AUTOMATIC CONTROL ALGORITHM FOR VMS AND SIGNAL COORDINATION IN URBAN TRAFFIC NETWORK

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Abstract: A feedback control algorithm for Variable Message Sign (VMS) of Urban Network is proposed. And traffic signal coordination with VMS is explicitly considered in the proposed VMS control algorithm. It is generally true that feedback control approach requires low computational effort and is less sensitive to model’s inaccuracy and disturbance uncertainties. Several issues in VMS control are raised and a feedback control algorithm is designed by incorporating the issues. To evaluate probable control benefit and detect logical errors of the proposed feedback algorithm, offline simulation test will be performed using real network in Daejeon, Korea. This research result is expected to upgrade the present VMS control practice and finally enhance the efficiency of network by achieving better traffic allocation.

Key Words: VMS Control, Coordinated Control, Feedback Control, Regulator Design

1. PROBLEM STATEMENTS

Recently, variable message signs are expanded through the whole urban network in several major cities in Korea and, therefore, network wide Variable Message Sign (VMS) control strategy is required to take advantage of the network-widely implemented VMSs. However, there is no proper methodology developed especially applicable for VMSs in urban signalized network. Most VMS control algorithm is developed for freeway or interurban arterial network.

Most previous researches related to VMS control are seeking for user optimal state. However, some other research showed that drivers’ wardropian behaviors cause concentration of the shortest route at short time interval and at last, reduce the system throughput (Daganzo, 1998). VMS itself has several limitations in its nature. It is generally known that VMS
causes overreaction and concentration problems, which may be more serious in urban network than highway network because, relatively speaking, diversion should be more easily made in urban network and those adverse effect on urban network be disastrous especially under congested condition.

In short, VMS display itself cannot automatically achieve desirable traffic allocation among alternative routes in the network. Strategic VMS message provision is the most crucial part in the VMS control. In this context, it is considered that the emphasis should be put on developing VMS message display strategy rather than simply calculating the optimal traffic allocation among alternative routes.

Furthermore, unless phase split of traffic signal is adequately adjusted to accommodate the additional traffic induced from diversion message of VMS, the consequence of VMS display may not guarantee better traffic condition in that the original phase split is based on the traffic splits without diversion. In developing VMS control algorithm for urban network, signal coordination is explicitly considered, which should be sensitive to the amount and/or the propensity of diversion.

Other issues should be addressed. Those routes related to multiple VMSs may be overloaded if diversion is recommended by the VMSs at the same time. Also drivers may be exposed to inconsistent messages through consecutive VMSs along a route. These problems should be explicitly considered in network-wide VMS control.

2. STATE-OF-THE-ART REVIEW

Recent researches related to route guidance through VMS and integrated control of VMS and traffic signals are briefly summarized in this chapter.

Mammar et al. (1996) presented a simple automatic control concepts with decentralized feedback loops aiming at approximating a user optimal traffic flow distribution in a mixed network of Aalborg, Denmark. They proposed the message set and display rules considering travel pattern and network conditions of the study area and finally showed the control algorithm improve network efficiency through a simulation study.

Pavlis and Papageorgiou (1999) presented a feedback route guidance strategy for complex, meshed traffic networks, in which measurable instantaneous travel times rather than predicted demand or O-D are used as inputs. They showed that the proposed P- and PI-regulator considerably reduce travel time delays compared to no-control case and concluded that these
are suitable for a route guidance system and sufficiently robust for real world uncertainties with minimum computational effort.

Oh and Jayakrishman (2001) argued that VMS is not generally useful in providing flow splits across alternate paths at any given time and that temporally changing VMS messages can achieve certain desirable flow split over time. A dynamic system optimum traffic assignment problem for temporal VMS route guidance was formulated as an integer programming problem and a heuristic algorithm was presented.

Dikakaki et al. (1999) presented a traffic-responsive control scheme of traffic corridors involving signal control, ramp metering, and VMS control. The scheme involves formulation and solution of a linear-quadratic control problem for signal control based on store-and-forward type of modeling, and the application of simple feedback regulators for ramp metering and VMS control.

Kotsialos et al. (1999) applied the discrete-time optimal control problem to the design of optimal coordinated and integrated motorway control strategies and used a feasible-direction algorithm for the numerical solution of the control formulation. The approach presented in this research incorporated, for the first time, a realistic nonlinear traffic flow model with various control measures.

Papageorgiou (1995) presented a unified control approach to the design of integrated control strategies for traffic corridors of arbitrary topology including both motorways and signal-controlled urban roads. The presented approach is a linear optimal-control problem based on the store-and-forward modeling philosophy, which involves a number of possible control actions, such as ramp metering, signal control, motorway-to-motorway control, route guidance, and VMS control.

Most VMS control algorithms have been developed for freeway or interurban arterial network, which is not readily applicable for urban signalized network. Strategic VMS message provision is not adequately addressed in the previous researches, which is considered as the most crucial part of VMS control in that VMS display itself cannot automatically achieve desirable traffic distribution and most probably brings on serious oscillation problem among alternative routes.
3. CONCEPTUAL DESIGN OF AUTOMATIC CONTROL ALGORITHM

The outline of coordinated control scheme proposed in this paper is shown in Figure 1. The proposed algorithm is consisted of the following three components, which are explained in each subsection in this chapter:

1. A regulator is designed to attain system optimal traffic allocation among alternative routes for each VMS in the network. From this regulator, desirable splitting rates are produced while equalizing the residual capacities of alternative routes. The concept of residual capacity is introduced for the control scheme to be robust for unsteady and congested traffic conditions. This will be explained more in Section 3.1.

2. Strategic messages should be prepared to realize the desirable traffic allocation, that is, output of the above regulator. As mentioned before, VMS display itself cannot achieve the desirable splitting rates produced from the above regulator. VMS display strategy module is designed in this context. In this module, VMS message intensity is introduced as a measure to achieve the desired splitting rates.

3. Traffic signal coordination module is designed to adjust the signal timing to accommodate the intended traffic allocation among the alternative routes. This module operates a regulator to adjust the signal timing produced from the existing signal control system.

![Figure 1. Feedback Scheme for Coordinated Control of VMS and Signal](Image)

3.1 ‘Residual Capacity’ Equalizing Module

In this module, a regulator is designed for equalizing the ‘residual capacity’ among alternative routes to achieve approximate system optimal traffic allocation. New concept of ‘residual capacity’ is introduced in this paper and will be explained in the later.

The proposed regulator is shown in Equation (1).

\[ \gamma(k) = \gamma^N (k) - K \times \Delta \Gamma' (k-I) \]  

where,

\( \gamma(k) = \) splitting rate at time slice \( k \)
\( \gamma^N(k) = \) normal splitting rate without information provision
(Use operator input value or real-time data)
\( K = \) Regulator Parameter
\( \Delta \Gamma(k-1) = \) Residual Capacity at time slice \( k-1 \)
\( = \Delta MR(k-1) - \Delta \text{Observed Demand}(k-1) \)
\( \Delta MR(k-1) = \) Max. Possible Input Rate
\( \gamma \) and \( \Delta \Gamma' \) are relative values among the alternative routes

For design feasibility, adequate number of alternative routes should be defined for each VMS spot to apply the regulator in Equation (1) to the complex and meshed urban network, in which, generally, there exist many, unspecified O-D trips and multiple alternative routes for each O-D. It is considered that the various alternative routes for various O-Ds are narrowed down to several major routes, depending on the network geometry and considering physical limitation of the installed VMS.

The ‘residual capacity’ in the regulator is defined as ‘Maximum Possible Input Rate’ minus observed demand. ‘Maximum Possible Input Rate’ is differentiated from the ‘nominal capacity’ in Highway Capacity Manual (HCM) in that the ‘Max. Possible Input Rate’ is calculated reflecting on the capacity reduction by the congestion propagation from downstream. The capacity in HCM is just a ‘Maximum Flow Rate’ in that it ignores the downstream congestion effect. However, it is critical in realtime control or information system to properly take the capacity reduction effect by the downstream congestion into account. In a previous research, a simple model was proposed to calculate the capacity reduction by downstream congestion (Pavlis and Papageorgiou, 1999). And Park(2002) presented a rough procedure for the ‘Maximum Possible Input Rate’. Sophistication of the proposed procedure for the ‘Maximum Possible Input Rate’ remains for future research.
There are some issues that should be addressed. As mentioned above, the major alternative routes are defined for each VMS spot as a first step of control scheme design. It is possible that the major alternative routes defined for each VMS may be overlapped with those for other VMSs. Then, the overlapped routes may be potentially overloaded in case the corresponding VMSs simultaneously display the messages for diverting traffic to the overlapped routes by chance.

Another issue to be addressed is an inconsistency problem. Mammar et al. (1996) proposed to check the message consistency among the consecutive VMSs. If there exist more than one VMS in a route, drivers are likely to meet conflict messages from the VMSs installed along the route. Therefore, there needs a routine to keep the message consistent for the multiple VMSs in a route and to avoid the overload of overlapped routes.

### 3.2 VMS Display Strategy Module

VMS display strategy module is to determine the message intensity that indicates how much diverted traffic the displayed message should induce. Generally speaking, when a message is displayed, the amount of diversion is dependent on the message intensity, that is, how strongly the message recommends drivers to switch their routes. In this section, the conceptual design procedure for determining a message intensity and content is presented. Message intensity is determined as a function of relative traffic conditions among alternative routes, driver compliances, etc., which is shown in Equation (2).

\[
\text{Message Intensity} = f(\Delta \gamma, \delta, \varepsilon, \text{relative splitting rate})
\]

where,

- \( \Delta \gamma = \gamma(k) - \gamma^O(k) \)
- \( \gamma(k) = \text{Desired Splitting Rates at time slice } k \)
- \( \gamma^O(k) = \text{Real-time Observed Splitting Rates} \)
- \( \delta = \text{O-D portion likely to Divert} \)
- \( \varepsilon = \text{Drivers' Compliance Rate} \)

Splitting rates are relative values among alternative routes.

The proposed procedure for message intensity is a 2-step procedure, that is, first step as Table 1 and second step as Equation (3), which is shown in Figure 2. Table 1 represents how initial message intensity and content are selected based on traffic conditions of alternative routes. Table 1 is prepared by assuming three alternative routes and three-level traffic conditions. However, this assumption is just for quick and clear understanding and should
be relaxed as physical circumstances of the area of interest.

And as a second step, if the traffic conditions of alternative routes (that is, desired splitting rates) are not changed and the desired splitting rates are not achieved, the regulator in Equation (3) is operated for adjusting message intensity. If the traffic conditions of alternative routes are changed, then the message intensity and contents should be renewed based on Table 1.

\[
Message\ Intensity(k) = Message\ Intensity(k-1) + \Phi\ (k-1) \tag{3}
\]

where,

\[
\Phi\ (k-1) = \begin{cases} 
-1 & \text{if}\ \Delta\gamma < 0 \\
0 & \text{if}\ \Delta\gamma = 0 \\
1 & \text{if}\ \Delta\gamma > 0
\end{cases}
\]

Message Intensity is adjusted in following steps:

Positive plus → Positive → Neutral if it is in positive steps.

Negative plus → Negative → Neutral, otherwise.
### Table 1. Traffic Conditions and Message Display Strategy

<table>
<thead>
<tr>
<th>Classification a)</th>
<th>Traffic Conditions of Alternative Routes b)</th>
<th>Message Intensity c)</th>
<th>Message Display d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. all is in the same traffic condition</td>
<td>r-r-r neutral</td>
<td>The messages leading to diversion are not desirable.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>y-y-y neutral or positive</td>
<td>Decide whether the messages leading to diversion should display or not depending on the magnitude of $\Delta \gamma$.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>g-g-g neutral</td>
<td>The messages leading to diversion are not desirable.</td>
<td></td>
</tr>
<tr>
<td>2. 2 routes are in congested condition</td>
<td>r-r-y neutral</td>
<td>The messages leading to diversion are not desirable.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r-r-g positive or positive plus</td>
<td>Display such messages as the route in condition 'g' is good or good enough to stay.</td>
<td></td>
</tr>
<tr>
<td>3. Only 1 route is in congested condition</td>
<td>r-y-y neutral</td>
<td>The messages leading to diversion are not desirable.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r-y-g negative</td>
<td>Display such messages as the route in condition 'y' is not good.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>r-g-g negative plus</td>
<td>Display such messages as the route in condition 'g' is not good enough to divert.</td>
<td></td>
</tr>
<tr>
<td>4. all is in fair traffic condition</td>
<td>y-y-g neutral or positive</td>
<td>Decide whether the messages leading to diversion should display or not depending on the magnitude of $\Delta \gamma$.</td>
<td></td>
</tr>
</tbody>
</table>

a) Assuming existence of three alternative routes, which can be easily generalized to any number of routes.

b) a-a-a represents the traffic conditions of each of three alternative routes.

r = congested, y = slowed down, g = normal flow
Traffic conditions are expressed in 3 steps tentatively, which is adjustable as desired.

c) negative: not good, negative plus: not good enough to divert
positive: good, positive plus: good enough to stay
neutral: no message that possibly leads to diversion

d) Exact sentence of messages should be created according to the size and other constraints of the VMSs implemented.

### 3.3 Traffic Signal Coordination Module

Traffic signal coordination module is to accommodate the additional traffic load resulting from the diversion induced by displayed VMS message. This module operates a regulator to adjust the signal timing plans produced from the existing signal control system based on the normal traffic state without diversion. The desired splitting rates are outputted from the ‘residual capacity’ equalizing module. The phase split from the existing control system is adjusted corresponding to the difference between the desired splitting rates and the splitting rates observed and/or estimated from traffic network.

\[
\phi'(k) = \phi(k) + n \cdot \Delta \phi \quad \text{if} \quad n \cdot \varepsilon \leq \Delta \gamma < (n+1) \cdot \varepsilon \quad (4)
\]

\[
\phi'(k) = \phi(k) - n \cdot \Delta \phi \quad \text{if} \quad -(n+1) \cdot \varepsilon \leq \Delta \gamma < -n \cdot \varepsilon \quad (5)
\]

where,
\[
\phi(k) = \text{phase split at time slice } k
\]
\[
\phi'(k) = \text{adjusted phase split}
\]
\[
n = \text{integer}
\]
\[
\Delta \gamma = \text{the difference between the desired and the observed splitting rates}
\]
\[
\Delta \phi, \epsilon = \text{minimum step size}
\]

4. SIMULATION TEST

To evaluate probable control benefit and detect logical errors of the proposed feedback algorithm, offline simulation test is performed using real network in Daejeon, Korea. Figure 3 shows the test network where traffic is usually concentrated on the Dae-duk street. Therefore, using the VMS upstream of Intersection (a), better traffic allocation needs to be achieved between Dae-duk street and E. City-Hall Street.

TSIS NETSIM is adopted for simulation test. The data and three scenarios for this study is summarized in Table 2. The simulation results are presented in Table 3. It is shown that the VMS message display without signal coordination (that is Scenario B) does not make the network any good. It is also stated from Table 3 that traffic condition upstream of Intersection (a) is improved and those of two alternative routes are evenly tuned by adjusting the mal-distribution, which is expected to result in the enhancement of network efficiency.

The control benefit in Table 3 is under the assumption that the desired traffic allocation is 100% achieved. The performance tests of the regulators proposed in this paper are remained for future work. The effects of drivers’ compliance and VMS message intensity are not considered in this study because of the limitation of off-line simulation.
Figure 3. Simulation Network in Daejeon, Korea

Table 2. Simulation Scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
</table>
| A no control | • 2002. 8. weekday, 18:00-19:00 am  
• Splitting rates: Dae-Duk street 90.1% (2,823 veh)  
E. City-Hall street 9.9% (290 veh) |
| B Reallocation of splitting rates | • Reallocation of splitting rates by equalizing the 'Residual capacity' among alternative routes:  
Dae-Duk street 74.8% (2,329 veh)  
E. City-Hall street 25.2% (784 veh) |
| C Reallocation of splitting rates + Adjustment of signal phase | • Reallocation of splitting rates by equalizing the 'Residual capacity' among alternative routes:  
Dae-Duk street 74.8% (2,329 veh)  
E. City-Hall street 25.2% (784 veh)  
• Signal phases and lane distribution of Intersection 3 are adjusted. |

<table>
<thead>
<tr>
<th>Phases</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
<th>$\phi_3$</th>
<th>$\phi_4$</th>
<th>$\phi_5$</th>
<th>Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>17(3)</td>
<td>42(3)</td>
<td>23(3)</td>
<td>34(3)</td>
<td>29(3)</td>
<td>160</td>
</tr>
<tr>
<td>Adjusted</td>
<td>25(3)</td>
<td>35(3)</td>
<td>23(3)</td>
<td>32(3)</td>
<td>30(3)</td>
<td>160</td>
</tr>
</tbody>
</table>

'Residual Capacity' is calculated by 'nominal capacity' minus demand in this study.
Table 3. Simulation Results

<table>
<thead>
<tr>
<th></th>
<th>Average Speed (km/h)</th>
<th>Delay Time (sec/vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Upstream of Intersection</td>
<td>17.0</td>
<td>18.9</td>
</tr>
<tr>
<td>Dae-duk Street</td>
<td>19.2</td>
<td>20.1</td>
</tr>
<tr>
<td>E. City-Hall Street</td>
<td>23.3</td>
<td>22.1</td>
</tr>
</tbody>
</table>

18:00-19:00 in weekday, Southbound direction

5. CONCLUDING REMARKS

This paper proposed an automatic VMS control and traffic signal coordination algorithm for a signalized network. Feedback control concept is applied, which is generally known robust for unpredictable disturbances and modeling errors. Three-component algorithm is proposed: residual capacity equalizing regulator module, VMS display strategy module, traffic signal coordination module. In real time control and information, capacity reduction by congestion propagation from upstream should be fairly estimated and explicitly taken into consideration when calculating the desirable traffic distribution among alternative routes. Otherwise, control and information provision might make network even worse. In this context, the new concept of ‘Residual Capacity’ that is different from the nominal capacity in HCM is proposed and the development of calculation method remains for further study.

The proposed algorithm is expected to upgrade the present VMS control practice and finally enhance the efficiency of network by achieving better traffic allocation. However, VMS message display itself, unlike ramp metering or other signal controls, cannot automatically achieve desired traffic allocation among alternative routes. Evaluation of the performance of VMS display strategy module is crucial in that the traffic allocation is completely dependent upon strategic message display. Field trial tests for the proposed algorithm should be performed for future work.

One of major drawbacks of feedback control is an oscillation problem, which may be fatal in roadway network control. To overcome this oscillation problem, a predictive scheme may be incorporated with the proposed model in a timely manner. This work is ongoing for a separate research.
REFERENCES


