A Study on the Relationship Between Capacity Drop and the Number of Lanes in Freeway Merging Sections

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Abstract: The capacity drop, which is defined as discharge flow drop after bottleneck activation, has been frequently observed in urban freeway, especially in merging sections. Although many previous researches on capacity drop have been studied, still measurement methods for freeway capacity and discharge flow vary case by case according to researchers, and the results cannot be compared each other. In this paper, we first introduced a systematic methodology to estimate roadway capacities and discharge flows from the detector data to find capacity drops. Secondly, we found the relationship on how the number of lanes influences the amount of capacity drop in merging sections in California freeways. The results clearly showed that the capacity drop is strongly related to the number of lanes.

Key Words: Bottleneck, Discharge flow, Capacity drop, Traffic flow

1. INTRODUCTION

To know roadway capacity, since the first observation by Greenshields (1935), is important for traffic operators and transportation planners to keep the roadway system under the capacity and to prevent congestion from the demand surge. However, in merging area, capacity has been observed to drop significantly during some period of time. This phenomenon happens repeatedly during the peak hours at the same locations, and is called “capacity drop”.

Capacity drop, which is defined as the discharge flow drop after bottleneck activation, has been observed by researchers including Banks (1991), Hall and Agyemand-Duah (1991), Persaud et al. (1998), Cassidy and Bertini (1999), Bertini and Malik (2004), Bertini and Leal (2005), Cassidy and Rudjanakanoknad (2005), Banks (2006), and Chung et al. (2007). However, the reported amount of capacity drop varies among different sites because of: i) different measurement methodology, ii) different geometric feature, and iii) the number of lanes.

Persaud et al. (1998) measured breakdown flow ($Q_b$) and mean queue discharge flow ($Q_d$) using 5-min moving average data at 3 study sites including two sites in Highway 401 (Site1, Site2) which is 3-lane freeway. They compared Pre-queue and Queue discharge flows and estimated the capacity drop as 11.6% and 15.3% for Site 1 and 10.6% for Site 2. Cassidy and Bertini (1999) observed the capacity drop on freeways by analyzing the N-curve and revealed some traffic features in bottleneck sites: i) when the roadway capacity drops, ii) the patterns of discharge, iii) the consistency of long-run discharge flow from day to day, and lastly iv)
locations of bottleneck activations. By the visual inspection of N-curve, they found the flow pattern in capacity and its drop to discharge flow as well as the recovery flow. Their observation on Queen Elizabeth Way (QEW) and the Gardiner Expressway showed that the capacity drops 4%-10%.

Bertini and Malik (2004) studied the dynamic traffic features at on-ramp merging section, US169-N, and they estimated the percent drop as 4% using N-curve. Bertini and Leal (2005) studied the bottleneck area caused by lane drop at M4 (2-lane) and analyzed the shock waves and flow reduction. They observed the percent drop as averagely 9.7%.

Banks (2006) estimated Pre-Queue Flow (PQF) and Queue Discharge Flow (QDF) by taking the reciprocal of the average headway, and took mean flow for each of PQF and QDF respectively. He analyzed flow characteristics of both PQF and QDF for the 21 study sections in the Minneapolis-St. Paul area, the San Diego area, and the Seattle area, and reported 1.8% to 15.4% difference in PQF and QDF. Study sections contain 2 to 5 lanes, and the geometric type also varies. Chung et al. (2007) estimated the capacity drop using N-curve for 3 on-ramp merging sections, I805-N (4-lane): 12.42%, SR24-W (2-lane): 6.27%, and Gardiner Expressway (3-lane): 5.75%.

Although there is not much research and explanations on the mechanism of the capacity drop phenomenon, Yeo (2008) provided an explanation on the mechanism of the capacity drop phenomenon as inherent from the asymmetric behavior; the difference between $Q_C$ (Maximum flow) and $Q_D$ (Maximum discharge flow) lying on D-curve (Deceleration curve) and A-curve (Acceleration curve) causes the capacity drop as shown in Figure 1. Before the bottleneck activation, the maximum flow reaches $Q_C$ following D-curve, while the discharge flow from queued traffic follows A-curve and reaches $Q_D$ after the bottleneck activation.

![Figure 1 Capacity drop from the asymmetric traffic flow theory perspective](image)

Because of the wide range of the amount of capacity drops observed as suggested in the previous sections, it is required to find the relationship between the amount of capacity drop and other factors such as the number of lanes. The rationale lies on that in bottleneck situation caused by merging, lane-changing event is the main causal factor determining the amount of capacity drop, and the number of lane changing events varies across the lanes. Therefore, we can simply conjecture that the number of lanes influences the amount of capacity drop.

In this research, we measured the capacity flow and discharge flow for each station by finding the maximum 5-minute sustaining flow, and found the amount of “capacity drop” from PeMS database for typical weekdays during peak periods. Then, we compared the relationship
between the number of lanes and the rate of capacity drop. The obtained result may have contribution in preventing congestion and congestion mitigations by providing more understanding on roadway capacity and how it drops according to different roadways features.

Section 2 provides explanations on data used, and section 3 gives methodologies to extract capacity drop followed by Section 4 providing analysis results. Finally, Section 5 concludes this paper.

2. DATA

The data was collected through PeMS (the California freeway Performance Measurement System) database system, which provides the detector data for freeway sections in twelve districts in California. The study sections have less than 2 miles distance between upstream and downstream, and contain active bottlenecks on typical weekdays (Tuesday, Wednesday and Thursday). Isolated active bottlenecks, which satisfy that the flow at downstream of bottleneck is not affected by further downstream traffic conditions, are used for study.

We gathered i) 30-sec flow data to estimate the capacity, the discharge flow and the amount of capacity drop in each study section, and ii) 5-min speed data to identify bottleneck location, activation time, duration, and traffic state. We used speed data as the main indicator for bottleneck identification because it is more sensitive than flow and occupancy data (Chen, 2004).

3. METHODOLOGY FOR ESTIMATING THE AMOUNT OF CAPACITY DROP

3.1 Capacity

According to HCM (Highway Capacity Manual, Transportation Research Board, 2000), the capacity is defined as the maximum flow rate that can be reasonably expected to traverse a facility under prevailing roadway, traffic and control conditions. HCM defines the freeway capacity as the maximum flow sustained for 15-min. Table 1 shows the duration of capacity flow estimated by other researchers. Because capacity flow does not sustain more than 15 min in many cases as shown in Table 1 and Figure 2, using 15-min time period to estimate freeway capacity cannot be applied to all freeway sites.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Freeway (#-Lanes)</th>
<th>Capacity (vph)</th>
<th>Duration (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassidy and</td>
<td>QEW (3-lane)</td>
<td>7000</td>
<td>12:00</td>
</tr>
<tr>
<td>Bertini (1999)</td>
<td></td>
<td>6890</td>
<td>25:00</td>
</tr>
<tr>
<td></td>
<td>Gardiner Expressway (3-lane)</td>
<td>7120</td>
<td>10:30</td>
</tr>
<tr>
<td>Bertini et al. (2004)</td>
<td>US169-N (2-lane)</td>
<td>6490</td>
<td>21:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6620</td>
<td>2:40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6120</td>
<td>21:40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4475</td>
<td>32:30</td>
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<tr>
<td></td>
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<td>4440</td>
<td>19:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4340</td>
<td>10:00</td>
</tr>
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</table>
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<table>
<thead>
<tr>
<th>Study</th>
<th>Lane Configuration</th>
<th>Year</th>
<th>Capacity 1 (vph)</th>
<th>Time</th>
<th>Capacity 2 (vph)</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bertini et al.</td>
<td>M4 (2-lane)</td>
<td>2005</td>
<td>3690</td>
<td>14:45</td>
<td>3840</td>
<td>8:07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3750</td>
<td>11:57</td>
<td>3510</td>
<td>13:12</td>
</tr>
<tr>
<td>Cassidy et al.</td>
<td>I805-N (4-lane)</td>
<td>2005</td>
<td>9500</td>
<td>4:30</td>
<td>9730</td>
<td>13:00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10100</td>
<td>roughly 3:00</td>
<td>9600</td>
<td>4:00</td>
</tr>
<tr>
<td>Chung et al.</td>
<td>SR24-W (2-lane)</td>
<td>2007</td>
<td>4070</td>
<td>roughly 10:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gardiner Expressway</td>
<td></td>
<td></td>
<td>6500</td>
<td>roughly 30:00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 N-curves at I805-N from Cassidy and Rudjanakanoknad (2005)

Figure 3 shows the difference between 5-min and 15-min capacity of one lane of freeway. 195 samples are extracted from 14 study sections; I8-E, I80-E (Site2; near Abs PM 90), SR51-N, SR78-E, SR91-E, I80-E (Site1; near Abs PM 17), I80-E (Site3; near Abs PM 23), I280-N, US50-E, SR2-E, SR101-S (Site1; near Abs PM 404), SR101-S (Site2; near Abs PM 387), 18-W, and 115-N. The average value of 5-min capacity and 15-min capacity is 2094.62(vph), 1991.25(vph) respectively. The difference between 5-min and 15-min capacity is about 103(vph), and 15-min capacity shows approximately 95% of 5-min capacity. This difference changes with the number of lanes. The 15-min capacity shows 93.33% of 5-min capacity in 2-lane freeway, and 94.84%, 95.30% and 96.42% at 3-lane, 4-lane, and 5-lane respectively.
Figure 3 5-min and 15-min capacities for each capacity group

We defined capacity as the maximum number of vehicles that persisted for 5 minutes during free-flow state. Through the speed comparison between upstream and downstream location, following features of bottleneck were identified:

i) The bottleneck location,
ii) The activation time,
iii) Bottleneck duration,
iv) The traffic state; free-flow, transition to bottleneck, bottleneck, recovery from bottleneck and free-flow.

We applied 5-min moving window to 30-sec data, and took the maximum value before formation of upstream queue as the capacity. Suppose that there are N of 30-sec flow data before bottleneck activation, and \( Q_{i}^{30\text{sec}} \) is the \( i^{th} \) 30-sec flow in the set \( N \). Then the 5-min flow is:

\[
Q_{i}^{5\text{min}} = \sum_{i}^{i+9} Q_{i}^{30\text{sec}}, \quad \text{where } i = 1,2,3,\ldots,N
\]  

Then the capacity \( Q_c \) can be defined as:

\[
Q_c (\text{veh/hr}) = \text{Max } Q_{i}^{5\text{min}}
\]  

3.2 Discharge Flow (\( Q_D \))

Discharge flow, \( Q_D \) can be defined as the persisting flow after bottleneck activation under stable traffic condition for 5-min. The stability of discharge flow can be estimated by downstream speed \( V_d \) and upstream \( V_u \). In free-flow condition, the upstream traffic affects
downstream traffic following the direction of traffic, while in congested traffic, the downstream traffic affects upstream traffic. But, as Figure 4 shows, we can find correlation between the upstream speed and the downstream flow from the empirical data from 187 cases. This histogram is collected in the bottleneck period only. In 71% of all cases we can see correlation more than 0.6 or less than -0.6, which means the variables, \( V_u \) and \( Q_d \), are strongly correlated. Therefore, to extract discharge flow at stable condition, we distinguished stable traffic condition with standard deviation of upstream and downstream speed (\( std. V_d \), \( std. V_u \)) for 15 minutes to meet the stability requirements. We chose \( Q_D \) when the sum of std. \( V_d \) and std. \( V_u \) is the minimum during the bottleneck period:

\[
\text{Min} \left( (\text{std.} V_d + \text{std.} V_u) \text{ for 15 minutes} \ (t - 1, t, t + 1) \right) \Rightarrow Q_D
\]

Figure 4 Histogram of correlation coefficients between \( V_u \) and \( Q_d \) during bottleneck period

### 3.3 Measuring Capacity Drop

The study section for the example is near 56 absolute postmile (Abs PM) of SR91-E on January 26th, 2010 illustrated in Figure 5. Bottleneck head is located between VDS 801552 (upstream) and VDS 811408 (downstream), and is activated after 07:05 (07:06~07:10), which are clearly visible.

The maximum 5-min flow before bottleneck activation was observed as 7284 (vph) at 06:47 (06:47~06:51), which can be called capacity (Figure 6).

\[
Q_C = 7284 \text{ (veh/hr)}
\]

After this peak point, we can observe transition state in which the speed of upstream drops abruptly while downstream speed remained high between 07:06 and 07:29. The downstream speed remains high throughout the observation during the upstream speed are low in bottleneck period.
The discharge flow was observed as 6120 (vph) at 07:40 (07:40–07:44) time period in which the sum of standard deviation of upstream and downstream speed is minimum:

$$\text{Min} \left( (\text{std. } V_u + \text{std. } V_d) \text{ for } 15 \text{ minutes } (t - 1, t, t + 1) \right) = 1.552$$

$$\Rightarrow Q_d = 6120 \text{ (veh/hr)}$$

And the amount of capacity drop between the capacity ($Q_c$) and the discharge flow ($Q_d$) was estimated as 15.98%.

Figure 6 Analysis of (a) flow($Q_d$) and (b) speed($V_u, V_d$) at SR91-E(2010 0126)
4. RESULTS

We analyzed 203 cases of data from 16 study sections as; SR4-W, I8-E for 2-lane freeway, SR91-E, SR78-W, SR51-N, I80-E(Site2; near Abs PM 90), and SR78-E for 3-lane, SR101-S(Site2; near Abs PM 387), I80-E(Site1; near Abs PM 17), SR2-E, SR101-S(Site1; near Abs PM 404), I280-N and I80-E(Site3; near Abs PM 23) for 4-lane, and I15-S, I15-N, and I8-W for 5-lane freeway. The study sections don’t contain HOV lanes disturbing the net amount of capacity drop. Figure 7 provides the results showing capacity drops with respect to the number of lanes. Each point in Figure 7 indicates the average rate of capacity drop on each study section, and Table 2 summarizes the average rate for each site.

The average amount of capacity drop by the number of lanes of freeway is 16.33% for 2-lane, 13.68% for 3-lane, 11.61% for 4-lane, and 8.85% for 5-lane respectively. Figure 8 provides the distribution of capacity drop according to the number of lanes. We can find that the capacity drop decreases with the number of lanes from 16% in 2-lane freeway to 9% in 5-lane freeway. This result shows good match with our initial conjecture on the relationship between capacity drop and the number of lanes.

![Figure 7](image-url)  
Figure 7  The relationship between capacity drop and the number of lanes

<table>
<thead>
<tr>
<th>Freeway</th>
<th>Ramp at downstream</th>
<th>#-Lanes</th>
<th>Average capacity drop (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR4-W</td>
<td>No ramp</td>
<td>2</td>
<td>16.45</td>
</tr>
<tr>
<td>I8-E</td>
<td>No ramp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR91-E</td>
<td>No ramp</td>
<td></td>
<td>14.67</td>
</tr>
<tr>
<td>SR78-W</td>
<td>Off-ramp (1-lane)</td>
<td></td>
<td>13.91</td>
</tr>
<tr>
<td>SR51-N</td>
<td>No ramp</td>
<td>3</td>
<td>13.71</td>
</tr>
<tr>
<td>I80-E(Site2)</td>
<td>Off-ramp (2-lane)</td>
<td></td>
<td>13.58</td>
</tr>
<tr>
<td>SR78-E</td>
<td>Off-ramp (2-lane)</td>
<td></td>
<td>12.53</td>
</tr>
</tbody>
</table>

Table 2  Average capacity drop of each freeway
We can also observe an impact of off-ramp on capacity drop. In Table 2, there are 5 freeways with 3 lanes. No ramp is in SR91-E, SR51-N case and a 2-lane off-ramp is in I80-E (Site2), SR78-E case at downstream location. Two sites with no ramp show higher amount of capacity drop than the other two sites with a 2-lane off-ramp. This result gives us that the off-ramp at downstream location mitigates the capacity drop. It seems that the increase in the number of lanes at downstream of the off-ramp overwhelms the impact of increasing lane-changing events to exit through the off-ramp.

Figure 8 Distributions of the capacity drop(%) for the each number of lanes of freeway
5. CONCLUSIONS

In this study, we proposed a method to measure the capacity drop. Firstly, capacity was defined as 5-min rate instead of 15-min because of quantity and sustainability. Secondly, we estimated the discharge flow by taking the value when both upstream speed and downstream speed are relatively stable which gives minimum standard deviation. The process was applied to 16 study sections. We found the relationship between the number of lanes on freeway and the amount of capacity drop. Most of the rate of capacity shows decreasing tendency as the number of lanes increases.

The main contribution of this paper is that we proposed a method for measuring capacity drop which can be applied to capacity related study, and revealed the impact of the number of lanes in merging sections. This research can further be extended to investigate other factors such as ramps, and geometry of the roadway on capacity.

REFERENCES


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