CAPACITY DROP: A RELATION BETWEEN THE SPEED IN CONGESTION AND THE QUEUE DISCHARGE RATE

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ABSTRACT

It has been empirically observed for years that the queue discharge rate is lower than the pre-queue capacity. This is called the capacity drop. The magnitude of capacity drop varies over a wide range depending on the local traffic conditions. However, right now it is unknown what determines the capacity drop value. In fact, there is still no thorough empirical analysis revealing a quite reliable relation between the capacity drop and the congestion level. Therefore, this paper tries to fill in the gap by revealing the relation between the vehicle speed in congestion and the queue discharge rate through empirical analysis. Our research studies congested states where speed ranges from 6 to 60 km/h. The queue discharge rate is shown to increase considerably with increasing speed in the congestion. In contrast to previous research, this study draws the relation based on empirical data collected on freeways and the data presents a sufficiently large observation sample. A discussion about the influence of weather and study site characteristics on the discharge rate indicates that the relation needs site-specific calibrations. This study sheds light on a better prediction of capacity drop and a better understand in a theoretical sense on the fluctuation of capacity drop.

1. INTRODUCTION

Traffic congestion is a daily phenomenon in major urbanized areas. During peak hours, road capacity is insufficient for the traffic demand and traffic jams occur. Due to the traffic jam, the capacity of the road reduces. This phenomenon is called the capacity drop. Due to the capacity drop, the traffic delays increase once congestion sets in. There are control strategies trying to avoid the capacity drop by limiting the inflow. Another option would be to minimize the capacity drop after congestion sets in. It is however unclear what determines the size of the capacity drop.

In this paper we will consider the queue discharge rate, which we define here as the outflow of a congestion without influences from downstream. Throughout the paper, we will use the word flow for the number of vehicles passing a location per unit of time; in other papers this is sometimes referred to as 'traffic volume' or 'flow rate'. Hence, the queue discharge rate is the maximum flow out of a queue. The term *queue* in this paper refers to a general concept of congestion, including the standing queue with head fixed at the bottleneck and stop-and-go waves with congestion front moving upstream. The *bottleneck* means a fixed point upstream of which a queue forms.

From literature, we know that the capacity drop itself, defined as the difference between the capacity and the queue discharge rate, is not a constant value; it differs under the influence of several factors, such as the characteristics of the study site (e.g. the number of lanes, the traffic flow composition, etc.) and also for different conditions for the same bottleneck. Literature on empirical data shows that the same location can produce different discharge rates [1] and that in the same link the discharge rate can vary in a wide range [2]. These empirical observations reveal a high possibility that control strategies can promote discharge rate to evacuate vehicles in a queue quickly and finally reduce delays [1, 3, 4]. To increase the discharge rate, it is important to know which factors influence the queue discharge rates. However, as far as authors know, there are few empirical analyses revealing what indicates the discharge rate. This might be due to the fact that there is still debate on the mechanism of the various discharge rates (see also section 2).

Speed is mentioned as a possible explanatory variable for the capacity drop. This relationship is tested and quantified in this paper using empirical data. The influence of weather and site-specific calibration is also discussed. The outline of the paper is as follows: we start reviewing literature in section 2, followed by section 3 describing methodologies of identifying the outflow of different types of congestion. The data and study sites are shown in section 4. Section 5 claims an empirical relation between speed in congestion and the outflow of congestion. Section 6 presents conclusions.

2. LITERATURE REVIEW

This section starts with the finding that the capacity drop is a traffic-responsive phenomenon in section 2.1, that is the magnitude of capacity drop depends on different traffic situations. Even at the same location, the queue discharge rate varies due to

different traffic situations. Literature shows congestion levels might be one relevant indicator of the queue discharge rate. Section 2.2 describes previous efforts on revealing the relation between the discharge rate and the congestion level. Finally, this section ends with knowledge gap and research objectives.

2.1 Fluctuations of the capacity drop

The magnitude of the capacity drop mentioned in literature fluctuates. This section first gives the examples of the quoted values for the capacity drop. Then, it is indicated which variables are claimed to influence this value.

The capacity drop hypothesis was confirmed for the first time in 1991 [5, 6]. In literature a large amount of empirical observations of capacity drop can be found. They show that the magnitude of capacity drop can vary in a wide range. Hall and Agyemang-Duah [5] report a drop of around 6% based on empirical data analysis. Banks [6] observes a slight decrease (3%) in capacity across all lanes after breakdown. Cassidy and Bertini [7] estimate the drop between 8% and 10%. Srivastava and Geroliminis [8] observe that the capacity falls by approximately 15% at an on-ramp bottleneck. Chung et al. [1] present a few empirical observations of capacity drop from 3% to 18% at three active bottlenecks. Excluding influences of light rain, they show at the same location the capacity drop can range from 8% to 18%. Cassidy and Rudjanakanoknad [4] observe capacity drop values ranging from 8.3% to 14.7%. An overview of the values is given by Oh and Yeo [9], which collects empirical observations of capacity drop in nearly all previous research before 2008. The drop ranges from 3% up to 18%.

Literature shows that the various capacity drop values do not occur stochastically. The change of traffic conditions, for instance congestion types and on-ramp flow, accompanies different capacity drop values. Srivastava and Geroliminis [8] observe two different capacity drop values, around 15% and 8%, at the same on-ramp bottleneck. These two different magnitudes of the capacity drop accompany different on-ramp flows. It is shown that the higher on-ramp flow, the larger capacity drop is. Chung et al. [1] study the relation between traffic density and capacity drop at three freeway bottlenecks with distinct geometries. Their paper proposes a concept that the upstream density correlates with capacity drop. Leclercq et al. [10] and Laval and Daganzo [11] believe the capacity drop is determined by voids due to lane changing. The void is influenced by both of the number of lane changing and the speed in the congestion at the same time. They model the magnitude of capacity drop as a dependent variable relying on lane changing number and vehicles' speed in congestion. Yuan et al. [2] observe different discharge rates at the same freeway section with a lane-drop bottleneck upstream. It is found the capacity drop can differ depending on the type of queue upstream. Overall, the capacity drop correlates with the local traffic situations, and the vehicles' speed in the congestion seems correlate well with the queue discharge rate.

2.2 Relation between discharge rate and congestion levels

The capacity drop is a traffic-responsive dependent variable. Previous studies contribute to the knowledge of the capacity drop phenomenon, including some indicators on the discharge rate for instance congestion levels, that is the discussion in this section. Muñoz

and Daganzo [12] find a positive relation between the speeds of a moving bottleneck and the queue discharge rate for speeds of 50 km/h and lower. But the empirical data points are very limited and the speed range is very narrow. Moreover, the upper and lower bounds in their research are taken from other data sources in different traffic conditions. Laval and Daganzo [11] extent this research by simulating the same experiment in a broader speed range. They show a positive relation between the capacity and bottleneck speed when speed is higher than 20 km/h and a negative one when speed in congestion is lower than 20 km/h. But this result relies on their simulation model which holds that the mechanism of capacity drop is due to lane changing behavior. This assumption in the model about the lane changing mechanism might be incomplete [13]. Therefore, until now, as far as authors know there is still no thorough empirical analysis revealing a reliable relation between the outflow of congestion and the congestion levels, though this relation is relevant. This paper tries to fill in this gap.

This study expresses the congestion level as vehicle speed in congestion. The reason for the preference of speed in congestion is twofold. Firstly theoretically, previous models [10, 11] and empirical observations [2, 12, 14] hold a promising relation between the speed in congestion and the queue discharge rate. Secondly practically, a promising control strategy which is mainstream metering [3] has a fundamental dependence on the relation between the speed in congestion and the discharging rate.

3. METHODOLOGY

In this paper we want to analyze the queue discharge rate for speeds in the upstream congestion which vary strongly. We will consider a traffic situation with different types of congestion (standing queues and stop-and-go waves) and analyze the queue discharge rate at the same location. Section 3.1 describes the traffic scenario this paper targets. In this scenario, we can observe different traffic congestion states with various vehicle speed at the same location. Section 3.2 presents some requirements about the data for the analysis. The requirements restrict the availability of data and the choice of study sites.Section 3.3 applies shock wave analysis to quantitatively and qualitatively identify the discharge rates and the speed in the corresponding congestion in the traffic scenario. Finally, we choose to fit data with linear and quadratic function to investigate the relation between the speed in congestion and the queue discharge rate, described in Section 3.4.

3.1 Traffic scenario

To obtain a sufficiently wide range of speed in congestion, we need to consider the capacity drop in stop-and-go waves because standing queues where vehicles' speed can not be as low as that in stop-and-go waves are not sufficient for our study. First order traffic flow theory predicts that a bottleneck is activated immediantely after a stop-and-go wave passing by. This traffic scenario is graphically presented in figure 1. The occurance of this traffic state is also empirically confirmed by our previous work [2]. In this scenario different congestion states, including standing queues and stop-and-go waves, and different outflows of congestion can be observed at the same location. This scenario can provide data of different congestion speeds at the same bottleneck. Hence, this paper targets the data collected from this traffic scenario to collect data efficiently.

At bottlenecks which are actived due to local break-down, this scenario can also be found because of boomerang effects. The so-called boomerang effect [15] means that small perturbation in a free traffic flow first travels downstream. While doing so, it increases and traffic breaks down, downstream of the point where the disturbance has entered, close to on-ramp bottleneck. The congestion then propagates upstream. The boomerang effect usually can be observed around an on-ramp bottleneck [7, 16]. This effect can provide the stop-and-go wave we need if the standing queue forms spontaneously.

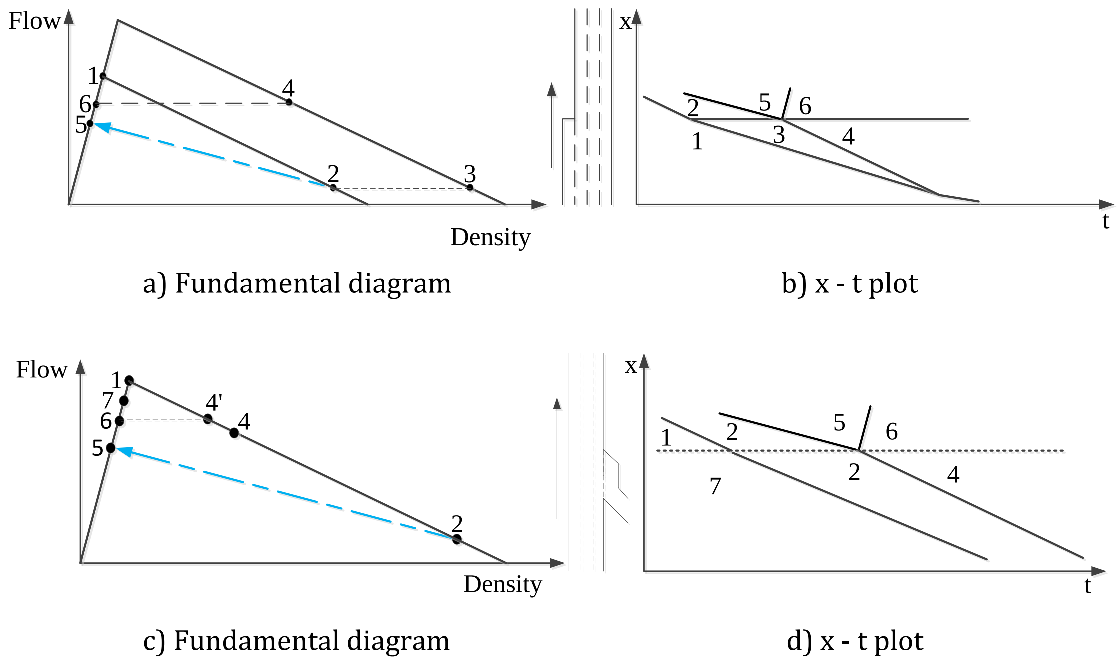


FIGURE 1 Shock wave analysis for distinguishing different outflows with different congestion upstream at a lane-drop (a & b) and an on-ramp (c & d) bottleneck.

3.2 Data requirements

To reveal the relation between the speed in congestion and the discharge rate with thorough empirical analysis, there are several requirements about the data and study sites.

Firstly the data should present a wide range of speed in congestion, that can be solved with the traffic scenario presented in section 3.1. Secondly, to detect the discharge rate of the congestion, the state downstream of the congestion should be free flow. Thirdly, to ensure the detected discharge rate is stable, we need to observe the discharge rate for a certain time, for which we choose 10 mins. Therefore, if the stop-and-go wave originates downstream of a standing queue and propagates soon into the standing queue at the bottleneck, then the short-life discharge rate will not be considered as a stable discharge rate, and the speed data in that stop-and-go wave will be excluded. Meanwhile, as shown in Figure 1 b & d), the long-time observation (10 min) of queue discharge rate (for instance state 5) requires a long homogeneous road section in the downstream of the bottleneck. Last but not least, because capacity drop can be influenced by the number of lanes and the presence of off-ramp in the downstream [9], so when choosing the

appropriate data collection sites we have to ensure there are no such geometrical disturbances. So there should be a homogeneous freeway section downstream the bottleneck for instance at least 2.5 km to ensure vehicles have reached free-flow speed in the homogeneous section and state 5 in Figure 1 can be observed for a long time.

Due to the limited observation samples at one bottleneck, this study chose two different bottlenecks, a lane-drop bottleneck and an on-ramp bottleneck, to collect data. On the one hand, two different study sites impose two more restrictions. Firstly, we have to ensure both of bottlenecks meet the requirements of study sites. Secondly, the number of lanes downstream the bottleneck and the slope of the road section should be the same. On the other hand, two different bottlenecks can shed light on the discussion of site-specific calibration.

Moreover, to see the influence of weather, we also analyse data from a rainy day.

3.3 Analytical solution

The next step of the research, which is the key of the analysis, is to identify traffic states and their accompanying discharge rates. The analytical solution in this study for the identification of different traffic states is to apply shock wave analysis in the studied scenario. Figure 1 shows the shock wave analyses applied for identifying congestion states and their accompanying outflows. The fundamental diagram for the analysis is triangular fundamental diagram. Two bottlenecks, lane-drop (a & b) and on-ramp (c & d) bottleneck shown in Figure 1, are analyzed. Yuan et al. [2] present that the outflow of a stop-and-go wave is lower than that of a standing queue. Note that in [2] the speed in the stop-and-go wave is lower than that in the standing queue. Therefore, this paper expects the outflow of a standing queue (state 6) is higher than that (state 5) of a stop-and-go wave. When a stop-and-go wave passes one detector, we can observe states transformation from state 2 to state 5 at one location. When a bottleneck is active, in the downstream of the bottleneck we can observe traffic states from state 4 to state 6 in a sequence along the freeway.

Figure 1 b) & d) show the spatio-temporal plots of traffic situations. There is a forward moving shock wave between state 5 and state 6. Since these two free flow states, state 5 and 6, always lie in the free flow branch, the shock wave between them should always be positive no matter whose flow is higher. So the assumption that state 5 is below state 6 does not influence the analysis. Therefore, this paper distinguishes these two capacities via this shock wave. Note that the targeted shock wave between state 5 and 6 is not influenced by the state 1. Therefore, the shock wave analysis in Figure 3 can be applied to identify the outflow of stop-and-go wave originating downstream a standing queue.

As shown in Figure 1, discharge rates of both discharge rates of stop-and-go waves and standing queue, i.e. state 5 and state 6 respectively, can be observed in the downstream of the bottleneck. However, the detection of discharge rate of these two different congestion differs slightly. In the downstream of a stop-and-go wave, the detected flow grows as speed increases while the discharge rate of a standing queue remains one value as speed increases. So in Figure 1 the state 5 close to the shock wave between state 2 and 5

actually should lie in the line connecting point 5 and point 2 in fundamental diagram, that is the flow in those states is lower than that in state 5. Only state 5 can show the discharge rate of the stop-and-go wave. Hence, the outflow of standing queue can be detected at any location downstream the bottleneck but that of stop-and-go wave should be detected far away from the bottleneck Overall, at downstream locations far away from the bottleneck both of outflows of stop-and-go waves and standing queues can be detected. Moreover, as shown in Figure 1, the location far away from the bottleneck can clearly show a long-period observation of two outflows, which benefits identifying the stable discharge rate.

3.4 Quantitative solutions

After the identification of traffic states, we need to investigate them quantitatively. This paper applies slanted cumulative curves to investigate flow. The flow is the slope of each slanted cumulative count minus a reference flow. Because during the traffic state transition from state 5 into state 6, there is no remarkable speed in/decrease. Speed in both states is critical speed (maximum speed around critical density)), so we cannot see the shock wave expected in section 3.1. But we can observe the shock wave relying on the change of flow during the traffic state transition, that is we expect to observe the shock wave (between state 5 and state 6 in Figure 1) in the flow evolution plot presented as slanted cumulative curves.

The speed in stop-and-go wave is calculated as the average of all the lowest speed detected at each downstream locations when the studied stop-and-go wave passes and the speed in standing queue is calculated as the average of speed detected at the location close to the downstream front of the standing queue. That means that for each observation, we have two, fairly accurate since averaged, data points. We prefer this method over using all one-minute aggregated data points individually since in this way, each day has the same weight and each traffic condition has the same weight. Otherwise, congestion which lasts longer becomes more influential.

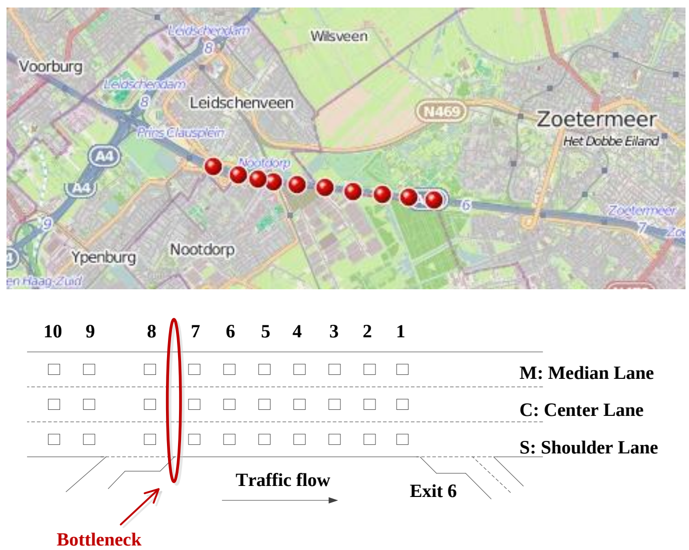
After obtaining the empirical data, this paper fits the flow as function of speed in congestion. Both first order (linear) and a second order (quadratic) polynomial function are used, and it is tested which function can show the relation better. If some data is collected in different weather, then they are separately fitted to show the influence of weather.

4. DATA COLLECTION

To reveal the relation between the speed in congestion and the outflow of congestion, empirical data have been collected at a macroscopic level. The data is collected using dual-loop inductive detectors on the freeway, providing (time mean) average speed and flow on a lane specific level per aggregation interval of 1 minute. According to the requirements in Section 3 about the collection sites, this study studies the targeted scenario on the freeway A4 and freeway A12 in the Netherlands. To test the calibration of the relation in different weather, we also collect the data on A12 on 18 March 2011 marked as a rainy day with 8.8 mm precipitation.

4.1 Data collection sites

a) Data collection site on freeway A4



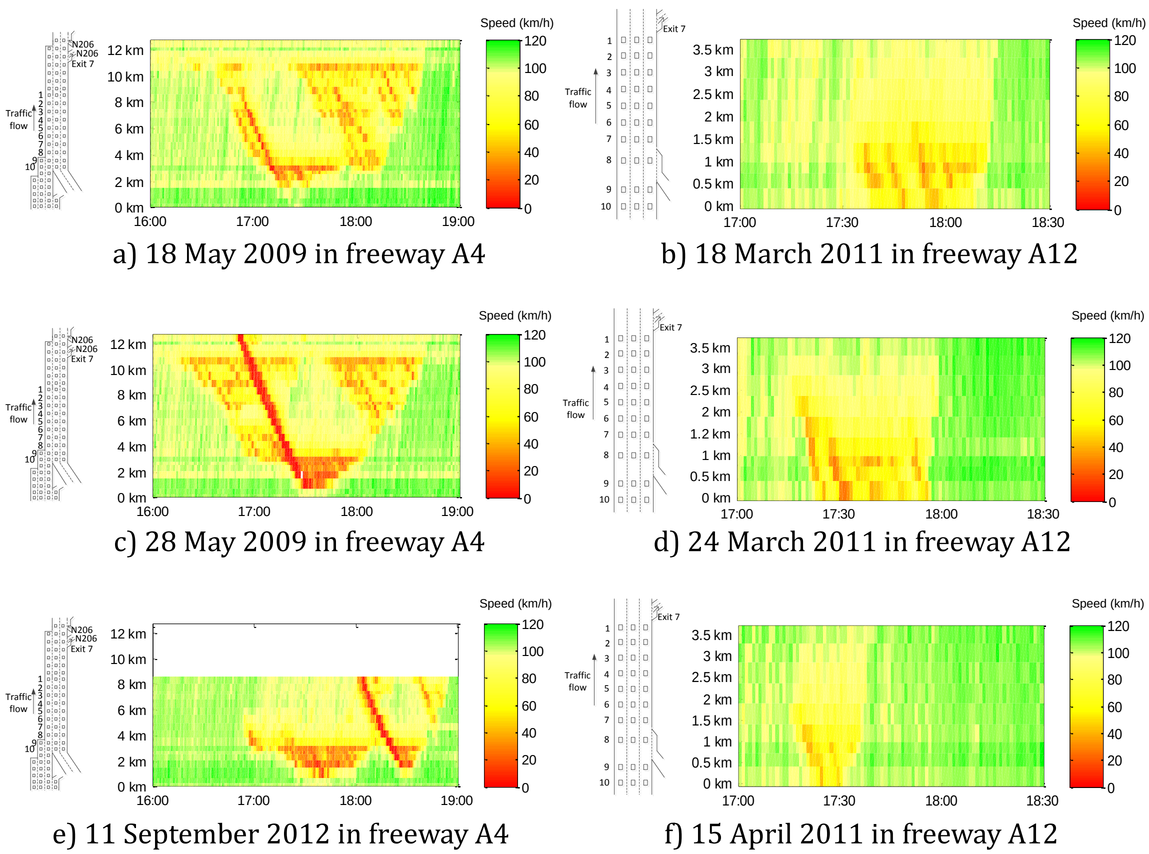
b) Data collection site on freeway A12

FIGURE 2 Data collection site of freeway a) A4 and b) A12.

On the freeway A4 (see Figure 2a), the data is collected around a lane-drop bottleneck in the northbound direction just downstream of Exit 8 (The Hague). Drivers in the targeted road section are driving from a four-lane section to a three-lane section. Thus, the outflow of congestion should be representative for the queue discharge rate of a three-lane freeway. In the downstream end of this bottleneck, there is another lane-drop bottleneck next to Exit 7, which is around 6.5 km further downstream. The data is collected from 10 locations around 5 km, of which 2 are located in the four-lane section and 8 are located in the three-lane section. In this paper, we restrict our study to 10 locations because the speed at location 1 should have reached the critical speed which is vehicles' possible maximum speed after accelerating from congestion and there the state of outflow of congestion can last long enough for a clear observation. In the considered data set (May 2009 and September 2012), three days fulfill the requirement that a stop-and-go wave

triggered a standing congestion. These days are (18 May, 28 May and 11 September). At all these dates, there was no precipitation.

On the freeway A12 (see Figure 2b), we consider an on-ramp bottleneck in the eastbound direction upstream the Exit 6 (Zoetermeer city center). The study sections are three-lane section upstream and downstream of the bottleneck. Hence, the outflow of congestion at this site should be representative for the discharge rate of a three-lane freeways, too. The data is collected from ten locations around 5 km, of which there are 2 upstream of the acceleration lane, 1 in the acceleration lane area as well as 7 in the downstream of the bottleneck. The on-ramp bottleneck is around 2.5 km away from the off-ramp in the downstream end. At location 1 the speed has reached the critical speed and the states of capacities can be identified clearly. The data for March and April 2011 have been checked and 3 days have been found to fulfil the requirements of a stop-and-go wave (included by the boomerang effect) leading to a standing queue, being 18 March, 24 March and 15 April. Note that on 18 March 2011 there is 8.8 mm precipitation. The other two observations are made on sunny day.



a) 18 May 2009 in freeway A4
b) 18 March 2011 in freeway A12
c) 28 May 2009 in freeway A4
d) 24 March 2011 in freeway A12
e) 11 September 2012 in freeway A4
f) 15 April 2011 in freeway A12

FIGURE 3 Speed contour plots of study traffic situations at freeway A4 (a, c, e) and freeway A12 (b, d, f).

4.2 Traffic conditions

To observe various congestion states at the same location, we target both of standing queues and stop-and-go waves in this study. Figure 3 shows the speed contour plots of the traffic operations on freeway A4 (Figure 3a, 3c, 3e) and A12 (Figure 3b, 3d, 3f).

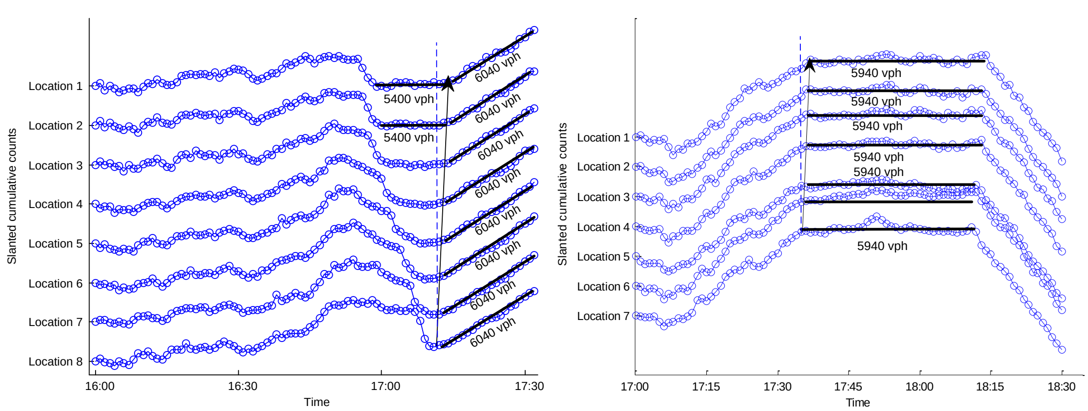
On freeway A4, the targeted bottleneck is the lane-drop bottleneck between the 4-lane section and the 3-lane section. The observations on freeway A4 show the scenario that the lane-drop bottleneck is activated when a stop-and-go wave passes. After the activation of the lane-drop bottleneck, there comes a second stop-and-go wave which is not taken into consideration in this paper. On 11 September 2012, the lane-drop bottleneck was activated at around 17:10 before the stop-and-go wave arrived the bottleneck. Therefore, these three days' data provides 7 congestion states and accompanying discharge rates in total.

In freeway A12, the study bottleneck is an on-ramp bottleneck. The bottleneck is the original location where break down occurs. On 24 March and 15 April 2011, before the break down at the bottleneck, a stop-and-go wave originates in the downstrean of bottleneck. This observation could due to boomerang effects [15] or the drivers relaxation impacts [16]. On 18 March, the stop-and-go wave originated very close to the downstream front of the following standing queue, so we believe there is only standing queue counting for the discharge rates. Therefore, there are 5 congestion states observed in freeway A12.

These congestion states correspond to a broad range of speed, from 5km/h to 60 km/h, that means the data can provide a reliable empirical relation between the speed in congestion and the outflow of the conegstion. Accoring to section 3, all the outflows of congestion are identified at location 1 in both of freeways, A4 and A12.

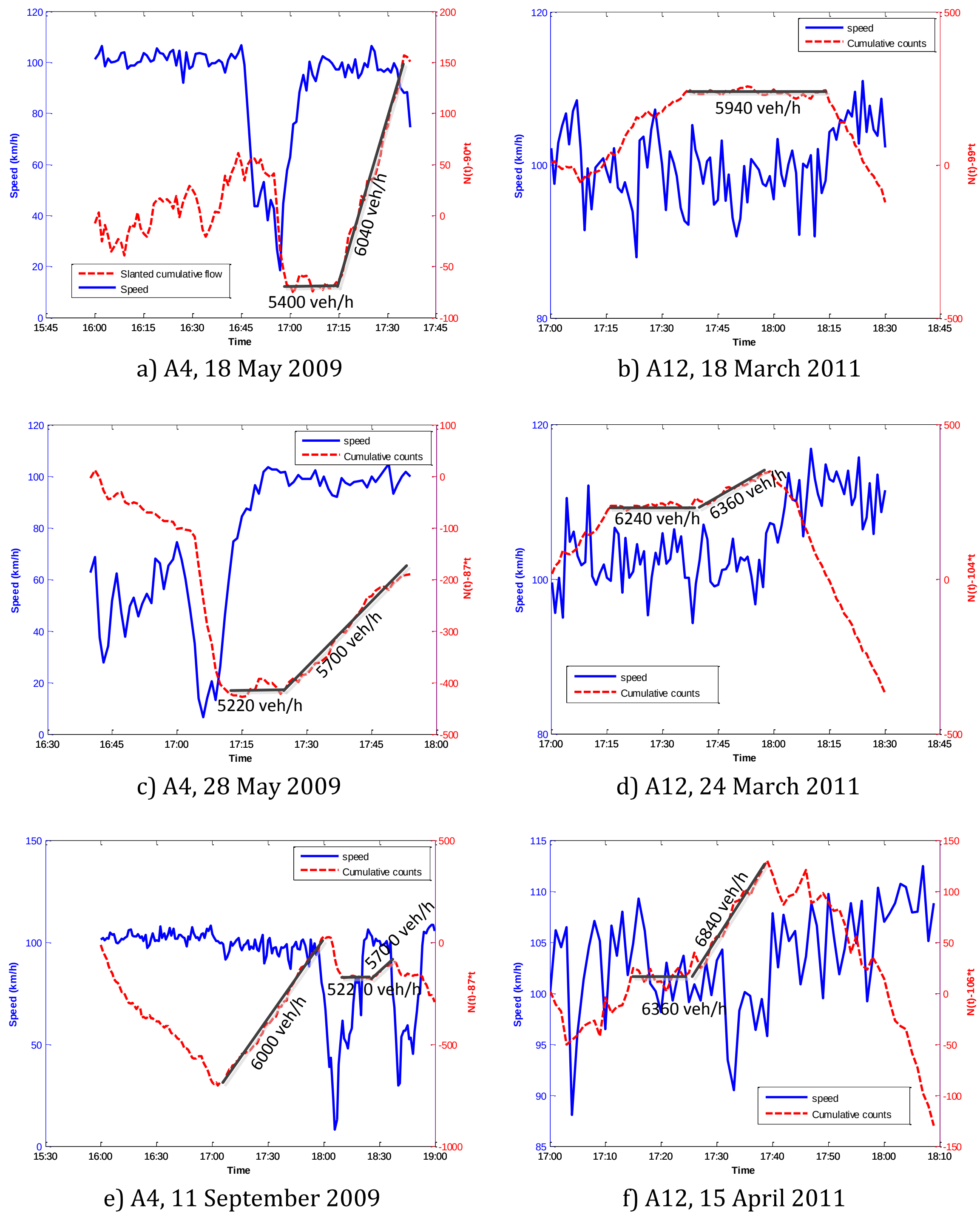
5. RESULTS

5.1 Empirical observations



a) A4, 18 May 2009 b) A12, 18 March 2011

Figure 4 Slanted cumulative counts over three lanes at locations downstream the lane-drop (a) and on-ramp (b) bottlenecks on two study days.



a) A4, 18 May 2009
b) A12, 18 March 2011
c) A4, 28 May 2009
d) A12, 24 March 2011
e) A4, 11 September 2009
f) A12, 15 April 2011

Figure 5 Discharge rates and the average time mean speed detected at location 1 on different study days at freeway A4 (a, c, e) and A12 (b, d, f).

Figure 4 presents slanted cumulative counts over three lanes at 8 locations downstream the lane-drop bottleneck in A4 on 18 May 2009 (Figure 4a) and 7 locations downstream the on-ramp bottleneck in A12 on 18 March 2012 (Figure 4b). The arrow in each figure

shows a clear shock wave which propagates downstream from the bottleneck. Secondly, because the speed before the off-ramp have been over 100km/h (see Figure 5), so we believe that the off-ramp (Exit 7 in A4 and Exit 6 in A12) have negligible or even no influence on the discharge rate.

The empirical observations matches the shock analysis in section 3. At the upstream end of the shock wave, we can see the corresponding congestion. Then the speed in corresponding congestion is extracted.

Figure 5 shows all the stable discharge rates and the average speed detected on at location 1 on both of three-lane freeways. In Figure 5, blue lines stand for speed at location 1 and red dashed lines are the slanted cumulative counts. The black bold lines highlight the stable discharge rates. The value of the discharge rate is attached next to the corresponding black bold line. Note that Figure 3b) shows on 18 March 2011 several clear stop-and-go waves during the activation period of the on-ramp bottleneck, but all those stop-and-go waves originates near location 7 which is only around 0.5 km away from the bottleneck, that means the discharge rate of those stop-and-go waves only persist for a quite short time and hardly influence the standing queue discharge rate detected at location 1. Therefore, in contrast to the observations in other days, there is only one discharge rate indicated on 18 March 2011 (see Figure 5b). Figure 5 shows there are 12 discharge rates extracted in total, including 7 discharge rates on freeway A4 and 5 discharge rates on freeway A12. The twelve discharge rates and the speed in the corresponding congestion are listed in Table 1.

Table 1 Empirical speed in congestion and the outflow of congestion

<table>
<tr><th>Freeway</th><th>Date</th><th>Speed in congestion (km/h)</th><th>Queue discharge rate (veh/h)</th></tr>
<tr><td rowspan="7">A4</td><td rowspan="2">18 May 2009</td><td>13.4</td><td>5400</td></tr>
<tr><td>30.8</td><td>6000</td></tr>
<tr><td rowspan="2">28 May 2009</td><td>6.3</td><td>5220</td></tr>
<tr><td>29.2</td><td>5700</td></tr>
<tr><td rowspan="3">11 September 2012</td><td>34.0</td><td>6000</td></tr>
<tr><td>7.0</td><td>5220</td></tr>
<tr><td>30.1</td><td>5700</td></tr>
<tr><td rowspan="5">A12</td><td>18 March 2011</td><td>45.0</td><td>5940</td></tr>
<tr><td rowspan="2">24 March 2011</td><td>37.6</td><td>6240</td></tr>
<tr><td>48.7</td><td>6360</td></tr>
<tr><td rowspan="2">15 April 2011</td><td>48.7</td><td>6360</td></tr>
<tr><td>61.2</td><td>6840</td></tr>
</table>

5.2 Relation between speed in congestion and capacities

Empirical observations provide 12 data points (listed in Table 1) to show the relation between the speed in congestion and the corresponding discharge rate or outflow of congestion. Their relation is graphically presented in Figure 6. The data collected on sunny days is shown as circles (collected on A4) and squares (collected on A12) while

the data presenting the discharge rate on rainy day is shown as a five-point star. The reason there is only 11 circles in Figure 6 is that two data points corresponding to a same discharge rate 6360 veh/h overlap (see Table 1).

In contrast to previous observations and simulations, this observation shows a broad speed range, from 6 km/h to 60 km/h. In Figure 6 within the wide range of speed, the outflow of congestion also range broadly from 5220 veh/h to 6840 veh/h. Note that the observations of the outflow is much higher than that in [12], which might be due to the different traffic flow compositions, different set up of observations and even different drivers' characteristics in different countries. Meanwhile, the discharge rate in our observations, for instance 6840 veh/h, can be even substantially higher than the three-lane free flow capacity (with 15% proposition of trucks) 6300 veh/h [17] in the Netherlands. The capacity is estimated through Product Limit Method [18]. Though there is no data showing the traffic flow composition in A4 and A12, personal experience shows that the proposition of trucks in A4 and A12 is not as high as 15%. So we believe the discharge rate can be influenced considerably by the proposition of trucks. It is even possible that the discharge rate might increase as the proposition of trucks decreases.

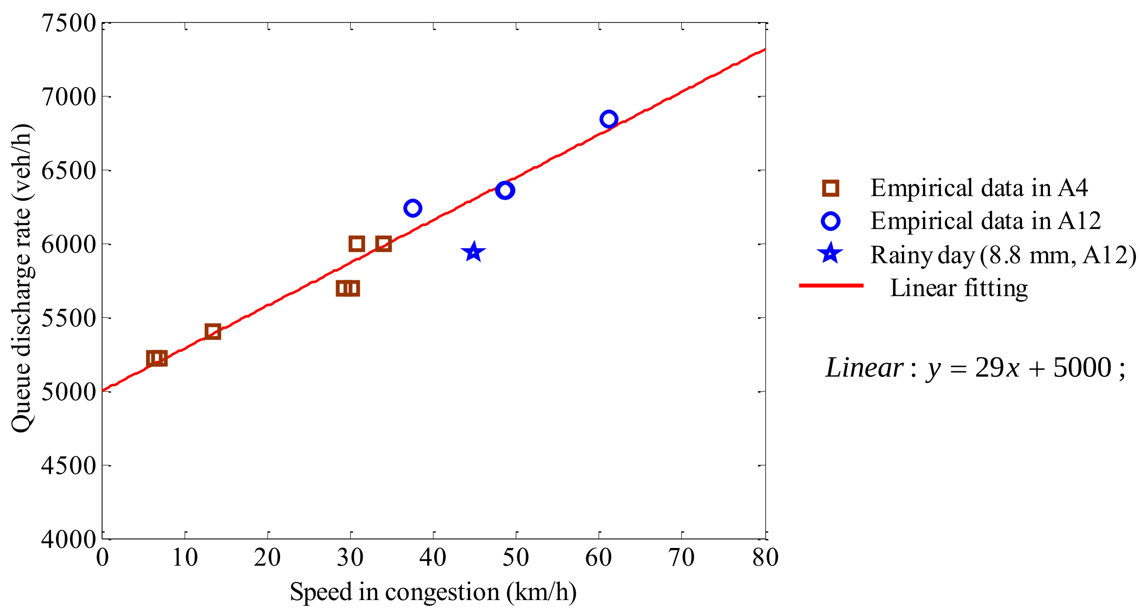


Figure 6 Relation between queue discharge rate and the speed in congestion.

At first, the size of the capacity drop is remarkable. The flows go almost as low as 5000 veh/h, which equals almost a 25% capacity drop. Moreover, the measurements from both locations seem to match quite well. There is a clear influence of speed, but apart there is not much noise.

To quantify the influence of speed, we fit a first order polynomial function to the empirical data (excluding the one collected in rainy day). The linear function fits the data very well. The correlation coefficient γ is 0.9819. The functions are listed in the right of Figure 6. Clearly, that the queue discharge rate increases as the speed in congestion

increases. Even when the speed in congestion is lower than 20km/h the discharge rate still decreases as the speed in congestion decreases, that is different from the simulation results in [11].

Because the data in this study is collected from road sections downstream two different bottlenecks, the qualitative trend that the outflow of congestion increases as the speed in congestion increases might can be applied to lane-drop and on-ramp bottlenecks. But the quantitative function could be greatly influenced by the site characters, such as traffic flow compositions and weather, so it is necessary to calibrate the relation in different set up of traffic conditions.

Moreover, the observation in rainy day, shown as the five-point star in Figure 6, shows a lower discharge rates than that in days without precipitation.

6 CONCLUSION

This paper reveals a relation between the speed in congestion and the outflow of the queue. This relation shows that as the speed in congestion decreases, the outflow decreases substantially. This research targets empirical data on three-lane freeway. The range of speed in congestion is broad enough, from 6 km/h to 60 km/h. The flow at three-lane section ranges from 5220 veh/h to 6840 veh/h. Compared to previous research on the relation between the congestion levels and the queue discharge rate, this paper presents sufficiently large empirical observation samples with a broad speed range.

The most important finding is the very large influence of the speed of the upstream congestion on the queue discharge rate. Depending on the speed the capacity might drop up to 25%. The qualitative trend of the relation between the speed in congestion and discharge rate could be applied to lane-drop bottleneck and on-ramp bottleneck. In fact, the relation is shown for data collected from these two different bottlenecks. However, the quantitative relation requires calibration because this study found the discharge rate is greatly influenced by local traffic situations, such as weather and proposition of trucks. The rainy day in this study shows an exception with a lower queue discharge rate than the other observations. The queue discharge rate here is also considerably different from other research results in different traffic situations.

In the future, the study of the influence of the relation on the fundamental diagram is relevant, which can lead to a better capacity drop prediction. Meanwhile, it is necessary to see how the other conditions such as number of lanes, slope of freeway and weather influence the relation.

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