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A Study on the Average Travel Speed on Interrupted Flow Multi-Lane Highways

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Abstract

Intersections, whether signalized, STOP controlled, or YIELD controlled form some of the main features that define interrupted flow facilities. In addition to the imposition to stop that comes with the red indication of traffic signals, other settings such as the cycle length and offsets have a great impact on the amount of delay encountered, and therefore the average travel speed. Improper settings are likely to bring about a reduction in the performance of the highway, and therefore it is important to forecast their potential impacts on the planned highways' performance. In this study, we examine the variation in the average travel speed along a hypothesized two-lane highway by changing the segment length, density of signalized intersections, cycle length, and offset settings. Results showed that average travel speed reduced with increased signalized intersection density, and that the network layout also had a significant impact on the travel speed. Furthermore, it was shown that based on the link length and the free flow travel time, the choice of cycle length and offset settings has a very significant impact on the travel speed.

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Keywords: Interrupted flow; Average travel speed; Multi-lane highways; Simulation analysis; Signal control

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1. Introduction

1.1. Background and objective

Performance based planning of highway facilities has not yet been fully utilized in Japan. Nakamura et al. (2005) discussed the fact that travel speed on Japan's arterial streets was low, and attributed it to the lack of clear performance goals based on the road functions such as traffic and access.

According to Oguchi et al. (2005), the planning and design criteria at the time was mainly based on determining the necessary number of lanes to serve the traffic. They argued that from the viewpoint of traffic operation, it was also necessary to consider controlling the occurrence of traffic congestion at the planning and design stage. The study further proposed a draft planning and design procedure for streets that involved calculating travel speed of a target section considering intersection density, cycle length, and road geometry, among others.

Although the operation of the signalized intersections or indeed their spacing/density is not commonly decided at the planning stage, it is important to take into account their impact on the planned roadway. This can be achieved by setting the target speed, and then considering which range of factors would be acceptable towards its achievement.

Without doing this kind of work (performance based planning), there is a risk of having a large gap between the planned service level and the operational service level of the roadway. This is certainly the case in some areas in Japan, where there are roads with densely spaced signalized intersections, many with excessively long cycle lengths. An analysis of the road census data for the years 2010 and 2015 showed that congested travel speed on Aichi's (Japan) roads with speed limits 60 km/h or less was below 30 km/h.

The objective of this work, however, is not limited to Japan. This work aims to evaluate the actual attainable travel speed along networks with different sets of hypothesized characteristics such as signalized intersection densities, cycle lengths, offsets, and network layouts. Then by comparing this travel speed to the target travel speed, an insight into the requirements for yielding the target travel speed can be obtained.

1.2. Brief literature review

Vlahogianni (2007) studied the impact of percentages of various vehicle types on the travel speed – flow relationship in urban signalized arterials. One of the major findings of their study was the characterization of the three main traffic patterns observed in the speed – flow plots; 1) small changes in speed over a large range of flow, 2) low variation in flow but great variation in speed, and 3) low speeds possibly corresponding to the congested region of the speed-flow relationship. This describes a shape that is generally similar to the speed – flow relationships developed from data on motorways (Chin and May, 1991; Smith et al., 1996; Brilon and Lohoff, 2011), which show a transition from free flow, speed changes, and finally congestion with increasing flow.

Through a field experiment, Koshi (1989) illustrated the relationship between cycle length, delay, and average number of stops along a coordinated two-way link with signalized intersections at both ends. The key simplifying assumptions in the work included common cycle times and green splits, a green time of 50% of the cycle length, and no platoon dispersion. It was then demonstrated that total delay in both travel directions could be zero if the cycle length C were a one nth of the link roundtrip travel time T, where n is a positive integer.

Additional significant findings from Koshi (1989) include the following:

- Delay and the number of stops on a link are minimized when $C = T/n$ $(n = 1,2,3,\ldots)$, and delay is maximized when $C = 2T, 2T/3, 2T/5,\ldots,T/2n+1$.

We reformulate Koshi's (1989) results into Equation 1 for the delay minimizing cycle length, C_{d_min} (s) based on link length L (m), and speed V (m/s).

$$C_{d\_\min} = \frac{2L}{nV} \tag{1}$$

2. Methodology

2.1. Preliminary study

Data from a 12.5 km road section on Japan's National Highway Route 1 was used in the preliminary study. The section has 20 signalized intersections, two lanes per travel direction with a right-turn bay at each intersection in the major travel direction. Data was collected on 27th July 2016 – a cloudy Wednesday, from 07:00 – 19:00.

Traffic flow was collected using counters, and was not separated by lane, therefore "traffic flow" refers to two-lane flow in the travel direction. Travel time data was collected by matching the arrival times of vehicles at successive antennas set up along the highway section. The antennas functioned by detecting electromagnetic waves emitted by ETC devices set up in the majority of cars on Japan's roads.

The objective was to quantify the relationship between the average travel speed and the flow along sections with varying geometry such as section length, number and density of signalized intersections, and access points in the travel direction.

The section was divided into five segments per travel direction, for a total of ten segments, and plots were made of the relationship between average travel speed and traffic flow using data from all sections, and sorted by each geometric characteristic. Figure 1 shows the impact intersection density and segment length on the travel speed – flow relationship, with darker colors representing an increasing tendency in the intersection density/ segment length.

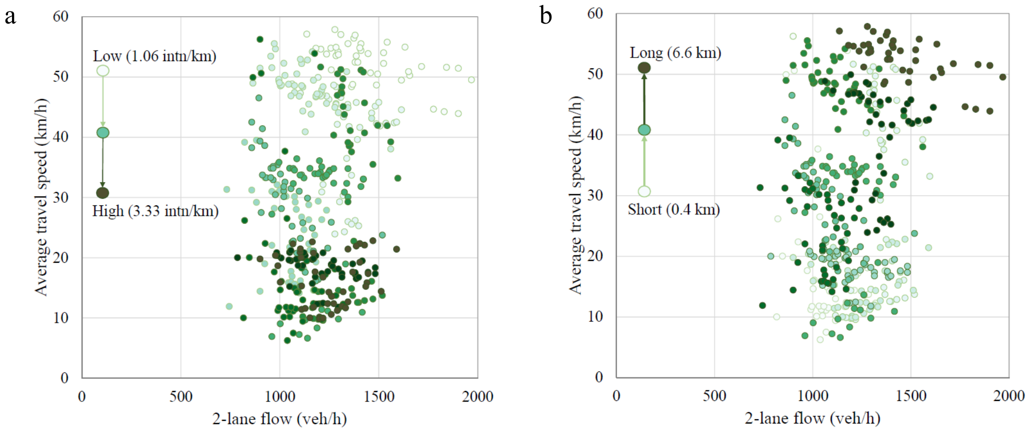

Fig. 1. Average travel speed by; (a) intersection density, and (b) section length

From Figure 1, it can be seen that higher intersection densities led to lower travel speed, while travel speeds tended to be higher on longer segments. Data from this preliminary study could only be used to analyze the impact of intersection density and segment length, but not for the impact of cycle lengths and offset settings. To further study these impacts, it was decided to undertake microsimulation analysis using microsimulation software VISSIM 7. To aid in the calibration of the simulation model, an additional study was carried out on a road section in Nagoya, Japan to collect the necessary data. A description of this study is given in subsection *2.2*.

2.2. Simulation calibration study

A 600 meter road section with a speed limit of 50 km/h, and consisting of four signalized intersections with a common cycle length was chosen for this study. Video cameras were located at the boundary intersections of the section, and video of vehicles entering and exiting the section was captured in a way that enabled the collection of data such as; *time of crossing the stop-line, traffic light indication, and vehicle number plate.*

The time period 10:30 – 10:45 on Wednesday, February 14th 2018 was used to compute the 15-minute flow rate at the boundary intersections. By matching the number plates of vehicles departing from upstream intersections to those arriving at the downstream intersections, the through travel times were obtained for at least forty vehicles in each travel direction in the same period.

In addition to flow and travel time data, data was also collected on the traffic signal settings such as phasing, green time allocation, cycle lengths, and offsets between successive intersections.

The objective of the microsimulation calibration were set as the reproductions of the observed flow rate, average travel time, and travel time distribution in the simulation model. Figure 2 shows the network used for the calibration.

Fig. 2. 600 meter section used for VISSIM calibration

It should be noted that although the actual network in the field included pedestrian traffic, this was not input into the simulation model. Pedestrian presence has an impact on the left-turning vehicles and can reduce the lane group's discharge flow rate as well as increase the travel time of the vehicles in that lane group. To avoid this effect in the travel time measurements, only vehicles that passed through the stop line as through vehicles were used in measuring the field travel time.

In addition, the proportion of heavy vehicles as measured in the field was in the range of 3.2 – 7.8%, and this was duly implemented in the simulation for purposes of calibration. However, since attributes such as the acceleration and deceleration profiles of the heavy vehicles could not be ascertained, they were not included in the hypothetical network traffic explained in the proceeding subsection.

The inputted flow rates were reproduced in the simulation model with slight errors, which arose from the imposition of no more than 1 second for a vehicle to successfully change lanes.

The simulated average travel times were also close to the field measured values, though with slightly higher errors than the traffic volume. The errors could be attributed to the different driver characteristics such as levels of aggressiveness or trip purpose during the field observation period, which could not be incorporated into the simulation model. However, an examination of the distributions of the observed individual travel times and the simulated values showed that the distributions were similar, and the calibration was deemed satisfactory.

It was also observed that although the speed limit of this section was 50 km/h, the drivers tended to drive at lower speeds. Based on this result, the desired speed distribution's lower limit was also set lower in the scenario design described in the next subsection.

2.3. Simulation analysis scenario design

Hypothetical networks were designed, and the scenarios set based on the geometry and traffic attributes whose impacts on the average travel speed were desired. These included; segment length, density of signalized intersections, cycle length, and offset settings. Since only the impacts of these four factors were to be examined, some limitations were imposed on the hypothetical network, such as considering no pedestrians and considering only passenger cars in the network, without the impact of heavy vehicles.

Regarding offsets, two offset settings were used in this study: *simultaneous offsets* – in which traffic signals at adjacent intersections turn green at the same time, and *alternative offsets* – in which when one signal turns green, the signal at the adjacent intersection turns red at that same time. Based on these various factors, different scenarios were designed as shown in Table 1. The one-way link travel time is also shown in the table.

The notation used for the scenario names is *Offset type Cycle length-Case number*, so that S60-1 denotes simultaneous offsets, 60-second cycle length and case 1 (two signalized intersections).

Table 1. Simulation scenario design

Case No.	Segment Length (m) and *One-way link travel time* (s)	Simultaneous Offsets				Alternative Offsets			
	Cycle length (seconds)	60	90	120	150	60	90	120	150
1	3000 *(216)*	S60-1	S90-1	S120-1	S150-1	A60-1	A90-1	A120-1	A150-1
2	1000 *(72)* – 2000 *(144)*	S60-2	S90-2	S120-2	S150-2	A60-2	A90-2	A120-2	A150-2
3	1500 *(108)* – 1500 *(108)*	S60-3	S90-2	S120-3	S150-3	A60-3	A90-2	A120-3	A150-3
4	750 *(54)* – 750 *(54)* – 1500 *(108)*	S60-4	S90-4	S120-4	S150-4	A60-4	A90-4	A120-4	A150-4

The speed limit on the hypothetical sections was set to 50 km/h, and the desired speed distribution in the simulation model set in the range of 40 – 60 km/h.

For each selected cycle length, the green, amber and red times were allocated based on Japan's Manual on Traffic Signal Control, Revised Edition (2006). A four-phase system was adopted, with dedicated right-turning phases. The signal timings were based on traffic volumes of 1000 veh/h at each approach of all intersections, and although different volumes were inputted to obtain the travel speed – flow curve, the signal settings remained unchanged. The effective green times for cycle lengths 60, 90, 120, and 150 seconds were 17, 32, 43, and 55 seconds, respectively.

All intersections in the four cases were modeled as major intersections with balanced major and minor approach traffic volumes. Fig. 3 (a) shows the intersection layout, with each approach having a right-turn bay. The turning percentages are shown in Figure 3 (b).

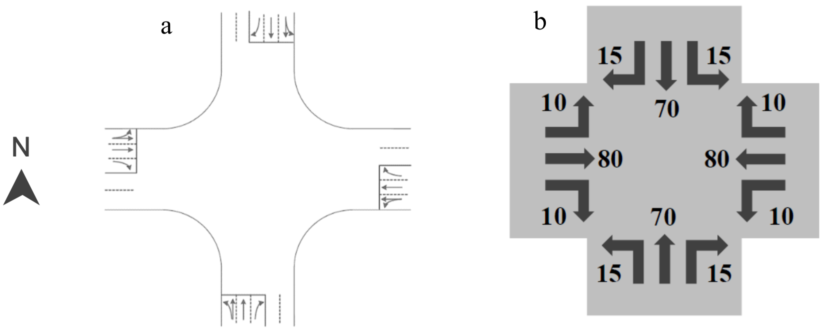

Fig. 3. Intersection configuration; (a) lane usage, and (b) turning ratios at all intersections

Travel time was collected for vehicles entering and exiting the "segment" which was defined as in the Highway Capacity Manual – from the stop line of the upstream intersection to the stop line of the downstream intersection. The average travel speed was obtained from the segment length, and the average travel time of all vehicles passing through the segment in the simulated one-hour period.

Traffic volume was also collected during the simulation runs, and was measured at the downstream intersection stop line. To obtain the speed-flow relationship, during each scenario shown in Table 1, the input two-lane traffic volume was varied from 100 to 1300 vehicles per hour.

3. Results

3.1. Impact of network layout

In this subsection, the discussion is limited to Cases 2 and 3, whose sections have the same intersection density, but are made up of two links of different lengths.

With a cycle length of 60 seconds and simultaneous offsets, the travel speed was higher in case 3 than in case 2, as shown in Figure 4 (a). Applying Eq. 1 shows that a C = 57.6 minimizes delay for the link 1 (Eastbound) in case 2, and C = 54 minimizes delay on both links in case 3. Therefore, the higher delay in link 2 of case 2 contributes largely to the lower travel speed observed in Fig. 4 (a). Similarly, when C = 90 delay is low on both links in both cases as seen at low flow in Figure 4 (b). However, as the flow increases, travel speed in case 3 reduces because only the last 14 seconds of green are available when the vehicles arrive at the downstream intersections, and cannot be used effectively.

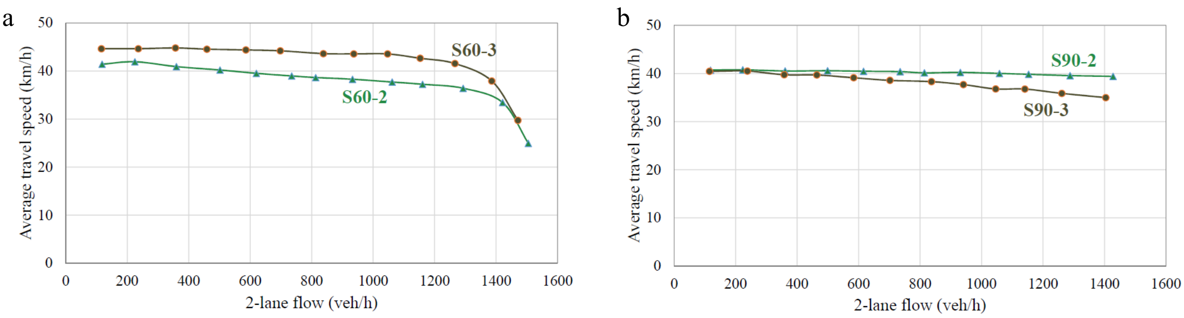

Fig. 4. Cases 2 and 3, Eastbound, simultaneous offsets; (a) C = 60s, and (b) C = 90s

3.2. Impact of cycle length and offset settings

In Figure 5, we notice that cycle lengths of 60 and 120 seconds have almost the same travel speeds in case 1. This result is simple to understand since at both cycle lengths a delay of 24 seconds is incurred at the downstream intersection. We also note from the same figure that travel speed is lowest for C = 150s due to the increased delay. By using this result, the planners can avoid adopting poor road designs that would make long cycle lengths like 150 seconds necessary. This would also reduce the minor street delay. Such a “performance feedback”-based selection of cycle length is one of the potential applications of this kind of analysis.

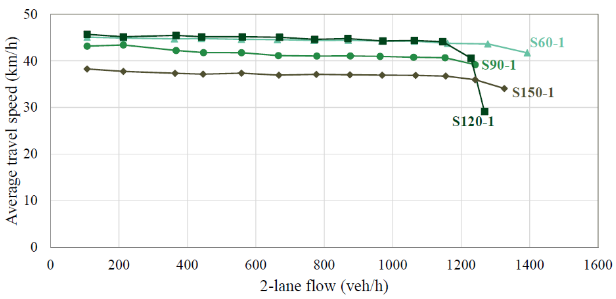

Fig. 5. Impact of cycle length in case 1

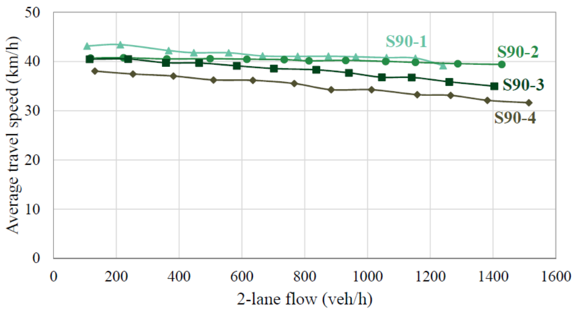

Fig. 6. Impact of signalized intersection density

3.3. Impact of signalized intersection density

Intersection densities for cases 1 through 4 were 0.33, 0.67, 0.67 and 1.00 intersections per kilometer, respectively. This trend was generally observed, with travel speed being highest in case 1 and lowest in case 4 as shown in Fig. 6 for a cycle length of 90 seconds under simultaneous offset settings.

From Fig. 6, it can be seen that at the lowest flow rate, the least dense network has the highest travel speed, whereas the densest has the lowest, and the trend is maintained even as flow increases. With a higher number of intersections, the accumulation of delay at each intersection further decreases the travel speed at all demand levels.

3.4. Impact of section length

Sections of different lengths were not directly measured in this research, but some inferences could be made from observations of sections composed of varying segment lengths. Discussions in subsection 3.2 showed that different travel speeds could be achieved depending on the constituent link lengths in the network.

3.5. Case study based on most appropriate settings

As was discussed previously, the impacts of the cycle length and the offset settings are not independent of each other. Therefore, in this section, we looked at each of the cases (1 – 4) and selected the scenarios whose combination of cycle length and offset settings gave the largest observed travel speeds in both the eastbound and westbound directions. The following scenarios were chosen for comparison: S120-1, A120-2, S120-3, A90-4. The travel speed – flow curves for these scenarios are shown in Figure 7.

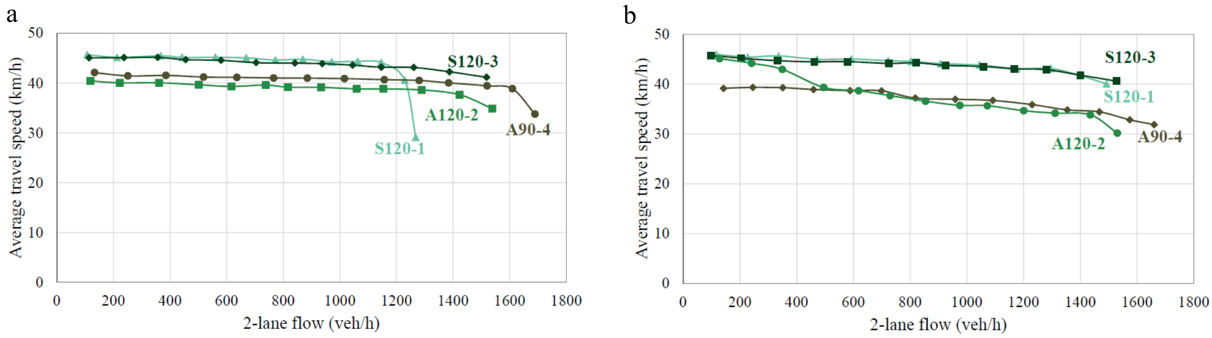

Fig. 7. Comparison of 'best case' scenarios with highest travel speed; (a) Eastbound direction, and (b) Westbound direction

As can be seen in Figure 7, case 1 had the highest travel speed, closely followed by case 3. Because the scenario chosen to represent each case was chosen based on the maximization of travel speed through offset and cycle length, the resulting differences in the travel speed – flow curves could be explained by the geometry of the section in each of the cases. The higher travel speed in case 1, as can be seen in both Figures 7 (a) and 7 (b) is most likely as a result of having the lowest intersection density (0.33 intersections/km).

The expectation would then be that case 4, with the highest intersection density would have the lowest travel speed, but this is only true in the westbound direction with traffic below 500 veh/h/2-lane. This is possibly because the variation of delay with cycle length and choice of offset is not linear, and selecting the best possible offset to strike a balance between both directions may not always be feasible.

From these results, however, it can be seen that for the network configurations considered in this study, cycle lengths up to 120 seconds are sufficient to obtain relatively high travel speeds.

4. Conclusions and future work

4.1. Conclusions

In this study, it was demonstrated that better performance (higher travel speed) along corridors could be achieved by jointly considering the link length, and 'speed limit' in the setting of the cycle length. This result is a proof of concept, and will be applied by the authors to the more common network layouts in order to find the travel speed tendencies.

With these preliminary results, it is possible to suggest an additional step in the traffic signal setting methodology, requiring the consideration of a corridor rather than simply the capacity of individual intersections.

The results provide evidence of the necessity of building a new model of travel speed that can take into account the traffic operational conditions at the planning stage.

4.2. Future work

The future goal of this work is the proposal of a clear methodology and/or model(s) that can be followed by practitioners to determine the acceptable signalized intersection density/ location, cycle lengths, offsets that can enable that a given target travel speed is achievable in the field. This requires analyzing additional network configurations, more densely signalized highways, additional cycle lengths based on the exact values given by Eq. 1, and various speed limits/target travel speeds.

Another task to be covered in the future work is the consideration of heavy vehicle proportions as well as the presence of pedestrians in the network. This is important to the realization of models that can be applicable to the real world traffic conditions.

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