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# Capacity Drop

## Relationship Between Speed in Congestion and the Queue Discharge Rate

Kai Yuan, Victor L. Knoop, and Serge P. Hoogendoorn

**It has been empirically observed for years that the queue discharge rate is lower than the prequeue capacity. This difference is called the capacity drop. The magnitude of capacity drop varies over a wide range, depending on the local traffic conditions. However, it is unknown what determines the capacity drop value. No thorough empirical analysis has yet revealed a reliable relationship between the capacity drop and the congestion level. This paper fills the gap by revealing, through empirical analysis, the relationship between vehicle speed in congestion and the queue discharge rate. The research studies congested states in which 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 bases the relationship on empirical data collected on freeways, and the data present a sufficiently large observation sample. A discussion about the influence of weather and study site characteristics on the discharge rate indicates that the relationship needs site-specific calibrations. This study provides a better prediction of capacity drop and a better theoretical understanding of the fluctuations in capacity drop.**

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. Traffic jams reduce the capacity of the road. This phenomenon is called the capacity drop. Because of capacity drop, traffic delays increase once congestion sets in. Control strategies are used to avoid capacity drop by limiting the inflow. An option is to minimize the capacity drop after congestion sets in. However, it is unclear what determines the size of the capacity drop.

This paper considers the queue discharge rate, defined here as the outflow of congestion without influence from downstream. Throughout the paper, “flow” means the number of vehicles passing a location per unit of time; in other papers this is referred to as traffic volume or flow rate. Hence, the queue discharge rate is the maximum flow out of a queue. “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 the congestion front moving upstream; “bottleneck” means a fixed point upstream of which a queue forms.

The literature has shown 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., number of lanes, traffic flow composition) and different conditions for the same bottleneck. The 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, the factors that influence the queue discharge rates must be known. However, few empirical analyses have revealed what indicates the discharge rate, perhaps because there is still debate on the mechanism of the various discharge rates.

Speed is mentioned in the literature as a possible explanatory variable for the capacity drop. Empirical data are used in this paper to test and quantify this relationship. The influence of weather and site-specific calibration is also discussed. The outline of the paper is as follows. A literature review in the next section is followed by a description of methodologies for identifying the outflow of various types of congestion. Then the data and study sites are given. An empirical relationship is then claimed between speed in congestion and the outflow of congestion. The final section presents conclusions.

## LITERATURE REVIEW

This section starts with the finding that the capacity drop is a traffic-responsive phenomenon, that is, the magnitude of capacity drop depends on the traffic situation. Even at the same location, the queue discharge rate varies because of the traffic situation. The literature shows that congestion levels may be a relevant indicator of the queue discharge rate. Then, previous efforts to reveal the relationship between discharge rate and congestion level are described. This section ends with the knowledge gap and research objectives.

### Fluctuations of Capacity Drop

The magnitude of the capacity drop mentioned in literature fluctuates. This section gives 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*). Many empirical observations of capacity drop can be found in the literature. These show that the magnitude of capacity drop can vary in a wide range. Hall and Agyemang-Duah reported a drop of about 6% on the basis of an empirical data analysis (*5*).

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Banks observed a slight decrease (3%) in capacity across all lanes after breakdown (*6*). Cassidy and Bertini estimated the drop as between 8% and 10% (*7*). Srivastava and Geroliminis observed that the capacity falls by approximately 15% at an on-ramp bottleneck (*8*). Chung et al. presented a few empirical observations of capacity drop from 3% to 18% at three active bottlenecks (*1*). Excluding influences of light rain, they showed that at the same location the capacity drop can range from 8% to 18%. Cassidy and Rudjanakanoknad observed capacity drop values ranging from 8.3% to 14.7% (*4*). An overview of the values was given by Oh and Yeo, which collects empirical observations of capacity drop in nearly all research before 2008 (*9*). The drop ranges from 3% to 18%.

The literature shows that the various capacity drop values do not occur stochastically. Changes in traffic conditions, for instance, congestion type and on-ramp flow, accompany different capacity drop values. Srivastava and Geroliminis observed two different capacity drop values, of about 15% and 8%, at the same on-ramp bottleneck (*8*). These two different magnitudes of the capacity drop accompanied different on-ramp flows. That work showed that the higher the on-ramp flow, the larger the capacity drop. Chung et al. studied the relationship between traffic density and capacity drop at three freeway bottlenecks with distinct geometries (*1*). Their paper proposed a concept that the upstream density correlates with capacity drop. Leclercq et al. (*10*) and Laval and Daganzo (*11*) believed that capacity drop is determined by voids caused by lane changing. The void is influenced by both the amount of lane changing and the speed in the congestion at the same time. They modeled the magnitude of capacity drop as a dependent variable relying on lane changing number and vehicle speed in congestion. Yuan et al. observed different discharge rates at the same freeway section with a lane-drop bottleneck upstream (*2*). They found that the capacity drop can differ depending on the type of queue upstream. Overall, the capacity drop correlates with local traffic situations, and the vehicles' speed in the congestion appears to correlate well with the queue discharge rate.

### Relationship Between Discharge Rate and Congestion Level

The capacity drop is a traffic-responsive dependent variable. Previous studies have contributed to knowledge on the capacity drop phenomenon, including some indicators on the discharge rate, for instance, congestion levels. Muñoz and Daganzo found a positive relationship between the speeds of a moving bottleneck and the queue discharge rate for speeds of 50 km/h and lower (*12*). But their empirical data points are limited, and the speed range is narrow. Moreover, the upper and lower bounds in their research are taken from other data sources in different traffic conditions. Laval and Daganzo extended this research by simulating the same experiment in a broader speed range (*11*). They showed a positive relationship between 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 relied on their simulation model, which holds that the mechanism of capacity drop is related to lane changing behavior. This assumption in their model about the lane changing mechanism may be incomplete (*13*). Therefore, there is still no thorough empirical analysis revealing a reliable relationship between the outflow of congestion and the congestion levels, although this relationship is relevant. This paper fills 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. First, theoretically, previous models (*10, 11*) and empirical observations (*2, 12, 14*) found a promising relationship between the speed in congestion and the queue discharge rate. Second, practically, a promising control strategy, mainstream metering (*3*), has a fundamental dependence on the relationship between the speed in congestion and the discharging rate.

## METHODOLOGY

This paper analyzes the queue discharge rate for speeds in the upstream congestion, which vary strongly. A traffic situation with two types of congestion (standing queues and stop-and-go waves) is considered, and the queue discharge rate at the same location is analyzed. In the targeted traffic scenario, different traffic congestion states with various vehicle speeds can be observed at the same location. Data requirements for the analysis restrict the availability of data and the choice of study sites. Shock wave analysis is applied to quantitatively and qualitatively identify the discharge rates and the speed in the corresponding congestion in the traffic scenario. Finally, data are fit with linear and quadratic functions to investigate the relationship between speed in congestion and queue discharge rate.

### Traffic Scenario

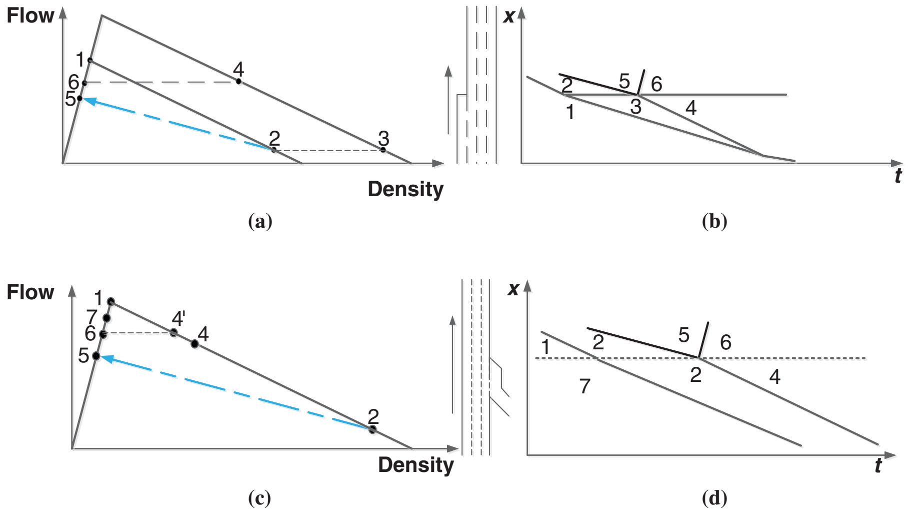
To obtain a sufficiently wide range of speed in congestion, the capacity drop in stop-and-go waves is considered, because standing queues where vehicle speed cannot be as low as that in stop-and-go waves are not sufficient for the study. First-order traffic flow theory predicts that a bottleneck is activated immediately after a stop-and-go wave passes by. This traffic scenario is graphically presented in Figure 1. The occurrence of this traffic state was empirically confirmed in 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 on different congestion speeds at the same bottleneck. Therefore, this paper targets the data collected from this traffic scenario to collect data efficiently.

At bottlenecks that are active because of local breakdown, this scenario can also be found because of so-called boomerang effects (*15*). In the boomerang effect, a small perturbation in a free traffic flow travels downstream. While doing so, it increases and traffic breaks down, downstream of the point where the disturbance has entered, close to the 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 needed in the study if the standing queue forms spontaneously.

### Data Requirements

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

First, the data should present a wide range of speeds in congestion that can be solved with the presented traffic scenario. Second, for detecting the discharge rate of the congestion, the state downstream of the congestion should be free flow. Third, to ensure that



(a) (b)

(c) (d)

**FIGURE 1** Shock wave analysis for distinguishing outflows with different congestion upstream at lane-drop and on-ramp bottlenecks: (*a*) fundamental diagram, lane drop; (*b*) *x-t* plot, lane drop; (*c*) fundamental diagram, on-ramp; and (*d*) *x-t* plot, on-ramp.

the detected discharge rate is stable, the discharge rate must be observed for a certain time, 10 min in this study. If the stop-and-go wave originates downstream of a standing queue and propagates soon into the standing queue at the bottleneck, 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* and *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, because capacity drop can be influenced by the number of lanes and the presence of an off-ramp in the downstream (*9*), the choice of appropriate data collection sites must ensure no such geometrical disturbances. Therefore, there should be a homogeneous freeway section downstream of the bottleneck, for instance, at least 2.5 km, to ensure vehicles have reached free-flow speed in the homogeneous section and State 5 as shown in Figure 1 can be observed for a long time.

Because of the limited observation samples at one bottleneck, two bottlenecks, a lane-drop bottleneck and an on-ramp bottleneck, were used in this study for collecting data. On the one hand, two study sites impose two more restrictions. First, both bottlenecks must meet the requirements of study sites. Second, the number of lanes downstream of the bottleneck and the slope of the road section should be the same for both. On the other hand, two bottlenecks can shed light on the discussion of site-specific calibration.

Moreover, to determine the influence of weather, data from a rainy day are also analyzed.

## Analytical Solution

The next step of the research, which is the key to 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. Two bottlenecks, lane drop (Figure 1, *a* and *b*) and on-ramp (*c* and *d*), are analyzed. Yuan et al. showed that the outflow of a stop-and-go wave is lower than that of a standing queue (*2*). The speed in the stop-and-go wave is lower than that in the standing queue in the work of Yuan et al. (*2*). Therefore, in this paper the outflow of a standing queue (State 6) is expected to be higher than that of a stop-and-go wave (State 5). When a stop-and-go wave passes one detector, states transform from State 2 to State 5 at one location. When a bottleneck is active, in the downstream of the bottleneck one can observe traffic states from State 4 to State 6 in a sequence along the freeway.

Figure 1, *b* and *d,* shows the spatiotemporal plots of traffic situations. There is a forward moving shock wave between States 5 and 6. Since these two free-flow states always lie in the free-flow branch, the shock wave between them should always be positive no matter which 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 through this shock wave. The targeted shock wave between States 5 and 6 is not influenced by State 1. Therefore, the shock wave analysis in Figure 2 can be applied to identify the outflow of the stop-and-go wave originating downstream a standing queue.

As shown in Figure 1, discharge rates of both stop-and-go waves and the standing queue, that is, States 5 and 6, respectively, can be observed in the downstream of the bottleneck. However, detection of the discharge rate of these two congestions 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, State 5 close to the shock wave between States 2 and 5 should lie in the line connecting points 5 and 2 in the 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. Therefore, the outflow of standing queue can be detected at any location downstream of the bottleneck, but that of a stop-and-go wave should be detected far from the bottleneck. At downstream locations far from the bottleneck, outflows of both stop-and-go waves and standing queues can be detected. Moreover, as shown in Figure 1, the location far from the bottleneck can clearly show a long-period observation of two outflows, which benefits identifying the stable discharge rate.

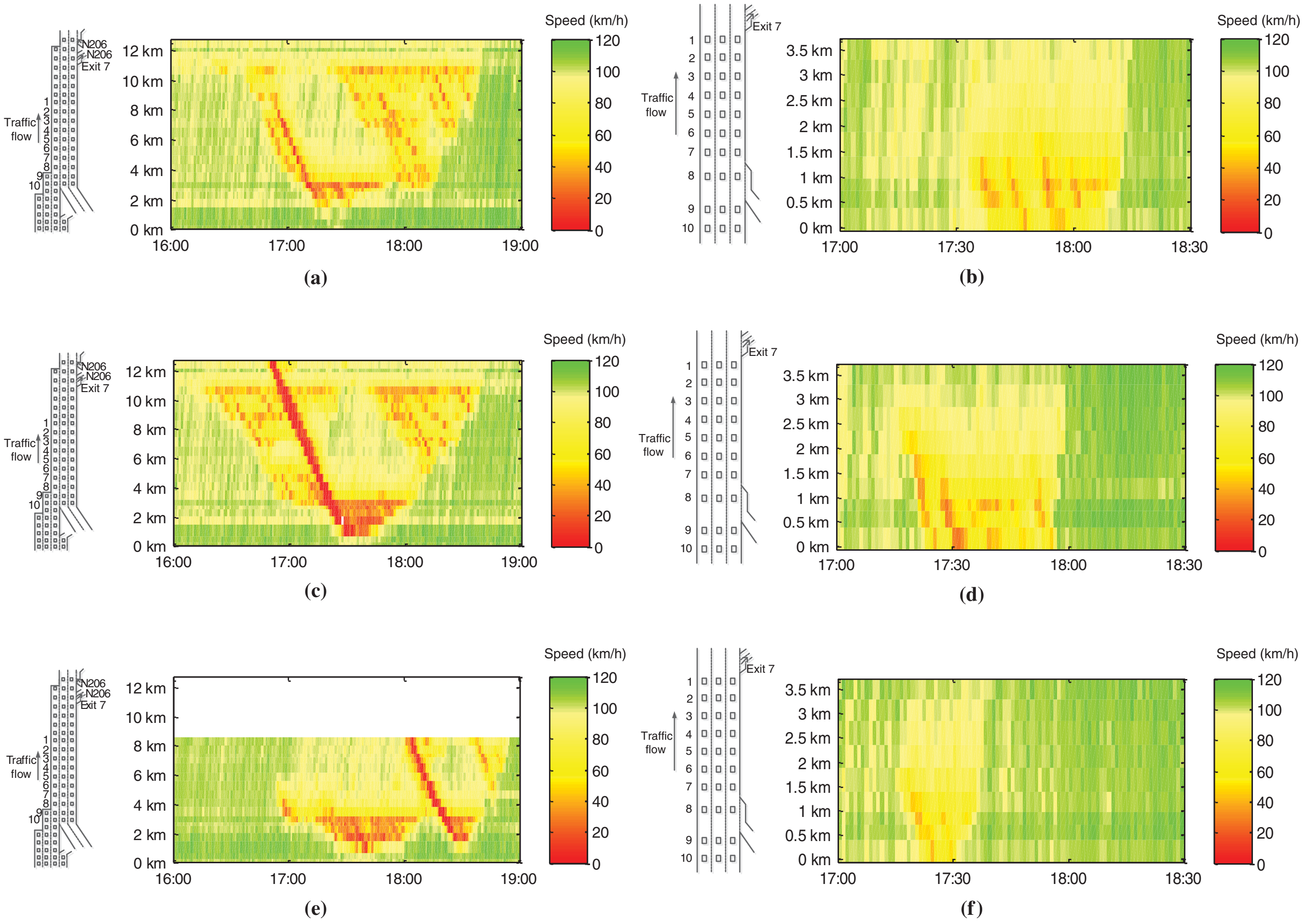


**FIGURE 2** Speed contour plots of study traffic situations: (*a*) May 18, 2009, A4 freeway; (*b*) March 18, 2011, A12 freeway; (*c*) May 28, 2009, A4 freeway; (*d*) March 24, 2011, A12 freeway; (*e*) September 11, 2012, A4 freeway; and (*f*) April 15, 2011, A12 freeway.

### Quantitative Solutions

After the traffic states are identified, they are investigated quantitatively. This study applies slanted cumulative curves to investigate flow. The flow is the slope of each slanted cumulative count minus a reference flow. During the transition from State 5 to State 6, there is no remarkable speed increase or decrease. Speed in both states is critical speed (maximum speed around critical density), so the expected shock wave is not seen. However, one can observe the shock wave relying on the change of flow during the traffic state transition, that is, one expects to observe the shock wave (between States 5 and 6 in Figure 1) in the flow evolution plot presented as slanted cumulative curves.

The speed in the stop-and-go wave is calculated as the average of all the lowest speeds detected at each downstream location when the studied stop-and-go wave passes, and the speed in the 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, there are two data points, which are fairly accurate because they are averaged. This method is preferred to the use of all 1-min aggregated data points individually because, this way, each day has the same weight and each traffic condition has the same weight. Otherwise, congestion that lasts longer becomes more influential.

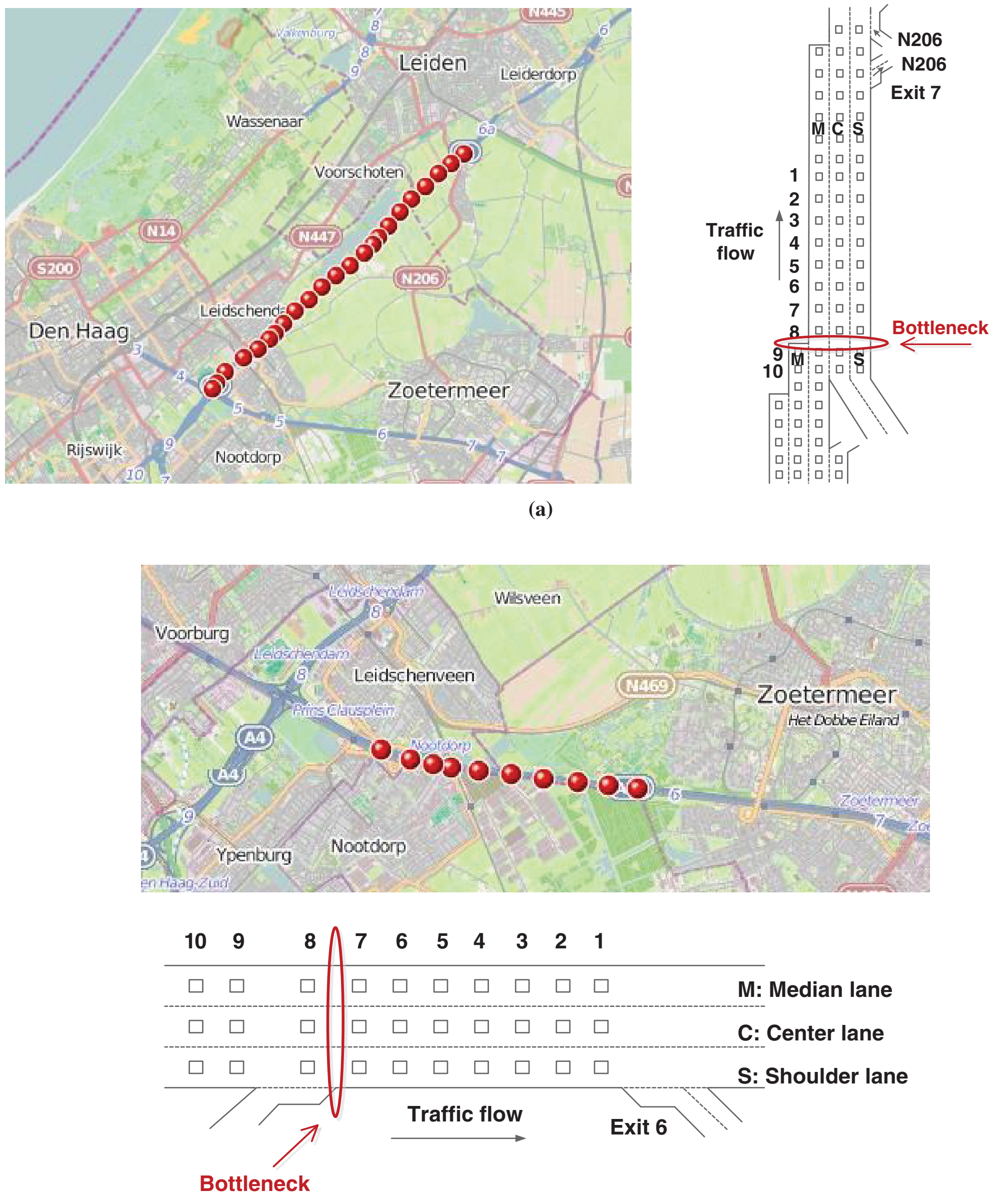
After the empirical data are obtained, this study fits the flow as a function of speed in congestion. Both first-order (linear) and second-order (quadratic) polynomial functions are used, and which function can show the relationship better is tested for. Data collected during different weather conditions are separately fitted to show the influence of weather.

## DATA COLLECTION

To reveal the relationship between the speed in congestion and the outflow of congestion, empirical data were collected at a macroscopic level. The data were collected with dual loop inductive detectors on the freeway, providing (time mean) average speed and flow on a lane-specific level per aggregation interval of 1 min. According to requirements for collection sites, this study used a targeted scenario on the A4 and A12 freeways in the Netherlands. Data were also collected on the A12 freeway on March 18, 2011, a rainy day with 8.8 mm of precipitation, for testing the calibration of the relationship in different weather.

### Data Collection Sites

On the A4 freeway (Figure 3*a*), the data were collected around a lane-drop bottleneck in the northbound direction just downstream



(a)

(b)

FIGURE 3 Data collection sites: (*a*) A4 freeway and (*b*) A12 freeway.

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 are collected from 10 locations around 5 km, of which two are located in the four-lane section and eight are located in the three-lane section. For this paper, the study is restricted to 10 locations because Location 1 should have achieved critical speed, which is the 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), 3 days fulfill the requirement that a stop-and-go wave trigger standing congestion; these days were May 18, May 28, and September 11. On all these dates, there was no precipitation.

On the A12 freeway (Figure 3*b*), an on-ramp bottleneck in the eastbound direction upstream of Exit 6 (Zoetermeer city center) is considered. The study sections are three-lane sections upstream and downstream of the bottleneck. Therefore, the outflow of congestion at this site should be representative for the discharge rate of a three-lane freeway, too. The data are collected from 10 locations around 5 km, of which there are two upstream of the acceleration lane, one in the acceleration lane area, and seven 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 critical speed was reached, and the states of capacities could be identified clearly. The data for March and April 2011 were checked, and 3 days were found to fulfill the requirements of a stop-and-go wave (included by the boomerang effect) leading to a standing queue; these days were March 18, March 24, and April 15. On March 18, there was 8.8 mm of precipitation. The other two observations were made on sunny days.

### Traffic Conditions

To observe various congestion states at the same location, this study targets both standing queues and stop-and-go waves. Figure 2 shows the speed contour plots of the traffic operations on the A4 freeway (Figure 2, *a, c,* and *e*) and the A12 freeway (Figure 2, *b, d,* and *f*).

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

On the A12 freeway, the study bottleneck is an on-ramp bottleneck. The bottleneck is the original location where breakdown occurs. On March 24 and April 15, 2011, before the breakdown at the bottleneck, a stop-and-go wave originated in the downstrean of the bottleneck, which may have been caused by boomerang effects (*15*) or the effect of driver relaxation (*16*). On March 18, the stop-and-go wave originated very close to the downstream front of the following standing queue, so it is thought that there is only a standing queue counting for the discharge rates. Therefore, there are five congestion states observed on the A12 freeway.

These congestion states correspond to a broad range of speed, from 5 to 60 km/h, which means the data can provide a reliable empirical relationship between the speed in congestion and the outflow of the congestion. According to the methodology section, all outflows of congestion are identified at Location 1 on both the A4 and A12 freeways.

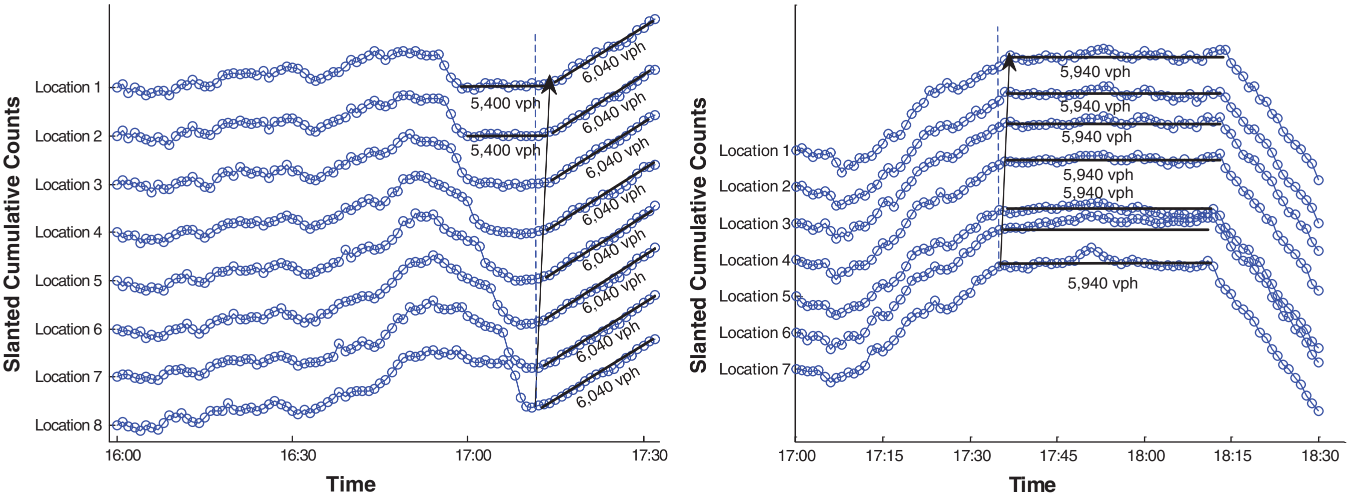
## RESULTS

### Empirical Observations

Figure 4 presents slanted cumulative counts for three lanes at eight locations downstream of the lane-drop bottleneck on the A4 freeway on May 18, 2009 (Figure 4*a*), and seven locations downstream of the on-ramp bottleneck on the A12 freeway on March 18, 2012 (Figure 4*b*). The arrow in each figure shows a clear shock wave, which propagates downstream from the bottleneck. Also, because the speed before the off-ramp was greater than 100 km/h (Figure 5), the off-ramp (Exit 7 on the A4 freeway and Exit 6 on the A12 freeway) is thought to have negligible or even no influence on the discharge rate.

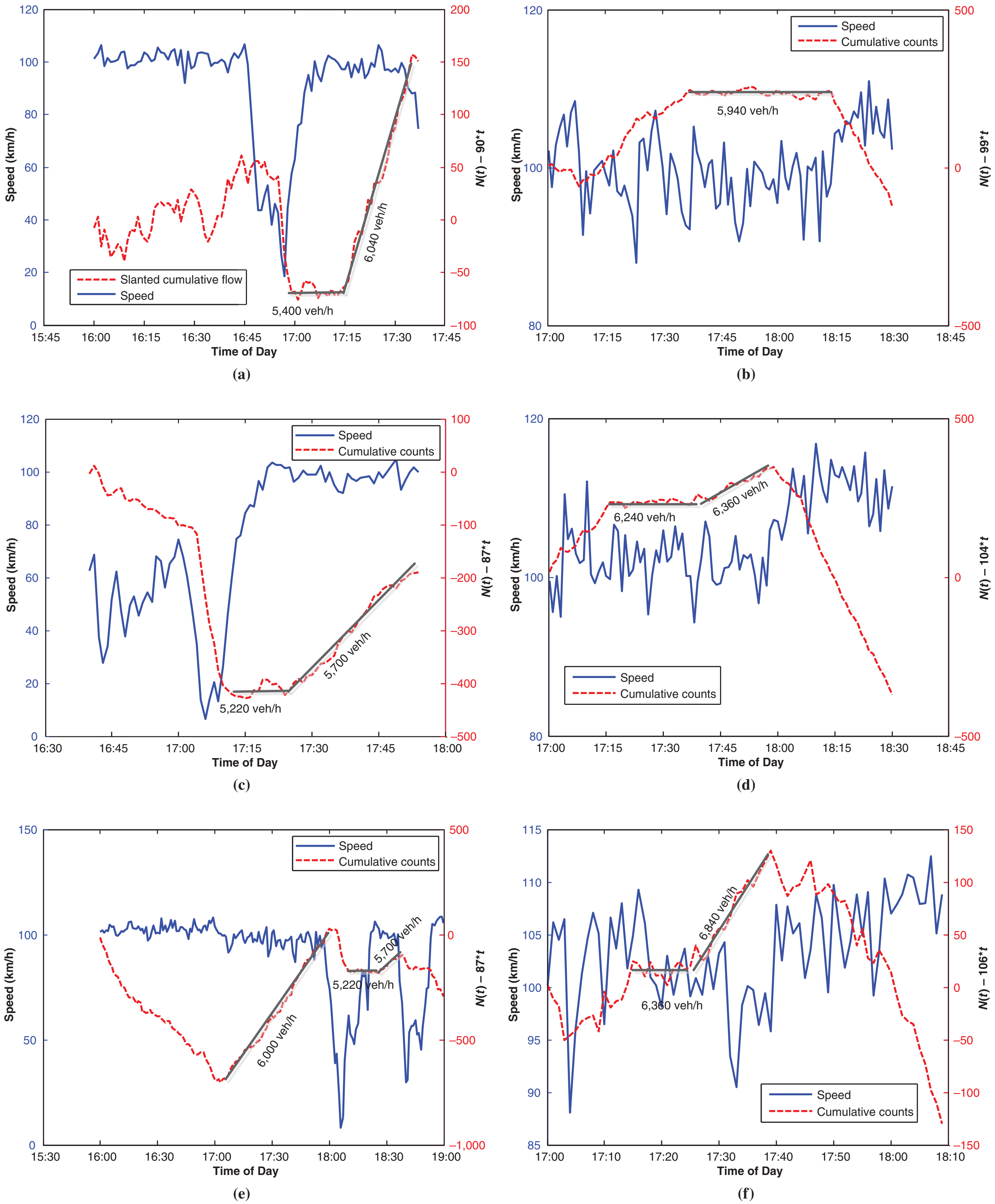
The empirical observations match the shock analysis in the methodology section. The corresponding congestion can be seen at the upstream end of the shock wave. Then the speed in the corresponding congestion is extracted.

Figure 5 shows all the stable discharge rates and the average speed detected at Location 1 on both three-lane freeways. In Figure 5, blue lines indicate speed at Location 1 and red dashed lines indicate the slanted cumulative counts. The bold black lines highlight the stable discharge rates. The value of the discharge rate is attached next to the corresponding bold black line. Figure 2*b* shows on March 18, 2011, several clear stop-and-go waves during the activation period of the on-ramp bottleneck, but all those stop-and-go waves originate near Location 7, which is only about 0.5 km from the bottleneck, which means that the discharge rate of those stop-and-go waves persists only for a very short time and has little influence on the standing queue discharge rate detected at Location 1. Therefore, in contrast to the observations on other days, there is only one discharge rate indicated on March 18, 2011 (Figure 5*b*). Figure 5 shows that 12 total discharge rates are extracted, including seven discharge rates on the A4 freeway and five on the A12 freeway. The 12 discharge rates and the speeds in the corresponding congestion are listed in Table 1.



(a) (b)

FIGURE 4 Slanted cumulative counts over three lanes at downstream locations on two study days: (*a*) lane-drop bottleneck, A4 freeway, May 18, 2009, and (*b*) on-ramp bottleneck, A12 freeway, March 18, 2011 (vph = vehicles per hour).



(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 5 Discharge rates and average time at which mean speed was detected at Location 1: (*a*) A4 freeway, May 18, 2009; (*b*) A12 freeway, March 18, 2011; (*c*) A4 freeway, May 28, 2009; (*d*) A12 freeway, March 24, 2011; (*e*) A4 freeway, September 11, 2009; and (*f*) A12 freeway, April 15, 2011.

**TABLE 1 Empirical Speed in Congestion and Outflow of Congestion**

| Freeway | Date | Speed in Congestion (km/h) | Queue Discharge Rate (vph) |
|---|---|---|---|
| A4 | May 18, 2009 | 13.4 | 5,400 |
| | | 30.8 | 6,000 |
| | May 28, 2009 | 6.3 | 5,220 |
| | | 29.2 | 5,700 |
| | September 11, 2012 | 34.0 | 6,000 |
| | | 7.0 | 5,220 |
| | | 30.1 | 5,700 |
| A12 | March 18, 2011 | 45.0 | 5,940 |
| | March 24, 2011 | 37.6 | 6,240 |
| | | 48.7 | 6,360 |
| | April 15, 2011 | 48.7 | 6,360 |
| | | 61.2 | 6,840 |

## Relationship Between Speed in Congestion and Capacities

Empirical observations provide 12 data points (listed in Table 1) to show the relationship between the speed in congestion and the corresponding discharge rate or outflow of congestion. Their relationship is graphically presented in Figure 6. The data collected on sunny days are shown as circles (collected on the A4) and squares (collected on the A12 freeway); data presenting the discharge rate on rainy days are shown as a five-point star. There are only 11 circles in Figure 6 because two data points corresponding to the same discharge rate of 6,360 vehicles per hour (vph) overlap (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 ranges broadly, from 5,220 to 6,840 vph. The observation of the outflow is much higher than that in the work of Muñoz and Daganzo (*12*), possibly because of the different traffic flow compositions, different setup of observations, and even different driver characteristics in various countries. Meanwhile, the discharge rate in the observations in this study, for instance, 6,840 vph, can be even substantially higher than the three-lane free flow capacity (with 15% proposition of trucks) of 6,300 vph in the Netherlands (*17*). The capacity is estimated with the product limit method (*18*). Although there are no data showing the traffic flow composition on the A4 and the A12 freeways, the authors' experience has shown that the proposition of trucks on the A4 and the A12 freeways is not as high as 15%. Thus the discharge rate can be influenced considerably by the proposition of trucks. It is even possible that the discharge rate could increase as the proposition of trucks decreases.

At first, the size of the capacity drop is remarkable. The flows go almost as low as 5,000 vph, almost a 25% capacity drop. Moreover, the measurements from both locations appear to match quite well. There is a clear influence of speed, but there is not much noise.

To quantify the influence of speed, a first-order polynomial function was fit to the empirical data (excluding those collected on a rainy day). The linear function fits the data very well. The correlation coefficient $\gamma$ is 0.9819. The functions are as shown in Figure 6. The queue discharge rate is shown to increase as the speed in congestion increases. Even when the speed in congestion is lower than 20 km/h, the discharge rate decreases as the speed in congestion decreases, different from other simulation results (*11*).

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

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

## CONCLUSION

This paper revealed a relationship between the speed in congestion and the outflow of the queue. This relationship shows that as the speed in congestion decreases, the outflow decreases substantially. The research targeted empirical data on a three-lane freeway. The

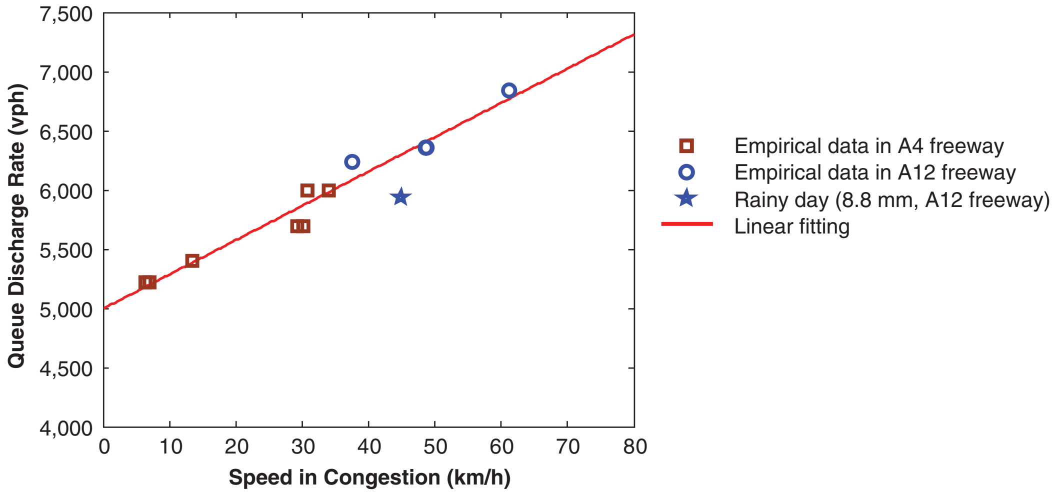


FIGURE 6 Relationship between queue discharge rate and speed in congestion (linear, $y = 29x + 5{,}000$).

range of speed in congestion is broad enough, from 6 to 60 km/h. The flow at the three-lane section ranges from 5,220 to 6,840 vph. Compared with previous research on the relationships between congestion levels and queue discharge rate, this paper presented sufficiently large empirical observation samples with a broad speed range.

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

The study of the influence of the relationship on the fundamental diagram can lead to better capacity drop prediction. Meanwhile, it is necessary to observe how other conditions, such as number of lanes, slope of freeway, and weather, influence the relationship.

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