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

2 **queue at lane-drop bottleneck**

3

4 Kai Yuan (Corresponding Author)

5 *Department of Transport and Planning, Delft University of Technology, Delft, The*

6 *Netherlands*

7 Victor L. Knoop

8 *Department of Transport and Planning, Delft University of Technology, Delft, The*

9 *Netherlands*

10 Ludovic Leclercq

11 *LICIT, IFSTTAR/ENTPE, Université de Lyon, Rue Maurice Audin, 69518 Vaulx-en-*

12 *Velin Cedex, France*

13 Serge P. Hoogendoorn

14 *Department of Transport and Planning, Delft University of Technology, Delft, The*

15 *Netherlands*

16

17 Corresponding author. Email: k.yuan@tudelft.nl

18

22

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.

18

19

20

21

22

23

24

25

26

27

28

29

30

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 quantitively. 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

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.

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**

9   **REFERENCES**

10   Banks, J. H. (1991). "The two-capacity phenomenon: some theoretical issues."
11   Transportation Research Record(1320): 234-241.
12   Bertini, R. L. and M. T. Leal (2005). "Empirical Study of Traffic Features at a Freeway
13   Lane Drop." Journal of Transportation Engineering **131**(6): 397-407.
14   Cassidy, M. J. and R. L. Bertini (1999). "Some traffic features at freeway bottlenecks."
15   Transportation Research Part B: Methodological **33**(1): 25-42.
16   Cassidy, M. J. and J. Rudjanakanoknad (2005). "Increasing the capacity of an isolated
17   merge by metering its on-ramp." Transportation Research Part B: Methodological
18   **39**(10): 896-913.
19   Chung, K., J. Rudjanakanoknad and M. J. Cassidy (2007). "Relation between traffic
20   density and capacity drop at three freeway bottlenecks." Transportation Research Part
21   B: Methodological **41**(1): 82-95.
22   Daganzo, C. F. (2002). "A behavioral theory of multi-lane traffic flow. Part I: Long
23   homogeneous freeway sections." Transportation Research Part B: Methodological
24   **36**(2): 131-158.
25   Hall, F. L. and K. Agyemang-Duah (1991). "Freeway Capacity Drop and The
26   Definition of Capacity." Transportation Research Record(1320): 8.
27   Kerner, B. S. (2002). "Empirical macroscopic features of spatial-temporal traffic
28   patterns at highway bottlenecks." Physical Review E **65**(4): 046138.
29   Knoop, V. L., S. P. Hoogendoorn and H. van Zuylen (2009). Empirical Differences
30   Between Time Mean Speed and Space Mean Speed. Traffic and Granular Flow '07. C.
31   Appert-Rolland, F. Chevoir, P. Gondret et al., Springer Berlin Heidelberg**:** 351-356.
32   Laval, J. A. and C. F. Daganzo (2006). "Lane-changing in traffic streams."
33   Transportation Research Part B: Methodological **40**(3): 251-264.
34   Oh, S. and H. Yeo (2012). "Estimation of Capacity Drop in Highway Merging
35   Sections." Transportation Research Record: Journal of the Transportation Research
36   Board **2286**(-1): 111-121.
37   Ou, Q. (2011). Fusing Heterogeneous Traffic Data: Parsimonious Approaches using
38   Data-Data Consistency. Doctor, Delft University of Technology.

1 Srivastava, A. and N. Geroliminis (2013). "Empirical observations of capacity drop in
2 freeway merges with ramp control and integration in a first-order model."
3 Transportation Research Part C: Emerging Technologies **30**(0): 161-177.
4 Treiber, M. and A. Kesting (2013). Traffic Flow Dynamics: Data, Models and
5 Simulation, Springer.
6 Yuan, Y., J. W. C. Van Lint, T. Schreiter, S. P. Hoogendoorn and J. L. M. Vrancken
7 (2010). Automatic speed-bias correction with flow-density relationships. Networking,
8 Sensing and Control (ICNSC), 2010 International Conference on.
9 **List of Tables**

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

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

1

2

3

4

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.
13
14
15
16
17
18
19
20
21
22