

Optimal Control Model and Simulation Studies for Intelligent Corridor Management

Ta-Yin Hu ¹⁺, Wei Ming Ho ² and Tung-Yu Wu ³

^{1,2,3} Department of Transportation and Communication Management Science.

National Cheng Kung University, No.1, Ta-Hsueh Road, Tainan 701, Taiwan, R.O.C.

Abstract. Traffic congestion arises in metropolitans are common problems due to insufficient traffic facilities and major bottlenecks occur on main urban arterials, freeways and expressways. This research aims at proposing an optimal control model for corridor management, including freeway segments, on-ramps, off-ramps, and arterial streets, to relieve possible congestion. Traffic control strategies for corridor management include ramp metering, signal control, and route guidance. Based on the concept of the store-and-forward method, the problem is formulated as a linear optimal control model; and the objective function is to minimize total queue length for considered traffic corridors. Numerical experiments and simulation studies are conducted to illustrate the proposed models.

Keywords: optimal control, corridor management, simulation-assignment, DynaTAIWAN

1. Introduction

Due to the rapid growth of private vehicles, the large number of vehicles causes serious traffic jams along many major traffic corridors. Many traffic management centers design different strategies, such as infrastructure extension and integrated corridor management, to improve the traffic service quality and relieve traffic congestions. Under the technology of intelligent transportation systems (ITS), the intelligent corridor management utilizes several control measures, including route guidance, ramp control and signal control, to improve the efficiency and enhance the service quality. Integrated corridor management is becoming an important application in ITS. Several approaches have been developed for the design of control strategies based on ramp metering, variable message signs, freeway-to- freeway control, and coordination between arterial streets and freeways. These approaches include expert systems, fuzzy systems, neural networks, and classical feedback control. Among these approaches, solutions obtained from the optimal control methods provide control decisions based on the explicit minimization of a suitable control criterion. Papageorgiou (1995) developed a linear optimal control model for traffic corridors and the concept of the optimal control model is derived from the store-and-forward model (Gazis, 2002). The store-and-forward method is used to manage the dynamic traffic corridor under saturated traffic conditions situation. This research proposes a modified optimal control model for integrated corridor management based on the store-and-forward method. The route allocation is implicitly introduced in the formulation to incorporate the concept of route guidance. The objective is to minimize total queue length for the corridor.

2. Literature Review

Several approaches have been developed for the design of control strategies based on ramp metering, variable message signs, freeway-to- freeway control, and coordination between arterial streets and freeways. Among these approaches, solutions obtained from the optimal control methods provide control decisions

⁺ Corresponding author. Tel.: +886-6-2757575-53224; fax: +886-6-2753882.
E-mail address: tyhu@mail.ncku.edu.tw.

based on the explicit minimization of a suitable control criterion. Based on a simplified traffic flow model, Moreno-Banos et al. (1993) proposed an integrated control strategy addressing both route guidance and ramp metering. Papageorgiou (1995) proposed a linear programming method for integrated control, including traffic signal control, route guidance and ramp metering. Diakaki et al. (1997) described a feedback approach with consideration of the overall network. Kotsialos et al. (2002) proposed a generic formulation for designing integrated traffic control strategies for traffic corridor networks with the use of ramp metering, route guidance, and freeway-to-freeway control measures. The problem is formulated in the format of discrete-time optimal control and solved through a feasible-direction algorithm. In the past, traffic control systems within corridor have been developed independently for each individual control measure attempting to optimize traffic flow on either freeway or urban road network. However, a traffic corridor constitutes an entity in terms of operational objectives, user requirements and impact of individual control measures. Haj-Salem et al. (1995) showed that ramp metering on a freeway may have a considerable impact on the adjacent road traffic. The store-and-forward approach is well suited for dynamic corridor queue management under saturated traffic conditions. As the literatures shown above, the integration of integrated corridor management and ITS is an important issue around the traffic management. Therefore, the optimization management could be a way to solve this problem.

3. Methodology

The intelligent corridor management is modeled as a linear optimal control model based on the store-and-forward approach. However, route allocation is explicitly modeled as decision variables. The store-and-forward approach to traffic control problems was originally suggested by Gazis and Potts (1963) and have been utilized for the design of signal control systems.(Michalopoulos and Stephanopoulos, 1977a, 1977b). The main objective of this research is to build an intelligent traffic management model. The objective function is equation (1).

$$\text{Min } J_D = \tau \sum_{i,j \in I} \sum_{k=0}^K x_{i,j}(k), \quad I = U, R, H \quad (1)$$

The constraints of intelligent traffic management model are:

$$x_{i,j}(k+1) = x_{i,j}(k) + \tau [q_{i,j}(k) - u_{i,j}(k)] \quad (2)$$

$$x_i(k) = \sum_{j \in I} x_{i,j}(k) \quad (3)$$

$$q_i(k) = \sum_{j \in I} u_{j,i}(k) \quad (4)$$

$$u_i(k) = \sum_{j \in I} u_{j,i}(k) \quad (5)$$

$$u_i(k) \leq \frac{S_i g_{\gamma,f}(k)}{c} \quad (6)$$

$$r_i(k+1) = r_i(k) + H [o_i^* - o_{out,i}(k)] \quad (7)$$

$$\rho_{cr,Hj}(k) = \frac{q_{Hj}(k)}{\beta_{Hj} \times n_{Hj}} \quad (8)$$

$$o_{out,i}(k) = \frac{(\beta_v + \beta_d) \times \rho_{cr,Hj}(k)}{1000} \quad (9)$$

$$u_{Ri}(k) \leq \alpha \times r_i(k) \quad (10)$$

$$u_{Rj}(k) \leq u_{sat,Rj} \quad (11)$$

$$0 \leq u_i(k) \leq u_{max,i} \quad (12)$$

$$0 \leq u_i(k) \leq u_{max,i} \quad (13)$$

$$g_{min} \leq g_{\gamma,f}(k) \leq g_{max} \quad (14)$$

where,

$x_{i,j}(k)$: In the time interval k , the queue length from section i to section j (veh),
 $q_{i,j}(k)$: In the time interval k , the inflow from section i to section j (veh),
 $u_{i,j}(k)$: In the time interval k , the outflow from section i to section j (veh),
 $x_i(k)$: In the time interval k , the queue length of section i (veh),
 $q_i(k)$: In the time interval k , the inflow of section i (veh),
 $u_i(k)$: In the time interval k , the outflow of section i (veh),
 S_i : The saturated flow rate of section i ,
 $g_{\gamma,f}(k)$: The effective green time of intersection γ at μ phase (second),
 $r_i(k)$: In the time interval k , the metering rate of section i (veh),
 o_i^* : The target occupancy of ramp metering,
 $o_{out,i}(k)$: In the time interval k , the occupancy of downstream section i ,
 H : A parameter from calibration,
 $\rho_{cr,Hj}(k)$: In the time interval k , the critical density of downstream section i ,
 n_{Hj} : The number of lanes along the mainstream,
 β_v : Average vehicle length (meter),
 β_d : The length of detector (meter),
 α : A transform parameter between $u_{Ri}(k)$ and $r_i(k)$,
 $u_{sat,Rj}$: The saturated flow rate of off-ramp j ,
 u_{maxi} : The maximum outflow of section i (veh),
 x_{maxi} : The maximum queue length of section i (veh),
 g_{min} : The minimum effective green time (second), and
 g_{max} : The maximum effective green time (second).

When queue length exists for a certain road section, the queue length $x_{i,j}(k)$ is determined by the previous interval and difference between inflow and outflow (constraint 2). Under route allocation, the queue length, inflow and outflow of a link are equal to the summation of different turn movement flow (constraint 3, 4, 5). The outflow for a link at the intersection is controlled by the saturated flow rate times green time (constraint 6). The constraint (7), ALINEA feedback control rule, shows that the metering rate is impacted by the rate of last interval and occupancy of downstream. The constraint (8) shows the critical density of mainstream on freeway. The constraint (9) describes the occupancy of downstream. The constraint (10) describes that the ramp metering rate takes effect to the outflow. The outflow of an off-ramp is less or equal to the saturated flow (constraint 11). The constraint (11) limits the range of outflow on a link, and constraint (12) limits the range of queue length. The constraint (13) is about the minimum and maximum green time. The mathematical program is solved through CPLEX to get the optimal solution.

4. Numerical Experiment

Numerical experiments were conducted in a Taoyuan traffic corridor in the northern part of Taiwan (see Fig. 1). The network has 54 links, 35 nodes, and 8 traffic zones. The Taoyuan traffic corridor covers a north-south freeway (National Highway I) and an east-west freeway (National Highway II). There are three lanes for each direction on Freeway I and two lanes for each direction on Freeway II. The saturation flow rate is assumed to be 0.75 vehicles/second/lane. The speed limit is 110 km/hour for Freeway I and 90 km/hour for Freeway II. There are three interchanges in the network. The speed limit is 60 km/hr and there are two lanes for on-ramp and off-ramps. The saturation flow rate is assumed to be 0.5 vehicles/second/lane. For other arterial streets, the speed limit is 60 km/hr and most of the arterial streets are three lanes per direction.

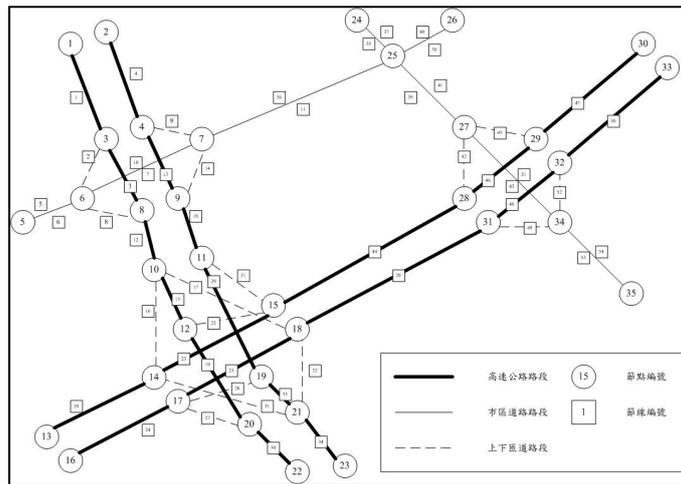


Figure 1 Taoyuan Network in DynaTAIWAN format

The total considered time period in the experiment is one hour, and each time interval is 10 minutes. There are six time intervals. In order to observe the system performances under different demand levels, several loading factors are tested. The loading factor is defined as the ratio of the total number of vehicles generated in the network during the simulation period. When the loading factor is equal to 1, the number of vehicles is 13491. There are 11 cases in the basic experiments and the loading factors are 0.5, 0.6, ...and 1.5, respectively. The cycle lengths, depending on demand levels, are pre-assumed to be 60 seconds, 90 seconds, and 120 seconds.

The objective function is the summation of queue length of each section times the time interval, so that the larger of objectives means the corridor is more congested. The results are summarized in Figure 2(a). When the demand level is 0.5, the total delay time is 13279 min-veh. When the demand level is 1.0 and the total delay time is 107742 min-veh. When the demand level is 1.5 and the total delay time is 319382 min-veh. The results indicate that the total delay time increases with respect to demand levels. The difference between consecutive demand levels is calculated and the results are shown in Figure 2 (b). When the demand level increases to 1.2, the difference of delays reaches a nearly constant value and it indicates highly saturated traffic conditions.

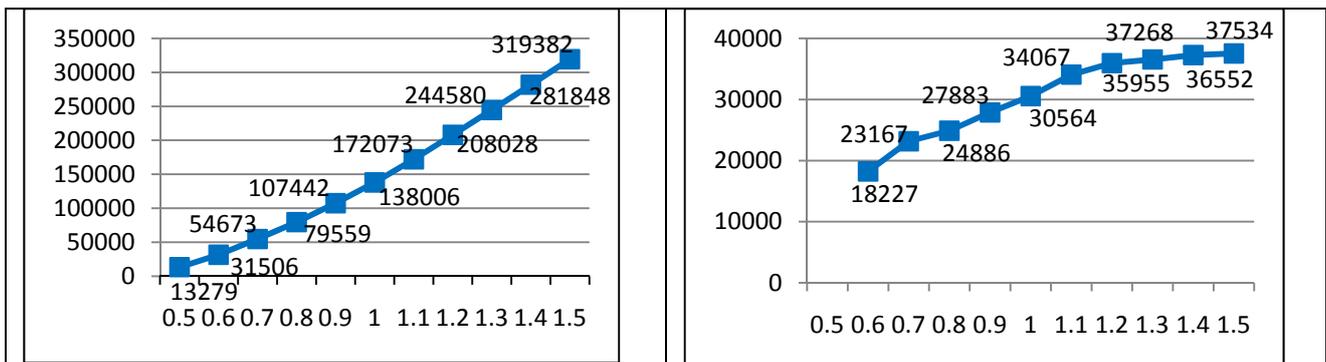


Figure 2 (a) Variation of objective values (b) Difference between Objective Function

5. Simulation Studies for Intelligent Corridor management

In this section, the optimal control model is applied to generate traffic control settings for freeway corridors and these scenarios are compared in a simulation-assignment model, DynaTAIWAN. The total number of generated vehicles is 13,491 vehicles.

The first result to be compared is signal settings. The signal settings for urban streets for original setups and results from the optimal control model are compared. The lost time is assumed to be 10 seconds per cycle. For the same cycle length, 90 seconds, the green time for the phase 1 is changed from 40 seconds to 15 seconds under the optimal control model and the green time for the phase 2 is changed from 40 seconds to 15 seconds under the optimal control model.

Three scenarios, including original signal settings, optimal control setting, and actuated signal control settings, are considered in the comparison. System performance is summarized in Table 1. The results show that the optimal control model reduce the travel time from 9.03 to 5.62 minutes and the stopped time is reduced from 4.51 minutes to 1.53 minutes. Although the actuated signal control provides the best results, the cost of operating actuated signal control is considerably very high.

Table 1. System performance under different signal settings

	original signal setting	optimal control setting	actuated signal control settings
ATT (minutes/vehicle)	9.03	5.62	4.64
AST (minutes/vehicle)	4.51	1.53	0.54
ATD (km/vehicle)	5.339	5.172	5.175
ATS (km/hr)	35.5	61.06	66.9

6. Conclusions

The modified optimal control model based on the store-and-forward approach is proposed in this paper and decision variables for queue lengths from section to sections are explicitly modeled. The model is solved through CPLEX. The results from numerical experiments show applicability to apply in route guidance. The results show that the number of congested links increases with respect to demand levels. The ramp metering rate decreases when congestion occurs on the freeway to limit number of vehicles entering the freeway. The green time of signalized intersections is also important in corridor management.

In the experiment, the time interval is set to 10 minutes; however, shorter intervals might provide more details for the corridor management. In order to verify the results, simulation experiments can be applied in the future to evaluate possible benefits based on generated optimal control variables.

7. Acknowledgements

This paper is based on work partially supported by National Science Council, Taiwan, R.O.C.. Of course, the authors are solely responsible for the contents of this paper.

8. References

- [1]. Diakaki, C., Papageorgiou, M., and Mclean, T., Simulation studies of integrated corridor control in Glasgow, *Transportation Research C*, Vol. 5, No. 3, 1997, pp. 211–224.
- [2]. Gazis, D. C., *Traffic Theory*, Kluwer Academic Publishers, 2002, pp. 165-168.
- [3]. Gazis, D. C., and Potts, R. B., The oversaturated intersection, *Proceedings of the 2nd International Symposium on Traffic Theory*, London, United Kingdom, 1963, pp. 221-237.
- [4]. Haj-Salem, H., and Papageorgiou, M., Ramp metering impact on urban corridor traffic: field results, *Transportation Research A*, Vol. 29A, No. 4, 1995, pp. 303–319.
- [5]. Kotsialos, A., Papageorgiou, M., Mangeas, M., and Haj-Salem, H. (2002), Coordinated and integrated control of motorway networks via non-linear optimal control, *Transportation Research C*, Vol. 10, No. 1, 2002, pp. 65-84.
- [6]. Michalopoulos, P., and Stephanopoulos, G., Oversaturated signal system with queue length constraints: single intersection, *Transportation Research*, Vol. 11, No. 6, 1977a, pp. 413–422.
- [7]. Michalopoulos, P., and Stephanopoulos, G., Oversaturated signal system with queue length constraints: systems of intersections, *Transportation Research*, Vol. 11, No. 6, 1977b, pp. 423–428.
- [8]. Moreno-Banos, J.C., Papageorgiou, M., and Schaffnet, C., Integrated optimal flow control in traffic networks, *European Journal of Operational Research*, Vol. 71, No. 2, 1993, pp. 317-323.
- [9]. Papageorgiou, M., An integrated control approach for traffic corridors, *Transportation Research C*, Vol. 3, No.1, 1995, pp. 19–30.
- [10]. Rathi, A. K., A control scheme for high traffic density sectors, *Transportation Research B*, Vol. 22, No. 2, 1988, pp. 81-101.