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Validation of Daganzo's Behavioral Theory of Multi-Lane Traffic Flow: Final Report

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ABSTRACT

A study was conducted to verify C. F. Daganzo's behavioral theory of multi-lane traffic flow (*1*, *2*). This study was conducted by teams from San Diego State University and the University of California at Berkeley who worked independently on a series of case studies to test predictions derived from the theory. The results of the study suggest that some of the phenomena predicted by Daganzo do occur, but not at all locations, and that the underlying behavioral assumptions are oversimplified. Specifically, the types of flow-density (or flow-occupancy) relationship assumed by Daganzo were found to occur at some sites but not others; semi-congested states and fast waves between semi-congested and fully-congested states, as predicted by Daganzo were observed at one site; an increase in average time gaps indicating a "loss of motivation" assumed by Daganzo was observed at one site but not at others; speeds were found not to be equalized among lanes in congested flow, contrary to Daganzo's assumption and most past literature; redistribution of flow among lanes was observed at flow breakdown despite the absence of speed equalization, contrary to Daganzo's behavioral assumptions; and distinct capacity and discharge flow states predicted by Daganzo were not observed downstream from queues. Observations not directly related to the test of Daganzo's theory included details of lane-by-lane speed behavior in congested flow, a case in which the location of the point of maximum density upstream from a bottleneck may have influenced its capacity, and observations of general characteristics of incident recovery flow.

EXECUTIVE SUMMARY

This report documents a study to validate a new macroscopic traffic flow theory by Daganzo (*1*, *2*). The study was conducted by teams from San Diego State University (SDSU) and the University of California at Berkeley (UCB) who worked independently on a series of case studies to test predictions derived from the study. The major goal of the study was to provide a better understanding of freeway traffic flow and thus to improve the basis for modeling and managing freeway traffic.

Daganzo's theory assumes two types of drivers, aggressive (*rabbits*) and timid (*slugs*), and two lane groups, shoulder and passing lanes. In free flow, rabbits travel faster than slugs, with all rabbits in the passing lane and all slugs in the shoulder lane. In high-volume uncongested flow, rabbits follow one another with very small headways so long as they are able to pass, and such drivers are referred to as *motivated* because the very small headways are motivated by their desire to pass. If anything happens to reduce the speed in the passing lane below the free-flow speed in the shoulder lane, however, the rabbits lose their "motivation," increase their headways, and change lanes to equalize speeds. The concept of motivation, the conditions under which it is gained or lost, and the consequences of transitions from motivated to unmotivated states (and vice versa) are the key innovations in Daganzo's theory. Taken together, they constitute a new theory of how transitions from uncongested to congested flow take place.

Validation of the theory involved an extensive literature review and a series of case studies. The literature review was intended to confirm the factual basis for the theory (as reflected in past empirical research) and establish its scope relative to the overall body of empirical knowledge about traffic flow. Case studies focused on merge bottlenecks and flow recovery following the removal of incidents and were intended to test specific predictions derived from the theory. Case studies of merge bottlenecks included four in the San Diego area (conducted by the SDSU team), two in the Toronto metropolitan area (one conducted by each team), and one in the San Francisco Bay Area conducted by the UCB team. The SDSU team also studied flow recovery for six incidents that occurred in the San Diego area. Specific merge bottleneck sites were:

San Diego area:

- Southbound Interstate 5, downstream from Manchester Avenue, morning peak
- Westbound Interstate 8, downstream from Fletcher Parkway, morning peak
- Southbound Interstate 805, downstream from Nobel Drive, evening peak
- Northbound Interstate 5, downstream from Via de la Valle, evening peak

Toronto area:

- Eastbound Queen Elizabeth Way, downstream from Cawthra Road, morning peak (SDSU team
- Westbound Gardiner Expressway, downstream from Spadina Avenue, evening peak (UCB team)

San Francisco Bay area:

- Westbound State Route 24, just east of the Caldecott Tunnel, evening peak

Data for all sites other than the State Route 24 merge bottleneck consisted of automatically-collected loop detector data. At the San Diego sites (both merge bottlenecks and incidents), these included vehicle counts and occupancies; the sites in the Toronto metropolitan area also provided measured speeds from double-loop detectors. Data recording intervals were 30 seconds in San Diego and 20 seconds in Toronto. Data for the State Route 24 consisted of individual vehicle arrival times for several locations; these data were manually extracted from videotapes.

Significant limitations of the data collection sites included:

- Although Daganzo's theory is worked out in detail for freeways with two lanes in the direction of travel only, all of the sites involved more than two lanes. Where applicable, it was assumed that the most aggressive drivers would be found in the median (leftmost) lane and the least aggressive in the shoulder lane, and the analysis focused on comparing the characteristics of the median lane and shoulder lane with averages for the freeway as a whole.

- All detector stations at San Diego sites were located immediately upstream of on-ramps. This restriction did not apply to the Toronto data.

- Daganzo's discussion of incident clearance flow assumes no interference from bottlenecks either upstream or downstream of the incident, but in many cases incident queue discharges were affected by bottlenecks.

The specific predictions tested were derived from the theory and adapted to the study sites and data that were available. Several predictions are outlined in Daganzo (*1*, *2*). Those that appeared most suitable for verification were stated in terms of flow states and associated changes in flow characteristics at specific locations relative to merge bottlenecks or incidents. In some cases these had to be modified to take into account the peculiarities of the sites and the data and, in other cases, new predictions were derived to test basic assumptions of the theory.

In their final form, the predictions tested included:

- Semi-congested states (that is, states in which there are queues in some lanes but not others) will form upstream of a merge bottleneck prior to the transition from uncongested to congested flow.

- Fast waves (that is, waves with speeds greater than those between different congested flow states) may occur between semi-congested and fully-congested states in the transition to congested flow.

- The most aggressive drivers will segregate themselves in the fastest lane so long as there are differences in speed among the lanes and will redistribute themselves when speeds are equalized; consequently, there will be a rapid redistribution of flow among the lanes when speeds are equalized across the lanes (or conversely, when they cease to be equal), but not otherwise.

- Speeds will be equalized among the lanes in congested flow but speed differences will be reestablished following acceleration downstream of queues.

- There will be two distinct flow states (which Daganzo refers to as capacity flow and discharge flow) downstream of queues.

- The average time gaps in the passing lane will increase when speeds in the passing lane drop to the level of those in other lanes.

In order to test the predictions, it was necessary to determine the time and magnitude of changes in traffic characteristics such as flow, speed, occupancy, average time gaps, and the relative flows and speeds in different lanes.

The principal technique for identifying changes in these characteristics was plots of re-scaled (or oblique) cumulative curves. In this technique, a plot of the cumulative value of a time series of data (counts, occupancies, speeds, etc.) is re-scaled by subtracting a background rate. For instance, if $N(t)$ is the cumulative vehicle count at time t, the value plotted is $N(t) - x_o(t - t_o)$, where x_o is the background rate and t_o is the starting time for the curve. This coordinate system magnifies the figure's vertical axis, which in turn amplifies features of the curves such as changes in their slopes. These slope changes correspond to changes in the measured flows. Vertical displacement between consecutive curves are also amplified and made more visible. In the case of vehicular counts, these vertical displacements are the excess vehicle accumulations between measurement locations due to the vehicular delay.

Event-based averaging was used to quantify changes in the various traffic characteristics. In this technique, data are averaged over periods defined by specific events. Re-scaled cumulative curves were used to identify periods of near-constant flow, speed, etc. that occurred before and after abrupt changes in these characteristics. Averages for these periods were compared to quantify the changes.

Data were also analyzed by inspecting flow-occupancy scatter plots and time series of speeds and flows.

Speed and flow distributions were characterized in terms of flow and speed ratios – that is, the ratio of the flow or speed in the median lane to the average flow or speed for all lanes. In this case, the re-scaling of the cumulative curve consisted of subtracting 1.0 from the ratio for each time interval as it was accumulated, so that a positive slope for the cumulative curve indicated that the ratio was greater than 1.0 and a negative slope that it was less.

Overall results of the test of Daganzo's theory were mixed. The theory is most applicable to cases in which the flow-density (or flow-occupancy) relationship for the median lane has a so-called reversed-lambda shape and that for the shoulder lane has a triangular shape. Both the literature review and the study showed that these patterns sometimes occur, but that median-lane flow-occupancy relationships are often tri angular and those in the shoulder lane sometimes have an inverted-U shape. In the study, reversed-lambda flow-occupancy plots were found at only two sites.

Semi-congested flow states and fast waves between semi-congested and fully-congested states were observed by the UCB team, particularly at the Gardiner Expressway site; the SDSU team did not test these aspects of the theory.

The SDSU team did observe increases in average time gaps when flow broke down at the southbound Interstate 5 site, but not at other sites. This may indicate that "loss of motivation" sometimes occurs, but it does not appear to occur consistently. The UCB team did not test this aspect of the theory.

Predictions related to relative speeds and flows in different lanes were generally not verified. It was found, contrary to most of the previous literature, that speeds were not equalized in congested flow. In most cases, speeds in the median lane remained above the average for all lanes, but in other cases, they were less. Furthermore, flow redistribution among the lanes was sometimes observed at flow breakdown despite the absence of speed equalization. Finally, distinct capacity and discharge states were not observed downstream from the queues; rather, where flow redistribution took place, there was a tendency for vehicles to move back into the median lane gradually as they moved downstream, and this pattern did not change over time during queue discharge.

The study also led to a number of observations not directly related to Daganzo's theory. These include the observation that speeds in congested flow tend to be equalized only in the minimum speed phases of speed oscillations, a case in which a stalled vehicle moved the point of maximum density upstream of a bottleneck and appeared thereby to increase flow through the bottleneck, and observations of some general characteristics of incident recovery flow.

The results of the study suggest that some of the phenomena predicted by Daganzo's theory do occur, but not at all locations, and that the underlying behavioral assumptions are oversimplified. Suggested follow-up research includes (a) development of more realistic theories of driver behavior, including a more accurate classification system for driver types and better understanding of lane-use behavior and (b) additional empirical research to verify and extend findings of this study regarding flow-occupancy patterns, speed equalization, the stability (or lack thereof) of the location of initial flow breakdown at bottlenecks, and the effect of the location of dense queuing on bottleneck capacity.

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1. INTRODUCTION

This report documents an attempt to validate a new macroscopic traffic flow theory proposed by Daganzo (*1*,*2*). This theory makes predictions for separate groups of lanes, based on the assumption that the traffic stream is composed of a mixture of timid and aggressive drivers. It assumes two types of drivers, aggressive (*rabbits*) and timid (*slugs*), and two lane groups, shoulder and passing lanes. In free flow, rabbits travel faster than slugs, with all rabbits in the passing lane and all slugs in the shoulder lane. In high-volume uncongested flow, rabbits follow one another with very small headways so long as they are able to pass, and such drivers are referred to as *motivated* because the very small headways are motivated by their desire to pass. If anything happens to reduce the speed in the passing lane below the free-flow speed in the shoulder lane, however, the rabbits lose their "motivation," increase their headways, and change lanes to equalize speeds. The concept of motivation, the conditions under which it is gained or lost, and the consequences of transitions from motivated to unmotivated states (and vice versa) are the key innovations in Daganzo's theory. Taken together, they constitute a new theory of how transitions from uncongested to congested flow take place, and they lead to a number of predictions about phenomena such as wave speeds and traffic states in, upstream, and downstream of queues.

The study was conducted by teams at San Diego State University (SDSU) and the University of California Berkeley (UCB) who worked independently on a series of case studies intended to test predictions derived from the theory. These case studies concentrated on verification of predictions that could be readily tested with available data, including automatically-collected freeway traffic flow data and highly-detailed data reduced from videotapes by the UCB team. Predictions tested related to the transition to congested flow at merge bottlenecks and to flow recovery following the clearance of incidents. Features of the theory that were examined included the concept of motivation, the characteristics of traffic flow states in and downstream of freeway queues, and the wave speeds of transitions between congested and semi-congested states (that is, traffic states in which there are queues in some lanes but not others).

1.1 Background and Motivation

In recent years, there has been active debate concerning macroscopic traffic flow models. Three basic types have been advanced: "kinetic" models based on Prigogine and Herman (*3*), "higher-order" models descended from Payne (*4*, *5*) and "kinematic wave" models based more directly on Lighthill and Withem (*6*) and Richards (*7*). Recent developments prior to Daganzo's behavioral theory include simplified kinematic wave models by Newell (*8*) and Daganzo (*9*) and development of a new version of the higher-order model by Kerner and Konhäuser (*10*, *11*). Along with the development of new versions of the macroscopic models there has been debate over their relative merits. Daganzo (*12*) questions the validity of the higher-order models and Kerner et al (*13*) claim that the Lighthill-Witham theory of shock waves cannot explain observed properties of traffic jams. This debate has led to further development of the models, such as attempts to develop kinetic (*14*) or higher-order (*15*) models that avoid Daganzo's criticisms, and, most recently, to Daganzo's behavioral model (*1*, *2*).

Much of the current interest in macroscopic traffic flow models stems from the relative abundance of empirical evidence and the difficulty of devising theories that explain all of it. Although some of the key evidence relies on other types of data, such as the well-known vehicle trajectory data of Treiterer and Myers (*16*), most recent empirical work on freeway traffic flow has used automatically-collected data from induction loops. As a basis for his theory, Daganzo assembled an extensive list of "facts" related to traffic flow, whose sources are documented in reference 1. Empirical literature related to traffic flow, including Daganzo's sources, is reviewed in more detail in Section 1.3 to evaluate the empirical basis of the theory and establish the limits of its applicability.

Independent validation of theory is a part of the basic process of scientific inquiry; consequently, the major goal of this study was to provide a better understanding of freeway traffic flow. Further, validation is of Daganzo's theory was regarded as being of special importance because of the failure of the "traditional" classes of macroscopic models to explain the full range of empirical findings without sometimes producing absurd results. If validated, it would be an extremely important advance in understanding traffic flow and would provide a basis for a very simple macroscopic model of freeway flow that can be used in the design of freeway control measures.

1.2 Conduct of Study

This study was a joint effort by teams from SDSU and UCB that worked independently to conduct a series of case studies. Those conducted by the SDSU team used automatically-collected freeway traffic data from the San Diego and Toronto metropolitan areas and focused primarily on flow characteristics in and downstream of queues at merge bottlenecks and in queue discharge following the removal of incidents. Those conducted by UCB were based on automatically-collected data from the Toronto area and highly detailed flow data reduced by hand from videotapes at a site in the San Francisco Bay area. These studies focused more on flow characteristics upstream of the point of flow breakdown, and included investigation of possible semi-congested states and so-called fast waves between semi- and fully-congested states.

1.3 Literature Review

Daganzo's theory may best be thought of as a limited generalization of the kinematic wave theory of Lighthill and Withem (*6*) and Richards (*7*). As such, it incorporates the phenomena commonly described by kinematic wave theory, such as the movement of shock waves, and seeks to explain other interesting phenomena that have been observed, especially decreases in flow in the passing lane that are often observed downstream of bottlenecks when flow breaks down. A literature review was undertaken to address the extent to which the facts forming the principal bases of the theory are established by previous empirical research and the scope of the theory relative to the overall body of empirical knowledge related to traffic flow – that is, the extent to which it addresses the full range of phenomena described in the empirical literature.

The principal bases of the theory include the following assumptions, which are believed by Daganzo to be supported by past empirical research:

1. Traffic in uncongested flow is segregated by lane in terms of speed, with the highest speeds typically found in the median lane. This speed segregation breaks down in the transition to congested flow.

2. The maximum flow rate in the passing lane (typically the lane nearest the freeway median) occurs prior to the transition to congested flow and is greater than the maximum flow rates in other lanes. Since the maximum flow in the passing lane occurs in uncongested flow, the typical flow-density (or flow-occupancy) relationship for the median lane has a reverse-lambda shape. Flow relationships for other lanes have triangular or inverted-V shapes.

3. The decrease in flow in the median lane is related to an increase in headway that occurs when the speed segregation breaks down. In Daganzo's interpretation, this is due to a "loss of motivation" by drivers in the fast lane because they can no longer pass other traffic. The concept of "loss of motivation" is unique to Daganzo's theory and may be regarded as its most important distinguishing feature.

4. Wave speeds in congested flow (i.e., between two flow states, both of which are fully congested) are constant and identical for all lanes. In particular, such wave speeds do not vary with flow or vehicular speed. "Fast waves" with velocities greater than this characteristic wave speed are believed to be possible, but are held in Daganzo's theory to exist only in (or on the borders of) semi-congested states in which speed segregation has not completely broken down.

Findings of the literature review that are related to the bases of Daganzo's theory may be summarized as follows:

1. *Traffic in uncongested flow is segregated by lane in terms of speed, with the highest speeds typically found in the median lane. This speed segregation breaks down in the transition to congested flow*. As a general rule, past empirical research supports this view (*17*, *18*), although the issue does not appear to have been studied extensively. The primary source of evidence is time series of speed. Where these appear in the literature, they almost always display this feature. The possible exception is that there are some reports of congested traffic which do not display speed synchronization. This occurs, for instance in "wide jams" as reported by Kerner and Rehborn (*17*) and in one case of "synchronized" flow reported by Kerner (*19*). In this latter case, however, there may be some question about the overall circumstances and whether or not flow is "congested" in the sense adopted here.

2. *The maximum flow rate in the passing lane (typically the lane nearest the freeway median) occurs prior to the transition to congested flow and is greater than the maximum flow rates in other lanes. Since the maximum flow in the passing lane occurs in uncongested flow, the typical flow-density (or flow-occupancy) relationship for the median lane has a reverse-lambda shape. Flow relationships for other lanes have triangular or inverted-V shapes.* Evidence related to this proposition includes published plots of flow-concentration data (*18*, *20-31*) and a series of studies related to transitions from uncongested to congested flow at bottlenecks(*26*, *32-39*). It is most often true that the maximum flow rate at a given site occurs in the median lane in uncongested flow. All studies of transitions to congested flow that document the time series of flow on a lane-by-lane basis report a decrease in flow in the most heavily loaded lane, although this is not always the median lane (*36*). It is not universally true, however, that the inner-lane flow-concentration relationship has a reversed-lambda shape and that those in other lanes have triangular shapes. In flow-concentration relationships reported in the literature to date, reversed-lambda and triangular shapes occur with about equal frequency in the median lane (*18*, *22-24*, *29-31*). Relationships for the shoulder lane are sometimes triangular (*18*, *27*), but inverted-U shapes are also encountered (*28*, *29*).

3. *The decrease in flow in the median lane is related to an increase in headway that occurs when the speed segregation breaks down. In Daganzo's interpretation, this is due to a "loss of motivation" by drivers in the fast lane because they can no longer pass other traffic.* Evidence related to the key concept of loss of motivation is mixed. Although it is generally true that headways increase in the most heavily loaded lane (the evidence is actually that flows decrease, but this implies an increase in headway), there is no clear evidence that this results from driver behavior in response to speed equalization. If the change in headway were due to driver behavior (rather than the increase in passage time that accompanies the rather sharp speed drop that occurs in the transition to congested flow) average time gaps should increase in the transition, and remain greater in congested flow than in uncongested flow. Banks (*40*) found that they did not. On the other hand, Dijker et al (*22*) found that distance gaps were greater in congested flow than in uncongested flow, and since speeds are less, time gaps must also have increased in the transition.

4. *Wave speeds in congested flow (i.e., between two flow states, both of which are fully congested) are constant and identical for all lanes. In particular, such wave speeds do not vary with flow or vehicular speed. "Fast waves" with velocities greater than this characteristic wave speed are believed to be possible, but are held in Daganzo's theory to exist only in (or on the borders of) semi-congested states in which speed segregation has not completely broken down.* In this case, the preponderance of the evidence is against the idea that wave speeds are literally constant and that there is a characteristic wave speed that applies universally to congested flow. Daganzo's theory does not require this, however, but only suggests that congested-flow wave speeds do not vary with the flow level, and that they are similar in all lanes for a given roadway segment. Some recent German work maintains that there is a characteristic speed, either for all types of waves (*42*) or for "wide jams" (*17*, *30*). In

the latter case, however, it is also stated that this speed varies by roadway segment, and with weather conditions (*42*). Evidence from Mika (*43*), Koshi (*18*), Iwasaki (*27*), Kerner (*45*), and Forbes and Simpson (*46*) document considerable variation in wave speeds. The prevalence of speed synchronization in congested flow would seem to indicate that wave speeds in different lanes are nearly identical in a given disturbance (that is, waves tend to involve the whole roadway rather than individual lanes), but the evidence (particularly in Forbes and Simpson) suggests that wave speeds are widely variable over short distances, and that the speed of an individual wave can change over time.

The review of empirical research related to traffic flow also demonstrated that Daganzo's theory, as presently developed, is of limited scope when compared with the full range of phenomena considered in the literature. In some cases, this is probably deliberate and may even be an advantage, since the theory's simplicity is one of its attractive features. In other cases, there may be potential for extending the theory to explain a wider range of phenomena, but so far this has not been done. One practical effect of this narrow scope was that it was difficult to find sites and data sets that fully matched the assumptions of the theory.

Phenomena described in the empirical literature that might possibly be addressed by extensions to the theory include the possible influence of ramps on lane use behavior, which is the subject of research by Hess (*46*, *47*) and Roess and Ulerio (*48*); functioning of bottlenecks other than merges in which ramp traffic is varying (*34*, *40*, *49*, *50*); evidence that the fraction of traffic in various lanes under uncongested conditions varies with traffic volume (*51*); and the dependence of flow characteristics, particularly speeds, on vehicle type as well as driver type (*52*). Phenomena that are generally (and probably deliberately) beyond the scope of the theory include microscopic and mesoscopic traffic characteristics, characteristics of congested flow, and the effects of location, weather, construction, incidents, etc. on flow characteristics.

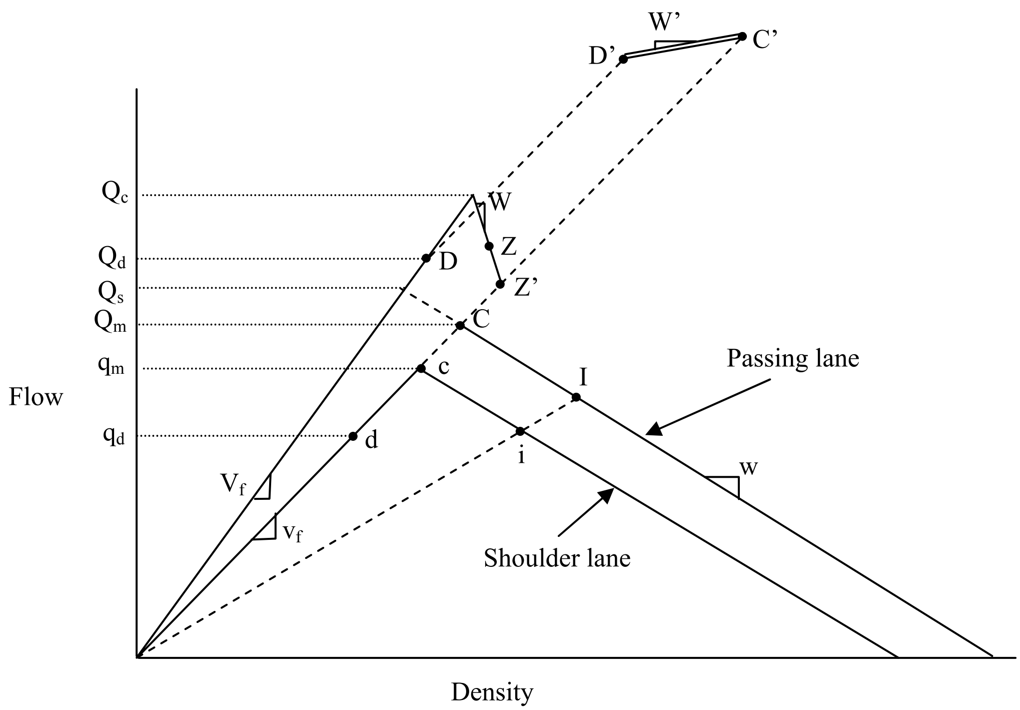
2. DAGANZO'S THEORY

2.1 Summary of Theory

Daganzo's theory (*1*, *2*) assumes two types of drivers, aggressive (referred to as *rabbits*) and timid (referred to as *slugs*), and two lane groups: *shoulder lanes* and *passing lanes*. In free flow, rabbits travel faster than slugs and the two groups are segregated in *two-pipe* flow, with the slugs all in the shoulder lane and the rabbits all in the passing lane. In high-volume uncongested flow, rabbits follow one another with very small headways so long as they are able to pass, and such drivers are referred to as being *motivated* because the very small headways are held to be motivated by the desire to pass slower vehicles. Whenever an event occurs that reduces speed in the passing lane to (or below) v_f, the free-flow speed in the shoulder lane, the rabbits change lanes to equalize speeds, lose their "motivation," and increase their headways. This results in *one-pipe* flow. Because of the difference in headways, maximum uncongested flow rates in the passing lane exceed its queue discharge rate.

Daganzo's discussion of transitions to and from congested flow assumes a flow-density diagram similar Figure 1. This diagram assumes (a) constant free flow speeds V_f on the passing lane and v_f on the shoulder lane; (b) identical wave speeds *w* for both lanes in congested flow, and hence identical slopes for the congested branches, but with that for the passing lane above that for the shoulder lane; (c) a so-called reverse lambda shape for the passing lane diagram, with maximum flows occurring in free flow; (d) a triangular shape for the shoulder lane diagram; and (e) a negatively-sloped portion of the passing lane diagram (with slope *W*) representing a semi-congested two-pipe state in which there is a queue in the passing lane, but speeds in this lane remain above v_f. In general, capital letters refer to features related to the passing lane and lower case letters to those related to the shoulder lane. Other important features include *critical flow* Q_c, the maximum flow on the passing lane in free flow; *saturation flow* Q_s, that is, flow at the projected intersection of the right branch of the diagram with the V_f-ray; Q_m, the *capacity flow* on the passing lane in the one-pipe state; q_m, capacity flow on the shoulder lane; and Q_d, the rabbit *discharge flow* on the passing lane downstream of the front of a one-pipe queue. Q_d is assumed to exceed Q_m.

FIGURE 1 Assumed Flow-Density Diagram



A fundamental feature of the theory is that rabbits distribute themselves in the lanes so as to maximize speed, but slugs always remain in the shoulder lane. In acceleration out of one-pipe queues, rabbits will use all lanes so long as speed is equalized across the lanes, but will switch to the faster lane (or lane group) when it is not. Daganzo assumes that in the queue, speed will be the same in both lanes, and less than free flow speed in either of them; this condition is illustrated on the diagram by points *I* and *i* (representing rabbits and slugs respectively) and the dashed line connecting them to the origin, whose slope represents the speed in the queue. As vehicles accelerate downstream of the queue, the points representing the two driver populations will move up until they reach points *C* and *c*. At this time, speed in both lanes is equal to v_f, the normal free-flow speed in the shoulder lane. This condition Daganzo refers to as the *capacity state*. The rabbits in the passing lane will continue to accelerate, however, and as soon as their speed exceeds v_f, rabbits in the shoulder lane will switch to the passing lane. Eventually, the speed of the rabbits returns to V_f, and the flow is represented by points *D* and *d*, referred to as the *discharge state*. Daganzo assumes that Q_d, the rabbit flow in the discharge state, will normally exceed Q_m but be less than Q_c.

The transition from the capacity state to the discharge state will normally involve changes in total flow and density as well as in the relative use of the lanes. Density is assumed to decline in the transition, but flow may either increase or decrease. The rabbit discharge flow Q_d is assumed to be a characteristic of the flow process, but the slug discharge flow is a function of the relative number of rabbits and slugs in the traffic stream. If the fraction of slugs is high, the combined flow will be large, and may exceed the combined flow in the capacity state; if not, it will be less. Flows and densities in the two states may be added to give points *C'* and *D'*. If the slope of a line connecting these points (*W'* on the diagram) is positive, the transition between them will move downstream; if it is negative, the transition moves upstream. Since the density in the capacity state will always be greater than that in the discharge state, the boundary between the two-pipe and one pipe states will move downstream if $Q_m + q_m > Q_d + q_d$, and upstream otherwise.

In analyzing transitions to congested flow at merge bottlenecks, Daganzo assumes that the critical point is downstream from the entrance, where the rabbits from the entrance ramp enter the passing lane. In reality, this takes place over some distance, but for simplicity, Daganzo represents it as occurring at a point. This point will be referred to as the *rabbit merge point*. As flows on the mainline and the entrance increase, flow on the passing lane downstream of the rabbit merge point increases, eventually reaching Q_c. Any further increase in the number of merging rabbits creates a queue in the passing lane upstream of the rabbit merge point. If flow in the passing lane queue exceeds that represented on the diagram by *Z'*, flow is forced onto the semi-congested branch of the flow-density diagram, as represented by point *Z* on the diagram; otherwise, there will be a direct transition to a one-pipe queue. In the two-pipe semi-congested state, speed still exceeds v_f and the rabbits remain motivated. Flow in the passing lane downstream of the rabbit merge point remains at Q_c. The queue in the passing lane spreads upstream at a speed that depends on the passing lane flow upstream of the queue, the flow of entering rabbits, V_f, Q_c, and *W*. The speed of this shock may must be less than *W* but may be either greater or less than *w*. Any changes in flow in the queue (for instance, those caused by fluctuations in the flow of rabbits merging into the passing lane) propagate upstream with a wave speed of *W*.

If the flow of merging rabbits continues to increase, eventually passing lane flow upstream of the rabbit merge point will be forced down to point *Z'*. At this point speed is reduced to v_f. As soon as speed drops below v_f, the rabbits lose their motivation and change lanes to equalize speeds, triggering a one-pipe queue represented by points *I* and *i*. The transition between the resulting fully-congested one-pipe queue and the semi-congested state moves upstream at a speed that depends on the proportion of rabbits and slugs in semi-congested flow. The speed of this wave may be either greater or less than *w*; however, in his discussion of merge bottlenecks, Daganzo considers only cases in which it is greater than or equal to *w* and less than or equal to *W*. Such waves are referred to as *fast waves*, since their speed exceeds *w*, the normal wave speed in congested flow.

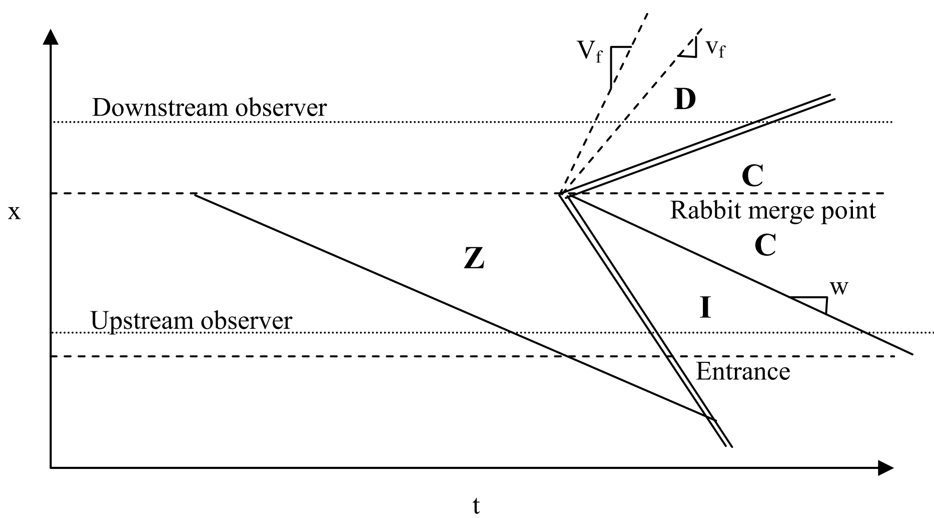
Upstream of the rabbit merge point but downstream of the entrance, if the boundary between the semi-congested state *Z* and the one-pipe queue *I* moves upstream with a speed that exceeds *w*, it will be followed by a wave between the one-pipe congested state and the capacity state, moving at speed *w*; and, if flow in the discharge state exceeds that in the capacity state, by the boundary between these two states. Farther upstream, beyond the entrance, the semi-congested state transitions to a one-pipe queue that continues indefinitely.

Figure 2 shows Riemann diagrams illustrating the cases just discussed. Traffic states are designated by capital letters, with *Z* representing the semi-congested state, *I* the one-pipe congested state, *D* the discharge state, and *C* the capacity state. Double lines represent boundaries between one-pipe and two-pipe states, dashed lines represent slips, which move downstream at the speed of traffic, and single solid lines represent waves between different one-pipe or two-pipe states. In Figure 2a the boundary between the discharge state and the capacity state moves downstream and in Figure 2b it moves upstream.

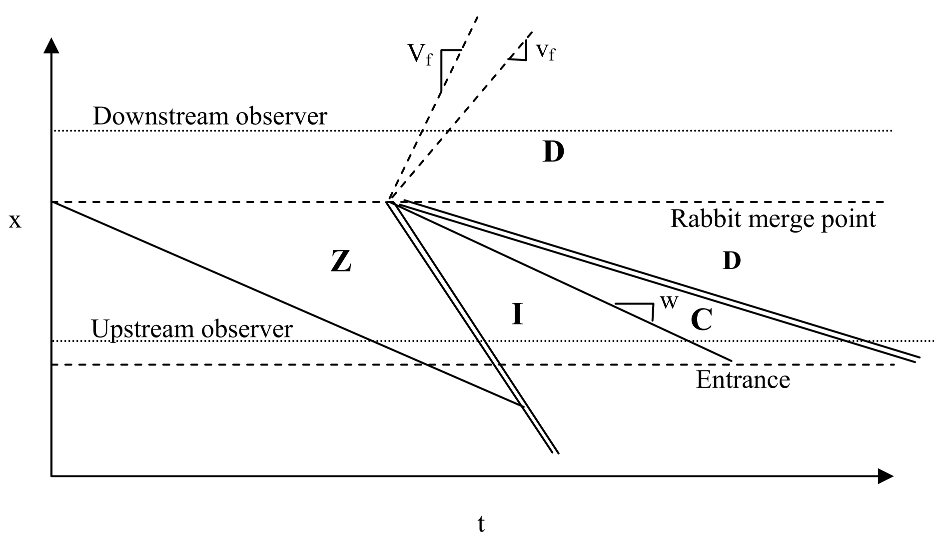
In analyzing flow recovery following incident clearance, Daganzo considers a case in which a freeway is completely blocked and then reopened. Most real incidents do not result in complete blockage of the freeway, however, and the flow patterns will be similar whether flow is blocked completely or severely reduced by the incident. Prior to removal of the incident, traffic immediately downstream will accelerate into a free-flow state, in which the flow in the different lanes will be determined by the proportions of rabbits and slugs in the traffic stream. Once the incident is removed, flow past the point of the incident increases suddenly and traffic at the downstream front of the queue begins to accelerate. As in the case of flow downstream of any queue, flow will pass through the capacity state and then, when the speeds of the rabbits in the passing lane exceeds v_f, will transition into the discharge state. As before, the transition between the capacity state and the discharge state may move either upstream or downstream. The major difference between incident clearance and the transition to congestion at merge bottlenecks is that in this case, no semi-congested state is to be expected. Instead, upstream of the point of the incident a transition between the incident queue and the capacity state moves upstream with speed *w*. Figure 3 is a Reimann diagram illustrating this case. On the diagram, *B* represents the free-flow state downstream of the incident prior to its removal.

FIGURE 2 Reimann Diagrams for Transition to Congested Flow at Merge

(a) $Q_m + q_m > Q_d + q_d$



(b) $Q_m + q_m < Q_d + q_d$

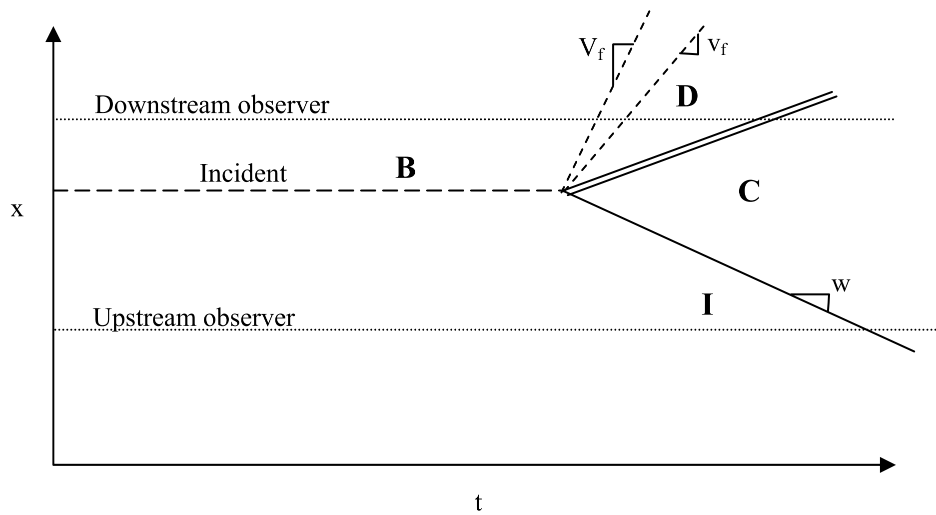


2.2 Predictions

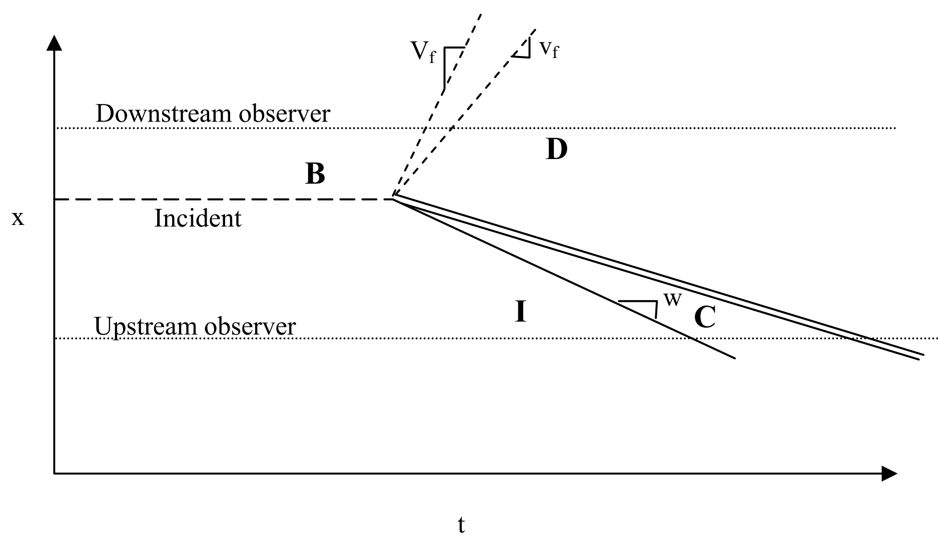
Consideration Figures 2 and 3, as well as the characteristics of the various traffic states predicted by the theory, forms the basis for several hypotheses describing what observers upstream and downstream of merge bottlenecks and incidents should see in transitions to and from congested flow. These are as follows:

FIGURE 3 Reimann Diagrams for Flow Recovery Following Incident Clearance

(a) $Q_m + q_m > Q_d + q_d$



(b) $Q_m + q_m < Q_d + q_d$



1. An observer a considerable distance downstream of a merge bottleneck will see first a drop in flow in the passing lanes but with speed in the passing lanes greater than in the shoulder lane, then a reduction of flow in the passing lane, a more even distribution of flow across the lanes, and an increase in overall flow. In cases in which slug flows are high, only the first reduction in flow in the passing lanes will be observed.

2. Immediately downstream of the entrance ramp at a merge bottleneck an observer will see first an increase in flow across all lanes, then a reduction in speed in the passing lane, then an increase in shoulder lane flow accompanied by a gradual decrease in speed and flow in the passing lane, then a sharp reduction in speed across all lanes, and finally the capacity state (in which flow is less than in the "motivated" state prior to the collapse). If the proportion of slugs is high, the capacity state may be followed by a discharge state in which flows and speeds on the passing lane increase and flows on the shoulder lane decrease.

3. An observer downstream of an incident that has just been removed will see first fast cars, then a two-pipe discharge state with a constant flow on the passing lane(s), and, if the flow on the shoulder lane is low (that is, flow in the discharge state is less than capacity), this will be followed by a capacity state with higher flows on the shoulder lane and slightly lower speeds on the passing lane.

4. A two-pipe discharge state may be seen upstream of an incident after the capacity state if the traffic stream is rich in slugs.

Hypotheses 3 and 4 are taken directly from Daganzo (*1*). It should be noted that these hypotheses are misstated in Daganzo and that the versions presented here are consistent with the exposition of the theory in that reference. Hypotheses 1 and 2 follow are not directly stated in Daganzo, but follow closely from the exposition of the theory in (*2*).

One difficulty in testing these hypotheses is that they require data to be available at very clearly defined locations. For instance, to evaluate Hypotheses 1 and 3 properly, data should be available from a site that is beyond the zone of acceleration downstream of the queue, but upstream of any entrances and exits that could disturb the queue discharge. Evaluation of Hypothesis 2 requires data to be available from a point immediately downstream from the critical entrance ramp. Hypothesis 4 requires data from a point upstream of the incident but downstream of any entrances or exits that could disturb the flow. Also, hypotheses 3 and 4 envision no interference from bottlenecks either upstream or downstream of the incident. Because of these restrictions, the hypotheses can best be tested in long sections without entrances or exits but with relatively closely-spaced loop detector stations or other data collection facilities. Such locations are rare on North American freeways.

An alternative approach to testing the theory is to note that it envisions rather abrupt shifts in the relative flows in the different lanes when speeds in these lanes equalize at v_f. The nature of these shifts depends on the location of the observer relative to the bottleneck or incident, but in all cases they can be detected by comparing time series of speeds and flows in individual lanes. Further, the general nature of these changes in relative speeds and flows is not likely to be affected by entering or exiting traffic. These changes in relative speeds and flows are predicted to be as follows:

1. Upstream of a merge bottleneck (whether upstream or downstream of the critical ramp) there should be a gradual change in both relative speeds and flows in the semi-

congested state, followed by an abrupt, simultaneous equalization of speeds and redistribution flow on the arrival of the regime-change wave between the semi-congested state and the one-pipe queue.

2. Downstream of a merge bottleneck, but within the zone of acceleration, there should be an abrupt, simultaneous equalization of speed and redistribution of flow immediately following the flow collapse upstream. This process should be reversed when the queue finally clears.

3. Downstream of a merge bottleneck or an incident, and beyond the zone of acceleration, there should be no change in relative speeds and flows unless and until the regime change from discharge flow to capacity flow arrives; if and when this occurs, there should be an abrupt, simultaneous equalization of speed and redistribution of flow.

4. Upstream of an incident, after the incident is removed, there should be an abrupt, simultaneous differentiation of speeds and a redistribution of flow, either at the regime change between capacity flow and discharge flow or when the queue clears from upstream.

These predictions may be further summarized as (a) the most aggressive drivers will segregate themselves in the fastest lane so long as there are differences in speed among the lanes and will redistribute themselves when speeds are equalized; consequently, there will be a rapid redistribution of flow among the lanes when speeds are equalized across the lanes (or, conversely, when they cease to be equal), but not otherwise; (b) speeds will be equalized among the lanes in congested flow but speed differences will be reestablished following acceleration downstream of queues; and (c) there will be two distinct flow states – capacity flow and discharge flow – downstream of queues. In all cases, rapid changes in relative speeds and relative flows should be simultaneous because the theory holds that speed equalization (or, vice versa, speed differentiation) triggers lane changes by rabbits that lead to changes in the relative flows on the different lanes.

Another aspect of Daganzo's theory that can be tested is the concept that the flow collapse involves an increase in headways that is in some sense voluntary. An increase in headways in the passing lane (and corresponding decrease in flow) does not in itself imply a loss of "motivation" on the part of drivers. The headway between any two vehicles consists of two parts: the time gap between the rear of the lead vehicle and the front of the trailing one, and time required for the lead vehicle to pass a point. Any decrease in speed will increase the headway unless the time gap decreases. A voluntary increase in headway due to a loss of "motivation" requires an increase in the time gap, not merely the headway. Consequently, the theory may be extended to include the hypothesis that average time gaps in the passing lane will increase when speeds in the passing lane drop to the level of those in other lanes.

It should be noted that an increase in average time gaps in the transition to congested flow is consistent with Daganzo's assumption of reverse-lambda flow-density or flow-occupancy diagrams. In such diagrams, average time gaps are represented by the slopes of lines radiating from zero flow and 100 percent occupancy (or jam density) and time gaps increase as the absolute value of the slope decreases (*29*). Since the uncongested flow portion of the reverse-lambda diagram extends beyond the congested flow portion, time gaps in maximum uncongested flow must be greater less than those in congested flow.

3. DATA AND METHODOLOGY

3.1 San Diego State University Case Studies

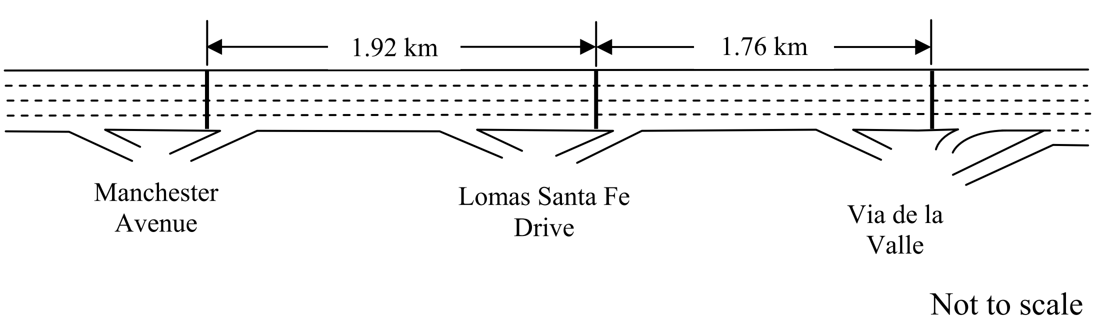
3.1.1 Merge Bottlenecks

Case studies of five merge bottlenecks were carried out by the SDSU team. These studies focused on verifying Daganzo's predictions related to flow in and downstream of queues and testing the hypothesis that transitions to congested flow would involve increases in average time gaps in the median lane. Case study sites included four bottlenecks in the San Diego area and one on the Queen Elizabeth Way (QEW) in the Toronto metropolitan area. Descriptions of these sites follow.

3.1.1.1 Site 1. Southbound Interstate 5, Downstream of Manchester Avenue, Morning Peak Period

Figure 4 is a schematic diagram showing the lane configuration and detector locations for Site 1. Terrain at this site is rolling, with a significant upgrade between Manchester Avenue and Lomas Santa Fe Drive and a significant downgrade between Lomas Santa Fe Drive and Via de la Valle. An active bottleneck exists in this section during the morning peak; however, it is not altogether certain exactly where it is or whether it is always at the same location. Comparisons of the times at which speed decreases and shifts in lane use occurred suggested that it is most commonly either just upstream or just downstream of the detectors at Lomas Santa Fe Drive; however, speed disturbances, including speed oscillations, were frequently observed as far downstream as Via de la Valle.

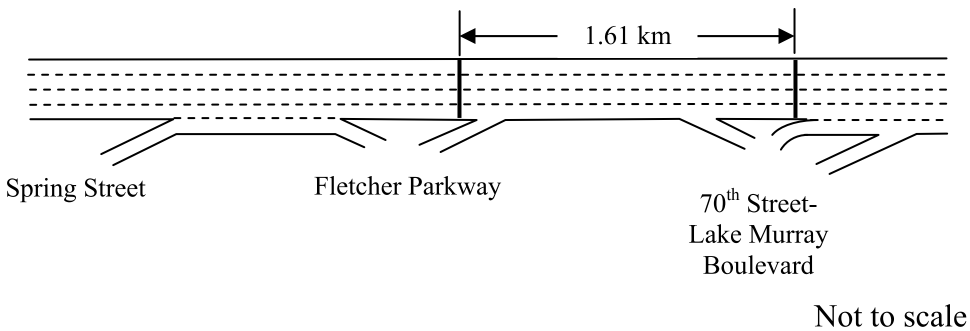
FIGURE 4 Merge Bottleneck Study Site 1



3.1.1.2 Site 2. Westbound Interstate 8, Downstream of Fletcher Parkway, Morning Peak Period

Figure 5 is a schematic diagram showing the lane configuration and detector locations at Site 2. Terrain at this site is level. An active bottleneck exists in this section during the morning peak period. Although the maximum flow per lane occurs just downstream from Fletcher Parkway, both the point of initial flow breakdown and the downstream front of the queue that forms at this location appear to be located just downstream of the detectors at 70th Street-Lake Murray Boulevard. In addition to local congestion from this bottleneck, this site is also subject to dense queuing later in the peak when queues from downstream grow into it.

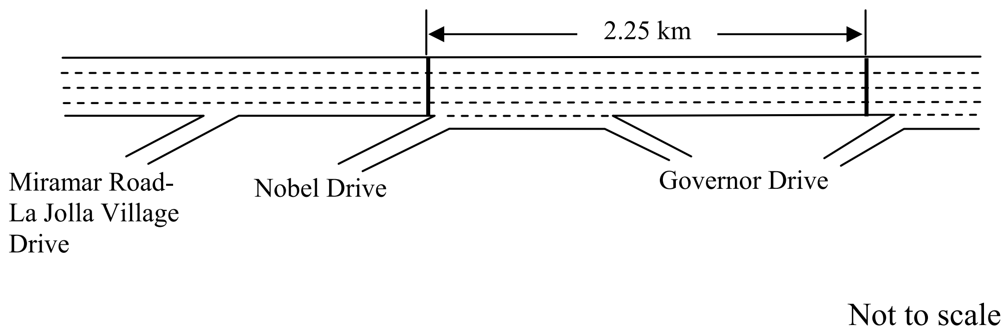
FIGURE 5 Merge Bottleneck Study Site 2



3.1.1.3 Site 3. Southbound Interstate 5, Downstream of Nobel Drive, Evening Peak Period

Figure 6 is a schematic diagram showing the lane configuration and detector locations for Site 3. Terrain at this site is rolling. Southbound Interstate 805 is on a downgrade as it approaches the Nobel Drive interchange, with a sag occurring in the immediate vicinity of the weaving section between the Nobel Drive on-ramp and the Governor Drive off-ramp. Downstream from this point, there is an upgrade to a structure over Governor Drive (between the Governor Drive on-ramp and off-ramp), and then a downgrade past the Governor Drive on-ramp. During the evening peak, an active bottleneck is located between the weaving section and the crest of the grade at Governor Drive. Traffic flow in this section is affected by the presence of major interchanges upstream and downstream. The Miramar Road-La Jolla Village Drive interchange upstream of Nobel Drive serves the Miramar Marine Air Station and an office and commercial complex in the La Jolla Village area and there is an interchange between Interstate 805 and State Route 52 immediately downstream from Governor Drive. The presence of these interchanges leads to an unusual distribution of traffic across the lanes, in which the greatest flows tend to occur in the shoulder lane (especially at Governor Drive). Also, note that this site is not strictly a merge bottleneck, since traffic enters from Nobel Drive through a weaving section. In terms of Daganzo's theory, however, it may be considered a merge bottleneck, since flow breakdown occurs at a point where vehicles from the Nobel Drive entrance are merging into the left lanes.

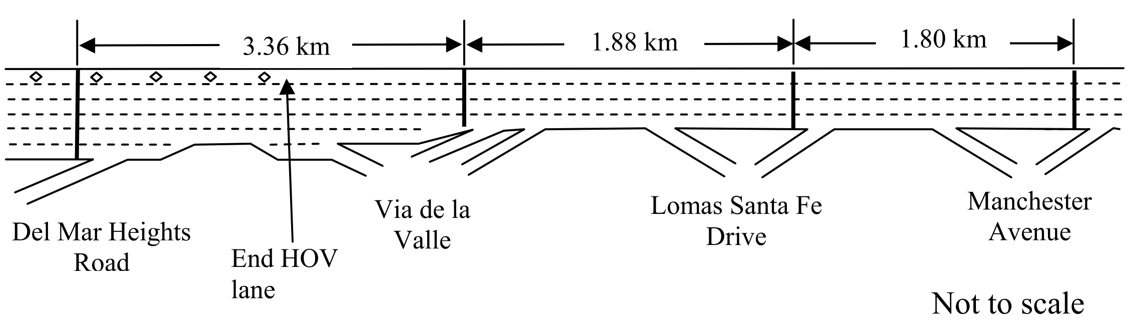
FIGURE 6 Merge Bottleneck Study Site 3



3.1.1.4 Site 4. Northbound Interstate 5, Downstream of Via de la Valle, Evening Peak Period

Figure 7 is a schematic diagram showing the lane configuration and detector locations for Site 4. Terrain at this site is rolling, with a downgrade between Del Mar Heights Road and Via de la Valle, an upgrade between Via de la Valle and Lomas Santa Fe Drive, and a downgrade between Lomas Santa Fe Drive and Manchester Avenue. During the evening peak period there is an active bottleneck between the Via de la Valle on-ramps and the Lomas Santa Fe Drive detectors. Changes in the lane configuration just upstream of Via de la Valle, in which a high-occupancy vehicle lane on the left side is terminated and the other lanes are shifted to the left results in an unusual lane use distribution at this point, with the maximum flow normally occurring in the second lane from the left.

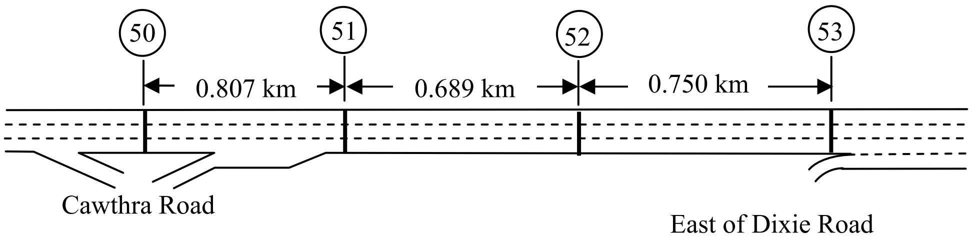
FIGURE 7 Merge Bottleneck Study Site 4



3.1.1.5 Site 5. Eastbound QEW, Downstream of Cawthra Road, Morning Peak Period

Figure 8 is a schematic diagram showing the lane configuration and detector locations for Site 5. Terrain for this site is level. During the morning peak period there is an active bottleneck between Detector Stations 51 and 52. The location of this bottleneck appears to be consistent from day to day.

FIGURE 8 Merge Bottleneck Study Site 5



Not to Scale

3.1.2 Incident Discharge Flow Case Studies

In addition to studies of merge bottlenecks, the San Diego team carried out studies of discharge flow following the removal of incidents. Incidents were identified by monitoring the California Highway Patrol computer aided dispatch system log (*53*) for incidents occurring in the San Diego area. Six incidents, all accidents that had a substantial impact on traffic flow, were studied in detail. Locations and times of these incidents were as follows:

1. Westbound Interstate 8 just west of Fletcher Parkway, 1:01 p.m., November 29, 2001

2. Westbound Interstate 8 between College Avenue and Waring Road, 7:26 a.m., December 3, 2001

3. Southbound Interstate 15 between Adams Avenue and El Cajon Boulevard, 2:17 p.m., May 9, 2002

4. Eastbound Interstate 8, just upstream of Fletcher Parkway, 4:22 p.m., June 3, 2002

5. Southbound Interstate 5 between Manchester Avenue and Lomas Santa Fe Drive, 2:35 p.m., July 2, 2002

6. Eastbound State Route 78, between Twin Oaks Valley Road and Barham Drive, 3:30 p.m., July 5, 2002

Preliminary investigation was carried out for a number of other incidents, but they were rejected because data were missing or incident queues appeared to have dissipated before the incidents were completely removed.

3.1.3 Data

Data available at the San Diego sites consisted of 30-second volumes and occupancies for individual lanes that were produced by single-loop detectors. Speeds for the San Diego sites were estimated from volumes and occupancies by

$$\hat{u} = \frac{q\overline{L}}{\Omega} \tag{1}$$

where $\hat{u}$ = estimated speed
q = flow
$\overline{L}$ = average effective vehicle length
Ω = occupancy, as a dimensionless ratio

The average effective vehicle length assumed was that used by the California Department of Transportation for speed calculations for the San Diego system (24.75 ft or 7.5 m), and was the same for all lanes. Because of this practice, speeds in the outer lanes, which have a higher percentage of large vehicles, tend to be underestimated. Data at the QEW site were produced by double-loop detectors and consisted of 20-second speeds, volumes, and occupancies for individual lanes. In this case, speeds were measured directly. At each merge bottleneck site, data from between 7 and 10 different weekdays were analyzed. Specifically, analyses for Sites 1 and 2 included data for 9 days, analyses for Sites 3 and 4 included data for 10 days, and analyses for Site 5 included data for 7 days.

In addition to the estimated speeds for the San Diego sites, a number of other transformations and reductions of the raw data were used in the analyses. These included calculation of average time gaps from flow and occupancy data and characterization of speed and lane use distributions in terms of speed and flow ratios.

Average time gaps may be estimated from flow and occupancy data by

$$\overline{g} = \frac{1-\Omega}{q} \tag{2}$$

where $\overline{g}$ = average time gap

Flow and speed distributions were characterized in terms of the ratio of flow or speed in the median lane to the average flow or speed for all lanes. These ratios will be referred to as the *flow ratio* and *speed ratio* respectively, and are defined as

$$r_q = \frac{nq_1}{\sum_{i=1}^{n} q_i} \tag{3}$$

and

$$r_u = \frac{n u_1}{\sum_{i=1}^{n} u_i} \tag{4}$$

where r_q = flow ratio
r_u = speed ratio
q_i = flow in lane i, with lanes numbered outward from the median
u_i = speed in lane i
n = number of lanes

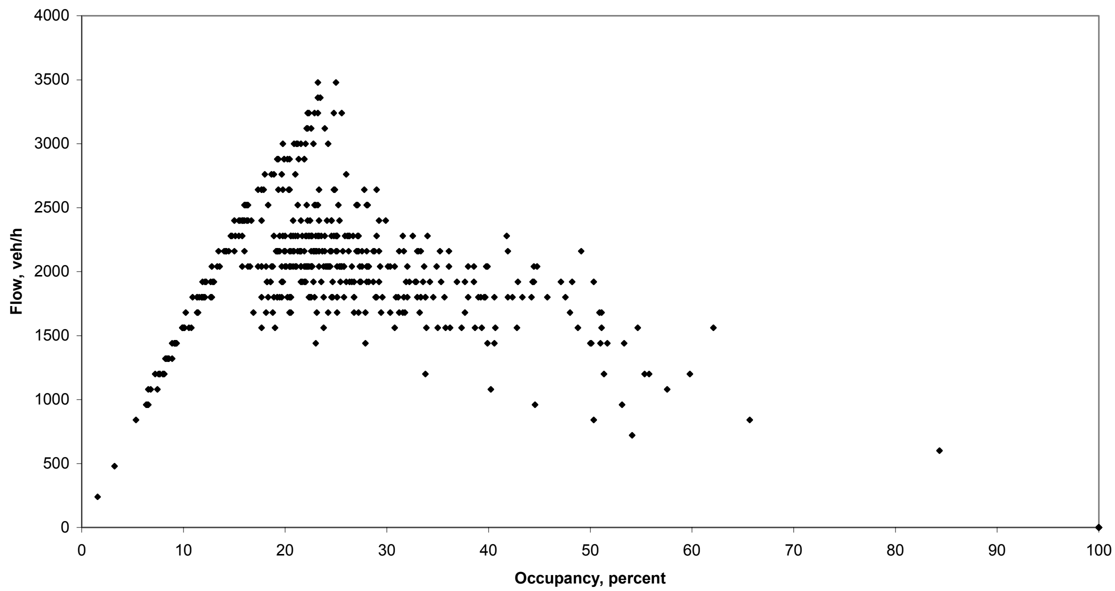
3.1.4 Study Site Limitations

One challenge in testing Daganzo's theory was that it was not possible to find study sites that matched all its assumptions. First, the theory is developed in detail only for freeways with two lanes in the direction of flow, yet all the sites that were otherwise suitable (both for merges and incidents) involved three or more lanes. The theory may be adapted to sections with more than two lanes by either grouping some of the lanes together or by assuming driver types intermediate between rabbits and slugs. In either case, the most aggressive drivers should be found in the lane closest to the freeway median (referred to as the median lane) and the least aggressive in the shoulder lane. Consequently, drivers in the median lane may be expected to resemble Daganzo's rabbits, and those in the shoulder lane to resemble slugs, regardless of what happens in the intermediate lanes. With that in mind, the analysis here focused on comparing the characteristics of the median lane and shoulder lanes with averages for the freeway as a whole.

A second mismatch between the theory and the characteristics of available sites is that detectors in the San Diego system are located immediately upstream of freeway entrances. Consequently, there were flows onto or off of the freeway between the downstream fronts of the queues and the measurement sites. Such flows could obviously alter the distributions of flow and speeds across the lanes, so that speed and flow distributions at different locations might not be comparable. Because of this problem (and the possibility that data from individual detectors may be biased) the primary evidence for changes in flow states was taken to be changes over time speed ratios or flow ratios at individual locations rather than comparisons between locations. Note that Site 5 did provide data immediately upstream and downstream of the point of flow breakdown; however, even in this case there was evidence of biases in counts, so that once again, comparisons over time for individual detector stations were considered more valid than comparisons between data from different stations.

A third mismatch is that several features of the theory depend on the assumption that the median lane has a reversed-lambda flow-density relationship (or flow-occupancy relationship, assuming a linear relationship between density and occupancy) and that the shoulder lane has a triangular flow-density relationship. As discussed in the literature review in Section 1.3, past studies indicate that these flow-concentration patterns do occur, but are not present at all locations. Examination of flow-occupancy plots for individual lanes showed that a distinct reversed-lambda pattern was present in the median lane data only at Site 1. Figure 9 is a typical median lane flow-occupancy plot for this section. Elsewhere, median lane flow-occupancy plots were triangular or resembled that in Figure 10, which might be characterized as triangular but with a region of high-volume congested flow missing. Some shoulder lane plots, on the other hand, had an inverted-U shape rather than a triangular shape. Figure 11 illustrates this pattern.

FIGURE 9 Reversed Lambda Median-Lane Flow-Occupancy Pattern, Site 1, Manchester Avenue



A final mismatch between the theory and the available data is that Daganzo's discussion of incident clearance flow assumes no interference by bottlenecks either upstream or downstream from the site of the incident. In practice, at least some of the incident queue discharges were affected by bottlenecks. The presence of these bottlenecks limited the amount of time for which pure incident recovery flow could be observed.

3.1.5 Analysis Techniques

In order to test hypotheses related to the theory, it was necessary to identify changes over time in speeds, flows, average time gaps, flow ratios, and speed ratios. In the case of speeds and flows, analysis had to consider both the freeway as a whole and individual lanes (especially the median and shoulder lanes). For some purposes, it was possible to base analyses on inspection of the raw time series data. For instance, bottlenecks were located and verified to be active for particular time periods by comparing speed time series for different locations. For other purposes, however, the random variations in the time series of 30-second data tended to obscure the changes in the average value of the time series that are critical to testing the theory.

FIGURE 10 Triangular Median-Lane Flow-Occupancy Pattern, Site 5, Detector Station 51

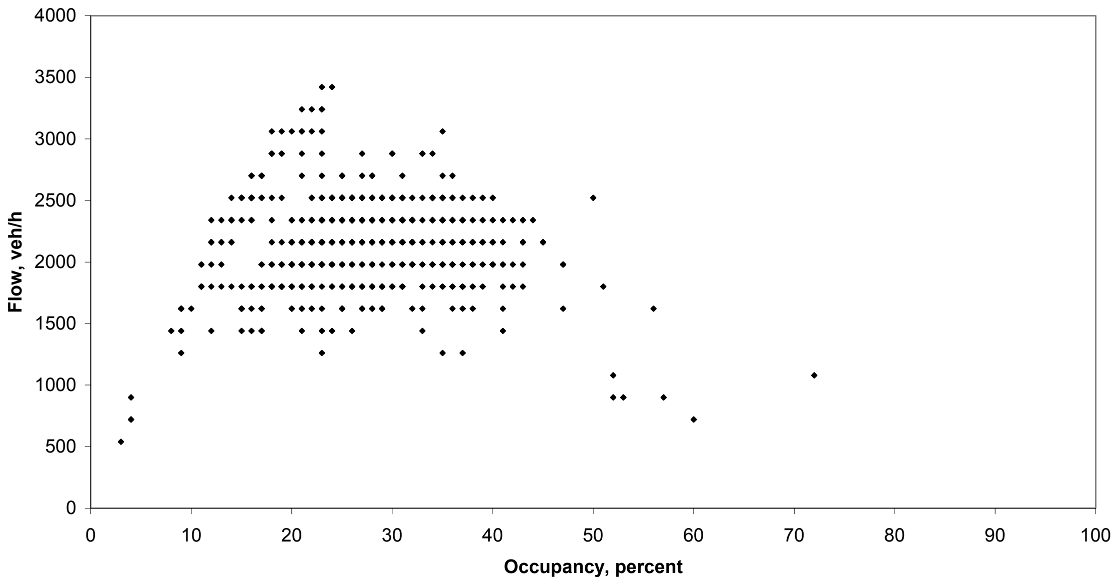
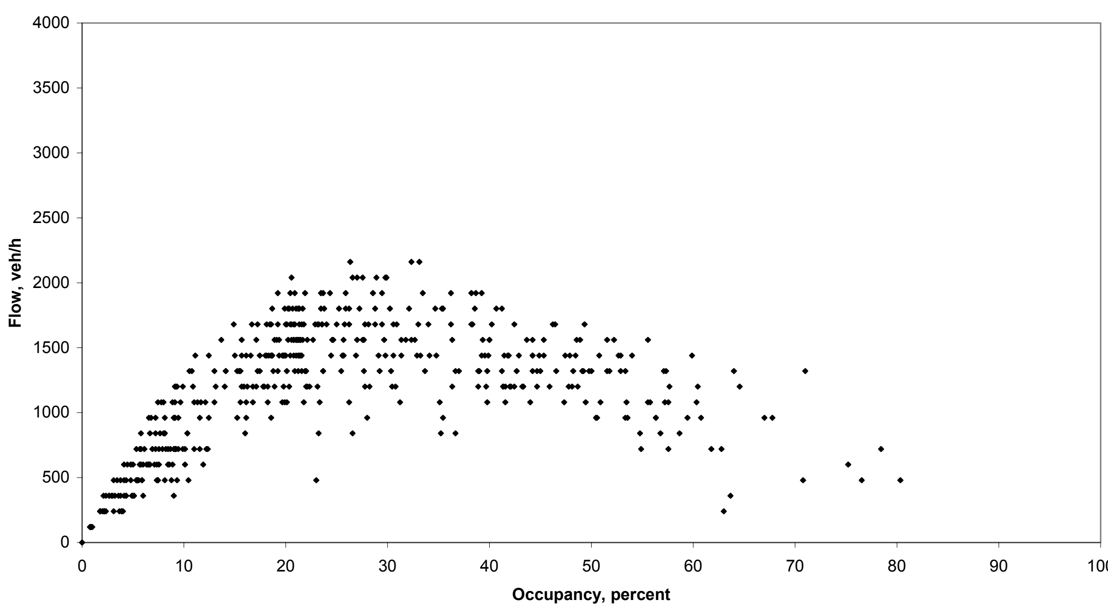


FIGURE 11 Inverted-U Shoulder Lane Flow-Occupancy Plot, Site 1, Manchester Avenue



In these cases, re-scaled cumulative curves (*54*) and event-based averaging techniques (*55*) were used to smooth the data and extract and compare average numerical values. In the case of re-scaled cumulative curves, the average slope of the cumulative curve represents the average rate of the time series; consequently, changes in the average of the underlying time series are signaled by changes in the slope of the cumulative curve. In the cases of speeds, flows, and average time gaps, re-scaling factors were selected by trial and error. In selecting the factors, the intent was to strike a reasonable balance between smoothing the data and emphasizing non-random changes in the time series. Also, in cases where different types of data were being compared (for instance, in trying to determine whether changes in speeds and flows coincided with one another) factors were selected so that numerical values of the re-scaled cumulative curves were similar enough at critical times to provide for easy comparison when they were plotted. In the case of the flow and speed ratios, the re-scaled cumulative functions were calculated as

$$R_q(T) = \sum_{t=0}^{T-1} (r_{qt} - 1) \tag{5}$$

and

$$R_u(T) = \sum_{t=0}^{T-1} (r_{ut} - 1) \tag{6}$$

where $R_q(T)$ = re-scaled cumulative flow ratio prior to time T
$R_u(T)$ = re-scaled cumulative speed ratio prior to time T
r_{qt} = flow ratio for time period t
r_{ut} = speed ratio for time period t

In this case, the re-scaling is accomplished by accumulating the terms $r_{qt} - 1$ and $r_{ut} - 1$ rather than r_{qt} and r_{ut}, thus rotating the cumulative curve so that a horizontal line indicates that the flow or speed in the median lane is equal to the average for all the lanes.

Event-based averaging was used to calculate numerical averages for data before and after significant changes. In this technique, averaging intervals are determined based on the occurrence of some significant event such as an abrupt change in speed or flow. As applied in this study, it was coupled with the re-scaled cumulative curves: the re-scaled cumulative curves were used to identify the time that a significant event occurred and periods with near-constant average values of the data before and after the event. Once these periods were identified, data were averaged over them to compare characteristics before and after the event. This technique was used primarily to quantify differences in flow before and after the transition to congested flow, but was occasionally used to quantify changes in other characteristics.

The overall process of analysis for the merge bottlenecks included the following:

- Time series of speeds for different detector stations were used to determine the location of the active bottleneck and the approximate time of transition to congested flow

- Re-scaled cumulative curves were used to determine and compare times of speed and flow decreases in the median lane. Event-based averaging was used to quantify differences in flow associated with the transition to congestion. These flow differences were calculated for the median lane and for flow across all lanes. At the San Diego sites, flow differences across all lanes downstream of the entrance ramps were calculated by adding ramp counts to the mainline counts taken just upstream of the entrances

- Re-scaled cumulative curves were used to determine the times of changes in speed and flow ratios

- Re-scaled cumulative curves were used to determine whether average time gaps in the median lane increased in the transition to congested flow

The overall process of analysis for incident discharge flows included the following:

- Time series of speeds and flows were used to verify the incident location and time of occurrence and to determine the approximate time of incident removal

- Re-scaled cumulative curves were used to determine changes in average speeds and flows during and at the end of queue discharge. Event-based averaging was used to quantify flows for different time periods during and following queue discharge

- Re-scaled cumulative curves of were used to identify changes in speed and flow ratios during and at the end of queue discharge flow.

3.2 University of California Berkeley Case Studies

The UCB team analyzed empirical data collected from two different sites. Both of these sites were plagued by merge bottlenecks. The first of these sites is the Gardiner Expressway, a 3.3 km long freeway stretch in Toronto, Canada. The site was selected because of its suitable geometry (i.e., its merge bottleneck) and its well-tuned loop detectors located upstream and downstream of the bottleneck. The site thus provided for an exceptionally good "laboratory" for testing Daganzo's behavior theory of drivers (*1, 2*). It turns out that the observations from this stretch qualitatively match the theory in a number of important ways, as will be described.

The second site is a 2.7 km stretch of westbound State Route (SR) 24 just upstream of the Caldecott Tunnel[1] in Orinda, California. This site provided a means for verifying

[1] The Caldecott tunnel spans the Berkeley and Orinda border

Daganzo's theory for "California conditions." It is especially suitable for this study thanks to its very disruptive bottleneck and to its numerous vantage points (i.e., adjacent hillsides) from which to videotape traffic. Four cameras were strategically deployed along this freeway stretch. The detailed traffic data (manually) extracted from these videos were, like the Toronto data, found to be qualitatively consistent with much of Daganzo's theory.

Moreover, the very detailed data from California have afforded us an opportunity to identify and study some noteworthy aspects of traffic flow. Namely, discharge flows increased when changes in traffic conditions caused the bottleneck to move upstream of the merge. These aspects of traffic flow lie beyond the scope of Daganzo's theory, but they may have important implications for freeway traffic control.

The following section describes the two sites used in this study. The descriptions of the analysis methods used are in section 3.2.2.

3.2.1 Data and Site Descriptions.

3.2.1.1 Toronto, Canada

The data were collected from the loop detectors along the 3.3-kilometer segment of the westbound Gardiner Expressway shown in Figure 12. These detectors record vehicle counts, occupancies (a dimensionless measure of density) and average vehicle speeds over 20-second sampling intervals. The detector station numbering scheme used by the City of Toronto is also shown in Figure 12 and this numbering scheme is used throughout the report.

Flow on the Spadina on-ramp is not metered and the Jameson on-ramp remains closed each weekday between 15:00 and 18:00. The bottleneck activates on some days between detectors 60 and 70. On other days, a bottleneck arises downstream of detector 80, as will be verified momentarily. The freeway is located on an elevated structure. Photographs taken from cameras located at detectors 50, 60 and 80 indicate this freeway section has no shoulders.

3.2.1.2 Westbound SR-24 near Caldecott Tunnel, Orinda, California.

The second site is a 2.7 km stretch of westbound State Route 24 near the Caldecott Tunnel in Orinda, California (see Figure 13). Four cameras were strategically deployed along this freeway stretch to record individual vehicle arrival times at locations 1, 2, 3 and 4 as shown in the figure. The detailed traffic data were manually extracted from videotapes.

Flows on the Fish Ranch road on-ramp and off-ramp each remained less than 100 vehicles per hour. The bottleneck is located between location 2 and 3, as will be verified shortly.

3.2.2 Research Methods

This section provides the description of the graphical tools used in this study; oblique count curves, oblique occupancy curves, and time series density plots. These techniques

FIGURE 12 Gardiner Expressway, Toronto, Canada [source:Bertini (56)]

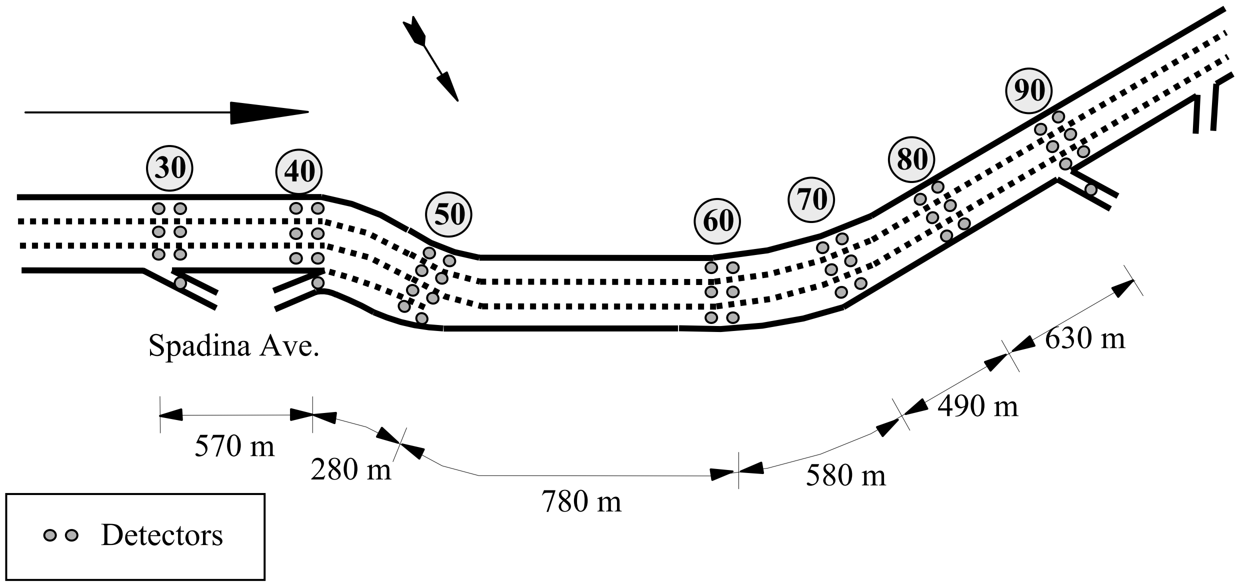
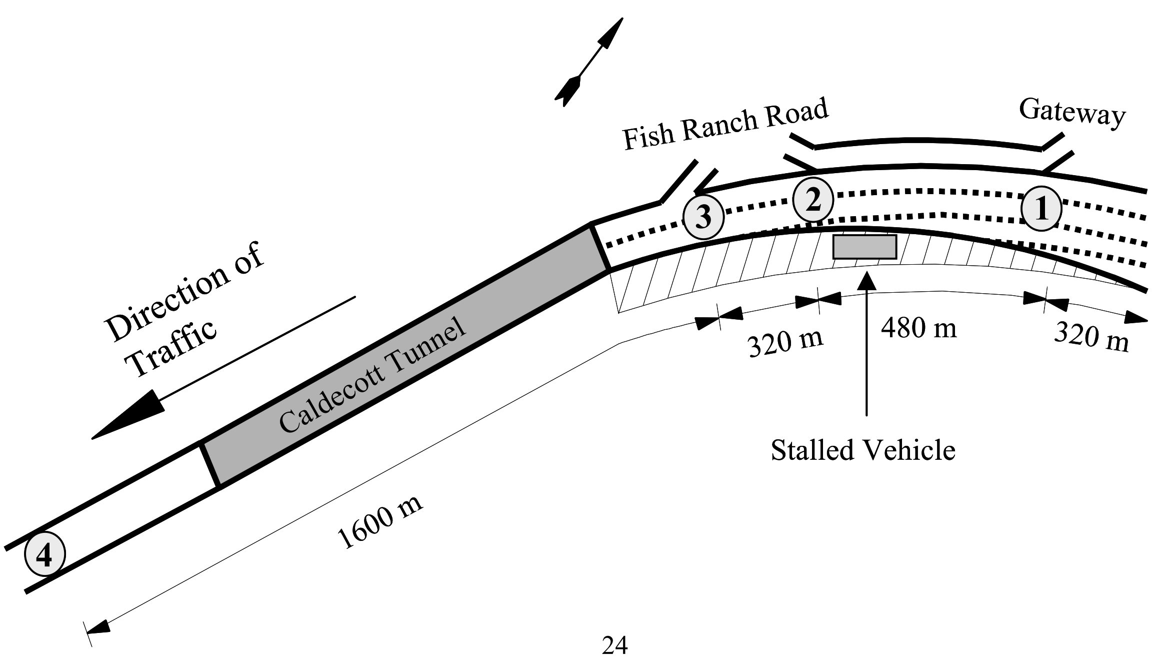


FIGURE 13 SR-24 West Bound, Orinda, California



revealed many important details of traffic that might not have been seen had the data were treated in some other ways.

3.2.2.1 Oblique Count and Occupancy Curves

An oblique count curve displays cumulative vehicle count on an oblique time axis (*54*). Figure 14 displays a set of oblique count curves from detectors 50 thorough 80. (An illustration of the site is also provided in the figure as convenience to the reader). The curves were constructed in such ways that the vertical displacements between any two of them at time, t, are the excess vehicle accumulations between the respective detector stations due to vehicular delays at time t.

An oblique time axis was used here to plot in effect, $N(t) - q_o \times (t - t_o)$ versus t for each curve's starting time, $t_{o,}$ and some choice of background flow $q_{o.}$ This coordinate system magnifies the figure's vertical axis, which in turn, amplifies not only the curves' vertical separations (the excess accumulations), but also changes in the curves slopes (the flows measured by detectors)

Figure 14 shows that the bottleneck is located between detectors 60 and 70. This is clear, first, in that N70 and N80 remain superimposed, indicating that traffic remained freely flowing on the intervening segment. The curves N50 and N60, however, diverge from their counterparts, indicating the presence of excess vehicle accumulations upstream of detector 70. Oblique N-curves constructed for longer periods confirm that this bottleneck remained active until another queue spilled over from downstream some time after t = 18:00.

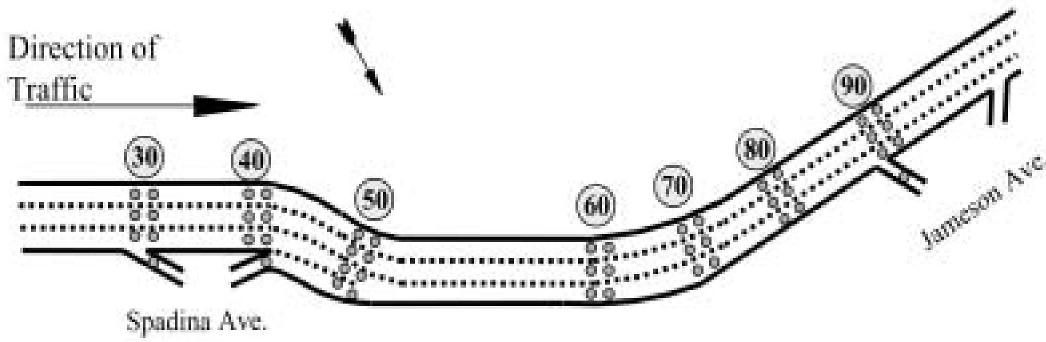
Our use of oblique count curves was vital for verifying the presence of an active bottleneck, an essential condition for evaluating Daganzo's theory. This high resolution data treatment method was also needed to exclude data during times when the bottleneck between detector 60 and 70 was not active; i.e., times when queues spilled-over from downstream.

Evidence of these (often subtle) downstream queues is displayed in Figure 15. The reader will note that, in this figure, the downstream curves N70 and N80 exhibit displacement starting before t =14:30. These two downstream curves continue to exhibit displacement until approximately t = 15:15. This displacement in the curves indicates the presence of a queue downstream of detector 70. Had data from this period been used in our assessments, erroneous conclusions would have been drawn. The bottleneck at this freeway location was actually de-activated in this manner on four of the nine days studied.

Our analyses were further refined using oblique curves of detector occupancy vs. time. The dotted line in Figure 16 displays cumulative occupancy to time t, $T(t)$,with a reduction of background occupancy rate, b_0. With this re-scaling trick, changing occupancy rates (i.e., the slopes of the dotted line in Figure 16) are clearly evident from visual inspection.

Using the oblique occupancy and count curves together, we were able to pinpoint the arrival times of the kinematic waves at detector locations. The oblique count and occupancy curves in Figure 16, for example, show the arrival time of a deceleration wave (signaling lower flow and higher occupancy) at one of the detectors.

FIGURE 14 Oblique Count-Curves, Detectors 50-80



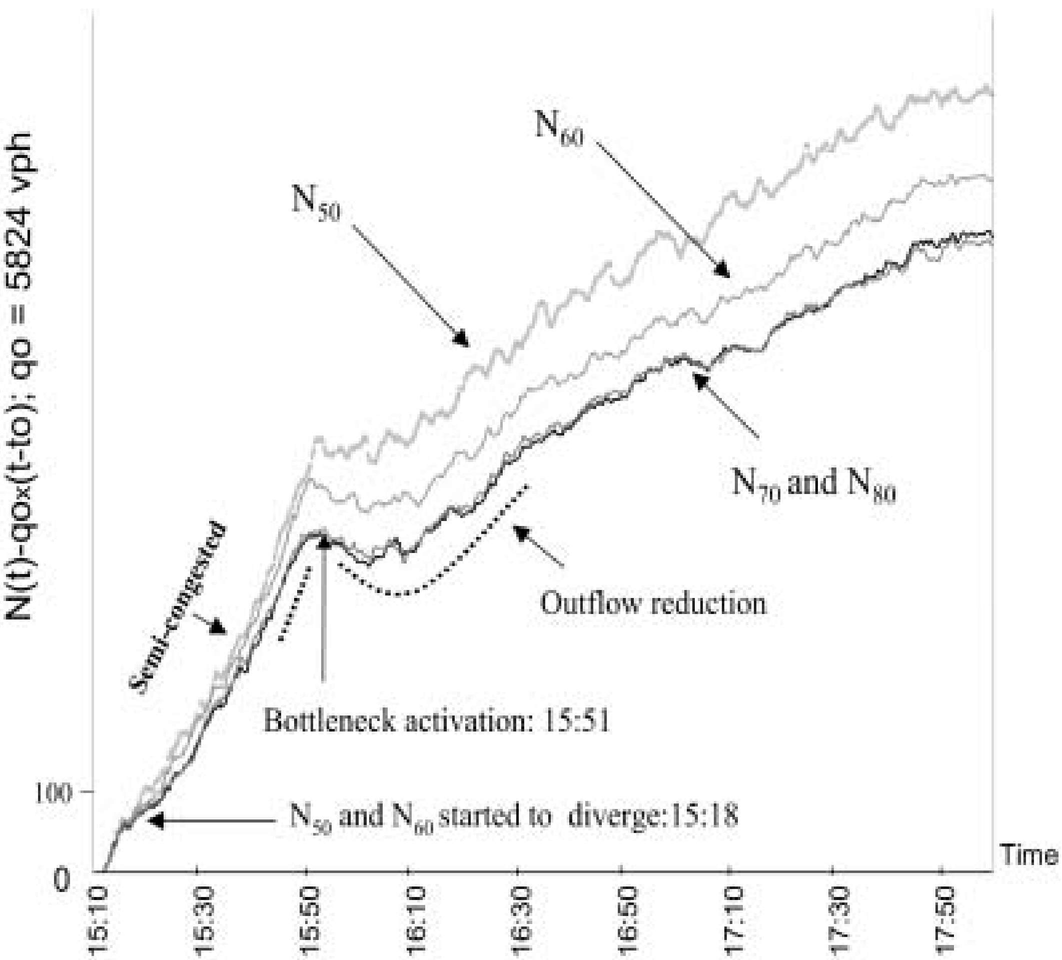
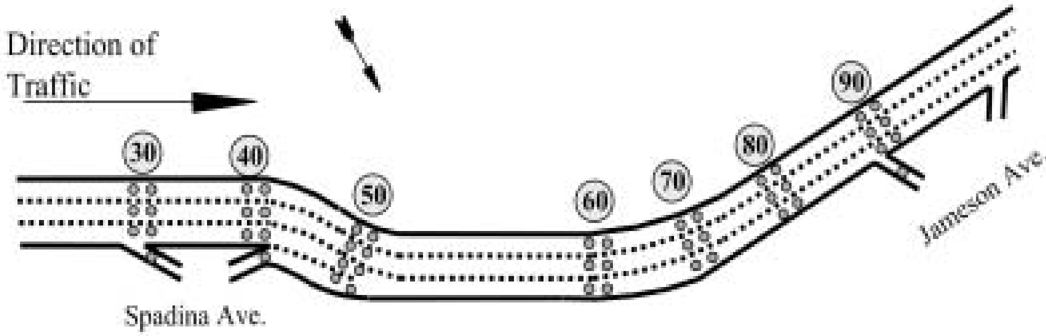


FIGURE 15 Oblique Count-Curves, Detectors 50-80


Direction of Traffic
30
40
50
60
70
80
90
Spadina Ave.
Jameson Ave.

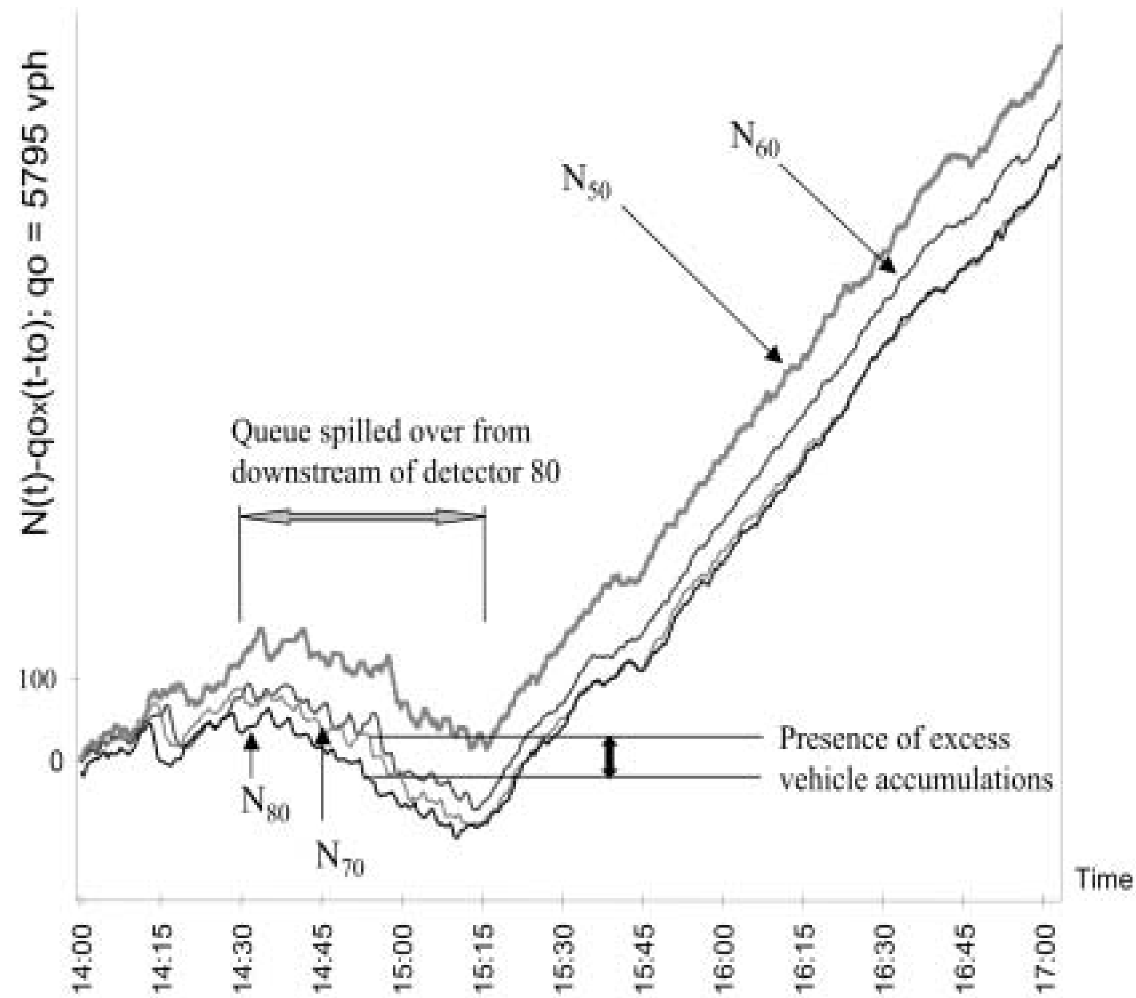
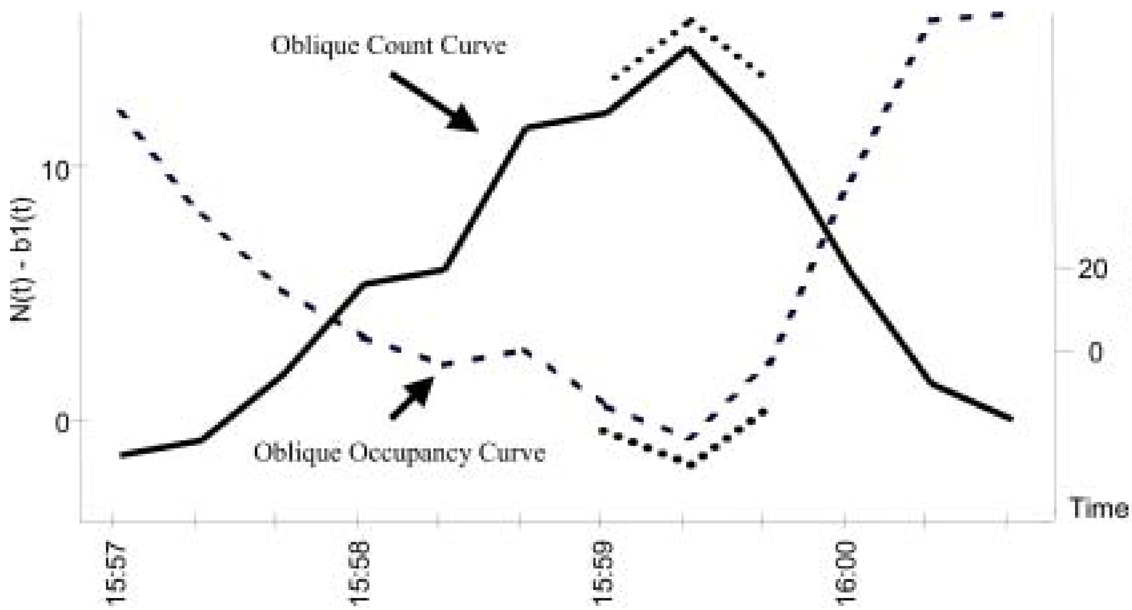

N(t)-qo×(t-to); qo = 5795 vph
N60
N50
Queue spilled over from downstream of detector 80
100
0
N80
N70
Presence of excess vehicle accumulations
Time
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
16:00
16:15
16:30
16:45
17:00

FIGURE 16 Arrival Time of Deceleration Wave



3.2.2.2 Time series density plot

Time series plots of density in the bottleneck vicinity were also used in our evaluation of Daganzo's theory. These plots will be presented later as needed.

4. RESULTS

4.1 Flow Characteristics in and Downstream from Queues

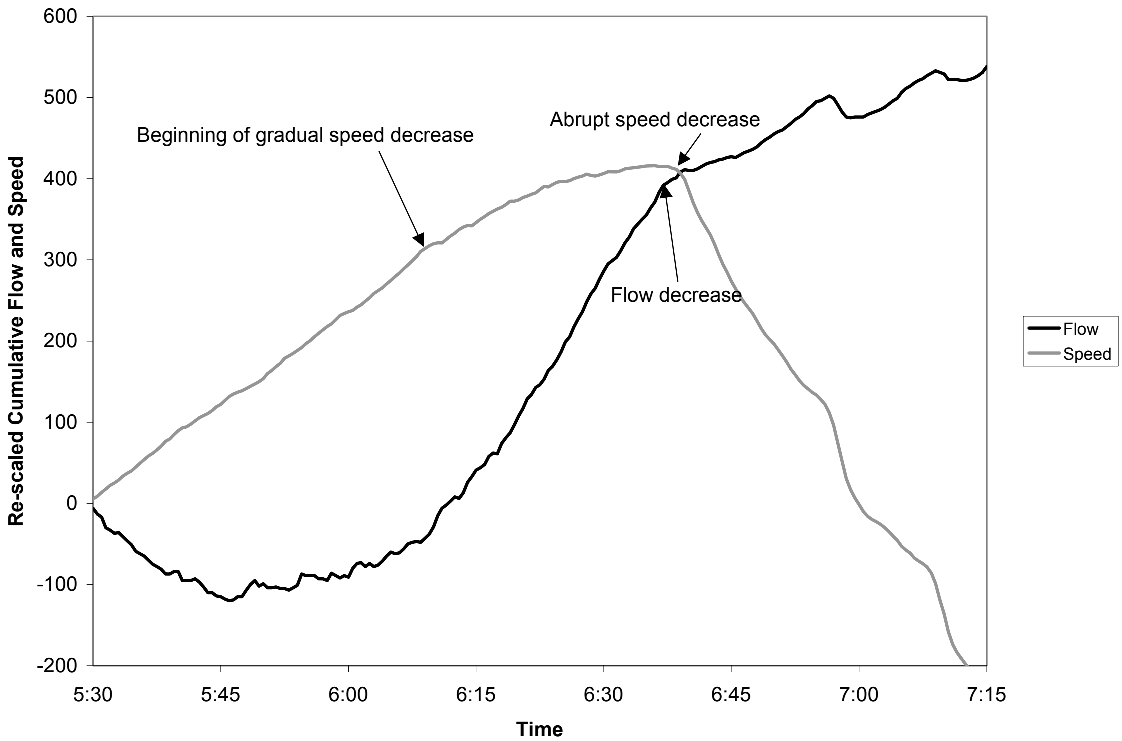
A number of hypotheses related to flow characteristics in and downstream from queues were advanced in Section 2.2. These hypotheses are expressed in terms of changes in speeds, flows, and the distributions of speeds and flows that should be observed at various locations upstream and downstream from merge bottlenecks and queues.

4.1.1 Speeds and Flows at Merge Bottlenecks

The initial abrupt decrease in speed in the median lane in the immediate vicinity of the bottleneck was taken as the primary indicator of flow breakdown. The theory indicates that this speed decrease should be accompanied by equalization of speeds across the lanes and a redistribution of flow in which flow in the median lane decreases and that in the shoulder lane increases. As discussed in Section 3.1.1, this initial speed decrease did not take place at the same location every day, especially at Site 1, leading in that case to uncertainty about the exact location of the bottleneck.

Comparison of re-scaled cumulative plots of speeds and flows in the median lane indicated that decreases in speeds and flows coincided roughly but not exactly. Comparison of the exact times of the median lane speed and flow decreases did not reveal any definite trend in terms of which occurred first or the amount of time that elapsed between one event and the other. Figure 17 is an example of a comparison of re-scaled cumulative plots to determine the exact times of median lane speed and flow decreases. Note that in this particular case, there was a gradual speed drop, followed by a fairly abrupt drop in flow and then, about a minute later, an abrupt drop in speed.

FIGURE 17 Re-scaled Cumulative Flow and Speed, Southbound Interstate 5, Manchester Avenue, April 23, 2001



Once the time of the initial median lane flow decrease was established, time periods before and after that had near-constant flows were identified. Event-based averaging was used to quantify flows during these periods. Such comparisons were made for median lane flows, average flow per lane for the whole freeway at the detectors, and (for San Diego sections where detectors were immediately upstream from on-ramps) for average flow per lane downstream of the ramp. This last calculation was made by adding the ramp flow to the mainline flow at the detectors. Table 1 presents averages of median lane flows before and after flow breakdown for all days observed at each site and the differences between them. Table 2 gives the number of days at each site that flows increased, did not change, and decreased. Tables 3 and 4 give similar information for average flow per lane and Tables 5 and 6 give similar information for flow per lane downstream of on-ramps. Details of changes in flow for individual days are given in the Appendix.

TABLE 1 Average Median Lane Flows Immediately Before and After Flow Drop

		Flow			
Site	Location	Before	After	Diff.	Pct. Diff.
1	Manchester Ave.	2,709	1,986	-723	-26.7
1	Lomas Santa Fe Dr.	2,808	2,329	-479	-17.1
1	Via de la Valle	2,752	2,385	-367	-17.7
2	Fletcher Parkway	2,588	2,191	-396	-15.3
2	70th St.-lake Murray Boulevard	2,727	2,422	-300	-11.0
3	Nobel Drive	2,287	2,140	-147	-6.4
3	Governor Drive	2,501	2,349	-151	-6.1
4	Via de la Valle	1,820	1,805	-15	-0.8
4	Lomas Santa Fe Drive	2,431	2,225	-206	-8.5
5	Station 51	2,448	2,195	-254	-10.4
5	Station 52	2,378	2,343	-35	-1.5
5	Station 53	2,220	2,223	+3	+0.2

Tables 1 and 2 show that on most days distinct drops in median lane flow coincided with flow breakdown at all the San Diego locations. These were most consistent at Sites 1 and 2, however. The smallest average decrease was at Via de la Valle on northbound Interstate 5; in this case, however, the lane use distribution was unusual because of the unusual lane configuration (see Figure 7). In the case of the QEW site, however, there was little or no decrease in average median lane flow at Stations 52 and 53 (downstream from the point of flow breakdown), although there was a comparatively large decrease at Station 51 (upstream). Tables 3 through 6 show that, on the average, there were also decreases in flow per lane at all sites except QEW Station 53. For sites at the downstream ends of the study sections (which may have been downstream of the bottlenecks) average decreases were in the range of zero to 7 percent. The differences between the QEW stations (especially 52 and 53) are probably the result of biases in the data, since there was no traffic entering or leaving the freeway between these sites, and very limited space for storing vehicles.

TABLE 2 Frequency of Changes in Median Lane Flows Immediately Before and After Flow Drop

		Number of days		
Site	Detector Location	Increase	No change	Decrease
1	Manchester Ave.	0	0	9
1	Lomas Santa Fe Dr.	0	0	9
1	Via de la Valle	0	0	9
2	Fletcher Parkway	0	0	9
2	70th St.-lake Murray Boulevard	1	0	8
3	Nobel Drive	2	0	8
3	Governor Drive	1	0	9
4	Via de la Valle	3	0	7
4	Lomas Santa Fe Drive	2	0	8
5	Station 51	1	0	6
5	Station 52	3	0	4
5	Station 53	3	1	3

TABLE 3 Average Flow per Lane Immediately Before and After Median Lane Flow Drop

		Flow			
Site	Location	Before	After	Diff.	Pct. Diff.
1	Manchester Ave.	2,114	1,785	-251	-15.6
1	Lomas Santa Fe Dr.	2,136	2,041	-94	-4.4
1	Via de la Valle	2,106	2,064	-42	-2.0
2	Fletcher Parkway	2,078	1,974	-105	-5.0
2	70th St.-lake Murray Boulevard	2,183	2,127	-56	-2.6
3	Nobel Drive	2,252	2,086	-184	-8.2
3	Governor Drive	2,247	2,167	-80	-3.6
4	Via de la Valle	1,913	1,649	-263	-13.8
4	Lomas Santa Fe Drive	1,959	1,824	-135	-6.9
5	Station 51	2,229	2,111	-118	-5.3
5	Station 52	2,150	2,146	-5	-0.2
5	Station 53	2,112	2,114	+2	+0.1

TABLE 4 Frequency of Changes in Flow per Lane Immediately Before and After Flow Drop

		Number of days		
Site	Detector Location	Increase	No change	Decrease
1	Manchester Ave.	0	0	9
1	Lomas Santa Fe Dr.	3	0	6
1	Via de la Valle	3	0	6
2	Fletcher Parkway	1	0	8
2	70th St.-lake Murray Boulevard	3	0	6
3	Nobel Drive	0	0	10
3	Governor Drive	2	0	8
4	Via de la Valle	0	0	10
4	Lomas Santa Fe Drive	0	0	10
5	Station 51	2	0	5
5	Station 52	3	0	4
5	Station 53	4	0	3

TABLE 5 Average Flow per Lane Downstream of On-ramp Immediately Before and After Median Lane Flow Drop

		Flow			
Site	Location	Before	After	Diff.	Pct. Diff.
1	Manchester Ave.	2,370	2,056	-314	-13.2
1	Lomas Santa Fe Dr.	2,252	2,179	-73	-3.5
2	Fletcher Parkway	2,253	2,152	-101	-4.5
4	Via de la Valle	2,016	1,754	-262	-13.0

TABLE 6 Frequency of Changes in Flow per Lane Downstream of On-ramp Immediately Before and After Flow Drop

		Number of days		
Site	Detector Location	Increase	No change	Decrease
1	Manchester Ave.	0	0	9
1	Lomas Santa Fe Dr.	4	0	5
2	Fletcher Parkway	1	0	8
4	Via de la Valle	0	0	10

4.1.2 Flow and Speed Ratios

According to Daganzo's theory, changes in the distribution of flow across the lanes, as indicated by the flow ratio, are directly related to changes in relative speeds in different lanes, as indicated by the speed ratio. In the transition to congested flow, speed and flow ratios are expected to decrease simultaneously as rabbits switch out of the median lane when speeds equalize. In transitions from congested flow, flow ratios are expected to increase as rabbits switch back to the median lane as soon as its speed exceeds those of the other lanes. Similarly, transitions between other one- and two-pipe states (for instance between capacity flow and discharge flow) are expected to be accompanied by simultaneous increases or decreases in speed and flow ratios.

Changes in flow and speed ratios were identified from plots of re-scaled cumulative curves. As explained in Section 3.1.5, the re-scaling of these data involved rotating the cumulative curves so that they would be horizontal when the flow or speed in the median lane is equal to the average flow or speed. Figures 18 through 22 show typical re-scaled cumulative flow and speed ratio plots for locations at the downstream ends of the merge bottleneck sections. In these plots, re-scaled cumulative flow ratio and speed ratio plots are superimposed to show how the times of increases or decreases in the two ratios relate to one another. Times of flow breakdown, as indicated by the speed time series for the location in question, are also noted. Figures 23 through 26 show similar plots for locations that were definitely upstream of the bottlenecks. No plot is shown for Site 4 because of the unusual lane configuration just upstream of the Via de la Valle detectors.

Figures 18 through 22 apply to locations at the downstream ends of the merge bottleneck sections. At the sites on southbound Interstate 5 and westbound Interstate 8, there were abrupt decreases in the speed ratio at about the time of flow breakdown and less abrupt decreases in the flow ratios at about the same time. Note, however, that at Via de la Valle on Southbound Interstate 5, there had been a larger drop in the speed ratio about 30 minutes earlier. Following these abrupt decreases, the slopes of the re-scaled cumulative curves are approximately zero, indicating that there was no difference between the speed in the median lane and the average speed for all lanes. At the 70th Street-Lake Murray

FIGURE 18 Re-scaled Cumulative Flow Ratio and Speed Ratio, Southbound Interstate 5 at Via de la Valle, April 24, 2001

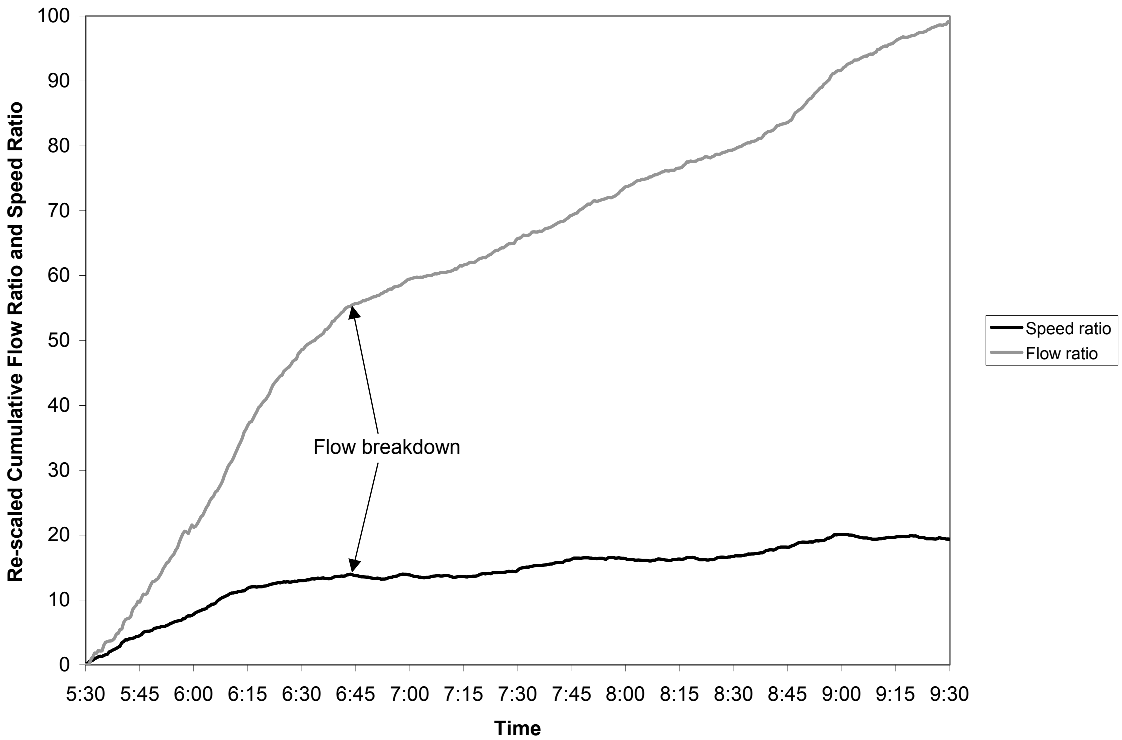


FIGURE 19 Re-scaled Cumulative Flow Ratio and Speed Ratio, Westbound Interstate 8 at 70th Street-Lake Murray Boulevard, October 18, 2001

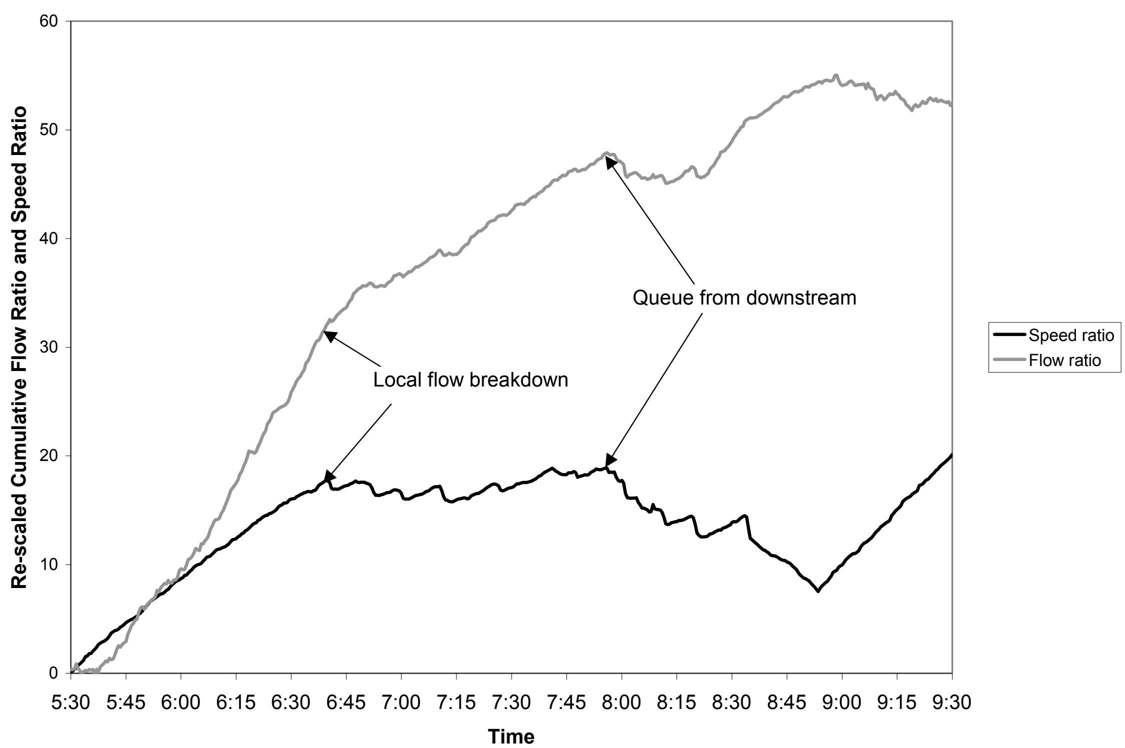


FIGURE 20 Re-scaled Cumulative Flow Ratio and Speed Ratio, Southbound Interstate 805 at Governor Drive, October 18, 2001

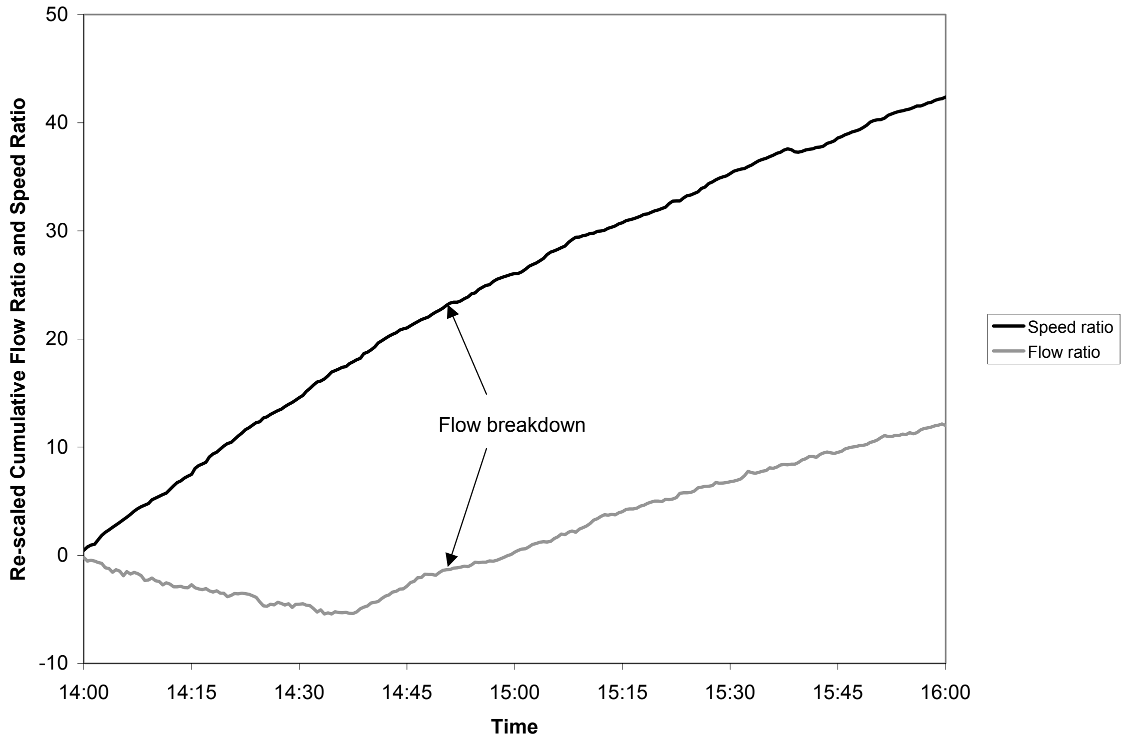


FIGURE 21 Re-scaled Cumulative Flow Ratio and Speed Ratio, Northbound Interstate 5 at Lomas Santa Fe Drive, October 18, 2001

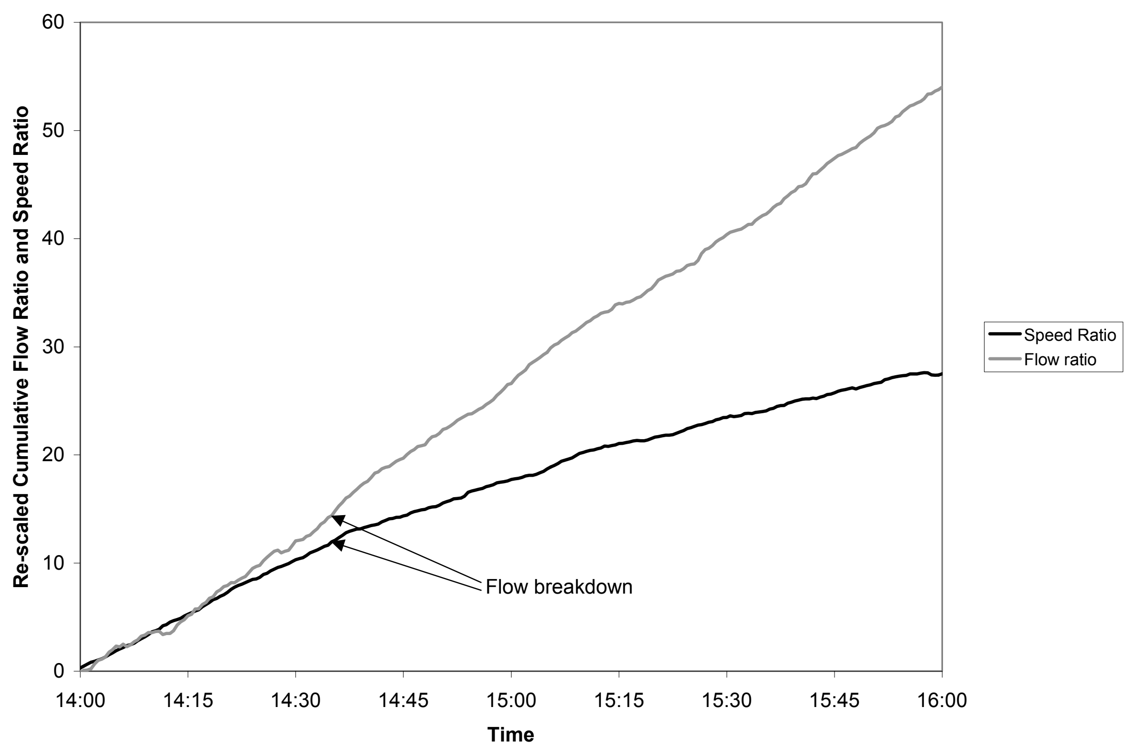


FIGURE 22 Re-scaled Cumulative Flow Ratio and Speed Ratio, Eastbound QEW at Detector Station 53, September 23, 1999

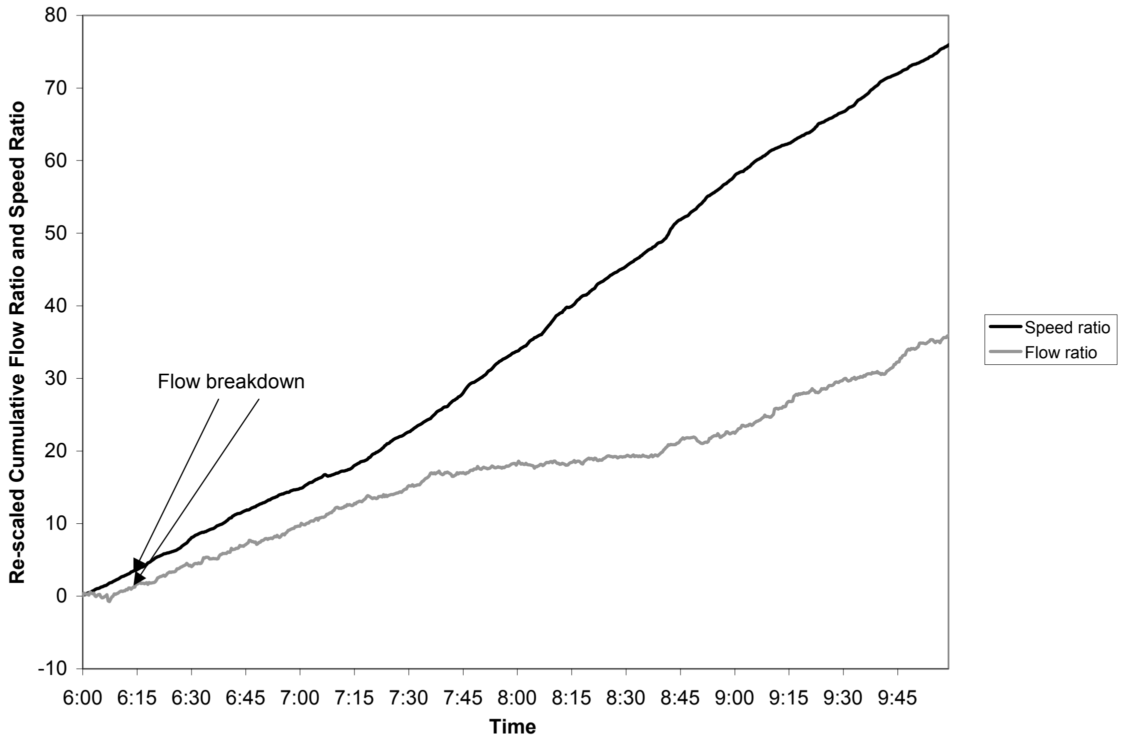


FIGURE 23 Re-scaled Cumulative Flow Ratio and Speed Ratio, Southbound Interstate 5 at Manchester Avenue, April 24, 2001

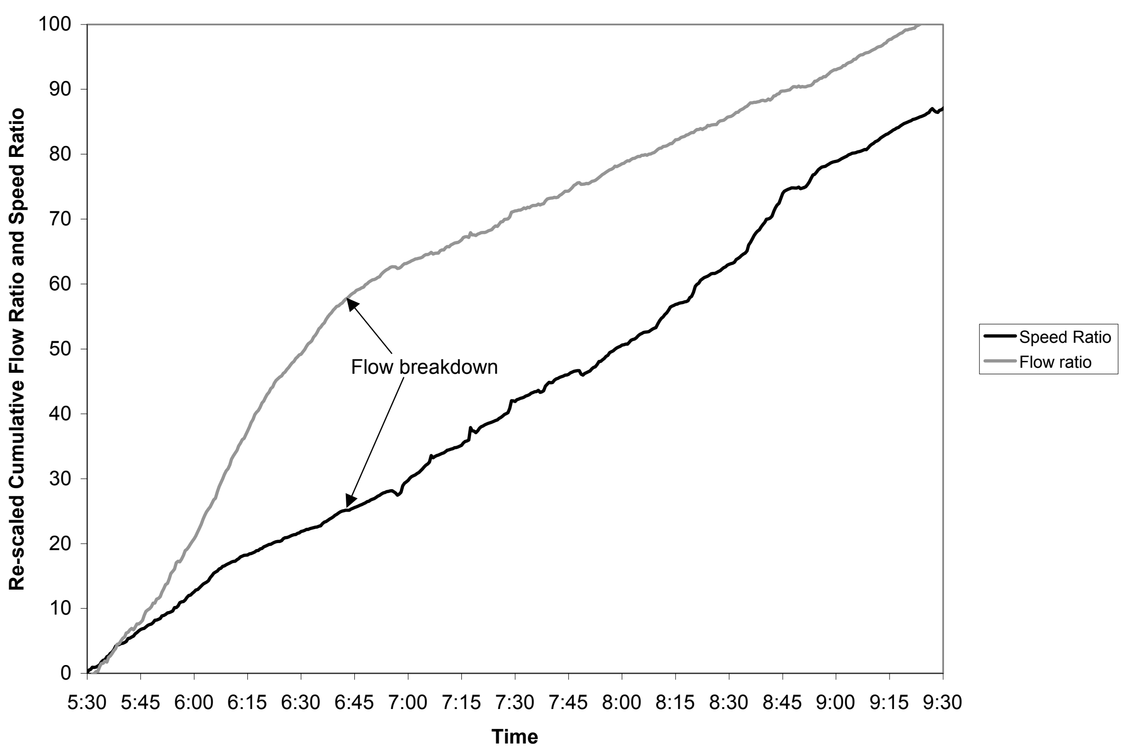


FIGURE 24 Re-scaled Cumulative Flow Ratio and Speed Ratio, Westbound Interstate 8 at Fletcher Parkway, October 18, 2001

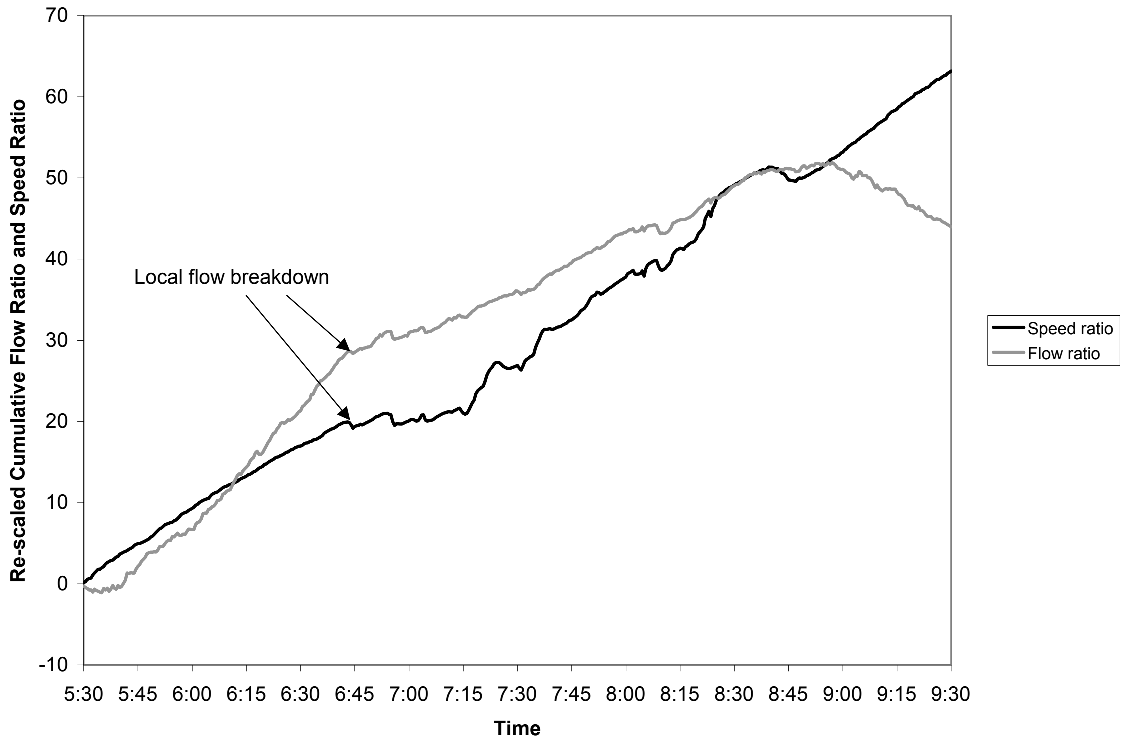


FIGURE 25 Re-scaled Cumulative Flow Ratio and Speed Ratio, Southbound Interstate 805 at Nobel Drive, October 18, 2001

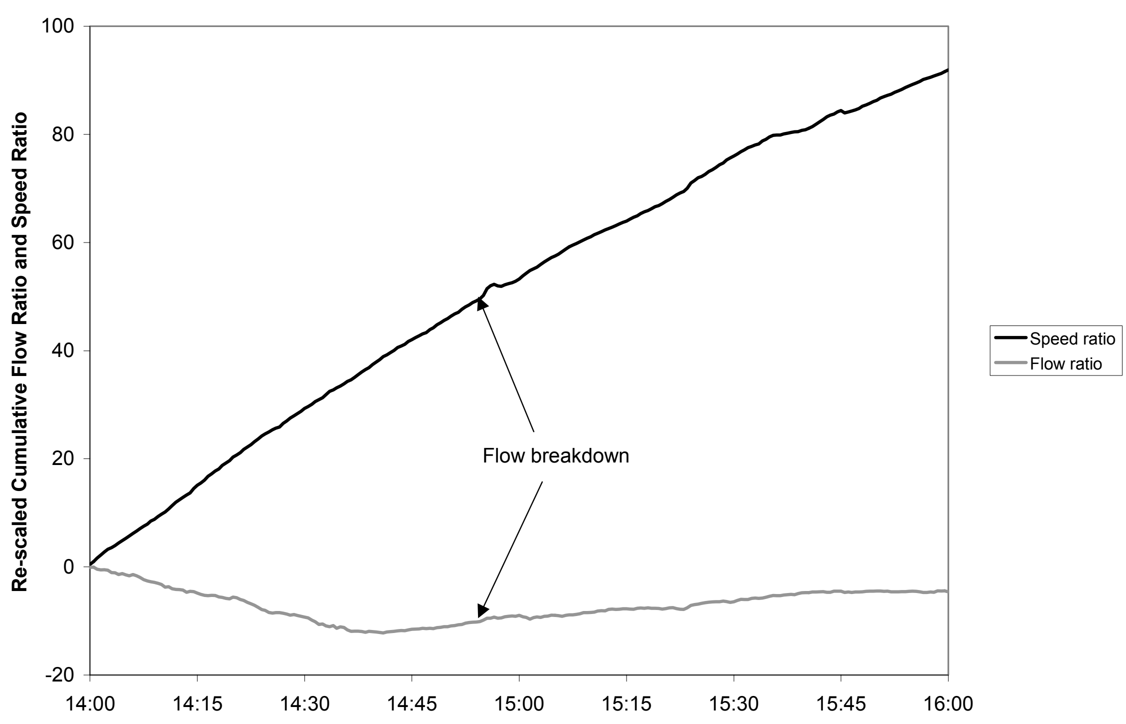
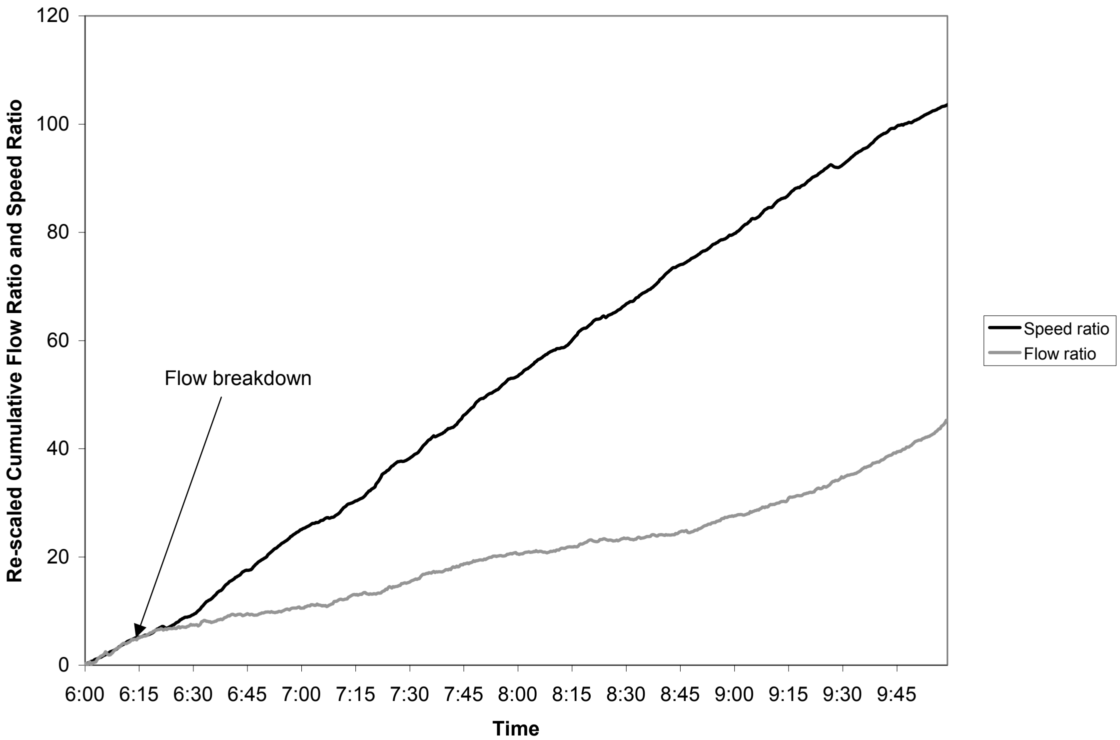


FIGURE 26 Re-scaled Cumulative Flow Ratio and Speed Ratio, Eastbound QEW at Detector Station 51, September 23, 1999



Boulevard site on westbound Interstate 8, there was another drop in the speed ratio (to an average of something less than 1.0) when a queue from downstream grew into the section later in the peak. At the other sites there was very little change in either the speed ratio or the flow ratio at the time of flow breakdown. At the Governor Drive site on southbound Interstate 805, there was no change in the speed ratio and what may have been a very slight decrease in the flow ratio; however, note that there had been a much more obvious increase in the flow ratio about 13 minutes before flow breakdown. At Lomas Santa Fe Drive on northbound Interstate 5 there was a slight decrease in the speed ratio at about the time of flow breakdown, but this corresponded with a slight increase in the flow ratio. At the site on the QEW, there was no change in either the speed ratio or the flow ratio at the time of flow breakdown, and only very minor changes thereafter.

Figures 23 through 26 show that at the locations farther upstream, there were only very minor variations in the speed ratios, and that all were greater than 1.0, with the possible exception of a period of about 30 minutes at Fletcher Parkway on Interstate 8. In this case, however, the speed ratio recovered long before the queue cleared. Flow ratios, on the other hand, show patterns of variation that are quite similar to those at the corresponding sites downstream.

Some of these results could be consistent with Daganzo's theory, but others definitely are not. On the basis of the lane configurations alone, all sites in Figures 18 through 22 should be downstream of the bottlenecks. If they are also downstream of the zone of acceleration, a transition to the discharge state should be observed at the time of flow breakdown, and there should be no change in their flow and speed ratios. The relatively unchanged speed and flow ratios at Governor Drive, Lomas Santa Fe Drive, and QEW Detector Station 53 are consistent with this hypothesis. Note that in none of these cases were there subsequent simultaneous decreases in the speed and flow ratios that would indicate the arrival of the capacity state, but the theory does not require this to happen.

The sharp downward breaks in the slopes at the other two San Diego locations could also be consistent with the theory provided the sites are not downstream of the zone of acceleration. Analysis of time series of speeds and flows, re-scaled cumulative speed curves, and changes in the number of vehicles stored in different sections (calculated by subtracting the sum of the mainline counts and the off-ramp counts at the downstream detectors from the sum of the mainline counts and the on-ramp counts at the upstream detectors) suggested that Via de la Valle was in the zone of acceleration on southbound Interstate 5 and that 70th Street-Lake Murray Boulevard was probably just upstream of the point of flow breakdown on westbound Interstate 8. Consequently, the results shown in Figures 18 and 19 could all be consistent with the theory.

On the other hand, the fact that speed ratios did not decrease at sites upstream of the points of flow breakdown, although the flow ratios sometimes did decrease, is clearly inconsistent with the theory's underlying behavioral logic. According to the theory, flow breakdown is precipitated when speeds are equalized across the lanes. If this is the case, speed ratios should always decrease in the transition to congested flow. Also, since the rabbits are held to change lanes because the median lane no longer offers a speed advantage, there should be an abrupt decrease in the flow ratio only if speeds are equalized. Since these sites were undoubtedly congested, a major assumption of the theory is contradicted by the observed decrease in flow ratios without speed equalization.

Taken together, the results at the upstream and downstream locations seem inconsistent with one another. Why should speeds equalize at locations at or just downstream of the bottlenecks, but not farther upstream in the queue? Further analysis of the data suggests that the results at Via de la Valle and 70th Street-Lake Murray Boulevard may be the result of data biases and special circumstances, and that those in Figures 23 through 26 are not altogether representative of conditions in the queues.

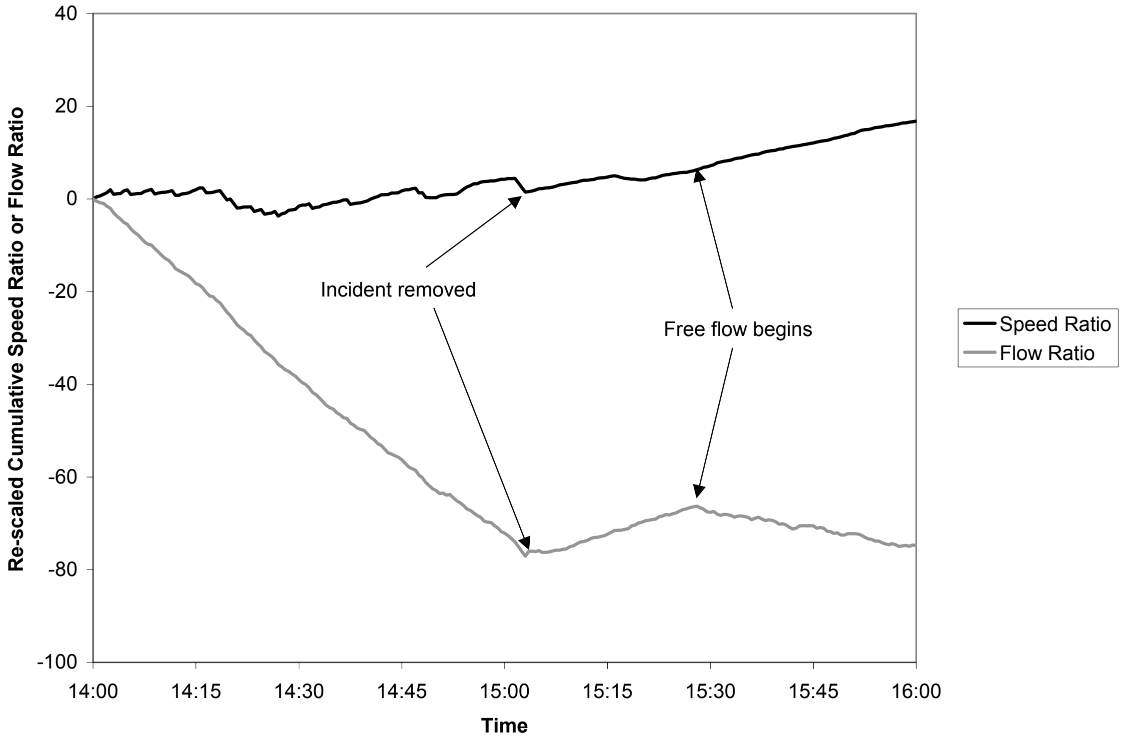
In the case of the Via de la Valle site, there is actually very little decrease in the speed ratio at the time of flow breakdown; a more pronounced decrease had taken place 30 minutes earlier. The time series of estimated speeds in the individual lanes suggests that this resulted from an increase in speed in the two outer lanes; this increase, in turn, may well have been a result of the bias in the San Diego speed estimates. Recall that these speed estimates assume a constant vehicle length and are underestimated if longer than average vehicles are present. Early in the data collection period, the outer lanes have little traffic and are used mostly by trucks. As flow increases, more passenger cars use these lanes and the bias decreases, causing the speeds in these lanes to appear to increase and the speed ratio to decrease. The Via de la Valle speed ratios may also be misleading because speeds in the median lane appear to be underestimated: they are somewhat less than those in Lane 2 even in free flow. Although the median lane speed ratio appears to be approximately 1.0 following flow breakdown, the Lane 2 speed ratio was consistently greater than 1.0.

At the 70th Street-Lake Murray Boulevard site, the time series of speeds in individual lanes shows major speed oscillations in the two left lanes following local flow breakdown, but very little oscillation in the two right lanes. During periods of minimum speed in the recurring jams, speed in the median lane is normally less than that in any of the other lanes; during periods of speed recovery, speed is highest in the median lane. This rapid oscillation in the speed ratio leads to the jagged appearance of the re-scaled cumulative speed ratio curve for this location (see Figure 19). Farther upstream, the jams spread to all lanes, and the average speed ratio consistently exceeded 1.0.

Analysis of re-scaled cumulative speed ratio plots for locations upstream of Cawthra Road in the eastbound QEW queue suggests that the results in Figures 23 through 26 are not altogether representative of speed behavior in queues. Speed ratios downstream of the exit to Cawthra Road (including those at Stations 50 and 51) are consistently greater than 1.0. Farther upstream, however, those at stations upstream of exits tended to be less than 1.0 and those upstream of entrances to be greater than 1.0. This might suggest that the relative speeds in different lanes in queues are influenced by entering and exiting traffic, and that speed is rarely equalized across all lanes.

Queue discharge flow following removal of incidents was found to be reasonably similar to flow in the vicinity of merge bottlenecks. In the incident queues themselves, speed and flow ratios varied and were sometimes greater than 1.0 and sometimes less. This was to be expected, since lanes were blocked and there was roadside activity on one side of the road or the other. In queue discharge following incident removal, both speed and flow ratios were typically greater than 1.0, although there were exceptions. The exceptions included the flow ratios at Adams Avenue and El Cajon Boulevard on southbound State Route 15, and the speed ratio at College Avenue on westbound Interstate 8. In all these cases, the flow or speed ratio at the location in question is typically less than 1.0, even under free flow conditions. The low speed ratio at College Avenue appears to be due to biases in the data; the low flow ratios at Adams Avenue and El Cajon Boulevard may be due to either biased data or unusual lane use in these sections. Major changes in speed and flow ratios that might indicate transitions between flow states were not observed, even in cases in which there was interference from bottlenecks upstream or downstream from the incident. Figure 27 shows re-scaled cumulative flow and speed ratios for a typical incident. Note that in this case, the flow ratio was less than 1.0 in free flow following the discharge of the incident queue.

FIGURE 27 Re-scaled Cumulative Flow and Speed Ratios at 70th Street-Lake Murray Boulevard for Incident of November 29, 2001



4.2 Loss of Motivation

Loss of motivation by aggressive drivers when speeds equalize across the lanes is a key concept in Daganzo's theory. In section 2.2, it was argued that truly voluntary increases in headways resulting from a loss of motivation should result in increases in average time gaps in the passing lane. The hypothesis that *average time gaps in the passing lane will increase when speeds in the passing lane drop to the level of those in other lanes* was advanced as an extension to the theory.

Re-scaled cumulative curves of average time gaps in the median lane were used to test this hypothesis. In these plots, the time series of speeds in the median lane was superimposed on the re-scaled cumulative plot to indicate the time of initial flow breakdown. Increases in average time gaps in the median lane were observed to occur consistently at all locations in the southbound Interstate 5 study site in San Diego and occasionally at the QEW study site. Elsewhere, increases in time gaps were not observed to coincide with flow breakdown. Figure 28 is a typical plot for the southbound Interstate 5 site, showing the increase in average time gap; Figure 29 is a similar plot for westbound Interstate 8, where the increase in average time gap did not occur. These results seem to support the idea that time gap increases are related to reverse-lambda flow-concentration

Figure 28 Re-scaled Cumulative Time Gap and Speed vs. Time, Median Lane, Southbound Interstate 5 at Manchester Avenue, April 25, 2001

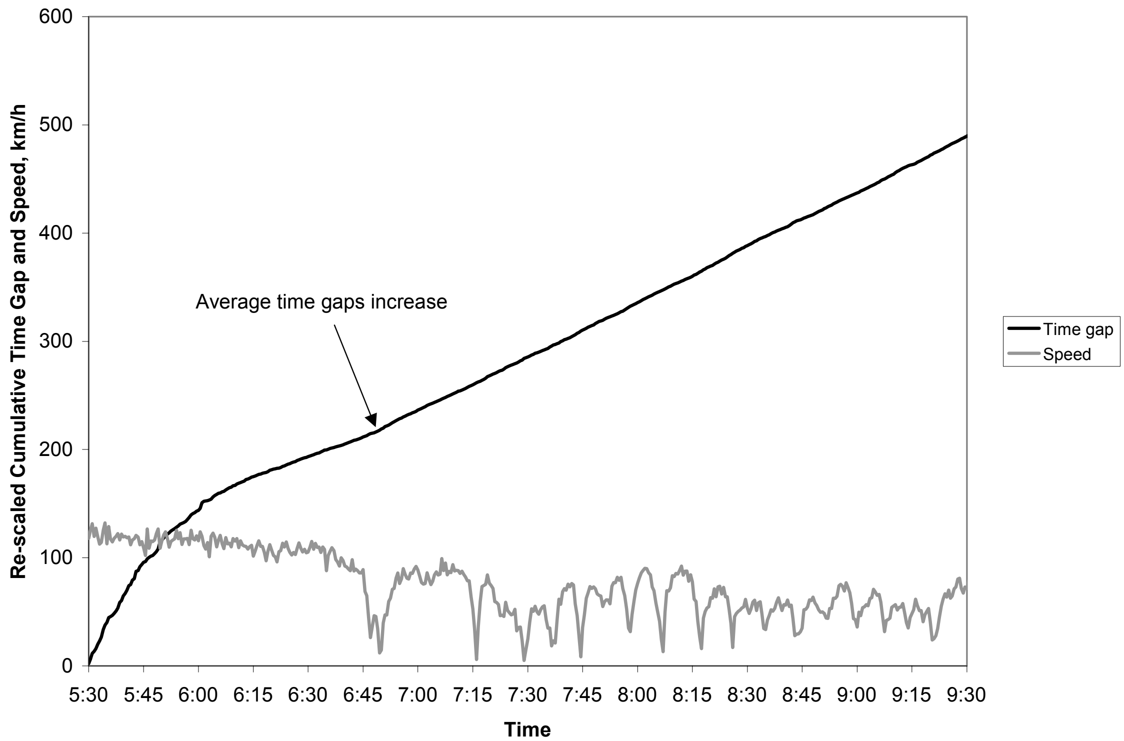
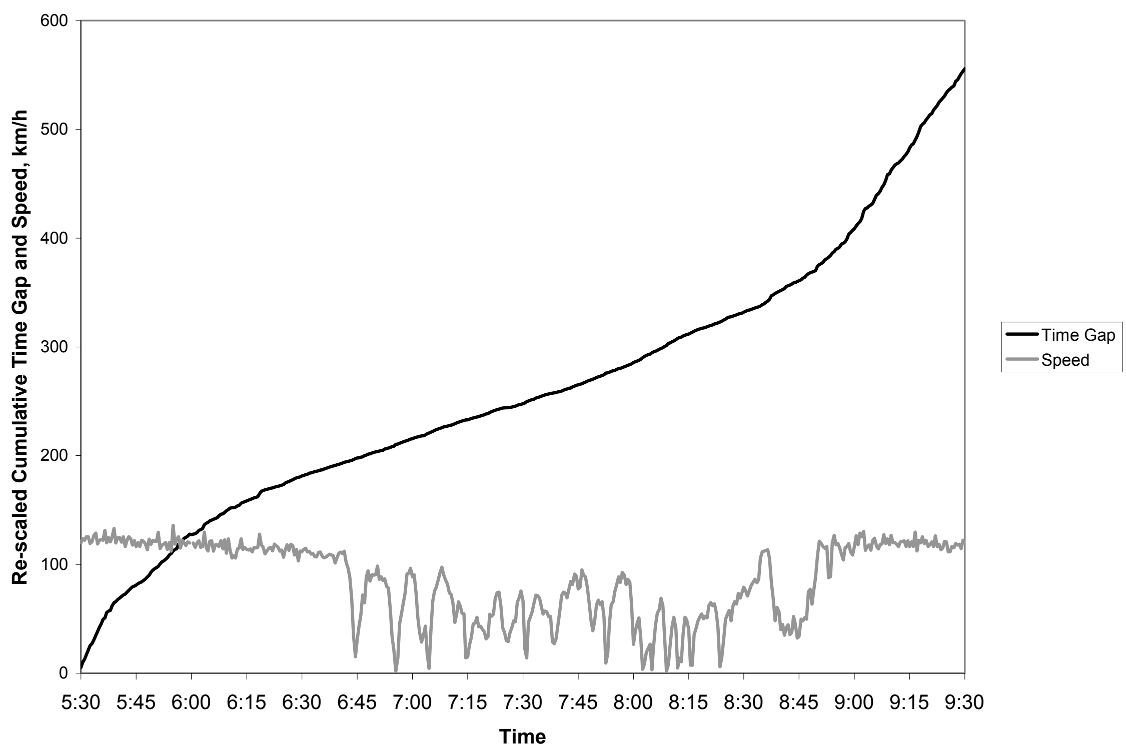


Figure 29 Re-scaled Cumulative Time Gap and Speed vs. Time, Median Lane, Westbound Interstate 8 at Fletcher Parkway, October 18, 2001

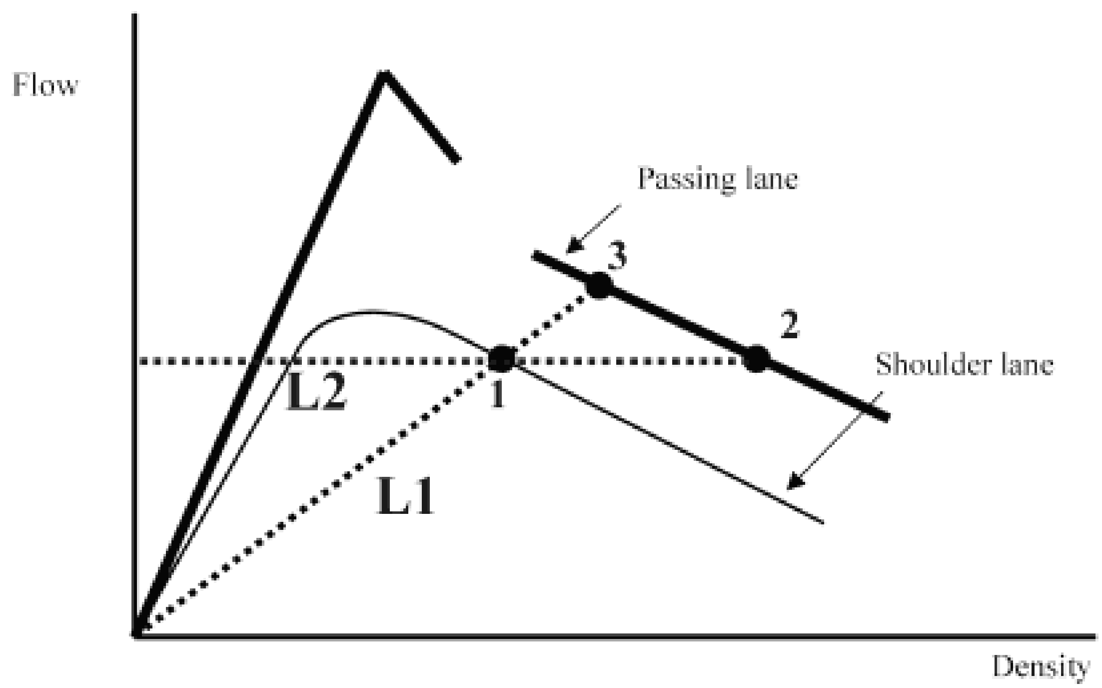


patterns, since both consistent time gap increases and reverse-lambda flow-occupancy patterns occurred only at the southbound Interstate 5 site.

4.3 Flow and Occupancy Plots

Flow-occupancy scatter plots were constructed for passing lane and the shoulder lane for detector 40 on the Gardiner Expressway. These are shown in Figures 31 through 34. Oblique count curves (like those in Figures 14 and 15) were used to distinguish time periods marked by free, semi-congested and congested states. The scatter plots from each of these states were collected over 120 second sampling intervals. The data displayed by the flow-occupancy scatter plots for the passing and shoulder lanes were qualitatively consistent with the flow-density model shown in Figure 30. This model is strikingly similar to the one proposed by Daganzo.

FIGURE 30 Observed Flow-Density Model



As an aside, Daganzo supposes that in congested traffic, the vehicle speeds in both lanes are equal, as exemplified by the dashed line (L1) in Figure 30. The data, however, revealed something slightly different. Namely, congested flows (and not vehicle speeds) were equal across lanes as exemplified by the points labeled 1 and 2 in the figure. But this observed feature is not, in itself, inconsistent with Daganzo's theory. After all, traffic states like points 1 and 2 are still described by Daganzo's flow-density model.

Daganzo's model implies that if the flows in each lane were equal, the vehicles in the shoulder lane should be traveling faster than the vehicles in the passing lane. The data from the double loop detectors showed that average vehicle speed measured in the shoulder lane was indeed faster than the average vehicle speed measured in the passing lane when the equalization of the flow was observed.

Figure 31 shows the flow-occupancy scatter plot for the passing and shoulder lane during the free flow state. The black solid dots are the data from the passing lane and the empty circles are the data from the shoulder lane. As per the theory, the speed of the rabbits in the passing lane was faster than the slugs in the shoulder lane[2].

Figure 32 shows the data from the semi-congested state. During this state, the speed of the rabbits in the passing lane was reduced (compare slopes *A* and *B* in this figure). The flow, however, did not reduce much as compared with the flow observed during the free flow state and this is consistent with the theory. The gray solid square is the average of the black solid dots (the data from the passing lane). The location of this gray solid square shown in Figure 32 would lie along to the semi-congested branch of Daganzo's proposed flow-density model. However, unlike the theory, the speed of the rabbits in the semi-congested state was not faster than the speed of the slugs (compare slopes *A* and *C* in Figure 32). This semi-congested state is further discussed in Section 4.4.

Figure 33 shows how the rabbits transitioned from the semi-congested state to the congested state. The black dots transitioned chronologically from left to right (as shown by the arrow in Figure 32). This transition was gradual because drivers responded to the shock by gradually altering their speeds.

Figure 34 shows how the slugs transitioned to fully congested state after the passing lane is fully congested. The transition occurred after the passing lane became congested, as per the theory

4.4 Semi-Congested state

In unqueued or freely flowing traffic, rabbits and slugs travel at different speeds; i.e., speed differences are observed between the passing and shoulder lanes. As flows increase during the rush, traffic can enter a so-called semi-congested state marked by reductions in speed among rabbits[3]. Traffic eventually evolves to a fully congested state that is accompanied by reduced outflows from the bottleneck. These flow reductions are said to occur because rabbits become "unmotivated;" i.e. rabbits are no longer willing to drive at small headways.

The oblique count curves in Figure 14 are superimposed until t = 15:18, indicating that freely flowing traffic initially prevailed on the freeway stretch. The displacements

[2] Vehicle speeds are proportion to the slopes of the chords passing through the data and the origin of the occupancy and flow plane.

[3] Speed reduction among the slugs was also observed during the semi-congested state. However, the speed reductions among the slugs were not as dramatic as the rabbits (compare slopes *C* and *D* in Figure 32).

between curves that came later reveal the gradual vehicle slowing as traffic transitioned to the semi-congested state. The oblique count curves separate more dramatically at t = 15:51, marking the start of the fully congested state.

The evidence of the semi-congested state is also shown in Figure 32. The figure shows that, while rabbits were in the semi-congested state, the flow of slugs in the shoulder lane sometimes rose a little above the flows observed earlier in freely flowing traffic; the reader can verify this by visually inspecting the unshaded circles in Figures 31 and 32. Figure 32 indicates that, in this semi-congested state, the speeds of slugs dropped below their free flow speeds. This is evident from the slopes of the lines labeled “C” and “D” (and this is part of what motivated us to illustrate the density-flow relation for slugs in Figure 30 with a non-linear shape near capacity).

Also of note, Figure 32 demonstrates that, in semi-congested traffic, the speeds of both rabbits and slugs were quite similar; i.e., these average speeds differed by only 4 mph. Careful inspection of the relations previously presented in Figure 30 will convince the reader that this observation is in keeping with Daganzo’s theory.

Figure 32 further shows that semi-congested flows in the median lane were greater than those in the shoulder lane; i.e., rabbits adopted smaller headways (and vehicle spacings) than did slugs. But this driver behavior of rabbits was evidently not sustainable. Traffic evolved into a fully congested state, as evident from Figure 33 and 34.

4.5 Fast Backward Moving Shock and Observed Lane Changing Behavior

The existence of the fast backward moving shock was observed on three of the nine days studied. (The reader will recall that four of these days were discarded due to queues emanating from downstream of the sites bottleneck). These shock speeds were identified using oblique count and occupancy curves as in Figure 16. On the three days marked by fast backward-moving shock, the percent differences in flows before and after the bottleneck’s activations were higher than on the other days. Table 7 presents summarizes of the five days for which data were suitable for testing Daganzo’s theory. The days presented in the first three rows of this table were marked by shock speeds of 35 km/hour or more. These shock speeds were always at least three standard deviations higher than the estimated average speeds of the kinematic waves.[4]

[4] The average speed of the kinematic waves observed in this day was 23.6 km/hour, and the standard deviation of this estimate was 3.8 km/hour. This estimated speed of the kinematic wave was consistent with the values reported in other literature [Mauch (58), Edie and Baverez (59)].

FIGURE 31 Flow-Occupancy Scatter Plot from Free Flow State

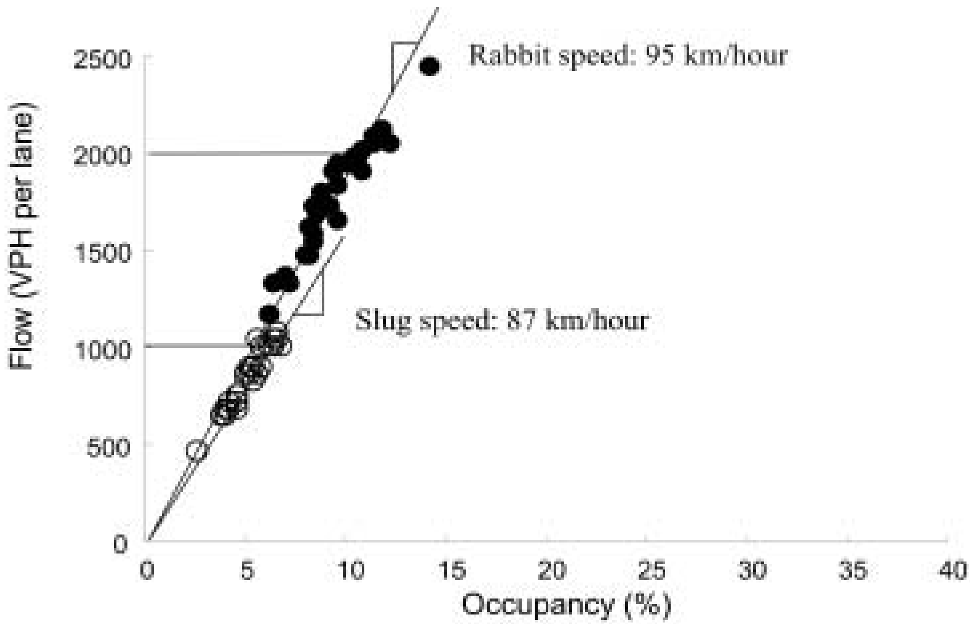


FIGURE 32 Flow-Occupancy Scatter Plot from Semi-Congested State

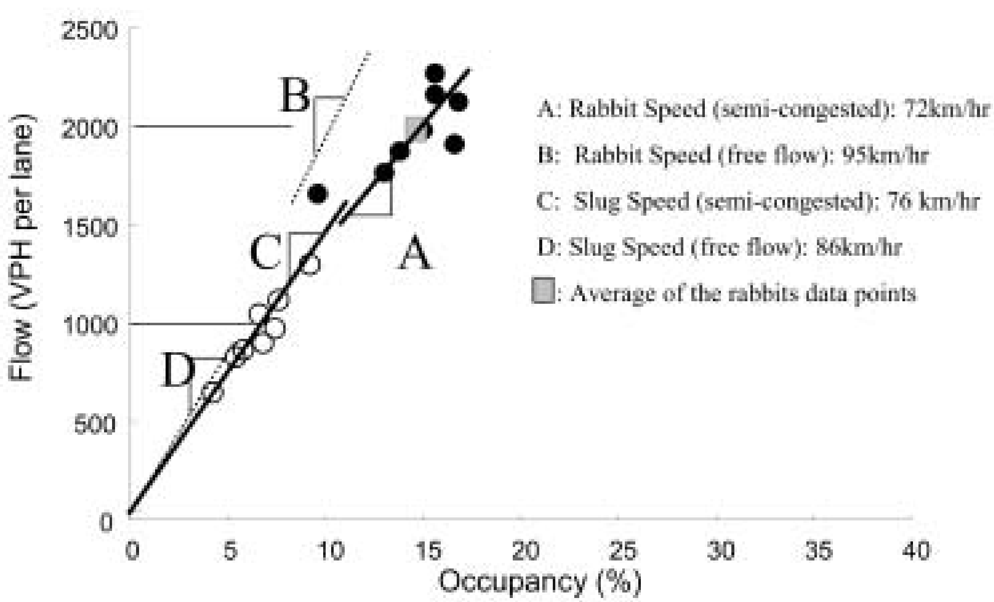


FIGURE 33 Flow-Occupancy Scatter Plot from Free Flow State

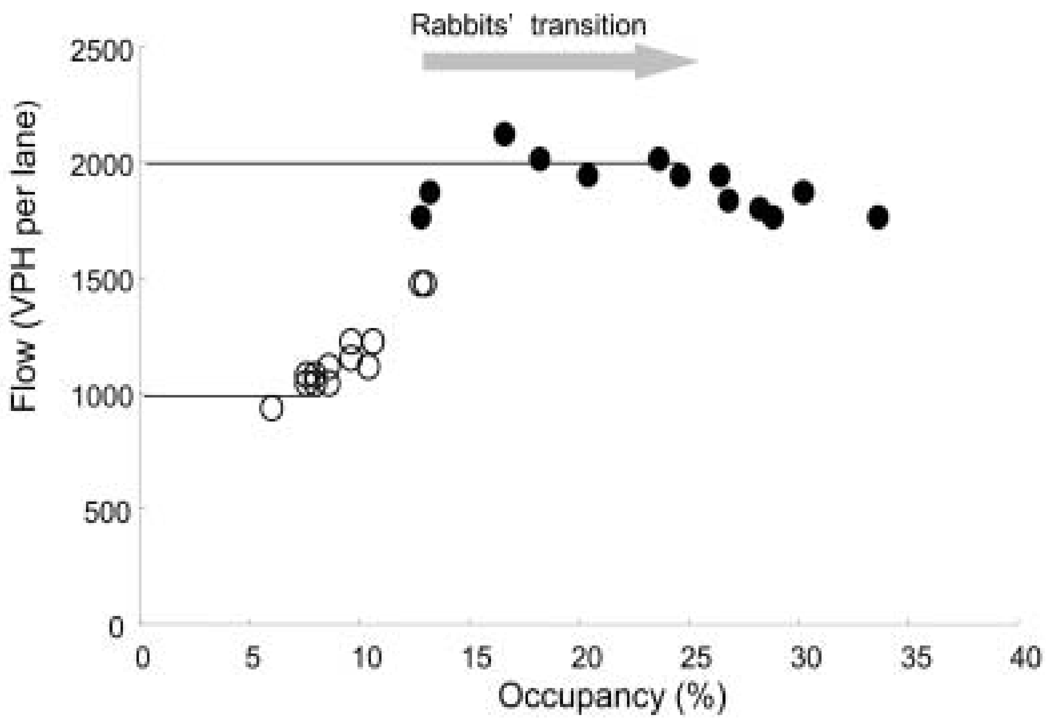


FIGURE 34 Flow-Occupancy Scatter Plot from Semi-Congested State

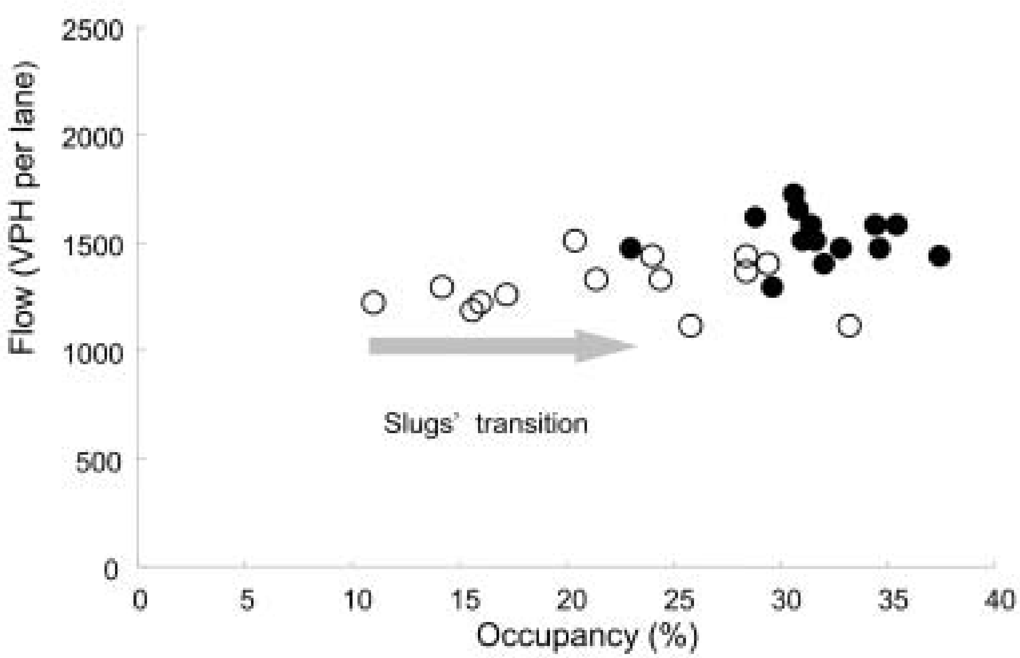


Table 7 Estimated Speed of the Shock

Date	Flow departing the site prior to the bottleneck activation	Flow departing the site after to the bottleneck activation	% difference in flow	Speed of the shock
3/5/97	6,670 vph	5,780 vph	13.3 %	35 km/hour
6/2/98	6,027 vph	5,125 vph	15.0 %	47 km/hour
5/21/98	5,912 vph	5,195 vph	12.1 %	35 km/hour
4/30/98	5,866 vph	5,617 vph	4.2 %	28 km/hour
3/13/98	5,723 vph	5,490 vph	4.1 %	16 km/hour

In order to study vehicle lane change behavior in the vicinity of the bottleneck, the flows measured in each lane at detector 60, 70 and 80 were closely examined. Figure 35 shows the oblique count curve constructed for flow measured in the passing lane at detectors 60, 70 and 80. Figure 36 shows the analogous data for the shoulder lane. These two figures indicate that the flow measured in the shoulder lane is decreasing with distance. The opposite is true for the passing lane. This is consistent with the lane change behavior described by Daganzo whereby rabbits return to the passing lane after passing through the bottleneck.

FIGURE 35 Oblique Count Curves from Detectors 60-80, Shoulder Lane

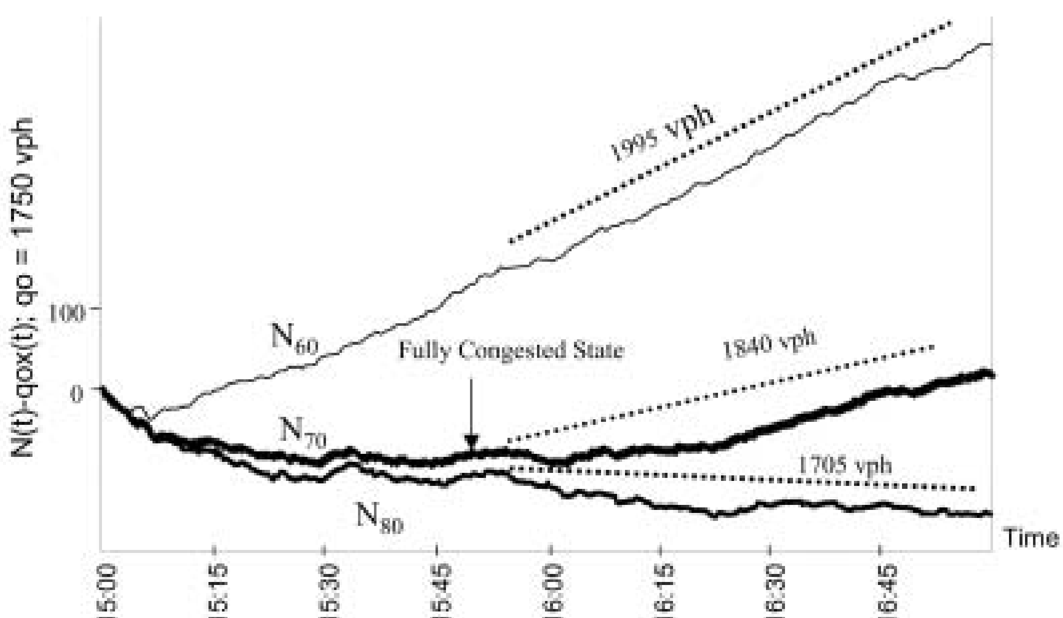
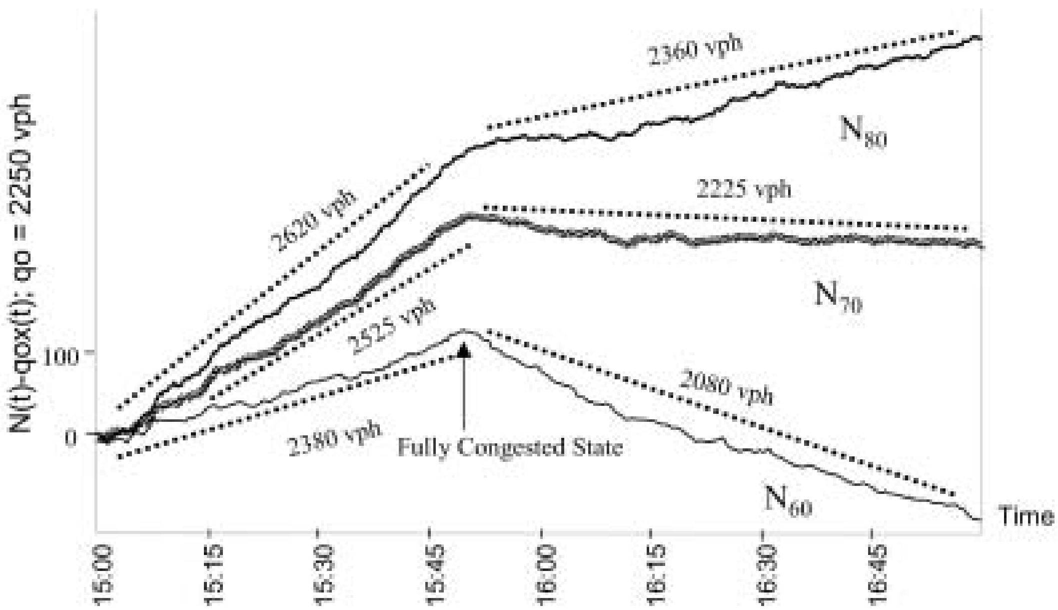


FIGURE 36 Oblique Count Curves from Detectors 60-80, Passing Lane



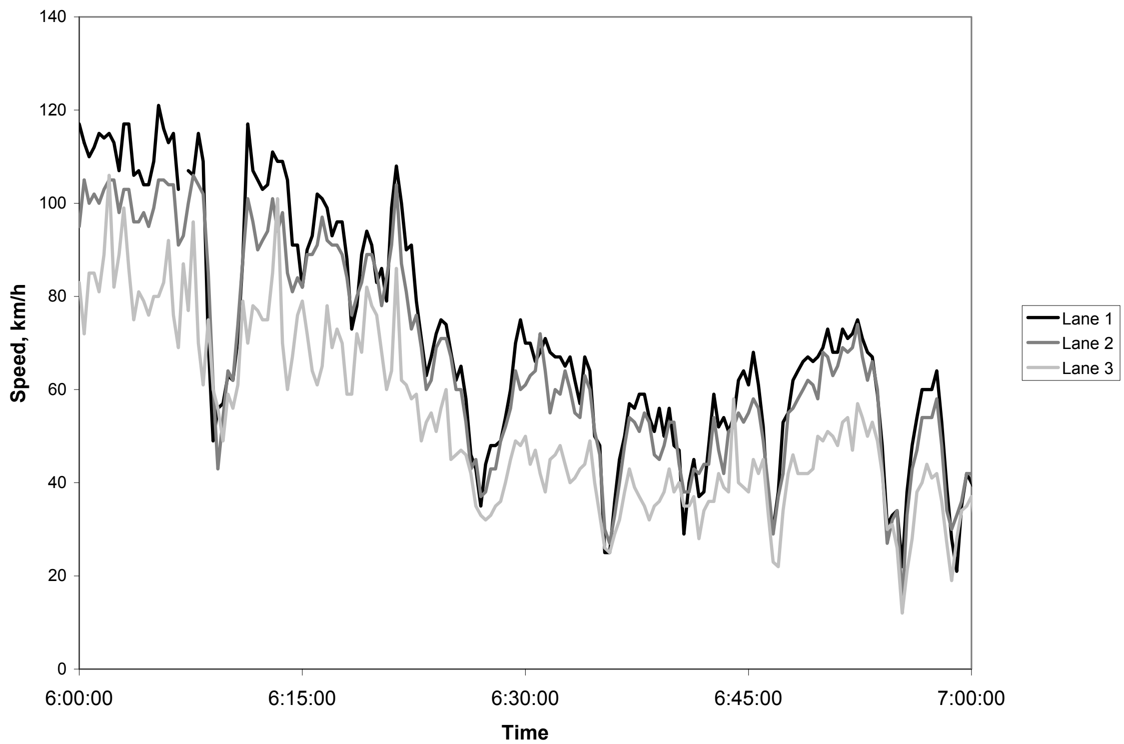
4.6 Other Observations

4.6.1 Speeds in Congested Flow

One of the underlying assumptions of Daganzo's theory is that speeds equalize across lanes in congested flow, and, indeed, that it is the equalization of speeds that triggers flow "collapse" in which average headways in the most heavily utilized lane increase. As noted in Section 1.3, this equalization of speeds has been very commonly reported in past literature. Section 4.1.2, however, presented evidence that this speed equalization often does not take place in congested flow. In most cases, average speeds in the median lane were greater than those in other lanes under all conditions, although, as discussed in Section 4.1.2, this was not necessarily the case for locations that were a considerable distance upstream from the bottleneck.

For locations that were immediately upstream from the merge bottlenecks studied by the SDSU team, however, there was a consistent pattern. This pattern is one of speed oscillations in which low speed jams alternate with periods in which speeds recover somewhat, but not to free-flow speed. Speeds equalize across the lanes only during the brief minimum-speed portion of the jams. Indeed, during these periods, the pattern in which speed in the median lane is greater that that in the shoulder lane often is reversed. This basic pattern was observed in both the San Diego and Toronto data; however, because of the possible biases in the San Diego data resulting from the way the speeds were estimated, the results from the QEW site are more convincing. Figure 37 illustrates the pattern at QEW detector station 51. In the figure, lanes are numbered outward from the median.

FIGURE 37 Speed Time Series, QEW Detector Station 51, September 16, 1999



4.6.2 Attributes of Density Near the Bottleneck

A remarkable event was observed at the SR-24 site. When a stalled vehicle in the median caused the density in the vicinity of the bottleneck to return to that of a free flow state, the flow departing the site rose substantially. This event is described in more detail below.

Figures 38, 39 and 40 present oblique N-curves to verify the presence of an active bottleneck on the SR-24 site.   The curves in Figure 38 were measured at locations 3 and 4 (see Figure 13). These two curves remain superimposed during the entire observation period, indicating that the traffic between the intervening segment was always freely flowing.

FIGURE 38 Oblique Count-Curves from Location 3 and 4 (Orinda, California)

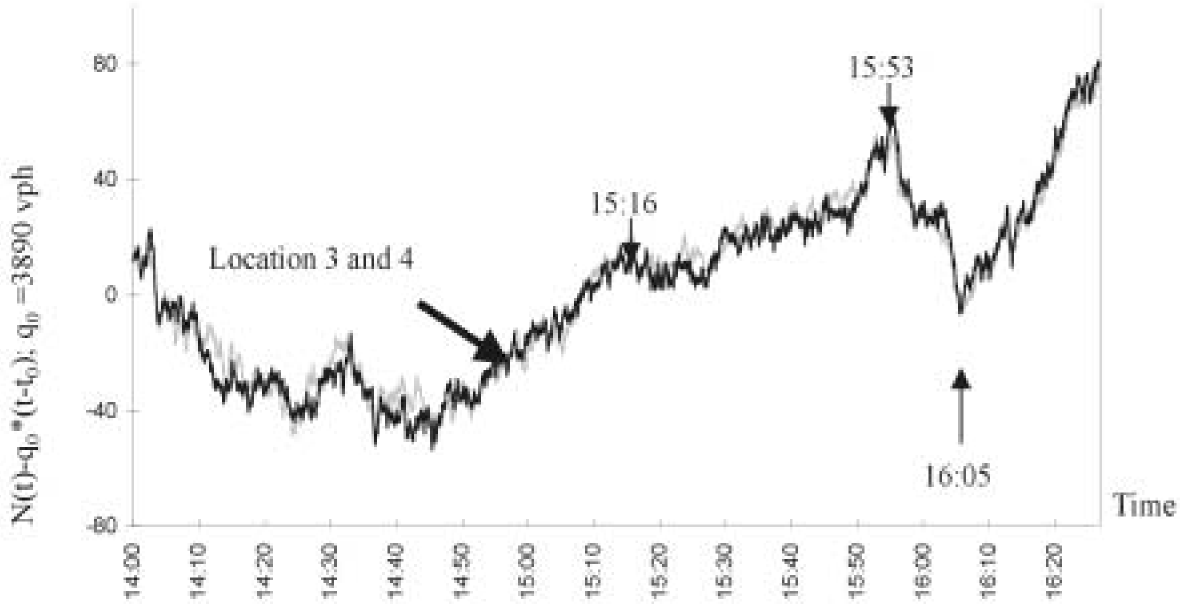


FIGURE 39 Oblique Count-Curves from Location 2 and 3 (Orinda, California)

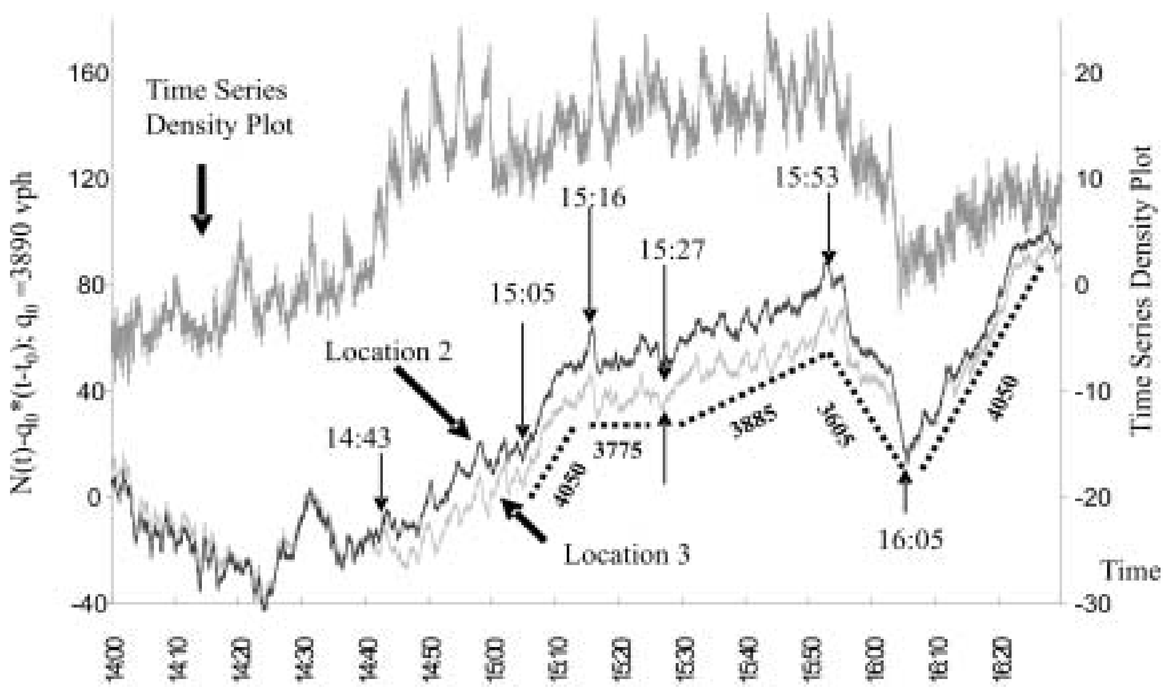


FIGURE 40 Oblique Count-Curves from Location 1 and 2 (Orinda, California)

Figure 39 displays N-curves measured at locations 2 and 3. The displacement between these two curves beginning at about *t* = 14:43 marks the outset of the semi-congested state. The sudden and pronounced reduction in flow at approximately *t* = 15:16 marks the beginning of the fully congested state. Figure 38 and 39 therefore collectively reveal that the downstream front of the queue was somewhere between locations 2 and 3.

High flow (from *t* = 15:05 to *t* = 15:16) departed from this site for a sustained period prior to the outset of the fully congested state; see Figure 39 (Flows are annotated on this figure). The fully congested state was then accompanied by a severe flow reduction (from *t* = 15:16 to *t* = 15:27) that persisted for about 10 minutes before discharge rates recovered somewhat (from *t* = 15:27 to *t* = 15:53), but these rates did not return to those very high flows observed at earlier times. The pattern of discharge flows exhibited by this (California) bottleneck is qualitatively like the pattern observed on the Gardiner Expressway in Toronto.

At *t* = 15:52, a passenger car made an emergency stop in the median at a location annotated in Figure 13, a short distance upstream of location 2. The stalled vehicle remained there until *t* = 16:31[5].

Although the stalled vehicle (at *t* = 15:52) did not block a travel lane, it temporarily reduced the flow departing the site. Figure 39 shows that flows dropped from 3,885 vph to 3,605 vph. Evidently, the vehicle stall initially caused a rubber-necking effect among passing motorists.

Since the stalled vehicle restricted flow from proceeding past locations 2 and 3, the vehicle accumulations on the intervening segment returned to those of freely flowing conditions. This is also evident in Figure 39; the vertical displacements between the N-curves completely disappeared by t = 16:05. Moreover, the density between locations 2 and 3 returned to that of the free flow state. This is evident in the time series density plot also shown in Figure 25. Excess vehicle accumulations did, however, remain between locations 1 and 2. This is clear from Figure 40.

Thus, the stalled vehicle moved the bottleneck to a location somewhere upstream of location 2 by t = 16:05. Remarkably, it was at this same time that discharge past location 3 rose substantially. Figure 39 shows that, at t = 16:05, the outflow measured at location 3 increased from an average rate of 3,605 vph to 4,050 vph. This new rate was even higher than the highest queue discharge rate (of 3,885 vph) observed prior to the vehicle stall. Moreover, this higher rate persisted for an extended time, as is evident in Figure 39.

At present, the explanation for this observed rise in capacity remains elusive. It may be that moving the bottleneck upstream of location 2 provided for smoother, less disruptive merging maneuvers at the Fish Ranch interchange (see Figure 13) and that this contributed to the higher outflow.

4.6.3 Characteristics of Incident Recovery Flow

Post-incident flow characteristics have not been discussed extensively in past literature. In addition to its contribution to the test of Daganzo's theory, the study of incident flow recovery resulted in documentation of post-incident flow characteristics for several incidents.

Important characteristics of post-incident flow include flow rates for individual lanes and the freeway as a whole and speeds. In interpreting data related to flow recovery, it is important to realize that incidents are often cleared in stages. For the incidents investigated, flows sometimes recovered gradually, over periods of time ranging from 12 to more than 30 minutes, and in other cases abruptly, with large increases taking place over 2 to 5 minutes.

Tables 8 and 9 summarize characteristics of flow following incident clearance. Table 8 shows median lane flow, flow per lane, and average speed for locations that were not active bottlenecks following incident clearance. Flow characteristics at these locations are primarily the result of the acceleration process at the downstream front of the incident queue, but are also affected by flows entering and exiting the freeway between the incident and the detectors. Separate data are shown for time periods for which the re-scaled cumulative plots indicated different average flow rates.

Table 9 gives flow per lane at bottlenecks downstream of incidents that were active following incident clearance. The flows given are the sum of the mainline and ramp

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[5] This event is documented on videotape.

flows entering the bottleneck section. Once again, separate flows are shown for time periods for which re-scaled cumulative plots indicated different average flow rates. Two locations, 70th Street-Lake Murray Boulevard on westbound Interstate 8 and Lomas Santa Fe Drive on southbound Interstate 5, are just downstream from morning peak period bottlenecks included in the study of merge bottlenecks. In these cases average queue discharge flows for the morning peak period are given for comparison. In addition, average queue discharge flow is given for a representative non-incident-related afternoon congestion episode at Lomas Santa Fe Drive.

Lomas Santa Fe Drive data (for the July 2, 2002 incident) appear in both tables. This is because the section downstream of Lomas Santa Fe Drive did not immediately become an active bottleneck when the incident was cleared. Rather, there was period of more than 30 minutes following incident clearance during which the active bottleneck was in the section upstream, between Lomas Santa Fe Drive and Manchester Avenue (see Figure 4).

TABLE 8 Flows and Speeds at Non-Bottleneck Locations

Date	Location	Location of incident	Time period	Median lane flow, vph	Flow per lane, vph	Ave. speed, km/h
12/3/01	Waring Rd.	Upstream	8:36:30 – 8:47:30	2,249	2,163	106
			8:48:00 – 9:06:00	2,072	2,043	109
12/3/01	College Ave.	Downstream	8:35:30 – 8:47:00	2,005	1,807	77
			8:47:30 – 9:08:30	2,297	1,777	90
5/9/02	El Cajon Blvd.	Upstream	16:36:00 – 16:46:00	1,931	1,699	93
5/9/02	Adams Ave.	Downstream	16:36:00 – 16:46:00	2,029	1,835	83
6/3/02	Fletcher Pkwy.	Upstream	16:23:30 – 16:39:00	1,913	1,867	91
			16:39:30 – 16:42:30	2,640	2,211	97
7/2/02	Lomas Santa Fe Dr.	Upstream	15:40:30 – 15:53:00	2,220	1,745	107
			15:53:30 – 16:14:00	2,113	1,751	94

Characteristics of post-incident flow as documented in Tables 8 and 9 may be summarized as:

1. Flow rates in unimpeded queue discharge following incident clearance and at bottlenecks activated by incident discharge tend to be considerably less than peak-period bottleneck queue discharge rates for similar roadway sections (compare Tables 8 and 9 with Tables 1, 3 and 5). They do appear to be similar to non-incident-related bottleneck queue discharge rates for similar times of day.

2. Speeds in discharge flow following incident clearance are similar to speeds in queue discharge at bottlenecks.

TABLE 9 Flows at Bottleneck Locations Downstream of Incidents

Date	Location	Time period	Flow per lane, vph	Non-incident queue discharge flows, vph	
				Peak period	Non-peak
11/29/01	70th St.-Lk. Murray Blvd.	15:06:00 – 15:15:00	1,579	2,127	
		15:15:30 – 15:27:00	1,666		
5/9/02	University Ave.	16:38:00 – 16:48:00	1,777		
7/2/02	Lomas Santa Fe Dr.	16:14:30 – 16:59:00	1,827	2,179	1,891
7/5/02	Barham Dr.	16:12:00 – 16:33:00	1,620		
		16:33:30 – 17:42:00	1,478		
		16:42:30 – 17:50:00	1,842		

3. Changes in average flow rates are frequently observed in both unimpeded discharge flow following incident clearance and at bottlenecks activated by incident queue discharge. In some cases these have obvious explanations (for instance, the activation of a bottleneck upstream), but in other cases they are unexplained, and may represent random variations.

5. CONCLUSIONS AND FUTURE DIRECTIONS

5.1 Conclusions

Daganzo's theory is an important contribution to the literature of traffic flow because it attempts to relate flow phenomena to a theory of driver motivation and behavior. Underlying behavioral assumptions are that aggressive drivers always act to maximize their speed, that speeds tend to equalize across the lanes in congested flow, and that when speeds equalize, aggressive drivers lose their motivation to maintain close headways. These assumptions lead to predictions regarding flow characteristics in and downstream of queues, behavior of drivers in the median lane in the transition to congested flow, existence of semi-congested states upstream of bottlenecks just prior to flow breakdown, and the possible existence of fast waves between semi-congested states and free-flow and semi-congested states and fully-congested states.

5.1.1 Flow Characteristics in and Downstream from Queues

The assumptions that speeds equalize across the lanes in congested flow and that aggressive drivers always act to maximize their speed leads to several predictions related to flow characteristics in and downstream from queues. These include (a) the most aggressive drivers will segregate themselves in the fastest lane so long as there are differences in speed among the lanes and will redistribute themselves when speeds are equalized; consequently, there will be a rapid redistribution of flow among the lanes when speeds are equalized across the lanes (or, conversely, when they cease to be equal), but not otherwise; (b) speeds will be equalized among the lanes in congested flow but speed differences will be reestablished following acceleration downstream of queues; and (c) there will be two distinct flow states – capacity flow and discharge flow – downstream of queues.

Conclusions related to these predictions are as follows:

- *The most aggressive drivers will segregate themselves in the fastest lane so long as there are differences in speed among the lanes and will redistribute themselves when speeds are equalized across the lanes (or, conversely, when they cease to by equal) but not otherwise*.

  This prediction was not verified. Redistribution of flow was sometimes observed to take place when speeds decreased in the transition to congested flow, but there was no equalization of speed.

- *Speeds will be equalized among the lanes in congested flow but speed differences will be reestablished following acceleration downstream of queues.*

  This prediction was not verified. In general, speeds were not equalized in congested flow. For the San Diego locations and the downstream end of the queue on the QEW, speeds in the median lane remained higher than those in other lanes in congested flow. On the other hand, at the Gardiner Expressway site and at some locations in the upstream portion of the QEW queue, speeds in the median lane were less than those in the shoulder lane. Also, speeds were sometimes equalized at locations that may have been downstream from the bottlenecks; however, these observations appear to have been the result of data biases or local conditions not considered in the theory.

- *There will be two distinct flow states – capacity flow and discharge flow – downstream of queues.*

  This prediction was not verified. No flow state transitions were observed downstream from queues, and no flow states meeting all the criteria for capacity flow or discharge flow were observed. Rather, at the Gardiner Expressway site, there was a tendency for vehicles to move back into the median lane gradually as they moved downstream from the bottleneck, as shown by Figures 35 and 36, and this pattern did not change over time during queue discharge.

5.1.2 Loss of Motivation

The assumption that when speeds equalize, aggressive drivers lose their motivation to maintain close headways, leads to the following prediction:

- *When speeds equalize, aggressive drivers lose their motivation to maintain close headways; this will be indicated by an increase in average time gaps in the passing lane.*

This prediction was not consistently verified. Increases in average median lane time gaps that corresponded with the transition to congested flow were observed consistently at one site and occasionally at a second site, but not elsewhere. Increases in average time gaps at flow breakdown appear to be related to reverse-lambda flow-occupancy patterns, but it is not clear how common these patterns are nor why they occur at some locations but not others.

5.1.3 Semi-congested State and Fast Backward Moving Shock

Both the Gardiner Expressway and SR-24 data support Daganzo's behavioral theory. The flow-density model implied by the empirical data (Figure 34) was notably similar to the model proposed by Daganzo. The existence of the semi-congested state (shown in Figure 14), and the observed lane changing behavior (Figure 35 and 36) were also consistent with the theory. The fast backward moving shock was also observed in three out of the nine days examined (See section 4.5.) There were only minor differences between Daganzo's descriptions and the observed empirical data. Namely, the vehicle speed in the passing lane dropped slightly below speed in the shoulder lane and vehicle speeds were the same in both lanes during the congested state.

5.1.4 Densities and Bottleneck Capacity

Also of note, the research has revealed some interesting relations between bottleneck capacity and the densities in the bottleneck's vicinity. The stalled vehicle at the California site eventually caused the density at the (original) bottleneck to return to that of free flow conditions. This state of affairs evidently triggered higher system capacities. These findings could have important implications for devising improved freeway traffic management schemes and further research is planned to explore this topic in the near future.

5.2 Future Directions

Daganzo's theory attempts to relate flow phenomena to a theory of driver motivation and behavior. This is an important because, ultimately, all traffic flow phenomena result from driver behavior. The research described here failed to confirm some predictions derived from the theory and has raised doubts about the validity of some of Daganzo's behavioral assumptions. These results create at least two points of departure for future research. The first is to build upon Daganzo's pioneering work by devising more realistic theories of driver behavior. The second is to provide a better empirical basis for behavioral traffic flow models.

Topics related to development of more realistic theories of driver behavior include:

1. There is a need for a more complete and accurate classification of drivers in terms of characteristics that affect macroscopic traffic flow. Specifically:

a. Is aggressiveness-passiveness (which is the basis for Daganzo's classification of drivers as rabbits or slugs) a meaningful scheme for classifying drivers? In particular, are there clusters of behavioral characteristics (for instance, high speed, close following, frequent lane changing, etc.) that are correlated with one another and that could serve to define aggressiveness or passiveness? Note that research into this topic could also have important implications for traffic safety.

b. Are there dimensions of driver behavior other than aggressiveness-passiveness that have a significant effect on traffic flow?

c. Are classification schemes involving discrete categories such as rabbits and slugs appropriate, since it is likely that distributions of driver characteristics are continuous?

2. A more complete theory of lane use behavior is needed. This, in turn, requires additional empirical research. Specifically:

   a. What are the overall patterns of lane use? How does relative flow in different lanes vary with the number of lanes, other site or section characteristics, the presence of entrances and exits, time of day, and average flow for the freeway as a whole? Is there a relationship between relative use of different lanes and bottleneck capacity (both maximum uncongested flow and queue discharge)? Exploratory research on this topic is currently underway at SDSU.

   b. Can lane use be described in terms of lane use strategies (for instance, stay in a particular lane except to pass, shift lanes to maximize speed, stay in the shoulder lane for short trips by switch to the inner or median lanes for longer ones, etc.)? How many such strategies can be identified? How prevalent are they in different driver populations? What effect, if any, do they have on traffic flow features such as bottleneck capacities?

Additional empirical research is needed to follow up on several of the findings of this study and thereby provide a better basis for behavioral traffic flow models. Topics that should be addressed include:

1. Daganzo's theory was intended to apply to locations where the median lane flow-occupancy or flow-density diagram has a reverse-lambda shape. Both the literature search and the study itself establish that these flow-concentration patterns sometimes occur, but not at all locations. Do locations with reverse-lambda flow-concentration patterns have a set of common characteristics that distinguish them from locations where these do not occur? Also, do locations with reverse-lambda flow-concentration patterns have consistently higher maximum uncongested flow rates in the median lane than other sites? Or, on the other hand, do they have consistently lower queue discharge rates?

2. Past literature suggests that speeds in congested flow are usually equalized across the lanes. In this study, speeds at locations near the downstream ends of queues were observed to be equalized (or the normal differences reversed) only in minimum-speed portions of jams. Is this commonly the case in congested flow at other sites? This research should be conducted at sites where speeds are measured directly rather than estimated from flow and occupancy.

3. At one of the study sites in San Diego, the location of the point of flow breakdown appeared to vary from day to day. How common is this phenomenon? What is the relative frequency of flow breakdown in different sections at such sites? preliminary research on this topic is underway at SDSU.

4. At one site, a stalled vehicle on the shoulder appeared to shift the point of dense queuing upstream and to increase the output of the bottleneck. Was this a random occurrence or is it a generally-occurring but previously unsuspected traffic flow phenomenon? If bottleneck capacity is affected by the exact location of the point at which dense queuing occurs, can this phenomenon be exploited as a traffic management tool to increase bottleneck capacity?

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APPENDIX

CHANGES IN FLOW IN TRANSITIONS TO CONGESTION AT MERGE BOTTLENECK SITES

TABLE 10 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 1, Manchester Avenue

	Flow			
Date	Before	After	Difference	Pct. Difference
4/23/01	2,922	2,091	-831	-28.4
4/24/01	2,589	1,914	-675	-26.1
4/25/01	2,600	1,819	-781	-30.0
4/26/01	2,646	1,680	-966	-36.5
4/27/01	2,577	2,088	-489	-19.0
4/30/01	2,857	2,226	-631	-22.1
5/1/01	2,834	2,040	-794	-28.0
5/3/01	2,730	1,896	-834	-30.5
5/7/01	2,623	2,118	-505	-19.2
Average	2,709	1,986	-723	-26.7

TABLE 11 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 1, Lomas Santa Fe Drive

	Flow			
Date	Before	After	Difference	Pct. Difference
4/23/01	2,862	2,457	-405	-14.2
4/24/01	2,703	2,097	-606	-22.4
4/25/01	2,737	1,977	-760	-27.8
4/26/01	2,771	2,130	-641	-23.1
4/27/01	2,743	2,472	-271	-9.9
4/30/01	2,977	2,412	-565	-19.0
5/1/01	2,800	2,482	-318	-11.4
5/3/01	2,811	2,368	-443	-15.8
5/7/01	2,863	2,562	-301	-10.5
Average	2,808	2,329	-479	-17.1

TABLE 12 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 1, Via de la Valle

	Flow			
Date	Before	After	Difference	Pct. Difference
4/23/01	2,715	2,358	-357	-13.2
4/24/01	2,654	2,328	-426	-15.5
4/25/01	2,689	2,280	-409	-15.2
4/26/01	2,611	2,124	-487	-18.7
4/27/01	2,720	2,502	-218	-8.0
4/30/01	2,880	2,556	-324	-11.3
5/1/01	2,749	2,375	-374	-13.6
5/3/01	2,897	2,425	-472	-16.3
5/7/01	2,749	2,514	-234	-8.5
Average	2,752	2,385	-367	-17.7

TABLE 13 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 2, Fletcher Parkway

	Flow			
Date	Before	After	Difference	Pct. Difference
10/15/01	2,539	2,217	-322	-12.7
10/16/01	2,757	2,318	-439	-15.9
10/17/01	2,418	2,075	-343	-14.2
18/18/01	2,573	2,192	-381	-14.8
10/19/01	2,549	2,130	-419	-16.4
10/22/01	2,739	2,113	-626	-22.9
10/24/01	2,607	2,160	-447	-17.1
10/25/01	2,517	2,177	-340	-13.5
10/26/01	2,590	2,340	-250	-9.7
Average	2,588	2,191	-396	-15.3

TABLE 14 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 2, 70th Street-Lake Murray Boulevard

	Flow			
Date	Before	After	Difference	Pct. Difference
10/15/01	2,628	2,538	-90	-3.4
10/16/01	3,011	2,601	-410	-13.6
10/17/01	2,557	2,115	-442	-17.3
18/18/01	2,801	2,412	-389	-13.9
10/19/01	2,425	2,444	+19	+0.8
10/22/01	2,617	2,150	-467	-17.8
10/24/01	2,911	2,501	-410	-14.1
10/25/01	2,774	2,514	-260	-9.4
10/26/01	2,778	2,520	-258	-9.3
Average	2,727	2,422	-300	-11.0

TABLE 15 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 3, Nobel Drive

	Flow			
Date	Before	After	Difference	Pct. Difference
10/16/01	2,436	2,091	-344	-14.1
10/17/01	2,234	2,074	-160	-7.2
10/18/01	2,403	2,074	-329	-13.7
10/19/01	2,328	2,137	-191	-8.2
10/22/01	2,366	2,142	-224	-9.5
10/23/01	2,217	2,144	-73	-3.3
10/24/01	2,149	2,280	+131	+6.1
10/25/01	2,323	2,133	-191	-8.2
10/26/01	2,143	2,177	+34	+1.6
10/29/01	2,275	2,149	-126	-5.5
Average	2,287	2,140	-147	-6.4

TABLE 16 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 3, Governor Drive

Date	Flow		Difference	Pct. Difference
	Before	After		
10/16/01	2,553	2,274	-278	-10.9
10/17/01	2,382	2,366	-16	-0.7
10/18/01	2,880	2,306	-571	-19.8
10/19/01	2,366	2,354	-12	-0.5
10/22/01	2,562	2,313	-248	-9.7
10/23/01	2,336	2,451	+115	+4.9
10/24/01	2,583	2,509	-75	-2.9
10/25/01	2,409	2,236	-173	-7.2
10/26/01	2,400	2,280	-120	-5.0
10/29/01	2,534	2,400	-134	-5.3
Average	2,501	2,349	-151	-6.1

TABLE 17 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 4, Via de la Valle

Date	Flow		Difference	Pct. Difference
	Before	After		
10/16/01	1,872	1,842	-30	-1.6
10/17/01	1,764	1,746	-18	-1.0
10/18/01	2,046	1,734	-312	-15.2
10/19/01	1,767	1,624	-144	-8.1
10/22/01	1,392	1,762	370	+26.6
10/23/01	1,848	1,824	-24	-1.3
10/24/01	1,926	1,866	-60	-3.1
10/25/01	1,764	1,926	+162	+9.2
10/26/01	1,932	1,770	-162	-8.4
10/29/01	1,884	1,956	+72	+3.8
Average	1,820	1,805	-15	-0.8

TABLE 18 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 4, Lomas Santa Fe Drive

Date	Flow		Difference	Pct. Difference
	Before	After		
10/16/01	2,622	1,992	-630	-24.0
10/17/01	2,538	2,148	-390	-15.4
10/18/01	2,346	2,280	-66	-2.8
10/19/01	2,316	2,370	+54	+2.3
10/22/01	2,190	2,124	-66	-3.0
10/23/01	2,370	2,190	-180	-7.6
10/24/01	2,382	2,370	-12	-0.5
10/25/01	2,208	2,292	+84	+3.8
10/26/01	2,760	2,202	-558	-20.2
10/29/01	2,574	2,280	-294	-11.4
Average	2,431	2,225	-206	-8.5

TABLE 19 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 5, Detector Station 51

Date	Flow		Difference	Pct. Difference
	Before	After		
9/13/99	2,415	2,130	-285	-11.8
9/15/99	2,610	2,070	-540	-20.7
9/16/99	2,483	2,250	-233	-9.4
9/17/99	2,565	2,063	-503	-19.6
9/20/99	2,244	2,268	+24	+1.1
9/23/99	2,280	2,258	-23	-1.0
9/24/99	2,543	2,325	-218	-8.6
Average	2,448	2,195	-254	-10.4

TABLE 20 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 5, Detector Station 52

	Flow			
Date	Before	After	Difference	Pct. Difference
9/13/99	2,355	2,258	-98	-4.1
9/15/99	2,568	2,376	-192	-7.5
9/16/99	2,412	2,340	-72	-3.0
9/17/99	2,532	2,322	-210	-8.3
9/20/99	2,280	2,358	+78	+3.4
9/23/99	2,088	2,310	+222	+10.6
9/24/99	2,412	2,436	+24	+1.0
Average	2,378	2,343	-35	-1.5

TABLE 21 Comparison of Flow in Median Lane Immediately Before and After Flow Drop, Site 5, Detector Station 53

	Flow			
Date	Before	After	Difference	Pct. Difference
9/13/99	2,280	2,280	0	0.0
9/15/99	2,388	2,328	-60	-2.5
9/16/99	2,382	2,202	-180	-7.6
9/17/99	2,100	1,926	-174	-8.3
9/20/99	2,190	2,268	+78	+3.6
9/23/99	1,950	2,250	+300	+15.4
9/24/99	2,250	2,310	+60	+2.7
Average	2,220	2,223	+3	+0.2

TABLE 22 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 1, Manchester Avenue

	Flow			
Date	Before	After	Difference	Pct. Difference
4/23/01	2,123	1,872	-251	-11.8
4/24/01	2,177	1,720	-457	-21.0
4/25/01	2,150	1,609	-541	-25.2
4/26/01	2,083	1,416	-667	-32.0
4/27/01	2,060	1,934	-126	-6.1
4/30/01	2,051	1,971	-80	-3.9
5/1/01	2,110	1,863	-247	-11.7
5/3/01	2,192	1,661	-431	-19.7
5/7/01	2,076	1,917	-159	-7.7
Average	2,114	1,785	-329	-15.6

TABLE 23 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 1, Lomas Santa Fe Drive

	Flow			
Date	Before	After	Difference	Pct. Difference
4/23/01	2,136	2,116	-20	-0.9
4/24/01	2,219	1,992	-227	-10.2
4/25/01	2,199	1,890	-309	-14.1
4/26/01	2,061	1,883	-178	-8.6
4/27/01	1,946	2,072	+126	+6.5
4/30/01	2,121	2,084	-37	-1.7
5/1/01	2,016	2,059	+43	+2.1
5/3/01	2,316	2,035	-281	-12.1
5/7/01	2,207	2,242	+35	+1.6
Average	2,136	2,041	-94	-4.4

TABLE 24 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 1, Via de la Valle

Date	Flow Before	Flow After	Difference	Pct. Difference
4/23/01	2,074	2,059	-15	-0.7
4/24/01	2,220	2,099	-121	-5.5
4/25/01	2,119	2,005	-114	-5.4
4/26/01	1,914	1,979	+65	+3.4
4/27/01	1,941	2,045	+104	+5.4
4/30/01	2,081	2,099	+18	+0.9
5/1/01	2,099	2,005	-94	-4.5
5/3/01	2,237	2,111	-126	-5.6
5/7/01	2,273	2,177	-96	-4.2
Average	2,106	2,064	-42	-2.0

TABLE 25 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 2, Fletcher Parkway

Date	Flow Before	Flow After	Difference	Pct. Difference
10/15/01	2,087	1,950	-137	-6.6
10/16/01	2,152	2,048	-104	-4.8
10/17/01	2,005	1,816	-189	-9.4
18/18/01	2,038	2,117	+79	+3.9
10/19/01	1,990	1,922	-68	-3.4
10/22/01	2,100	1,911	-189	-9.0
10/24/01	2,140	1,960	-180	-8.4
10/25/01	2,067	1,966	-101	-4.9
10/26/01	2,124	2,072	-52	-2.4
Average	2,078	1,974	-105	-5.0

TABLE 26 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 2, 70th Street-Lake Murray Boulevard

	Flow			
Date	Before	After	Difference	Pct. Difference
10/15/01	2,099	2,175	+76	+3.6
10/16/01	2,306	2,233	-73	-3.2
10/17/01	2,127	1,922	-205	-9.6
18/18/01	2,159	2,168	+9	+0.4
10/19/01	1,756	1,980	+224	+12.8
10/22/01	2,051	1,931	-120	-5.9
10/24/01	2,279	2,168	-111	-4.9
10/25/01	2,192	2,183	-9	-0.4
10/26/01	2,250	2,232	-18	-0.8
Average	2,183	2,127	-56	-2.6

TABLE 27 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 3, Nobel Drive

	Flow			
Date	Before	After	Difference	Pct. Difference
10/16/01	2,240	1,968	-272	-12.1
10/17/01	2,217	2,053	-164	-7.4
10/18/01	2,318	1,971	-346	-14.9
10/19/01	2,257	2,044	-213	-9.4
10/22/01	2,291	2,148	-142	-6.2
10/23/01	2,258	2,078	-180	-8.0
10/24/01	2,247	2,161	-86	-3.8
10/25/01	2,248	2,003	-245	-10.9
10/26/01	2,176	2,153	-23	-1.1
10/29/01	2,268	2,099	-170	-7.5
Average	2,252	2,068	-184	-8.2

TABLE 28 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 3, Governor Drive

	Flow			
Date	Before	After	Difference	Pct. Difference
10/16/01	2,220	2,089	-131	-5.9
10/17/01	2,193	2,141	-52	-2.4
10/18/01	2,482	2,164	-318	-12.8
10/19/01	2,166	2,170	+4	+0.2
10/22/01	2,242	2,113	-219	-5.7
10/23/01	2,172	2,269	+96	+4.4
10/24/01	2,282	2,250	-32	-1.4
10/25/01	2,241	2,107	-143	-6.0
10/26/01	2,190	2,108	-82	-3.7
10/29/01	2,284	2,256	-27	-1.2
Average	2,247	2,167	-80	-3.6

TABLE 29 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 4, Via de la Valle

	Flow			
Date	Before	After	Difference	Pct. Difference
10/16/01	1,949	1,646	-303	-15.6
10/17/01	1,896	1,538	-359	-18.9
10/18/01	1,947	1,670	-278	-1.3
10/19/01	1,874	1,466	-407	-21.7
10/22/01	1,662	1,554	-108	-6.5
10/23/01	1,925	1,683	-242	-12.5
10/24/01	2,010	1,716	-294	-14.6
10/25/01	1,904	1,785	-119	-6.2
10/26/01	1,994	1644	-350	-17.5
10/29/01	1,967	1,793	-174	-8.8
Average	1,913	1,649	-263	-13.8

TABLE 30 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 4, Lomas Santa Fe Drive

	Flow			
Date	Before	After	Difference	Pct. Difference
10/16/01	2,117	1,689	-428	-20.2
10/17/01	1,980	1,796	-185	-9.3
10/18/01	1,937	1,778	-159	-8.2
10/19/01	1,923	1,901	-23	-1.2
10/22/01	1,787	1,730	-57	-3.2
10/23/01	1,923	1,809	-114	-5.9
10/24/01	1,899	1,992	+93	+4.9
10/25/01	1,895	1,871	-24	-1.3
10/26/01	2,106	1,820	-287	-13.6
10/29/01	2,025	1,862	-164	-8.1
Average	1,959	1,824	-135	-6.9

TABLE 31 Comparison of Flow per Lane Immediately Before and After Flow Drop in Left Lane, Site 5, Detector Station 51

	Flow			
Date	Before	After	Difference	Pct. Difference
9/13/99	2,223	2,055	-168	-7.5
9/15/99	2,290	2,018	-273	-11.9
9/16/99	2,210	2,135	-75	-3.4
9/17/99	2,290	1,975	-315	-13.8
9/20/99	2,148	2,184	+36	+1.7
9/23/99	2,113	2,190	+78	+3.7
9/24/99	2,328	2,218	-110	-4.7
Average	2,229	2,111	-118	-5.3

TABLE 32 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 5, Detector Station 52

	Flow			
Date	Before	After	Difference	Pct. Difference
9/13/99	2,193	2,125	-68	-3.1
9/15/99	2,270	2,150	-120	-5.3
9/16/99	2,152	2,122	-30	-1.4
9/17/99	2,234	2,116	-118	-5.3
9/20/99	2,138	2,172	+34	+1.6
9/23/99	1,904	2,126	+222	+11.7
9/24/99	2,162	2,208	+46	+2.1
Average	2,150	2,146	-5	-0.2

TABLE 33 Comparison of Flow per Lane Immediately Before and After Flow Drop in Median Lane, Site 5, Detector Station 53

	Flow			
Date	Before	After	Difference	Pct. Difference
9/13/99	2,120	2,168	+48	+2.3
9/15/99	2,240	2,214	-26	-1.2
9/16/99	2,184	2,086	-98	-4.5
9/17/99	2,106	1,842	-264	-12.5
9/20/99	2,114	2,168	+54	+2.6
9/23/99	1,886	2,120	+234	+12.4
9/24/99	2,132	2,200	+68	+3.2
Average	2,112	2,114	+2	+0.1

TABLE 34 Flow per Lane Downstream from On-Ramps Immediately Before and After Median Lane Flow Drop, Site 1, Manchester Avenue

	Flow			
Date	Before	After	Difference	Pct. Difference
4/23/01	2,352	2,116	-236	-10.0
4/24/01	2,416	1,963	-453	-18.8
4/25/01	2,393	1,851	-542	-22.6
4/30/01	2,307	2,211	-96	-4.2
5/1/01	2,357	2,105	-252	-10.7
5/3/01	2,438	1,989	-449	-18.4
5/7/01	2,329	2,156	-173	-7.4
Average	2,370	2,056	-314	-13.2

TABLE 35 Flow per Lane Downstream from On-Ramps Immediately Before and After Median Lane Flow Drop, Site 1, Lomas Santa Fe Drive

	Flow			
Date	Before	After	Difference	Pct. Difference
4/23/01	2,187	2,209	+22	+1.0
4/24/01	2,347	2,113	-234	-11.1
4/25/01	2,287	2,113	-174	-8.2
4/30/01	2,180	2,184	+4	+0.2
5/1/01	2,074	2,152	+78	+3.6
5/3/01	2,397	2,139	-258	-12.1
5/7/01	2,290	2,340	+50	+2.1
Average	2,252	2,179	-73	-3.5

TABLE 36 Flow per Lane Downstream from On-Ramps Immediately Before and After Median Lane Flow Drop, Site 2, Fletcher Parkway

Date	Flow		Difference	Pct. Difference
	Before	After		
10/15/01	2,302	2,159	-143	-6.2
10/16/01	2,023	1,860	-163	-8.1
10/17/01	2,216	2,075	-141	-6.4
18/18/01	2,236	2,243	+7	+0.3
10/19/01	2,181	2,171	-10	-0.5
10/22/01	2,321	2,137	-184	-7.9
10/24/01	2,365	2,212	-153	-6.5
10/25/01	2,277	2,206	-71	-3.1
10/26/01	2,355	2,307	-48	-2.0
Average	2,253	2,152	-101	-4.5

TABLE 37 Flow per Lane Downstream from On-Ramps Immediately Before and After Median Lane Flow Drop, Site 4, Via de la Valle

Date	Flow		Difference	Pct. Difference
	Before	After		
10/16/01	2,069	1,754	-315	-15.2
10/17/01	2,030	1,631	-399	-19.7
10/18/01	2,087	1,791	-296	-14.2
10/19/01	1,931	1,565	-366	-18.9
10/22/01	1,737	1,655	-82	-4.7
10/23/01	2,034	1,796	-239	-11.7
10/24/01	2,148	1,832	-317	-14.7
10/25/01	1,982	1,898	-84	-4.2
10/26/01	2,076	1,742	-335	-16.1
10/29/01	2,072	1,883	-189	-9.1
Average	2,016	1,754	-262	-13.0