Queue Interactions on an Urban Freeway and Their Influence on Discharge Flow

by

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Abstract

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This thesis unveils a reason for the time-varying patterns in discharge flow that are commonly observed at freeway bottlenecks. Observations reveal that four well-known effects in freeway traffic can interact upstream of a bottleneck in ways that trigger periodic bursts in its discharge flow. A hypothesis concerning the capacity-increasing mechanism is that following an initial “capacity drop”, (i) the bottleneck’s expanding queue can trigger a new and more restrictive bottleneck further upstream. As a result, (ii) the queue downstream recedes toward the original bottleneck, leaving free flow conditions in its wake. If the tail of this receding queue (iii) passes an on-ramp junction that resides upstream of the original bottleneck, then (iv) a higher bottleneck discharge flow can temporarily ensue. We also hypothesize that this higher discharge rate should diminish after some minutes due to the capacity drop phenomenon. The process would then start anew. Detailed data collected from a 3-km freeway stretch over multiple days support this hypothesis.

The above suggests that the flow through the bottleneck can be increased by metering the freeway’s on-ramps in a coordinated but unconventional way. Experiments with this approach consistently produced long-run bottleneck discharge flows that were higher than those generated from a more traditional metering policy. The average difference over multiple days was nearly 3%.
DEDICATION

This dissertation is dedicated to my parents, Hwansoo Kang and Kijin Kim. Their endless support and encouragement enabled me to complete this work.

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Chapter 1

Introduction

This dissertation unveils a mechanism that arises naturally in freeway traffic. The mechanism is favorable in that it causes periodic short-run bursts in the discharge flows through a freeway bottleneck. Although periodic bursts of this kind have been widely reported in the literature on freeway traffic, the mechanism has not previously been explained.

We hypothesize that the capacity-increasing mechanism entails the interactions of four known effects in freeway traffic. The four effects can arise upstream of a freeway bottleneck, with one effect triggering the next. This hypothesis is confirmed by observing detailed traffic data extracted from video cameras and from loop detectors installed on a 3-km freeway stretch in Sacramento, California. Repeated observations reveal that the mechanism is a reproducible feature of the site. We suspect that the mechanism can occur at other freeway sites as well, especially since the mechanism’s four effects have already been reported individually on numerous freeways and expressways throughout the world.

The mechanism arose at the Sacramento site whenever a pocket of free flow traffic conditions materialized at an on-ramp merging area that resides in advance of the site’s downstream-most bottleneck. This pocket occurred due to a later-occurring and very restrictive bottleneck that formed further upstream. Further details will be presented in due course.

The lessons learned from these observations are translated into an unconventional on-ramp metering scheme. This proposed scheme was field-tested and compared against both, a more conventional scheme and the case of no ramp metering. Controlled experiments over 9 weekdays reveal that the long-run average discharge flows produced under the unconventional scheme were consistently higher than those produced under the conventional scheme and in the absence of ramp metering. Thus, the proposed scheme reduced delays collectively incurred by the freeway and on-ramp traffic during rush periods. Moreover, the proposed scheme produced smaller on-ramp queues than did the conventional metering scheme.

The conventional ramp metering strategy was found to be detrimental in that it tends to retard the capacity-increasing mechanism that naturally arises. On the other hand, the
proposed scheme modulated this mechanism to enhance its effect. By doing so, the proposed scheme prolonged periodic recoveries in bottleneck discharge flow.

The remainder of this dissertation is organized as follows. Chapter 2 summarizes the relevant literature. Chapter 3 presents the hypothesis concerning the interactions of the four known effects that constitute the capacity-increasing mechanism. The freeway site where this hypothesis was tested and the data collected there are described in Chapter 4. Chapter 5 reveals that the hypothesis is supported by detailed and repeated observations at the site. Chapter 6 describes the proposed metering strategy that modulates the capacity-increasing mechanism; and the repeated field-tests of this strategy that yielded favorable results. Generic lessons applicable to other freeways are furnished in Chapter 7. Practical implications and directions for future work are discussed in Chapter 8.
Chapter 2

Literature Review

The present dissertation pertains to two issues. These are i) details of freeway traffic flow, particularly details of flow through freeway bottlenecks; and ii) strategies for metering freeway on-ramps. The literature related to item i is reviewed in sect 2.1. Literature relevant to ii is reviewed in sect 2.2.

2.1 Details of Freeway Bottleneck Discharge Flow

Lighthill and Whitham (1955) and Richards (1956) were the first to postulate that traffic propagates as kinematic waves. Newell (1993) simplified the application of kinematic wave theory by assuming that the relation between traffic flow and density (the Fundamental Diagram) is triangular in shape; and applied the theory using curves of cumulative vehicle counts at fixed freeway locations. The theory has been used to provide realistic descriptions of queues’ expansion and dissipation (e.g. Cassidy and Windover, 1995; Daganzo et al, 1999; Cassidy and Mauch, 2001; Ni and Leonard, 2005; Coifman and Kim, 2011).

However, some traffic details are not fully explained by kinematic wave theory. Among these are the discharge flows through freeway bottlenecks. Details of this kind are of primary interest in the present study. Discussions on various other features not explained by kinematic wave theory can be found elsewhere (e.g. see Daganzo, 1997; Nagel and Nelson, 2005).

Researchers have long reported that the onset of queuing at a freeway bottleneck is accompanied by a reduction in its discharge flow (e.g. Banks, 1991; Hall and Agyemang-Duah, 1991; Persaud, et al, 1998). However, these early reports of the so-called “capacity drop” were inconclusive because they did not verify that the bottlenecks of interest were active.¹ Later empirical studies identified the time periods when freeway bottlenecks became active; and confirmed that the capacity drop is a reproducible feature of these bottlenecks (e.g. Cassidy and Bertini, 1999; Bertini et al, 2005; Chung et al, 2007).

¹ An active bottleneck is characterized by queue discharge that is not affected by downstream traffic conditions (Daganzo, 1997). Unless these conditions are present, one cannot be certain that measured flows correspond to bottleneck capacity.
Some have argued that capacity drops occur spontaneously. For example, Kerner (1999) reported that a capacity drop can spontaneously arise due to random local perturbations that are unrelated to a bottleneck, and can then be self-maintained. To refute this idea, Daganzo, el al (1999) showed that local perturbations, if not related to any bottleneck, dissipate after temporarily slowing-down vehicles upstream (i.e. local perturbations cannot be self-maintained).

It seems that the real cause of capacity drops are disruptive lane-changing maneuvers that occur just upstream of freeway bottlenecks. Cassidy and Rudjanakanoknad (2005) reported that lane-changing maneuvers played a key role in spreading queues laterally across all travel lanes just prior to the capacity drops at an on-ramp merge bottleneck. In line with this observation, Laval and Daganzo (2006) theorized that disruptive lane-changing maneuvers can create voids in the traffic stream departing from a freeway bottleneck. Furthermore, Patire and Cassidy (2011) observed that a capacity drop commonly occurred at an uphill bottleneck whenever traffic in the shoulder lane became denser and could no longer accommodate without disruption the lane-changing maneuvers into that lane that were performed by vehicles from adjacent congested lanes.

Curiously, the discharge flow following a capacity drop will usually not persist at a single low rate for the entire rush. Instead, this flow often recovers to a higher rate soon after the initial drop. The recovery can then persist for some minutes before returning to a lower rate; and the bottleneck’s active period is often characterized by multiple sequences of high and low discharge flow (e.g. see Figures 5 and 10 of Cassidy and Bertini, 1999).

The mechanism behind periodic discharge-flow recoveries has never been previously explained. However, some clues about the mechanism can be obtained by looking into certain known traffic effects. The present research will show that the interactions of four such known effects (previously termed the pinch, catch, pumping and driver memory effects) are the underlying causes of the mechanism. Descriptions of the individual effects are furnished below.

Kerner (2002) reported that a highly dense cluster of slow-moving vehicles can frequently form at a congested on-ramp merge. Each dense cluster (termed a “jam”), with its upstream and downstream fronts, was found to propagate upstream, against the flow of vehicles. This so-called “pinch effect” is known to be a reproducible feature of freeway on-ramp bottlenecks (see e.g. Knospe et al, 2002; Schönhof and Helbing, 2007).

It has also been commonly observed that the arrival of a queue from downstream can turn an on-ramp merge into an active bottleneck (see e.g. Kerner 2002; Schönhof and Helbing, 2007). This effect has been called the “catch effect”, presumably because a bottleneck is “caught” at a new location. Laval (2005) conducted a simulation study to identify traffic
conditions that cause this “catch effect” to occur at an on-ramp merging area. According to that study, the effect arises whenever traffic disturbances from downstream make the merging area’s lane-changing maneuvers disruptive, as this creates voids in the traffic stream discharging from the merging area.

Daganzo (2002) theorized that drivers can become “motivated” to pass a freely flowing but dense on-ramp merge and adopt shorter headways. This change in drivers’ psychology is supposedly fueled by high on-ramp inflows into the merge. This newfound motivation on the part of drivers may reflect their attempts to ward-off lane-changing maneuvers into their paths. This theory of the “pumping effect” has turned out to be consistent with empirical observations (Chung and Cassidy, 2004; Cassidy and Rudjanakanoknad, 2005).

Finally, Cassidy and Windover (1998) reported that drivers retain (or remember) their preferences to maintain their chosen headways (whether large or small) over extended distances. Interestingly, this “driver memory effect” was observed to hold even when drivers encountered traffic disturbances that temporarily forced them to slow down.

### 2.2 Freeway On-ramp Metering Experiments

Edie and Foote (1960) performed metering experiments to increase traffic discharge flow through an expressway tunnel. Vehicle platoons were restricted in size by introducing gaps between them at the upstream end of the tunnel. In this way, overloading the tunnel with traffic was avoided. This control method reportedly increased the discharge flow through the tunnel by preventing queues from forming inside it.

May (1964) proposed and field-tested a freeway on-ramp metering scheme in line with the above work. The goal was to avoid congestion on the freeway itself. To this end, on-ramp inflows were restricted during the time periods when the demand bound for the freeway’s downstream-most bottleneck was thought to exceed the bottleneck’s capacity. Following this same logic, Wattleworth and Berry (1965) formulated and solved a linear programming problem to determine how excess demand for a freeway bottleneck should be allocated to the “waiting pockets” behind the upstream on-ramps. Algorithms that incorporate this so-called “demand-capacity” metering logic have since been advanced for decades (e.g. Pinnell et al, 1967; Payne et al, 1973; Lipp et al, 1991).

Notable variants of the “demand-capacity” logic include a scheme proposed by Atol and Bullen (1973). It was designed to limit flows through a freeway bottleneck to the extent that the probability of capacity drop is maintained below a certain threshold. Such a threshold approach inevitably requires some degree of “over-control”, and therefore may result in rather moderate rates of long-run average discharge flow from the bottleneck.
Notably, some theoretical studies suggest that metering algorithms should be tailored to remedy the specific cause(s) of any freeway bottleneck because wholesale implementation of conventional (demand-capacity) metering schemes can exacerbate traffic congestion in certain instances. For example, Lovell and Daganzo (2000) showed that time-dependent patterns of origin-destination travel demand should be considered when optimizing on-ramp metering schemes. Cassidy (2003) considered freeway queues that are caused by vehicles exiting a freeway off-ramp; and pointed out that an on-ramp metering scheme in that situation should be designed specifically to reduce the flow of vehicles bound for the problematic off-ramp.

Many researchers have noted that restricting on-ramp inflows can create long ramp queues and thus induce some drivers to divert from the freeway to other underutilized routes along local streets (e.g. Newman et al, 1969; Allen and Newell, 1976; Nsour et al, 1992; Zhang and Recker, 1999; Banks, 2005). Diversion can save delays for those commuters who stick to the original route. However, commuters who divert to alternative routes likely incur additional delays relative to what they experienced prior to the deployment of meters; and the diversion often adds to the traffic delays on local streets. In all, diversion does not necessarily guarantee savings in system delay. To add complexity, the added delays on local streets are usually felt by other modes (e.g. city bus, bicycle, etc) as well as cars. Therefore, the full effects of diversion are difficult to evaluate. For this reason, diversion was not explored in the present dissertation.

It is well known that queues from freeway bottlenecks can grow long and thereby diminish output flows from busy off-ramps upstream (see e.g. Newman et al, 1969). Daganzo (1996) quantitatively showed that such a long queue on a rotationally symmetric “beltway system” can eventually cause the traffic to grind to a halt. The study also revealed that this so-called “gridlock effect” can be alleviated by metering on-ramp inflows. Freeway queues in the idealized beltway were assumed to be homogenous in terms of density. However, inhomogeneous queues are often created in real freeway systems such as the one studied for the present work; and as a result, additional curious phenomena may arise, as we shall see momentarily.

Some field studies have reported that on-ramp metering can reduce the total commute time that is spent in long freeway corridors (see e.g. Haj-salem et al, 1995; MnDOT, 2001; Ahn et al, 2007). One might be tempted to presume that less total travel time spent in a freeway means higher capacity of the freeway’s bottleneck. This is not necessarily true because freeway commute time could be saved merely because flows of vehicles exiting the freeway’s internal off-ramps increased due to the mitigation of gridlock-causing queues. This effect is beneficial, but does not imply the occurrence of higher freeway capacities.
Other field studies have reported in more explicit fashion that on-ramp metering increased flows downstream of an on-ramp merge (e.g. Papageorgiou et al, 1998; Diakaki et al, 2000). However, careful critiques of the study sites reveal that the locations where the flows were measured might sometimes have been restricted by exogenous queues from bottlenecks further downstream; see the review of Rudjanakanoknad (2005) for details. Therefore, these earlier findings are also inconclusive.

Finally, Cassidy and Rudjanakanoknad (2005) field-tested a metering strategy to reverse the capacity drop phenomenon at an on-ramp merge bottleneck. (Notably, the study verified that the bottleneck was indeed an active one.) That study revealed that capacity drops could be periodically recovered if restrictive and relaxed on-ramp metering rates were alternatively deployed in response to the level of queuing immediately upstream of the merge bottleneck. Furthermore, Zhang and Levinson (2010) conducted statistical tests to compare discharge flows from freeway bottlenecks with and without on-ramp metering; and confirmed that on-ramp metering increased the capacities of freeway bottlenecks.

Existing on-ramp metering strategies smooth the traffic by exploiting what we know so far about the capacity drop phenomenon. The cause of periodic recoveries in bottleneck capacity has not been explored, however. We will below unveil the cause of these recoveries and a way to exploit it.
Chapter 3

Hypothesis

This section presents a hypothesis concerning the four traffic effects that were individually reviewed in sect 2.1. The hypothesis furnishes a possible explanation about how these effects interact upstream of a freeway bottleneck. The traffic conditions and freeway geometries needed to induce the interactions are typical of those on urban freeways. It is conjectured that, under these conditions, the four effects can arise in sequence, with one effect triggering the next; and that this will ultimately cause the periodic recoveries often observed in bottleneck discharge flow. The hypothesis is described using the idealized freeway stretch shown in Figure 3.1 (a).

Consider a queue that forms at a freeway bottleneck; see the shaded area in Figure 3.1 (a). Recall that the onset of queuing at the bottleneck is commonly accompanied by a reduction in its discharge flow; the so-called “capacity drop”.

The queue from the bottleneck gradually expands when travel demand is persistently high. If the queue eventually reaches an upstream interchange (e.g. Merging Area 1 in Figure 3.1(a)), the queue would then disrupt the vehicle merging or diverging maneuvers there. This can create on-ramp queuing at the interchange, and cause a dense cluster of slow-moving traffic (i.e. a “jam”) to form within the freeway queue, often near its tail; see Figure 3.1 (b). Recall that this traffic feature called the “pinch effect” has been frequently reported (see again sect 2.1).

The jam’s upstream and downstream fronts can propagate intact, in the upstream direction. If the jam later arrives to another interchange further upstream (e.g. Merging Area 2 in Figure 3.1 (a)), and if merging or diverging maneuvers occur there in sufficient numbers, the resulting disruptions may cause the “catch effect”, as inferred from the previous studies (e.g. Kerner 2002; Laval, 2005) reviewed in sect 2.1. Thus, a new and very restrictive bottleneck would form at that upstream interchange.

The jam may continue to propagate upstream. The new bottleneck left behind starves the downstream queue of flow. The queue therefore decouples. The tail of the downstream queue will propagate forward, as in Figure 3.1 (c), leaving a pocket of free flow conditions in its wake. Kerner (2002) has reported that a jam’s arrival (attendant to the pinch effect) can trigger the catch effect, much as we have just described. The more novel aspects of the hypothesis are as follows.
(a) Hypothetical Freeway

(b) Pinch Effect

(c) Catch Effect

(d) Pumping and Driver Memory Effects

Figure 3.1 A hypothetical freeway and the four traffic effects
If the free flow pocket engulfs an on-ramp junction that resides upstream of the original bottleneck (Merging Area 1), then within this free flow pocket, traffic will flow at high rates, like those that invariably precede capacity drops. (Note that vehicles discharging from the on-ramp’s queue would no longer be constrained by a freeway queue.) Recall that Daganzo (2002) already theorized that these are the necessary conditions to trigger the “pumping effect”; see again Sect 2.1. Freeway drivers thus become motivated to accept small headways as they pass this ramp and approach the back of the queue.

As higher flows are now “pumped” from the merge, a fourth effect termed “driver memory” may arise. This final effect is known to continue usually for a mile or so even when localized queues temporarily slow down the traffic (e.g. Cassidy and Windover, 1998). Thus, motivated drivers would accept small headways as they approach and travel through the queue and the original bottleneck downstream; see Figure 3.1(d).

We know from observation (e.g. Cassidy and Bertini, 1999) that the resulting increase in bottleneck discharge flow will usually continue for only a few minutes. The high rate probably subsides for reasons akin to those that cause the initial capacity drop: disruptive vehicle lane-changing maneuvers made just upstream of the bottleneck. Once the recovery subsides, the above process can begin anew. Thus, sequential occurrences of the four effects would periodically repeat, as diagramed in Figure 3.2.

The hypothesis seems reasonable, given that it rests on four effects that are known to occur. We test the hypothesis against real data that were extracted both from videos and from loop detectors installed on a freeway site. Detailed descriptions of site and data are furnished in the following section.

![Figure 3.2 Periodic repetitions of the capacity-increasing mechanism](image-url)
Chapter 4

Site and Data

The study site is the 3-km stretch of northbound Interstate 5 shown in Figure 4.1. Its features include: a downstream bottleneck formed by a changing curvature in the site’s horizontal alignment; an upstream merge area formed by the on-ramp from Seamas Avenue (with rush-hour ramp demand of 600~700 vph); and a 0.5-km-long weaving section still further upstream (with on-ramp demand of 1400~1600 vph, and off-ramp demand of only 100~300 vph during the rush).

Figure 4.1 Study Site, Northbound I-5, Sacramento, California
The traffic data include vehicle arrival times that were extracted from videos at the locations labeled X₀~X₃ in the figure. (Note how our numeric labels increase in the upstream direction.) Vehicle entry and exit times at the on- and off-ramps were also extracted from videos, as were the vehicle accumulations (i.e. the numbers occupying a freeway segment at an instant) every 10 seconds in the three 200 m-long zones. These zones are numbered 1~3 to coincide with locations X₁~X₃ shown in the figure. We also recorded the times and locations at which vehicles began to perform merging maneuvers within zones 2 and 3 (i.e. on the upstream weaving section). In addition, the site’s loop detector stations measure vehicle counts and occupancies over 30-sec intervals. The detector stations of particular interest are labeled D₀ and D₁, also as shown in Figure 4.1.

All data were collected during morning rush periods. These include observations taken over three days in 2006 and 2008 when the ramps were not metered.² Additional observations were taken over another six days as part of metering experiments (to be described in Chapter 6). Attempts to collect data on several other days were foiled due to queues from downstream that spilled-over to the site early in the rush periods.

In the following section, the hypothesis concerning the capacity-increasing mechanism is tested against the real traffic data.

² Two of the days were in 2006 when meters had yet to be installed at the site. On the third day (in 2008), meters were present at the ramps, but rates were relaxed (i.e. raised) so that ramp vehicles were served as they arrived, and thus ramp queues were nearly non-existent.
Chapter 5

Observations

Empirical evidence furnished in this chapter confirm that i) four known traffic effects interact upstream of a freeway bottleneck and that ii) these interactions constitute the capacity-increasing mechanism that produces periodic recoveries in the bottleneck discharge flow.

The site’s downstream-most bottleneck and its time-varying pattern in discharge flow are examined first (sect 5.1). We then confirm how the pinch effect (sect 5.2) triggers the catch effect (sect 5.3), and unveil how these interactions trigger, in turn, the pumping effect (sect 5.4). These discussions are followed by the evidence of driver memory and the resulting recovery in bottleneck discharge flow (sect 5.5). We find that the recovery subsided after some minutes (sect 5.6). Finally, lessons learned from observing the interactions of the four known effects are presented (sect 5.7).

5.1 Downstream Bottleneck and Freeway Queues

A contour map of detector occupancy is shown for the site during part of a typical morning rush (on October 18, 2006, when ramps were not metered) in Figure 5.1. Note that in this figure, traffic moves in the downward direction, and that a sketch of the site is included on the left-hand side for the reader’s convenience. Occupancies of 17% or less (unshaded regions in the figure) denote free flow traffic conditions, where flow = demand; and occupancies greater than 17% (shaded regions) roughly denote queues, the darker the shade the denser the queue. The figure reveals that conditions remained freely flowing at locations downstream of the horizontal curve, just beyond kilometer-post 2.6. Thus we see that for the period shown in Figure 5.1, the discharge flows from the downstream curve were not constrained by other queues from further downstream. This state of affairs continued until a queue of this kind spilled over at 7:50 hrs. The day’s data were not analyzed beyond that time.

Queues arose upstream of the curve. Note that prior to 7:18 hrs, local queues periodically formed near the curve’s entrance. Beyond 7:18, a queue existed somewhere on the site through the remainder of the rush.
Figure 5.1 Occupancy contour map (Oct 18, 2006)

Figure 5.2 Discharge flow from the curve bottleneck (Oct 18, 2006)
The queuing pattern unveiled in Figure 5.1 means that from 7:18 until the curve bottleneck deactivated at 7:50, vehicles discharged from the bottleneck while it was active. These rates varied with time, however.

This variation is evident in Figure 5.2. It presents a curve of cumulative vehicle count plotted with an oblique axis for time (O-curve). Its counts were measured at location $X_0$, downstream of the curve bottleneck for a duration that spanned most of the bottleneck’s active period. Note that the slopes of an O-curve are flows in excess of a background rate (Cassidy and Windover, 1995; Cassidy and Bertini, 1999; Muñoz and Daganzo, 2002), which was 8000 vph in the present case. Flows are annotated on the O-curve in Figure 5.2. Visual inspection of the curve shows that following a capacity drop of 1000 vph beginning at 7:18 hrs, the bottleneck’s discharge flow temporarily recovered at 7:24 hrs.

Figure 5.1 reveals that a second backward jam emerged soon after 7:30 hrs, after the first free flow pocket disappeared; and that this was followed by a second catch effect and the emergence of a new (and smaller) free-flow pocket. As a result, the short-run bottleneck discharge flows were characterized by sequences of reductions and recoveries until the bottleneck deactivated; see again Figure 5.2.

Recall that the same kind of time-varying pattern in discharge flow has been reported at other freeway bottlenecks, as reviewed in sect 2.1. The mechanism behind these cycles turns out to be much like the one hypothesized in Chapter 3. The evidence follows.

### 5.2 Pinch Effect

The pinch effect is visible in Figure 5.1, and the figure has been annotated to highlight this. Note the darkly shaded region that traces the upstream and downstream fronts of a backward-moving jam. Further visual inspection of the figure shows that the jam initially formed near the Seamas merge, which suggests that the jam formed when the queue from the curve bottleneck disrupted merging traffic. The jam then propagated into the weaving section upstream.

Subtle details of the pinch effect are shown in Figures 5.3 and 5.4. Figure 5.3 presents O-curves measured at $X_1^+$, $X_2$ and $X_3$. (These locations annotated on the left-hand side of the figure.) The O-curves were constructed so that the vertical displacements between any two of them are the vehicle accumulations between their measurement locations (Newell, 1993). Note how the flow at $X_1^+$ (near the Seamas merge area) diminished at around 7:19

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3 The presence of queues upstream of the curve indicates that there was no shortage of demand; and the absence of queues downstream means that this excess demand was served at maximum rates.
Figure 5.3 O-curves at $X_1^+$, $X_2$ and $X_3$ (Oct 18, 2006)

Figure 5.4 Time series of vehicle accumulations in zones 1~3 (Oct 18, 2006)
hrs, as evident by the slope reduction in the lowest and thinly-drawn O-curve in the figure. Comparable slope changes in the O-curves at \( X_2 \) and \( X_3 \) occurred at successively later times, 7:19:30 and 7:21, respectively. These reveal how flows were constrained by an expanding queue from the site’s curve bottleneck (Cassidy and Windover, 1995; Cassidy and Bertini, 1999).

The passage of a backward-moving jam is revealed in Figure 5.4. It shows time-series curves of the vehicle accumulations in zones 1–3. Notice the dominant spike in each time-series curve, and how these three spikes coincide in time with the short-lived flow reductions brought by the jam, as highlighted by the boldly-drawn dashed arrow in Figure 5.3.

### 5.3 Catch Effect

The sequence of pinch and catch effects is also visible in Figure 5.1. Note the large region of dark shading that arose at the upstream end of the weaving section on the heels of the jam. This shading reveals a bottleneck that formed due to the catch effect. We further see from the figure how the queue downstream of the “caught” bottleneck gradually became less dense over time, to the point where a free flow pocket eventually emerged.

Figures 5.3 and 5.4 illustrate in more detail how the jam triggered the catch effect in the vicinity of zone 2, in the downstream portion of the weaving section. Note from the thinly-drawn O-curve in Figure 5.3 how the flow rose at \( X_1^+ \) shortly following the jam’s passage; i.e. the flow increased to 8000 vph at around 7:22 hrs. Further note that this flow is appreciably higher than the companion rise in flow at \( X_2 \); i.e. the flow there rose only to 7450 vph. This lower flow reflects the diminished discharge rate from a more recently formed bottleneck that was “caught” somewhere near zone 2 once the backward jam arrived there.

Once this new bottleneck formed, the high accumulation persisted (and even grew) in the weaving section. Note in Figure 5.3 the large and steadily expanding vertical deviations between the O-curves at \( X_2 \) and \( X_3 \), starting at around 7:24 hrs. Conversely, the accumulation downstream diminished over time. Note the shrinking vertical deviations between the O-curves at \( X_1^+ \) and \( X_2 \), starting at around 7:23 hrs. This gradual diminution occurred because the new bottleneck starved the downstream queue of flow. All this further confirms that the queue decoupled somewhere around zone 2, and that free flow conditions were gradually restored to much of the downstream portion of the site.
Complementary evidence of the catch effect is furnished in Figure 5.4. Note the low accumulations that eventually began fluctuating about 20 vehicles in zone 1, while congested accumulations continued to fluctuate around 30-plus vehicles upstream, in both zones 2 and 3.  

The pinch and catch effects, and their interaction described above add to the information that was previously reported in Kerner (2002). The underlying mechanism of the discharge-flow recovery will now be further explored by tracing the spatiotemporal patterns in merging events that occurred in the upstream weaving area.

Figure 5.5 presents a time-space diagram of the merging events that were performed from the weaving section’s auxiliary lane to the shoulder lane; see again Figure 4.1. Each data point of the diagram corresponds to the time and location at which a vehicle began to perform this mandatory maneuver. Similarly, Figure 5.6 presents a time-space diagram of optional merging maneuvers (i.e. leftward lane-changing maneuvers performed within the freeway mainline). Inspections of the shaded ellipses in both time-space diagrams reveal that following a jam’s passage (see the jam’s trajectory annotated as ‘A’ in both figures), there was a pronounced increase in the number of both mandatory and optional merging events at the downstream part of weaving section. Possible explanations for this change are furnished below.

Once the jam from the Seamas merge approached the 43rd Avenue weaving area (see again the jam’s trajectory ‘A’), traffic there became gradually dense, possibly because drivers slowed down in anticipation of the incoming jam ahead. When the jam eventually entered the weaving area, merging maneuvers became disruptive within and behind the jam. Thus, the weaving area became congested. Even after the jam had moved further upstream, the weave’s traffic congestion lasted for an extended time period largely due to high on-ramp inflows from the 43rd Avenue. In response to the weave’s congested traffic conditions, drivers who entered from the 43rd Avenue tended to stay in the auxiliary lane for longer distances until they performed disruptive merging maneuvers into the congested shoulder lane at the downstream portion of the weave. For this reason, mandatory merging maneuvers into the freeway’s shoulder lane were more frequently observed at the weave’s downstream portion in the wake of a jam; see again the shaded ellipses in Figure 5.5.

The change in the mandatory merging pattern caused the weave’s shoulder lane to be heavily congested. This, in turn, spurred on lane-changing maneuvers into the less congested freeway lanes to the left of the shoulder lane. We thus find optional merging

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4 The time-series curves for zones 2 and 3 do not display the steady growth in accumulation during this time that is visible in Figure 5.3. This is because much of that growth occurred in the weaving section’s auxiliary lane, which we excluded when measuring the accumulations in each zone (see Figure 4.1).
Figure 5.5 Time-space diagram of mandatory merging events (Oct 18, 2006)

Figure 5.6 Time-space diagram of optional merging events (Oct 18, 2006)
maneuvers were also more frequently performed in the wake of a jam, particularly at the weave’s downstream portion (see again the shaded ellipses in Figure 5.6).

The frequently-occurring disruptive lane-changing maneuvers spread queues laterally in the weaving area; and thus activated an upstream restrictive bottleneck in the wake of the jam’s passage. This kind of lateral transfer of queues has been previously reported (e.g. Cassidy and Rudjanakanoknad, 2005).

5.4 Pumping Effect

Following the catch effect, a pocket of free flow traffic conditions eventually enveloped the Seamas merge (see again Figure 5.1). As the pocket was forming, flow rose within it, and the pumping effect soon ensued. This sequence of the catch and pumping effects is visible in Figure 5.7. It presents 1-min measures of occupancy versus flow from detector station $D_1$, located just upstream of the Seamas merge (see the left-hand side of Figure 5.7). These points were measured over the 9-min period beginning at 7:18 hrs, which is shortly before the pinch effect was observed; and are numbered in chronological order of their occurrence from 1~9.

![Figure 5.7 Occupancy-flow plots at detector station $D_1$ (7:18~7:27; Oct 18, 2006)](image)

\[ ^{5} \text{The location where the pumping effect arose is the merging area that formed downstream of the Seamas Avenue on-ramp; see the sketch shown in Figure 5.7. We infer that the onset of the pumping effect caused flows at detector D1 to recover to a higher rate.} \]
The points labeled 1~4 show how traffic states gradually transitioned from free flow to queued, as the bottleneck’s queue and its attendant jam passed over D1. Points labeled 5~9 reveal how conditions gradually transitioned back to free flow, as the tail of the receding queue passed the merge and drivers became motivated to adopt small headways. That the transitions were gradual merely indicates that the tail of the expanding and receding queue exhibited transition zones, as described in Muñoz and Daganzo (2003).

The pumping effect is unveiled by examining the upper, boldly-drawn O-curve in Figure 5.8. Its counts were measured at location X1, just downstream of the Seamas merge. Visual inspection of that bold O-curve shows that a high flow of 9200 vph persisted at X1 prior to about 7:19 hrs. We further see that flow at X1 diminished soon thereafter, when it became constrained by the arrival of the queue from the curve bottleneck downstream. The flow diminished further still with the arrival of the backward-moving jam just after 7:20 hrs.

Further note from the bold O-curve that when the jam’s downstream front passed over X1 at about 7:21:30, the flow there began to increase: the flow was no longer constrained by the jam. And we see that by about 7:23:30, flow at X1 rose to 9300 vph. Distinctions in all these time-varying rates were confirmed, as described in footnote 4.

Interestingly, that high flow at location X1 (that began at 7:23:30 hrs) was not spurred-on by a rise in on-ramp inflow. This is evident in Figure 5.9, which displays the O-curve of inflows from the Seamas on-ramp. Note how the flow before and after 7:23:30 persisted at a rate of about 640 vph. In this case, the pumping effect arose due solely to motivated drivers who approached the Seamas merge via the freeway.

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6 This high flow emerged due to the pumping effect before the initial capacity drop occurred at the site’s downstream curve bottleneck. In this case, the pumping effect arose without the aid of the pinch and catch effects.

7 The diminished on-ramp inflow from 7:13:30 to 7:18:30 (350 vph) emanated from somewhere upstream of the ramp. Note as a further aside how the O-curve in Figure 5.9 displays pronounced wiggles from 7:18:30 to about 7:23:30. This is the period when the queue from the downstream curve bottleneck engulfed the Seamas merge (see again Figures 5.1 and 5.8). The wiggles reveal how small platoons of ramp vehicles were often impeded by the freeway queue before forcing their ways onto the freeway. The O-curve became smoother (the wiggles diminished in amplitude) from 7:23:30 to 7:28 hrs. This latter period roughly coincides with the emergence of the first free flow pocket and the attendant recovery in bottleneck discharge flow.
Figure 5.8 O-curves at $X_1$ and $X_0$ (Oct 18, 2006)

Figure 5.9 O-curve of Seamas Avenue on-ramp vehicles (Oct 18, 2006)
5.5 Driver Memory and Discharge Flow Recovery

The lower, thinly-drawn O-curve in Figure 5.8 was constructed from the counts at location X₀ located downstream of the curve bottleneck. (This O-curve was previously displayed for a longer duration in Figure 5.2.) The thin O-curve in Figure 5.8 shows that bottleneck discharge flow was only 8100 vph following the capacity drop at 7:18 hrs. Note, however, how discharge flow recovered to 9500 vph at around 7:24 hrs. From this we see how the high flows pumped out of the free flow pocket upstream continued through the curve bottleneck. Of note, the high flows continued even though a localized queue persisted for much of the time at the curve bottleneck’s entrance (see again Figure 5.1). As motivated drivers discharged from the Seamas merge, the small headways that they adopted did not ultimately meld into the local queue downstream. Rather, these drivers remembered their preferences for small headways, and retained these small headways as they pushed their way through the local queue. Visual comparison of the two O-curves in Figure 5.8 shows that the recovery flow (thin O-curve) was slightly higher than the flow pumped from upstream (bold O-curve). This finding is consistent with our hypothesis described in Chapter 3.

5.6 Collapse

The thin O-curve in Figure 5.8 shows that this recovery lasted for only about 4 minutes. When the recovery subsided, the system was left in a state similar to the initial one and the mechanism began anew.

5.7 Lessons Learned from the Observations

The empirical evidence shown above confirms that the capacity-increasing mechanism was indeed caused by the interactions of four known traffic effects. Furthermore, findings from the observations point to some lessons in the context of traffic control strategies, such as freeway on-ramp metering. (The lessons described below would be better understood by referring to Figure 4.1 showing the study site’s geometry.)

The merging area at Seamas Avenue should be enveloped by a pocket of free flow conditions to the extent possible to prolong the duration of the pumping and driver memory effects. This favorable state of affairs may be achieved by taking the following control actions.

1) If a queue from the site’s downstream-most bottleneck expands beyond the Seamas merge, a new and restrictive bottleneck is required to “catch” the queue’s upstream portion at the 43rd Avenue weaving section; i.e. queues need to be decoupled at the
downstream end of the weave. Once the queues are decoupled, the newly formed weave bottleneck thereafter need to serve as a throttle valve to starve the original bottleneck’s queue of input flows, so that this downstream queue should become sufficiently shortened.

2) If a pocket of free flow traffic conditions are created at the merging area at Seamas Avenue, the input flows into this merging area need to be modulated in timely manner to prolong the duration of pumping effect. More specifically, when the free flow pocket envelops most of the merging area, on-ramp inflows from the Seamas Avenue should be raised sufficiently to fuel the pumping effect. However, these high on-ramp inflows should not persist indefinitely. The reason is that high on-ramp inflows into the merging area would also increase the likelihood of disruptive lane-changing there and thus eventually shrink the free flow pocket.

Controlled experiments described in the following chapter were aimed at testing the efficacy of the above control actions. These experiments ultimately verified that the capacity-increasing mechanism can be modulated to favorable ends.
Chapter 6

Controlled Experiments

The observations presented in the previous chapter were reproduced across days. We next explore this reproducibility in the context of field experiments. These experiments also serve as means of testing the unconventional metering algorithm that was developed in light of our findings.

The unconventional on-ramp metering logic was designed to modulate the capacity-increasing mechanism (sect 6.1). Controlled experiments were conducted to field-test the unconventional logic against a more conventional metering scheme, as well as ‘no metering case’ (sect 6.2); and the outcomes turned out to be favorable (sect 6.3). The reasons for these outcomes are confirmed with detailed data (sect 6.4). Finally, lessons learned from controlled experiments are discussed (sect 6.5).

6.1 Proposed Metering Logic

An unconventional metering strategy was designed for use in the latter portion of each rush, after the queue from the curve bottleneck first spilled-over to the Seamas merge (see again Figure 4.1). This strategy was implemented at the study site. To this end, the curve bottleneck’s queue was detected and tracked via occupancy data from detector stations D₀ and D₁. Further details on this queue-identification technique are furnished in Appendix A.

Full details on the unconventional metering scheme are furnished in Appendix B. In the interest of brevity, the basic logic underlying this scheme is summarized below.

Immediately after detector occupancies inferred that the curve bottleneck’s queue had, for the first time, spilled over to the Seamas merge, the metering rate at the upstream-most on-ramp from 43rd Avenue is to be relaxed (i.e. set at a high rate of 1500–1600 vph).

---

8 The experiments were conducted in different months spanning multiple years. Though annual and seasonal differences in demand may have occurred, queues from the curve bottleneck filled the upstream portion of the site on all experimental days. And all experiments were conducted in good weather conditions. In these ways, the experiments—to test the effects of various control strategies on bottleneck discharge flows—were controlled for exogenous (e.g. seasonal) effects.
High ramp inflows would therefore flood the site’s weaving area. The intent is to create dense, slow-moving traffic there. This, in turn, was aimed at making restrictive the weaving section’s bottleneck that was eventually triggered (i.e. “caught”) by the arrival of a backward jam. Once the queue decoupled as a result, the receding portion of queue downstream would be fueled by low input flow (from the restrictive weave bottleneck). The tail of the receding queue should therefore propagate forward at high velocity.

Once detector occupancies inferred that free flow conditions are restored to the Seamas merge as a result, the metering rate at its on-ramp is to be relaxed to a rate of 600~700 vph. The intent was to modulate the capacity-increasing mechanism; i.e. we sought ramp inflows that are sufficiently high to produce the pumping effect, but low enough to reduce the likelihood that disruptive vehicle lane-changing will terminate the discharge-flow recovery. In this way, we sought to prolong the durations of the discharge-flow recoveries.

Relaxed metering persisted at the Seamas on-ramp until the queue from the curve bottleneck again spills over to that merge area. (The metering rate at Seamas was relaxed yet again whenever a free flow pocket was returned to the merge). In an effort to maintain a restrictive bottleneck in the weaving section, the 43rd on-ramp was metered at the relaxed rates until the curve bottleneck downstream was no longer active. The relaxed metering had the additional benefit of reducing the on-ramp queues.

6.2 Details of Controlled Experiments

The proposed strategy was tested for three days at the site. In each day’s test, the unconventional logic was deployed only after the queue from the curve bottleneck first expanded to the Seamas merge. Prior to that event, the meters were operated in a more conventional fashion: restrictive metering rates were deployed at each on-ramp whenever freeway queues were detected nearby. A full description of this conventional algorithm is furnished in Appendix C. This latter algorithm is compatible with so-called “demand-capacity” metering strategies that are prominent in the literature; refer to Sect 2.2 for relevant reviews.

For comparison, experiments were performed for three additional days, during which times the conventional metering algorithm was used throughout the rush periods. This conventional logic sought to retard the growth of freeway queues

Controlled experiments include investigating traffic operations that were realized when metering systems were not installed on the site’s on-ramp. To this end, traffic data taken from three representative days were analyzed. This “no metering” case was used as a
good measure for comparing the outcomes of deploying the above two metering strategies.

6.3 Outcomes

The outcomes of the controlled experiments are summarized in Table 6.1. Its third column displays the duration over which each day’s measurements were taken. Each of these periods spanned the time from the queue’s initial expansion to the Seamas merge, until the curve bottleneck was deactivated. The table’s fourth and fifth columns present each day’s average inflows from the site’s two on-ramps. As expected, these were highest in the absence of metering, and lowest under conventional metering. The sixth column presents (in bold) the curve bottleneck’s average discharge flow during the rush period. The seventh and final column displays the estimation error (in percent) associated with each measured discharge flow, based in part on the sample size (see Daganzo, 1997, page 254-258). Note that the error for any single observation is always less than 2% and that the error for the average of each experiment group is always close to 1%.

Table 6.1 Outcomes of Experiments

<table>
<thead>
<tr>
<th>(1) Experiment Group</th>
<th>(2) Date</th>
<th>(3) Measurement Duration (min)</th>
<th>(4) Average Inflow from On-ramp (vph)</th>
<th>(5) Average Discharge Flow (vph)</th>
<th>(6) Average % Error of Estimated Discharge Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Seamas</td>
<td>43rd</td>
<td></td>
</tr>
<tr>
<td>No Metering</td>
<td>Oct 18, 2006</td>
<td>18</td>
<td>620</td>
<td>1590</td>
<td>8560</td>
</tr>
<tr>
<td></td>
<td>Nov 2, 2006</td>
<td>64</td>
<td>610</td>
<td>1570</td>
<td>8550</td>
</tr>
<tr>
<td></td>
<td>Feb 13, 2008</td>
<td>21</td>
<td>740</td>
<td>1550</td>
<td>8440</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>34</td>
<td>660</td>
<td>1570</td>
<td>8520</td>
</tr>
<tr>
<td>Conventional Metering</td>
<td>May 20, 2009</td>
<td>29</td>
<td>510</td>
<td>1100</td>
<td>8660</td>
</tr>
<tr>
<td></td>
<td>Sep 16, 2009</td>
<td>42</td>
<td>450</td>
<td>1040</td>
<td>8480</td>
</tr>
<tr>
<td></td>
<td>Sep 17, 2009</td>
<td>18</td>
<td>450</td>
<td>1050</td>
<td>8420</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>30</td>
<td>470</td>
<td>1060</td>
<td>8520</td>
</tr>
<tr>
<td>Proposed Metering</td>
<td>Apr 15, 2009</td>
<td>54</td>
<td>570</td>
<td>1440</td>
<td>8790</td>
</tr>
<tr>
<td></td>
<td>Apr 29, 2009</td>
<td>34</td>
<td>640</td>
<td>1470</td>
<td>8730</td>
</tr>
<tr>
<td></td>
<td>May 14, 2009</td>
<td>37</td>
<td>610</td>
<td>1520</td>
<td>8870</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>42</td>
<td>610</td>
<td>1480</td>
<td>8800</td>
</tr>
</tbody>
</table>

9 On most days, the bottleneck was de-activated at the end of the rush. On three days (Oct 18, 2006; Feb 13, 2008; Sep 17, 2009), the bottleneck was deactivated late in each rush by the arrival of a queue from downstream.
Note too from the sixth column that, within a single experiment group, the average discharge flows did not vary much across days: daily differences were always less than 2%. Interestingly, we see that under conventional metering, the average discharge flow taken over the three days of experiments was identical to the 3-day average in the absence of metering: 8520 vph. Tellingly, the proposed logic produced a long-run discharge flow each day that was always larger than any day’s discharge flow from the other experiment groups. The likelihood that this outcome occurred purely by chance is about 1 percent. The 3-day average under the proposed logic (8800 vph) represents a 3% gain over the average of the other two groups.

It seems that the proposed logic performed as intended. The reasons for this favorable outcome are confirmed by examining the data in further detail.

6.4 A Closer Look

Closer inspection of the data indicates that the unconventional metering logic modulated the mechanism, such that the recoveries in discharge flow were less pronounced, but longer-lived, than those measured in the absence of ramp metering. As an example, Figure 6.1 displays O-curves measured on a day when the proposed logic was deployed (May 14, 2009). They are typical of the O-curves for that experiment group. The middle, boldly-drawn O-curve was constructed from vehicle counts at X₁, located just downstream of the Seamas merge. That O-curve shows how flows from the merge recovered on the heels of a jam’s passage, i.e. the flow rose to 8510 vph starting at around 7:34 hrs. The lower, thinly-drawn O-curve shows how the discharge flows (measured at X₀) began to rise very soon thereafter, at around 7:34:30. The recovery was small at first (8760 vph). Yet as the free flow pocket emerges, vehicles began discharging the curve bottleneck at a high rate of 9250 vph at about 7:36:30.

This high rate was soon fueled by increased on-ramp flows. At 7:39 hrs, the metering rate for the Seamas on-ramp was relaxed (the rate went from 530 vph to 750 vph). Note the evidence of the pumping effect: the bold O-curve in Figure 6.1 shows that the flow discharging from the merge increased to 9350 vph. The lower, thin O-curve shows how the discharge flow further increased as a result: discharge flow rose to 9380 vph. Note that the recovery subsided at 7:43:30. The average discharge rate during the 9-min recovery period (from 7:34:30 to 7:43:30) was 9200 vph.

10 That the outcome could be due to random chance is akin to randomly choosing nine numbers and discovering that the first three of these are the largest of the nine.
11 As an aside, the metering rate for the 43rd Avenue on-ramp was relaxed (i.e. its rate went from 1350 vph to 1600 vph) some minutes earlier at 7:32 hrs in an effort to promote the catch effect.
Figure 6.1 O-curves under proposed logic (May 14, 2009)

Figure 6.2 O-curves in the absence of metering (Oct 18, 2006)
Contrast this with the recovery observed in the absence of metering. For this purpose, we examine Figure 6.2. (Note that lower two O-curves in this figure have already been examined in Chapter 5; but are shown again here for the sake of reader’s convenience.) The lower thin O-curve in that figure showed that, with no metering, the recovery: occurred promptly at 7:24 (only 6 minutes after the capacity drop first occurred); and was slightly more pronounced (discharge flow rose to 9500 vph). However, the recovery was much shorter-lived (4 minutes). This latter observation is part of the reason why the proposed logic produced higher long-run average discharge flows, as compared against the “no metering” case.

Of further interest, we find that the discharge flows measured outside of the recovery periods were higher when ramps were metered. As an example, consider the discharge flow following a capacity drop in the unmetered case (8100 vph, see the lower thin O-curve in Figure 6.2); and compare it against the flow that followed a capacity drop when the proposed logic was used (8430 vph; see the lower O-curve in Figure 6.1). We suspect that by restricting inflows from the Seamas ramp, metering diminished flow disruptions caused by lane-changing. Diminished lane-changing has been shown to “smooth” and increase the discharge flows through freeway bottlenecks (see Cassidy et al, 2010).
The conventional logic, with its low metering rates, produced this latter benefit as well. Save for this, the conventional approach was counterproductive for two reasons. First, metering the 43rd Avenue on-ramp at low rates precluded the formations of free flow pockets; i.e., by preventing the on-ramp vehicles from swamping the weaving section, a bottleneck was never “caught” there. Second, the absence of a free flow pocket, coupled with the restrictive metering rates at the Seamas on-ramp, prevented the pumping effect from occurring. Evidence follows.

For comparison, consider again the O-curves in Figure 6.1. Recall that these were measured while the proposed logic was in use. The thin, upper-most O-curve in the figure was measured just upstream of the Seamas merge (and downstream of the weaving section) at a location that we labeled X1+. That O-curve shows that following the passage of a jam, flow departing the weaving section was only 8040 vph, and that this low rate persisted for 7 minutes. Eventually, disruptions in flow within the weaving section subsided somewhat and the “caught” bottleneck became less restrictive; i.e. the upper O-curve shows that the weaving section’s outflows increased to 8770 vph, starting at 7:41 hrs. Recall that by that time, however, the free flow pocket had formed and pumping had long taken effect.

O-curves shown in Figure 6.2 also illuminate the role played by the upstream “caught” bottleneck in inducing the pumping effect. Recall that the O-curves were measured on a day when metering systems have not been installed (Oct 18, 2006). The upper thin O-curve shows that following the passage of a jam, flows departing the weave bottleneck were lowest of all (i.e. 7200 vph). This severe flow restriction, in turn, enlarged the pocket of free flow traffic conditions at a drastically high velocity. After all, flow within the weaving section recovered to a higher rate (i.e. 8600 vph), as seen the upper-most O-curve once the pumping effect took place at the Seamas merge.

Contrast the O-curves of the above two cases with those shown in Figure 6.3. They were measured on a day when conventional metering was used throughout the rush (May 20, 2009), and are typical of the O-curves from that experiment group. The thin, upper-most O-curve in the figure was measured at X1+ and reveals that two distinct jams passed over the location during the period shown. On the heels of both jams, flows at X1+ were in excess of 8300 vph; i.e., flows departing the weaving section were high in the absence of a caught bottleneck there. Free flow pockets therefore did not form and there was no pumping effect. As a result, discharge flow never recovered. The thin, lower O-curve in Figure 6.3 shows instead that discharge flow persisted at a steady rate of 8660 vph following the capacity drop.
6.5 Lessons Learned from Controlled Experiments

The findings shown in sect 6.4 further confirm the validity of preliminary observations: i) the pumping effect could occur at an on-ramp merge when the traffic there was freely flowing (sect 5.4) and ii) this favorable state of affairs could be set into motion by diminishing the freeway’s upstream mainline inflows into the merge (sect 5.3).

Additional key lessons learned from controlled experiments are summarized below.

1) After a pocket of free flow conditions emerged at an on-ramp merge (e.g. Seamas Avenue merging area), restricting on-ramp inflows into the free flow pocket inevitably limited flows that are pumped out of the merge. The upside of this restrictive metering was that it prolonged the presence of the free flow pocket.

2) Whenever the free flow pocket enveloped most of the merge, relaxing the on-ramp inflows into the merge was helpful in fueling the pumping effect there. However, this relaxed metering eventually made the free flow pocket shrink (within several minutes, for the case of the present site).

One may suspect that the above findings can be valid in other freeways. In the following chapter, requirements for this transferability will be discussed in the context of generic lessons for other freeways.
Chapter 7

Generic Lessons for Other Freeways

The pumping effect is an essential component in the capacity-increasing mechanism that was unveiled above. The pinch and catch effects have their significance in the sense that they induce the pumping effect. Driver memory is meaningful only when it helps the pumping effect to be translated into a recovery of the bottleneck discharge flow.

Generic lessons applicable to other freeways are furnished below.

1) An on-ramp junction that resides upstream of a bottleneck is one key requirement for realizing the capacity-increasing mechanism unveiled here. For the present study, the downstream bottleneck happened to be formed by a change in horizontal alignment. We suspect that a bottleneck of almost any type will suffice, be it formed by an alignment change, a lane reduction, a merge, etc. Perhaps the only limitation is that the downstream-most bottleneck cannot be so restrictive that a free flow pocket cannot emerge upstream. Thus, we believe that this key requirement will be satisfied on many freeways and expressways throughout the world.

2) The pumping effect could be induced by dissipating queues that had formed at an on-ramp merge. This could be done when the pinch and catch effects triggered a restrictive bottleneck near another ramp junction upstream of the subject merge. From this observation, we can infer that any inhomogeneity in freeway alignment (e.g. a ramp junction, an up-hill, etc) should exist upstream of the on-ramp merge where the pumping effect is targeted to occur. Numerous segments on typical freeways and expressways meet this additional geometric requirement.

3) Even when the above two geometric requirements are met, there might be further requirements to be satisfied so that the pumping effect can be effectively induced. For instance, suppose that we consider a typical freeway segment where two on-ramp junctions neighbor each other upstream of a freeway bottleneck; see again Figure 3.1. Then, key criteria that should be identified include: i) how far should the downstream-most bottleneck be separated from its nearest ramp junction in the upstream? , ii) how far should the two junctions be separated from each other? and iii) how much on-ramp demand should be secured for each junction?
4) Given that all the conditions are favorable to induce the pumping effect, freeway control strategies should be targeted to expedite and prolong the duration of this effect.

Practical implications of the above lessons and possible improvements to freeway traffic control strategies are discussed next.
Chapter 8

Conclusions

Observations taken from an urban freeway revealed that periodic flow recoveries through the site’s downstream-most bottleneck arose due to the interactions of four known traffic effects. These periodic recoveries naturally arose (i.e. without any aid of traffic control systems) and usually lasted for several minutes. This capacity-increasing mechanism was reproduced on multiple observation days.

Repeated experiments indicate that this mechanism can be modulated to favorable ends by deploying an unconventional on-ramp metering scheme. This scheme was designed to create and prolong pockets of free flow conditions at the site’s downstream on-ramp merging area. Through this modulation, higher flows were pumped out from the freely flowing merging area and kept through the downstream-most bottleneck for an extended time period (e.g. 9 minutes). As a result, a 3% average gain in long-run discharge flow was achieved. Queuing analysis (Newell, 1971) indicates that this modest gain can save more than 300 vehicle-hours of travel at the study site during a typical morning rush alone.

Practical implications of the findings are discussed in sect 8.1; and directions for future work are discussed in sect 8.2.

8.1 Practical Implications

The capacity gains produced by the unconventional metering scheme can be shared by all commuters who pass through the site’s curve bottleneck. The proposed metering strategy may benefit commuters on surface streets as well. This is because the strategy can reduce on-ramp queues that might otherwise grow long and disrupt surface-street traffic.

We suspect that the present findings can be generalized to other freeways. After all, the mechanism’s four attendant effects have been reported on many different freeways and expressways. And the time-varying discharge flow from the site’s curve bottleneck is typical of the pattern observed at other freeway bottlenecks. And finally, the present site seems to be quite ordinary with few, if any distinctions from many other urban freeways.
If our suspicion concerning the generality of our findings is correct, then strategies that opportunistically induce free flow pockets, and that regulate the pumping effect, may constitute a promising new paradigm in freeway traffic control.

### 8.2 Future Work

The proposed metering logic has at least one potential downside: expanded freeway queues created by the “caught” bottleneck may block busy off-ramps upstream and starve them of exit flows, as reviewed in sect 2.2. This so-called “gridlock effect” seems negligible for the case of the present study site, which is radial in shape and contains only a single off-ramp with low exit demand. Future work can include testing the proposed scheme on other freeways with many busy off-ramps. In these future experiments, measured reductions in off-ramp flows (if any) should be compared against the gains in bottleneck capacity. Possible modifications of the proposed metering scheme should be targeted to maximize net gains in overall output flows from freeway systems.

Future experiments can also explore if refinements to the proposed ramp-metering strategy can further prolong discharge-flow recoveries. For the present study, metering rates at the study site’s on-ramps alternated between two distinct values (i.e. high vs. low rates) in response to time-series of vehicle occupancies taken at fixed detector locations upstream of the site’s downstream-most bottleneck. If more advanced technologies allow us to trace queue lengths in real-time, we can adjust metering rates more smoothly and opportunistically at on-ramps upstream of the bottleneck.

We might also test if more aggressive control actions can further prolong the duration of a free flow pocket that forms at the study site’s downstream on-ramp merge. For instance, as soon as the free flow pocket starts shrinking, we can temporarily cut off the on-ramp inflows that enter into the free flow pocket. Simultaneously, we can attempt to turn on only green light at the on-ramp that resides in advance of the site’s upstream bottleneck until the free flow pocket begins expanding again rapidly. This latter action is intended to make the upstream bottleneck more restrictive, so that the free flow pocket would be further starved of input flows.

However, there may be situations when on-ramp metering alone is not enough to adjust flows departing from the upstream bottleneck as effectively as intended. In those situations, combined use of control technologies can be considered. For example, freeway mainline metering or variable speed limits can augment on-ramp metering, so that the discharge flows from the upstream bottleneck might be more effectively modulated. Future experiments to test this advanced strategy would be worthwhile.
References


Appendix A

Indicators to Trace Freeway Queues

The freeway site used for testing the proposed logic is illustrated again in Figure A1.

Simple indicators were relied upon to detect when: (i) a queue formed at the curve bottleneck, and (ii) the freeway queue grew long and reached the upstream junctions at Seamas and then 43rd. Time series of occupancies across all lanes were used for this purpose. A 3-minute moving average was used to filter out fluctuations.

The indicators identified the queue’s arrival at detectors D₀ and D₁ within a minute of the actual occurrences. Figure A2 presents an O-curve (boldfaced) and a cumulative occupancy curve, i.e. T-curve (thinly-drawn) measured at detector D₀. These curves reveal that the queue arrived to detector D₀ at precisely 7:10:30: note how the slope of the O-curve declines simultaneously with an increase in the slope of the T-curve. This is the signature of a queue’s arrival at a detector (Cassidy and Bertini, 1999). Figure A3 shows that the occupancy at detector D₀ exceeded the critical value of 17% at 7:11:00; i.e. in this case, the simple time series identified the queue’s arrival to detector D₀ within 30 seconds.

Similarly, the indicators promptly determined when the long queue reached detector D₁. The O-curve and T-curve in Figure A4 show that the curved bottleneck’s queue arrived at D₁ at 7:19:00; while the time series of occupancies in Figure A5 detected this event only 30 seconds later.
Figure A2  O-curve and T-curve at $D_0$ (10/18/06)

Critical occupancy = 17%

Detecting queue's arrival at 7:11:00

Figure A3  Time series of occupancies at $D_0$ (10/18/06)
(3-minute moving average)
Figure A4  O-curve and T-curve at D1 (10/18/06)

Figure A5  Time series of occupancies at D1 (10/18/06)
(3-minute moving average)
Appendix B

Proposed Metering Algorithm

The proposed metering was designed to create a free-flow pocket to the extent possible at the merging area of Seamas. To this end, the occupancies at detector stations D0 and D1 are used to monitor the opening (or closing) of a free-flow pocket at the Seamas merge. Metering rates are relaxed to rates of 700 and 1600 vph at Seamas and 43rd Avenue, respectively, when the occupancy at D0 is below 17% regardless of the occupancy at D1. A restrictive metering rate (350 ~ 550vph) is to be deployed at the Seamas on-ramp, with a relaxed metering rate (1500~1600vph) at the 43rd on-ramp when the occupancy of D0 exceeds 17%.

The above procedure is summarized in the flow chart of Figure A6. The notation used for the proposed ramp metering algorithm is given below:

\[ t = t_0 \]  initial time
\[ \Delta \]  the cycle length of metering rate update ( \( \Delta = 30 \) seconds)
\[ K_0(t), K_1(t) \]  the time series indicator (i.e. occupancy of 3 minute-moving average),
  which is measured at time \( t \) at detector stations D0 and D1, respectively
\[ K_{cr} \]  a predetermined critical occupancy at detector stations D0 and D1 ( \( K_{cr} = 0.17 \))
\[ R_{Seamas}(t), R_{43rd}(t) \]  the variable denoting metering rate which is updated at time \( t \) at the Seamas and 43rd on-ramps, respectively
\[ R_{Seamas, restrict} \]  a predetermined restrictive metering rate which is applied to the Seamas on-ramp \( (R_{Seamas, restrict} = 550 \) vph)\)
\[ R_{Seamas, relax}, R_{43rd, relax} \]  a predetermined relaxed metering rate which is applied to the Seamas and 43rd on-ramps, respectively \( (R_{Seamas, relax} = 700 \) vph, \( R_{43rd, relax} = 1600 \) vph)\)
\[ \alpha \]  a constant which can be subtracted from \( R_{Seamas, restrict} \) to reduce the frequency of disruptive lane-changing maneuvers that arise upstream of the curve bottleneck at the expense of the on-ramp queues at the Seamas Avenue (\( \alpha \) is determined based on both \( K_0(t) \) and \( K_1(t) \); \( 0 \leq \alpha \leq 200 \))
\[ \varepsilon \]  a constant which can be subtracted from \( R_{43rd, relax} \) to modulate the amount of freeway mainline flow approaching the free-flow pocket that is created at the merging area near Seamas Avenue (\( \varepsilon \) is determined based on both \( K_0(t) \) and \( K_1(t) \); \( 0 \leq \varepsilon \leq 200 \)).
Figure A6 Flow chart of the proposed metering logic
Appendix C

Conventional Metering Algorithm

The conventional metering scheme is intended to retard the growth of freeway queues. In this scheme, metering rates are adjusted for each on-ramp based upon occupancies measured by the nearest detectors. Metering rates are relaxed to rates of 700 and 1600 vph at the Seamas and 43rd Aves, respectively when occupancies at detector stations D0 and D1 are below 17% (i.e. when traffic between D0 and D1 is presumed to be freely flowing). As the freeway queue from the curve bottleneck arrives at detector D0 and thus increases occupancies above 17% at that location, on-ramp inflows are to be restricted at Seamas Ave (to 350–550 vph). In many instances, this restrictive metering would not be enough to contain the growth of the freeway queue. Thus, occupancies at the upstream detector D1 eventually would surge above 17% when the queue arrives at that detector. In this case, very restrictive metering rates (of 350–550 vph and 1000–1300 vph) are to be deployed at the Seamas and 43rd Avenue on-ramps. This very restrictive metering continues until freeway queues disappear.

The above procedure is summarized in the flow chart of Figure A7. The notation used for the proposed ramp metering algorithm is identical with that of proposed algorithm that was previously described, except that $\varepsilon$ (i.e. the parameter attendant to $R_{\text{relax}}$) is not used; and that an additional constant $R_{\text{restrict}}$ and its attendant parameter $\beta$ are introduced as denoted below.

$R_{\text{restrict}}$ : a predetermined restrictive metering rate which is applied to the 43rd on-ramp ($R_{\text{restrict}} = 1300 \text{ vph}$)

$\beta$ : a constant which can be subtracted from $R_{\text{restrict}}$ to combat the site’s freeway queues more aggressively at the expense of the on-ramp queues at 43rd Avenue ($\beta$ is determined based on both $K_0(t)$ and $K_1(t)$; $0 \leq \beta \leq 300$)
Figure A7 Flow chart of the conventional metering logic