Modelling the Relationship between Flow and Section Travel Speed on Arterials

Edwin AKANDWANAHO[1], Azusa GOTO[2] and Hideki NAKAMURA[3]

[1]Student Member of JSCE, Doctor Course Student, Graduate School of Environmental Studies, Nagoya University
(C1-2(651), Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan)
Email: edwin@genv.nagoya-u.ac.jp
[2]Member of JSCE, Former Assistant Professor, Graduate School of Environmental Studies, Nagoya University
(Researcher, National Institute of Land and Infrastructure Management)
(1 Asahi, Tsukuba, 305-0804, Japan)
Email: goto-a92uj@mlit.go.jp
[3]Fellow Member of JSCE, Professor, Graduate School of Environmental Studies, Nagoya University
(C1-2(651), Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan)
Email: nakamura@genv.nagoya-u.ac.jp

Accurate estimation of travel speed along highways is essential to ensure that the required performance level is met. In this paper, a model for estimating travel speed based on the relationship between travel speed and flow has been developed from data collected along Hamamatsu Bypass in Hamamatsu City, Japan. A logarithmic function is adopted to fit onto the observed speed-flow relationship under uncongested conditions of each section of the bypass. Subsequently, the parameters of the function are modelled by linear regression with length, number of intersections, intersection density, and number of access points as the independent variables. Speed was found to increase with reduced number and density of intersections, as well as with reduced number of access points. Capacity slightly increased with increasing section length.

Key Words : *average travel speed, travel time, traffic flow, capacity, geometry*

1. INTRODUCTION

At low traffic flow rates, drivers are able to drive at their desired speeds, free from the influence of other vehicles. As the flow rate increases, vehicles start being influenced by the presence of other vehicles, and the speed gradually decreases. The speed reduction continues with increasing flow until the capacity of the roadway is reached. At capacity, vehicle movements become more difficult, leading to reduced speed and reduced flow.

For practical applications, the Highway Capacity Manual (HCM 2010)[1)] suggests that the space mean speed along a freeway segment is constant under low flow. After a certain point (the “breakpoint”), an increase in flow leads to a reduction in space mean speed based on a quadratic function.

Hall (1997)[2)] reviewed several empirical works detailing the relationship between speed and flow. In some cases, a speed drop was observable at capacity, but not in others. However, the empirical evidence supports the type of curve described in HCM 2010.

On the other hand, Brilon and Lohoff (2011)[3)] argue that even under flow rates below the “breakpoint” a certain decrease in speed is to be expected with increasing flow.

In addition to flow, the travel speed can also be influenced by other aspects of a roadway. HCM 2010 travel speed estimation methodologies show that the travel speed depends on several geometric, traffic, and control factors. In this study, the following factors are considered for inclusion in model development; signal settings, demand flow rate, section length, number of intersections, distance between intersections, intersection density, and number of access points.

2. METHODOLOGY

(1) Site description

A 12.5 km two-lane (in one direction) section of Hamamatsu Bypass is considered for this study. The bypass is divided into ten sections, five in each travel direction. The sections are defined based on the

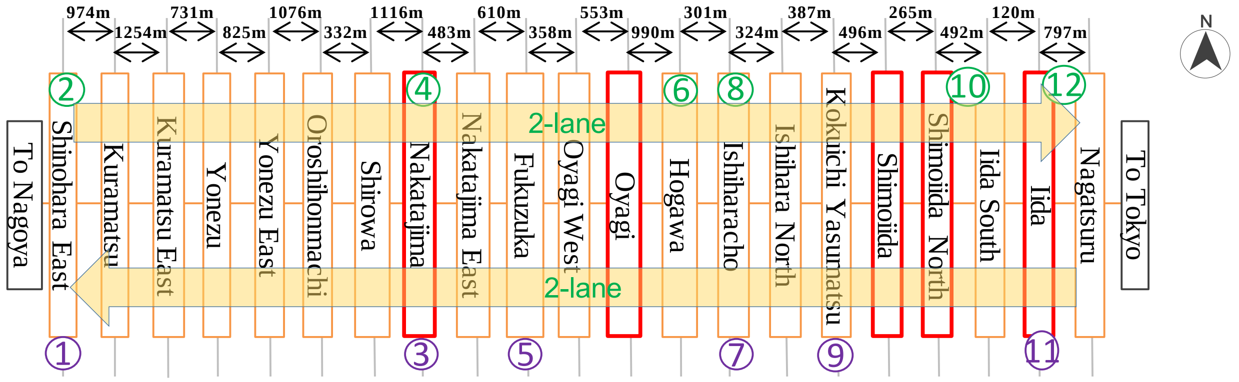

Fig. 1 Hamamatsu Bypass intersections

positioning of the travel time collection antennas described in the data collection section.

Fig.1 is a representation of the bypass, showing the signalised intersections along the bypass. The positions of the antennas are also shown in **Fig.1** Even numbered antennas i.e. 2 through to 12 represent travel in the Eastbound direction, towards Tokyo, while odd numbered antennas represent travel in the Westbound direction, in this case from antenna 11 through to 1. The road sections are defined as being bound by the antennas, and their lengths are shown in **Table 1**.

(2) Data collection

a) Traffic volume and signal settings

Traffic volume data was collected at five signalised intersections on Hamamatsu Bypass. The data was collected manually by using counters, and it was aggregated in intervals of 10 minutes during the hours 07:00 – 10:00 and 16:00 – 19:00, while between 10:00 – 16:00, the volume was aggregated in 1-hour intervals. Traffic signal setting data was also collected at these intersections. **Table 2** shows the cycle lengths, and the affective green-to-cycle length ratios of each of the five intersections.

b) Travel time and travel speed

Travel time data was collected using antennas set up along various locations on the bypass.

Twelve antennas, six for each travel direction, were set up along the bypass, and they functioned by picking up electromagnetic waves emitted by Electronic Toll Collection (ETC) devices that are installed in the majority of cars on Japan's roads. When an ETC device equipped vehicle passed an antenna, the electromagnetic waves emitted by the device were picked up by the antenna and recorded as the unique number corresponding to that reader – this was termed as the Wireless Call Number (WCN). Due to the WCN's uniqueness to each reader, it was also an indication of each unique vehicle. The time at which the vehicle was detected was also recorded.

Table 1 Hamamatsu Bypass section lengths

	Eastbound				
Section	2-4	4-6	6-8	8-10	10-12
Length (km)	6.4	2.9	0.40	1.8	0.85
	Westbound				
Section	11-9	9-7	7-5	5-3	3-1
Length (km)	1.1	0.90	1.8	1.5	6.6

Table 2. Signal settings of five representative intersections

Intersection Name	Cycle length, *C* (s)	Effective green-to-cycle length, *g*/*C*
Nakatajima	150	0.55
Oyagi	173	0.45
Shimo-iida	168	0.58
Shimo-iida North	167	0.69
Iida	169	0.59

By matching unique WCNs passing successive antennas and comparing the times at which they were detected, the travel time of each vehicle between successive antennas was obtained. Travel time was averaged in 10-minute and 1-hour intervals to correspond to the traffic volume data.

Average travel speed along each section was then obtained by dividing the length of the section by the average travel time along the section.

(3) Data analysis

a) Speed-flow relationships

The focus of this research was on the uncongested flow regime, that is typically the upper region of the speed vs. flow curve in which speed reduces with an increase in flow.

For each section, a plot was made of the average travel speed of the vehicle versus the flow along the section.

Fig.2 is a speed-flow plot of one section of the bypass.

b) Model specification

The relationship between average travel speed and flow was specified by the model shown in Equation (1). **Fig.3** is a graphical representation of the model.

$$v = a * \ln\left[b(c-q)\right] + d \qquad (1)$$

Where,
v = average travel speed (km/h)
q = traffic flow (veh/h)
a, b, c and d = model parameters

In **Fig.3**, *a*ln(bc)+d* corresponds to the free-flow speed, and *c* is an approximation of the capacity of the study section.

This model was chosen because it gives a slight reduction in travel speed with increasing flow under low flow conditions. This is in keeping with literature that suggests that there are no changes, or slight changes in the travel speed under low flow conditions.

3. RESULTS

(1) Fitting the model onto average travel speed vs. flow data

For all 10 sections of the bypass, speed-flow graphs such as shown in **Fig.2** were drawn. The distinction between the congested and the uncongested flow regime was not clear for some of the sections, and these were not used in the modelling. The model was therefore only fit onto data for five (5) sections.

Microsoft Excel Add-In "XLFit" was used to fit the models onto the observed speed-flow data for the five sections. Equation (1) was specified in the Add-In and the fitting process initiated. The best estimates of parameters *a*, *b*, *c*, and *d* were outputted, and are shown in **Table 3**.

(2) Modelling the parameters

The parameters *a*, *b*, *c* and *d* of Equation (1) were modelled based on the characteristics of the sections. First, each parameter was plotted against each section characteristic to observe if there was a logical relationship. **Table 4** shows the characteristics of the five sections that were used in the model development. The relationships were postulated as shown in Equations (2a) – (2d).

$$a_i = \alpha_0 + \alpha_1 X_{1,i} + \alpha_2 X_{2,i} + \ldots + \alpha_n X_{N,i} \qquad (2a)$$

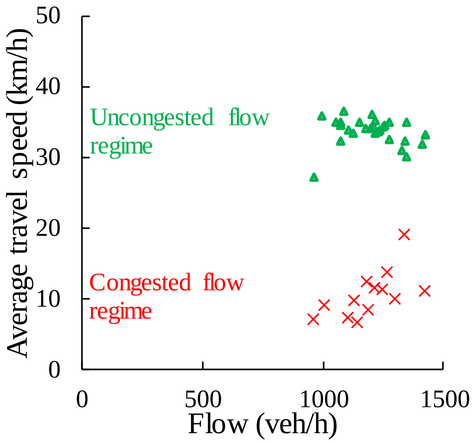

Fig.2 Average travel speed vs. flow (section 8-10)

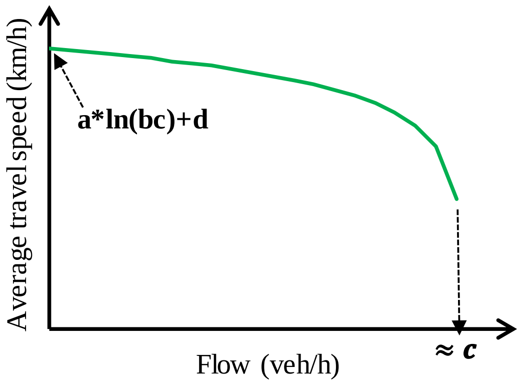

Fig.3 Model representation

Table 3 Model parameter estimation results

Section	Parameter Estimates			
	a	*b*	*c*	*d*
2-4	6.621	1.546	2030	-1.179
8-10	5.017	1.296	1962	-0.630
10-12	5.000	6.460	1627	7.562
3-1	12.17	0.2493	2782	-17.75
7-5	7.713	1.259	1723	-2.409

Table 4 Section characteristics

	Section				
	2-4	8-10	10-12	3-1	7-5
L	6.4	1.8	0.85	6.6	1.8
N_{intn}	8	4	2	7	3
N_{ap}	38	24	13	44	11
D_{intn}	1.3	2.3	2.4	1.1	1.7
g/C	0.51	0.58	0.58	0.51	0.40

L = section length (km), N_{intn} = number of intersections, N_{ap} = number of access points, D_{intn} = signalised intersection density (intersections/km), g/C = effective green-to-cycle length ratio

$$b_i = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \ldots + \beta_n X_{N,i} \quad (2b)$$

$$c_i = \gamma_0 + \gamma_1 X_{1,i} + \gamma_2 X_{2,i} + \ldots + \gamma_n X_{N,i} \quad (2c)$$

$$d_i = \delta_0 + \delta_1 X_{1,i} + \delta_2 X_{2,i} + \ldots + \delta_n X_{N,i} \quad (2d)$$

Where,
a_i, b_i, c_i, and d_i = logarithmic function parameters for section i
X = independent variables (section characteristics in **Table 4**)
α, β, γ, and δ = model parameters

Linear regression conducted in Microsoft Excel yielded the parameter estimates shown in **Table 5**.

The model for average travel speed based on traffic flow was thus developed as:

$$v = a * \ln\left[b(c - q)\right] + d \quad (1)$$

Where;

$$a = 14.37 - 4.105 D_{intn} \quad (3a)$$

$$b = 5.009 - 0.5931 N_{intn} \quad (3b)$$

$$c = 1572 + 130 L \quad (3c)$$

$$d = 8.866 - 0.4557 N_{ap} \quad (3d)$$

All variables are as previously defined.

(3) Sensitivity analysis

The sensitivity of the model was tested by applying it to section 2-4 whose characteristics are shown in **Table 4**. Each variable used in the model as shown in equation (3) was varied in turn while keeping the others constant, and the impact on the speed-flow relationship studied.

a) Number and density of signalised intersections

In the model, keeping the section length and the number of access points constant, as the number of intersections decreases, there will be a proportionate decrease in the intersection density. These two factors lead to an increase in the parameters *a* and *b* following Equations (3a) and (3b), respectively, and therefore an increase in the average travel speed. This change is shown in **Fig.4**.

This result is as expected since fewer intersections mean the vehicle is stopped fewer times while traversing the road section. In addition, each signalised intersection is associated with some lost time in each cycle, and fewer signals means reduced lost time, shorter average travel time and therefore higher average travel speed.

b) Section length

Fig.5 shows the sensitivity of the model to changes in section length. An increase in the section length is seen to increase the average travel speed. This is a combined result of an increase in parameter *c* according to equation (3c) and an increase in parameter *a* resulting from a reduction in the intersection density.

In addition to reduced delay from lower intersection density, a longer section is likely to provide more opportunities for a vehicle to accelerate and achieve higher travel speed.

Table 5 Linear regression results

Parameter	*a*	*b*	*c*	*d*
Constant	14.37 *(4.760)*	5.009 *(2.202)*	1572 *(6.464)*	8.866 *(1.245)*
L (km)			130.3 *(2.292)*	
N_{intn}		-0.5931 *(-1.389)*		
N_{ap}				-0.4557 *(-1.844)*
D_{intn} (intn/km)	-4.105 *(-2.450)*			
g/C				
Adjusted R^2	0.555	0.189	0.515	0.375

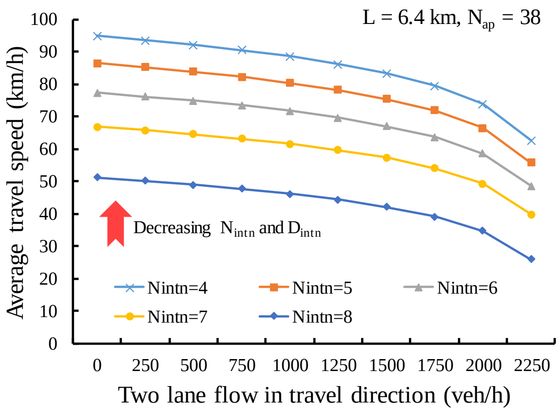

Fig.4 Sensitivity to number and density of intersections

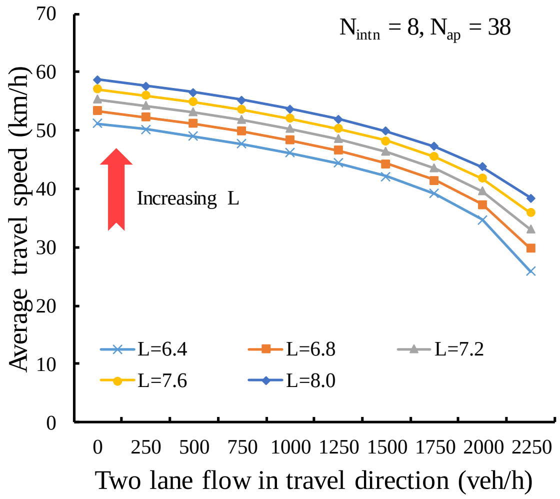

Fig.5 Sensitivity to section length

Recalling that parameter *c* is an approximation of the capacity of the arterial, according to Equation (3c), suggests that an increase in section length increases the capacity of the section. However, in this research the link lengths were small, and under these kinds of conditions, capacity can be affected by poor settings of signal offsets at intersections. This might have affected the tendency observed.

c) Number of access points

Fig. 6 shows that a decrease in the number of access points into or out of the section leads to an increase in average travel speed. This is due to fewer disruptions to the major traffic flow, which reduces delay and increases average travel speed.

4. CONCLUSIONS

A model was developed for the estimation of the average travel speed along an arterial section in Japan. To provide an estimate of average travel speed, the model requires the input of five parameters; flow along the section, section length, number of access points, number of signalised intersections and the density of signalised intersections in the section.

The sections used in the model development had moderately high flows. Because the speed-flow relationship was not observed under low flow conditions, the model is likely limited in its applicability to these conditions.

From Equation (3a) it can be seen that if the intersection density exceeds 3.5 intersections per kilometre, the value of parameter *a* would become negative, which is meaningless since the travel speed cannot be negative. The developed model is therefore limited to arterial sections with intersection densities lower than 3.5 signalised intersections per kilometre.

In addition, signal offset settings were not explicitly considered in the model development. This model would therefore be inappropriate for use on shorter sections since in that case the impact of the offset settings cannot be neglected.

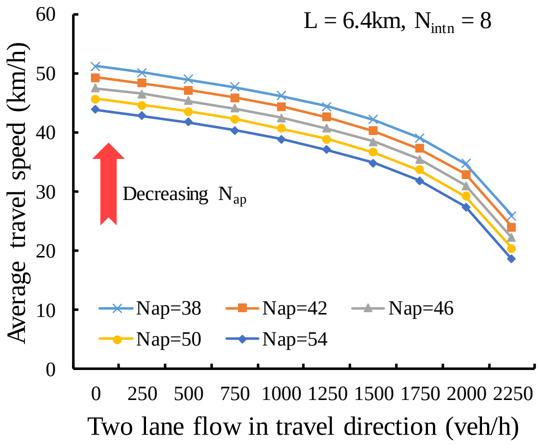

Fig.6 Sensitivity to number of access points

5. FUTURE WORK

The model in this paper was developed by using data from only one arterial, which limits its application to arterials with similar characteristics to the Hamamatsu Bypass. To ensure broader applicability, it is necessary to broaden the study area by collecting additional speed and flow data from sections of more varied characteristics.

ACKNOWLEDGEMENT: The authors would like to thank Dr. Kazuki Watanabe of Oriental Consultants Co. Ltd. for providing data on Hamamatsu Bypass that was used in this study.

REFERENCES

1) Transportation Research Board: Highway Capacity Manual, 2010.
2) Hall, F.H.: Traffic stream characteristics, Monograph on Traffic Flow Theory, Federal Highway Administration, 1997.
3) Brilon, W. and Lohoff, J.: Speed-flow models for freeways, *Procedia - Social and Behavioral Sciences*, 16, pp. 26-36.

(Received April 28, 2017)