# DEVELOPMEMT OF A NEW HIGHWAY CAPACITY ESTIMATION METHOD 

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#### Abstract

Highway capacity estimation is fundamental to the study of traffic. Previous research that contributed to HCM (Highway Capacity Manual) has been mainly interested in organizing various field data without considering shortcoming of the methodologies. In this study, DHCE (Dynamic Highway Capacity Estimation) methods are developed and applied to real traffic data. As a result of this study, the DHCE methods showed excellent performance in explaining real traffic situations, which can vary dynamically.


Key Words: Dynamic Capacity, Highway Capacity, Variable Traffic Condition

## 1. INTRODUCTION

Highway capacity estimation is fundamental to the study of traffic. False estimation pollutes other reasonable traffic studies. Errors caused by inaccurate or wrong estimation of highway capacity can easily effect the results of other studies. In Highway Capacity Manual (HCM), highway capacity is defined as "the maximum sustained 15 minutes flow rate, expressed in passenger cars per hour per lane, that can be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction of flow". This notion is somewhat ambiguous and is not constant. Observed 15 -min flow rate, which is used to estimate highway capacity, can be vary depending on the traffic condition and roadway condition. Because of this reason, highway capacity as defined by HCM is not generally a acceptable definition, but only particular road characteristics. The data of observed 15 minutes flow rate is aggregated data, which contain un-capacity traffic information. Highway capacity under this definition can be usually underestimated. The factors that effect highway capacity are road condition, traffic flow condition, traffic control condition and automobile technology. Previous research that contributed to HCM has been mainly interested in organizing various field data without considering shortcoming of the methodology. Developments in detection technology enable various and precise traffic data collection. The HCM method does not require such various and precise traffic data, and outputs only limited results. The objective of this study is to improve limitation of previous highway capacity estimation methods. The contents of this study are as follows: (a) Reviewing previous
highway capacity estimation methods and their limitations, (b) Developing highway capacity estimation method that can consider dynamic traffic conditions, (c) Modeling highway capacity using field data, (d) Comparing the results of the proposed method with the those of previous methods.

## 2. GENERALLY USED METHODS

Two widely used highway capacity estimation methods are the HCM method using speed-volume-density relationship (HCM, 2000), and the statistical method using observed traffic volume distribution (Chang \& Kim, 2000).
The HCM method executes the following: (1) detecting 15 min - base traffic data (speed, volume, density), (2) searching speed-volume-density relationship using data from step (1), and (3) determine highway capacity. The results of HCM method are Figure 1 and Figure 2.


Figure 1. Speed-Flow Relationships for Basic Freeway Segments


Assumption: FFS $=120 \mathrm{~km} / \mathrm{h}$.
Figure 2. Flow-Density Function With A Shockwave
The statistical method executes the following: (1) detecting peak hour 1 minute base volume and average speed, (2) transferring 1 minute base data to 15 minute base one, (3) finding time headway distribution using average volume, (4) determine highway capacity when confidence intervals are $99 \%, 95 \%$ and $90 \%$. The variance in the confidence interval obtained from this method greatly affects the result of highway capacity estimation. Chang and $\operatorname{Kim}(2000)$ found that the estimated highway capacity is $2200 \mathrm{pc} / \mathrm{h} / \mathrm{l}$ at the $95 \%$ confidence interval.

Whenever HCM is published, highway capacity is increased; $1,800 \mathrm{pc} / \mathrm{h} /(\mathrm{HCM}$, before 1986), $2,000 \mathrm{pc} / \mathrm{h} / \mathrm{l}(\mathrm{HCM}, 1986), 2,200 \mathrm{pc} / \mathrm{h} / 1$ (HCM, 1994), $2,400 \mathrm{pc} / \mathrm{h} / \mathrm{l}(\mathrm{HCM}, 2000)$. These results are due to two main reasons: One, previous research has not given much consideration to road conditions, traffic conditions, control conditions, technology factors, which affect highway capacity. Second, previous research has used rough 15-min base traffic data.

## 3. MOTIVE OF METHOD DEVELOPMENT

Previous research derived the traffic flow rate from 15 min observed traffic volume. Traffic flow rate can be used in estimating the roadway condition on the view of highway construction. This approach has some disadvantages in detecting dynamic traffic condition and in applying roadway operation.

The limitations of previous research have encouraged this study. The limitations as motives of method development can be summarized as three items. First, capacity bubble is a part of highway capacity. Capacity bubble is the outcome of exogenous variables, which are traffic characteristics, driver characteristics and roadway network characteristics etc. In the HCM method, the capacity bubble affects the adjustment factors, excluding the capacity bubble obtained from the highway capacity result in double excluding errors. With this notion, there is function (1) relationship between real capacity and previous research capacity.

$$
\begin{array}{lll}
C_{i}=k \cdot l=A+B &  \tag{1}\\
\text { where } & \mathrm{C}=\text { real capacity } & \mathrm{k}=\text { capacity rate } \\
& l=\text { unit time } & \mathrm{A}=\text { previous research capacity } \\
& \mathrm{B}=\text { arrival impedence (capacity bubble) }
\end{array}
$$



Figure 3. Real Capacity and Capacity Bubble (Arrival impedence)
Second, proper highway capacity is difficult to estimate when the meaningless information from data cannot be removed. 15 min observed data cannot overcome this problem. As shown Figure 4, the shorter observing unit time enable spreading observed data on traffic volume's axis, and reduce variations of data. At the end, headway data is appropriate for precise highway capacity estimation.


Figure 4. Traffic Volume Data Distribution by Observation Time
Third, highway capacity is a function of individual vehicle speed. A vehicle group with $80 \mathrm{~km} / \mathrm{h}$ average traveling speed consists of vehicles moving faster than $80 \mathrm{~km} / \mathrm{h}$ and vehicles moving slower than $80 \mathrm{~km} / \mathrm{h}$. The speeds of traveling vehicles make a certain distribution. Without considering these characteristics, we cannot estimate the highway capacity precisely by just using aggregated data. Additionally, to overcome these problems, we need to use disaggregated data and understand the relationship between time headway and speed.

Highway capacity is the aggregated result of individual vehicle behavior. The optimal operation speed can balance the safety and efficiency of a vehicle's behavior. However, a very dangerous circumstance condition, vehicle engineering condition, and driver's psychological resistance condition are paralleled in the optimal and low speed regions, driver's psychological resistance condition underestimated in over speed region. As a vehicle's speed increases, efficiency increases in the optimal and low speed regions, and safety decreases in the over-speed region.


Figure 5. Relationship Between Time Headway and Speed

## 4. DEVELOPMENT OF DYNAMIC HIGHWAY CAPACITY ESTIMATION METHOD

Highway capacity can be described as the ability of a roadway to respond to drivers and vehicles. The ability of roadway is revealed as a vehicle's speed and time headway. A roadway capacity is the function of the driver's and vehicle's conditions, vehicle speed, and time headway, as defined in Eq. (2).

$$
\begin{array}{rll}
C_{i}=f(D, V, S, H) &  \tag{2}\\
\text { where } & \mathrm{C}=\text { capacity of roadway } \mathrm{i} . & \mathrm{D}=\text { driver condition } \\
\mathrm{V}=\text { vehicle condition } & \mathrm{S}=\text { vehicle speed } \\
\mathrm{H}=\text { time headway (seconds) } &
\end{array}
$$

Unit time of highway capacity estimation is one hour. Eq. (3) can be drawn.

$$
\begin{equation*}
C_{i}=\left\{\left.\frac{3600}{H} \right\rvert\, H=g(D, V, S)\right\} \tag{3}
\end{equation*}
$$

If driver condition and vehicle condition follow certain distributions and set as error term, Eq. (3) can be restated as Eq. (4).

$$
\begin{align*}
& H_{c i}=g^{\prime}(S)+\varepsilon  \tag{4}\\
& \text { where } \quad H_{c i}=\text { time headway at } \mathrm{Ci} \quad \varepsilon=\text { error term }
\end{align*}
$$

Time headway of capacity $H_{c i}$ is estimated by using Eq. (4), and then various capacities changed by speeds $C a p_{s}$ are calculated by using Eq. (5).

$$
\begin{equation*}
\text { Cap }_{s}=\frac{3600}{H_{c i}} \tag{5}
\end{equation*}
$$

Eq. (4) and Eq. (5) explain the concept of the dynamic highway capacity, which can vary with the vehicle's speed. Figure 6 shows the application systems of Dynamic Highway Capacity Estimation (DHCE) method.


Figure 6. Dynamic Highway Capacity Estimation Algorithm

The DHCE algorithm is summarized as follows:

- step 1(data collecting) : collect disaggreated data (individual vehicle's time headway and speed),
- step 2 (data filtering) : reject abnormal data, select capacity data using capacity index,
- step 3(modeling) : estimate coefficients of DHCE model using filtered data,
- step 4(applying) : identify dynamic capacity using DHCE model.


## 5. THE APPLICATION OF DYNAMIC HIGHWAY CAPACITY ESTIMATION METHOD

### 5.1 Data for DHCE

Sample data from uninterrupted highway segments must be collected to apply the dynamic highway capacity estimation method. The data is collected according to the specification:

- Place: MyeongSuDae Hyundai Apt., Seoul, Korea
- Lane specification: 1 or 2 lane that the private car only pass
- Date: From May 5th to 7th, 2000 (3 days, total 13 hours)
- Collecting method: Digital Video Camera

The characteristics of collected data are presented in Table 1. The medians of velocity and time headway are smaller than their means; this means that the data distribution is unsymmetrical, with a dense distribution on the left side.

Table 1. The Statistical Characteristics of Sample Data

| The statistical characteristics | Velocity $(\mathrm{km} / \mathrm{h})$ | $\begin{gathered} \text { Time Headway } \\ (\mathrm{sec}) \\ \hline \end{gathered}$ |
| :---: | :---: | :---: |
| \# of sample | 5,953 |  |
| Mean | 26.07 | 3.29 |
| The standard deviation | 10.54 | 4.86 |
| The median | 24.4 | 2.56 |

### 5.2 Modeling

To determine the level of data scale, other specific studies are needed; without them, the upper $5 \%, 10 \%$, and $15 \%$ time headway data, which sorted in ascending order by time length, are the most likely alternative data. Chang \& Kim (2000) called as $95 \%, 90 \%, 85 \%$ model. The characteristics of the $95 \%, 90 \%$, and $85 \%$ model data ( $5 \%, 10 \%$, and $15 \%$ time headway data) are as following Table 2.

Model equations such as polynomial, liner, and exponential equations are built from the relationship between velocity and time headway using the above $95 \%, 90 \%, 85 \%$ model data. The polynomial equation has better value then liner and exponential equation in the view of "coefficient of determination $\left(\mathrm{R}^{2}\right)$ " as shown in Table 3.

Table 2. The Statistical Characteristics of The Data for Models

| Model specification |  | Velocity (km/h) | Time Headway (sec) |
| :---: | :---: | :---: | :---: |
| 95\% model | \# of sample | 298 |  |
|  | Mean | 16.67 | 2.26 |
|  | The standard deviation | 6.64 | 0.75 |
| 90\% model | \# of sample | 595 |  |
|  | Mean | 17.44 | 2.29 |
|  | The standard deviation | 6.4 | 0.77 |
| 85\% model | \# of sample | 893 |  |
|  | Mean | 18.01 | 2.32 |
|  | The standard deviation | 6.45 | 0.78 |

The following Figure 7, 8, and 9 can be plotted from the relationship between velocity and time headway using the above $95 \%, 90 \%$, and $85 \%$ model data.


Figure 7. Distribution and Series Line of 95\% Model Data


Figure 8. Distribution and Series Line of 90\% Model Data


Figure 9. Distribution and Series Line of 85\% Model Data
Table 3. Velocity (X)-Headway (Y) Model

| Model specification |  | Model Equation | Coefficient $\left(\mathrm{R}^{2}\right)$ |
| :---: | :---: | :---: | :---: |
| 95\% Model | Polynomial Eq. | $\mathrm{Y}=32.793 \times \mathrm{X}^{-0.9916}$ | 0.9819 |
|  | Liner Eq. | $\mathrm{Y}=-0.0948 \mathrm{X}+3.8452$ | 0.7119 |
|  | Exp. Eq. | $\mathrm{Y}=4.8205 \mathrm{e}^{-0.0487 \mathrm{X}}$ | 0.8875 |
| 90\% Model | Polynomial Eq. | $\mathrm{Y}=32.532 \times \mathrm{X}^{-0.9682}$ | 0.9587 |
|  | Liner Eq. | $\mathrm{Y}=-0.1036 \mathrm{X}+4.0941$ | 0.7427 |
|  | Exp. Eq. | $\mathrm{Y}=5.1573 \mathrm{e}^{-0.0498 \mathrm{X}}$ | 0.8952 |
| 85\% Model | Polynomial Eq. | $\mathrm{Y}=32.537 \times \mathrm{X}^{-0.9524}$ | 0.9347 |
|  | Liner Eq. | $\mathrm{Y}=-0.4043 \mathrm{X}+4.1936$ | 0.7428 |
|  | Exp. Eq. | $\mathrm{Y}=5.2724 \mathrm{e}^{-0.0487 \mathrm{X}}$ | 0.8826 |

The capacity estimation model can be built from applying Eq. (5) to Table 3. Below $35 \mathrm{~km} / \mathrm{h}$ condition, the built model is reliable with respect to its power of explanation, but above $35 \mathrm{~km} / \mathrm{h}$ condition, safety (notion of Figure 5) must be considered. Based on this idea, Figure 10 shows the capacity by speed in each model.


Figure 10. Capacity for velocity by each model

### 5.3 Result of DHCE Application

KHCM (Korean Highway Capacity Manual) presented the ideal service volumes for a basic freeway segment by design speed in the following Table 4. And, HCM (Highway Capacity Manual, USA) presented the service volumes for a basic freeway segment by free flow speed (FFS) in the separating urban and rural area in Table 5. The hatched area can be applied for an index of capacity in Table 4 because the design speed of the study area is $80 \mathrm{~km} / \mathrm{h}$.

Table 4. Example Service Volumes for Basic Freeway Segment

| LOS | Density (pcpkmpl) | Design speed 120 kph |  | Design speed100 kph |  | $\begin{gathered} \text { Design speed } \\ 80 \mathrm{kph} \end{gathered}$ |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Traffic volume (pcphpl) | v/c | Traffic volume (pcphpl) | v/c | Traffic volume (pcphpl) | v/c |
| A | $\leq 6$ | $\leq 700$ | $\leq 0.3$ | $\leq 600$ | $\leq 0.27$ | $\leq 500$ | $\leq 0.25$ |
| B | $\leq 10$ | $\leq 1,150$ | $\leq 0.5$ | $\leq 1,000$ | $\leq 0.45$ | $\leq 800$ | $\leq 0.40$ |
| C | $\leq 14$ | $\leq 1,500$ | $\leq 0.65$ | $\leq 1,350$ | $\leq 0.61$ | $\leq 1,150$ | $\leq 0.58$ |
| D | $\leq 19$ | $\leq 1,900$ | $\leq 0.83$ | $\leq 1,750$ | $\leq 0.8$ | $\leq 1,500$ | $\leq 0.75$ |
| E | $\leq 28$ | $\leq 2,300$ | $\leq 1.00$ | $\leq 2,200$ | $\leq 1.00$ | $\leq 2,000$ | $\leq 1.00$ |
| F | $>28$ | - | - |  |  |  |  |

Source: MOCT of Korea, Highway Capacity Manual, 2001. 19page
Table 5. Example Service Volumes for Basic Freeway Segment

| LOS | Urban area ( $110 \mathrm{~km} / \mathrm{h}$ base free-flow speed) |  |  |  | Rural area ( $120 \mathrm{~km} / \mathrm{h}$ base free-flow speed) |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | 2lane | 3lane | 4lane | 5lane | 2 lane | 3lane | 4lane | 5lane |
|  | 98km/h | $101 \mathrm{~km} / \mathrm{h}$ | $103 \mathrm{~km} / \mathrm{h}$ | 106km/h | $120 \mathrm{~km} / \mathrm{h}$ | $120 \mathrm{~km} / \mathrm{h}$ | 120km/h | $120 \mathrm{~km} / \mathrm{h}$ |
| A | 1,230 | 1,900 | 2,590 | 3,320 | 1,440 | 2,160 | 2,880 | 3,600 |
| B | 1,940 | 2,980 | 4,070 | 5,210 | 2,260 | 3,400 | 4,530 | 5,660 |
| C | 2,820 | 4,340 | 5,920 | 7,550 | 3,150 | 4,720 | 6,300 | 7,870 |
| D | 3,680 | 5,570 | 7,500 | 9,450 | 3,770 | 5,660 | 7,540 | 9,430 |
| E | 4,110 | 6,200 | 8,310 | 10,450 | 4,120 | 6,180 | 8,240 | 10,300 |

Source: TRB Highway Capacity Manual, 2000. 13-13page
The models were evaluated or tested by using 74 trip samples (total 290.56 sec ) of total 5,954 samples, characterized in Table 6 and Figure 11.

The road of the study area has same constant value $2,000 \mathrm{vphpl}$ for even different traffic conditions in the HCM (Highway Capacity Manual, USA, 2000). Under this concept of capacity, dynamically changing traffic condition cannot be considered, so the volume per capacity (V/C) of the roadway suddenly changes to an oversaturated condition. Because of this limitation, HCM methods cannot properly used to evaluate a traffic system. Using DHCE, it's not occurred those conditions that traffic volume excess the capacity of the roadway (V/C is larger than 1) as shown Figure 11. In other words, DHCE is a more feasible method than the previously used method in terms of traffic characteristics.

Table 6. The Example Sample Data for Evaluating The Models

| Num. | Traffic characteristics |  | Num. | Traffic characteristics. |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Speed <br> (km/h) | Headway (sec) |  | Speed <br> (km/h) | Headway (sec) |
| : | : | : | 23 | 36.82 | 1.98 |
| 15 | 18.87 | 3.10 | 24 | 34.62 | 4.41 |
| 16 | 24.07 | 4.34 | 25 | 32.47 | 2.58 |
| 17 | 17.82 | 4.29 | 26 | 32.78 | 1.79 |
| 18 | 16.20 | 2.79 | 27 | 30.83 | 2.22 |
| 19 | 33.91 | 3.30 | 28 | 44.66 | 8.46 |
| 20 | 27.82 | 2.42 | 29 | 42.70 | 6.26 |
| 21 | 39.23 | 1.84 | 30 | 40.08 | 2.97 |
| 22 | 39.14 | 3.02 | : | : | : |



Figure 11. The Characteristic of Data for Model Evaluation


Figure 12. Comparison between Instantaneous Traffic Volume and Capacity by KHCM (2001)


Figure 13. The result of $95 \%$ dynamic capacity model

## 6. CONCLUSION

This study is an initiative to overcome the HCM's shortcomings. Problems of HCM methods were due to the following reasons: (1) misunderstanding of roadway capacity without capacity bubble, (2) underestimating of roadway capacity with non-capacity data information, (3) no consideration of the ability of a roadway to change according to the traveling speed of an individual vehicle. To overcome the problems associated with HCM's, DHCE methods were developed, and it gave very good results in its explanation of dynamic real traffic situations.

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