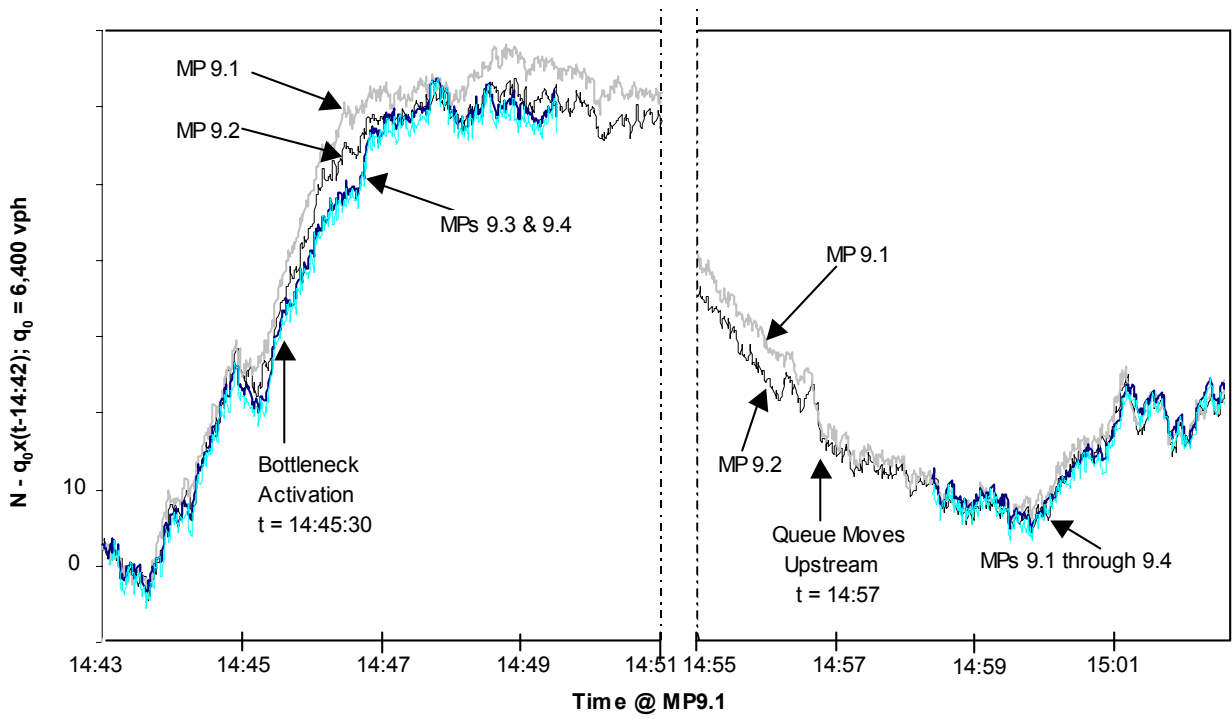


Figure 3(a)  
Oblique N-curves at MPs 9.1 through 9.4 (February 20, 2001)

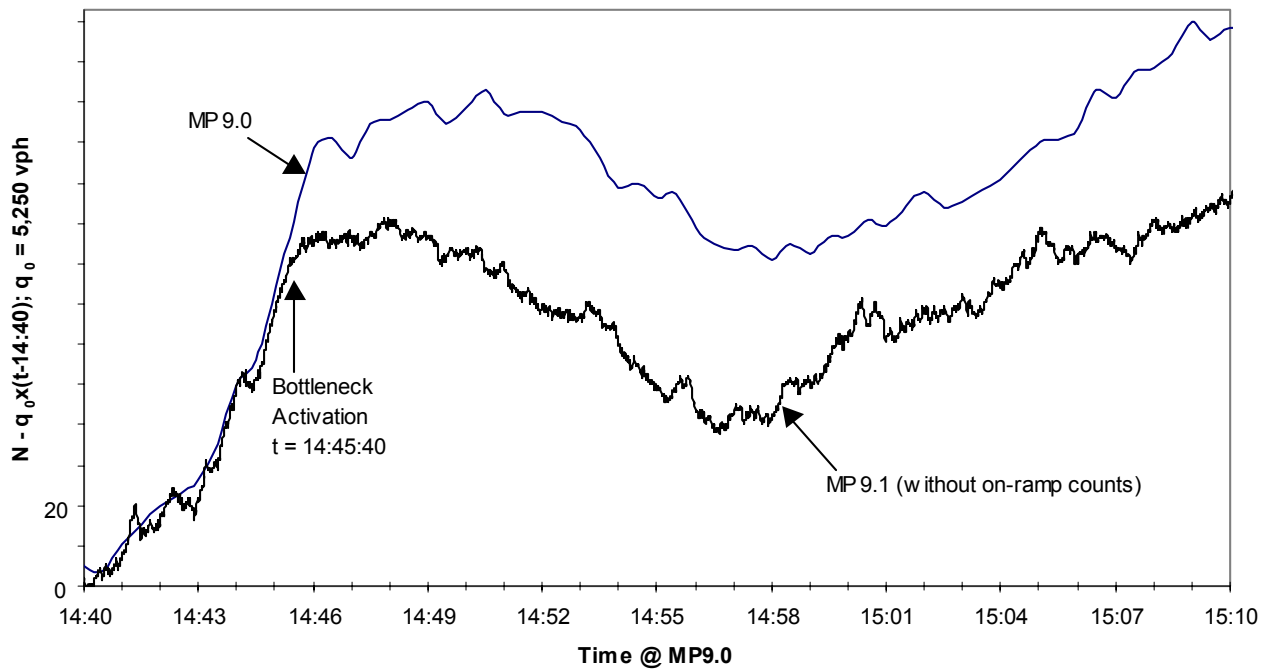


Figure 3(b)  
Oblique N-curves of freeway traffic at MPs 9.0 and 9.1 without on-ramp counts (February 20, 2001)

Figures 3(a) and 3(b) are oblique N-curves from another observation day (February 20, 2001). The former displays portions of curves sufficient to verify that the bottleneck again activated between MPs 9.2 and 9.3, on this day at  $t = 14:45:30$ . As in the day presented earlier, flows departing the merge (measured at MPs 9.3 or 9.4) dropped just after the activation. Figure 3(a) also shows that the head of the queue moved upstream by  $t = 14:57$ , leaving virtually no evidence of any delays downstream of MP 9.1 beyond this time. But Figure 3(b) demonstrates that queuing remained just upstream of MP 9.1 for some time thereafter.

Figure 4 provides a more detailed presentation of the outflow reductions that accompanied the bottleneck's activation on this day. It displays an oblique N-curve at MP 9.3. The counts for this curve started earlier in the rush. It shows that the merge accommodated an average flow of 6,960 vph for a full 15 mins prior to bottleneck activation. Given the persistence of this high flow, it cannot be attributed to statistical variation. And notably, this high rate was 10 percent greater than the average queue

discharge that eventually ensued; (the latter was measured for an hour following this activation).

So the bottleneck's activations had the undesirable consequence of reducing outflows from the merge. In the following section, we show that ramp metering can forestall these outflow reductions.

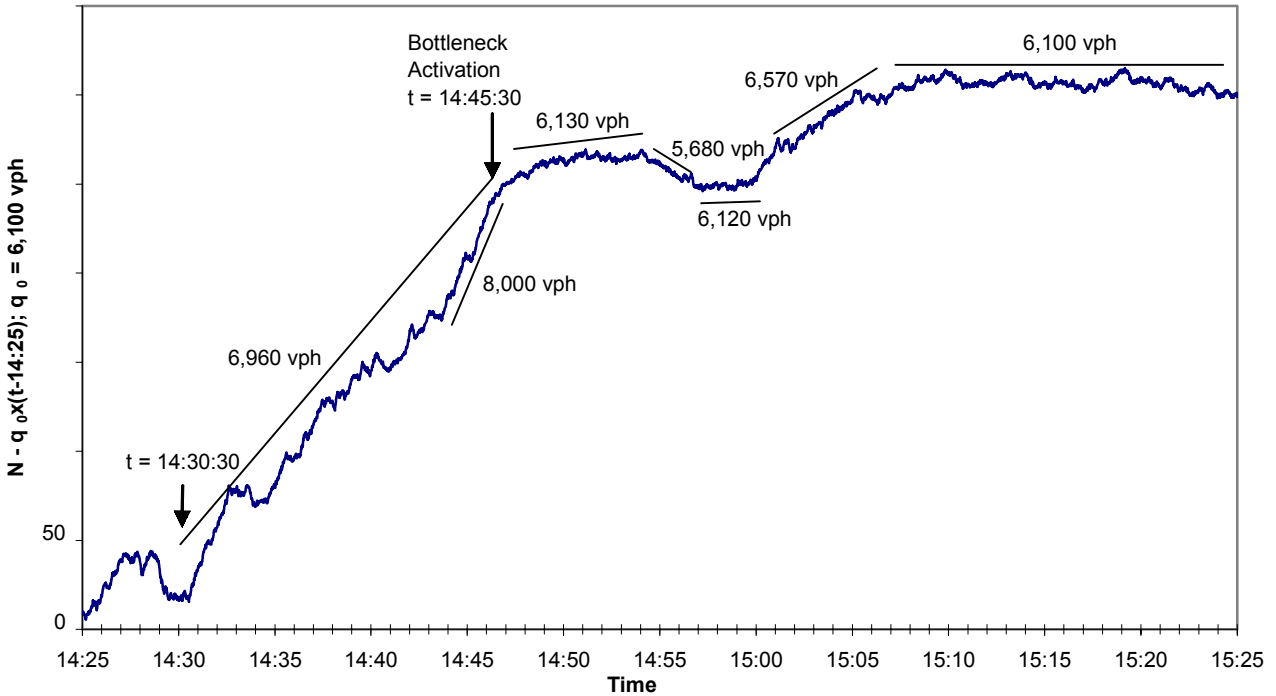


Figure 4  
Oblique N-curve at MP 9.3 (February 20, 2001)

#### 4. POSTPONING BOTTLENECK ACTIVATION VIA METERING

In this section, we provide evidence that metering the on-ramp can postpone the bottleneck's activation and the lower outflows that result. This important finding came by studying oblique N-curves from each observation day to determine the flows that accompanied the bottleneck's activations. This included studying N-curves of counts from the on-ramp (and examples of these curves are presented in later sections).

Figure 5 presents the results of this study. It displays the on-ramp surges that accompanied each day's activation of the bottleneck vs the merge area's outflows measured for several minutes immediately prior to each activation. The correlation

shown in this figure is remarkable. It indicates that keeping surges from this ramp small can result in higher short-run outflows. The range observed in these outflows is substantial. It extends from as low as 6,730 vph on November 8, 2000, a day when the on-ramp meter was not in service, to 8,050 vph on February 21, 2001 when diminished demand at the ramp kept its inflows low.<sup>3</sup>

This finding does not suggest that by restrictively metering the on-ramp, outflows comparable to the highest rates shown in Figure 5 will be realized for extended periods. (We restate, for emphasis, that most of the outflows displayed in this figure were measured for only a few minutes and that there is no evidence the higher values shown there could have been sustained for long durations). Rather, each data point in Figure 5 indicates that the merge did accommodate the outflows leading up to the one that accompanied that particular bottleneck activation. It follows that sufficiently restrictive metering at this on-ramp can at least postpone bottleneck activation and thereby forestall the outflow reductions that result.

The N-curve previously shown in Figure 4 illustrates a case in point. On the day counts were measured for this curve (February 20, 2001), an average outflow of nearly 7,000 vph was sustained for many minutes before an even higher flow occurred and the bottleneck activated. Inflows from the ramp during this time did not exceed 1,100 vph (and evidence of this is shown later in Figure 7(a)).

Notably, Figure 5 indicates that this high flow of nearly 7,000 vph would not have been sustained had its contribution from the on-ramp been allowed to exceed about 1,350 vph. This indicates that metering inflows from the on-ramp can prolong higher outflows from the merge.

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<sup>3</sup> The observation from March 26, 2002 shows that the on-ramp surged to a rate that is slightly higher than the fixed metering rate of 1,200 vph. We suspect this surge might have resulted from a small number of commuters who chose to violate the meter's assignment of right-of-way

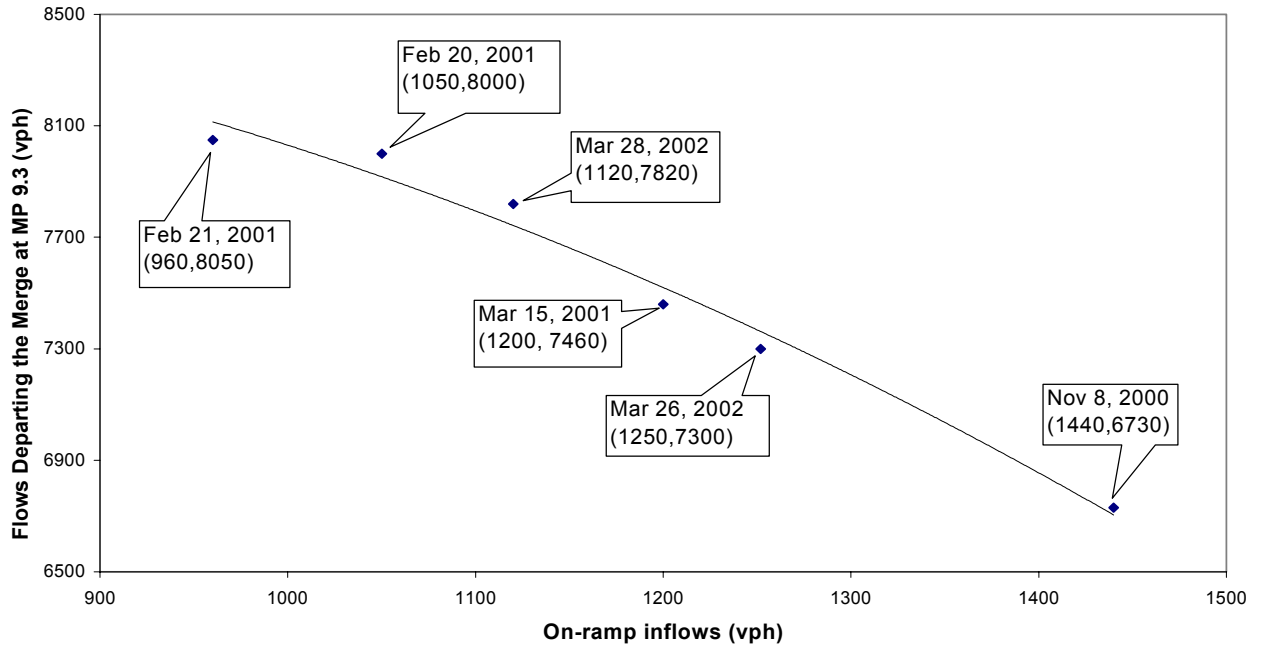


Figure 5  
On-ramp and downstream flows measured just before the bottleneck activations on each observation day

## 5. AN EXPLANATION

Further study of the measured data provided insight into the vehicular interactions that triggered the bottleneck's activations and the reason for the subsequent reductions in outflow. The findings explain why these events can be postponed by metering the on-ramp in suitable fashion.

Namely, it appears that the bottleneck activations were caused by excessive rates of vehicular maneuvering from the shoulder lane to the center lane at locations just downstream of the merge. Bursts in this lane-changing activity created vehicle slowing near the merge and reductions in outflow. Notably, these bursts in lane changing coincided with surges in inflow from the on-ramp; evidently, much of this lane changing was negotiated by drivers who had only recently merged onto the freeway from the on-ramp and/or by other drivers overtaking them.<sup>4</sup> So metering is apparently beneficial in that restricting inflows from the ramp limits disruptive lane-changing downstream.

<sup>4</sup> Some of the on-ramp vehicles may have entered the freeway at relatively slow speeds and this would have motivated vehicle overtaking.

In this section, we provide a demonstration of the phenomena described above using data taken from one of the observation days (March 15, 2001). We begin this presentation by showing that the bottleneck's activation was marked by vehicle slowing in the shoulder lane just downstream of the merge (as will be evident in Figure 6(a)) and that this slowing soon spread to all freeway lanes (Figure 6(b)). Following this, we will show that the initial vehicle slowing was accompanied by reductions in outflows from the merge and that periodic slow-downs and outflow reductions continued after the bottleneck became active (Figure 6(c)). Having demonstrated the link between vehicle slowing and outflows, we then demonstrate that on-ramp surges coincided with slow-downs (Figure 6(d)) because these surges evidently triggered excessive lane changing downstream (Figure 6(e)).

We begin with Figure 6(a). It displays vehicle trip times sampled over a stretch of the shoulder lane that lies between MPs 9.1 and 9.2; (the videotaped images facilitated trip time measurements here). The figure presents the ratios of the actual trip times to the average free flow trip time; the latter was estimated from samples drawn early in the rush.<sup>5</sup> The data are expressed as these ratios to facilitate comparisons with other lanes and on another day (since the segment lengths used for sampling trip times changed in each of these instances). The ratios are plotted against the times vehicles arrived at the upstream end of the stretch and the inter-arrival times between sampled vehicles were only about 5-secs long. The trip time ratios for each vehicle sampled are shown in the figure with the thin line. The bold line is the 30-sec moving average of these.

Figure 6(a) shows that trip times began to rise in the shoulder lane by  $t = 13:30$ , the time previously identified (in Figure 2(a)) as marking the bottleneck's activation. These trip times rose sharply soon thereafter and then diminished by  $t = 13:34$ , the time when the head of the queue had moved upstream.

Slow-downs in the center and median lanes, although less dramatic, followed close on the heels of the shoulder lane's trends, as evident in Figure 6(b). This shows that vehicle slowing in the shoulder lane spread quickly across the freeway.

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<sup>5</sup> Designating the denominator of this ratio as the free flow trip time may be a misnomer; i.e., the denominator may actually be slightly higher than the average trip time under very low flows. This detail would not, however, affect our diagnoses.

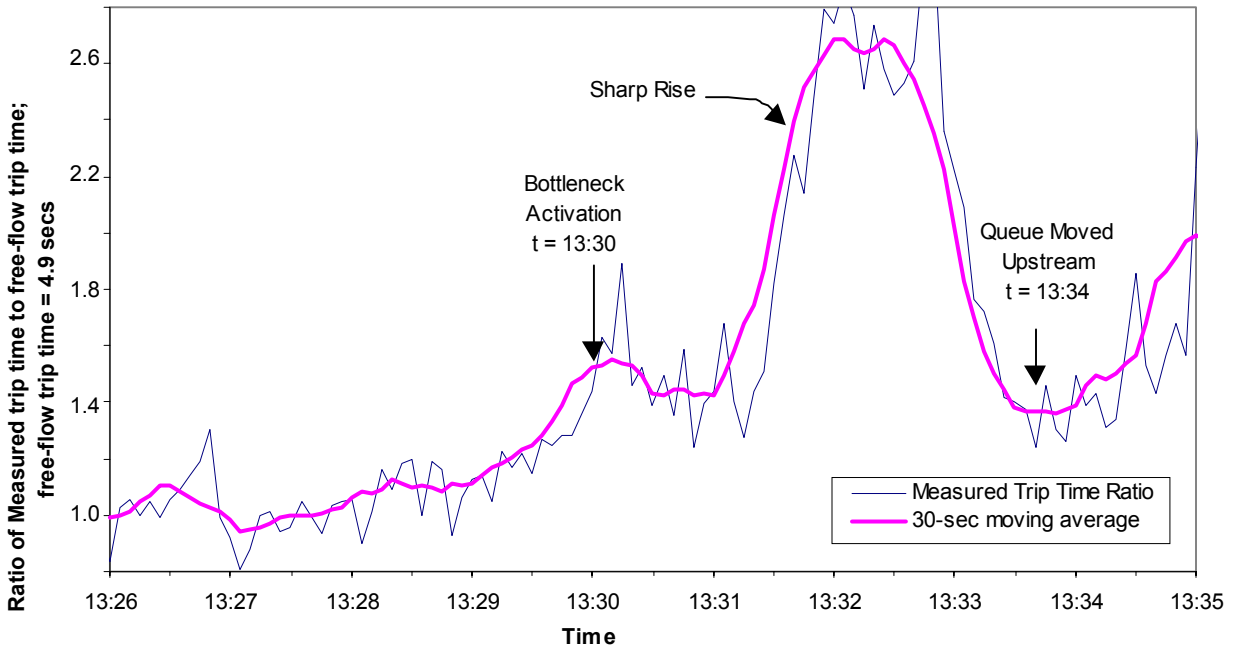


Figure 6(a)  
Sample Trip Times in the shoulder lane (March 15, 2001)

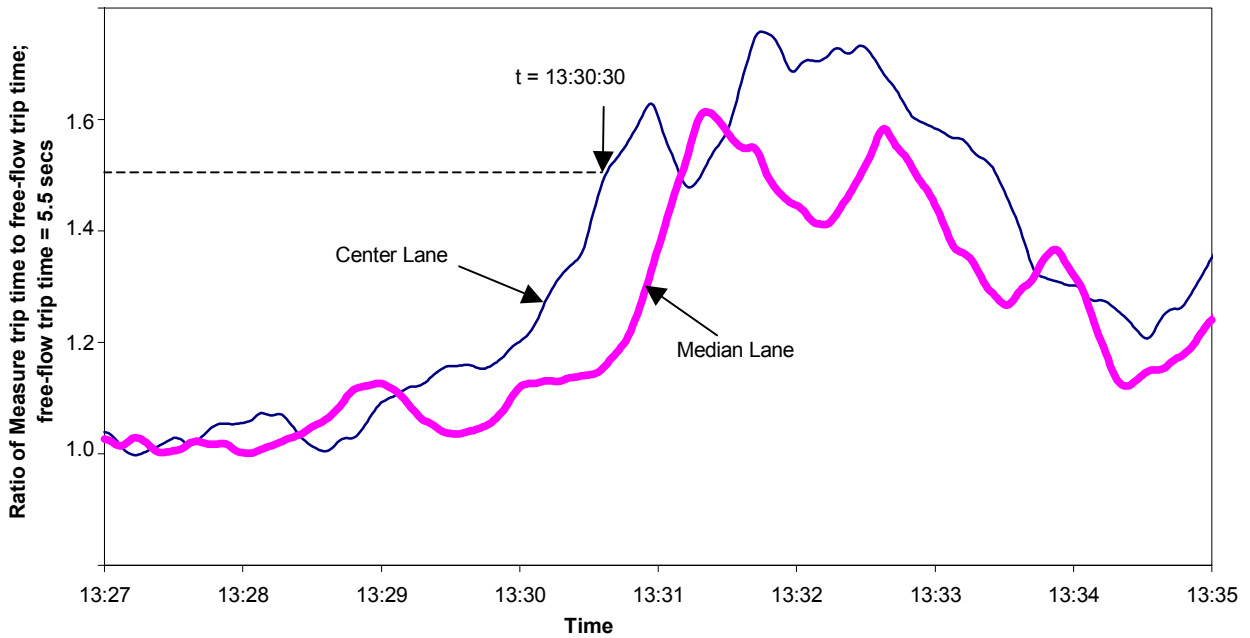


Figure 6(b)  
Sample Trip Times in the center and median lanes (March 15, 2001)



While the bottleneck remained active, shoulder lane slowing periodically re-occurred downstream of the on-ramp, although to lesser extent.<sup>6</sup> This important detail is exemplified in the figure next presented.

Figure 6(c) displays trip time ratios in the shoulder lane (as in Figure 6(a), but for a longer time) along with an oblique N-curve of counts departing the merge at MP 9.3 during this same period. The figure indicates that reductions in the latter tended to accompany rises in the former.

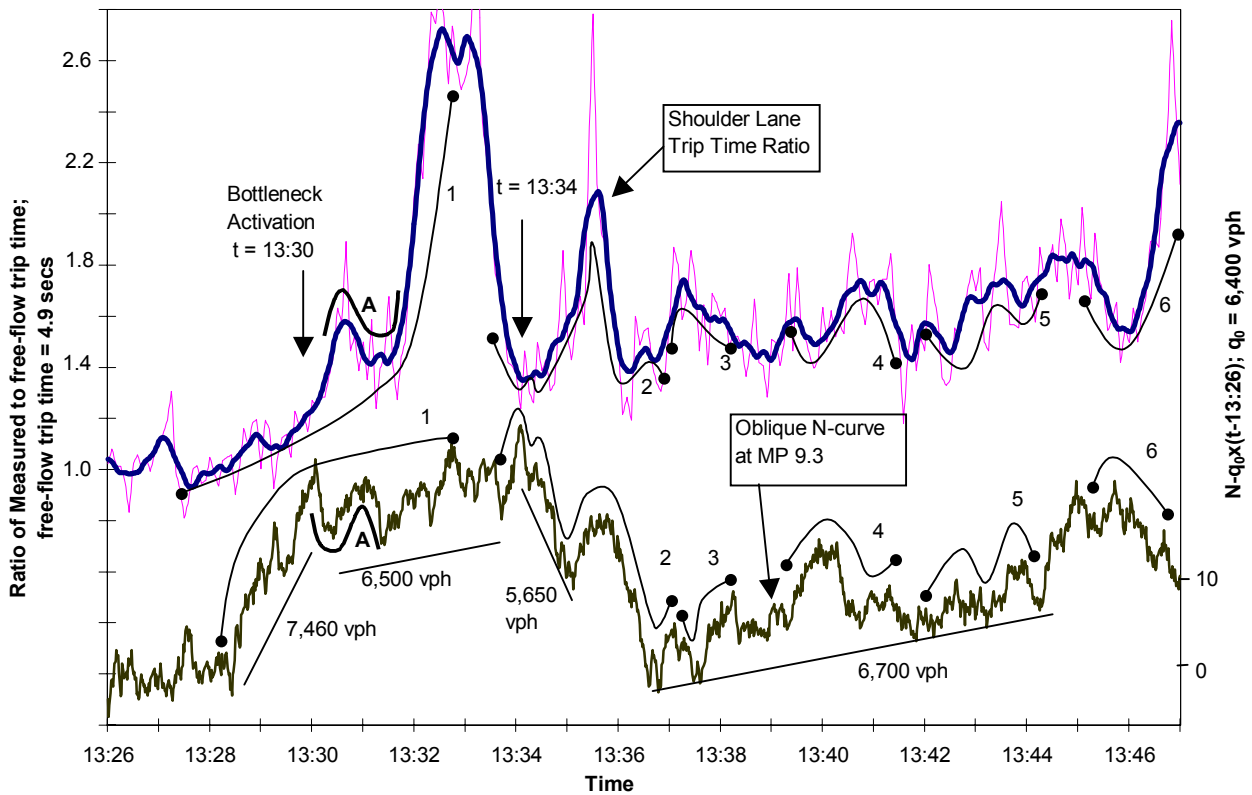


Figure 6(c)  
Correlations between slowing and bottleneck discharge (March 15, 2001)

The initial (and most pronounced) slowing that immediately followed the bottleneck's activation coincided with marked reductions in the flow, as highlighted with the smooth curve segments labeled 1 in the figure. The latter dropped by nearly 1,000 vph, as highlighted with piece-wise linear interpolations of the N-curve.

<sup>6</sup> Downstream slowing was even less pronounced in the center and median lanes after  $t = 13:34$ , such that the effects are scarcely evident in Figure 2(a).

Moreover, the slow-downs that occurred shortly after  $t = 13:34$  accompanied further discharge reductions, as highlighted with the curve segments labeled 2. And the discharge flows eventually recovered (to an average rate of about 6,700 vph) once the shoulder lane trip time ratios consistently fell below 2.0. Yet even during this period, there seems to be evidence that these trip times were negatively correlated with bottleneck discharge; i.e., a convex trend in one was often accompanied by a concave trend in the other, as highlighted by the curve segments labeled 3 through 6. The slow-downs thus appear to have had deleterious effects on outflows from the merge.

As an important aside, the data in Figure 6(c) are presented in such a way that short-run changes in measured traffic variables are clearly visible to the eye. Any efforts to quantify (numerically) the correlations between two variables should be done so as not to average-out features of interest; i.e., time intervals used for the analysis should be small.

As an example, we denoted the shoulder lane trip time ratios as  $X_i$  for every  $i^{\text{th}}$  second following the bottleneck's activation; (our time intervals were thus 1-sec long). We set  $X_i$  equal to +1 if the value of this ratio in second  $i$  was greater than the value in second  $i-1$ ;  $X_i = -1$ , otherwise. The analogous operation was preformed for bottleneck discharge rates,  $Y_i$ . We then defined the index variable  $Z_i = 1$  if  $X_{i-15 \text{ secs}} = -Y_i$ ;  $Z_i = 0$ , otherwise. A 15-sec difference was used to capture the time lag in this cause and effect relation. For March 15, 2001 (shown in Figure 6(c)), the average of these  $Z_i$  was 0.60 during the first 15 minutes following the bottleneck's activation. Thus, vehicle trip times in the shoulder lane were negatively correlated with outflows from the bottleneck; i.e., greater vehicle slowing further diminished outflows.

That disruptive vehicle slow-downs were, in turn, linked to surges in the on-ramp's inflows seems evident from Figure 6(d). This figure displays shoulder lane trip time ratios along with an oblique N-curve of the on-ramp vehicles as they merged into freeway traffic near MP 9.1. The latter shows that, on this day, on-ramp inflows regularly surged to about 1,200 vph.

The figure shows clear correlation between these ramp surges and the shoulder lane trip times. Virtually every peak in the latter arose at or near the end times of the former and vertical arrows are included in Figure 6(d) to aid the reader in verifying this.

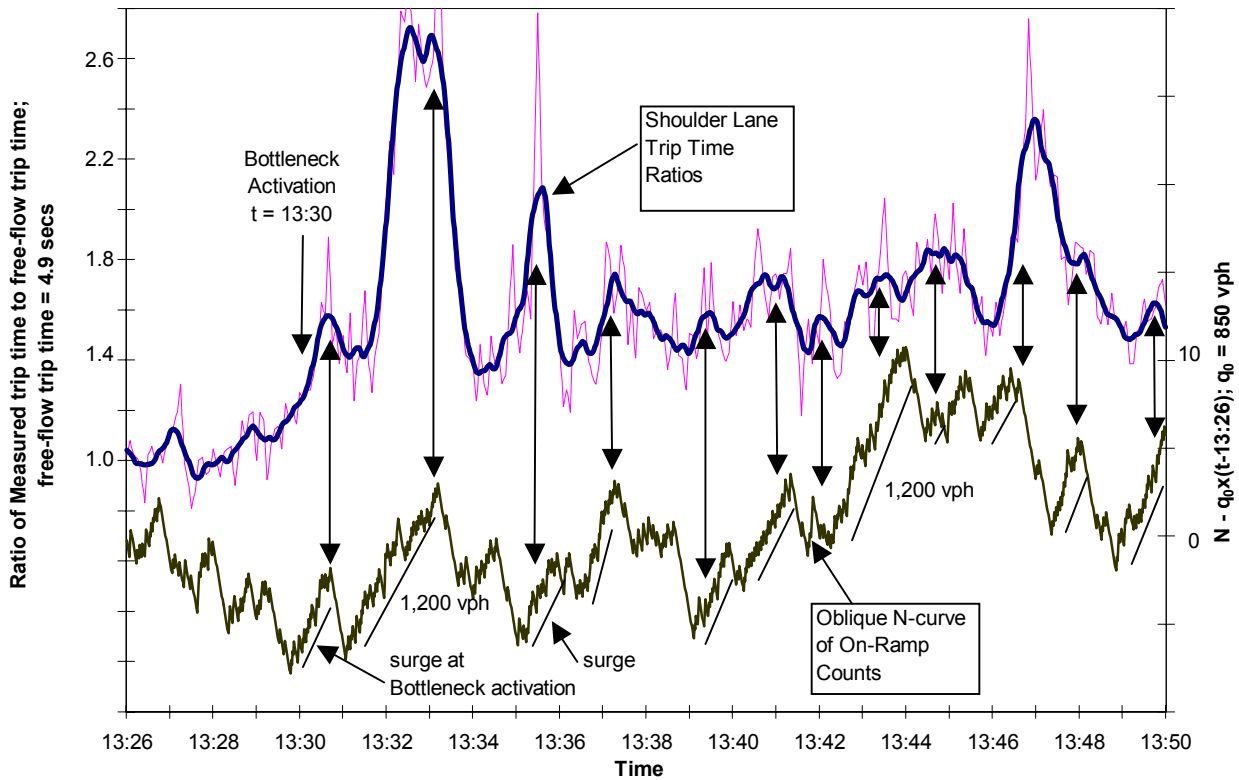


Figure 6(d)  
Correlations between on-ramp surges and slowing downstream (March 15, 2001)

And with few exceptions, each ramp surge that followed the bottleneck's activation corresponded to a rise in the trip times. Some linear approximations accompany the on-ramp's N-curve to highlight this.

Similar to our earlier correlation analysis of trip times and bottleneck outflows, we again denoted the shoulder lane trip time ratios as  $X_i$  for every  $i^{\text{th}}$  second following the bottleneck's activation. We set  $X_i$  equal to +1 if the value of this ratio in second  $i$  was greater than the value in second  $i-1$ ;  $X_i = -1$ , otherwise. The analogous operation was performed for on-ramp counts  $Y_i$ . The index variable  $Z_i = 1$  if  $X_{i+5 \text{ secs}} = Y_i$ ;  $Z_i = 0$ , otherwise. Here a 5-sec time lag was used.

For March 15, 2001, the average of these  $Z_i$  was 0.75 during the first 5 minutes following the bottleneck's activation, a strong correlation. This correlation diminished slightly as we investigated durations longer than 5 mins, but the averages of our index variable consistently remained above 0.60.

Figure 6(d) also shows that the bottleneck's activation was itself accompanied by a surge from the on-ramp. And by referring back to Figure 2(b), the reader can verify that this particular surge from the ramp was the first after the freeway traffic's arrival rate had climbed to its highest measured value (7,320 vph).

Finally, Figure 6(e) shows that the on-ramp surges tended to bring higher rates of lane changing (departing the shoulder lane) just downstream. An oblique N-curve of ramp inflows is again included in this figure. Also shown is a curve displaying the net lane changing of interest; i.e., its slopes are the net egress rates from the shoulder lane between MPs 9.1 and 9.3. (Negative slopes on this curve mark periods with net movements into the shoulder lane).

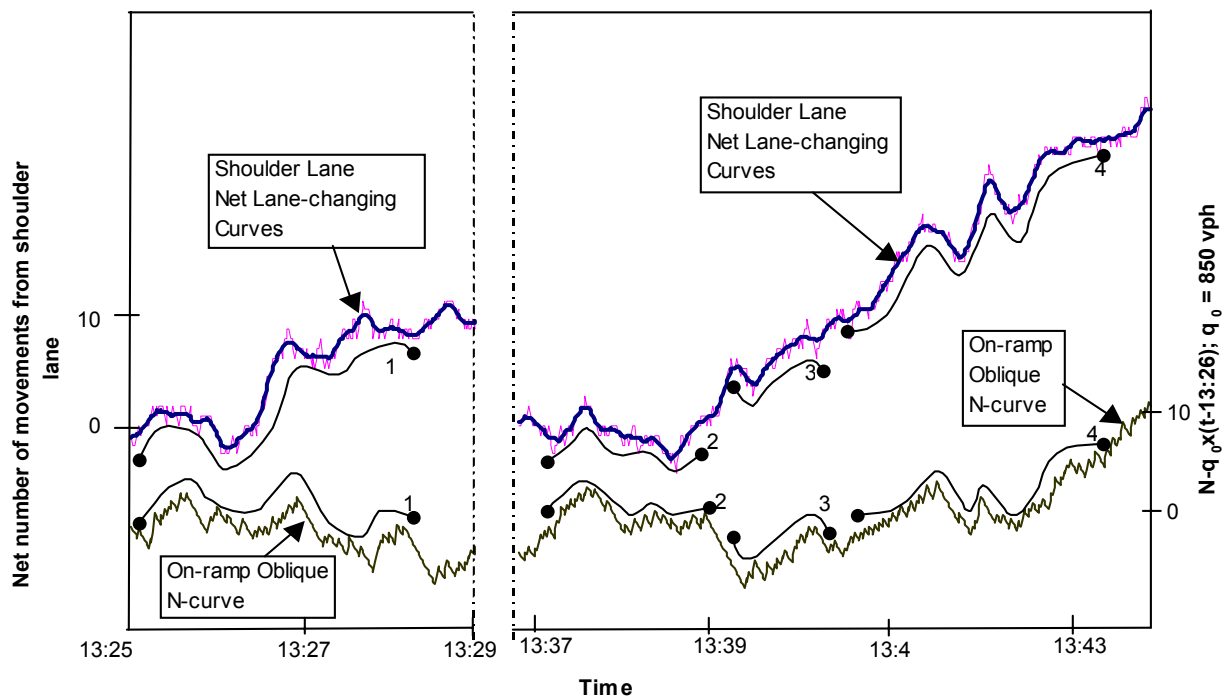


Figure 6(e)  
Correlations between on-ramp inflows and lane changing downstream (March 15, 2001)

The lane-changing rates displayed in Figure 6(e) were estimated using N-curves of shoulder lane vehicle counts at MPs 9.1 and 9.3. These N-curves were constructed only during periods when trip times between these MPs did not appear to be varying

markedly and the two periods shown in this figure are instances of this.<sup>7</sup> By shifting the upstream N-curve for one such period forward by the average trip time between the MPs, the rates of (vertical) divergence between it and its downstream counterpart can be taken as approximations of the net lane-changing rates (*Mauch and Cassidy, 2001*). A thin line is used in Figure 6(e) to display these rates of divergence. The bold line shows their 10-sec moving averages.

The on-ramp inflows shown in Figure 6(e) tend to display positive correlation with the net lane-changing rates. A convex (or a concave) trend in one is often accompanied by the same trend in the other. Smooth curve segments have been added to Figure 6(e) to aid the reader in seeing these coinciding trends.

It thus appears that disruptive lane changing (and the outflow reductions that evidently result) can be mitigated by metering the on-ramp to restrict inflow surges from there. These findings are further supported in the following section using data from a different observation day.

## **6. SOME ADDITIONAL OBSERVATIONS**

The data presented in this section came from another observation day (February 20, 2001). They are presented, in part, to confirm certain causal links identified in the previous section. Namely, we will use Figure 7(a) to verify apparent links between vehicle slow-downs and inflow surges from the on-ramp. Figure 7(b) will then be used to demonstrate links between this vehicle slowing and reductions in outflow from the merge. Further inspection of these figures will suggest that on-ramp metering, if sufficiently restrictive, can increase queue discharge flows from the merge even after the bottleneck there has become active.

Figure 7(a) presents the oblique N-curve of the on-ramp counts together with the shoulder lane's trip time ratios (just downstream) for a 30-min period during the rush. On this day, the bottleneck activated at  $t = 14:45:30$  (and this can be verified by referring back to Figure 3(a)). Figure 7(a) shows that prior to this activation, the peaks in the trip times closely correspond to the ending times of surges from the on-ramp; vertical arrows

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<sup>7</sup> The reader can use figure 6(c) to confirm that the period from  $t = 13:37$  to  $t = 13:44$  was marked by relatively small peaks in the shoulder lane trip time ratios.

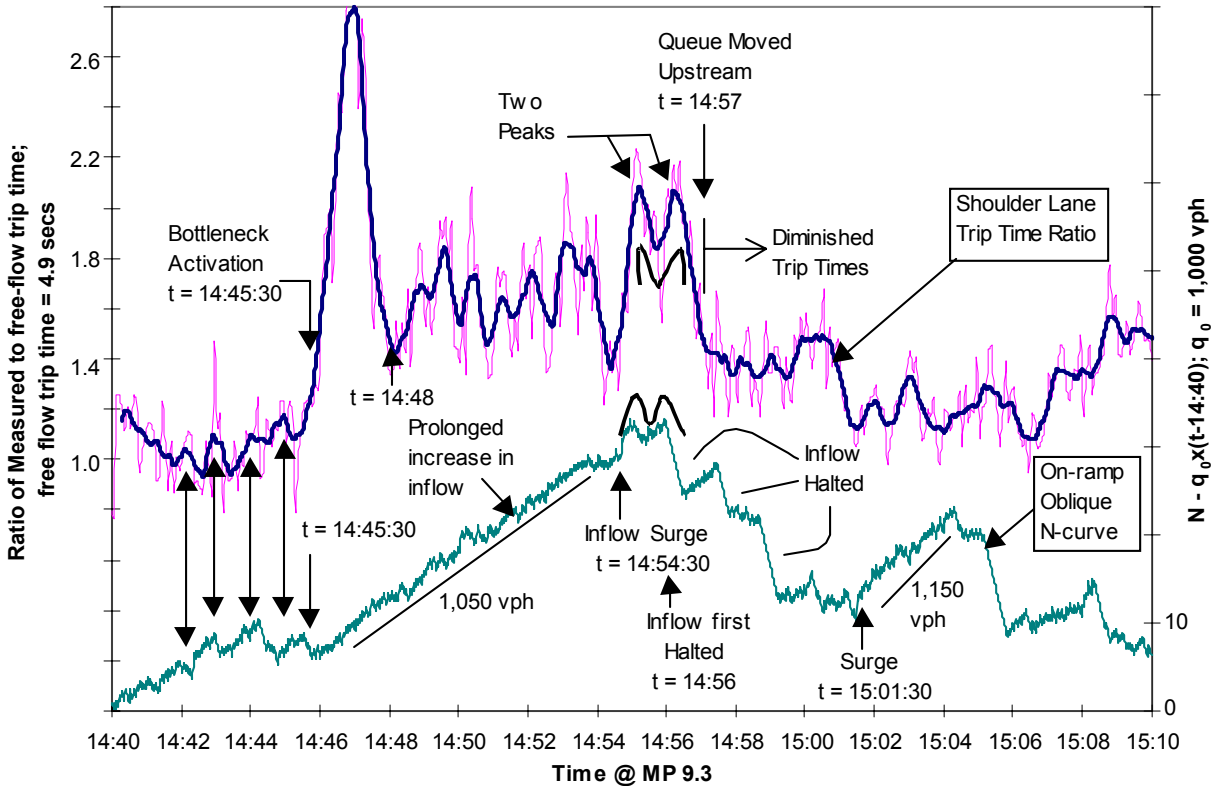


Figure 7(a)  
Correlations between on-ramp surges and slowing downstream (February 20, 2001)

are included in the figure to highlight this.<sup>6</sup> The figure also shows that the bottleneck's activation was accompanied by a prolonged increase in ramp inflow and a marked rise in the trip times. The latter receded by  $t = 14:48$ , although ratios remained well above 1.0 for some minutes thereafter.

At  $t = 14:54:30$ , a rapid sequence of two inflow surges from the ramp caused trip times to rise (and display two pronounced peaks). But notably, these were followed by a sequence of three periods, each of about 30-secs in duration, whereby ramp inflows were completely halted. Consequently, the trip times diminished downstream; (these ratios were below those observed while the bottleneck was active for the day shown in the previous section). With this vehicle slowing all but eliminated, an eventual surge in ramp

<sup>6</sup> Although the time scale used to display the curves in Figure 7(a) makes it difficult at times to verify by eye, similar correlations between trip times and ramp surges were also evident after the bottleneck's activation.

inflow (at  $t = 15:01:30$ ) did not cause trip times to rise; they actually dropped slightly, such that ratios nearly returned to 1.0.

Figure 7(b) presents both the shoulder lane's trip time ratios and an oblique N-curve of counts departing the merge at MP 9.3. The figure shows that, at  $t = 14:47$ , the peak in trip times (brought by the bottleneck's activation) caused outflows from the merge to drop to 6,130 vph. And the later rise in trip times at  $t = 14:54:30$  caused discharge flows to drop even further to 5,680 vph. Discharge rates began to recover just after  $t = 14:56$ , the time when the ramp inflows were first halted. Moreover, the highest of these recovery discharge flows (6,540 vph) corresponded to the 5-min period when shoulder lane trip time ratios returned nearly to 1.0.

Thus, the ramp metering on this day was rather restrictive; it included brief periods when inflows from the on-ramp were halted. This evidently served to increase queue discharge flows from the merge bottleneck. Some final thoughts are offered in the following section.

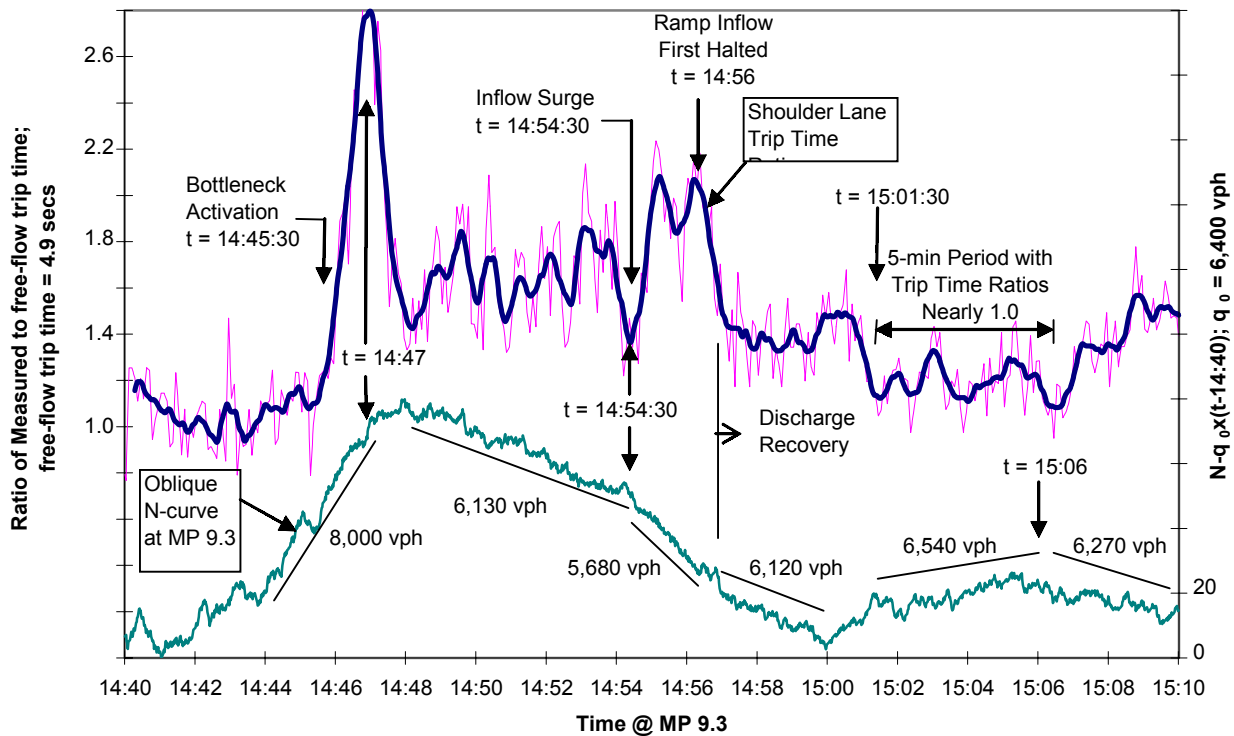


Figure 7(b)  
Correlations between slowing and bottleneck discharge (February 20, 2001)

## 7. CONCLUSIONS

The work has shown that the outflows from the freeway merge studied here diminished once the site became an active bottleneck. This finding is consistent with previous observations at other freeway merge bottlenecks (*Cassidy and Bertini, 1999*) and it underscores the potential value of postponing a bottleneck's activation. It is thus fortuitous that the six days studied in the present research indicate that sufficiently restrictive on-ramp metering can forestall this bottleneck's activations and the resulting reductions in its outflow (or capacity).

It appears that the key to these postponements stem from vehicle lane-changing maneuvers made just downstream of the merge. By restricting surges in inflows from the ramp, metering evidently limits these lane changes and their disruptive effects. It seems that damping high flows from the on-ramp even promotes higher queue discharge flows after this bottleneck has activated.

The present findings indicate that metering the on-ramp to the merge studied here actually helps to increase outflows from this merge. Higher such outflows mean diminished commuter delays; (the reader can refer to section 3 of *Cassidy, 2002* for discussion of this).

In designing a specific metering scheme, one need consider local conditions on the freeway where the scheme is to serve. Key considerations include the demands at the on-ramps and the space available there for storing queued vehicles. Evidence that sufficiently restrictive metering can increase the capacity of a merge bottleneck would be important to factor into the design process as well. Of course, determining the extent to which the present findings hold at other freeway merge areas will require observations at other sites.



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