ESTIMATING DESIRED SPEEDS IN JAPAN TWO-LANE HIGHWAYS*

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1. Introduction

Following behavior, or at least the amount of time spent following a lead vehicle while driving, is a widely accepted measure of driver satisfaction, which consequently reflects the level of service of that particular highway facility. This is even more emphasized in a two-lane highway with passing restriction, for once a driver encounters a leader with a current speed that is lower than his desired speed, he will be following for the rest of the way. Determining the number of followers at any given time interval can provide useful insight on how the highway is performing in terms of service quality based on user perception. It is still however an issue how a vehicle can be classified as either following or free (traveling at the driver's desired speed).

The problem arises from the fact that the desired speeds of different drivers vary significantly, making it difficult to assess whether a vehicle is constrained or unconstrained based on directly accessible data (i.e. time headway, speed, etc.) alone. If the desired speed distribution of drivers are known for a given highway facility, it would then be possible to reasonably replicate existing conditions, including following behavior, in a simulation environment.

A recently developed procedure could now provide a means to estimate free speed distributions using observed headway distributions. It is the goal of this study to use this methodology to obtain free speed distribution estimates of Japan two-lane highways in varying traffic, ambient and geometric conditions, which could then be later used as input for simulation. It was found that follower density is a very promising service measure for Japan two-lane expressways[1)], although the critical headway used for that study was still the 3-second threshold suggested by the HCM[2)]. Should the simulation runs using the desired speed distribution estimates obtained from this study prove to be successful, the 'true' quantities of following behavior characteristics (including follower density) can then be investigated accordingly. However, the applications and the underlying assumptions of the succeeding procedures to be described will just be limited to two-lane highway sections where passing is not allowed.

2. Theoretical Background

(1) Composite Headway Distribution Model

Headway distribution models can be classified into two main types – simple models and mixed (or composite) models. The former consists of single statistical distributions that possess properties of observed headway distributions, while the latter is a decomposition of the total distribution into distribution models of following and non-following vehicles, in suitable proportions.

Over the past few decades, several time-headway distribution models have been proposed. Cowan presented his M3 and M4 models as more realistic representations of the arrival process in single lane, no-passing zone highways, without necessarily having to go through extreme mathematical difficulties[3)]. A generalized queuing model was formulated by Branston (also know as the BGQ or Branston's Generalized Queuing Model)[4)], which also distinguishes between free-flowing and following vehicles. Another mixed distribution model, introduced by Buckley in 1968, provides a means to calculate both the constrained and unconstrained components of the total headway distribution. The general form of this model, which is also widely known as the Semi-Poisson model[5)], is given by the following probability density function *f(t)*:

$$f(t) = \phi g(t) + (1-\phi)h(t) \qquad (1)$$

where $g(t)$ and $h(t)$ are the constrained and unconstrained components, respectively, and ϕ is the proportion of the constrained vehicles. Without following vehicles (i.e. $\phi = 0$), all of the headways would belong to the unconstrained group and this can be suitably described by an exponential function corresponding to random arrival times.

(2) Non-Parametric, Distribution-Free Estimation

To estimate composite headway distribution models, different approaches exist. Some suggest specifying the functional form of the sustained tracking headway distribution (also referred to in most literature as the *empty zone*) and estimate the parameters of the mixed model[6)]. In this study however, we shall use the non-parametric, distribution-free approach proposed by Wasielewski, which reformulated the Semi-Poisson model into an integral equation wherein the components can be directly calculated from the observed headway distribution[7)]. For convenience, the original model was first rewritten to define components $g_1(t) = \phi g(t)$ and $h_1(t) = (1-\phi)h(t)$, so that

$$f(t) = g_1(t) + h_1(t) \qquad (2)$$

The fraction ϕ can be expressed as:

$$\phi = \int_0^\infty g_1(t)dt = \int_0^\infty [f(t) - h_1(t)]dt \qquad (3)$$

and the free distribution $h_1(t)$ as:

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$$h_1(t) = \frac{A\lambda e^{-\lambda t}\int_0^t g_1(s)ds}{\int_0^\infty g_1(s)ds}$$

$$= \frac{A\lambda e^{-\lambda t}}{\phi} e^{-\lambda t}\int_0^t \left[f(s) - h_1(s)\right]ds \qquad (4)$$

For large headway values, the headway distribution of free-flowing drivers can be expressed solely in its exponential form, so that for $t > T$, we can write

$$f(t) = h_1(t) = A\lambda e^{-\lambda t} \qquad \text{for } t > T \qquad (5)$$

T here is defined as a headway value where there is no significant probability of interactions between vehicles, while the parameters λ and A are the arrival rate for free vehicles and the normalization constant, respectively. The details on these parameters are discussed more intensively in Buckley, 1968 and Wasielewski, 1978[8]. Based on Wasielewski's proposed methodology, the parameter λ can be estimated using Maximum-Likelihood, given by the following maximum-likelihood estimate for λ:

$$\hat{\lambda} = \left[\frac{1}{m}\sum_i (t_i - T)\right]^{-1} \qquad (6)$$

where m is the number of headway observations greater than T ($t_i > T$). With this estimate for λ, the value T and the total number of headway samples n, an estimate for the normalization constant A can now be solved:

$$\hat{A} = \frac{m}{n} e^{\hat{\lambda} T} \qquad (7)$$

Given the maximum-likelihood estimates of the parameters required for the unconstrained distribution function, $h_1(t)$ can be transformed and then solved using an iterative approach where the i^{th} estimate can be approximated from the $(i-1)^{th}$ estimate using the equation:

$$\hat{h}_1^{(i)}(t) = \hat{A}\hat{\lambda} e^{-\hat{\lambda} t}\left\{1 - \frac{1}{\hat{\phi}^{(i-1)}}\int_t^\infty \left[\hat{f}(s) - \hat{h}_1^{(i-1)}(s)\right]ds\right\} \qquad (8)$$

Once the unconstrained headway distribution has been solved, the constrained distribution can be easily derived by applying:

$$\hat{g}_1(t) = \hat{\phi}\hat{g}(t) = \hat{f}(t) - \hat{h}_1(t) \qquad (9)$$

(3) The Modified Kaplan-Meier Approach

A new approach in estimating the distribution of free speeds was introduced by Hoogendoorn in 2005, which is a generalization of the original distribution-free method of Kaplan-Meier[9] that includes partially censored observations (i.e. observations that are constrained with a certain probability). This methodology requires the modification of the Kaplan-Meier estimate of the survival function given by:

$$\hat{S}(v^0) = \prod_{j=1}^{n_{v^0}} \left(\frac{n-j}{n-j+1}\right)^{\delta_j} \qquad (10)$$

where n_{v^0} is the number of samples of v_i that are smaller than or equal to v^0, n equals the total number of headway observations and δ_j is the factor that identifies whether a vehicle is following or not (i.e. $\delta_j = 0$ if unconstrained and $\delta_j = 1$ if constrained). The modification of this function stems from the derivation of a conditional probability function $\theta(t)$, which can be solved using the equation $\theta(t) = g_1(t)/f(t)$, where $g_1(t)$ is the constrained headway distribution function derived from the previous section while $f(t)$ is the distribution of observed headways. After solving for the conditional probability function, this can then be applied to the Kaplan-Meier method to yield the estimator of the free speed distribution, $\hat{F}_\infty(v^0)$ given by the modified survival function:

$$\hat{S}_\infty(v^0) = \prod_{j=1}^{n_{v^0}} \left(\frac{n-j-1}{n-j-\theta_j}\right) = 1 - \hat{F}_\infty(v^0) \qquad (11)$$

For the detailed derivation of this function, refer to Hoogendoorn (2005)[10].

3. Data Reduction

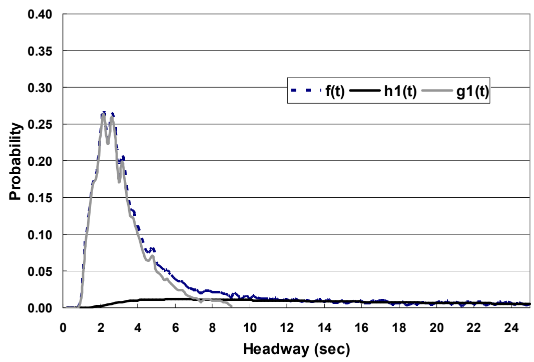
Raw pulse data collected from an installed vehicle sensor at Route 19 in Kiso, Nagano was used for this study. The data were collected everyday during the whole month of May 2006 and each day was categorized as either a weekday or a holiday (includes weekends). The individual headways were classified according to different driving conditions, mainly considering vehicle types (passenger car or heavy vehicle) and ambient conditions (daytime and nighttime, rain and no rain). The vehicle sensor has been calibrated so that the distinction between vehicle types can be done using the detected length, which is among the data output of the detector. The details of this calibration process and the resulting thresholds are discussed in a separate report[11] (see Catbagan, et al., 2006). Daytime and nighttime conditions are defined to be the period from 8:00 AM to 4:00 PM and from 8:00 PM to 4:00 AM, respectively. This distinction was necessary to check the effects of dark driving conditions on the drivers' desired speeds. The rest of the time periods within the day (4:00 – 8:00 AM and 4:00 – 8:00 PM) were intentionally excluded to eliminate the possible effects of these 'transition' periods. Classification according to gradient was also done although only two gradient types were available – the two opposite lanes of the detector site with gradients of +4.44% and -3.66% in the northbound and southbound directions, respectively.

The data were classified into several data sets according to the distinctions described above and are shown in **Table 1**. Because this study mainly serves as a preliminary field test of the new approach for Japan traffic conditions, and also due to the relatively extensive procedures in data processing, only one month's worth of data were used, although data from April 2006 to January 2007 are also available. This is why only the data during daytime and 'no rain' conditions were analyzed, just to get the necessary information for these 'ideal' driving conditions. It is also important to note that if a data set

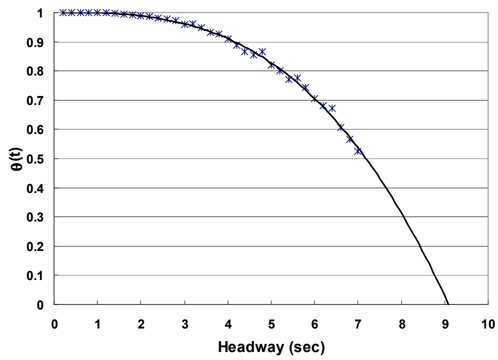
Table 1: Data set classifications for estimating desired speeds

Direction/ Gradient	Weather	Flow Rate (veh/h)	Holiday				Weekday			
			Day-time		Night-time		Day-time		Night-time	
			PC	HV	PC	HV	PC	HV	PC	HV
South-bound/ -3.66%	No Rain	0-100	✓	✓	×	×	✓	✓	×	×
		100-200	✓	✓	×	×	✓	✓	×	×
		...	✓	✓	×	×	✓	✓	×	×
	Rain	0-100	×	×	×	×	×	×	×	×
		100-200	×	×	×	×	×	×	×	×
		...	×	×	×	×	×	×	×	×
North-bound/ +4.44%	No Rain	0-100	✓	✓	×	×	✓	✓	×	×
		100-200	✓	✓	×	×	✓	✓	×	×
		...	✓	✓	×	×	✓	✓	×	×
	Rain	0-100	×	×	×	×	×	×	×	×
		100-200	×	×	×	×	×	×	×	×
		...	×	×	×	×	×	×	×	×

Note: Only those data sets with check marks (and without shading) are included in this study (May 2006 data only)



(a) Composite headway model



(b) Conditional probability function

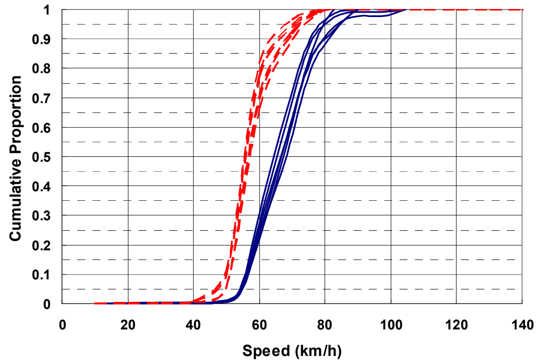
Figure 1: Sample output

size falls below 1000 samples, it will not be included in the analysis.

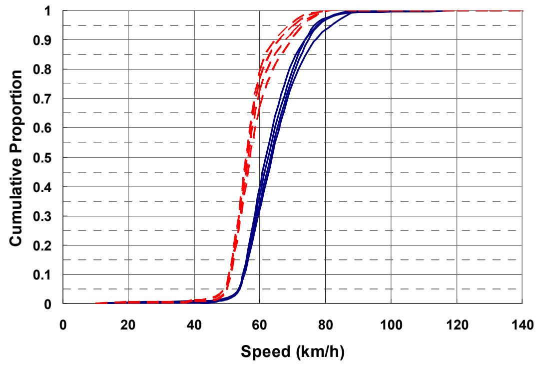
4. Desired Speed Estimation

To get an estimate of the conditional probability function *θ(t)*, composite headway models for each 100 veh/h flow rate interval were derived using the given data. Shown in **Figure 1** is a sample output for a single data set category, which in this case is the passenger car with a flow rate range of 300-400 veh/h during the weekday, daytime period in the southbound direction, with no rain.

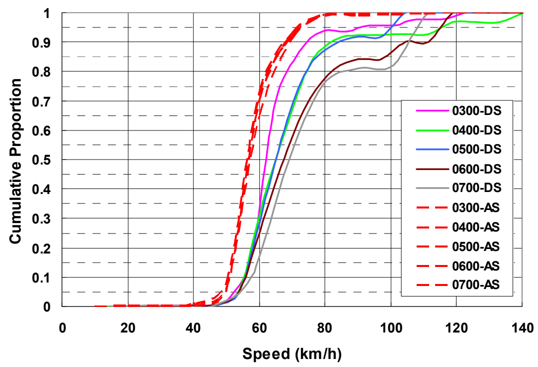
From the resulting free speed distribution estimates, the presence of followers can be deduced for both holiday and weekday periods by comparing the differences between the actual and desired speed distributions as



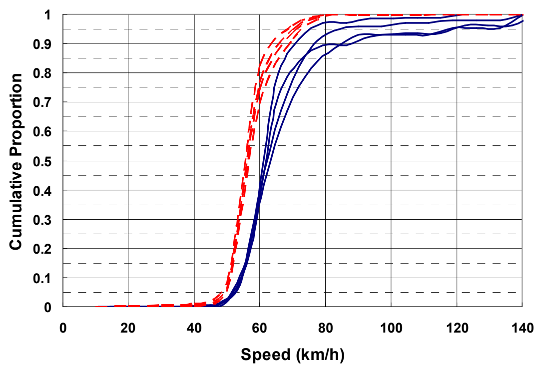
(a) Passenger car, holiday



(b) Passenger car, weekday



(c) Heavy vehicle, holiday



(d) Heavy vehicle, weekday

Figure 2: Actual and desired speed distribution comparisons

shown in **Figure 2**. The figures shown here are all in the northbound direction. Broken and solid lines are actual and desired speeds, respectively. The speed differences between actual and desired speeds are relatively larger during holidays (charts *(a)* and *(c)*) compared to those during weekdays (charts *(b)* and *(d)*), which indicates higher follower flow in the former. For passenger cars, the variation in desired speeds across different flow rates does not vary too much (**Figures 2a** and **2b**) but this is quite significant for heavy vehicles as seen in the two bottom charts. In **Figure 2c**, the free speed distributions of heavy vehicles at different flow rates are illustrated in varying colors to emphasize the seemingly increasing desired speeds by heavy vehicle drivers as traffic volume increases. This could mean that as flow rates increase, the probability of heavy vehicles becoming followers also increase. It can also be seen from the charts that the free speeds of passenger cars and heavy vehicles vary depending on the flow rate level. At lower volumes (around 100 – 500 veh/h), the desired speeds of heavy vehicles are less than or almost the same as those of passenger cars. At higher volumes however, the desired speeds of heavy vehicles also become higher than those of passenger cars.

Figure 3 shows the comparison between the distributions for the two gradient conditions. Desired speeds appear to be higher if vehicles are going downgrade, although the results presented here may not be the general case for all grade levels. Some previous studies stated that vehicles tend to prefer lower speeds when traversing steep downgrades, for safety reasons. Further research on other grade levels are thus recommended to come up with a more generalized conclusion on the effect (or non-effect) of gradient to desired speeds.

5. Conclusions and Recommendations

The modified Kaplan-Meier approach in estimating free speed distributions was applied to Japan two-lane highway conditions and produced satisfactory results. Higher follower flow during holidays were confirmed, indicated by the relatively larger differences in actual and free speed distributions as compared to those during weekdays. It was also found that heavy vehicles tend to have higher desired speeds as volume increases, which is probably an indication of higher freight vehicle composition during peak, daytime periods. Although the results showed higher desired speeds at the downgrade section, these were still inconclusive with only two gradient conditions analyzed.

With these results, it is recommended to move the research forward in analyzing the other conditions (i.e. weather, ambient) and include data collected in the other months to dramatically increase the reliability and accuracy of all the estimates.

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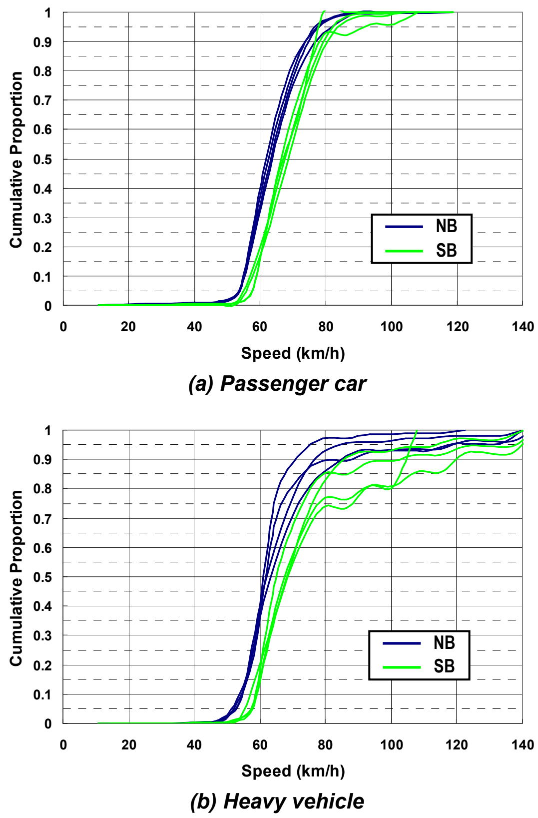

Figure 3: Upgrade (NB) and downgrade (SB) free speed distribution comparisons during weekdays

References

1) Catbagan, J. L. and Nakamura, H. (2006), Evaluation of Performance Measures for Japan Two-Lane Expressways. Transportation Research Record 1998, pp. 111-118.
2) Highway Capacity Manual (2000), Transportation Research Board, USA.
3) Cowan, R. J. (1975), Useful Headway Models. Transportation Research, Vol. 9, Issue 6, pp. 371-375.
4) Branston, D. (1976), Models of Single Lane Time headway Distributions. Transportation Science, Vol. 10, No. 2, pp. 125-148.
5) Buckley, D. J. (1968), A Semi-Poisson Model of Traffic Flow. Transportation Science, Vol. 2, No. 2, pp. 107-132
6) Hoogendoorn, S. P. and Botma, H. (1997), Modeling and Estimation of Headway Distributions. Transportation Research Record 1591, pp. 14-22.
7) Wasielewski, P. (1974), An Integral Equation for the Semi-Poisson Headway Distribution Model. Transportation Science, Vol. 8, pp. 237-247.
8) Wasielewski, P. (1979), Car-Following Headways on Freeways Interpreted by the Semi-Poisson Headway Distribution Model. Transportation Science, Vol. 13, No. 1, pp. 36-55.
9) Kaplan, E. L., Meier, P. (1958), Nonparametric Estimation from Incomplete Observations. Journal of the American Statistical Association, Vol. 53, No. 282, pp. 457-481.
10) Hoogendoorn, S. P. (2005), Unified Approach to Estimating Free Speed Distributions. Transportation Research Part B, Vol. 39, Issue 8, pp. 709-727.
11) Catbagan, J. L., Nakamura, H. and Utsumi, T. (2006), Effects of Heavy Vehicles on Following Behavior in Two-Lane Highway Sections. Proceedings of Infrastructure Planning (CD-ROM), Vol. 34, Japan Society of Civil Engineers (JSCE).