EVALUATION OF DYNAMIC TRAFFIC MANAGEMENT STRATEGIES FOR URBAN FREEWAY CORRIDOR

Hun KIM
Research Fellow
Korea Transport Institute
Tel: +82-031-910-3197
Fax: +82-31-910-3224
E-mail: khun@koti.re.kr

Yong Seok KWON
Professor
Department of Urban Engineering
Jeonju University, Korea
Tel: +82-063-220-2292
Fax: +82-63-220-2750
E-mail: jisankys@jeonju.ac.kr

Seung Pil Kang
Professor
Department of Urban Engineering
Seoul National University, Korea
Tel: +82-02-882-2144
Fax: +82-2-889-0032
E-mail: spkang@snu.ac.kr

Tchang Ho KIM
Professor
Department of Urban and Regional Planning
Illinois University, USA
Tel: +1-217-244-5369
Fax: +1-217-244-1717
E-mail: t-kim7@uiuc.edu

Abstract: In this paper, we evaluate the dynamic traffic management strategies for urban freeway corridor. So as to evaluating the management strategies, we propose the dynamic traffic management model consist of two main components: Dynamic traffic assignment model and dynamic traffic control model. We design and evaluate three experimental factors about traffic management strategy and evaluate in a pilot freeway corridor. Two of these factors pertain to control: (1) signal control strategy, and (2) ramp control strategy. The third experimental factor consists of the provision of en route traffic information through VMS. Under the various corridor traffic conditions, the results show that there exists a potential improvement in network traffic performance, especially significant reduction in network travel time under the non-recurrent congestion resulting from freeway capacity decreasing.

Key Words: dynamic management, freeway corridor, control strategy

1. INTRODUCTION

Urban freeway corridor is defined as a longitudinal network consisting of at least one freeway plus one or more viable and essentially parallel alternative routes, such as arterial roads. Overloading of traffic demand on freeway, especially around the ramp, and lack of coordinated operating systems have caused congestion, flow breakdown and reduction capacity in corridor. The growing these problems have increased both the scope and scale of traffic management tasks, while simultaneously constraining the range of alternative solutions that are available to alleviate such problems.

Usually, traffic control techniques have had the aim of coping with increasing traffic demand trying to maximize the capacity of the network by means of the control over the time. But the advances in traffic control, control techniques alone are not enough to solve the problem. The pattern of traffic in urban network is the result of interaction between people's wish to travel in the area and the available road system, including the regulation governing any control system that is in operation. These interaction lead to imbalances in the use of available network capacity due to stochastic variations in traffic demand, incidents and so on and, meanwhile, routes not overcrowded are not used by drivers due to lack of information and control action. So, there is a need for integrated management of freeways and surface roads in a corridor. Since these components interact, their management authorities should exchange information and cooperate in their operations to provide a better overall system. Clearly, there is a need for simultaneously modeling freeways and surface roads, traffic assignment, traffic diversion, ramp-metering and traffic signal control within a dynamic management model.

The existing control models for corridor in the literature have a shortcoming either control or state prediction. Instead of having advantage of predicting equilibrium network states, analytic models have disadvantage of representing real traffic flow and control (Yang, 1994). The linear programming based on macroscopic simulation mainly approximate the link travel time functions in order to solve easily the control problem (Chang et al., 1994).

The objectives of this paper are two–fold; (1) to develop a dynamic management model for urban freeway corridor; and (2) to evaluate the management strategies using developed model. The presented dynamic traffic management model consists of two main components: dynamic traffic assignment (DTA) model and dynamic traffic control (DTC) model. We combine two separate efforts on control and assignment in order to improve the network traffic performance in urban freeway corridor.

2. MODELLING FRAMEWORK

2.1 Conceptual Model

The presented model consists of a dynamic simulation-assignment model, which is predicting network state at meso-scopic level, and a dynamic instantaneous control model for system optimizing.

The simulation-assignment model, which is composed of a dynamic network model, route choice model and dynamic network-loading (DNL) model, includes pre-trip path selection in addition to en-route switching decisions. Therefore it can simulate the process of users' choice in a traffic dynamics and evaluate the effect of providing information in the imperfect reactive route guidance system.

The proposed DTC model is applied to design of heuristic integrated corridor control strategies that consider different type of control measures. It incorporates nonlinear traffic flow model with various control measures and decomposed nonlinear optimization algorithms required for the determination of the control variables' optimal trajectories over time.

In the case of combining of assignment model and control model, we don't probe a fixed-point solution to be mutually consistent in the planning side but emphasize the system optimal solution in the operational aspect. In this model, corridor traffic management problem can be described as a leader-follower, where the system manager is the leader and the corridor users are followers. It is assumed that the system manager can influence, but cannot control, the users' route choice behavior by providing information, metering access at on ramps and signal control at intersections on surface streets. So it is efficient for the proposed model to represent the transient network state result from perturbation on the side of dynamic management, such as providing en-route information, adaptive control.

2.2 Dynamic Network Representation

The road network consists of nodes, links and segments. A node is either an intersection of several roadways or a sink or source where traffic flows enter or leave the dynamic network.

We assume that dynamic choices available to drivers with access to guidance restricted at nodes established VMS (Variable Massage Sign).

Link is physically directional roadway that connects between two nodes. But we represent the roadway as one or more links considering approach lane at downstream node. Each link may consist of one or two segments and is characterized by its type (freeway, ramp, and arterial road). Especially, the controlled link is composed of common inbound segment and outbound approach segment at the downstream intersection. The selection of suitable link travel time functions for discrete-time dynamic network largely depends on the length of the analysis time interval and the method of network loading. It is reasonable to assume that stochastic delay is negligible during such a short time. For an arterial link, average link travel time $T_a(k)$ per vehicle during time interval k can be expressed as the sum of two main components. The first is the travel time over the common inbound segment of the link; the second is queue delay over the approach segment at the intersection.

$$T_a(k) = T_a^1(k) + T_a^2(k) \tag{1}$$

Where,

$T_a^1(k)$: Cruising time over the inbound segmentation of the link a

$T_a^2(k)$: Average delay over the approach segment of the link a

The cruising time $T_a^1(k)$ is basically derived from cruise speed and length of uncongested segment. But we regard the cruise as design speed or limited speed on an arterial link, and substitute the whole length of link for segment length because of the weakly dependency of cruise speed on inflow and difficulty in calculation for length of uncongested segment. If there is a queue over the storage capacity on the approach segment, it is necessary to reflect increment of cruising time. This increased time resulted from overflow on approach segment usually affect all links common with inbound segment in the roadway.

$$T_a^1(k) = \frac{l_a}{w_a^o} + \Delta T_a^1(k) = \frac{l_a}{w_a^o} + \frac{x_a^1(k) \times \Delta k}{\sum_{a \in \{Q_a^2 \le x_a\}} S_a \times g_a} \qquad \forall a \in L_a^{in} \tag{2}$$

$$x_a^1(k) = \sum_{a \in L_a^{in}} \max\left[x_a(k) - Q_a^2(k), \;\; 0\right] \tag{3}$$

Where,

l_a : Total length of link a

w_a^o : Design speed of link a

$x_a^1(k)$: Vehicle on common inbound segment of link a at time k

$x_a(k)$: Vehicle on link a at time k

$S_a(k)$: Saturation flow rates of link a at time k

$g_a(k)$: Green split ratio of link a at time k

$Q_a^2(k)$: Storage capacity of approach segment of link a at time k

L_a^{in} : Set of links whose common with inbound segment of link a

The average delay per vehicle, $T_a^2(k)$, for vehicles arriving at the downstream intersection of link a during time interval k can be composed of uniform delay, $d_a^u(k)$, and overflow delay $d_a^o(k)$.

$$d_a^u(k) = \frac{0.5C^m(k) \times [1 - g_a]^2}{1 - Min[1,\ \rho_a] \times g_a} \tag{4}$$

$$d_a^o(k) = \Delta k \times \frac{Max[x_a(k) - S_a \times g_a\ ,\ 0]}{S_a \times g_a} \tag{5}$$

In case of estimating saturation flow rates (or capacities) for links and intersection approaches, we propose following equation based on the HCM concept of saturation flow rate and method of DNL.

$$S_a = S_a(\Delta k) \times f(\Delta k, l_a\ ,\ w_a^o\ ) \tag{6}$$

Because of using the time-based discrete DNL in this paper, we should consider properties of the relationship between time interval for network loading and link free-flow cruise time, $f(\Delta k, l_a\ ,\ w_a^o\ )$. That is, if link length is too long, it takes two or more time interval to travel the link with free flow speed. Thus this traffic is considered as queue, which affects the travel time of next interval traffic. Certainly, it is necessary to adjust capacity for these links.

For a freeway link, it is very difficult to divide free-flow cruising segment from flow-dependent delay segment on the freeway link. So, we make use of traditional BPR function which the traffic is distributed uniformly.

2.3 Dynamic Network Loading

The dynamic network loading (DNL) aims at finding time-dependent link flows, link costs and path costs, given route choices and link performance models. There have been to approaches to modeling dynamic network loading problem. One is simulation-based modeling, another is based on flow based analytical models. The model is formulated as a system equation representing the link dynamics, link flow conservation, flow propagation and boundary conditions.

In this paper, we apply iterative-load model developed by Chabini and He (1997), that can be implemented as either a simulation-based model or a flow-based analytical model. Each iteration, DNL model implement to fix the link travel time temporarily, load path flows, aggregate link flows, compute and update link travel time. On the other hand, we supplement the flow conservation equation at route choice node and spillback queue adjustments in presented model.

The flow conservation equation at route choice node is applied to each pre trip choice node, such as origin node, and en-route choice node, that is VMS established node.

PRE TRIP CHOICE NODE

$$\sum_{p \in P^{od}} u_{ap}^{od}(k) = D^{od}(k), \quad a \in A(o) \tag{7}$$

EN-ROUTE CHOICE NODE

$$\sum_{p \in P^{od}} v_{ap}^{Od}(k) = D^{o^*d}(k+1), \quad a \in B(o^*) \tag{8}$$

Where,

$u_{ap}^{od}(k)$: Inflow on link a from origin (o) to destination (d) along path p at time k

$v_{ap}^{Od}(k)$: Outflow on link a from route choice node (O) to destination

$D^{o^*d}(k+1)$: Demand from en-route choice node (o^*) to destination at time k+1

$A(o)$, $B(o^*)$: Set of links whose head node is o or tail node is o^*, respectively

In this paper, we assumed that additional time for upstream link, $a+$, owing to spillback queue from downstream link a is time to clear vertical queue on downstream link.

$$\Delta T_{a+}(k) = Max\left[x_a^1(k) - Q_a^1, \quad 0\right] \times \frac{\Delta k}{\sum_{a \in \{Q_a^2 \le x_a\}} S_a \times g_a} \qquad \forall a \in L_a^{in} \tag{9}$$

2.4 Dynamic Route Choice Model

The presented model aims to gain more insight into the implications of information provision to drivers on the performance of road networks with non-recurrent congestion. For this purpose, a dynamic simulation-assignment model consisting of three components has been written. The first component is the path-based static traffic assignment model, the second component is the decision-making process and the third component is the DNL model as above described.

Even though there are many discrepancies between static and dynamic, we implement the path-based static traffic assignment model, which is an adapted version of the one used by Jayakrishnan (1994), in order to gain fixed available path and path choice probability. So, we represent the static network similar to dynamic network and use static O/D data that assumed recurrently to be happened during analysis period.

We suppose that drivers base their travel choice upon both their own experiences, which are fixed path choice probabilities, U_p^2 , derived from path-based static traffic assignment, and time-varied probabilities, $U_p^1(IP)$, calculated from logit model using the path travel time based on the en-route information during information interval, IP.

$$U_p(IP) = \alpha_u \times U_p^1(IP) + (1-\alpha_u) \times U_p^2 \tag{10}$$

Thus, drivers choose route based upon the combined utility, $U_p(IP)$, composed of fixed utility, time-varied utility and preference to provided information during their trip in this paper.

2.5 Dynamic Control Model

The interaction between traffic control and traffic assignment is essentially the conflict between drivers, who choose their routes to minimize their own travel times, and the traffic authority, who sets the signal timings to minimize an overall system objective such as total travel time. In this paper, we approach instantaneous system optimal based on predicted link volume during control interval, CP.

$$Min\ Z = \sum_a u_a(CP) \times T_a\left[u_a(CP), x_a(CP), g_a(CP)\right] \tag{11}$$

$s.t.\ g_a \in \Omega_g , \quad u_a, x_a \in \Omega_d$

Where, Ω_g is feasible region of control variable and Ω_d is feasible condition of input and state variable respectively.

When we use the decomposition method which optimize only control variable separate state variable, it is necessary to search the minimal marginal link travel time, as the partial derivative of the total link travel time with respect to link green time split, with considering state variables. But it is difficult to search the marginal link travel time because there is asymmetric and non-separable characteristic resulted from interaction between links, such as spillback. In addition to, because of dissimilarity of control characteristic by road type, it is difficult to apply unified optimization method to control problem in freeway corridor. So, we design separate control strategies, formulations and solution algorithms in order to minimize total travel time in a freeway corridor, given link traffic volume resulted from assignment model. We use a heuristic approach based on dynamic decomposition method which decomposes the system into the control and state spaces. Thus only the control variables are treated as optimization variables, whereas state variables are solved by dynamic network loading.

3. DYNAMIC MANAGEMENT STRATEGIES

3.1 Information Provision Strategy

In order to analyze the potential effects of information provision to drivers, we present the three kinds of information provision strategies. Information provision type A assumes that information on different paths is acquired solely through own experience. So, drivers decide pre-trip route choice on origin zone, and don't switch their decision en-route. Information provision type B and C provide drivers with en-route information on specified node each 3minute, 6minute information provision interval. Thus, drivers enable to switch their route on node where implemented information provision system with VMS.

3.2 Ramp Metering Strategy

Ramp control can be defined as a method of improving overall freeway operations by limiting, regulating and timing the entrance of vehicles from one or more ramps onto the mainline. Freeway ramp-metering control cannot be evaluated without the traffic performance statistics from related arterial surface streets. Therefore, the ramp metering strategy should be extended towards the direction of corridor control.

In case of control objectives for freeway traffic, we use the minimization of the total time spent by all drivers on freeway systems, which includes total travel time and total waiting time at on-ramps. Generally, when the problem of ramp metering is formulated, it is necessary to reflect the constraints related with capacity, such as freeway capacity constraint, ramp queuing constraint. But, if there is congestion on corridor, we can not ascertain whether or not these constraints should be considered.

In this paper, we suggest that control objective function is minimization of the total time, which sum total waiting time and total travel time after merging at on ramp. In case of the constraint, control variable and input variable constraint is requisite and mainline capacity constraint is optional.

$$Min\ Z_{time} = \sum_{a \in L^{ramp}} \left[u_a(CP) \times T_a(g_a) + u_{a-}(g_a) \times T_{a-}(g_a) \right] \tag{12}$$

$$\begin{aligned} s.t.\ & g_a^{\min} \le g_a \le 1 \\ & u_{a-}(CP) = v_b(CP) + Min[x_a(CP), S_a(CP)] \times g_a \\ & u_{a-}(CP) \le Q_{a-}(CP) \quad (optional) \end{aligned} \tag{13}$$

Where,

L^{ramp} : Set of links relates to the ramp

u_{a-} : Inflow on mainline link merged with on-ramp a

v_b : Outflow on mainline link not merged with on-ramp a

3.3 Signal Control Strategy

Traffic signals are readily available flexible means of controlling arterial road traffic in a freeway corridor. Subject to constraints, the signal timings can be optimized with respect to any of several objectives established for traffic conditions. The usual criteria of signal control performance are traffic capacity and average delay per vehicle. In under saturated conditions, the goal is to reduce the amount of delay to a minimum and this is accomplished by determining the split appropriate to the traffic demand. In over saturated conditions, the goal is to maximize traffic flow, so priority shifts to splits reflecting the nature and length of congestion on incoming routes.

The approach delay minimization strategy and the queue formation minimization strategy are considered respectively in this paper. The queue formation minimization strategy can efficiently decrease the additional travel time resulted from spillback.

$$Min\ Z_{delay} = \sum_{a \in I^m} u_a(CP) \times T_a^2(g_a) \tag{14}$$

$$Min\ Z_{queue} = \sum_{a \in I^m} u_a(CP) \times \frac{x_a(g_a) \times l_v}{n_a^2 \times l_a^2} \tag{15}$$

$$\begin{aligned} s.t.\ \ & g_a = \sum_{\phi \in \Phi^m} g_\phi^m \times \delta_{\phi,a}^m \\ & \sum_{\phi \in \Phi^m} g_\phi^m = 1 \\ & g_\phi^{m,\min} \le g_\phi^m \le g_\phi^{m,\max} \end{aligned} \tag{16}$$

4. ALGORITHMS

4.1 Organization of Dynamic Traffic Management Algorithm

The organization of the presented dynamic traffic management algorithm mainly consist of dynamic traffic assignment algorithm and dynamic traffic control algorithm(see figure 1).

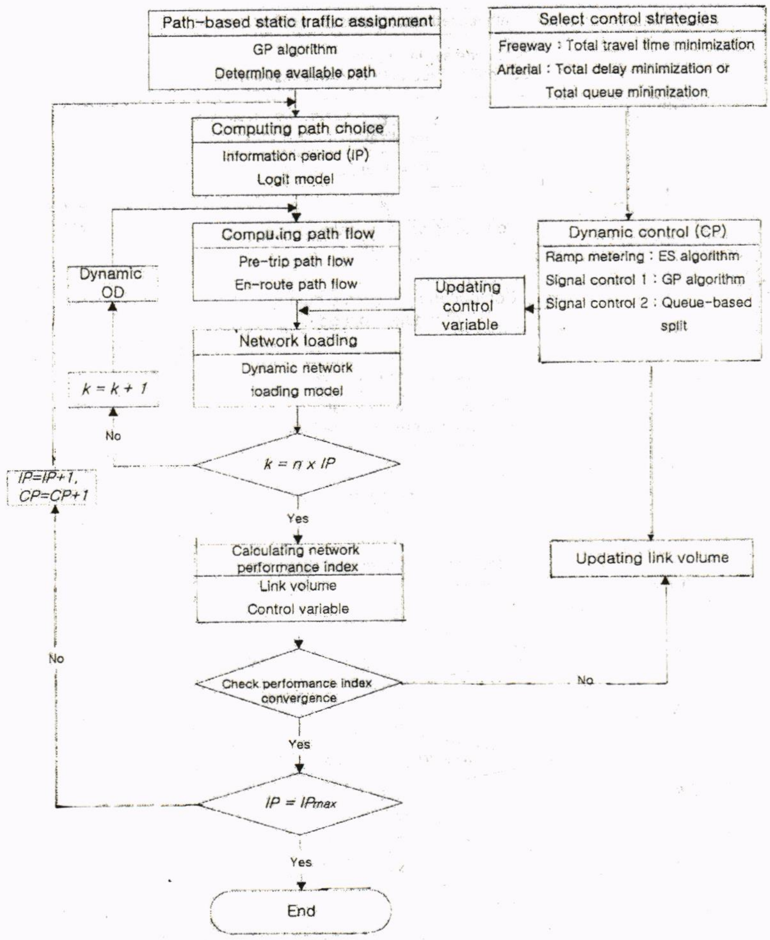

Figure 1. Organization of Dynamic Traffic Management Algorithm

4.2 Dynamic Traffic Assignment Algorithm

As shown figure 2, dynamic traffic assignment determines available path and compute fixed path choice probability at initial step. And then, computing path flow algorithm and dynamic network loading algorithm are repeatedly performed through 2step ~ 4step.

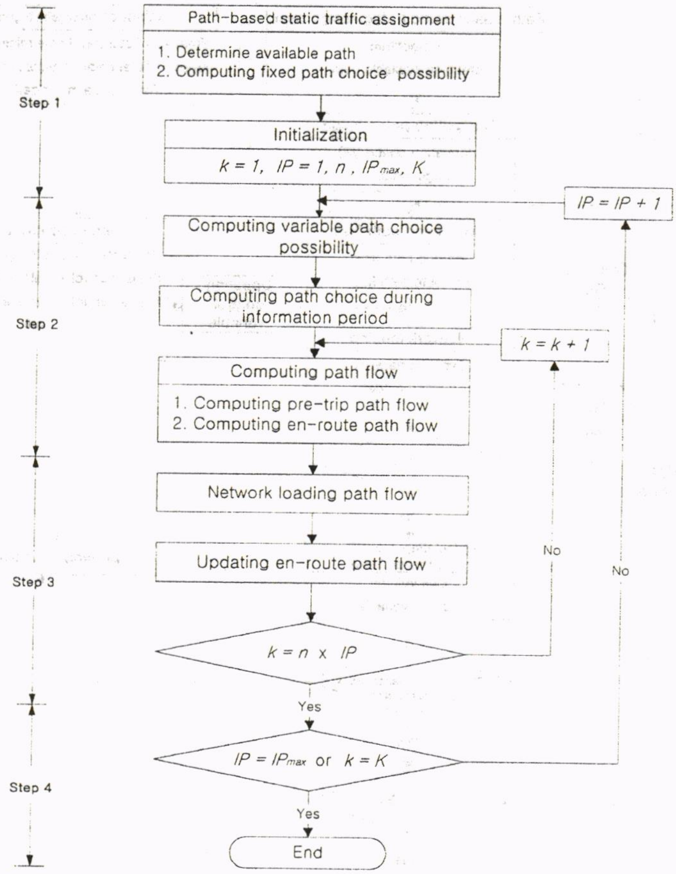

Figure 2. Flowchart of Dynamic Traffic Assignment

4.3 Dynamic Traffic Control Algorithm

As shown figure 3, given the path flow, dynamic feedback control is performed through optimization for each control strategy and dynamic network loading.

Optimizing for ramp metering on freeway is implemented ES (Evolution Strategy) algorithm a kind of random searching technique.

In case of signal control based on delay, equalizing marginal phase delay optimizes delay minimization problem. But signal control problem based on queue length has difficulty in directly grasping the analytic relation between green split and queue. Thus we split based on the phase queue intensity in this paper.

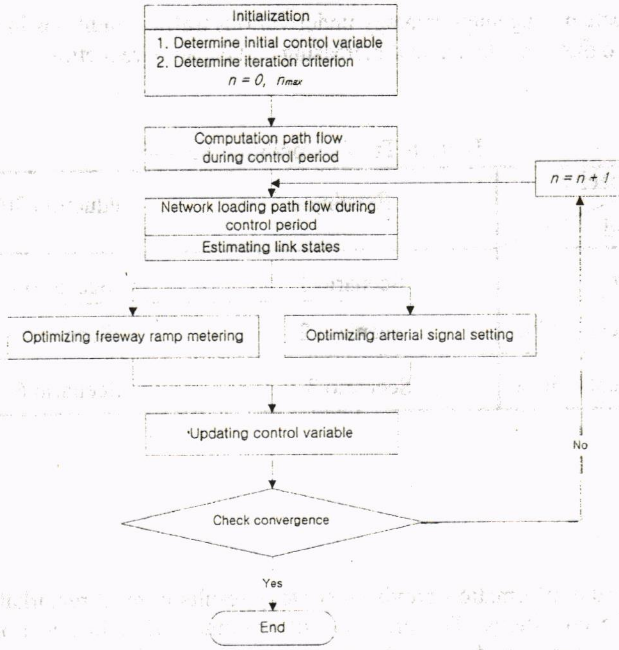

Figure 3. Flowchart of Dynamic Traffic Control

5. EXPERIMENTS AND RESULTS

5.1Experimental Design

We design a pilot freeway corridor network that consist of one freeway plus two viable and essentially parallel alternative routes. The distance between ramps is designed to be short for the purpose of choosing alternative ramps according to corridor traffic conditions.

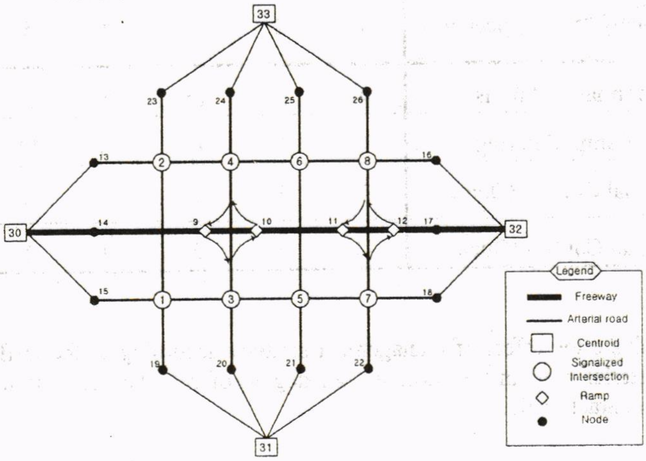

Figure 4. A Pilot Freeway Corridor Network

In order to evaluate management strategy under various traffic conditions in freeway corridor, we make scenario that include demand increasing and capacity reduction.

Table 1. Traffic Condition Scenario

Capacity / Demand	Existing	Reduction 30%
Current	Scenario 1	Scenario 4
Increment 30%	Scenario 2	Scenario 5
Increment 50%	Scenario 3	Scenario 6

5.2 Results

As shown table2, the information provision strategy results in most remarkable improvement of network traffic conditions. The provision of en-route traffic information through VMS showed that there exists significant reduction in network travel time under the non-recurrent congestion resulting from freeway capacity decreasing. The ramp metering also can be evaluated efficient management strategy for improvement of network performance. But the signal control strategy was evaluated less effectively in overall network because allocating the green time is restricted. Signal control based on delay minimization had stable outcome to improve network performance under various traffic conditions. On the other hand, effect of signal control based on queue length was unstable under traffic condition. But as increasing traffic, it made more feasible solution comparison with solution based on delay minimization.

Table 2. Improvement of Link Travel Time (%)

Strategy / Scenario	1	2	3	4	5	6
Information Provision	4	11	15	19	23	24
Ramp Metering	0	1	6	11	13	14
Signal Control (Delay)	3	3	2	2	2	2
Signal Control (Queue)	-3	1	2	0	2	3

In order to evaluate the effect of management strategy according to the traffic condition on freeway and arterial road in corridor, we set degree of relative congestion on freeway as corridor traffic characteristic.

$$\text{degree of relative congestion on freeway} = \frac{(\rho_{\text{freeway}})^2}{\rho_{\text{freeway}} + \rho_{\text{arterial}}} \tag{17}$$

Each $\rho_{freeway}$, $\rho_{arterial}$ means degree of saturation on freeway, arterial road.

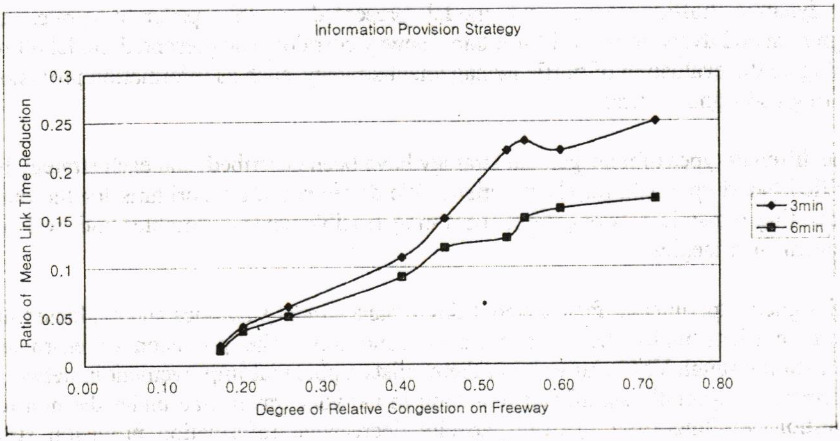

Figure 5. Results of Information Provision Strategy Experiment

With a shorter information provision interval, the provision of en-route traffic information through VMS showed that there exists more potential improvement in network traffic performance, especially significant improvement of network performance under the non-recurrent congestion on freeway.

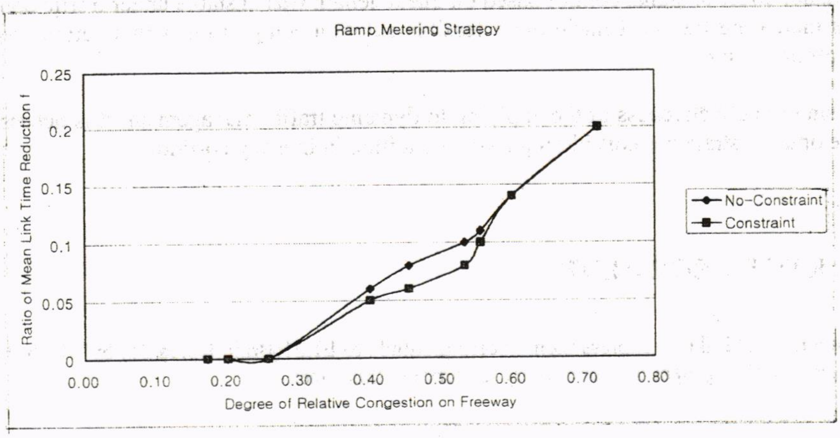

Figure 6. Results of Information Ramp Metering Strategy Experiment

The effect of ramp metering strategy depends on relatively corridor traffic condition. Not considering mainline capacity constraint in ramp metering, it is more efficiently to improve the network performance comparison with reflecting capacity constraint.

6. CONCLUSION

The dynamic traffic management model presented in this paper integrates dynamic assignment and dynamic control for urban freeway corridor. The presented model allows us to investigate the evaluation of traffic management strategy, such as information provision, ramp metering and signal control.

Three different types of management strategy have been described, and each strategy has been specified based upon control characteristic. We developed the algorithms for the purpose of representing dynamic network states, obtaining feasible control variables and evaluating the management strategies.

We designed experimental factors about three management strategies and evaluated in a pilot freeway corridor under the various traffic conditions. The provision of en-route traffic information through VMS showed that there exists a potential improvement in network traffic performance, especially significant reduction in network travel time under the non-recurrent congestion resulting from freeway capacity decreasing. Information provision strategy is more efficient improving network performance than any other strategy, especially shorter information provision interval. The effect of ramp metering strategy depends on relatively corridor traffic condition. Not considering mainline capacity constraint in ramp metering, it is more efficiently to improve the network performance comparison with reflecting capacity constraint.
Applying the signal control strategy were evaluated less effectively in overall network because allocating the green time is restricted. Signal control based on delay minimization had stable outcome to improve network performance under various traffic conditions. On the other hand, effect of signal control based on queue length was unstable under traffic condition. But as increasing traffic, it made more feasible solution comparison with solution based on delay minimization.

Increasing the effectiveness of the applying to dynamic traffic management, it is necessary to choose optimal strategies considering traffic condition in freeway corridor.

7. ACKNOWLEGEMENT

The authors would like to express their sincere gratitude to BK21(Brain Korea 21) by which they are supported, for giving them the opportunity to carry out this paper.

REFERENCE

Back, T., Rudolph, G. and Schwefel, H. P. (1993) Evolutionary programming and evolution strategies - similarities and differences. **Proceeding of the 2nd Annual Conference on Evolutionary Programming**

Chang, G. L., Ho, P. K. and Wei, C. H. (1993) A dynamic system optimum control model for commuting traffic corridors, **Transportation Research 1C**, pp. 3-22

Chang, G. L., Wu, J. and Lieu, H. (1994) Real time incident-responsive system corridor control: Modeling framework and preliminary results, **Transportation Research Record 1452**, pp. 42-51

Chang, G. L., Wu, J. and Cohen, S. L. (1994) Integrated real time ramp metering control for non-recurrent congestion: modeling and strategy development. **Proceedings of IVHS America Annual Meeting,1994**. pp.867-877

Chen, O. J. (1998) Integration of dynamic traffic control and assignment. Ph. D. thesis, University of MIT

He, Y. (1997) A flow-based approach to the dynamic assignment problem : Formulations, algorithms, and computer implementations. MST thesis, MIT.

Jayakrishman, R., Tsai, W. K., Prashker, J. N. and Rajadhyaksha, S. (1994) Faster path-based algorithm for traffic assignment. **Transportation Research Record 1443**, pp. 75-83

Lee, C. (1998) Combined traffic signal control and traffic assignment : Algorithms, implementation and numerical results. Ph.D. thesis. The University of Texas at Austin

Papageorgiou, M .(1995) An integrated control approach for traffic corridors, Transportation Research 3C, 19-30

Ran, B. and Boyce, D. E. (1994) Dynamic urban transportation network models: Theory and Implication for Intelligent Vehicle-Highway System, Lecture Notes in Economics and Mathematical Systems, Springer Verlag

Schwefel, H. P. and Rudolph, G. (1996) Contemporary evolution strategies. **Evolutionary Programming.**

Yang, H. and Yagar, S. (1995) Traffic assignment and traffic control in saturated road networks. **Transportation Research 29A**, pp. 125-139