

Capacity drop

A comparison between stop-and-go wave and standing queue at lane-drop bottleneck

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1 **Capacity drop: a comparison between stop-and-go wave and standing**
2 **queue at lane-drop bottleneck**

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1 **Capacity drop: a comparison between stop-and-go wave and standing**

2 **queue at lane-drop bottleneck**

3 In freeways, the capacity drop means that the maximum traffic flow is higher
4 than congestion discharge rates there. Various capacity drop magnitudes have
5 been empirically observed before. But the mechanism behind this wide capacity
6 drop range is not yet found. This contribution fills in the gap by relating the
7 congestion discharge rates to different congestion in empirical observations. Two
8 days' data show that the outflows of stop-and-go waves are always lower than
9 that of standing queues. Different discharge rates, ranging from 5220 veh/h to
10 6040 veh/h at the same site, always accompany different congestion states.
11 Moreover, the different observations show that a higher discharge rate means a
12 higher density in free flow branch in fundamental diagram. This contribution
13 shows that discharging rates probably could be controlled by transforming the
14 congestion states. For instance, transforming a stop-and-go wave into a standing
15 queue at a bottleneck might increase the bottleneck throughput.

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

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1 **1. Introduction**

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

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

1 observe capacity drop ranging from 8.3% to 14.7% from on-ramp bottlenecks . Oh and
2 Yeo (2012) collect empirical observations of capacity drop in nearly all previous
3 research before 2008. The drop ranges from 3% up to 18%.

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

14 The question answered in this paper is: what are differences between traffic
15 states downstream of stop-and-go waves compared to downstream of standing queues at
16 the same site. In answering this question, we use the following four subquestions. First,
17 to what extent does the capacity reduce downstream of a stop-and-go wave? Most of
18 previous research observe capacity drop phenomenon at active bottlenecks. Few of
19 those studies reveals features of capacity drop downstream of a stop-and-go wave.
20 Kerner (2002) observes that the outflow of wide moving jam can be higher than
21 minimum outflow of synchronized flow, and lower than the maximum outflow of
22 synchronized flow. We categorize congestion into stop-and-go waves and standing
23 queues, showing present empirical observations of capacity drop in stop-and-go waves.
24 Second, to what extent does the outflow of congestion, i.e. the capacity with congestion
25 upstream, vary at the same road section without other disturbances such as weather and

1 road layouts? In short, this subquestion hence discusses the stochasticity of the outflow
2 of the queue. Previous research shows that discharging flows of standing queues at one
3 bottleneck only exhibit small deviations (Cassidy and Bertini 1999). But those research
4 only target standing queue at an active bottleneck. In contrast to the standing queue,
5 whose traffic states are limited in a narrow range because the road layout dictates the
6 congested traffic state upstream, different stop-and-go waves can result in different
7 congestion states. The study of stop-and-go waves can enlarge the observation samples.
8 Third, what is the flow in each lane in queue discharge conditions? This might shed
9 light to the capacity drop as well. Four, what is the traffic flow distribution over lanes
10 downstream of an bottleneck with compulsory merging behaviours upstream, especially
11 locations near bottlenecks? The study of the flow distribution can show the utilization of
12 lanes when the capacity drop is observed, which can benefit increasing queue discharge
13 rates with multi-lane dynamic management.

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

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

24 **2 Methodologies**

25 This paper targets a homogeneous freeway section with a lane-drop bottleneck

1 upstream. In the expected scenario, a standing queue forms immediately after the
2 passing of a stop-and-go wave. It seems like the bottleneck is activated by the stop-and-
3 go wave. In this way, we can compare the outflows of congestion at that location and
4 possible location specific influences are excluded from the analysis.

5 Since the differences in the capacity drop (in standing queues) between any two
6 days at the same bottleneck lies in a small range among days (Cassidy and Bertini
7 1999), it is difficult to observe standing queues in distinctly different congestion states
8 at the same bottleneck. However, the congestion level in stop-and-go wave is
9 considerably different from the congestion in a standing queue. Congestion level is
10 represented by vehicle speed in the congestion and density. Previous research (Laval
11 and Daganzo 2006, Chung, Rudjanakanoknad et al. 2007) shows that the capacity drop
12 is strongly related to the congestion level, hence it is expected that downstream of a
13 stop-and-go wave traffic states differ from that downstream of a standing queue. In this
14 way, several state points at the same road stretch can be observed empirically,
15 including free flow and congestion states. Shock wave analysis is applied to identify
16 those congestion states qualitatively.

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

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

7 *2.1 Shock wave analysis*

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

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

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

11 **2.2 Data Handling**

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

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

1 harmonic speed. This relation is applied to space mean speed calculation in (Ou 2011).
2 This paper also applies the relation to calculate the space mean speed and the density.

3 **3 DATA**

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

17 Data for analysis is collected on two days, Monday 18 May 2009 and Thursday
18 28 May 2009. Figure 4 shows the speed contour plots in the study section on two days.
19 There are two similar traffic situations in both of days. The first event is a stop-and-go
20 wave. On 18 May the stop-and-go wave originated from the lane-drop bottleneck near
21 Exit 7 at about 16:45. On 28 May the stop-and-go wave enters the selected stretch from
22 further downstream at around 16:55. At 17:40 and 17:50 (18 and 28 May respectively),
23 the next stop-and-go wave reaches the lane-drop bottleneck. Downstream of the second
24 stop-and-go wave there is congestion. When calculating the outflows, this study
25 analyzes the data before the entering of the second stop-and-go wave in order to avoid

1 influences of this congestion. When analyzing the flow distribution, we analyze the data
2 collected from 16:00 to 19:00. During the targeted period, there is no other influence
3 from downstream, i.e., the bottleneck is active.

4 **4 RESULTS**

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

7 *4.1 State Identification*

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

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

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

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

17 ***4.2 Capacity Estimation***

18 Figure 6 shows the capacities (with congestion upstream) which are the outflow of
19 congestion at a homogeneous three-lane freeway section. In Figure 6, all red dashed
20 lines show the slanted cumulative curves at the downstream locations and the blue bold
21 lines represent speed evolution there. All figures in Figure 6 show firstly a decrease of
22 flow (during the time the stop-and-go wave is present), indicated by a cumulative flow
23 line with a negative slope. Afterwards, at location 1 the flow is constant for about 20
24 minutes, at approximately 5400 veh/h on 18 May and 5220 veh/h on 28 May. Figure 6c)
25 and 6d) show the slanted cumulative curves for the location 8, just downstream of the

1 bottleneck. After the stop-and-go wave reaches location 8, the jam soon transforms into
2 a standing queue and the outflow increases up to 6040 veh/h and 5700 veh/h
3 respectively. These two discharging flows propagate downstream from the bottleneck
4 and reaches location 1. In Figure 6, we label the moment when the higher discharge rate
5 reached as “A”. The higher outflow (6040 veh/h and 5700 veh/h) is not temporary and
6 remains for at least 15 minutes at each location. The solid black line in each of the
7 figures indicates a flow to which the slanted cumulative curve can be compared. In each
8 figure, the increasing slope of black lines shows that the outflow of stop-and-go wave is
9 lower than the discharging flow of the standing queue. Typically, we find that the
10 outflow of the stop-and-go wave lies in the range of 5220 veh/h to 5400 veh/h and the
11 outflow of the standing queue is in the range of 5700 veh/h to 6040 veh/h. All data
12 points are collected in Table 1. The number of states corresponds to Figure 1.

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

17 ***4.3 Outflows in Each Lane***

18 When congestion occurs, each lane presents different features regarding to outflows. In
19 Figure 7, slanted cumulative counts and speed in each lane are presented, shown as a
20 red dashed line and a blue bold line respectively. Slow vehicles and trucks usually drive
21 in the shoulder lane due to the Keep Right Unless Overtaking rule. Therefore, the flow
22 and speed detected in each lane at the same location differ from each other. In both of
23 Figure 6a) and 6b), aggregated data over 3 lanes shows an increase of outflow at the
24 moment the wave separating the outflow from the stop-and-go wave and the outflow
25 from the standing queue reaches the detector. In Figure 7a) and 7c), this increase of the

1 outflow is observed in the median and center lane at location 1 on 18 May 2009, but not
2 in the shoulder lane. At 28 May this increase is found in all lanes. The lack of change in
3 flow in the shoulder lane is remarkable, but at the moment is it unclear what could be
4 the reason.

5 ***4.4 Flow Distribution Over Lanes***

6 When the bottleneck has been active, there are several different traffic states in the
7 downstream of the bottleneck. Along the distance, the density decreases. Therefore, in
8 the targeted scenario, a large range of density can be detected, which can reveal the flow
9 distribution as a function of density across lanes. The flow distributions are shown in
10 Figure 8. Red lines show the fast lane (median lane), black lines show the center lane
11 and the blue lines show the slow lane (shoulder lane). Three bold lines (see Figure 8a &
12 8b) represent average flow distribution at three lanes based on all data. Circles and
13 triangles are the empirical data collected in each lane at location 1 (see Table 1 and
14 Figure 7). Those circles and triangles stand for the state of the outflow in each lane at
15 location 1, i.e., state 5 and state 6 (see Figure 1) respectively. Note that we at location 1
16 on 18 May 2009 there is no distinguish between the state 5 and state 6. Therefore, when
17 calculating the flow distribution in these two states (state 5 and 6), we use the same
18 flow, that is 1437 veh/h as shown in Figure 7e). Note that, the lower flow in state 5
19 (compared to state 6) in the center lane (see Figure 7d) does not mean the flow
20 distribution in state 5 should be lower than that in state 6. That explains why in the
21 center lane the flow distribution in state 5 is higher than that in state 6 (see Figure 8b).
22 The rest thin lines (in Figure 8c & 8d) represent the flow distributions at each location.
23 The lines with five-point stars stand for the distribution at location 8.

24 Figure 8a) and 8b) shows flow distributions on two different days. Both figures
25 show a common feature. When the density lies within the range 22 - 60 veh/km, the

1 flow in the center lane is higher than that in both other lanes, although it keeps
2 decreasing as density grows. When the density is around 60 veh/km, the fraction of the
3 flow at shoulder lane reaches the minimum at around 23%. For shoulder lane the
4 decrease of the fraction of the flow was sharp, but afterwards the increase is only
5 marginal. Meanwhile from 60 veh/km the fraction of the flow in median lane stops
6 increasing with density and begins to stabilize at around 38%. Note that the density of
7 60 veh/km corresponds to a typical critical density, that is 20 veh/km/lane (Treiber and
8 Kesting 2013).

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

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

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

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

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

1 Figure 10 shows the flow distributions in the four-lane freeway section upstream
2 the lane-drop bottleneck. Note that the outflow of the upstream four-lane freeway
3 section is the inflow of the downstream three-lane freeway section. There are 2
4 locations for the data collection, location 9 and location 10 in Figure 3. Traffic flow
5 moves from location 10 to location 9. The figure only shows the data for 18 May, the
6 data for 28 May is similar. In fact, we can distinguish two pairs of lanes. First, lane 1
7 and 2 are the median and shoulder lane of one of the upstream branches of the road. The
8 flow distributions at lane 3 and 4 are similar to that of lane 1 and 2 respectively, also
9 originating from a two lane road upstream. The flow distribution at two the locations
10 differs considerably. On one hand, in contrast to location 10 which is in the upstream of
11 the location 9, location 9 shows a lower flow in the median lane, especially for low
12 densities. On the other hand, at location 9 the flow in the shoulder lane is higher for low
13 densities. The non-compensated amount of lane changes can be estimated by the
14 difference in flow per lane between the two detectors for a certain density (e.g., one can
15 see how much lower the flow is). Compensation is possible be by other vehicles making
16 opposite movements (e.g., vehicles moving into the lane). In lane 3, the right center
17 lane, the flow is higher at location 9. Downstream of location 9, all vehicles in the
18 median lane have to merge into lane 2. Drivers in lane 2 (the left center lane) might
19 anticipate this and make space for the drivers merging from the median lane. These lane
20 changes can be considered as an explanation for the changes in lane flow distribution
21 we observe between location 10 and 9. The relative flow in lane 2 does not change as
22 much, because there is a similar amount of lane changing from the median lane to lane
23 2; what is observed is a decrease of the utilization of the median lane. The number of
24 lane changing decreases as the average density over lanes increases. The flow
25 distribution at lane 2 and 4 is nearly stable for both locations and study days. At location

1 9 near the bottleneck, the flow in the lane 3 is always the highest for both study days.
2 Note that the demand in the upstream two two-lane freeway sections could possibly
3 greatly influence the flow distribution at location 10.

4 **5 CONCLUSIONS**

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

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

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

7 **Acknowledgement**

8 <removed to the title page for review>

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9 **List of Tables**

10 Table 1. Speed and Flow in Different Traffic State Points

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5 **List of Figures**

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

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

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

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

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

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

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

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

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

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

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