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In freeways, the capacity drop means that the maximum traffic flow is higher than congestion discharge rates there. Various capacity drop magnitudes have been empirically observed before. But the mechanism behind this wide capacity drop range is not yet found. This contribution fills in the gap by relating the congestion discharge rates to different congestion in empirical observations. Two days' data show that the outflows of stop-and-go waves are always lower than that of standing queues. Different discharge rates, ranging from 5220 veh/h to 6040 veh/h at the same site, always accompany different congestion states. Moreover, the different observations show that a higher discharge rate means a higher density in free flow branch in fundamental diagram. This contribution shows that discharging rates probably could be controlled by transforming the congestion states. For instance, transforming a stop-and-go wave into a standing queue at a bottleneck might increase the bottleneck throughput.

Keywords: capacity drop; stop-and-go wave; standing queue; discharging rate; congestion states; flow distribution

1. Introduction

Generally congestion is observed as a form of vehicular queueing, which can be categorized into stop-and-go waves and standing queues. In the stop-and-go waves, two congestion fronts move upstream along a freeway. While in the standing queue, the head of the queue is fixed at a bottleneck. An active bottleneck is a bottleneck with free-flow situation downstream and a traffic jam upstream. The activation of a bottleneck signals the onset of a standing queue. Theoretically downstream of an active bottleneck the outflow of the standing queue should be the maximum flow on the road or capacity. However, the queue discharging rate of congestion is often lower than the maximum flow on a road without congestion. This phenomenon is called the bottleneck capacity drop (Banks 1991, Hall and Agyemang-Duah 1991, Cassidy and Bertini 1999, Bertini and Leal 2005).

Researchers have observed the capacity drop phenomenon for decades at bottlenecks. Those observations point out that the range of capacity drop, difference between the bottleneck capacity and the queue discharging rate, can vary in a wide range. The capacity of the road and the queue discharging flow is essential for the total delay on the road. Hall and Agyemang-Duah (1991) report a drop of around 6% on empirical data analysis at an on-ramp bottleneck. Cassidy and Bertini (1999) place the drop ranging from 8% to 10% from bottlenecks formed by lane-drop or horizontal curve. Srivastava and Geroliminis (2013) observe that the capacity falls by approximately 15% at an on-ramp bottleneck. Chung, Rudjanakanoknad et al. (2007) present a few empirical observations of capacity drop from 3% to 18% at three active bottlenecks. The three bottlenecks are formed by on-ramp merge, lane-drop and a horizontal curve. Excluding the influences of light rain, they show at the same location the capacity drop can range from 8% to 18%. Cassidy and Rudjanakanoknad (2005) observe capacity drop ranging from 8.3% to 14.7% from on-ramp bottlenecks . Oh and Yeo (2012) collect empirical observations of capacity drop in nearly all previous research before 2008. The drop ranges from 3% up to 18%.

Even though a large amount of research effort has put into the capacity drop, some significant macroscopic features on capacity drop are still unclear. For example, it is not clear to what extent the capacity reduces when different congestion occurs upstream. Moreover, it is not clear what is the amount of traffic on each lane (flow distribution over lanes), especially at the downstream of a bottleneck with compulsory merging behaviours upstream. Hence, this paper tries to show more empirical observations to forward traffic research to reveal more empirical features. These findings can contribute to a better understanding of the traffic processes, possibly leading to control principles mitigating congestion. Moreover, it also gives an indication of the lane change behaviour at the bottleneck locations.

The question answered in this paper is: what are differences between traffic states downstream of stop-and-go waves compared to downstream of standing queues at the same site. In answering this question, we use the following four subquestions. First, to what extent does the capacity reduce downstream of a stop-and-go wave? Most of previous research observe capacity drop phenomenon at active bottlenecks. Few of those studies reveals features of capacity drop downstream of a stop-and-go wave. Kerner (2002) observes that the outflow of wide moving jam can be higher than minimum outflow of synchronized flow, and lower than the maximum outflow of synchronized flow. We categorize congestion into stop-and-go waves and standing queues, showing present empirical observations of capacity drop in stop-and-go waves. Second, to what extent does the outflow of congestion, i.e. the capacity with congestion upstream, vary at the same road section without other disturbances such as weather and road layouts? In short, this subquestion hence discusses the stochasticity of the outflow of the queue. Previous research shows that discharging flows of standing queues at one bottleneck only exhibit small deviations (Cassidy and Bertini 1999). But those research only target standing queue at an active bottleneck. In contrast to the standing queue, whose traffic states are limited in a narrow range because the road layout dictates the congested traffic state upstream, different stop-and-go waves can result in different congestion states. The study of stop-and-go waves can enlarge the observation samples. Third, what is the flow in each lane in queue discharge conditions? This might shed light to the capacity drop as well. Four, what is the traffic flow distribution over lanes downstream of an bottleneck with compulsory merging behaviours upstream, especially locations near bottlenecks? The study of the flow distribution can show the utilization of lanes when the capacity drop is observed, which can benefit increasing queue discharge rates with multi-lane dynamic management.

To answer those questions, this paper studies a traffic scenario where a standing queue forms immediately after a stop-and-go wave passes. It seems that the standing queue is induced by the stop-and-go wave. In this scenario, there can be at least two congestion states and two outflow states observed at the same road section at the same day.

The remainder of the paper is set up as follows. Section 2 describes methodologies applied in this paper. This section applies shock wave analysis to recognize those different congestion. Section 3 shows the study site and the study data. In section 4, empirical observations are presented, including various traffic states and flow distribution in each lane. Finally, section 5 presents the conclusions.

2 Methodologies

This paper targets a homogeneous freeway section with a lane-drop bottleneck upstream. In the expected scenario, a standing queue forms immediately after the passing of a stop-and-go wave. It seems like the bottleneck is activated by the stop-and-go wave. In this way, we can compare the outflows of congestion at that location and possible location specific influences are excluded from the analysis.

Since the differences in the capacity drop (in standing queues) between any two days at the same bottleneck lies in a small range among days (Cassidy and Bertini 1999), it is difficult to observe standing queues in distinctly different congestion states at the same bottleneck. However, the congestion level in stop-and-go wave is considerably different from the congestion in a standing queue. Congestion level is represented by vehicle speed in the congestion and density. Previous research (Laval and Daganzo 2006, Chung, Rudjanakanoknad et al. 2007) shows that the capacity drop is strongly related to the congestion level, hence it is expected that downstream of a stop-and-go wave traffic states differ from that downstream of a standing queue. In this way, several state points at the same road stretch can be observed empirically, including free flow and congestion states. Shock wave analysis is applied to identify those congestion states qualitatively.

By comparing the outflows downstream of congestion, this paper shows the capacity drop corresponding to the two different congestion types, stop-and-go wave and standing queue. The key of the traffic state analysis is to identify those traffic states. To avoid unnecessary deviations, this paper applies slanted cumulative counts to calculate flow. The slanted cumulative curve, also known as oblique cumulative curves, is drawn by subtracting a reference flow from the cumulative number of passing vehicles. The slanted cumulative curve can promote the visual identification of changing flows (Cassidy and Bertini 1999).

Both of these two outflows are flow detected downstream of the congestion. There are repetitive observations. For the duration of congestion until the congestion is dissolved, there are no other influences from downstream. The outflow of a stop-and-go wave can be detected at some location where the speed returns to the free flow speed after the break down phenomenon, and the discharging flow can be detected at each location downstream of an active bottleneck.

2.1 Shock wave analysis

The states which occur are determined using shock wave analysis. Figure 1 shows the resulting traffic states, including the regions in space-time where the outflows can be measured. For the sake of simplicity, we choose triangular fundamental diagrams, Figure 1a) shows these fundamental diagrams, the smaller one for three-lane section and the larger one for the four-lane section. The outflow of a stop-and-go wave, shown as state 5, and discharging flow of standing queue, shown as state 6, both lie in the free flow branch, see Figure 1. The flows in both of these two states are lower than the capacity shown as state 1 to represent the capacity drop. A stop-and-go wave, state 2 in Figure 1, propagates upstream to the bottleneck and this triggers a standing queue, state 4. Figure 1b) shows that once the bottleneck has been activated both of state 5 and 6 can be observed in the downstream of the bottleneck. The further away from the bottleneck, the longer time state 5 can be observed. Note that because state 5 and 6 are always located in the free flow branch, the shock wave between these two states are always a positive line parallel to the free flow branch. Therefore, in Figure 1b) the shock wave between state 5 and 6 are always the same in x-t plot, no matter which state shows a higher flow. All those states are predicted theoretically by shock wave analysis, which should be observed in empirical observations.

Hence, for measuring the outflow observations at locations far away from the bottleneck are preferred. In that case, the outflow of stop-and-go wave can be measured for a long enough time and compared clearly there.

With the same methodology, different outflow features in different lanes are analyzed. This shows the performance of each lane during the transition from outflow of stop-and-go wave to queue discharging flow. This paper applies slanted cumulative counts to calculate the outflow in each lane. Note that in the Netherlands the rule is Keep Right Unless Overtaking. This asymmetric rule might lead to a different lane choice, for instance for slugs and rabbits (Daganzo 2002), as well as leading to different traffic operations.

2.2 Data Handling

This paper reveals the flow distribution in each lane as a function of average density over lanes in section 4.4. The density (ρ) which is estimated through dividing flow (q) by space mean speed (v_S) is necessary.

In the Netherlands, loop detector data is time mean speed (v_T) and flow (q). Knoop, Hoogendoorn et al. (2009) point out the substantial difference between the time mean speed v_T and space mean speed v_S, especially when the speed in congestion. Yuan, Van Lint et al. (2010) presents a correction algorithm based on flow-density relations to calculate space mean speed. This method requires that traffic states should lie on the linear congested branch of the fundamental diagram. However, this paper considers acceleration states downstream a bottleneck, so we need another method. Knoop, Hoogendoorn et al. (2009) shows an empirical relation between space mean speed and time mean speed, see Figure 2. The space mean speed actually is estimated as harmonic speed. This relation is applied to space mean speed calculation in (Ou 2011). This paper also applies the relation to calculate the space mean speed and the density.

3 DATA

The data analyzed is one minute aggregated, collected around a lane-drop bottleneck on the freeway A4 in the Netherlands. This paper considers the northbound direction just around Exit 8 (The Hague) in A4 shown in Figure 3. The layout of the study site is shown in the right part of Figure 3. The targeted bottleneck is a lane-drop bottleneck which is circled in Figure 3. Downstream of this bottleneck, there is another lane-drop bottleneck next to Exit 7. Drivers in the targeted road section are driving from a four-lane section to a three-lane section (the upward direction in Figure 3), so a lane-drop bottleneck occurs. The data is collected from 10 locations with approximately 500m spacing between them, giving a total length of around 5 km. There are 2 detectors in the four-lane section, followed by 8 in the three-lane section. this paper does not consider detectors further downstream because vehicles will change into shoulder lane to leave freeway through Exit 7, possibly leading to external disturbances, for instance lane changing near the off-ramp.

Data for analysis is collected on two days, Monday 18 May 2009 and Thursday 28 May 2009. Figure 4 shows the speed contour plots in the study section on two days. There are two similar traffic situations in both of days. The first event is a stop-and-go wave. On 18 May the stop-and-go wave originated from the lane-drop bottleneck near Exit 7 at about 16:45. On 28 May the stop-and-go wave enters the selected stretch from further downstream at around 16:55. At 17:40 and 17:50 (18 and 28 May respectively), the next stop-and-go wave reaches the lane-drop bottleneck. Downstream of the second stop-and-go wave there is congestion. When calculating the outflows, this study analyzes the data before the entering of the second stop-and-go wave in order to avoid influences of this congestion. When analyzing the flow distribution, we analyze the data collected from 16:00 to 19:00. During the targeted period, there is no other influence from downstream, i.e., the bottleneck is active.

4 RESULTS

This section first presents the different states, then the capacity estimates, and then in section 4.3 and 4.4 the lane-specific features are discussed.

4.1 State Identification

This section describes empirical observations. Figure 5 shows empirical slanted cumulative counts across three lanes at 8 locations downstream the bottleneck on two study days. The arrow in each figure shows the shock wave which propagates downstream from the bottleneck. This means the traffic is in a free flow state, and not influenced by the off-ramp downstream. The outflow of the stop-and-go wave and the discharging flow of the standing queue are clearly distinguishable with the shock wave between these two states, see the upward arrows in Figure 5. Generally, the empirical observations are in line with the expectations presented in in section 2.

This shock wave separates the outflow of stop-and-go wave from the discharging flow of standing queue. This shock wave has been expected in section 2 (see Figure 1b). At one location, we first observe the outflow of the stop-and-go wave and then observe the discharging flow of the standing queue. First, we find the outflow of the stop-and-go wave only directly downstream of the stop-and go wave. The wave travels upstream, from location 1 to location 8. Once it reaches location 8, the traffic state will change, with a wave propagating downstream, which takes some time before it reaches location 8. During that whole time, at location 1 the outflow of the stop-and-go wave can be detected.

The discharging flows found for the two days are constant for each day, at 6040 veh/h (18 May) and 5700 veh/h (28 May), see figure 4. Although they are different for both days, the flows are remarkably constant over time. There is also a difference between the flows downstream of the standing queues at 18 and 28 May. This holds for all locations downstream of the bottleneck, including the acceleration phase. The flow is the different but constant for both days. During the acceleration process, the density continuously decreases. Since the flows differ for the two days, the speeds must differ for the two days for situations with an equal density. This means that drivers leave a larger gap than necessary in the day with the lower flow (28 May), since apparently - given the speed-density relationship for the other day - they can drive with lower speeds given the spacing.

Moreover, the downstream direction of the shock wave implies that the off-ramp (Exit 7 in Figure 3) does not influence the discharging flow. Oh and Yeo (2012) implies that the off-ramp at the downstream location mitigates the capacity drop. In our study site, the off-ramp which is located far away has no effects. The shock waves propagating downstream imply no influence from downstream.

4.2 Capacity Estimation

Figure 6 shows the capacities (with congestion upstream) which are the outflow of congestion at a homogeneous three-lane freeway section. In Figure 6, all red dashed lines show the slanted cumulative curves at the downstream locations and the blue bold lines represent speed evolution there. All figures in Figure 6 show firstly a decrease of flow (during the time the stop-and-go wave is present), indicated by a cumulative flow line with a negative slope. Afterwards, at location 1 the flow is constant for about 20 minutes, at approximately 5400 veh/h on 18 May and 5220 veh/h on 28 May. Figure 6c) and 6d) show the slanted cumulative curves for the location 8, just downstream of the bottleneck. After the stop-and-go wave reaches location 8, the jam soon transforms into a standing queue and the outflow increases up to 6040 veh/h and 5700 veh/h respectively. These two discharging flows propagate downstream from the bottleneck and reaches location 1. In Figure 6, we label the moment when the higher discharge rate reached as “A”. The higher outflow (6040 veh/h and 5700 veh/h) is not temporary and remains for at least 15 minutes at each location. The solid black line in each of the figures indicates a flow to which the slanted cumulative curve can be compared. In each figure, the increasing slope of black lines shows that the outflow of stop-and-go wave is lower than the discharging flow of the standing queue. Typically, we find that the outflow of the stop-and-go wave lies in the range of 5220 veh/h to 5400 veh/h and the outflow of the standing queue is in the range of 5700 veh/h to 6040 veh/h. All data points are collected in Table 1. The number of states corresponds to Figure 1.

State 2, 4, 5 and 6 in Figure 1a) are identified quantitively. State 2 and 4 stand for congestion states. State 5 and 6 represent states of capacities. We thus find a correlation between the type of congestion and its outflow. In fact, the outflow of a stop-and-go wave is lower than the outflow of a standing queue at the same location.

4.3 Outflows in Each Lane

When congestion occurs, each lane presents different features regarding to outflows. In Figure 7, slanted cumulative counts and speed in each lane are presented, shown as a red dashed line and a blue bold line respectively. Slow vehicles and trucks usually drive in the shoulder lane due to the Keep Right Unless Overtaking rule. Therefore, the flow and speed detected in each lane at the same location differ from each other. In both of Figure 6a) and 6b), aggregated data over 3 lanes shows an increase of outflow at the moment the wave separating the outflow from the stop-and-go wave and the outflow from the standing queue reaches the detector. In Figure 7a) and 7c), this increase of the outflow is observed in the median and center lane at location 1 on 18 May 2009, but not in the shoulder lane. At 28 May this increase is found in all lanes. The lack of change in flow in the shoulder lane is remarkable, but at the moment is it unclear what could be the reason.

4.4 Flow Distribution Over Lanes

When the bottleneck has been active, there are several different traffic states in the downstream of the bottleneck. Along the distance, the density decreases. Therefore, in the targeted scenario, a large range of density can be detected, which can reveal the flow distribution as a function of density across lanes. The flow distributions are shown in Figure 8. Red lines show the fast lane (median lane), black lines show the center lane and the blue lines show the slow lane (shoulder lane). Three bold lines (see Figure 8a & 8b) represent average flow distribution at three lanes based on all data. Circles and triangles are the empirical data collected in each lane at location 1 (see Table 1 and Figure 7). Those circles and triangles stand for the state of the outflow in each lane at location 1, i.e., state 5 and state 6 (see Figure 1) respectively. Note that we at location 1 on 18 May 2009 there is no distinguish between the state 5 and state 6. Therefore, when calculating the flow distribution in these two states (state 5 and 6), we use the same flow, that is 1437 veh/h as shown in Figure 7e). Note that, the lower flow in state 5 (compared to state 6) in the center lane (see Figure 7d) does not mean the flow distribution in state 5 should be lower than that in state 6. That explains why in the center lane the flow distribution in state 5 is higher than that in state 6 (see Figure 8b). The rest thin lines (in Figure 8c & 8d) represent the flow distributions at each location. The lines with five-point stars stand for the distribution at location 8.

Figure 8a) and 8b) shows flow distributions on two different days. Both figures show a common feature. When the density lies within the range 22 - 60 veh/km, the flow in the center lane is higher than that in both other lanes, although it keeps decreasing as density grows. When the density is around 60 veh/km, the fraction of the flow at shoulder lane reaches the minimum at around 23%. For shoulder lane the decrease of the fraction of the flow was sharp, but afterwards the increase is only marginal. Meanwhile from 60 veh/km the fraction of the flow in median lane stops increasing with density and begins to stabilize at around 38%. Note that the density of 60 veh/km corresponds to a typical critical density, that is 20 veh/km/lane (Treiber and Kesting 2013).

When the density exceeds 132 veh/km (18 May) and 95 veh/km (28 May), the fraction of the flow in median is almost equal to the fraction of the flow in the center lane, at around 35% for each while the flow percentage at shoulder lane is around 30%. So even in states with a very high density, flows in shoulder lane are still lower than that in the other lanes. When density reaches up to 220 veh/km, the flow begins to be distributed evenly over three lanes on 18 May while the flow distribution is more unstable on 28 May. It is not surprising because in extremely high density situation standing vehicles can lead to some detection problems.

Figure 8c) and 8d) show the flow distribution at 8 locations. The flow distribution in median lane (red line) at location 8 (marked as red five-point stars) is much higher than that at the other locations, see Figure 8c) and 8d). In contrast, the flow distributions in the center and median lanes at location 8 are the lowest. That is because vehicles merge into median lane when passing through the lane-drop bottleneck. In the downstream of location 8, the flow distribution in median lane is lower than that at location 8. For the other locations, the distribution situations are similar to each other. We explain this by the following. Vehicles force themselves into the traffic stream and it takes some time – and hence distance – before equilibrium distribution sets in again.

Therefore, it is believed that a high percentage of vehicles choose to leave median lane by changing lane between location 8 and location 7. This situation is only visible when the density reaches up to 130 veh/km. In the future research, more empirical data (especially trajectory data set) are needed for justifying the behavioural explanation on the different flow distributions at different locations.

Among three lanes, due to the Keep Right Unless Overtaking rule in the Netherlands, we can assume that the shoulder lane (slow lane) is first choice for drivers when the density is extremely low. As the density increases to around 20 veh/km, the occupation of center lane begins to be higher than that in the shoulder lane. The use of median lane (fast lane) is the least at that time. As the density increases, in contrast to the shoulder lane whose flow fraction reduces considerably, the use of median lane sharply grows. Finally, the median lane and center lane are highly made use of while the shoulder lane is being underutilized.

Figure 9 shows the speed in each lane at the same average density over three lanes. Circles, triangular and dots indicate the speed in the median lane, center lane and shoulder lane, respectively. When the density is lower than around 70veh/km, the speed decrease from the median lane towards the shoulder lane, that is due to the Keep Right Unless Overtaking rule. The median lane is the fastest lane. In Figure 9, when the average density is higher than 70 veh/km, circles, triangulars and dots are greatly overlapped. That means the speed is becoming more equal among the lanes. Because in congestion the speeds are almost equal in all lanes (shown as the highly overlapped area among circles, triangulars and dots), so the low flow in the shoulder lane must be due to a low density or large spacing. That means that microscopically in congestion the spacing between successive vehicles in the shoulder lane is the largest among three lanes.

Figure 10 shows the flow distributions in the four-lane freeway section upstream the lane-drop bottleneck. Note that the outflow of the upstream four-lane freeway section is the inflow of the downstream three-lane freeway section. There are 2 locations for the data collection, location 9 and location 10 in Figure 3. Traffic flow moves from location 10 to location 9. The figure only shows the data for 18 May, the data for 28 May is similar. In fact, we can distinguish two pairs of lanes. First, lane 1 and 2 are the median and shoulder lane of one of the upstream branches of the road. The flow distributions at lane 3 and 4 are similar to that of lane 1 and 2 respectively, also originating from a two lane road upstream. The flow distribution at two the locations differs considerably. On one hand, in contrast to location 10 which is in the upstream of the location 9, location 9 shows a lower flow in the median lane, especially for low densities. On the other hand, at location 9 the flow in the shoulder lane is higher for low densities. The non-compensated amount of lane changes can be estimated by the difference in flow per lane between the two detectors for a certain density (e.g., one can see how much lower the flow is). Compensation is possible be by other vehicles making opposite movements (e.g., vehicles moving into the lane). In lane 3, the right center lane, the flow is higher at location 9. Downstream of location 9, all vehicles in the median lane have to merge into lane 2. Drivers in lane 2 (the left center lane) might anticipate this and make space for the drivers merging from the median lane. These lane changes can be considered as an explanation for the changes in lane flow distribution we observe between location 10 and 9. The relative flow in lane 2 does not change as much, because there is a similar amount of lane changing from the median lane to lane 2; what is observed is a decrease of the utilization of the median lane. The number of lane changing decreases as the average density over lanes increases. The flow distribution at lane 2 and 4 is nearly stable for both locations and study days. At location

9 near the bottleneck, the flow in the lane 3 is always the highest for both study days. Note that the demand in the upstream two two-lane freeway sections could possibly greatly influence the flow distribution at location 10.

5 CONCLUSIONS

This paper compares the downstream states of a stop-and-go wave with that of a standing queue. The standing queue in this paper is induced at a lane-drop bottleneck by a stop-and-go wave. Therefore, at one bottleneck there are two different congestion states observed. In the downstream of the congestion there are free flow states, that means the two outflows detected downstream of congestion are the capacities of the road section. This paper applies shock wave analysis to find those two outflows at the same road section, which is well traceable in the real data. The most important finding is that the outflow of stop-and-go waves is be much lower than that of a standing queue. Therefore, the capacity with congestion upstream can vary in a rather wide range, e.g. from 5220 veh/h to 6040 veh/h at a three-lane road section. The various capacities could be related to congestion states, which means a promising traffic control strategies could increase the queue discharge rate and minimize traffic delays.

There are two other findings. First, different features of outflow from congestion in different lanes can be found. Strong fluctuations occasionally can be observed in the shoulder lane, which might even trigger stop-and-go waves later on, for instance near a next bottleneck. Second, the flow distribution over three lanes is presented. This shows that particularly near head of a standing queue more vehicles can merge into the lane adjacent to the ending lane, thereby locally increasing the capacity of that lane. The capacity of the shoulder lane is markedly wasted when in congestion. The reason for the low flow distribution in shoulder lane is the large spacing between successive vehicles.

Future research should show the mechanisms behind these features, from a behavioural perspective (whether people behave differently), from a vehicle perspective (what the influences of different acceleration profiles are) or from a flow perspective (what for instance the influence of voids is). In the future, a promising control strategy, based on our empirical research, should be proposed to minimize queue discharge rates and traffic delays.

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Table 1. Speed and Flow in Different Traffic State Points

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Figure 1. Shock wave analysis on one traffic scenario at a lane-drop bottleneck.

Figure 2. The impact of difference between time mean speed harmonic mean speed: 10 seconds aggregation (blue line), 60 seconds aggregation (black dashed line) and 900 seconds aggregation (red line with circles). (Reproduced by permission of Knoop, Hoogendoorn et al. (2009)).

Figure 3. Open street figure of targeted section in freeway A4 in the Netherlands (left) shown in red dots and the layout of the study site (right). The bottleneck is a lane-drop bottleneck highlighted with a red circle. This paper only targets 10 locations. The total distance from the location 1 to location 10 in the freeway is approximately 4.5 km. The bottleneck is around 6.5 km far away from the downstream off-ramp.

Figure 4. Layout of the study site and data on two days (18 May and 28 May 2009) for study. The lane-drop bottleneck located between Detector 8 and 9 is activated by a stop-and-go wave from downstream. The numbers show locations of detectors. This study restricts to 10 locations around the targeted lane-drop bottleneck.

Figure 5. Slanted cumulative counts across three lanes at 8 locations downstream the bottleneck on two days, 18 May 2009 (left) and 28 May 2009 (right).

Figure 6. Average time mean speed (blue bold line) and slanted cumulative counts (red dash line) across three lanes at location 1 and location 8 on 18 May 2009 (a & c) and 28 May 2009 (b & d).

Figure 7. Speed and slanted cumulative count in each lane on 18 May 2009 (a, c & e) and 28 May 2009 (b, d & f) at location 1. Flows are shown next to the coinciding slanted cumulative counts (bold black lines).

Figure 8. Flow distributions at different densities at three-lane freeway section. a) and b) shows average flow distributions over 3 lanes, median lane (red), center lane (black), and shoulder lane (blue) on two days, 18 May (left) and 28 May (right). Circles and triangles show the performance of each lane in state 5 and state 6 respectively, corresponding to data in Figure 7. c) and d) shows flow distributions at each 8 locations. Each thin line shows a flow distribution at each location. Five-point stars represents the flow distribution at location 8.

Figure 9. Speed – Density plot in each lane in the three-lane section on two study days, 18 May (left) and 28 May (right). The density is the average density over three lanes.

Figure 10. Flow distributions at different densities at four-lane freeway section on 18 May. The distribution on 28 May is the similar. The traffic flow is moving from location 10 to location 9.