Empirical Proof of the Characteristics of the Queue Discharge Rate under Different Rainfall Conditions on an Active On-Ramp Bottleneck

Hanzel Mejia[a], Ampol Karoonsoontawong[b], Kunnawee Kanitpong[c]

[a]Department of Civil Engineering, Faculty of Engineering, Visayas State University, Visca, Baybay City, 6521, Leyte, Philippines.
[b] Department of Civil Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand.
[c]Department of Civil Engineering and Infrastructure Engineering, School of Engineering and Technology, Asian Institute of Technology, Klong Luang, Pathumthani 12120, Thailand.

Abstract: Empirical studies show that queue discharge rate is lower than pre-queue capacity in congestion. This is the capacity drop phenomenon. All previous research about this event used data during clear weather conditions. This is the first time that empirical relationships between queue discharge rate and weather conditions have been studied. Previous studies show that the capacity drop is triggered by a critical density. Once this density is reached, a drop in the discharge rate is expected. We show that this critical density decreases during any weather condition. Previous studies also prove that the capacity drop is related to speed in congestion but that this might not be true during inclement weather. We show that queue discharge rate is correlated to the speed of congestion in any weather condition. We have also shown for the first time that the speed in congestion and the percentage of the capacity drop have a negative linear relationship.

Keywords: capacity drop; critical density; speed-in-congestion; discharge rate; weather conditions

1. INTRODUCTION

The roadway capacity is one of the most important variables in the dynamics of traffic flow. Determining capacity is critical in dynamic traffic management and control strategies. It also has implications in planning, design, and operations together with other traffic flow variables. It has been widely observed that when oversaturation starts, queues ensue, and vehicles discharge from the bottleneck at a rate lower than the pre-queue flow. This is known as the "the capacity drop phenomenon", as defined by the Highway Capacity Manual (2022).

The capacity value is often considered constant, which represents the maximum traffic a roadway facility can carry. The Highway Capacity Manual (HCM) is a publication frequently used by researchers, academics, and transportation practitioners to estimate capacity. Freeway segment capacity is defined as "the maximum flow rate associated with the occurrence of some type of breakdown, which results in lower speeds and higher densities" (HCM, 2022). With this, HCM calculates capacity as a function of free flow speed (FFS). Capacities presented in the manual are under base conditions and can be adjusted through capacity adjustment factors (CAF) and speed adjustment factors (SAF).

Capacity concepts are directly related to flow, and HCM mentions three types of flow, namely oversaturated flow, undersaturated flow, and queue discharge rate. In the HCM methodology, a breakdown in the bottleneck is "the sudden drop in speed of at least 25% below the free-flow speed (FFS) for a sustained period of at least 15 min that results in queuing upstream of the bottleneck" (HCM, 2022). The bottleneck is considered to have recovered when speeds return to 10% of the pre-queue speed and are sustained for at least 15 min.

Over the years, a number of studies have examined the effects of adverse weather conditions on road traffic with a focus on pre-breakdown flow rates and maximum flow rates. It has been found that weather conditions, especially precipitation rates, incur detrimental effects on traffic flow variables. HCM incorporates weather adjustment factors to base capacities.
The flow in a highway segment is a function of the speed of the traffic stream and the density. Under bad weather conditions, drivers tend to decrease speed and increase the distance between them and the next vehicle in front. Actions such as these could reduce maximum flow and corresponding traffic intensities. For this reason, it is important to incorporate traffic management strategies and techniques in response to bad weather conditions.
While there have been many studies considering the effect of weather on pre-breakdown flows, this has not been considered at all for queue discharge rates. In fact, it was not until the 2016 HCM edition that the queue discharge rates were incorporated in the Highway Capacity Manual based on the paper of Hu, Schroeder, and Rouphail (2012).

Once the breakdown occurs and queues begin to form, the flow rates discharging from the queue at the bottleneck are generally lower than the pre-breakdown capacity. This post-breakdown or queue discharge flow rate is defined as the 15 min flow rate during oversaturated conditions. The difference between queue discharge flow rate and pre-breakdown capacity varies considerably in the literature, with an average value of about 7% according to Hu, Schroeder, and Rouphail (2012), and this is used in the HCM as a default value for the capacity drop. This reduced capacity is used in the oversaturated analysis procedure to estimate the rate at which queues will form and dissipate once demand exceeds capacity. When the queue is cleared, the segment's original pre-breakdown capacity is restored.

Banks (1990) was one of the first to suggest the capacity drop phenomenon, but there are earlier papers, such as Gazis and Edie (1968), who did not mention the phenomenon of the capacity drop but were able to fit a fundamental diagram that has a gap based on the experimental data they have taken in the Lincoln Tunnel in New York City.

The capacity drop phenomenon was also confirmed by Hall and Agyemang-Duah (1991). Since then, many empirical studies have been conducted to quantify the capacity drop ranging between 0.5% and 35% (Cassidy and Bertini, 1999; Cassidy and Windover, 1995; Bertini and Malik, 2004; Cassidy and Rudjanakanoknad, 2005; Chung et al., 2007; Oh and Yeo, 2012; Srivastava and Geroliminis, 2013; Yuan et al., 2015; Chen et al., 2017; and Lee et al., 2021). In consideration of overall traffic delays, the rate of queue discharge is of significant importance.

Numerous research was already conducted about the capacity drop, but some significant features are still unclear. The extent of how the queue discharge rate reduces downstream on the onset of rainfall and whether it has a relationship with traffic flow variables is still unknown. There have been a significant amount of studies that look into the effect of weather conditions on the pre-breakdown flow rate at a given location (Ibrahim and Hall, 1994; Smith et al., 2005; Agarwal et al., 2006; Mejia and Sigua, 2018; and Heshami et al., 2019) but not on the queue discharge rates.

This current study will then exhibit additional empirical observations to forward an understanding of the capacity drop. Findings can be used in control principles mitigating congestion and to further understand traffic processes. This study would also answer the gap in previous research on the capacity drop, which excludes the effects of rainfall since most studies about the capacity drop were conducted during clear conditions, albeit there are a few exceptions.

2. LITERATURE REVIEW

In the reverse lambda fundamental diagram suggested by Koshi and Iwasaki (1981), the congested branch does not reach the maximum point compared to the uncongested side. The discontinuity is the capacity drop phenomenon. Previous studies give the value of the capacity drop between 0.5 and 35% of the pre-queue capacity. In those studies, traffic data are collected from bottlenecks such as merges, lane reductions, and horizontal curves.
The following are the causes and relationships found by researchers related to the capacity drop:

- The capacity drop is caused by variance-driven gaps, which is the difference in time headways adapted by drivers (Treiber and kesting, 2013);
- Due to lane changes on the highway, voids are created. This is the cause of the capacity drop together with speed in the congestion (Laval and Daganzo, 2006; Leclercq et al., 2011);
- The density near the bottleneck is highly correlated with the capacity drop. Once the critical density is reached, the capacity drop can be expected (Chung et al., 2007);
- The number of lanes is a critical influencing factor of the capacity drop. If there are more lanes, the drop decreases due to the drivers having more options for lane changing (Oh and Yeo, 2012);
- The higher the on-ramp flow, the larger the capacity drop is (Oh and Yeo, 2012);
- The value of mainline flow divided by ramp flows has a significant effect on the level of the drop (Oh and Yeo, 2012);
- The capacity drop can differ depending on the type of congestion upstream (Yuan et al., 2016);
- Variable driver characteristics cause traffic hysteresis for different drivers and have an impact on the development of traffic oscillations and the bottleneck discharge rate, which causes the capacity drop. This indicates that driving behavior is different for drivers before they enter the congestion compared to after they come out of the congestion (Chen et al., 2014);
- Vehicles' speed in congestion seems to have a linear correlation with the queue discharge rate (Yuan et al., 2015);
- Lane-changing behavior is not more of a reason for the capacity drop than the type and severity of congestion upstream (Oh and Yeo, 2015);
- Spatially distributed lane changing contributes to the capacity drop (Chen and Ahn, 2018);

- The relationship between the capacity drop and on-ramp ratio, which is the on-ramp traffic flow divided by the on-ramp traffic flow plus the upstream traffic flow at a given interval, is a convex quadratic polynomial (Lee et al., 2015).

"The main cause of the capacity drop is not identified yet. Some argue it is lane changing, others argue it is the limited acceleration, whereas others argue it is the difference in acceleration. This remains an active field of research, both for causes of the capacity drop and for ways to control it" (Knoop, 2021).

While several pieces of research were already conducted about the capacity drop, there are still empirical characteristics that are unknown. Table 1 summarizes the existing knowledge about the capacity drop, showing weather condition considerations. This paper will answer the gap in previous studies on capacity drop, which excludes the effects of rainfall. Most of the studies presented in Table 1 do not mention bad weather conditions. It is assumed that the data gathered in those research were during clear weather conditions. Others specifically mention data gathering during clear skies and no measurable precipitation, such as Cassidy and Bertini (1999). Bertini and Malik (2004) specified that data were gathered during dry and sunny conditions except for one day when light rain was experienced. Nevertheless, they considered the event negligible and used the data in the analysis. In the literature, two papers specifically mentioned gathering data under bad weather conditions (Chung et al., 2007; Yuan et al., 2015). These two papers will be discussed in detail.

Chung et al. (2007) studied the relationship between density, which is the accumulation of vehicles in the shoulder lane, and the capacity drop near a bottleneck on three different bottleneck sites. They concluded that density is a good predictor of the capacity drop. When a certain threshold is reached, the capacity drop can be expected to happen. They called this the critical density. They showed the potential of managing the capacity drop by controlling this density. The average capacity drop is 13.09%, 6.27%, and 5.75% for merge, lane drop, and horizontal curve bottlenecks, respectively. While there are variations across days, the capacity drop is common among them. The only exception with the normal value of the drop is on the day with light rain (23 October, 2003). They mentioned that this is unique and that there is a long way in explaining the observation. The densities at the capacity drop were also common across days. They conclude that when a density of 208 veh/km is reached, the capacity drop will follow. Again, this is not the case during bad weather when the density at capacity is at 188 veh/km.

Another research that included rainfall data in their analysis is in Yuan et al.(2015). They discussed that prediction of the capacity drop could be improved by relating it to the speed of congestion. They plotted the speed in congestion against the queue discharge rate and fitted a linear function. The correlation coefficient is 0.9819. As the speed in congestion increases, the queue discharge rate also increases. Although they gathered data on a rainy day (18 March 2011), this observation was not included in the linear fit. However, they noted that the rainy data produced a lower discharge rate than that for days with clear weather conditions.

Since other traffic flow parameters are affected by weather conditions, as shown in previous research, this current paper conjectures that the light rain observations of Chung, Rudjanakanoknad, and Cassidy (2007) can be expanded. It will be shown later in this paper that the capacity drop follows when a certain density is achieved. However, the value will be reduced significantly under different rainfall conditions. This observation is reproducible across many days.

Both research that included a rainy day in their data observed abnormalities in their observation. While both claim to have reduced queue discharge observation on those days, a relationship cannot be concluded as only one data point was involved. Both studies also did not explain the cause of this happening.

This paper will expand on this limitation to include more data points with bad weather conditions and specifically address this. One feature that has not been explored yet is the relationship between weather and capacity drop. Most of the proposed explanations on the cause of the capacity drop describe a relationship between driving patterns also affected by weather conditions. With this, the current research will show more empirical observations to forward traffic research on the capacity drop phenomenon. The relationships will be used in management strategies to mitigate congestion.

3. STUDY SITE, DATA, AND ANALYSIS

The data analyzed are 5 min aggregated traffic data collected using a microwave radar sensor on an on-ramp bottleneck at the Burapha Withi Expressway in Bangkok, Thailand. The expressway is an elevated limited-access highway. This paper considers the southbound direction at Sta. 16 + 600I to 21 + 150I. This on-ramp was selected because of its proximity to the Automatic Weather Station (AWS) in the area, which is around 3 km away from Sta. 16 + 600I. This consideration will be important to the analysis since this paper relates precipitation rate to traffic flow dynamics. The activation of the bottleneck is measured 650 m from it, and the queue discharge rate is measured using the sensor at 21 + 150I, which is 4550 m away downstream. This distance ensures that there is no external cause of congestion further downstream and that the cause of the breakdown will be endogenous. This site occasionally becomes an active bottleneck where the queue discharge rate is not affected by downstream traffic conditions. This is an important consideration for the phenomenon to be considered a capacity drop. The study area diagram is shown in Figure 1.

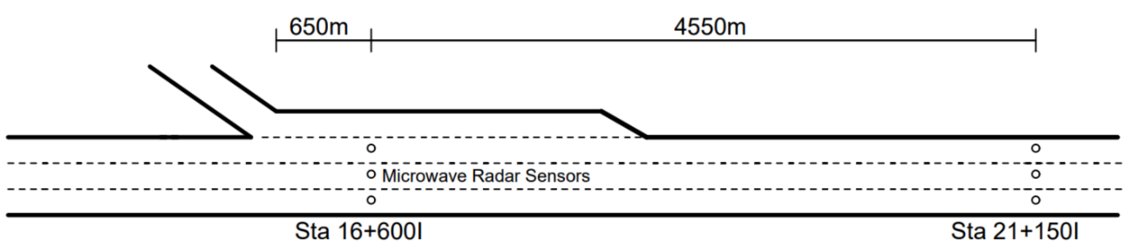

Figure 1. On-ramp bottleneck data site, Burapha Whiti Expressway, Bangkok, Thailand.

Data for analysis are collected for the whole year of 2022. This includes days with and without precipitation. Data is representative of clear, light, medium, and heavy rainfall conditions. The characteristics of the bottleneck are identified by comparing the upstream and downstream location speeds. The bottleneck is considered active when the upstream speeds dramatically drop while the downstream remains at free-flow speed. After this, the activation time, bottleneck duration, and traffic states can be identified. Classifications are free-flow, transition to bottleneck, bottleneck, and recovery from the bottleneck. The bottleneck period is when the upstream speed is less than 70 kph, and the downstream speed is sustained at more than 80 kph for at least 15 min.

Table 1. Weather consideration in previous studies.

Researcher	**Traffic Data**	**Findings**	**Weather Condition Consideration**
Banks (1990)	23 days in June 1989 (only nine days were used in the analysis)	One of the first papers to show the capacity drop phenomenon wherein bottleneck capacities start to decrease when queues near the on-ramp form.	Not mentioned
Bertini and Leal (2005)	Five days of 16 November–3 December 1998	Further proof of the capacity drop that occurs sequentially in time and space. They used slanted cumulative curves to show the change in flow.	
Srivastava and Geroliminis (2013)	Five days across different years (one in 2000, two in 2001, and two in 2008)	Showed empirical evidence of the capacity drop phenomenon using a new methodology known as phase diagrams.	
Oh and Yeo (2012)	203 cases of data from 16 study sections (dates not mentioned)	Showed that the capacity drop and the number of lanes have a negative relationship. They also used a systematic methodology of detecting the capacity drop using downstream and upstream speed comparisons.	
Cassidy and Bertini (1999)	Six days between 1995–1997	Concluded that bottlenecks occur at a fixed reproducible location. They also described the discharge flows as nearly constant that only vary slightly with a fixed rate.	Only used data during clear skies and no measurable precipitation.
Bertini and Malik (2004)	20–23 March 2000 (4 days)	Showed that the bottleneck is activated because of drivers slowing down as they enter the shoulder lane.	Dry and sunny except on 23 March 2000, when a light rain was experienced and was considered negligible.
Chung, Rudjanakanoknad, and	12 morning rush periods in 2002–2004	They showed that the capacity drop has a relationship with vehicle densities. They were the first ones to also extend the capacity drop observations to other bottleneck types: merge bottleneck, reduction on	One day was marked with inclement weather (light rain).

Cassidy (2007)		travel lanes, and horizontal curve. They also observed a difference in the capacity drop when there is inclement weather but did not explain it further.	
Yuan, Knoop, and Hoogendoorn (2015)	Six days across different years (two in 2009, three in 2011, and one in 2012)	They showed that the capacity drops and the speed in congestion have a linear relationship. They also showed that weather may have an effect on the capacity drop but it was inconclusive since they only have one observation.	Gathered data on a rainy day (18 March 2011) but was not used in the linear fit between the speed in congestion and queue discharge rate.
Our work	Twenty-one days from January to December 2022.	This paper shows that the critical density significantly decreases during any weather condition (clear, light, medium, and heavy rain). Previous studies also prove that the capacity drop is a function of the speed in congestion but that this might not be true during inclement weather. The findings of this research show otherwise. The queue discharge rate is highly correlated to the speed of congestion in any weather condition. It is also shown for the first time that as the speed in congestion increases, the percentage in the capacity drop between the pre-queue capacity and the queue discharge rate decreases.	Included 21 data points representing different weather conditions (clear, light, medium, and heavy rain).

230

After verifying that the on-ramp is an active bottleneck, cumulative vehicle count curves measured at the data locations plotted in oblique or slanted coordinates were used to determine the capacity drop. The vertical displacements represent vehicle accumulations. In the oblique coordinate system, the cumulative counts are plotted against time. However, in order for the change in slope to be more noticeable, a background flow multiplied by each time interval is subtracted from the cumulative counts. This is a popular approach to observing the capacity drop at upstream and downstream locations near the bottleneck based on the work of Newell (1993), who used assumptions about wave motion to predict the features of cumulative vehicle arrival curves. The methodology was improved by Cassidy and Windover (1995) by rescaling the N-curve. Capacity and queue discharge rates can be measured through the oblique cumulative curve downstream. The change in slope indicates the change in flow.

At the activation time, density is then measured at the location near the bottleneck to show the density triggering the capacity drop. The discharge before and after the capacity drop is then measured from the slanted cumulative curve. This is also shown quantitatively in the data as the maximum flow sustained for at least 10 min before and after bottleneck activation. The capacity drop is then calculated based on the difference between the two discharges. The speed in congestion is calculated as the average of speeds detected at the upstream location near the bottleneck during its activation.

Shown in Figure 2 is the traffic data analysis for 1 June 2022, which is shown as an example of typical data analysis. The same analysis was done for all the other days. The mechanism of the capacity drop began when the upstream and downstream oblique cumulative curves started diverging (Figure 2a). It will be seen that the bottleneck can be considered active since the downstream speeds remain free-flowing throughout the morning peak while the upstream speeds change from free-flowing to bottleneck and back to free-flowing again (Figure 2b). In between the transitions, the discharge rates can be measured from the slanted cumulative curves, which are also reflected in the time series graph of flow rates (Figure 2c). Figure 2d also shows that the density triggering the capacity drop can be determined from the time series graph of the densities near the bottleneck (Figure 2d). The measurement is done during the bottleneck activation. The time of the start of the capacity drop is shown in the slanted cumulative curves as the change in slope. This change in slope also represents the change in flow.

Further, Figure 2d shows a time series of the densities triggering the capacity drop. Density was gathered through detections near the bottleneck in all lanes. The figure shows that density coincided with the reaching of the time series to 80 vehicles/km and that this value was steady throughout the bottleneck. It is also evident that discharges recover to pre-queue capacity once the density departs from this critical value. This result is observable across many days. However, there is a significant difference of what is considered critical density when the capacity drop is triggered between days with and without precipitation. This observation is also observed with upright reproducibility. The speed in congestion during different weather conditions was then plotted against accompanying queue discharge rates to see a relationship between the capacity drop and precipitation rates, and a regression analysis was performed. This is also done for the speed in congestion and the corresponding percentage of the capacity drop.

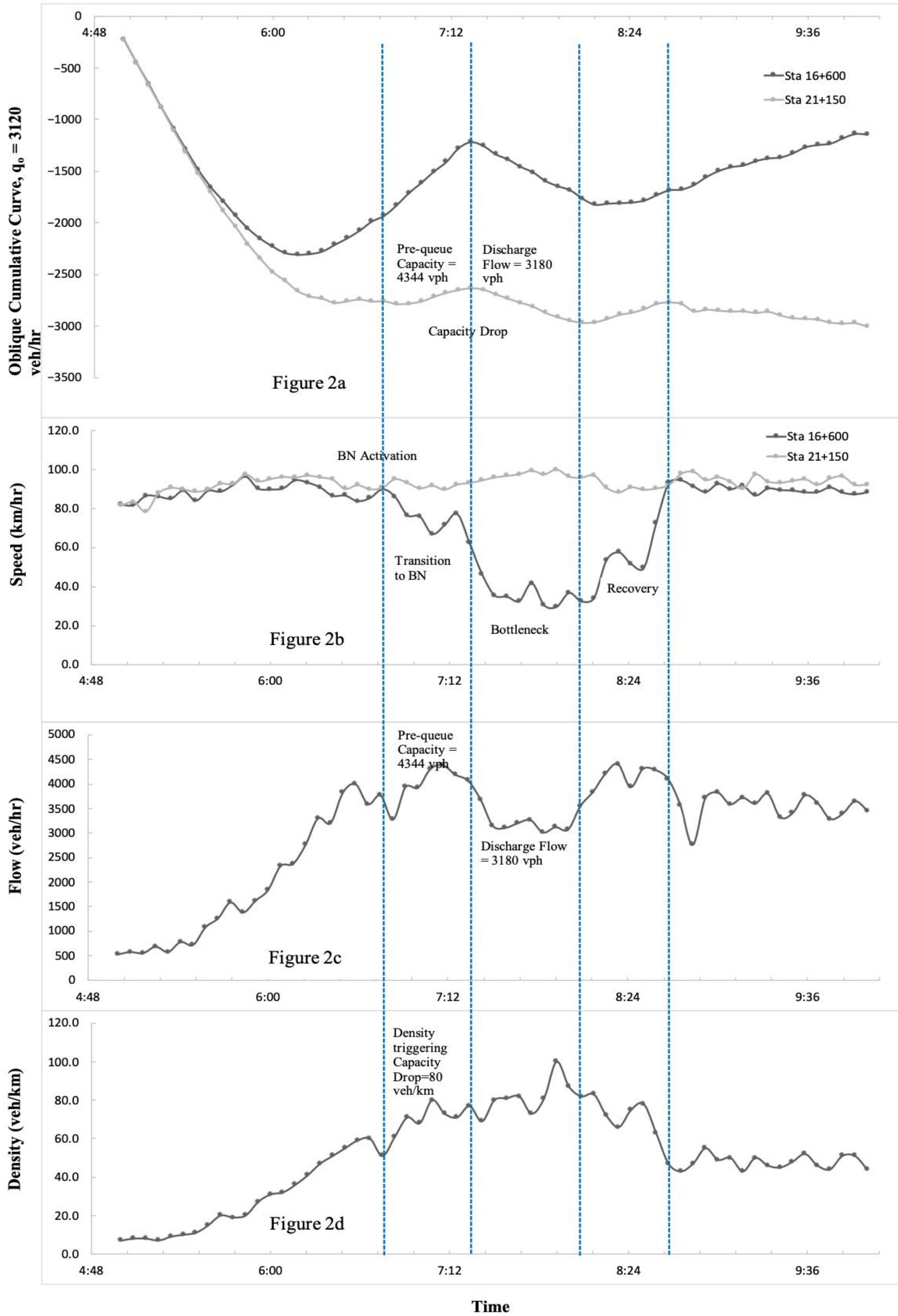

Figure 2. Oblique cumulative curves, speed, flow, and density on 1 June 2022.

4. RESULTS AND DISCUSSIONS

A total of 21 morning peak hour traffic was considered for analysis. These involved different weather conditions consisting of different speeds in congestion ranging from 32.5 km/h to 58 km/h. Column 1 and 2 in Table 2 shows the dates of the analysis and the time of the capacity drop phenomenon, respectively. As shown in previous studies, such as by Chung, Rudjanakanoknad, and Cassidy (2007), the capacity drop seems to correlate with the first passage of a critical density. This current paper is consistent with those findings, except that the critical density becomes significantly lower during any weather condition. On clear days, the average density triggering the capacity drop is 78 veh/km. This value significantly lowers to 65 veh/km during any rainfall condition, which is representative of the light, average, and heavy rainfall. This can be explained by drivers increasing the headway between them and the vehicles in front of them during rainy conditions making the total number of vehicles in the same span of roadway lower. This condition is fairly reproducible across different days. This shows that density directly measured from the field compared to previous studies' measurements explains the capacity drop mechanism. It can be concluded that a density of about 78 vehicles/km can serve as a kind of threshold for clear weather conditions. When densities at this bottleneck rise to this value, it is expected that the queue discharge rate will be significantly lower than the pre-queue capacity. The threshold for a rainy day is about 65 vehicles/km with uncanny reproducibility. These critical densities are shown in the fifth column of Table 2.

As discussed earlier, this is the first time this finding is being evaluated, as previous studies have always considered clear conditions in their analysis. This has a very important significance considering that rainfall is a common event in most countries. This has also not been considered in traffic management schemes such as ramp metering, variable speed limits, or a combination of both. Currently, there are already traffic control management strategies that prevent the capacity drop phenomenon by controlling the density to not exceed the specified threshold. However, they are using the same value of density for clear conditions and during bad weather conditions. With this, there will be errors in the real-time computations since the critical density decreases during rainy days. This follows that the capacity drop will not be averted if weather factors are not considered in the simulations. Once the threshold is adjusted for bad weather conditions, traffic management strategies of this nature can be used with more accuracy.

Discharge flows before the capacity drop and the accompanying queue discharge rates are shown in columns 6 and 7, respectively. The flows persist for at least 10 min and, in most cases, for more than 15 min. While there is a considerable difference across days, the occurrence of a capacity drop is common. The range of the capacity drop in terms of % reduction from the pre-queue capacity is between 1.62 and 47%. It will be shown later that these capacity drops highly correlate with the accompanying speeds in congestion.

While Yuan, Knoop, and Hoogendoorn (2015) conclude that the queue discharge rate increases with increasing speed in congestion, they mentioned that the effects of site characteristics, traffic flow compositions, and weather need to be calibrated in relation to the capacity drop. In fitting the linear relationship, they excluded those collected on a rainy day as it gave a lower queue discharge rate than those collected on clear weather conditions. However, this was only a single event.

Table 2. Precipitation, speed in congestion, flow rates, and the capacity drop at the bottleneck.

Date	**Time of Capacity Drop**	**Precipitation (mm/hr)**	**Speed in Congestion (km/hr)**	**Critical Density Triggering Capacity Drop (veh/km)**	**Discharge Flow Before Capacity Drop (veh/hr)**	**Queue Discharge Rate (veh/hr)**	**Capacity Drop (%)**
1-Jun-2022	7:20	0	41.91	77	4344	3180	26.80
9-Jun-2022	6:55	0	53.96	77	4746	4505	5.08
18-Apr-2022	7:00	0	51.78	80	4613	4119	10.71
20-Jun-2022	7:35	0	50.95	75	4620	4308	6.75
17-Jun-2022	7:45	0	50.40	82	4326	4114	4.90
15-Aug-2022	7:00	0	57.97	77	4806	4728	1.62
24-Jan-2022	7:00	0	37.41	79	4250	2640	37.88
29-Jun-2022	7:10	0	43.90	80	4068	3264	19.76
14-Jun-2022	6:45	0.2	48.13	68	4440	3726	16.08
28-Jun-2022	6:40	0.2	45.95	64	4509	3728	17.32
6-Oct-2022	6:40	0.2	54.61	64	4560	4368	4.21
7-Oct-2022	6:50	0.2	49.35	68	4932	3928	20.36
24-Nov-2022	6:50	0.2	45.42	64	4332	3324	23.27
17-May-2022	6:40	0.4	46.16	65	4392	3336	24.04
15-Jun-2022	7:00	1.4	46.65	66	4464	3852	13.71
26-Sep-2022	6:30	5.4	49.68	66	4248	3870	8.90
27-Sep-2022	7:00	5.6	53.74	67	4620	4316	6.58
22-Jun-2022	7:05	5.8	32.50	64	4152	2200	47.01
7-Jun-2022	7:15	9.4	46.74	64	4776	3795	20.54
30-Jun-2022	6:50	11.4	54.96	65	4776	4602	3.64
3-Oct-2022	6:30	14.2	55.35	67	4716	4440	5.85

In this current study, when other bad weather conditions are included in the correlation analysis representing different speeds in congestion, it can be seen that there is not much difference in the linear correlation. When the speed in congestion is plotted against the queue discharge rate using all the data points collected under different rainfall conditions, the correlation of the coefficient is 0.96 with the function Queue Discharge Rate = 103.21 (Speed in Congestion) − 1175.2 (Figure 3). When only the traffic data from rainy conditions are plotted, the correlation coefficient is 0.95 with the function Queue Discharge Rate = 100.59 (Speed in Congestion) − 1062.2 (Figure 4). In the same figure, when the speed in congestion is plotted against the queue discharge rate under clear weather conditions only, the coefficient of correlation is 0.978 with the function Queue Discharge Rate = 106.66 (Speed in Congestion) − 1319.7. All of the functions follow a linear fit. A Chow test was conducted to determine whether the relationship between speed in congestion (km/h) and queue discharge rate (veh/hr) differs between the two models of clear and bad weather conditions representing different datasets. Model 1 (Bad weather conditions with n = 13) and Model 2 (Clear weather conditions with n = 8) were first estimated separately, followed by a pooled regression using all observations. The resulting Chow F-statistic was 0.373 ($df_1 = 2$, $df_2 = 17$), which is not statistically significant at conventional levels. This indicates that the regression coefficients do not differ between the two models, and that the pooled regression provides an adequate representation of the relationship between speed in congestion and queue discharge rate across both datasets. This shows that weather is not directly an influencing factor of the queue discharge rate but of the speed in congestion alone. This exhibits that speed in congestion is still the strong explaining factor of the queue discharge rates regardless of the weather condition. It displays that traffic management techniques controlling the speed in congestion to increase capacity recovery can be used under different rainfall rates. This important finding can also be used in extending traffic flow theory, such as using and extending the kinematic wave model and simulation setups.

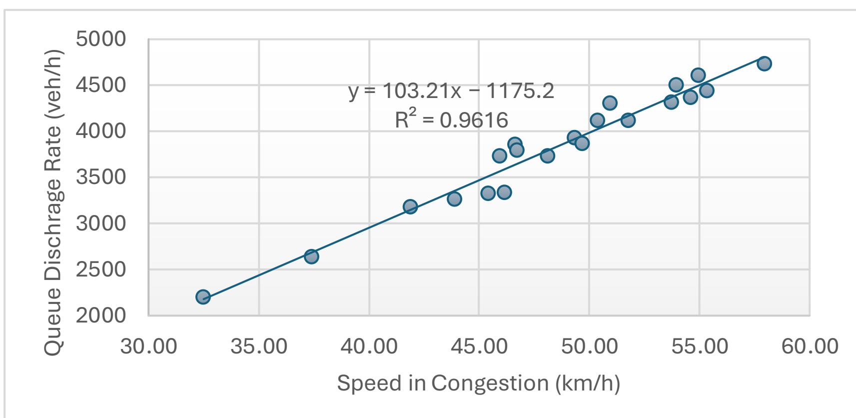

Figure 3. Relationship between queue discharge rate and speed in congestion (all data points).

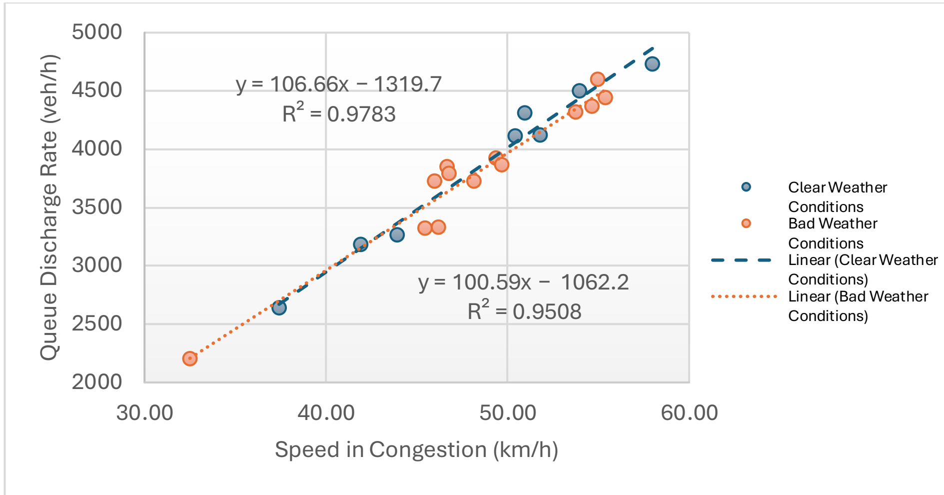

Figure 4. Relationship between queue discharge rate and speed in congestion (clear and bad weather conditions separated).

For the first time, we have also shown a linear relationship between the speed in congestion and the capacity drop, as shown in Figure 5. As the speed in congestion increases, the percentage of the capacity drop dramatically decreases with a linear relationship. The capacity drop Percentage = 1.8362 (Speed in Congestion) + 104.45 with a coefficient of correlation of 0.9151. This is further evidence that traffic management techniques to control the speed in congestion, such as variable speed limits (VSL), can mitigate the capacity drop phenomenon. This can be used in presenting a new macroscopic model for VSLs that will have the capability of modeling different capacities and critical densities at any weather condition, including further analysis of the fundamental diagram in any weather event.

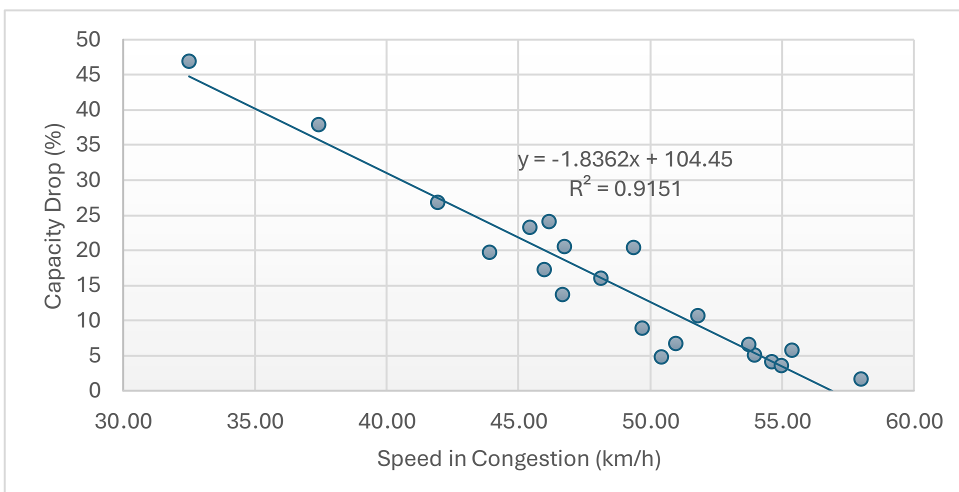

Figure 5. Relationship between the capacity drop and speed in congestion.

5. CONCLUSIONS

There are three important findings in this paper. First is that under bad weather conditions, the critical density that is explained to trigger the capacity drop significantly decreases from an average

of 78 veh/km to 65 veh/km, which was discovered through empirical analysis. This is an important discovery since this is the first time weather considerations are included in the capacity drop analysis. There are existing traffic management strategies that avert the capacity drop by controlling density, although measuring densities over extended lengths can be costly as it will involve the installation of closer detectors every few hundred meters, which might be impractical. This paper shows that a single density value can be used to infer the capacity drop on an on-ramp bottleneck. This finding needs to be verified and calibrated for other bottlenecks with the consideration of on-site-specific characteristics. This also exhibits that detector locations are important for the validation.
The second important finding of this study is the validation of previous studies about the correlation of the speed in congestion with that of the queue discharge rate. However, this current research shows that the relationship can be extended under different rainfall conditions. This shows that weather does not directly become the influencing factor of the queue discharge rate but that of the speed in congestion. This exhibits that the speed in congestion is still the strong explaining factor of the queue discharge rates regardless of the weather condition.

The third finding of this research is the negative linear relationship between the percentage of the capacity drop and the speed in congestion shown for the first time. As the speed in congestion increases, the percentage in the capacity drop between the pre-queue capacity and the queue discharge rate decreases. The observed differences between the queue discharge rate accompanying the speed in congestion can be explained by site-specific characteristics such as the number of lanes, positions of traffic detectors, and vehicle composition. Furthermore, driver behavior from different study areas can also have an impact on these values and must be taken into consideration.

Rainfall is the most important climatic element, which happens all throughout the year in many countries, most especially in monsoon seasons. Unlike other events known to reduce capacities, such as road incidents, rainfall conditions are predictable through weather forecasts. With this, transportation system facilities can be efficiently improved if weather data can be incorporated into traffic management techniques, especially in consideration of the capacity drop. Such strategies would be important since higher queue discharge rates mean lower overall system delay. On-going follow-up studies of this paper include incorporating these findings into traffic flow models and using those for active traffic management strategies through simulations.

References

1. TRB (Transportation Research Board). *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*; National Academies Press: Washington, DC, USA, 2022.
2. Hu, J.; Schroeder, B.J.; Rouphail, N.M. Rationale for Incorporating Queue Discharge Flow into Highway Capacity Manual Procedure for Analysis of Freeway Facilities. *Transp. Res. Rec.* **2012**, *2286*, 76–83.
3. Banks, J.H. Flow Processes at a Freeway Bottleneck. *Transp. Res. Rec.* **1990**, *1287*, 20–28.
4. Gazis, D.C.; Edie, L.C. Traffic Flow Theory. *Proc. IEEE* **1968**, *56*, 458–471.
5. Hall, F.L.; Agyemang-Duah, K. Freeway Capacity Drop and the Definition of Capacity. *Transp. Res. Rec.* **1991**, *1320*, 91–98.
6. Cassidy, M.J.; Bertini, R.L. Some Traffic Features at Freeway Bottlenecks. *Transp. Res. Part B Methodol.* **1999**, *33*, 25–42.
7. Cassidy, M.J.; Windover, J.R. Methodology for Assessing Dynamics of Freeway Traffic Flow. *Transp. Res. Rec.* **1995**, *1484*, 73–79.
8. Bertini, R.L.; Malik, S. Observed Dynamic Traffic Features on Freeway Section with Merges and Diverges. *Transp. Res. Rec.* **2004**, *1867*, 25–35.
9. Cassidy, M.J.; Rudjanakanoknad, J. Increasing the Capacity of an Isolated Merge by Metering its On-ramp. *Transp. Res. Part B Methodol.* **2005**, *39*, 896–913.

10. Chung, K.; Rudjanakanoknad, J.; Cassidy, M.J. Relation Between Traffic Density and Capacity Drop at Three Freeway Bottlenecks. *Transp. Res. Part B Methodol.* **2007**, *41*, 82–95.
11. Oh, S.; Yeo, H. Estimation of Capacity Drop in Highway Merging Sections. *Transp. Res. Rec.* **2012**, *2286*, 111–121.
12. Srivastava, A.; Geroliminis, N. Empirical Observations of Capacity Drop in Freeway Merges with Ramp Control and Integration in a First-order Model. *Transp. Res. Part C Emerg. Technol.* **2013**, *30*, 161–177.
13. Yuan, K.; Knoop, V.L.; Hoogendoorn, S.P. Capacity Drop: Relationship between Speed in Congestion and the Queue Discharge Rate. *Transp. Res. Rec.* **2015**, *2491*, 72–80.
14. Chen, J.; Lin, L.; Jiang, R. Assigning On-ramp Flows to Maximize Capacity of Highway with Two On-ramps and One Off-ramp in Between. *Phys. A Stat. Mech. Its Appl.* **2017**, *465*, 347–357.
15. Lee, J.; Kim, T.; Son, B. Empirical Observation of Maximum Throughput Change in Isolated Merging Bottlenecks Depending on On-Ramp Traffic Flow Ratio. *KSCE J. Civ. Eng.* **2021**, *25*, 1865–1873.
16. Ibrahim, A.T.; Hall, F.L. Effect of Adverse Weather Conditions on Speed- Flow-Occupancy Relationships. *Transp. Res. Rec.* **1994**, *1457*, 184–191.
17. Smith, K.; Byrne, G.; Copperman, R.B.; Hennessy, S.M.; Goodall, N.J. An Investigation into the Impact of Rainfall of Freeway Traffic Flow. Presented at the 83rd annual meeting of the Transportation Research Board, Washington, DC, USA, 11–15 January 2004.
18. Agarwal, M.; Maze, T.H.; Souleytette, R. The weather and Its Impact on Urban Freeway Traffic Operations. Presented at the 85th Transportation Research Board Annual Meeting, Washington, DC, USA, 22–26 January 2006.
19. Mejia, H.N.; Sigua, R.G. Impacts of Different Rainfall Intensities to Key Traffic Flow Parameters Using Underwood's Exponential Model. *Philipp. Transp. J.* **2018**, *1*, 1–16.
20. Heshami, S.; Kattan, L.; Gong, Z.; Aalami, S. **Deterministic and Stochastic Freeway Capacity Analysis Based on Weather Conditions.** *J. Transp. Eng. Part A Syst.* **2019**, *145*, 04019016.
21. Koshi, M.; Iwasaki, M. Some Findings and an Overview on Vehicular Flow Characteristics. In Proceedings of the Eighth International Symposium on Transportation and Traffic Theory, Toronto, ON, Canada, 24–26 June 1981; pp. 403–426.
22. Treiber, M.; Kesting, A. *Traffic Flow Dynamics: Data, Model and Simulation*; Springer: Berlin, Germany, 2013.
23. Laval, J.A.; Daganzo, C.F. Lane-Changing in Traffic Streams. *Transp. Res. Part B Methodol.* **2006**, *40*, 251–264.
24. Leclercq, L.; Laval, J.A.; Chiabaut, N. Capacity Drops at Merges: An Endogenous Model. *Transp. Res. Part B Methodol.* **2011**, *45*, 1302–1313.
25. Yuan, K.; Knoop, V.L.; Leclercq, L.; Hoogendoorn, S.P. Capacity Drop: A Comparison Between Stop-and-Go Wave and Queue Congestion at Lane-Drop Bottleneck. *Transp. B Transp. Dyn.* **2016**, *5*, 145–158.
26. Chen, D.; Ahn, S.; Laval, J.; Zheng, Z. **On the Periodicity of Traffic Oscillations and Capacity Drop: The Role of Driver Characteristics.** *Transp. Res. Part B Methodol.* **2014**, *59*, 117–136.
27. Oh, S.; Yeo, H. Impact of Stop-and-Go Waves and Lane Changes on Discharge Rate in Recovery Flow. *Transp. Res. Part B Methodol.* **2015**, *77*, 88–102.
28. Chen, D.; Ahn, S. **Capacity-drop at Extended Bottlenecks: Merge, Diverge, and Weave.** *Transp. Res. Part B Methodol.* **2018**, *108*, 1–20.
29. Knoop, V.L. *Traffic Flow Theory: An Introduction with Exercises*; TU Delft Open: Delft, The Netherlands, 2021.
30. Bertini, R.L.; Leal, M.T. Empirical Study of Traffic Features at a Freeway Lane Drop. *J. Transp. Eng.* **2005**, *131*, 397–407
31. Newell, G.F. A Simplified Theory of Kinematic Waves in Highway Traffic Part I: General Theory. *Transp. Res. Part B Methodol.* **1993**, *27*, 281–287.