# Development of Capacity Estimation Method from Statistical Distribution of Observed Traffic Flow

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## ABSTRACT

The objective of this study is to present a quantitative method for highway capacity determination by evaluating alternative approaches in developing capacity from the statistical distribution of observed traffic flow. Extremely long headways are considered to be unreasonable for sufficient demand and for the maximum flow rate defining capacity. Therefore, the longer headways are removed from measured data. To determine the threshold which defines "long headways" confidence intervals of 90%, 95%, and 99% from headway distribution have been used. Further, cumulative distribution of volumes were evaluated at their 85, 90, and 95 percentiles. Then the composite evaluation of headways corrected by the "long headway" and volume distribution percentiles is performed. The result revealed that maximum flow rate is between 2,130 pcphpl and 2,315 pcphpl. Compared to the capacity of 2,200 pcphpl used in the Korea highway capacity manual, capacity appears to correspond to a confidence headway interval of 95%. The study suggests that the rational capacity estimation alternative is to take the 95% of cumulative distribution of observed traffic flows at 95% confidence headway interval eliminating 5% of long headways (i.e., 95-95 Rule).

## 1. INTRODUCTION AND LITERATURE REVIEW

Each country has its own method of measuring traffic capacity that slightly varies across the border, but the definition of traffic capacity uses a similar concept. The U.S.A. *Highway Capacity Manual* (USHCM) (*1*) defines capacity of a facility as the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a roadway. It further stated that:

> Capacity is defined on the basis of 'reasonable expectancy'. That is, a stated capacity for a given facility is a rate of flow that can be repeatedly achieved during peak periods for which sufficient demand exists and that can be achieved on facilities with similar characteristics throughout North America. It is not the absolute maximum rate of flow ever observed on such a facility type. Driver characteristics vary from region to region and the absolute maximum rate of flow may vary from day to day and from location to location. Occasionally, measured rates of flow at some locations will exceed the defined capacity of the facility type. Such rates, however, are usually not sustainable or cannot be achieved repeatedly.

Traffic engineers raise the following three points in their study of capacity. First, the quantitative method to determine the reasonably expected and repeatedly achieved maximum flow rate for a point on the road should be proposed based on a distribution of observed flow rates. Second, when flow rates entail statistical distribution, the question raised is what percentage on this statistical distribution can become the rational capacity (*2*). Third, when analyzing traffic capacity under prevailing non-ideal conditions, adjustment factors are independently multiplied to the capacity of ideal conditions, but it is questionable that this independent multiplicative adjustment of capacity is truly rational.

## 2. STUDY OBJECTIVE

The objective of this study is to define capacity in a quantitative form and to express capacity as a certain percentage found on a distribution of observed flow rate. Then, it can resolve the two problems of the subjectivity of capacity definition and underestimation or overestimation of capacity that has been calculated by using adjustment factors, the previous method of capacity adjustment under non-ideal conditions.

This can be achieved by comparing the capacity of 2,200 pcphpl under ideal conditions specified by the *Korean Highway Capacity Manual* (KHCM) (*3*) with the alternatives to be selected from the statistical distribution of observed flow rate.

The capacity of 2,200 pcphpl in KHCM is set when the capacity of USHCM is 2,000 pcphpl. It is derived from the collective consideration of three criteria of capacity determination which are maximum observed field data, derived value from traffic stream model among speed, flow rate, and density, and the average headway of passenger car only traffic.

## 3. DATA COLLECTION

Field sites that meet the ideal conditions were selected and data were collected by videotaping. Further, the selected sites have sufficient demand volume in the upstream and no bottleneck from merging in the downstream of the sites. The collected data were analyzed through computer programs to measure traffic capacity per unit time, as well as headway and traffic speed. Using a video recorder, the videotape is played and a reference line is drawn on the screen. Each car is inputted by stroking any character or number key on the keyboard when it passes the line, and the passage time of the reference line is calculated by the computer. The attained data of passage time are analyzed to derive traffic variables such as headway, speed, and flow rate.

Our field examination revealed that road sections of A, B, C, and D on Olympic freeway with design speed of 100 km/h meet the above requirements. The innermost lane having passenger cars only without heavy vehicles due to our regulation was videotaped.

To analyze the capacity, data on the transition from stable to unstable flow were collected. This study examined not only specific periods (morning and afternoon peak hours) but the entire time periods in which the traffic pattern shifts from stable to unstable flow rates. However, in the analysis following, the unstable flow data were discarded. Table 1 summarizes the data collection characteristics.

**TABLE 1 Data Collection Characteristics**

| Site | Collected Days | Observed Time (h) | Observed Data (min) | Samples in 15 min |
|---|---|---|---|---|
| A | 5 | 1–2 hours in morning and afternoon peak | 440 | 73 |
| B | 5 | | 660 | 110 |
| C | 4 | | 510 | 87 |
| D | 3 | | 160 | 22 |

## 4. STUDY DATA AND METHOD OF ANALYSIS

### 4.1 Volume and Speed Data

The volume and speed data observed are presented in Figure 1 and Table 2.

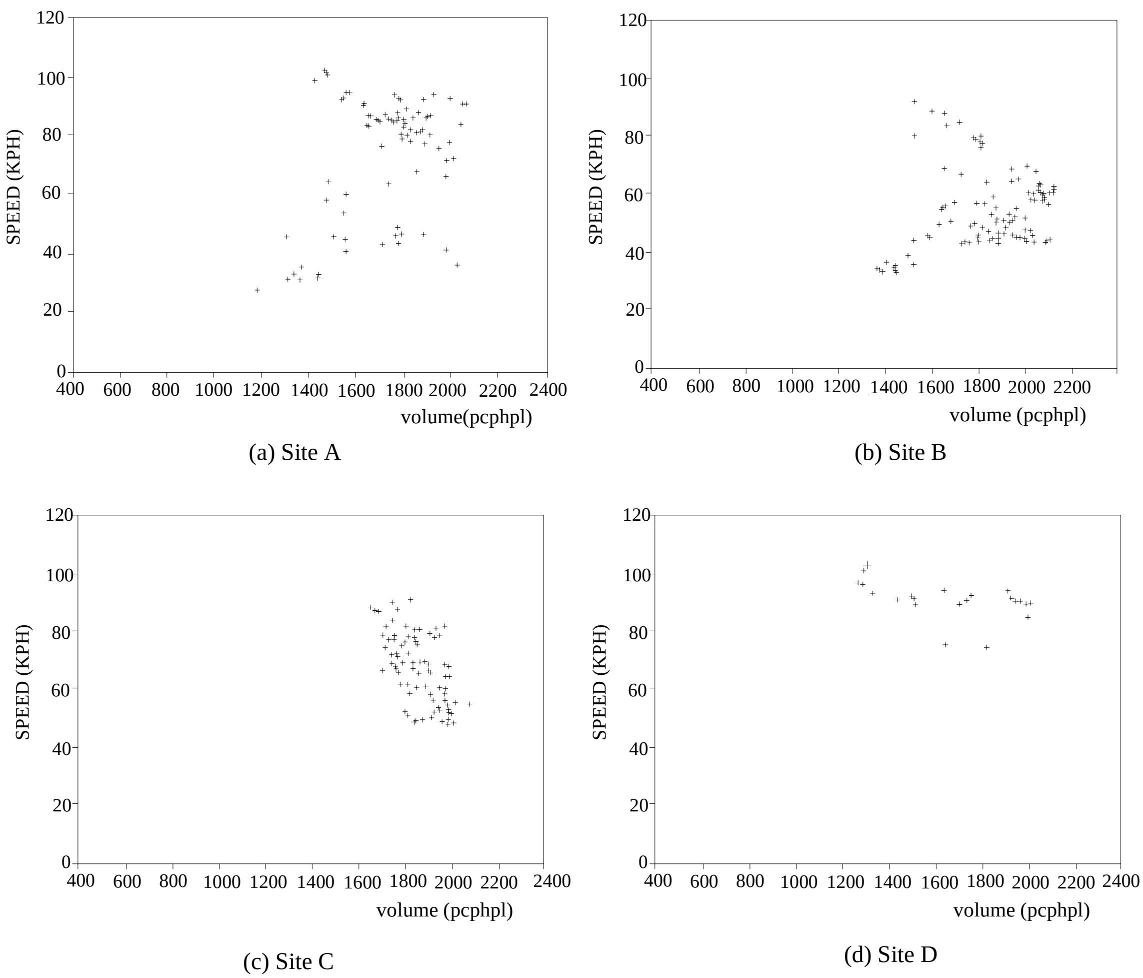


**FIGURE 1 Speed and volume data on sites.**

**TABLE 2 Volume and Speed Characteristics**

| Site | Maximum Flow Rate (pcphpl) | Average Headway (sec) | Average Speed (km/h) |
|---|---|---|---|
| A | 2,071 | 1.74 | 89.3 |
| B | 2,122 | 1.70 | 60.2 |
| C | 2,069 | 1.74 | 55.0 |
| D | 2,061 | 1.75 | 90.7 |

## 4.2 Capacity Variation by Average Headway

The headway follows a statistical distribution. The general headway distribution is shown on Figure 2. When the area exceeding the specific headway $h_i$ is removed, the average headway in the section moves from $h_1$ to $h_2$. By converting the average headway into an hour, the flow rate in one hour can be calculated by Equation (1).

$$q = \frac{3,600}{h} \tag{1}$$

where: $q$ = flow rate in an hour (vph)
$h$ = average headway (second)

The distribution of average headway, hence, signifies the distribution of capacity. For instance, if we postulate that the revised average headway is 1.6 sec after removing the long headway from the observed average headway of 1.8 sec, we can see that the capacity has increased from 2,000 vph to 2,250 vph.

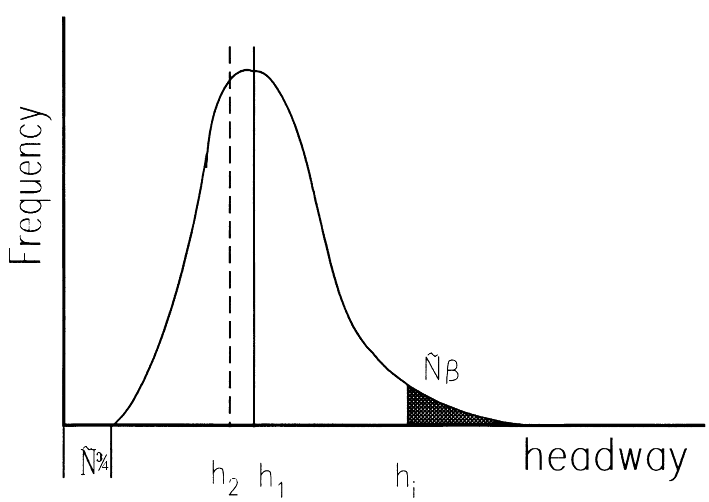


**FIGURE 2 Effect of headway distribution.**

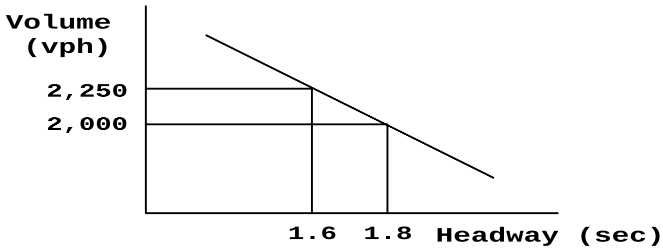


**FIGURE 3 Effect of headway on volume.**

In determining capacity, extremely long headway is considered unreasonable for sufficient demand and the maximum flow rate defining capacity.

### 4.3 Fitting of Headway Distribution Model

When revising the average headway, the long headway corresponding to $h_i$ in Figure 2 must be estimated. Because the long headway cannot be artificially set within the distribution of the observed headway, headway distribution model that conforms to the observed one should be selected, and the long headway is estimated from the fitted distribution model.

The headway distribution models of negative exponential distribution, shifted exponential distribution, and gamma distribution including erlang distribution is fitted to the observed headway distribution. The results as tested by $\chi^2$ and shown in Table 3 revealed that the shifted exponential distribution with $\tau = 0.95$ sec is the best fitting model for the observed headway distribution.

**TABLE 3 Headway Distribution Fitting Test by $\chi^2$**

| Head-way (sec) | Mid value (X) | Fre-quency ($f_0$) | $f_0x$ | $f_0x^2$ | Erlang (K=5) | | Shifted Negative Exponential Distribution ($\tau$ = 0.95 sec) | | Shifted Negative Exponential Distribution ($\tau$ =1.0 sec) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Expected frequency ($f_t$) | $(f_0 - f_t)^2/f_t$ | Expected frequency ($f_t$) | $(f_0 - f_t)^2/f_t$ | Expected frequency ($f_t$) | $(f_0 - f_t)^2/f_t$ |
| 0~1 | 0.5 | 36 | 18 | 9.0 | 46 | 2.17 | 20 | | 0 | |
| 1~2 | 1.5 | 248 | 372 | 558.0 | 198 | 12.63 | 258 278 | 0.13 | 278 278 | 0.13 |
| 2~3 | 2.5 | 108 | 270 | 675.0 | 140 | 7.31 | 102 | 0.35 | 105 | 0.09 |
| 3~4 | 3.5 | 31 | 109 | 379.8 | 49 | 6.61 | 40 | 2.03 | 40 | 2.03 |
| 4~5 | 4.5 | 12 | 54 | 243.0 | 11 | 7.14 | 16 | 1.00 | 15 | 0.60 |
| 5~6 | 5.5 | 5 | 28 | 151.3 | 3 14 | | 7 | | 6 | 1.00 |
| 6~7 | 6.5 | 3 | 20 | 126.8 | 0 | | 2 11 | 0.09 | 2 9 | |
| 7~8 | 7.5 | 1 | 8 | 56.3 | | | 1 | | 1 | |
| 8~9 | 8.5 | 1 | 9 | 72.3 | | | 1 | | | |
| 9~0 | 9.5 | 1 | 10 | 90.3 | | | | | | |
| > 10 | 10.5 | 1 | 11 | 110.3 | | | | | | |
| Sum 447 909 2471.8<br>Mean 909 / 447 = 2.03 | | | | | 447 | 35.87[a] | 447 | 3.60[b] | 447 | 3.85 |

* $\chi^2_{2,0.05} = 5.992$.
[a] rejected; [b] accepted.

### 4.4 Flow Rate Revised by Long Headway

The distribution of observed headway is measured for 15 minutes, this study's unit of measurement. The long headway corresponding to the significance levels of 1%, 5%, and 10% is then removed. The effects of this removal on flow rate is analyzed and compared to the observed data and the capacity of 2,200 pcphpl. The long headway corresponding to each significance level from the shifted exponential distribution is calculated by Equation (2).

$$P(h \geq t) = \mathrm{EXP}\left[-\frac{(t-\tau)}{(T-\tau)}\right] = \alpha$$
$$t = \tau - (T - \tau)\ln\alpha \tag{2}$$

Where: $T$ = mean headway (sec)
$\alpha$ = 0.01, 0.05, and 0.10
$\tau$ = minimum allowable headway (0.95 sec)

**TABLE 4 Long Headway by Significance Level**

| **Significance Level Mean Headway (*T*)** | | **1%** | **5%** | **10%** |
|---|---|---|---|---|
| A | 2.11 | 6.29 | 4.43 | 3.62 |
| B | 1.97 | 5.65 | 4.00 | 3.30 |
| C | 1.90 | 5.32 | 3.80 | 3.14 |
| D | 2.17 | 6.57 | 4.60 | 3.76 |
| Average | 2.04 | 6.00 | 4.21 | 3.46 |

Unit: sec.

## 5. PROPOSED QUANTITATIVE APPROACH FOR CAPACITY

### 5.1 Evaluation of Confidence Interval for Headway Distribution

The confidence headway intervals in this study mean the distributional rates of headway, excluding the long headway that are considered to be unreasonable as capacity. The maximum flow rate corresponding to the confidence headway intervals of 100%, 99%, 95%, and 90% is presented in Table 5.

**TABLE 5 Maximum Flow Rate by Confidence Headway Interval**

| Site | Confidence Interval | | | |
|---|---|---|---|---|
| | 100% | 99% | 95% | 90% |
| A | 2,071 | 2,173 | 2,283 | 2,379 |
| B | 2,122 | 2,156 | 2,259 | 2,385 |
| C | 2,069 | 2,101 | 2,195 | 2,278 |
| D | 2,061 | 2,089 | 2,195 | 2,245 |
| Average | 2,081 | 2,130 | 2,233 | 2,315 |

Unit: pcphpl.

When the confidence headway interval is 100%, that is, when all observed headways are taken into account without excluding long headway, the maximum flow rate is 2,081 pcphpl, falling far short of the current capacity of 2,200 pcphpl.

When the confidence headway interval is 99%, where 1% of headways having long headways exceeding 6.0 sec are excluded, the maximum flow rate at 2,130 pcphpl is less than the current capacity of 2,200 pcphpl.

When the confidence headway interval is 95%, where 5% of headways having long headways exceeding 4.2 sec are excluded, the maximum flow rate at 2,233 pcphpl meets the current capacity of 2,200 pcphpl.

When the confidence headway interval is 90%, where 10% of headways having long headways exceeding 3.5 sec are excluded, the maximum flow rate at 2,315 pcphpl exceeds the current capacity of 2,200 pcphpl. This appears to be an excessive revision even excluding the headways that approximate the capacity.

From this analysis it is concluded that the confidence headway interval most appropriate for capacity is found at 95%, smaller than the 99% overestimating and larger than the 90% underestimating. The cumulative volume distribution of four sites at confidence headway interval of 95% is shown on Figure 4.

## 5.2 Evaluation of Volume Distribution

After eliminating the long headway, taking a 95% confidence interval of headway distribution in this study, there still remains a question of which level of volume distribution is appropriate for capacity.

There may be two approaches to consider. The first is to select certain percentage (i.e., 90%, 95%, etc.) of volume distribution and then check if it matches with the capacity value used. The second is to fix the capacity value and determine the percentage from volume distribution. We took the first approach for uniform application.

This study has analyzed four alternatives of 100%(Alt. A), 95%(Alt. B), 90%(Alt. C), 85%(Alt. D) volume distribution based on 95% confidence interval of headway distribu-

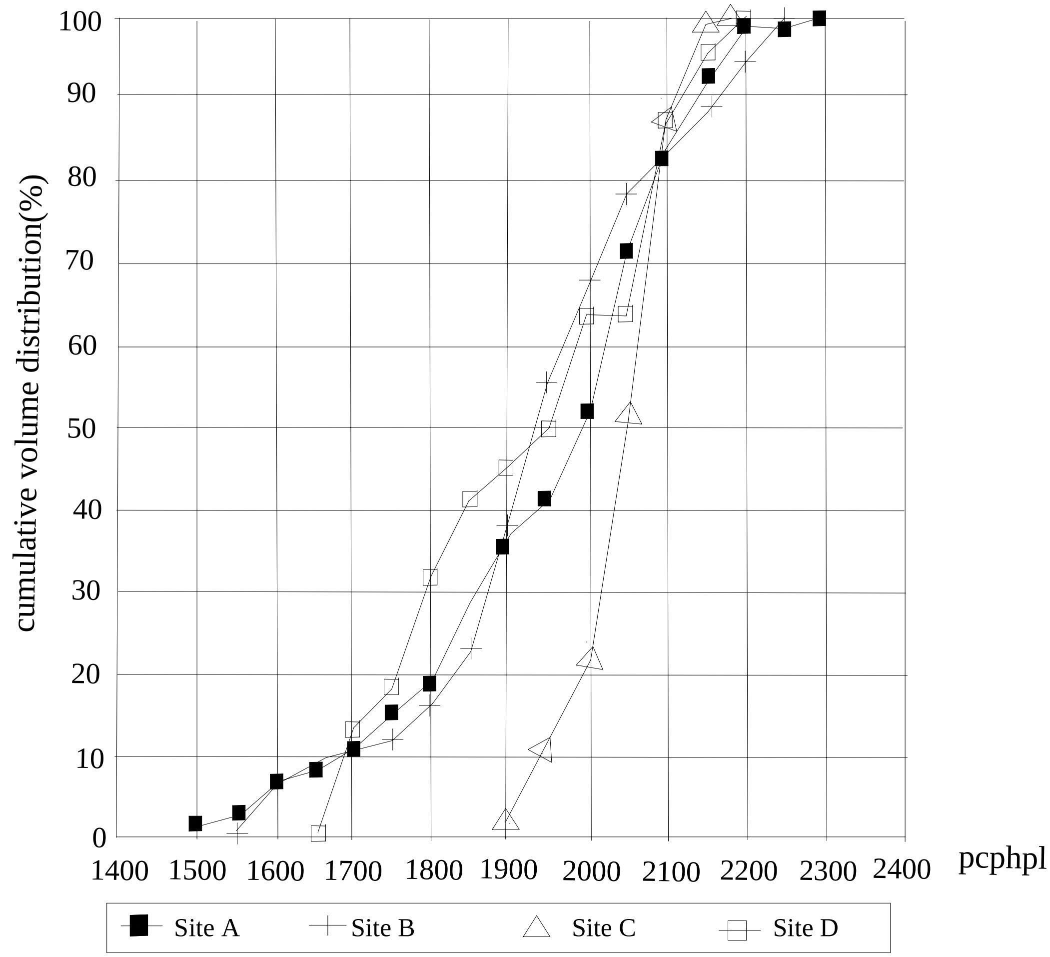


**FIGURE 4 Cumulative volume distribution with 95% confidence headway interval.**

tion. The flow rate for each alternative is evaluated. The following explains the reason behind the selection of the four alternatives.

Alternative A is provided to examine whether or not the maximum flow rate that occurs only once can really be considered as capacity. Alternatives B, C, and D deal with the research objective of this study, which is to examine the level of capacity postulated on a statistical distribution of observed flow rate.

When planning or designing transportation infrastructures, basing the project on maximum demand requires large investment that reduces economic efficiency, while basing it on minimum demand requires less investment but invites congestion due to the lack of capacity. Thus, what percentage of the demand will be met is decided by past experience on rule of thumb. For instance, when designing a road, the 30th highest hourly volume of the year is taken as the design hourly volume. The speed limit is taken at 85% of the distribution of driving speed. What is attempted here is to examine the distributional ratios (i.e., 95%, 90%, 85%) considered to be appropriate for capacity among the distribution of observed traffic flow rate.

We will now examine the four alternatives and decide which alternative is most appropriate to suggest for capacity. Looking at the average flow rate, as shown in Table 6, of each alternative over the four sections of road in consideration reveals the following: alternative A at 2,233 pcphpl exceeding the current capacity of 2,200 pcphpl; alternative B at 2,187 pcphpl showing a similar value to the current capacity; and alternatives C and D at 2,153 and 2,125 pcphpl, respectively, falling short of the current capacity.

**TABLE 6 Maximum Flow Rate by Cumulative Volume Distribution for 95% Confidence Headway Interval**

| Site | Cumulative Volume Distribution | | | |
|---|---|---|---|---|
| | 100%(Alt. A) | 95%(Alt. B) | 90%(Alt. C) | 85%(Alt. D) |
| 1 | 2,283 | 2,205 | 2,154 | 2,125 |
| 2 | 2,259 | 2,227 | 2,186 | 2,147 |
| 3 | 2,195 | 2,141 | 2,130 | 2,118 |
| 4 | 2,195 | 2,173 | 2,143 | 2,110 |
| Average | 2,233 | 2,187 | 2,153 | 2,125 |

Unit: pcphpl.

### 5.3 Composite Evaluation of Headway and Volume Distribution.

The flow rate obtained from the consideration of long headway removed and flow rate based on volume distribution is compositively evaluated. The capacity of 2,200 pcphpl generally accepted value in the Korea and worldwide practice is referenced as base value for evaluation.

Table 7 shows the composite capacity by confidence headway interval and cumulative volume distribution of five alternatives based on the current capacity of 2,200 pcphpl.

**TABLE 7 Flow Rate by Headway and Volume Distribution**

| Alternative | Confidence Headway Interval | Cumulative Volume Distribution | Maximum Flow Rate (pcphpl) |
|---|---|---|---|
| 1 | 95% | 100% | 2,233 |
| 2 | 95% | 95% | 2,187 |
| 3 | 95% | 90% | 2,153 |
| 4 | 90% | 90% | 2,237 |
| 5 | 90% | 85% | 2,212 |

Alternative 1, in addition to having the problem of assigning a one-time occurrence of observed maximum flow rate as the capacity, has a measured flow rate of 2,233 pcphpl, exceeding the current capacity of 2,200 pcphpl. It is therefore overestimated and considered to be inappropriate for a rational capacity.

Alternative 2, flow rate of 2,187 pcphpl with a 95% confidence headway interval and a 95% volume distribution quite close to the current capacity of 2,200 pcphpl, appears to be the appropriate method of capacity estimation when the concept and distribution of capacity are considered.

Alternative 3, flow rate of 2,153 pcphpl with a 95% confidence headway interval and a 90% volume distribution, falls short of the 2,200 capacity and appears to be an underestimation of capacity.

Alternative 4, flow rate of 2,237 pcphpl with a 90% confidence headway interval and 90% volume distribution, overestimates capacity. Further, at the 90% confidence interval, it distorts the headway distribution under the given conditions too greatly. It is hence inappropriate.

Alternative 5, flow rate of 2,212 pcphpl with a 90% confidence headway interval and a 85% volume distribution, its capacity closely approximates the current 2,200 capacity. However, 85% of volume distribution does not conform well to the concept of maximum flow rate. Further, it distorts headway distribution by truncating too much headways (10%) having long headways. It is, hence, an inappropriate method.

Evaluating the confidence intervals of the headway distribution and the cumulative volume distribution both separately and together lead us to conclude that the confidence headway interval at 95% and the cumulative distribution of flow rate at 95% (95-95 Rule) appears to be the most rational standard of capacity estimation to use.

## 6. CONCLUSION AND RECOMMENDATION

This study analyzed the quantitative method to define capacity by evaluating the headway and volume distribution from observed traffic flow. The findings of this paper can be summarized as follows.

First, using the shifted exponential distribution and applying the significance levels of 1%, 5%, and 10%, the long headways corresponding to each significance level were 6 sec at 1%, 4.2 sec at 5%, and 3.5 sec at 10%.

Second, the maximum flow rates with confidence headway intervals at 99%, 95%, and 90% of the headway distribution, where 1%, 5%, and 10% of headways having long headways are excluded, show 2,130 pcphpl at 99% and 2,315 pcphpl at 90%. With the 95% confidence headway interval that excludes the 5% long headways, the estimation is 2,233 pcphpl. When compared to the current capacity, this confidence interval of 95% is conformed to be the most appropriate level for capacity estimation.

Third, analyzing the flow rates corresponding to 95%, 90%, and 85% on the cumulative distribution of observed traffic flows with a 95% confidence interval of headway distribution, the flow rate was at 2,187 pcphpl at 95%, 2,153 pcphpl at 90%, and 2,125 pcphpl at 85%. When compared to the current capacity, this 95% level is verified as the most appropriate level.

Fourth, the flow rate that corresponds to the 95% of cumulative distribution of observed traffic with a 95% confidence interval of headway distribution (95-95 Rule) is identified as the rational basis for capacity estimation.

It is recommended that there should be extensive research on capacity under non-ideal conditions following the capacity estimation method identified in this study. Further, suggestions should be made on the standard of field observation practice to derive capacity from observed traffic.

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