

**A congestion mechanism for uphill expressways, Part I:
the shoulder lane “release valve”**

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Abstract

A mechanism is unveiled by which congestion forms and persists near the base of an uphill expressway segment, causing significant reductions in output flow. The traffic condition in the expressway’s shoulder lane is key to the mechanism. When shoulder-lane flow was low, drivers maneuvered around speed disturbances that periodically arose in the median lane. The shoulder lane accommodated high rates of vehicle migrations, thus acting as a “release valve” for the excess accumulation created by the speed disturbances. The release valve failed only when demand increased later in the rush. The resulting higher flows in the shoulder lane impeded drivers’ attempts to maneuver around the median-lane speed disturbances that occurred thereafter. These attempts disrupted traffic and spread the excess accumulation laterally across all lanes. When this queue filled the approach to the hill, vehicles arrived to its base at low speeds. This impeded vehicle ascent; output flow dropped by about 10%; and this state of affairs persisted for the remainder of the rush.

The more conspicuous details of this mechanism were observed in loop detector data measured over many days at the site, and are consistent with observations previously made at other sites. The more subtle details became visible by examining thousands of vehicle trajectories extracted from a series of eleven roadside video cameras. Many of the subtleties are compatible with an existing theory of multi-lane traffic. All of this suggests that the present findings can be generalized to other uphill expressway segments. Practical implications are discussed.

1. Introduction

Examined here is a stretch of 3-lane expressway where a downhill segment is followed by a steep incline of extended length. Though it is free of ramp junctions, queues that engulf all three lanes can form on the site and cause its output flows to diminish. Loop detector data indicate that this state of affairs is reproducible across days. Detailed video data obtained for a single day from eleven roadside cameras unveil the mechanism behind both the congestion formation and the ensuing reduction in output flow.

We find that speed disturbances (SDs) initially forming in a single lane, along with the vehicular lane changing that these SDs induce, are elements of the mechanism. This is reassuring: the finding reinforces qualitative details previously reported of similar sites (Koshi et al., 1992). Moreover, the video data unveil added detail, such that the site’s congestion and flow-drop mechanism can now be more fully explained.

The explanation begins with phenomena observed over a period of about 30 minutes just before persistent congestion took hold at the site. This period was marked by a sequence of SDs that sporadically formed in the median lane along the incline, causing vehicles to slow temporarily (and output flows in the median lane to diminish). The first few instances of this arose while traffic was in an uncongested, “two-pipe” regime (Daganzo, 2002), with high vehicle speeds in the median and center lanes, and slightly lower speeds in the shoulder lane. Conditions at this time were further marked by uneven distributions of vehicles in the three lanes: only about 20% of the expressway’s total flow was traveling in the shoulder lane while almost 50% used the median lane. (Flows averaged around 840 vph and 2100 vph in the shoulder and median lanes, respectively.) Many drivers avoided these early-occurring SDs soon after they formed by migrating out of the median lane. A number of these drivers maneuvered all the way to the shoulder lane, and the migrations were aided by many other drivers who moved from the center lane to the shoulder lane.

This maneuvering was beneficial; it enabled much of the excess accumulation to clear from the median lane. In the lower density wake just downstream of each SD, uphill vehicular speeds recovered to their prior values. Key to this was the low demand for the shoulder lane: the beneficial lane changing was facilitated by large gaps between shoulder-lane vehicles. In this sense, the lane acted as a “release valve.” Traffic eventually become queued in all lanes – with persistent reductions in output flow – when this release valve

failed; i.e. when demand rose later in the rush and forced more vehicles to travel in the shoulder lane. (At this later time, shoulder-lane flows exceeded 1200 vph.)

In the midst of this high demand, another SD arose (again in the median lane, but almost immediately affecting the center lane as well). The rate of vehicular lane-changing (LC) maneuvers was drastically reduced, evidently due to lack of space in the shoulder lane. In the comparatively higher density wake just downstream of this SD, ascending vehicles were unable to accelerate quickly. A second SD formed on the incline immediately thereafter as the front of the first SD propagated beyond the base of the hill. LC maneuvers now became disruptive, much as described in previous empirical studies, e.g. (Wang and Coifman, 2008). These disruptions caused the queue to spread laterally, and vehicle speeds in this queue soon became nearly equal across lanes. For a time, very little LC ensued within and around the queue and its flows were fairly high (on average about 1760 vph per lane). The queue therefore expanded longitudinally very slowly.

The real damage occurred when the next sequence of SDs arose in the midst of this congested, single-pipe traffic. The LC induced by these later-occurring SDs severely disrupted and diminished flows, causing the queue to expand rapidly. Once it filled the downhill approach, vehicles thereafter arrived to the base of the incline at constrained (slow) speeds, which impeded traffic's ascent. The resulting reduction in the site's output flow (which dropped to an average of about 1560 vph per lane), persisted thereafter.

Much of the above mechanism is described by a theory of multi-lane traffic that was specifically developed to explain puzzling phenomena observed at bottlenecks of various geometries (Daganzo, 2002). This too is reassuring: it, together with the earlier observations cited above, suggests our findings are general enough to hold for other uphill bottlenecks. The earlier observations and the theory are briefly described in the following section. The site and its data are described in Section 3. Empirical evidence for the congestion and flow-drop mechanism is furnished in Section 4. Interpretation of the evidence and its compatibility with the above-cited traffic theory is discussed in Section 5. Practical implications of our findings, including ideas for managing the mechanism to favorable ends, are discussed in Section 6.

2. Literature Review

Koshi et al. (1992) reports that two ingredients are necessary for bottleneck activation on a hill: 1) a series of long platoons in the median lane, and 2) a slight speed drop by a vehicle in one of these platoons. The result is a SD that increases in amplitude as it propagates upstream (downhill), and that causes vehicles at the bottom of the hill to decelerate abruptly. Median lane vehicles reportedly react by changing lanes, causing disturbances in the shoulder lane, and queuing across all lanes. Furuichi et al. (2003) supports this finding, adding that severe congestion on hills occurs on holiday weekends when traffic demand consists primarily of passenger cars with few heavy vehicles.

Other studies describe deleterious effects of LC. For example, Cassidy and Rudjanakanoknad (2005) found that LC is part of the mechanism that caused congestion to form at a merge bottleneck. Studies have also concluded that LC can cause additional delay in queues (Coifman et al., 2006), and are a source of oscillations in speed and flow (Wang and Coifman, 2008; Mauch and Cassidy, 2002; Ahn and Cassidy, 2007). By modeling an LC maneuver as a moving bottleneck with bounded acceleration, Laval and Daganzo (2006) showed that LC introduces voids in traffic flow, thus causing the capacity of fixed bottlenecks to drop. In addition to providing an excellent literature review, Duret et al. (2008) measures the impact of LC on vehicle platoons.

Our interpretation of the shoulder lane as a release valve has been presaged by others to some degree. For example, Mika et al. (1969) also studied a 3-lane expressway, and concluded that the shoulder lane behaves differently from the center and median lanes. Tadaki et al. (2002) reports empirical differences in velocity and flow across lanes on a 2-lane expressway segment.

Our empirical findings can be explained using a theory of multi-lane traffic proposed by Daganzo (2002). The theory assumes the existence of two driver types: ‘slugs’ that travel with a maximum speed v_f ; and ‘rabbits’ that travel with a maximum speed $V_f > v_f$. According to this theory, regime changes (between multi-pipe and single-pipe flow) can have forward moving or backward moving interfaces. This feature enables us to describe how a single-pipe queue can become fixed to the base of a hill, rather than to continue propagating upstream.

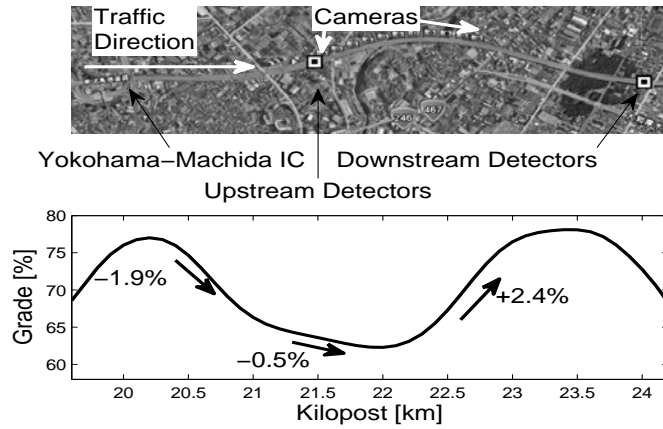


Figure 1: Tomei Expressway study site. There are three lanes of traffic moving from left to right. One (upstream) set of loop detectors is positioned just behind the first camera at KP 21.5 (kilopost 21.5), and a second (downstream) set of loop detectors is positioned at KP 24.0 (beyond the uphill grade). A series of eleven cameras are placed about 120 m apart, on the left-side of the road facing forward from KP 21.57 to KP 22.73.

3. The Site and its Data

The site is a stretch of expressway near Tokyo with three lanes and no ramps, as shown in Figure 1. A downward slope of about 2 km in length approaches a 2.4% incline. The site is instrumented with a series of eleven video cameras and two sets of loop detectors. The approach from the Yokohama-Machida Interchange to the upstream detectors (located at KP 21.5) is about 1.8 km in length. Camera surveillance extends from about KP 21.6 to KP 22.9. The downstream detectors are located beyond the incline, at KP 24.0, on a downhill section. From six months of loop detector data, we found 14 days in which congestion persisted at the site, in the absence of spillovers from downstream queues.

Vehicle trajectories were extracted from videos taken during the onset of congestion on one day. These videos were synchronized by detecting simultaneous events in the overlapping field of view of adjacent cameras. A software tool was developed to facilitate semi-automatic identification of vehicles in one camera and reidentification at control points in all other cameras. Some passenger cars were occluded by heavy trucks at certain camera locations. In each of these cases, a best guess for vehicle position was made by a human supervisor. The result is an internally consistent set of 2284 vehicle trajectories over the crucial 30 minutes up to and including the onset of persistent congestion.

4. Empirical Evidence

The data presented below unveil the mechanism of congestion formation and output flow reduction at the site, including the role played by the shoulder lane. Certain clues to this mechanism are unveiled in the macroscopic loop detector data that were collected over several months, as described in Section 4.1. Further details are uncovered by close inspection of vehicle trajectories as explained in Section 4.2.

4.1. Chronic Macroscopic Features

Data from the site's two loop detector stations reveal an interesting, time-varying pattern in traffic that is reproducible across days. We will unveil this pattern by examining data in each lane.

Figures 2a and 2b present average speed versus flow data measured by the upstream and downstream detectors, respectively. Each data point is a

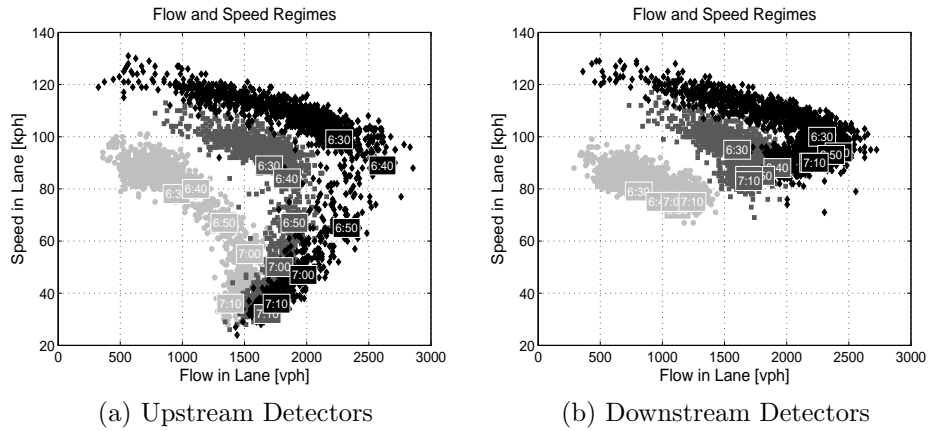


Figure 2: Time course of congestion. Speeds versus flows are plotted with upstream detector measurements (KP 21.5) on the left, and downstream detector measurements (KP 24.0) on the right. Light-gray circles, medium-gray squares, and black diamonds are 5-minute aggregated loop detector data for shoulder, center, and median lanes, respectively. Shown here are several hours of data from each of the 14 days when persistent congestion was observed in all three travel lanes at the upstream detectors, while absent at the downstream detectors. On the day for which video data are available, time-of-day tags from 6:30 to 7:10 am are plotted at 10-minute intervals. Each tag shows the measured traffic state at the corresponding 5-minute interval, and the timeseries of tags illustrates the time course of traffic on that day.

five-minute aggregated measurement on one of the 14 days when congestion persisted at the site. Time-of-day tags are shown (in ten-minute increments) for data points on one of these days (December 23rd, 2005). The time course that these labels reveal for that day is qualitatively the same for the other days as well.

Visual inspection of Figure 2a shows that the earliest portion of a rush (at around 6:30 am) was characterized by multi-pipe, uncongested traffic at the upstream end of the site. Average speeds were markedly different in each lane; these ranged from about 100 kph in the median lane to about 80 kph in the shoulder lane. Flows at that time were similarly unbalanced across lanes. They were especially high in the median lane, rising from around 2200 vph at 6:30 to about 2500 vph at 6:40. The median lane thus carried almost 50% of the expressway's total flow, and headways in that lane averaged below 1.5 s. Flows in the shoulder lane, on the other hand, were low at this time (around 1000 vph), and constituted only about 20% of the total flow.

As the rush wore on, however, traffic gradually transformed to a single-pipe, congested state with speeds and flows that were much more balanced across lanes. By 7:10, speeds in all lanes were about 40 kph (with the low speed indicating the presence of congestion); and flows ranged only from about 1800 vph in the median to about 1400 vph in the shoulder lane. Thus, the latter lane eventually carried about 30% of the expressway's total flow with vehicle headways in that lane dropping to an average of about 2.5 s. The shoulder lane's increased utilization (which was repeated on all days observed) turns out to be a key part of the congestion mechanism, as we shall see in the following sections.

The time course of the traffic measured at the downstream detectors (near KP 24) also provides clues to the mechanism. Figure 2b reveals that traffic was initially in a multi-pipe, uncongested state as it was upstream. However, traffic at the downstream location never exhibited a single-pipe regime: once having passed through the congestion that had formed later in the rush, drivers evidently re-distributed themselves across the three expressway lanes. Upon reaching the downstream detector, speeds and flows were highest in the median lane and lowest in the shoulder lane. The significance of this pattern is part of what will be examined next.

4.2. Microscopic Inspection

Displayed in Figure 3 is the velocity field for each lane of the expressway segment during the onset of congestion on one day (December 23rd, 2005).

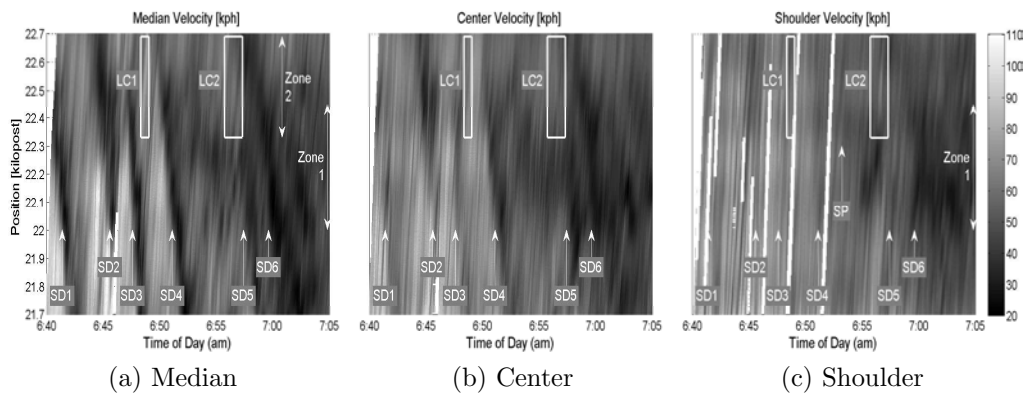


Figure 3: Speed Disturbances. Using trajectory data, speeds are calculated as per generalized definitions (Edie, 1963) using a moving time-space window of 6.4 s in duration and 40 m in extent. Regions devoid of vehicle trajectories appear as white streaks in the shoulder lane. Voids also appear in the median and shoulder lanes after SD2. Regions of high and low speed are colored light and dark, respectively. SDs are numbered, with arrows pointing to space-time coordinates of interest. The first emergence of a single-pipe, congested regime is labeled SP in (c). Zones 1 and 2 are the spatial regions extending from KP 20.0 to KP 22.45, and from KP 22.33 to KP 22.69, respectively. Rectangles LC1 and LC2 demark regions of high LC activity in zone 2.

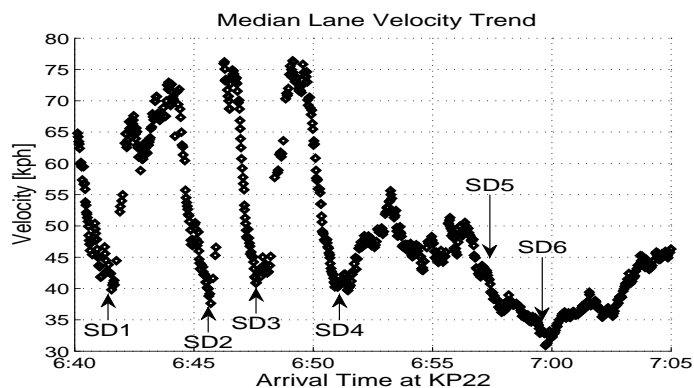


Figure 4: The average speeds of vehicles that stay in the median lane (and do not change lanes) as they traverse zone 1 (KP 22.0 to KP 22.45) are displayed. At 6:52:00 there is a partial recovery from SD4, but speeds remain relatively low. The arrival time of SDs at KP 22 are numbered.

At a glance, this figure summarizes the narrative presented in Section 1. Two spatial zones are defined to illustrate key traffic features. Zone 1 (between KP 22.0 and KP 22.45) begins at the bottom of the sag and extends 450 m downstream, encompassing the area in which a single-pipe regime first appears. Zone 2 (between KP 22.33 and KP 22.69) overlaps the downstream end of zone 1, and extends for 360 m. Labels LC1 and LC2 identify periods of time when high LC activity into the median lane is observed in spatial zone 2. These spatio-temporal regions are bounded by rectangles in Figure 3. Prominent speed disturbances (appearing dark) are labeled SD 1 through 6, with arrows indicating the point in time when a vehicle would encounter the SD at KP 22. Before 6:52 am, vehicles approach the sag at higher speeds in the median, and lower speeds in the shoulder, as indicated by the shades of gray. Shoulder lane traffic during this interval ascends the hill at a relatively consistent speed of 70 kph. Furthermore, very large headways are present between vehicles in the shoulder lane (shown by white streaks in Figure 3c).

We first consider SDs that occurred during the early part of the rush when traffic existed in a multi-pipe regime. Although Figure 3 begins at 6:40 am, several SDs in the median lane occurred prior to SD1 (not shown). The final three of these SDs are labeled 1 through 3 in Figure 3. These SDs share many attributes, including a time coincidence of LC maneuvers, reductions in vehicular accumulation in zone 1, and increases in outflow measured from

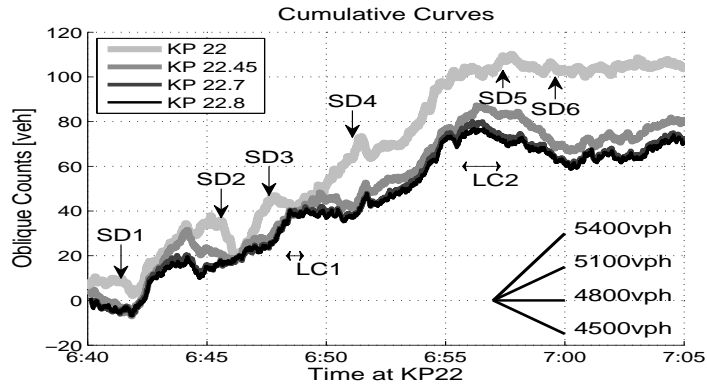


Figure 5: Cumulative oblique counts of vehicles at the following kiloposts: KP 22, KP 22.45, KP 22.7, and KP 22.8 are plotted in the usual way, (Cassidy and Windover, 1995). Note that plots for the downstream positions (KP 22.7 and KP 22.8) are almost exactly coincident. Before 6:50:00, the curves show intermittent excess accumulation resulting from speed disturbances (see Figure 4). The excess accumulation in zone 1 (KP 22 to KP 22.45) is not sustained until after 6:50:00. A persistent drop in outflow begins at about 6:57:00, coincident with the surge of LC into the median lane in zone 2, labeled LC2.

KP 22.45. Figure 4 plots the average speeds at which vehicles travel through zone 1 (from KP 22 to KP 22.45), and indicates (with arrows) SD arrival times at KP 22. As an SD approaches KP 22, average speeds fall off gradually. As an SD propagates beyond KP 22, arriving vehicles are no longer impeded by an SD in the zone, and average speeds quickly recover to about 75 kph. This pattern is observed for all SDs up to and including SD3.

Figure 5 plots cumulative vehicle count at KP 22, KP 22.45, KP 22.7 and KP 22.8, and the oblique curves are shifted with respect to time measured at KP 22. The vertical separation between curves indicates excess accumulation with respect to the prevailing shoulder-lane speed (about 70 kph). As expected, the arrivals of SD1, SD2, and SD3 at KP 22 coincide with high excess accumulations in zone 1, and these accumulations are promptly discharged. Of note, SD1 and SD3 occur immediately before, or during an increase in downstream outflow (and coincident with the migrations to the shoulder lane). The only anomaly is SD2, which lacks an increase in outflow. This is easily explained by a lack of demand (see Figure 3).

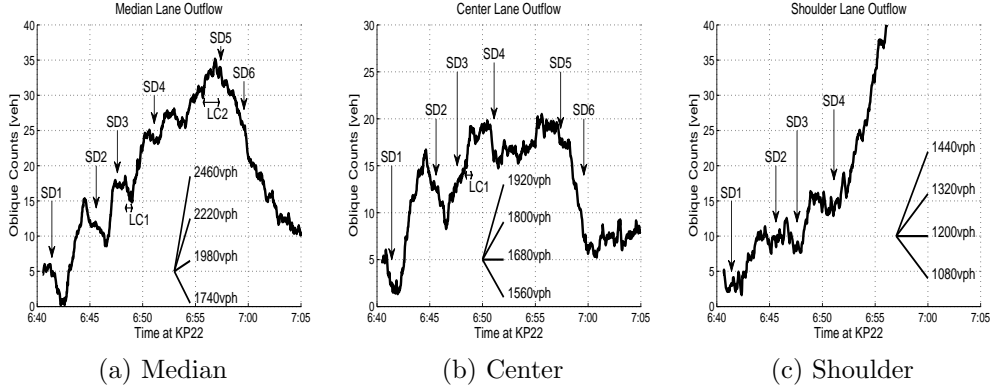


Figure 6: Outflow Recoveries. An oblique count of vehicle arrivals in each lane is measured at KP 22.45, and displayed so that instantaneous flow is related to the slope of the curve. The time axis is shifted to match that in Figure 5. (a) Median lane outflow exhibits recoveries for SD1 and SD3 at 6:42:43 and 6:49:01, respectively. (b) Center lane outflow exhibits recoveries for SD1 and SD3 at 6:42:10 and 6:48:30, respectively. (c) Shoulder lane outflow exhibits recoveries for SD1 and SD3 at 6:42:22 and 6:48:00, respectively. Between 6:52 and 6:57 am, shoulder lane outflow averages about 1560 vph; it then drops to about 1440 vph for the remainder of the rush.

We further illustrate the component flow, lane-by-lane, at KP 22.45 in Figure 6. Note how the outflow recoveries for SD1 and SD3 begin about 20 s to one minute sooner in the center and shoulder lanes, than in the median lane. In addition, although the median lane suffered the largest flow fluctuations, that lane only accounted for about half of the total outflow increase during the outflow recovery periods.

Figure 7 presents a cumulative count of LC maneuvers i) out of the median lane (zone 1), ii) into the median lane (zone 2), and iii) into the shoulder lane (zone 1). The highest rates of LC maneuvers out of the median lane and into the shoulder lane in zone 1 coincide with SD1, SD2, and SD3, and immediately precede the outflow recoveries noted above. Interestingly, many drivers return to the median lane after passing the SDs. This tendency is observed in zone 2 during time interval LC1, as shown in Figure 7. Although not shown, this tendency is also observed in other parts of the study site for other SDs.

We observe a transition in shoulder lane flow at about 6:52 am. This

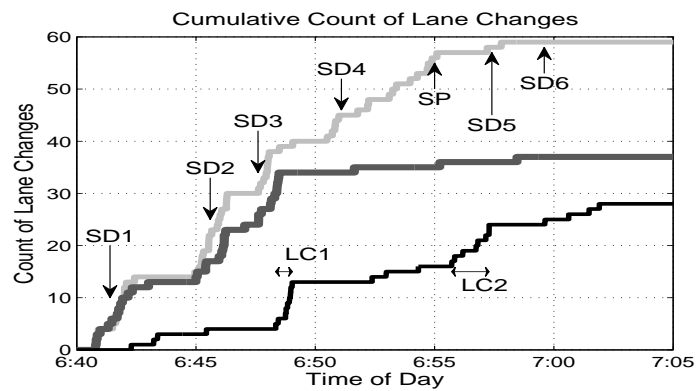
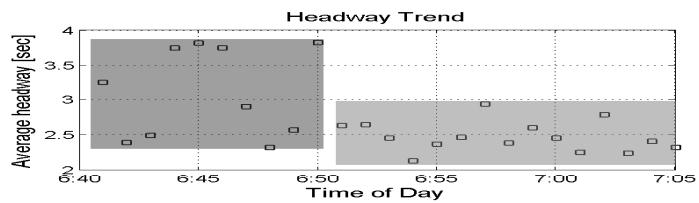
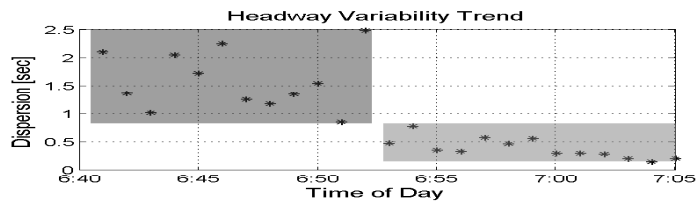


Figure 7: Cumulative Count of Lane Changes. The light-gray, medium-gray, and black lines plot cumulative counts of lane changes for vehicles *entering* the shoulder lane in zone 1 (KP 22.0 to KP 22.45), *exiting* the median lane in zone 1, and *entering* the median lane in zone 2 (KP 22.33 to KP 22.69), respectively. High concentrations of lane changes out of the median and into the shoulder are marked with the labels SD1, SD2, and SD3, respectively. After 6:49:00 there are very few lane-changes out of the median lane. The highest rates of lane-changing into the shoulder happen before 6:52:00. There are two periods of very high concentrations of lane changes into the median in zone 2, labeled LC1, and LC2.



(a) Average Headway



(b) Headway Dispersion

Figure 8: The headways of vehicles that pass through the shoulder lane at KP 22.2 (in the middle of zone 1) are measured and grouped into one-minute bins. Before 6:52:00, headways are highly variable—having both large and small values. After 6:50:00, average headway stays below 3 s, and large headway no longer occur after 6:52:00 as evidenced by the low variability. (Dispersion was calculated as headway variance divided by headway mean.) The trend is identical for the entirety of zone 1 (KP 22 to KP 22.45).

change, in which large headways become unavailable, is illustrated in Figure 8. Before 6:52 am, average headways exhibit high variability as shown in Figure 8b. After 6:52 am, average headways in the shoulder lane stay below 3 s (flow stays above 1200 vph), with low variability. The trend in shoulder lane headways at KP 22.2 is representative of all headways measured in zone 1 as suggested by the pattern of white streaks in Figure 3c. A similar trend is shown upstream (although coarsely) in loop detector data from the same day at KP 21.5 in Figure 2a.

SD4 straddles the transition in shoulder lane flow at about 6:52 am. Like SDs 1, 2, and 3, SD4 exhibits a time coincidence of LC maneuvers into the shoulder lane, and an increase in downstream outflow. However unlike SDs one, two, and three, SD4 does not exhibit high rates of LC into the median lane, or a decrease in vehicular accumulation in zone 1. Vehicles do not recover speeds on the downstream (uphill) side of SD4 as shown in Figure 4. Instead, a SD appears immediately in its wake and speeds remain low in zone 1. Additional lane changes into the shoulder lane are observed as shown in Figure 7, but these lane changes occur in the absence of large headways. Figure 3c reveals the emergence of a sustained region of low speed in the shoulder lane, thus forming a single-pipe regime, labeled SP, in which vehicle speeds become nearly equal across lanes. However, outflow remains high (on average about 1760 vph per lane, or 5280 vph for three lanes) as shown in Figure 5.

In the midst of this congested, single-pipe traffic, additional SDs arose. Figure 7 reveals a sudden increase in lane-change maneuvers into the median at about 6:57 am in zone 2, labeled LC2. These lane changes occur despite the fact that the median lane is already heavily utilized at this region in space and time. As a result of SD5, the queue had already expanded to the base of the hill. However, SD6 helps to further expand the queue, filling the downhill approach. Thereafter, vehicles arrive to the base of the incline at constrained (slow) speeds, impeding traffic's ascent. The resulting reduction in the site's output flow (which drops to an average of about 1560 vph per lane, or 4680 vph for three lanes), persists until a drop in demand ending the rush allows the queue to clear.

5. Discussion

The data reveal two distinct patterns of behavior: one pattern during the early portion of the rush, and another when the shoulder lane flow rises

above 1200 vph. Early in the rush, median lane flow is high and SDs repeatedly plague that lane, resulting in excess accumulation on the uphill slope. Aggressive drivers react to the SDs by temporarily migrating to the shoulder lane. These LC maneuvers are accommodated by the shoulder lane when large headways are available, i.e. when the lane is underutilized. The result is higher outflow and a reduction in vehicular accumulation on the uphill slope. For a time, this “release valve” behavior preserves the multi-pipe character of flow on the site.

However as the rush wears on, flow increases in the shoulder lane and large gaps between vehicles no longer exist. LC maneuvers in response to median lane SDs become disruptive, spreading the queue laterally, and causing a persistent disturbance to form in all lanes. Thus emerges a single-pipe regime in which all lanes are slowed; although initially, the single-pipe regime results in high outflow and a more equitable distribution of flow across lanes. Additional SDs in the midst of this queue generate disruptive LC maneuvers that reduce speed and flow, causing the queue to expand longitudinally, beyond the base of the hill. Newly arriving vehicles are forced to slow down on the downhill approach, and those vehicles with the worst acceleration characteristics determine uphill speed and flow.

5.1. Comparison with Other Studies

While we are able to report on the onset of isolated SDs, we are unable to provide a complete description of their cause. As evidenced repeatedly by video data, periods of high flow in the median lane on an uphill grade are typically marked by periodic speed disturbances. Similar observations have been reported in NGSIM data (Laval and L., 2009). Others have documented spontaneous appearance of speed disturbances in dense conditions (Sugiyama et al., 2008). We observe that a small drop in speed by a lead vehicle (causing a delay on the order of 0.3 s over a distance of 1 km) is amplified by successive vehicles and results in a speed disturbance as described by Koshi et al. (1992). On average, following vehicles brake later than predicted by Newell’s simplified car following model (Newell, 2002). As a result, successive vehicles decelerate more quickly and over a shorter distance to avoid collision. A series of these over-reactions coalesce into a high-density, backward-moving speed disturbance.

In contrast with Koshi et al. (1992), we find not one, but a series of SDs on the hill prior to queue formation. These SDs will always cause some LC. In most cases, traffic flow will recover. However, one SD might be different. For

this particular SD, events will transpire as described in Koshi et al. (1992). We have enhanced the description in Koshi et al. (1992) by explaining the triggering mechanism, and how the release-valve in the shoulder lane makes it possible for traffic to recover from some SDs but not others.

As reported elsewhere in the literature (see Section 2), we too find that LC maneuvers in a queue result in decreased outflow. However we also show that when the target lane is underutilized, and contains large headways, then LC can be accommodated without deleterious effects. In addition, the re-distribution of flow across lanes mitigates the effect of speed disturbances arising in the median lane.

5.2. Similarities to Multi-lane Theory

A multi-lane traffic theory (Daganzo, 2002) can explain previous observations, including the pattern by which traffic may deteriorate or recover from SDs. In multi-pipe free flow, or semi-congested flow, vehicles self-segregate among lanes according to their desired speeds. Using the nomenclature in Daganzo (2002), ‘rabbits’ use the center and median lanes, and ‘slugs’ (content to drive more slowly) use the shoulder lane. Rabbits react to a median lane speed disturbance by redistributing themselves across lanes. In so doing, some rabbits will realize a speed advantage, but the macroscopic effect is for traffic to approach a single-pipe regime in which speeds are equalized across lanes. If initial shoulder utilization (or flow of slugs) is low, then the discharge of rabbits through the speed disturbance will be high, and the recovery will propagate backward (upstream), immediately following the decelerated state. The decelerated state will propagate beyond the bottom of the hill, and newly arriving vehicles will once again reach the uphill grade at high speed. If initial shoulder utilization (or flow of slugs) is high, such that few large headways are available for LC, then the discharge of rabbits through the speed disturbance will be low. In this case, we observe a transition from the multi-pipe to the persistent single-pipe regime. Theoretically, the transition may propagate backward or forward, but on our site, we observe that it stays fixed at the base of the hill.

After passing the speed disturbance, vehicles will once again self-segregate according to speed preferences (as indicated by LC1 in Figure 7, and shown by the multi-pipe flows downstream in Figure 2b).

Although elements of the observed mechanism can be described by a theory of multi-lane traffic, there are aspects that violate the idealizations in Daganzo (2002). We call attention to fact B3 of Daganzo (2002) in which

it is stated that temporal changes in speed (or flow) are synchronized across lanes (Mika et al., 1969). To the contrary, we find that speeds below the preferred cruising speed of slugs (about 70 kph) may vary significantly across lanes when influenced by an SD. However Mika et al. (1969) used acoustic detector data averaged over one-minute intervals, which is too coarse to unveil the details of the phenomena discussed here. Furthermore, the SDs we observe in the early part of the rush have a longitudinal expanse on the order of the characteristic length of an interface between traffic states, about 500 m (Daganzo, 2002). Therefore it is not surprising that an SD may come and go through a group of vehicles before rabbits can change lanes so as to equalize speeds on all lanes.

As long as the release valve continues to function, rabbits can enter the shoulder lane without causing significant disruptions, and a two pipe-regime is preserved. However when the release valve fails, and another SD appears, we find it takes about 1-3 minutes for rabbits to redistribute themselves so as to equalize speeds on all lanes. When this occurs, we say that traffic has made a regime change from multi-pipe to single-pipe. Koshi et al. (1992) notes that bottleneck activation requires the presence of a long platoon ascending the hill. We find that a sustained high flow interval is required for the release valve to fail.

With regard to output flow, the single-pipe regime is not disadvantageous. To the contrary, we observe some of the highest output flows (a 5-min sustained rate of 5300 vph for three lanes) upon entry to the single-pipe state. The efficiency gain is realized by greater utilization of the shoulder lane, typically with a flow increase exceeding 50% in that lane. Unfortunately, we observe that high outflow is not maintained in the congested, single-pipe state. Additional SDs induce demand for lane changing in excess of the supply of large headways. As a result, lane change maneuvers become disruptive by reducing the flow in the abandoned lane and reducing the speed in the adopted lane. The result is a loss in outflow, and a denser queue that grows beyond the base of the hill. Vehicles arrive at the base of the hill at low speeds, and those with the worst acceleration determine the uphill velocity for all vehicles in the queue. The uphill velocity, in turn, determines the uphill flow.

6. Conclusion

Strategies to mitigate congestion may attempt to address stability in the median, or enable the release valve mechanism in the shoulder. If average median lane headway were increased to 2 s, then the severity of speed disturbances may be reduced. On our site, there is a shoulder area to the left of the shoulder lane. This area is reserved for the use of emergency vehicles. However during appropriate circumstances, this area could also be used to clear the queue on the hill, and allow traffic to recover to higher speed and flow.

Another strategy might be to stimulate lane migration while reducing the occurrence of disruptive LC after queues develop. For example, we speculate that variable message signs can be deployed to announce downstream speeds (on the uphill segment), thus allowing some drivers to make LC maneuvers before getting stuck in a SD. Drivers given advance notice could change lanes while their speed is similar to that of vehicles in the adjacent lane. This could potentially yield a safety dividend by reducing LC maneuvers involving vehicles in a slower lane cutting over into a faster-moving lane. This approach may stimulate lane migrations resembling those observed in the release valve mechanism, and encourage drivers to distribute themselves more equitably across available lanes. Once a lane is chosen (on the downhill segment), lane changes on the uphill segment would be prohibited.

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