Vol.2012-MBL-64 No.19
Vol.2012-ITS-51 No.19
2012/11/16

A Development of Signal Control System along Arterials

HIKARU SHIMIZU †1 HARUKO MASUDA†2

A signal control system is developed along an arterial in Hiroshima city from the viewpoint of a deterministic control for traffic flow dynamics. The signal control system of the congestion length is described by a nonlinear time-varying discrete dynamic system and synthesized by using the feedback control based on the volume balance at each signalized intersection. Two signal control algorithms are presented to balance congestion lengths which cross each other on a road. These control algorithms are such that the sum of congestion lengths along each approach is minimized. The signal control system is developed systematically according to the procedure from the road analysis to the simulation. From the comparison of congestion lengths between measurement values controlled by a pattern selection method such as the MODERATO and simulation values controlled by the proposed signal control algorithm, it is confirmed that the signal control system and its development procedure work effectively along the Route 2 in Hiroshima city.

1. INTRODUCTION

In recent years, the congestion has increased in urban traffic networks along with the increase of the number of vehicles registered in Japan. Traffic flow control is exercised through the combination of road markings, traffic signs, signals and dynamic route guidance system. The signal control is an effective on-line method to control the congestion of arterials and networks. On-line signal control methods such as the SCOOT [1], decentralized control [2], MODERATO [3], [4], parameter optimization method [5] and dynamic programming method [6] have been presented to control the congestion in traffic networks. The SCOOT is a signal control technique which on-line controls the three signal control parameters consisting of the cycle length, green split and offset so as to minimize the delay. The three signal control parameters are defined as follows: The cycle length is the time which makes a round for the phase. The green split is the ratio of dividing the green time by the cycle length. The offset is the time difference for the beginning of green time between adjacent signalized intersections. The decentralized control is such an on-line signal control method that queue length perturbations of the network at all signalized intersections are asymptotically “balanced”; this is done by changing the nominal “signal-split” percentage of a cycle length using only a local knowledge of queue length at each signalized intersection. The MODERATO is such a real-time signal control system that the three signal control parameters are controlled separately so as to reduce the delay and stops. The dynamic programming method employs fuzzy logic and genetic algorithm to handle the local control and the learning process, respectively. The coordination among signalized intersections is introduced to the local controllers in the shape of the projected numbers of vehicles arriving through the connecting traffic links. The local controllers then allocate green time to the four phases of a cycle by the dynamic programming method.

†1 Fukuyama University, Fukuyama, Japan
†2 Yuge National College of Maritime Technology, Ehime, Japan

Although the above-mentioned studies [1]–[4], [6] are effective to reduce the delay, they have such problems as the description of traffic flow dynamics, the parameter optimization method and the performance criterion.

This paper studies the signal control of congestion lengths along an arterial in Hiroshima city from a deterministic control viewpoint. A signal control system is synthesized applying the feedback control of the congestion length for the arterial. Two signal control algorithms are presented to balance congestion lengths which cross each other on a road. The signal control algorithms are such that the sum of congestion lengths is minimized. The signal control system is developed systematically according to the procedure from the road analysis to the simulation. The signal control system and the signal control algorithm are simulated along the Route 2 in Hiroshima city, Japan during evening rush hours. From the comparison between measurement values controlled by a pattern selection method such as the MODERATO and simulation values controlled by the proposed signal control system, it is confirmed that the proposed system development of signal control system works well to control congestion lengths so as to minimize the performance criterion along the two-way traffic arterial.

2. SIGNAL CONTROL SYSTEM

The signal control system of the congestion length is synthesized for two-way traffic arterials shown by Figure 1. The volume balance for each lane at each signalized intersection is shown by Figure 2 and written along the arterials by

$$x_e(j,m,k) = x_e(j,m,k-1) + x_i(j,m,k) - x_o(j,m,k) \quad (1)$$

$$\begin{cases} x_o(j,m,k) = \xi(j,m,k)\cdot\psi_x(j,m,k) \\ x_e(j,m,k) \ge 0 \end{cases} \quad (2)$$

where $k = k\varDelta T$ denotes time, j and m denote the location of each signalized intersection and the approach of vehicles respectively. The variables represented by $x_e(j,m,k)$, $x_i(j,m,k)$ and $x_o(j,m,k)$ denote the excess incoming volume, incoming volume and outgoing volume. The variable shown by $\psi_x(j,m,k)$ denotes the net traffic flow rate and $\xi(j,m,k)$ is evaluated by taking the value of dividing $x_o(j,m,k)$ by $\psi_x(j,m,k)$ under any traffic flow conditions.

It is assumed that the incoming volume $x_i(j,m,k)$ is measured and the outgoing volume $x_o(j,m,k)$ is controlled by the three signal control parameters at the signalized intersection concerned. As the result, the outgoing volume $x_o(j,m,k)$ is replaced by the control input $u(j,m,k)$.

The signal control system is then written by

$$\begin{cases} x_e(j,m,k) = x_e(j,m,k-1) + x_i(j,m,k) - u(j,m,k) \\ y_c(j,m,k) = l_m(j,m,k) \cdot x_e(j,m,k) \end{cases} \quad (3)$$

where the upper limit of the control input is determined by Equation 2. The observation equation of the congestion length $y_c(j,m,k)$ is described in such a way that the state variable is multiplied by a "transformation factor" $l_m(j,m,k)$.

The signal control system of the congestion length is considered on the arterials; in this control system, the reference input, control input and output are given by the permitted congestion length $l_r(j,m,k)$, the three signal control parameters and the congestion length respectively.

In this way, the signal control system of the congestion length is synthesized using the feedback control at each signalized intersection as shown in Figure 3.The purpose of the signal control system of two-way traffic arterials is to find such control input that it makes the following performance criterion $J_a(k)$

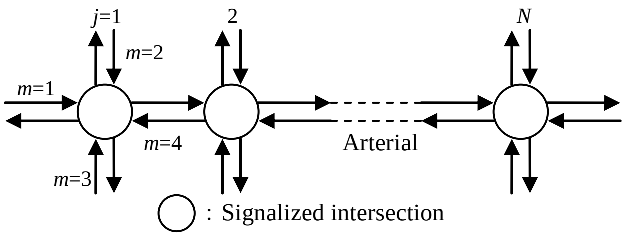

Figure 1 Two-way traffic flows along arterial.

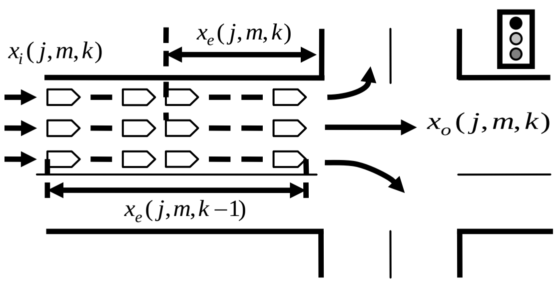

Figure 2 Volume balance for each lane at each signalized intersection.

minimize

$$J_a(k) = \sum_{j=1}^{N} \sum_{m=1}^{4} g(j,m,k) \quad (4)$$

where N denotes the number of signalized intersections along the direction for j, and the function $g(j,m,k)$ and the control error $e(j,m,k)$ are defined by using reference input $l_r(j,m,k)$

$$g(j,m,k) \triangleq \begin{cases} 0 & e(j,m,k) \geq 0 \\ |e(j,m,k)| & e(j,m,k) < 0 \end{cases} \quad (5)$$

$$e(j,m,k) \triangleq l_r(j,m,k) - y_c(j,m,k) \quad (6)$$

because degrees of saturation are different to approaches at signalized intersections.

3. SIGNAL CONTROL ALGORITHMS

The purpose of the signal control system is to search systematically the three signal control parameters which minimize the sum of congestion lengths on the approach of signalized intersections according to the variation of incoming volumes at each lane and during each cycle length. The signal control algorithms both at single signalized intersection and along arterials are considered from the viewpoint of a parameter optimization.

3.1 Single Signalized Intersection

A balance control algorithm is applied for the congestion length control at single signalized intersection which is a basic component of the arterials. The balance control algorithm means that the maximum values of congestion lengths which cross each other on a road are controlled so as to become equal, and the two signal control parameters consisting of the cycle length and the green split are systematically and sequentially searched so as to minimize the following performance criterion $J_s(k)$.

$$J_s(k) = \sum_{m=1}^{4} g(m,k) \quad (7)$$

The balance control algorithm is described as follows:

Step 1. The initial values, upper and lower limits and increment of signal control parameters are set at a signalized intersection. The approach of vehicles is set as m = 1 at first.

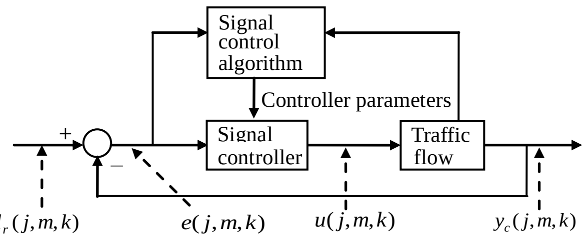

Figure 3 Signal control system of congestion length at each signalized intersection.

Step 2. The incoming volume $x_i^{(n)}(m,k)$ is inputted and the duration ΔT is equally set to the cycle length $c_y^{(n)}(m,k)$. The symbol (n) denotes the repetition times of computation.

Step 3. The incoming volumes of congestion cases are recalculated for each lane by

$$\begin{cases} x_{il}'^{(n)}(m,k) = x_{il}^{(n)}(m,k) + x_{el}(m,k-1) \\ x_{is}'^{(n)}(m,k) = x_{is}^{(n)}(m,k) + x_{es}(m,k-1) \\ x_{ir}'^{(n)}(m,k) = x_{ir}^{(n)}(m,k) + x_{er}(m,k-1) \\ x_{isl}'^{(n)}(m,k) = x_{isl}^{(n)}(m,k) + x_{esl}(m,k-1) \end{cases} \quad (8)$$

where $x_{il}^{(n)}(m,k)$, $x_{is}^{(n)}(m,k)$, $x_{ir}^{(n)}(m,k)$, $x_{isl}^{(n)}(m,k)$ are incoming volumes of left-turn-, straightforward-, right-turn- and straightforward-left-turn-lanes respectively.

Step 4. The net traffic flow rate for the straightforward-lane at the signalized intersection is evaluated by

$$\psi_{xs}^{(n)}(m,k) = r_{gs}^{(n)}(m,k) \cdot c_{xs}(m,k) \quad (9)$$

where $c_{xs}(m,k)$ is the capacity and $r_{gs}(m,k)$ is the green split of the straightforward-lane. The net traffic flow rates for other lanes are evaluated in the same way.

Step 5. The green time for each lane are evaluated by multiplying the cycle length by the green split.

Step 6. The excess incoming volume $x_{es}^{(n)}(m,k)$ for the straightforward-lane is evaluated based on the volume balance

$$x_{es}^{(n)}(m,k) = x_{is}'^{(n)}(m,k) - x_{os}^{(n)}(m,k) \quad (10)$$

$$\begin{cases} x_{os}^{(n)}(m,k) = \xi(m,k) \cdot \psi_{xs}^{(n)}(m,k) \\ x_{es}^{(n)}(m,k) \geq 0 \end{cases} \quad (11)$$

where $x_{os}^{(n)}(m,k)$ is the outgoing volume of the straightforward-lane. The excess incoming volumes for other lanes are evaluated in the same way.

Step 7. The congestion length $y_{cs}^{(n)}(m,k)$ for the straightforward-lane is evaluated by

$$y_{cs}^{(n)}(m,k) = l_m(m,k) \cdot x_{es}^{(n)}(m,k) \quad (12)$$

where $y_{cs}^{(n)}(m,k)$ is the congestion length of the straightforward-lane. The congestion lengths for other lanes are evaluated similarly.

Step 8. The green time and green splits are evaluated for all approaches based on the phase at each signalized intersection.

Step 9. If the following control index

$$\max\{ \left|e^{(\kappa)}(1,k)\right|, \left|e^{(\omega)}(2,k)\right|, \left|e^{(\mu)}(3,k)\right|, \left|e^{(\lambda)}(4,k)\right| \} \leq \varepsilon \quad (13)$$

$$\varepsilon > 0$$

is satisfied, we apply the green splits and the cycle length at optimum time values and set $k = k + 1$, then proceed to Step 1.

Step 10. Otherwise

$$\max\{ \left|e^{(\kappa)}(1,k)\right|, \left|e^{(\omega)}(2,k)\right|, \left|e^{(\mu)}(3,k)\right|, \left|e^{(\lambda)}(4,k)\right| \} > \varepsilon \quad (14)$$

$$\varepsilon > 0$$

the green split whose approach of vehicles take the maximum control error is corrected using

$$r_{gs}^{(n+1)}(m,k) = r_{gs}^{(n)}(m,k) + \Delta r_{gs}(m) \quad (15)$$

If $r_{gs}^{(n+1)}(m,k) > r_{gs,\max}$, then proceed to Step 11.

If $r_{gs}^{(n+1)}(m,k) \leq r_{gs,\max}$, then return to Step 4.

where $r_{gs,\max}$ is the upper limit of the green split for the straightforward-lane. The green splits for other lanes are corrected similarly.

Step 11. The cycle length is corrected by

$$c_y^{(n+1)}(m,k) = c_y^{(n)}(m,k) + \Delta c_y(m) \quad (16)$$

If $c_y^{(n+1)}(m,k) > c_{y,\max}$, then we set $k = k + 1$, proceed to Step 1.

If $c_y^{(n+1)}(m,k) \leq c_{y,\max}$, then return to Step 2.

where $c_{y,\max}$ is the upper limit of the cycle length.

This control algorithm is executed sequentially from $k = 1$ to $k = k_f$. In this control algorithm, the cycle length and the green splits are corrected starting from the lower limits to the upper limits by their increments.

3.2 Arterial

The balance control algorithm is extended to the arterial by adding the offset control. The balance control of the congestion length along the arterial means that the maximum values of congestion lengths which cross each other on a road are

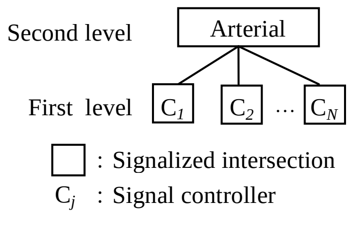

Figure 4 Hierarchical structure of balance control algorithm along arterial.

Table 1 Performance criteria of balance control algorithm along arterial.

Level	Performance criteria
First level	Minimize $J_a(k)$ c_y, r_g
Second level	Minimize $J_a(k)$ r_g, t_{off}

controlled so as to become equal, and the three signal control parameters consisting of the cycle length, green split and offset are systematically and sequentially searched so as to minimize the performance criterion $J_a(k)$.

The balance control algorithm from Step 1 to Step 11 at single signalized intersection is applied for the arterial by adding the subscript j and the offset control described by following Step 12.

Step 12. By using the optimal values of the green splits and cycle length, the balance offset which maximizes a through band width along the arterial is evaluated by the Fieser's method.

This control algorithm is executed sequentially from k = 1 to k = kf and from j = 1 to j = N. The control algorithm consists of a hierarchical structure as shown in Figure 4. At the first level, two signal control parameters consisting of the cycle length $c_y(j,m,k)$ and the green split $r_g(j,m,k)$ are searched so as to minimize $J_a(k)$ as shown in Table 1. The maximum values of cycle lengths at N signalized intersections are set in common at all signalized intersections from the viewpoint of the offset control. At the second level, two signal control parameters consisting of the green split $r_g(j,m,k)$ and the offset $t_{off}(j,m,k)$ are searched so as to minimize $J_a(k)$ as shown in Table 1.

4. DEVELOPMENT OF SIGNAL CONTROL SYSTEM

A signal control system which realizes the traffic flow smoothness and safety from the viewpoint of the digital control for traffic flow dynamics is developed according to the procedure of Figure 5. Each step of the procedure is summarized as follows: At the first step, the configuration for the cross section, type and lane arrangement of a road, which are necessary for the capacity analysis and the development of the signal control system, are investigated along the arterial. At the second step, the volume and the queue vehicle for each lane and each cycle length as well as the mix ratio of truck, the ratio of left-turn and the phase, which are required for the capacity analysis and the simulation, are examined along the arterial. At the third step, the capacity is evaluated by using correction factors such as the lane width, lateral clearance and mix ratio of truck. At the fourth step, the signal control system is described by a nonlinear time-varying discrete dynamic system based on the volume balance at each signalized intersection. At the fifth step, such the balance control algorithm that the three signal control parameters are searched systematically and sequentially so as to minimize the performance criterion $J_a(k)$ is proposed. At the sixth step, the simulations of the signal control system are performed along the arterial in real circumstances. The signal control algorithm is programmed and executed by inputting the road conditions and traffic conditions. At the last step, the convergence of the solutions is judged from the properness of three signal control parameters, volumes and congestion lengths along the arterial. If the solutions are reasonable the computation is completed, otherwise the computation is repeated again from the description of signal control system.

5. AN EXAMPLE FOR DEVELOPMENT OF SIGNAL CONTROL SYSTEM

The signal control system was developed according to the procedure in Figure 5 along the Route 2 in Hiroshima city shown in Figure 6. The simulation of congestion length control was executed based on the signal control system of Equation 3 and by using the balance control algorithm during evening rush hours. In the name of the signalized intersection along the arterial that consists of three signalized intersections, j = 1 is Sumiyoshicho, j = 2 is in front of Hiroshima City Office, and j =

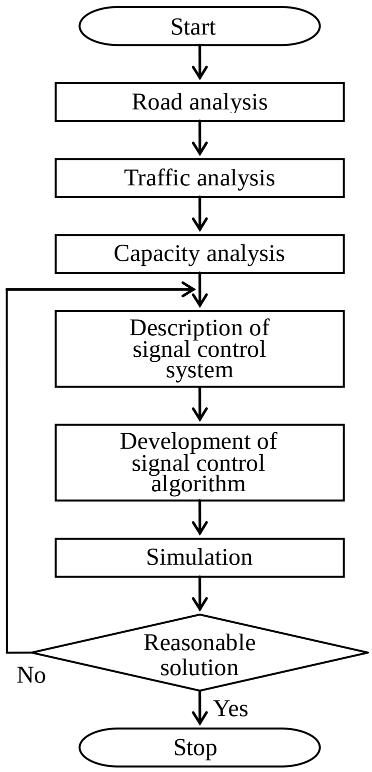

Figure 5 Development procedure of signal control system.

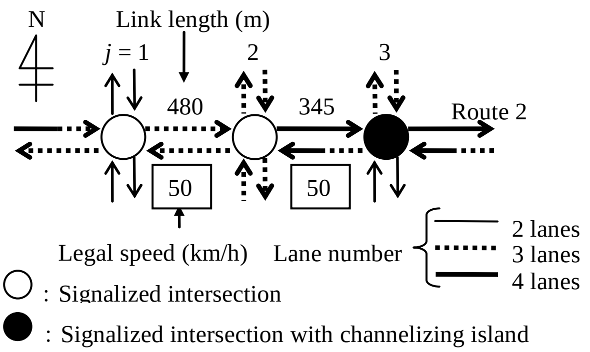

Figure 6 Arterial consisting of three signalized intersections in Hiroshima city.

3 is Kokutaiji. The lane number is three or four and the legal speed is 50 km/h along the Route 2. The road and traffic conditions are analyzed for the capacity estimation. The reference input is set as $l_r(j, m, k) = 0$ m for all approaches.

The simulation results are considered mainly for $m = 4$ at $j = 3$ signalized intersection because the maximum congestion has occurred. The lane configuration and the phase at $j = 3$ signalized intersection are shown in Figure 7. The lane configuration consists of a left-turn, a straightforward- left-turn and two straightforward lanes for $m = 4$ at $j = 3$ signalized intersection. The solid and dotted lines of the phase show the movement of vehicles and pedestrians respectively in Figure 7. The variation of incoming volumes is shown for each lane in Figure 8. The incoming volumes increased suddenly nearly at 18:30 on straightforward 2-lane. The lane number for straightforward is labeled from down to up-ward as shown in

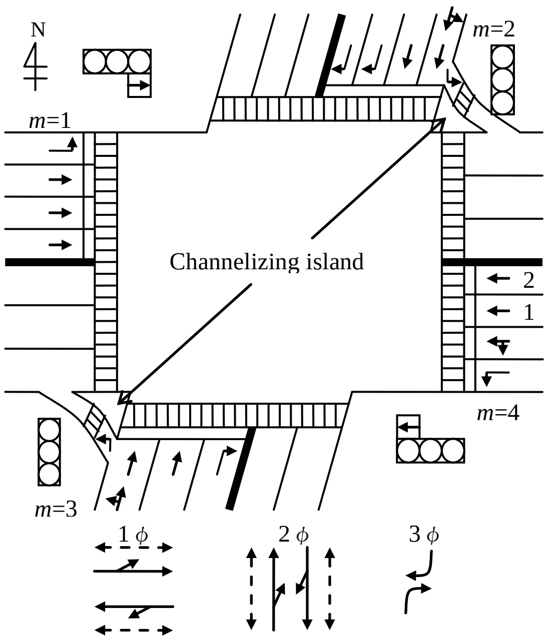

Figure 7 Type and phase at j=3 signalized intersection.

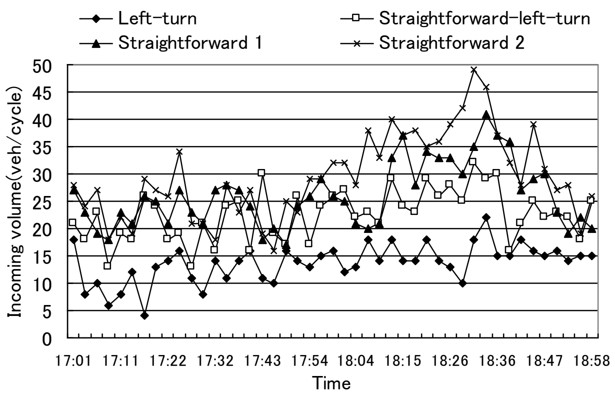

Figure 8 Incoming volumes for m=4 at j=3 signalized intersection.

Figure 7. Cycle lengths are compared between the measurement values controlled by a pattern selection method and the simulation values controlled by the proposed control algorithm at $j = 3$ signalized intersection in Figure 9. Measurement values of the cycle length vary in a narrow range about 160 seconds. On the other hand, simulation values of the isolated control are controlled at the maximum value of 196 seconds according to a rapid increase of the incoming volume at about 18:30. The isolated control means that the balance control algorithm at single signalized intersection is applied for only one signalized intersection. To the contrary, simulation values of the systematic control increase rapidly two times at about 17:40 and 18:30. The systematic control means that the balance control algorithm along the arterial is applied for the three signalized intersections. In the systematic control, the maximum value of cycle lengths at about 17:40 occurs from the sudden increase of incoming volumes at the adjacent signalized intersection, $j = 2$. The green split for straightforward-lane is compared between measurement values and simulation values. Simulation values are controlled more widely according to the variation of incoming volumes.

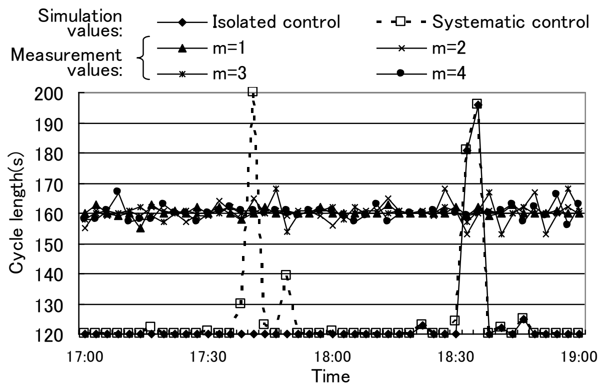

Figure 9 Comparison of cycle length between simulation values and measurement values at j=3 signalized intersection.

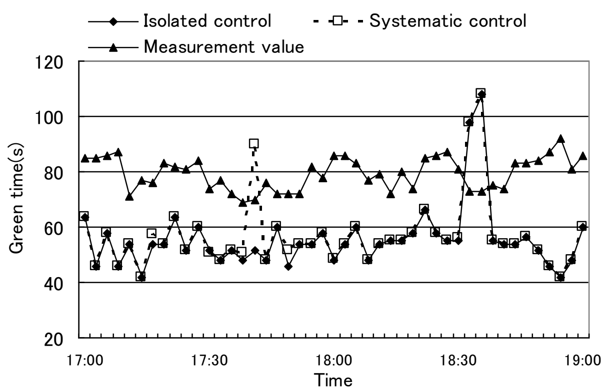

Figure 10 Comparison of green time for straightforward vehicles between simulation values and measurement values for m=4 at j=3 signalized intersection.

The values of the green split of the isolated control and systematic control are almost similar excluding at 17:40. The green time for straightforward-lane defined by the product between the cycle length and the green split is compared between measurement values and simulation values in Figure 10. Simulation values are controlled more widely according to the variation of incoming volumes. The difference between the isolated control and the systematic control appear once at about 17:40 depending on the unlikeness of the cycle length as shown in Figure 9. The offset values are obtained among the three signalized intersections using the Fieser's method. The maximum value of the through band width becomes 42.3 seconds at 18:33 as shown in Figure 11. The vehicles existing within the through band width are able to run through among the three signalized intersections without stopping. As mentioned above, the three signal control parameters consisting of the cycle length, green split and offset are controlled systematically and sequentially responding to the variation of incoming volumes using the balance control algorithm. As the results, the congestion has been controlled so as to become 0 meter during evening rush hours at j = 3 signalized intersection as shown in Figure 12. Although the congestion has occurred at every signalized intersection along the Route 2 in real circumstances, by using the proposed signal control algorithm the congestion has disappeared completely at three signalized intersections as shown in Figure 13.

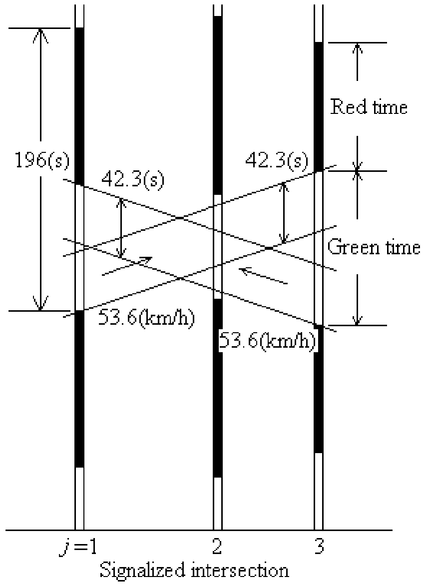

Figure 11 Balance offset for straightforward vehicles at three signalized intersections.

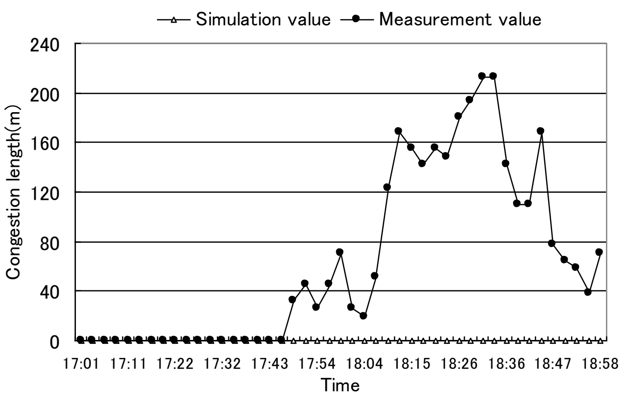

Figure 12 Comparison of congestion length for straightforward vehicles between simulation values and measurement values for m=4 at j=3 signalized intersection.

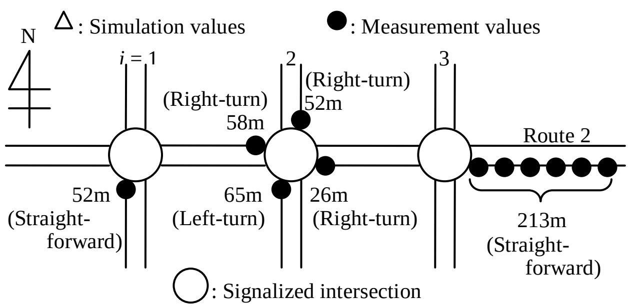

Figure 13 Comparison of congestion length between simulation values and measurement values along the Route 2 in Hiroshima city.

6. CONCLUSIONS

This paper studies a signal control system along the arterial from the viewpoint of a deterministic control for traffic flow dynamics. The following have been shown.

i) A signal control system of the congestion length is described by a nonlinear time-varying discrete dynamic system and synthesized using the feedback control for two-way traffic arterials.

ii) The signal control parameters of the arterial are optimized systematically and sequentially using the balance control algorithm.

iii) The development procedure of the signal control system is described systematically from the road analysis to the simulation.

iv) From the comparison between the simulation values and the measurement values, it is confirmed that the signal control system and the signal control algorithm work effectively so as to minimize the congestion length.

It is a future problem that the proposed technique will be confirmed to be effective for more signalized intersections and arterials.

REFERENCES

1) P. B. H unt., D. I. Robertson, R. D. Bretherton and R. I. Winton, "SCOOT – a Traffic Responsive Method of Coordinating Signals", TRRL Laboratory Report 1014 (1981).

2) E. J. Davison and *Ü. Özgüner* , “Decentralized Control of Traffic Networks”, IEEE Trans., AC-28, No.6, pp.677-688 (1983).
3) H. Sakakibara, T. Usami, S. Itakura and T. Tajima, “MODERATO (Management by Origin – Destination Related Adaptation for Traffic Optimization)”, Proc. of IEEE/ IEEJ/ JSAI International Conference on Intelligent Transportation Systems, pp.38-43 (1999).
4) K. Hayashi and M. Sugimoto, “Signal Control System (MODERATO) in Japan”, Proc. of IEEE/ IEEJ/ JSAI International Conference on Intelligent Transportation Systems, pp.988-992 (1999).
5) H. Shimizu, H. Mashiba, Y. Sobata and M. Kobayashi, “Optimization of Signal Control Parameters for Two-Way Traffic Arterials”, Preprints of the 9th IFAC/ IFORS/ IMACS/ IFIP/ Symposium on Large Scale System: Theory and Applications, pp.485-490 (2001).
6) T. H. Heung, T. K. Ho and Y. F. Fung, “Coordinated Road-Junction Traffic Control by Dynamic Programming”, IEEE Trans. ITS-6, pp.341-350 (2005).