Evaluating the Travel Speed Estimation Methodology in Highway Capacity Manual 2010 for Use in Japan

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As one of the functions of a highway, smooth traffic flow is of increasing importance to transportation specialists, requiring careful planning and design of the highway to meet this function. Current highway planning and design practice in Japan prioritizes demand and capacity, but not performance. This study aims to examine the possibility of using an existing methodology to incorporate performance into the planning stage of highways. In this study, a comparative analysis is carried out on travel speed predicted by the Highway Capacity Manual 2010 speed model as applied to a road section in Nagoya, Japan, and the actual travel speed collected by GPS along the same section. Some of the model parameters are relevant for use in Japan, but they need to be reduced to those available at the planning stage. It is also necessary to propose adjustment factors to replace some of the parameters.

Key Words : *performance oriented highway planning, HCM, delay, travel speed, GPS*

1. INTRODUCTION

Travel speed is an important indicator of highway performance, and forms the basis of many performance evaluation methods in use in the transportation planning field. At the operational level, travel speed can be estimated by methods such as those outlined in the “urban street segments” chapter of the Highway Capacity Manual (HCM) 2010[1)].

Considering that highways have a long design life, and that later improvements may pose significant challenges, it is also important to evaluate their performance at the planning stage in order to ensure that they will meet certain performance standards. However, according to Goto & Nakamura (2016)[2)], highways in Japan are typically planned and designed only based on traffic demand and capacity, without evaluating performance at the planning stage.

The HCM 2010 methodology is primarily developed for operational performance analysis, and therefore requires a lot of data inputs. Despite this, the manual advises that area specific default values can be used for some parameters, and the rest of the procedure followed to provide a travel speed estimation at the planning stage.

Based on this background, this paper seeks to test the applicability of the HCM 2010 travel speed estimation methodology to Japan’s roads. The approach taken is to compare the travel speed predicted by HCM 2010 to the actual, field measured travel speed. The intermediate variables such as travel time and delay are also compared.

2. LITERATURE REVIEW

(1) Travel speed estimation method in HCM 2010

a) Model parameters

The methodology for computing travel speed

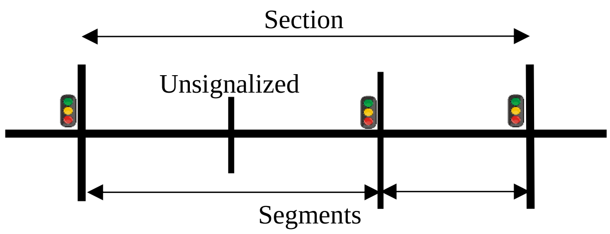

Fig.1 Segments and sections

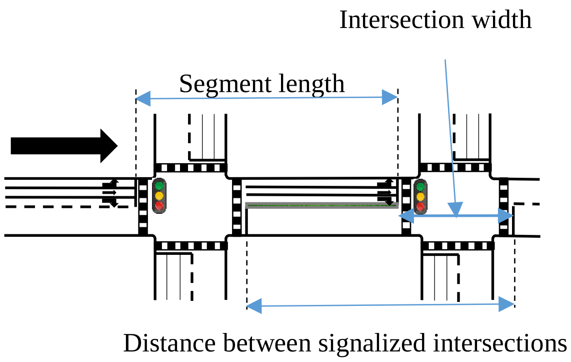

Fig.2 Definition of methodology parameters

along an urban street segment, outlined in chapter 17 of the HCM 2010, is used in this paper.

This methodology also requires computation of control delay at the segment boundary intersections, and since for this study, all the segments are bound by signalized intersection, the delay is estimated using the methodology in chapter 18 of the HCM 2010. **Fig. 1** and **Fig.2** show some of the terms used in this methodology. Segment boundaries can only be controlled intersections. In **Fig.1**, each of the three signalized intersections is a boundary intersection – making two segments. A section is made up of a series of segments, and is typically about 1.6 km or more in downtown areas, and 3.2 km or more in others[1)]. The two segments in **Fig.1** therefore make up the section in this example.

In the HCM 2010, travel speed along an urban street segment is calculated by equation (1)

$$S_{T,seg} = \frac{3{,}600\ L}{5{,}280(t_R + d_t)} \qquad (1)$$

Where;

$S_{T,seg}$ = travel speed of through vehicles for the segment (mi/h)
L = segment length (ft.)
t_R = segment running time (s)
d_t = through delay (s/veh)

For a segment bound by signalized intersections, the running time is calculated using equation (2).

$$t_R = \frac{6.0 - l_1}{0.0025\ L} + \frac{3{,}600L}{5{,}280 S_f} f_v + \sum_{i=1}^{N_{ap}} d_{ap,i} + d_{other} \qquad (2)$$

Where;

l_1 = start-up lost time (s)
L = segment length (ft.)
f_v = proximity adjustment factor
S_f = free-flow speed (mi/h)
$d_{ap,i}$ = delay due to left and right turns from the street into access point intersection *i* (s/veh)
N_{ap} = number of influential access point approaches along the segment
d_{other} = delay due to other sources along the segment (s/veh)

The proximity adjustment factor is given by;

$$f_v = \frac{2}{1 + \left(1 - \frac{v_m}{52.8 N_{th} S_f}\right)^{0.21}} \qquad (3)$$

Where;

v_m = midsegment demand flow rate (veh/h)
N_{th} = number of through lanes on the segment in the subject direction of travel, and S_f is as previously defined.

Free-flow speed is calculated from equation (4)

$$S_f = S_{f0} \times f_L \qquad (4)$$

Where;

S_{f0} = base free-flow speed (mi/h), and
f_L = adjustment factor for segment length

These two factors require a further set of equations for their calculation;

$$f_L = 1.02 - 4.7 \frac{S_{f0} - 19.5}{\max(L_s, 400)} \leq 1.0 \qquad (5)$$

Where;

L_s = distance between adjacent signalized intersections (ft.), and the other factors are as previously defined.

$$S_{f0} = S_0 + f_{cs} + f_A \qquad (6)$$

Where;

S_0 = speed constant (mi/h)
f_{cs} = adjustment factor for cross section (mi/h)
f_A = adjustment for access points (mi/h)

$$S_0 = 25.6 + 0.47 S_{pl} \qquad (7)$$

$$f_{cs} = 1.5 p_{rm} - 0.47 p_{curb} - 3.7 p_{curb} p_{rm} \qquad (8)$$

$$f_A = \frac{-0.078 D_a}{N_{th}} \qquad (9)$$

$$D_a = \frac{5{,}280(N_{ap,s}+N_{ap,o})}{(L-W_i)} \quad (10)$$

The parameters in equations (7) – (10) represent;

S_{pl} = posted speed limit (mi/h)
p_{rm} = proportion of segment length with restrictive median
p_{curb} = proportion of segment with curb on right hand side
D_a = access point density
$N_{ap,s}$ = access point approaches on right side in travel direction
$N_{ap,o}$ = access point approaches on right side in *opposing* travel direction
W_i = width of signalized intersection

Another important parameter in the HCM model is the delay experienced by vehicles due to the presence of control devices such as traffic signals. This control delay can be computed by procedures in Chapter 18 of the HCM 2010, and is given by the formula;

$$d = d_1 + d_2 + d_3 \quad (11)$$

Where;
d = control delay (s/veh)
d_1 = uniform delay (s/veh)
d_2 = incremental delay (s/veh), and
d_3 = initial queue delay (s/veh)

Uniform delay is given by;

$$d_1 = \frac{0.5C(1-g/C)^2}{1-[min(1,X)g/C]} \quad (12)$$

Where;
d_1 = uniform delay (s/veh)
g = effective green time (s)
C = cycle length (s)
X = volume-to-capacity ratio.

The values of g and C for each intersection were manually collected, while the volume-to-capacity ratio was calculated from the following formula

$$X = {}^{v}/_{c} \quad (13)$$

Where v is the demand flow rate (veh/h), and c is the capacity (veh/h). The capacity was in turn calculated from equation 14 below

$$c = Ns\,{}^{g}/_{C} \quad (14)$$

Where N is the number of lanes in the lane group, s is the adjusted saturation flow rate, and g and C are as previously defined.

b) Parameter values at the planning stage

The previous subsection with equations (1) – (14) showed the various input parameters that are required to estimate travel speed using the HCM 2010 methodology. These values are readily available when a road facility has already been constructed. It is, however, not possible to have all this data at the planning stage of a road. In this subsection, comments are given about application to the planning stage.

The road (section) length would be a known input, and by deciding the level of access to provide at the facility, the location and spacing of signals can be decided. In this way, the segment length is available at the planning stage.

The start-up lost time is also known.

Regarding delay due to vehicle turning into access points, rather than using the table provided in HCM, it would be better to have an adjustment factor for the segment running time (equation (2)) rather than using the third term in the equation. This factor can be based on the segment length and the presence of a restrictive median instead of the number of access points (including driveway access), which are unknown at the planning stage.

The posted speed limit can be decided at the planning stage, as can be the number of through lanes, and the decision to include a restrictive median on the road. The proportion of the curb, however, remains unknown at this stage. An empirical study on the effects of number through lanes can be conducted, and an adjustment factor proposed for converting the speed limit into the free-flow speed. In this way, equation (6) can be reduced to just the speed constant, S_0 plus an empirically determined coefficient.

Equation (5) reflects that the HCM model is not suitable for use on segments shorter than 400 ft. (122 m). However, Japan has many segments of this length or shorter. It is therefore necessary to modify this adjustment factor to better reflect Japanese road conditions.

The uniform delay equation (12) uses cycle length, green time split, and intersection capacity. All these parameters require knowledge of the signal time settings, which are typically not known at the planning stage. Two alternatives can be explored at this stage; a method to estimate a representative g/C ratio for the facility, or a delay formula that does not greatly depend on the g/C ratio.

The base saturation flow rate is known at the planning stage. It does, however, require adjustments based on the road geometry, and some traffic characteristics such as the proportion of heavy vehicles, whose adjustment factors are also known.

But since these characteristics may not be known at the planning stage, it might be worthwhile to explore the accuracy of any developed model that simply uses the base saturation flow rate. The demand flow rate is also typically known at the planning stage.

It can be seen that this methodology requires several inputs that are not available at the planning stage. It is therefore necessary to identify which inputs are important and should be considered, and then propose methods of their estimation at the planning stage.

(2) Delay based travel speed evaluation

Utsumi *et al.* (2007)[3] estimated travel speed based on the average delay at key intersections along a given road section. Travel speed was estimated as the section length divided by travel time, which was divided into travel time under free-flow speed, and signal delay. Their delay estimation considered various scenarios of signal coordination through platoon arrival patterns.

Tarko *et al.* (2006)[4] used the HCM 2000 delay formula and micro-simulation studies to propose a formula for estimating travel speeds along urban arterial streets. The developed equation was able to provide a reasonable approximation of travel speed by using inputs of cruise speed (which they recommended could be approximated as, or just below, the speed limit), one-way traffic volumes, number of through lanes, and the distance between intersections.

These results indicate the possibility of developing a simple travel speed prediction method for use at the planning stage.

3. METHODOLOGY

(1) Site description

A 2.9 kilometer road section was selected in Nagoya city, Japan, for testing the applicability of the HCM 2010 methodology. **Table 1** gives the relevant characteristics of the section.

Table 1 Study site characteristics

Length	2.9 km		
Posted speed limit, S_{pl}	50 km/h		
Segment characteristics	Min	Max	Mean
Length, L (m)	138	332	222
Width of upstream intersection, W_i (m)	101	193	129
Proportion of restrictive median, p_{rm}	1	1	1
Proportion of curb, p_{rm}	0.9	1	0.96
Number of through lanes, N_{th}	2	2	2
Number of access points in subject travel direction, $N_{ap,s}$	0	18	9
Number of access points in opposite travel direction, $N_{ap,o}$	2	26	10
Distance between adjacent signalized intersections, L_s (m)	138	332	222

Apart from the section boundary intersections, there is only one major intersection (the cross street has 2 lanes per direction) in the middle of the section. This intersection is shown in bold in **Fig.3**, which is a map showing the study section.

(2) Data collection

a) GPS data

A driving survey was conducted in a GPS device equipped vehicle on 5th and 6th July 2016 (Tuesday and Wednesday) to collect distance, time, and speed data. The GPS device was set to record the vehicle's position every 1.0 seconds. A total of five runs were undertaken in each direction of the road section from intersection 1 to 14 in **Fig.3**.

Because data from only one vehicle (the test vehicle) was to be employed in this study, efforts were made to ensure that the collected data represented the average of the traffic conditions. To this effect, the "average car" driving style – where the driver is instructed to drive according to their judgement of the average speed of the traffic stream[5] – was used. An additional check was employed, with an observer in the test vehicle taking note of the time

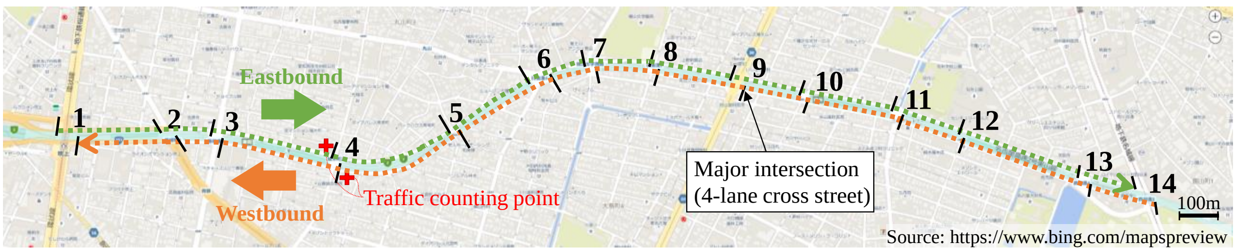

Fig.3 Study road section showing segment boundary intersections

at specified check points along the study road section.

b) Traffic volume and signal setting data

Traffic volume data was collected by observers along the roadside on 5th July 2016. Two observers were stationed at intersection 4, each at one of the locations indicated by a red cross in **Fig.3**. The volume survey was conducted for a 15 minute period during the off-peak hour 15:00 – 16:00. **Table 2** shows the results of the traffic volume survey.

Traffic signal setting data was also manually recorded using timers at each intersection during the off peak period. Cycle lengths varied along the section between 100 and 150 seconds.

(3) Data analysis

a) HCM 2010 analysis

Signal setting data for the HCM methodology was collected as described in subsection (2), and the rest of the data required by equations (1) to (10) was obtained from a combination of field observations and the use of google maps.

The data was then input into the methodology, and free-flow speed, running time, delay, and travel speed were calculated.

In applying this methodology, some assumptions were made, and these are discussed below;

i) Start-up lost time, l_1 is 1.0 seconds
ii) Traffic volume was assumed as the same over the entire section, and constant during the analysis period.
iii) Base saturation flow rate of 2000 and 1800 pcu/h/ln for exclusive through lanes and turn lanes respectively. These are the recommended values for use in Japan[6].
iv) Signal delay was computed with only the uniform delay term given by equation (12).

b) Field data analysis

Data obtained from the GPS device was used to compute the required comparative parameters of travel time, delay, free-flow speed and travel speed.

The first step in this analysis was plotting time-space diagrams for each run, shown in F**ig.4**. Each curve on the plots indicates a different run.

To obtain free-flow speed, running time, and delay, the time-space diagrams were analyzed as shown in **Fig.5**. A linear trend line was fitted onto the data points during which the test vehicle experienced no delay. The inverse of this line's gradient gave the free-flow speed in the given section. The segment length was then divided by this free-flow speed to give running time. Delay was then obtained by

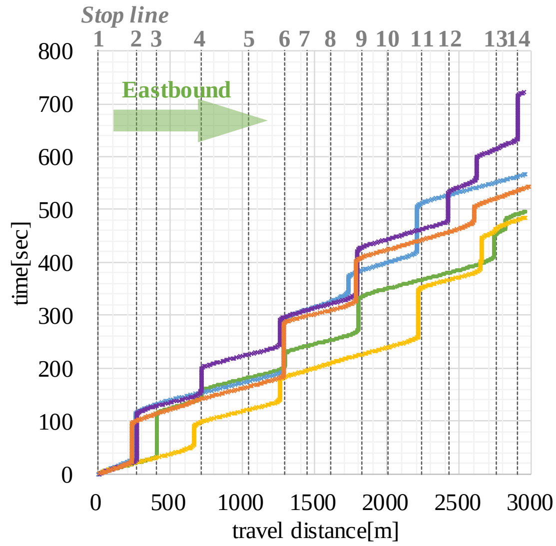

Fig.4a Time-space diagram from intersection 1 to 14

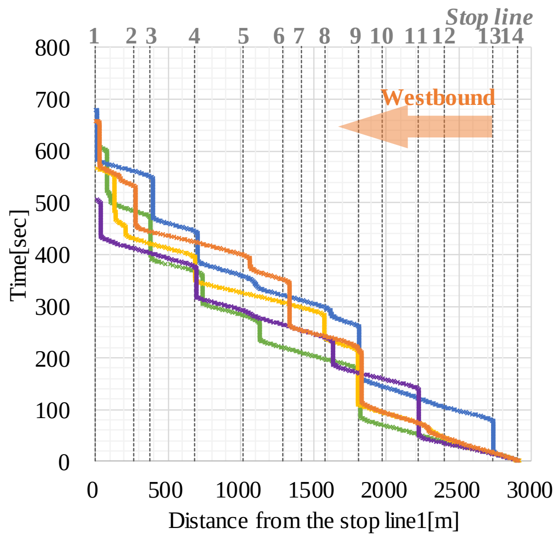

Fig.4b Time-space diagram from intersection 14 to 1

Table 2 Hourly traffic volume along the section

	15 min traffic count	Flow rate (veh/h)
Eastbound	179	716
Westbound	130	520

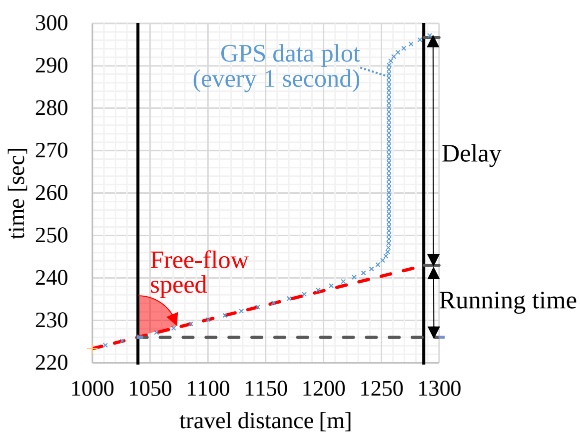

Fig.5 Space-time diagram analysis

subtracting the running time from the measured total travel time.

The free-flow speed, running time, and delay data was then aggregated for the five runs, and then compared with the HCM 2010 prediction. The next chapter is the discussion of the results of this comparison.

4. RESULTS

(1) Free-flow speed

The square points represent westbound travel along the section, while the triangular points represent eastbound travel.

The HCM 2010 model over-estimated free-flow speed in 17/26 cases (65.4%), as shown in **Fig.6**.

The model gives a Root Mean Square Error (RMSE) value of 1.2km/h. The variations are most likely due to traffic volume changes that are were not accounted for in the application of the model.

(2) Delay

Field delay was measured based on the principles shown in **Fig.5**. A comparison with predicted delay is shown in **Fig.7**.

It was found that delay was over-estimated 54% of the time.

The highest overestimation was by 26 seconds. The downstream intersection at this segment had a low g/C ratio hence high delay, but the test vehicle was only stopped once by the signal. This led to the large difference between predicted and field measured delay.

The largest underestimation was by 63 seconds on the segment with the highest delay. The downstream intersection of this segment is shown in **Fig.8**, a screenshot from the video taken while approaching intersection 1 in the westbound direction. The test vehicle was stopped by the traffic light at this intersection during all the five runs, thereby experiencing the highest delay.

The circled points in **Fig.7** represent segments in which the test vehicle was stopped, leading to large delays. The discrepancy between these extreme field values and the predicted delay is therefore most likely because the arrival flow patterns were not considered in the delay estimation using HCM 2010.

The RMSE for the delay estimation was 19.9 seconds. This is a very large deviation considering field delay ranged between 0 – 96 seconds.

The intersections at which the highest delays were

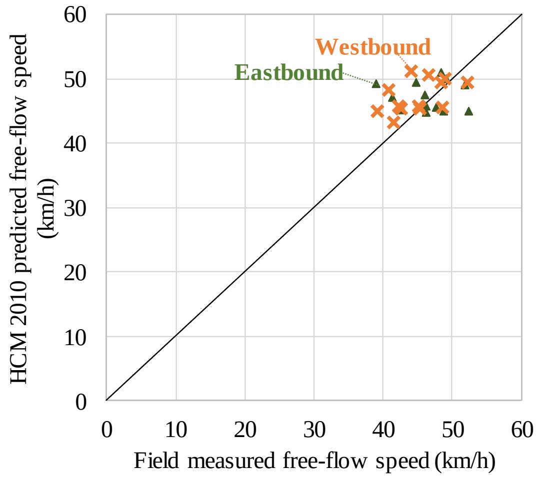

Fig.6 Predicted vs. field measured free-flow speed

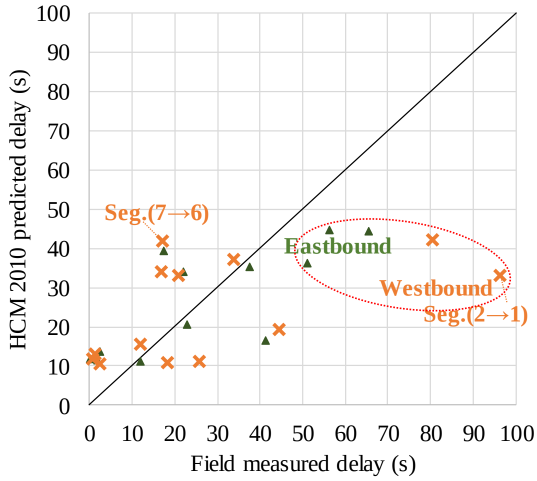

Fig.7 Predicted vs. field measured delay

Fig.8 Intersection 1, westbound – highest field delay

also observed to have lower g/C ratios as can be seen in **Fig.9**.

This result follows the expected trend. However, the tendency was not as clearly defined as the HCM prediction (**Fig.10**). This could be a result of variations in traffic volume both over the different segments, and during different runs, which was not considered in the application of the HCM methodology.

Signal delay also varied based on the arrival time of the test vehicle at the downstream segment boundary intersection as shown in **Fig.4**.

The points circled in **Fig.9** are short segments (less than 180 meters). This means the test vehicle required little time to traverse them, hence reducing the likelihood of experiencing delay.

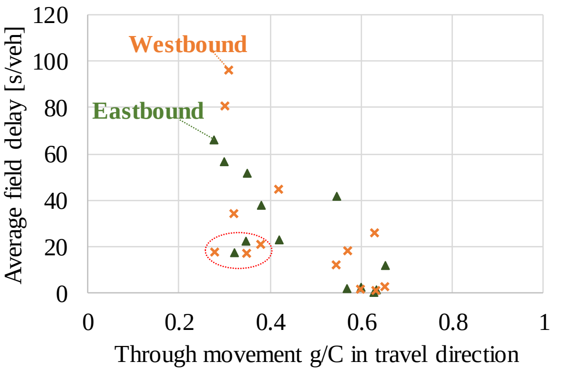

Fig.9 Average field delay vs. effective green-to-cycle length

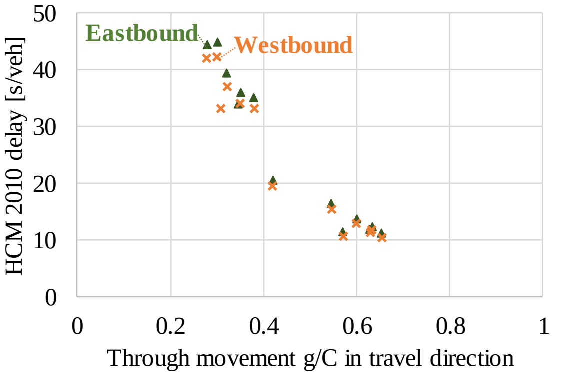

Fig.10 Predicted delay vs. effective green-to-cycle length

(3) Travel speed

a) Segment travel speed

Fig.11 shows the speed-distance diagrams across the entire study section for the eastbound and westbound directions. The differently colored plots indicate different runs.

It can be seen that the running speed of the test vehicle oscillated about the posted speed limit of 50 km/h. It should also be noted that the highest achieved travel speed varies in each run for each segment. This was due to variations in traffic volumes and downstream traffic signal conditions.

A visual analysis of **Fig.11** shows slightly higher travel speeds along segments of longer length.

A plot of predicted travel speed vs. field measured travel speed is shown in **Fig.12**.

Except for the outlying points circled in red in **Fig.12**, the predicted vs. field measured travel speed data points seem to lie evenly, although with some errors, across the 45 degree (perfect fit) line.

The outlying points correspond to segments where the test vehicle did not stop or stopped for no more than 3 seconds.

The rest of the variation in the two data sets could be accounted for by the difference in delay estimates, and possibly the difference in the measurement method of free-flow speed in the study compared to the HCM.

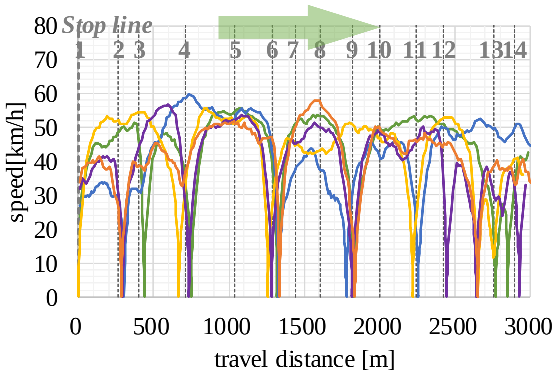

Fig.11a Speed-distance diagram, eastbound

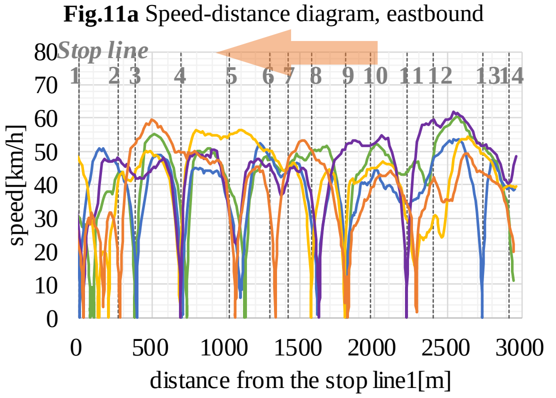

Fig.11b Speed-distance diagram, westbound

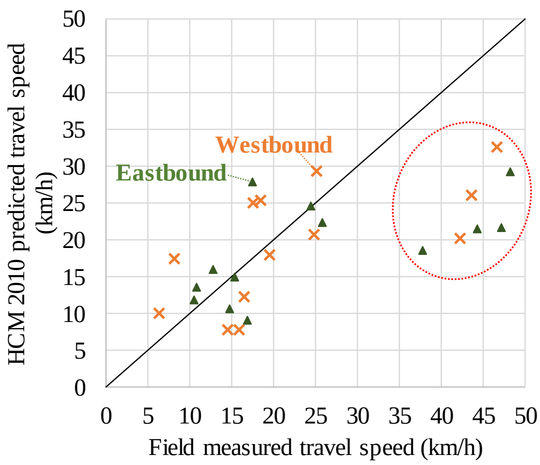

Fig.12 Predicted vs. field measured travel speed

Table 3 predicted and field measured travel speed

Section travel speed (km/h)	Eastbound	Westbound
HCM 2010 Predicted	17.5	18.1
Field measured	18.7	17.3
Error (Predicted – field)	-6.4%	+4.6%

b) Section travel speed

Section travel speed was computed as ratio of section length to section travel time. The results are shown in **table 3**.

The travel speed for the section was underestimated in the eastbound direction, but overestimated in the westbound direction.

Taking an average of the two directions gives an underestimation of only 1% in the segment travel speed.

5. CONCLUSIONS

Although it under- or over-estimated the intermediate parameters at the segment level, the HCM 2010 travel speed model provided a reasonable approximation of the travel speed along the study road section.

However, this was after inputting a lot of data, most of which is unavailable at the planning stage.

It is likely that the data inputs used in the methodology are also relevant in Japan's situation, therefore a more detailed analysis of the independent variables used in the model could yield information crucial to the development of a simpler travel speed estimation model.

6. FUTURE WORK

Broaden the study area to include road sections with more variation in the input parameters such as those required for estimating free-flow speed, then identify and the most relevant parameters for travel speed estimation.

Simulation analysis studies to supplement the field studies by making it possible to explore geometric and traffic cases that may not be easily observable in the field.

Reducing data requirements to enable a simple, yet accurate travel speed estimation model.

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