Changes in Bottleneck Capacity at a Freeway Diverge in Bangkok

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Abstract: This manuscript presents changes in bottleneck capacity at a freeway diverge in Bangkok. This bottleneck was caused by an exit ramp queue moving upstream onto the freeway. Detailed traffic data from an expressway in Bangkok show that traffic states during bottleneck activation could be grouped into three states with different levels of capacity based on vehicle speeds on through-movement lanes and the rates of lane changing maneuvers near the off-ramp queue. Data also indicate that the transitions of traffic states were primarily caused by the changes in exit flows. The lower capacity was initiated by a more restrictive off-ramp flow that causes cut-through vehicles on the adjacent lane impeding through-movement traffic. Once relaxing the exit flow, impeding vehicles could move out of the adjacent through lane and higher capacity often restored. These findings also show how automatic off-ramp control strategies could generate higher bottleneck capacities through detecting traffic speeds on the freeway.

Key Words: Bottleneck Capacity; Traffic Flow Theory; Freeway Operations, Diverge

1. INTRODUCTION

Daganzo (1997) defined an active bottleneck as a point on a roadway system between two locations if the traffic is detected to be queued upstream of the location and unqueued downstream. The study of an active bottleneck as well as its capacity is very important since any improvement that results in the increase in bottleneck capacity would obviously alleviate traffic congestion and save delay for traffic commuters. In this present research, the capacity of a freeway system with an off-ramp queue is defined as the sustained through-movement discharge flow (excluding a restricted off-ramp flow) when the upstream entrance is queued and the downstream freeway is unblocked by exogenous restriction. An exogenous restriction could be a queue that spills-over from further downstream. This paper will show that this capacity is altered over time based on exit flows of an off-ramp queue as well as traffic conditions adjacent to the queue. This traffic phenomenon is called “the capacity change mechanism”.

This manuscript unveils a more complete picture of the capacity change mechanism at an active diverge bottleneck caused by a queue from an exit ramp moving upstream onto the freeway. In the literature, it was well understood that an off-ramp queue blockage is a main cause of problem at a diverge bottleneck. However, the previous research did not capture several details of the capacity change mechanism. Specifically, little attention has been paid on vehicles cutting-into the off-ramp queue and block through-movement on adjacent through lanes. Data from this study reveal that diverge bottleneck’s capacities, defined as the
maximum outflows of through-movement traffic, were significantly affected not only by the off-ramp outflows, but also depended on the behavior of traffic speeds on adjacent lanes and lane changing maneuvers near an off-ramp.

Empirical data over four days from an expressway in Bangkok, Thailand, show that traffic states during bottleneck activation could be categorized into three distinct ones based on the mechanism of cut-through traffic, lane changing maneuvers, and traffic speeds on adjacent-to-queue lanes. These states will be designated as high-capacity (H), medium-capacity (M), and low-capacity (L) states according to the magnitude of outflows from these states. The differences of capacities among these states were reported to be varied up to 48% of the highest capacity recorded at the site on the same day.

Understanding of the capacity change mechanism and what influences the transitions in traffic states are the key for traffic management around bottleneck’s area. The paper also demonstrates that relaxing off-ramp queue can favorably affect the capacity change mechanism and provides a discussion on traffic control schemes to enhance higher capacity at the diverge based on these findings.

The remainder of the manuscript is organized as follows. Section 2 relates the present work to earlier work described in the literature. The freeway site used for this study and the data collected there are described in Section 3. Section 4 presents the traffic data from four observation days in detail. Summary of the capacity change mechanism is shown in Section 5. Proposed traffic control strategies based on the findings are provided in Section 6. The concluding remarks are discussed in the seventh and the final section.

2. BACKGROUND

There have been several researches concerning a freeway bottleneck caused by an oversaturated queue from an exit ramp back onto the freeway. Newell (1999) proposed a theory of delays caused by a queue at a freeway exit ramp with graphical techniques to describe the traffic situation at the bottleneck. In the paper, only two types of vehicles on the freeway are considered, i.e., type 1 vehicles can travel in any freeway lane but type 2 must stay in the deceleration lane or the adjacent one throughout the length of freeway section. Then, based on this simple assumption, evolution of the queues (delay, back of the queue, etc) could be solved graphically. However, the research treats traffic on all lanes homogenously except one on the shoulder lane. This later seems to be inconsistent with empirical observations.

The empirical studies relating to diverge bottlenecks are rare since the study site must be an active bottleneck with vantage points (e.g., over-crossings) for videotaping traffic and/or having reliable loop detectors located at the appropriate locations. Two previous relevant studies that use empirical data to analyze diverge bottlenecks are the followings:

Muñoz and Daganzo (2002a) studied a section of Northbound Interstate 880, upstream of the connecting off-ramp with Interstate 238 in Hayward, California. The data used in this study were only from loop detectors on one day. In this paper, they described that at immediate upstream location (2 km to the off-ramp), multi-pipe traffic states happened, where each lane moves at different speeds (Non-FIFO congestion regimes). However, at more upstream location, off-ramp queue grew across all lanes and entrap through-movement vehicles with
similar speeds on all lanes (FIFO blockage). In addition, the discharge flow from the bottleneck could change significantly when the percent of exiting vehicles changes. Although Muñoz and Daganzo (2002a) provided several key findings regarding the mechanism of diverge bottleneck. This research is based on merely one day of loop detector data. More observations are needed to confirm the findings. Also, we claim that loop detector data might be crude for this kind of research since each loop detector at the study site is located about 500 meters apart from the adjacent ones and number of lane changing maneuvers could not be recorded from the detectors.

Cassidy et al. (2002) observed traffic from a segment of Southbound Interstate 5 in Orange County, California, through the combination of loop detectors, video cameras, as well as, a floating car. They reported that on two out of four days with an oversaturated off-ramp queue, a disruptive freeway bottleneck happened and the discharge flow dropped from 10 up to 40%. Once the exit lane’s queue dissipated, the bottleneck disappeared. Also, the lengths of exit queues were negatively correlated with the discharge flows in the freeway segment’s adjacent lanes. Besides these key findings, Cassidy et al. (2002) mentioned that exiting vehicles rarely entrapped traffic with destinations further downstream and that exiting drivers were disciplined to move into the exit lane upstream of the queue and did not impede traffic. The observed rates of cut-through vehicles were reported to be never exceeded 1 or 2 per minute. Unfortunately, the temporal data of cut-through vehicles and lane changes at the site were not reported. Therefore, it was inconclusive whether cut-through vehicles and lane changes would affect discharge flows of through traffic.

From the literature, due to the lack of comprehensive data from the study sites, several details of the capacity change mechanism, e.g., disruptive cutting-into the queue, lane changing maneuvers from slow to fast lane, blockage near the head of the queue, etc, were not yet reported. Therefore, it was unclear whether and how relaxing off-ramp flows and/or rates of vehicles cut-through off-ramp queue, as well as banning lane changing maneuvers near the off-ramp, would result in the increase of diverge bottleneck capacity. To amend the gap, the data in this study herein were manually extracted from videos at a strategic diverge bottleneck site with varied off-ramp outflows. These unprecedented data revealed a reproducible trigger of capacity changes and could lead to traffic control strategies at an off-ramp to manage traffic bottleneck to reverse the capacity drop and maintain a high capacity.

3. STUDY SITE

Fig. 1 is a sketch of the study site, a stretch of southbound Phahon Yothin Expressway (Highway 1) at Km.31 in Bangkok, Thailand. The Expressway has three main lanes with a standard two-lane exit ramp. The ramp is connected to a congested frontage road with periodically controlled by a police officer that made off-ramp outflows fluctuated over time. This exit ramp is 1 km apart from the nearest upstream on-ramp such that weaving effect is disregarded. Video cameras were set up on two pedestrian over-crossings shown in the figure.
Figure 1. Southbound Phahon Yothin Expressway, Bangkok, Thailand.

From the site, traffic data were collected during afternoon rush hours for seven days, beginning August 2009 to February 2010. However, data from three of these seven days were unusable due to an exogenous downstream queue, low traffic demand, and bad weather. Since there were no loop detectors at the site, all traffic data were analyzed manually from the videos to ensure high-resolution. These data include individual vehicle arrival times at four fixed locations (labeled $X_0$ through $X_3$ in Fig. 1) along the freeway stretch, sampled vehicle travel times on Lane 3 and Lane 4, and lane changing maneuvers between measurement locations.

Further discussion on some notable findings is provided in the next section, along with figures that verify findings on four observation days.

4. TRAFFIC DATA

This section describes details of the capacity change mechanism from four days at the site. The presentations provided below verify that traffic states during bottleneck activation were separated into three distinct ones based on the mechanism of cut-through traffic. These states will be designated as high-capacity (H), medium-capacity (M), and low-capacity (L) states according to the magnitude of outflows from these states and their different mechanisms.

Fig. 2 displays cumulative curves of vehicle count versus time, $t$, measured from video at the locations labeled $X_1$ through $X_3$; (in Fig. 1) on August 10, 2009 (Day 1). Note that the off-ramp counts were excluded from total counts at $X_1$. These curves were constructed such that the vertical displacements between any two of them are the excess vehicle accumulations between respective measurement locations due to vehicular delays.

These vertical displacements were amplified and made visible to the naked eye by plotting the curves on an oblique coordinate system. The plots presented here are the oblique coordinates, the curves display the quantity $O(t) = V(t)-q_0(t-t_0)$ versus $t$; i.e., the cumulative virtual vehicle count to time $t$, $V(t)$, minus a background reduction, $q_0(t-t_0)$; $q_0$ is a background flow. The oblique coordinate system not only amplifies vertical displacements, it also amplifies changes in slopes. Since the slopes of the $O$-curves are proportional to the flows at each measurement location, these plots facilitated visual identification of the times when these flows actually changed. Further discussion on the construction and interpretation of these
curves are available in several references (e.g., Cassidy and Windover (1995); Muñoz and Daganzo (2002b)). Also, readers might find the applications of $O$-curves in the studies of bottleneck capacities in many references (e.g., Cassidy and Rudjanakanoknad (2005); Chung et al. (2007))

Figure 2. $O$-curves at $X_1$ through $X_3$ on August 10, 2009 (Day 1).

The curves thus reveal that unqueued conditions persisted between $X_2$ and $X_3$ (the curves at these locations were always superimposed) while queueing (curve displacements) arose upstream of $X_2$ after $t = 17:17$. These features verify that a bottleneck activated between $X_1$ and $X_2$. Fig. 2 includes dashed lines showing flow trends. These indicate that bottleneck was active at $t = 17:17$ with average outflow of 2,760 vph. Then, at $t = 17:36$, it dropped to 2,300 vph, a reduction of nearly 17 percent. These capacity states are now called “high-capacity” (H) and “medium-capacity” (M) states, respectively. Note that the capacity during M-state was less than the maximum demand flow before bottleneck activation (2,570 vph), or “free-flow” state (F), the traffic state without excess vehicle accumulations between any two measurement locations. Note that the low-capacity state (L) did not occur during the observation period on this day; however, the L-state was apparent on other days that will be explained later. The capacity change mechanism on this day can be shown by Figs. 3(a)-3(d) below.

Fig. 3(a) is an oblique cumulative curve of counts at the off-ramp. Fig. 3(b) shows the vehicle speeds on Lane 3 and Lane 4 at the distance of 100-meter downstream of $X_1$ sampled (from video) every 5 secs and averaged over 1-min interval. It represents the traffic condition on Lane 3 and Lane 4. Figs 3(c) and 3(d) display the oblique cumulative count curves of lane changing maneuvers to the left (from Lane 3 to 2 and Lane 4 to 3) and to the right (from Lane 3 to 4), respectively.

Beginning at $t = 17:17$, a police officer periodically blocked traffic on the frontage road to relax the off-ramp’s congestion. Fig. 3(a) shows that the exit flows with police assistance were 3,120-3,390 vph comparing with the natural outflows of 1,960-2,160 vph. However, the
long-run average ramp flow during the H state was 2,820 vph, while the one during the M state was 2,370 vph. This indicates that higher (long-run) off-ramp flows coincide with higher discharge flows of through vehicles.

Figure 3. Traffic data on Monday, August 10, 2009 (Day 1).

The cause of this can be explained by vehicle speeds on Lane 3 and Lane 4 (shown in Fig. 3(b)). Notably, during the H state, speeds on Lane 4 were generally unchanged from the free-flow state of 80-95 kph while speeds on Lane 3 dropped slightly to a range between 45-65 kph. The exceptions were some short periods during police assistance; speeds on Lane 3 could restore. This means that during the H state, slow running vehicles were limited to Lane 3 only. In contrast, during the M state, speeds on both lanes were trending lower, and stabilized in the level of 45-65 kph.

The major cause of the capacity transition on this day was a restrictive exit rate of 2,000 vph.
that started at $t = 17:36$ and extended for 7 minutes until $t = 17:43$ (see Fig. 3(a)). From video observations, this prolonged restrictive exit rate made the queue denser and the cut-through vehicles on lane 3 had more difficulty in cutting through it. Fig. 3(c) displays the number of lane changing maneuvers to the left (from Lane 3 to Lane 2 and from Lane 4 to Lane 3). During the H state, the rates of cut-through traffic were relatively high (1,120-1,380 vph). The rate was lower at $t = 17:36$ when the off-ramp queue was denser (Note that since the off-ramp queue was fully congested during the bottleneck activation period and controlled by downstream police operations, fewer cut-through vehicles during this period were not due to a change in O-D demand. With less complete cut-through rates, some exit vehicles were trapped on Lane 3 (or between Lane 2 and Lane 3) and impeded through-movement vehicles. To avoid blockage, through vehicles on Lane 3 changed their lanes to the right but few vehicles could do that at first (from $t = 17:36$ to $t = 17:47$) since vehicles on Lane 4 were running at high speeds of 70-100 kph. Until after $t = 17:47$, both lanes were running at relatively similar speeds; therefore, high rates of lane changing maneuvers from Lane 3 to Lane 4 were observed (see Fig. 3(d)) and persisted. This lane-changing spread the queue laterally and brought slow speeds on Lane 4 until the end of the observation period.

The traffic states observed at this site were not only H- and M-states. On Day 2 (Thursday, February 11, 2010), another capacity state was found. Figs. 4(a)-4(e) show traffic data on Day 2 with the same order as Fig. 2 along with Figs. 3(a)-3(d). Fig. 4(a) displays an oblique plot of cumulative curves of vehicle count versus time, $t$, measured from video at the locations labeled $X_1$ through $X_3$; (in Fig. 1) on this day. These curves remained nearly superimposed before $t = 17:44$. The average outflow for 5 minutes during this time (from $t = 17:39$ to $t = 17:44$) was 2,700 vph. At about $t = 17:44$, the off-ramp was significantly restricted (from 3,130 vph to 1,900 vph, see Fig. 4(b)) and caused the bottleneck activation between $X_1$ and $X_2$, i.e., freeway queue arose upstream of $X_2$ while downstream traffic were freely flowing. The outflows dropped to an average of 2,660 vph. This outflow level persisted for four minutes. During this period (from $t = 17:44$ to $t = 17:48$), speeds on Lane 3 dropped slightly; while speeds on Lane 4 were relatively unchanged. This suggests that the traffic state during this period is similar to Day 1’s H-state. Note that there were not many lane changes in any direction due to speed differences between Lane 3 and Lane 4 (see Figs. 4(d) and 4(e)). Subsequently, at time $t = 17:48$, off-ramp was re-restricted (see Fig. 4(b)). This resulted in the drop of capacity to an average of 2,340 vph, persisting for 10 minutes until $t = 17:58$. From Fig. 4(c), speeds on Lane 3 and Lane 4 trended lower during this period. Note that more cut-through vehicles as well as lane changing maneuvers to the right were observed since both lanes were travelling at slower and closer speeds since $t = 17:48$. This traffic state is considered to be an M-state since the mechanism was similar to Day 1’s M-state.

At $t = 17:58$, the capacity dropped to an unprecedented level of 1,490 vph. This is approximately 48% drop from the maximum capacity observed on this day (2,850 vph). The cause of this drop was due to a surge of cut-through vehicles (from 1,000 to 1,460 vph) while the off-ramp outflow was restricted to only 1,770 vph. Since more vehicles were cutting through the exit queue with low service rate, they were stuck on Lane 3, greatly impeded through-movement traffic. Notably, the average speeds of vehicles on Lane 3 decreased below 45 kph. During this time ($t = 17:58$), a surge of lane changing maneuvers from Lane 3 to Lane 4 was observed (as high as 810 vph, see Fig. 4(e)). This interrupted lane changes laterally brought slower speeds to Lane 4, resulting in the lowest capacity observed at this site. We call this state a “low-capacity” state, or abbreviated as an “L state”.
Figure 4. Traffic data on Thursday, February 11, 2010 (Day 2): (a) $O$-curves at $X_1$ through $X_3$, (b) oblique cumulative curve of off-ramp counts, (c) 1-minute moving average of vehicle speeds on Lane 3 and Lane 4, (d) oblique cumulative curve of lane changes to the left (Lane 4 to Lane 3 and Lane 3 to Lane 2), (e) oblique cumulative curve of lane changes to the right (Lane 3 to Lane 4).
Fortunately, the L-state did not persist for long. At $t = 18:02$, the off-ramp was relaxed with a high exit flow of 3,390 vph (see Fig. 4(b)). This high exit flow cleared stuck vehicles out of Lane 3. This is evident by a higher average speed on Lane 3 (see Fig. 4(c)). Once vehicles on Lane 3 moved faster, the number of lane-changing maneuvers from Lane 3 to Lane 4 diminished (see Fig. 4(e)) and the capacity was restored to 2,280 vph. Traffic during this period matched with an M-state since speeds on both Lane 3 and Lane 4 were slow (but still above 45 kph, a threshold set to separated M- and L-state). Afterward, at $t = 18:06$, a high exit flow of 3,330 vph was extended for six minutes. This helped clearing slow vehicles near the head of the queue. The average speeds on Lane 3 and Lane 4 rose. The capacity during this period (from $t = 18:06$ to $t = 18:12$) was as high as 2,850 vph, the maximum capacity recorded on this day. Finally, due to demand drop, the rush period on this day ended at $t = 18:12$.

The capacity change mechanism of this diverge bottleneck is not necessary to happen in orders of H-M-L or L-M-H. The Data on Day 3 (Monday, August 17, 2009) will be presented to verify the reproducible findings of state characteristics and display that an L state could lie in the middle of two H-states.

Figs. 5(a)-5(e) show traffic data on Day 3 with the similar order to Figs. 4(a)-4(e). The bottleneck on this day activated at $t = 17:03$ between locations $X_1$ and $X_2$. (The reader could verify this by looking at curve displacements arose upstream of $X_2$ after $t = 17:03$ in Fig. 5(a)). The bottleneck activation was due to a more restrictive off-ramp flow (from 2,270 to 2,050 vph) since $t = 17:03$ (see Fig. 5(b)). The initial bottleneck capacity was 2,400 vph. We claim that this state is an M-state since speeds of vehicles on Lane 4 were trending lower (see Fig. 5(c)).

At $t = 17:07$, the exit was relaxed (back to 2,300 vph) and the capacity rose to 2,840 vph until $t = 17:10$. During this period, the rates of cut-through traffic were lower (see Fig. 5(d)). Since most exit vehicles stayed on Lanes 1 and 2, speeds on Lane 3 and Lane 4 rose (see Fig. 5(c)). At $t = 17:10$, the police officer started blocking the frontage road and the exit queue began to flow at a high rate of 3,320 vph (see Fig. 5(b)). During that time, some upstream exit vehicles that saw opportunity to cut through the off-ramp queue made their lane changing maneuvers near the head of the queue and exit. This high cut-through rate of 1,260 vph occurred until $t = 17:16$. The capacity during this period (from $t = 17:10$ to $t = 17:16$) was 2,660 vph. Note that the capacity was slightly lower than the earlier period (from $t = 17:07$ to $t = 17:10$) due to the rate of cut-through traffic. However, both periods was considered to be an H-state since traffic speeds on Lane 4 were mostly high (> 65 kph).

At $t = 17:16$, the police officer stopped blocking the frontage road. This immediately damped the exit flow from 3,000 to 2,320 vph (see Fig. 5(b)). Due to the denser exit queue, exiting vehicles that stayed on Lane 3 could not easily cut through the queue. The cut-through rate dropped from 1,260 vph to 1,010 vph resulting in some cut-through vehicles impeded traffic on Lane 3. This lowered speeds of vehicles on Lane 3 and Lane 4 (see Fig. 5(c)) and M-state ensued. The capacity during this period was 2,430 vph. Later, at $t = 17:21$, the off-ramp was relaxed again. Speeds on Lane 3 and Lane 4 were trending higher, showing that an H-state was returned. The capacity was increased to 2,690 vph.
Figure 5. Traffic data on Monday, August 17, 2009 (Day 3): (a) O-curves at X1 through X3, (b) oblique cumulative curve of off-ramp counts, (c) 1-minute moving average of vehicle speeds on Lane 3 and Lane 4, (d) oblique cumulative curve of lane changes to the left (Lane 4 to Lane 3 and Lane 3 to Lane 2), (e) oblique cumulative curve of lane changes to the right (Lane 3 to Lane 4).
Remarkably, beginning at $t = 17:25$, the exit flow was restricted from 3,180 vph to 2,600 vph (see Fig. 5(b)). The average speeds on Lane 3 dropped precipitously (from 70 kph to 30 kph, see Fig. 5(c)). Again, this was caused by a high rate of cut-through traffic (1,320 vph) during a low exit flow period. This brought vehicles stuck on the exit queue and on the adjacent lane (Lane 3). Through-movement vehicles on Lane 3 were blocked behind them. This phenomenon resulted in a capacity of only 1,900 vph, considered to be an L state. During this state, vehicles on Lane 4 also slowed down due to the abrupt slow-down on the adjacent lane. However, during this L-state, we did not observe significant lane changes from Lane 3 to Lane 4 (see Fig. 5(e)) as previously observed on Day 2, since the speed differences between these two lanes were high (see Fig. 5(c)).

Again, the L-state on this day persisted only two minutes. At $t = 16:27$, the police officer began to block the frontage road once more and the exit flow was increased from 2,600 vph to 3,200 vph. This high exit flow cleared stuck vehicles out of Lane 3. Speeds on Lane 3 and Lane 4 were trending higher (signaling that the traffic returned to an H-state). The capacity was restored to 2,760 vph and persisted for three minutes until the end of the rush at $t = 17:30$.

More evidence of the reproducible capacity change mechanism was observed on another observation day. Figs. 6(a)-6(e) show traffic data on Day 4 (Thursday, February 4, 2010). On this day, the bottleneck was active at $t = 17:16$ between locations $X_1$ and $X_2$ (see Fig. 6(a)). The average outflow following bottleneck activation was 2,600 vph and this high outflow persisted for six minutes until $t = 17:22$, when the demand temporarily dropped. This initial capacity was considered to be an H-state since traffic speeds on Lane 4 were still high (> 65 kph), see Fig. 6(c). We also observed a higher rate of lane changing maneuvers from Lane 3 to Lane 4 to avoid slowness on Lane 3 (see Fig. 6(e)).

At $t = 17:32$, due to some exogenous restriction downstream of the exit ramp, the exit rate was lowered from 2,700 vph to 2,350 vph (see Fig. 6(b)). Shortly thereafter, at $t = 17:33$, the bottleneck reactivated with the capacity level of 2,770 vph. This capacity is again an H-state due to the same reason, i.e., traffic was slow on Lane 3, while being fast on Lane 4 (see Fig. 6(c)). The H-state sustained for seven minutes until $t = 17:40$. At this time, the exit ramp was more restrictive. The exit rate dropped from 2,350 vph to 1,990 vph (see Fig. 6(b)). Simultaneously, the rate of cut-through traffic increased from 1,120 vph to 1,540 vph (see Fig. 6(d)). Apparently, the L-state ensued due to impeding vehicles on Lane 3. This brought the capacity down to 1,670 vph, a reduction of nearly 40 percent from the previous capacity. Happily, this lasted for only two minutes. At $t = 17:42$, a police officer began blocking traffic on the frontage road to relax the off-ramp queue. Due to his action, the exit rate was increased from 1,990 vph to 3,520 vph (see Fig. 6(b)). It cleared the blockage queue and increase traffic speeds on both Lane 3 and lane 4 (see Fig. 6(c)) and restored the bottleneck capacity to 2,690 vph, another H-state. Note that the number of lane changing maneuvers on both directions also dropped. This H-state continued through the end of this day’s rush at $t = 17:47$.

The summary of the capacity change mechanism and proposed traffic control strategies based on these findings to increase diverge bottleneck’s capacities are described in Sections 5 and 6, respectively.
Figure 6. Traffic data on Thursday, February 4, 2010 (Day 4): (a) O-curves at $X_1$ through $X_3$, (b) oblique cumulative curve of off-ramp counts, (c) 1-minute moving average of vehicle speeds on Lane 3 and Lane 4, (d) oblique cumulative curve of lane changes to the left (Lane 4 to Lane 3 and Lane 3 to Lane 2), (e) oblique cumulative curve of lane changes to the right (Lane 3 to Lane 4).
5. SUMMARY OF THE CAPACITY CHANGE MECHANISM

Data from four days presented herein provide several details of the reproducible capacity change mechanism at a freeway diverge with an oversaturated off-ramp queue as follows:

Three-capacity states. Traffic states during the bottleneck activation at this site could be categorized into three distinct states depending upon the traffic conditions of freeway through lanes and the rates of lane-changing maneuvers as shown in Table 1 below.

<table>
<thead>
<tr>
<th>Traffic State</th>
<th>High-capacity (H)</th>
<th>Medium-capacity (M)</th>
<th>Low-capacity (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>slow-moving traffic on Lane 3 but free-flow traffic on Lane 4</td>
<td>slow-moving traffic on Lane 3 and Lane 4</td>
<td>impeded traffic on Lane 3 &amp; slow traffic on Lane 4</td>
</tr>
<tr>
<td>Illustration</td>
<td>Exit Queue</td>
<td>Exit Queue</td>
<td>Exit Queue</td>
</tr>
<tr>
<td>(Darker shades mean higher densities)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic speeds on Lane 3</td>
<td>between 45-65 kph</td>
<td>between 45-65 kph</td>
<td>abruptly fall to below 45 kph</td>
</tr>
<tr>
<td>Traffic speeds on Lane 4</td>
<td>&gt; 65 kph</td>
<td>gradually lower and stabilize between 45-65 kph</td>
<td>abruptly fall and stabilize between 45-65 kph</td>
</tr>
<tr>
<td>Exit flow rate (vph)</td>
<td>1,960-3,320 (medium-to-high)</td>
<td>1,770-3,230 (low-to-high)</td>
<td>1,770-2,600 (low-to-medium)</td>
</tr>
<tr>
<td>Rate of vehicles cutting through the queue</td>
<td>low to high</td>
<td>medium to high</td>
<td>high</td>
</tr>
<tr>
<td>Rate of lane-changing maneuvers from Lane 3 to Lane 4</td>
<td>low to medium</td>
<td>low to high*</td>
<td>low to very high*</td>
</tr>
<tr>
<td>Capacity range (vph)</td>
<td>2,600-2,850</td>
<td>2,280-2,430</td>
<td>1,490-1,900</td>
</tr>
<tr>
<td>Percentage of capacity drop (from the highest capacity)</td>
<td>-</td>
<td>15-20%</td>
<td>33-48%</td>
</tr>
</tbody>
</table>

*High rates of lane-changing maneuvers occurred while traffic speeds on Lane 4 were being slow with small speed gaps between both lanes.

Transition of traffic states. Data indicate that the changes of traffic states were primarily caused by the changes in exit flows. We found that H-to-M, H-to-L, and M-to-L transitions were always coincided with more restrictive exit flows. Specifically, L states only appeared when a sharp drop of off-ramp flows coincided with a higher rate of cut-through traffic. Similarly, relaxing exit flows was proved to be very effective in restoring the bottleneck’s capacities, i.e., inducing M-to-H, L-to-M, and L-to-H transitions. In particular, data show that all transitions of L-state to either H- or M-states were due to the sharp increase in exit flows (see Day 2 at t = 18:02, Day 3 at t = 17:27, and Day 4 at t = 17:42). Nevertheless, all changes in exit outflows did not necessarily result in traffic state transition. This is probably due to the changes in exit flow might be in small magnitudes or did not adequately prolong for the traffic to realize the impact.

The proposed traffic control strategies based on these findings to increase freeway diverge capacities are described in the following section.
6. PROPOSED TRAFFIC CONTROL STRATEGIES

This section discusses two proposed traffic control strategies: off-ramp control and banning lane-changing maneuvers near the off-ramp. These strategies share a similar idea, i.e., to increase the freeway diverge capacities by eliminating impeding exit vehicles out of through-movement lanes.

Off-ramp control. The findings prove that relaxing off-ramp flows could result in the restoration of an H-state at the diverge. First, a strategy is needed to detect immediately the time when the impeding traffic (M- and L-states) occurred and relax an off-ramp queue immediately. This could be done automatically through detecting vehicle speeds on adjacent through lanes just upstream of the off-ramp. For this particular site, average vehicle speeds on both Lane 3 and Lane 4 would be used together to set up a control strategy. For example, traffic on the frontage road would be restricted to allow fully relaxation of the expressway’s off-ramp queue when the speeds on Lane 3 dropped below 65 kph, and speeds on Lane 4 had been trending down, signaling that an M- or L-state already happened. This relaxation would be maintained for a suitable period until speeds on Lane 3 rise above 65 kph, indicating that traffic already became in an H-state.

Banning lane-changing maneuvers near the off-ramp. The findings show that cut-through vehicles impede through-movement traffic (for both M- and L-states). Also, the lane-changing maneuvers to the left (from Lane 3 to Lane 4) spread the queue laterally and brought slow speeds on the other lane (especially during an L-state). Therefore, banning lane changes in one or both directions for some distance upstream of an off-ramp could be an effective means of generating higher diverge capacity. However, it is possible that this strategy might merely result in shifting the bottleneck to another upstream location where lane-changing maneuvers are allowed. The capacity of this freeway system with this control might not actually be increased. More research is needed to obtain further observations of this kind and to generalize the findings.

7. CONCLUDING REMARKS

This manuscript has unveiled a more complete picture of the capacity change mechanism at a freeway diverge and has proposed traffic control strategies to increase long-term capacity at the diverge. In summary, this research has delivered the following findings:

1) Three capacity states at the diverge site have been identified. The lower capacity is initiated by a more restrictive off-ramp flow that causes some cut-through vehicles on the adjacent lane impeding through-movement vehicles. Later, lane-changing maneuvers increase sharply as drivers attempt to avoid slow traffic in this lane. This maneuvering spread the queue laterally and caused lower freeway capacity.

2) Field data prove that relaxing the exit flow can induce higher capacity through moving impeding exit vehicles out of an adjacent through lane. Therefore, restoring capacity can be done automatically by fully relaxing the off-ramp (or blocking the off-ramp’s competing traffic stream) once the speeds of through traffic drop below a critical value and maintain the control until vehicle speeds on the through lanes rose above the critical value.

3) Banning lane changing maneuvers especially the cut-through traffic near an off-ramp may
be an effective mean of generating higher diverge capacity. However, a field experiment is needed to confirm this conjecture. It would be noted that the strategy of automatic off-ramp control as well as the requirement of banning lane-changing maneuvers near the off-ramp are difficult to implement in the real world. Further analyses of traffic data at other diverge sites are required to compare findings and confirm the reproducibility of the observed traffic mechanism described herein. The generality would be important for developing traffic control strategies and for formulating a more realistic theory as well. Given these findings, this manuscript can help traffic researchers to better understand the traffic phenomena at a diverge bottleneck and help traffic engineers to operate freeway diverge properly.

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