MEASURING EFFECT OF INTELLIGENT TRANSPORTING SYSTEMS USING NN-CA TRAFFIC SIMULATOR

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Abstract: Usually what traffic safety information refers to gradient or accident points, where advanced car navigation systems, nowadays, provide real-time presentation of this kind of information. This study's aim is to find out what kinds of traffic safety information are needed by users. In this report, 'point information' is defined to represent traditional traffic signs situated on the road and 'linear information' is defined to represent continuous information regarding the course of the road. Upon seizing how movements of vehicle change according to the quality and the quantity of the 'linear information', the study aims mainly to estimate the value of 'linear information'.

Key Words: ITS, Traffic Safety Improvement, Neural Cellar Automata

1. INTRODUCTION

While development of hardware is progressing for research on evaluation of information using ITS, there are several problems concerning its practical use. The largest problem is, as the relationship between information and people's travel behavior is still unclear, determining how much and what kind of information should be provided to drivers. This is a problem because excess information may lead to reduce driving speeds and lower reliability of information, with the net result of deterioration in the traffic environment. Regarding information provision methods, FHWA in the U.S.A. has already begun research on a traffic safety system to provide sectional traffic information. This is called the Interactive Highway Safety Design Model (IHSDM) and indicates points of frequent traffic accidents and other data on a GIS for drivers. Its effectiveness has already been investigated through social experiments.

Regarding research on ITS, regional ITS is a field in which Japan is falling behind other countries. "Region" is one of the elements of regional ITS in addition to "drivers", "roads" and "vehicles" that constitute ITS in general. There are two types of information depending on its providers - running environment factors (alignment of road, traveled surface condition, road congestion condition, etc.) provided mainly by road administrators and information prepared and provided by regional authorities (e.g., regional analysis and compilation of road information using interactive vehicle information as a platform).

The purpose of this study was to develop a simulator to understand how drivers would evaluate information on alignment of road, traveled surface condition, road congestion condition and other aspects by providing it as linear information. More specifically, its aim was to consider development of a traffic simulator as a platform of interactive vehicle information to understand the effectiveness of linear information, as well as regional management and the provision of information in a transition period between the present and the time when interactive vehicle information (effects of an ITS network cannot be expected unless equipment is in common use to a certain degree) will be realized. In the study, linear information using a Neural Network-Cellular Automata (NN-CA) simulator was prepared from the results of a social experiment conducted at Nakayama Pass, Hokkaido, in 1999. Effectiveness of the linear information was evaluated by conducting a social experiment (Fig. 1).

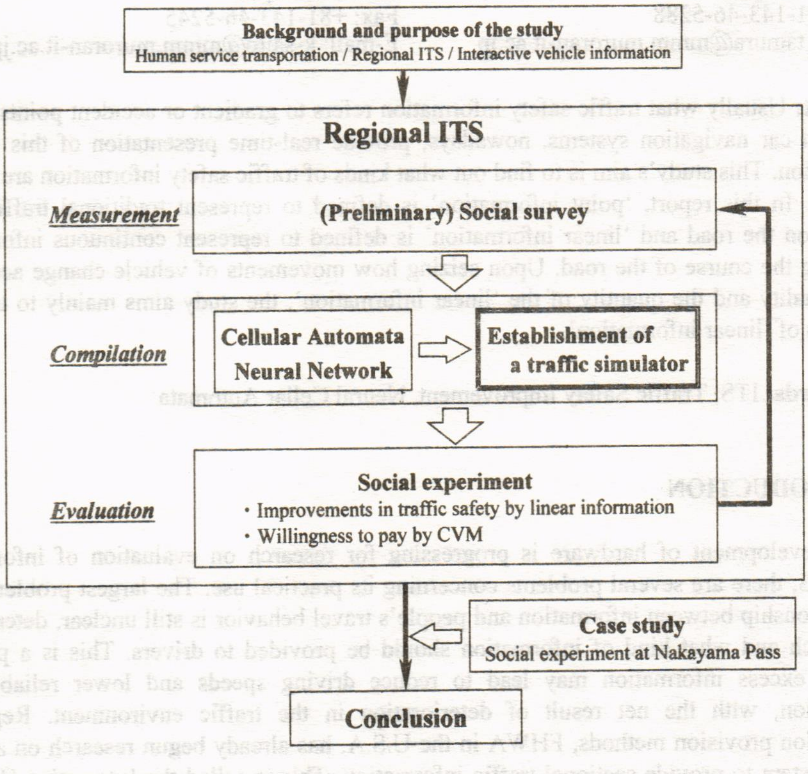

Figure 1. Study process

2. INTERACTIVE VIHCLE INFORMATION

In current traffic networks, real-time information can be provided using sensors or cameras on the road. However, it is only for sections equipped with sensors or cameras and spatial restrictions have not been eliminated. There is also a managerial problem because the amount of information is enormous, even if it is available. Information exchange by equipment loaded on each vehicle (hereinafter referred to as interactive vehicle information) was therefore considered as a method for expanding the space in which information would be managed from collection to distribution. It is a system to enable the establishment of dynamic local road information networks by repeating exchanges of observation information among devices loaded on vehicles that happen to pass by the area.

Due to the simple network structure, easiness of management and other factors, interactive vehicle information was considered effective as a platform for regional ITS. In a study of Kobayashi, it is mentioned that "a dense and complex network with diverse modes is necessary to satisfy the complex demand of people (regional ITS) in a knowledge society." There are, however, many pending problems, such as the fact that effects of an ITS network cannot be expected unless car-loaded equipment is in wide use to a certain extent.

3. RESIONAL ITS

A road information system using regional ITS may be designed in three phases - (1) measurement, (2) compilation and (3) evaluation of road information. It is considered that more advanced ITS can be completed in cycles by repeating these phases (Fig. 1).

(1) Measurement of road information

Conventional road information consists of data obtained from road design, road traffic census and original survey data of traffic accidents. When technologies are developed in the future concerning acquisition of positional information on moving traffic, vehicles themselves may be able to serve as observation devices to measure detailed road information by establishing interactive vehicle information.

(2) Compilation of information

The measured road information will be compiled (analyzed) into information service that can be provided. In the past, information was provided as in the form of point information with signs placed at dangerous sections by road administrators. With the development of information technology in recent years, however, it has become possible to provide linear information such as alignment of road (Fig. 2), two-dimensional information with spatial expansion, as well as multidimensional information (e.g., GIS). When using such information in the form of regional ITS, however, it is necessary to (1) apply flexible technical skills to keep up with the progress of technologies so as to fully understand the problems concerning information service and improve service on a continuous basis and (2) give sufficient consideration to users, especially drivers who are constantly at the risk of road traffic accidents.

In this study, therefore, information was compiled using an NN-CA traffic simulator using a cellular automata traffic simulator established in the study of Sasaki et al. and a neural network model (NN model) as its internal rule. The NN-CA simulator was thought to be effective for compilation of regional ITS because (1) it is a simple model that can be continuously updated, (2) information can be generalized by eliminating noises (e.g., speed maniacs) using the NN model and (3) the local rule by NN can be spatially expanded using CA.

(3) Evaluation of information

The compiled information was evaluated. It was assumed that the market would socially evaluate information provided. In other words, information concerning the cost of special equipment for obtaining information and the method of obtaining information by paying would be exchanged through the market. In this case, price and demand would be high for information required or considered useful by people. In this study, therefore, the above NN-CA model was evaluated by the CVM (contingent valuation method).

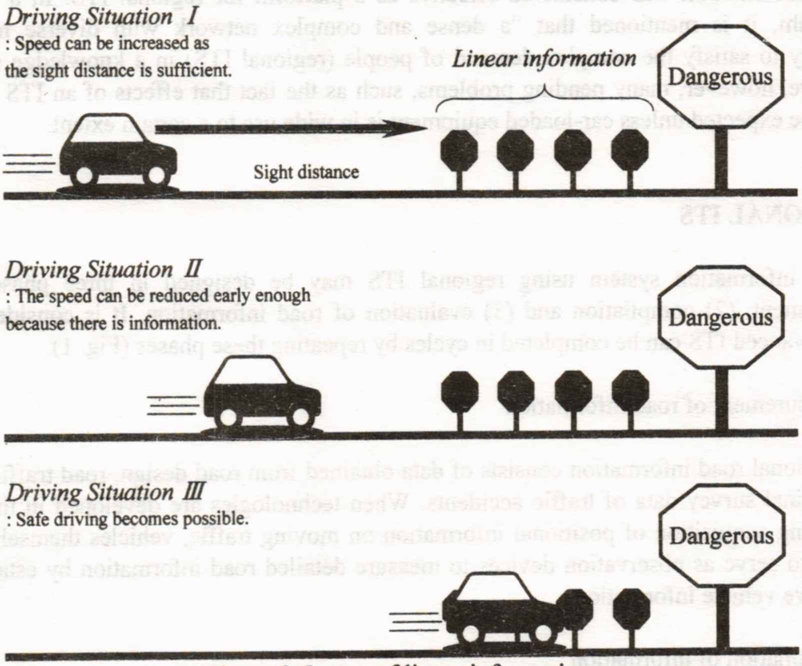

Figure 2. Image of linear information

4. TRAFFIC SIMULATOR USING CA

4.1 Positioning of this simulator

Cellular automata (CA) were developed by Ulam in the 1940s. A CA system consists of three elements –cells, environment, and rules. Cells are the smallest units which must manifest some adjacency or proximity. The environment of cell can change according to transition rules. The advantages of CA are that the future trajectory of traffic behavior can be shown virtually during the simulation processes.

The traffic simulator was first classified into three types and their respective characteristics were listed (Figure 3 shows the three concepts that will be explained below).

1 With the conventional type of simulator, the behavior of vehicle A is determined by the traffic stream of the previous period, influenced by vehicles B and C in front of it.

$$A_{t+1} = f(A_t, B_t, C_t, \cdots) \tag{1}$$

In this case, vehicles A, B and C have a common local rule. It is a behavior to maintain a certain vehicular gap to avoid a collision with the vehicle in front. If the driver of the vehicle in front (B_t) applies the brakes, the driver of the vehicle behind it (A_{t+1}) does the same. The traffic stream represented is using this concept.

2 Although the study of Fujii et al., which is an advanced study of complex systems, aimed to address the route selection of individual drivers, it can be positioned, if expressed by the concept of CA, as a means to experience and learn the recognitive time distance (t_{ij}) from driving patterns on the previous day, under a daily time interval basis, to change the internal rule as well as to shift to the next time zone.

$$A_{t+1} = f(A_t, t_{ij}) \tag{2}$$

3 CA proposed in this study is the analysis of changing behavior with the changes in the surrounding environment on assumption that the internal rule is uniform (common to all drivers). The surrounding environment refers to information on the existence of a vehicle in front ($B_t, C_t, \cdots$), alignment of the road, point of frequent traffic accidents and other items.

$$A_{t+1} = f(A_t, B_t, C_t, \cdots, I) \tag{3}$$

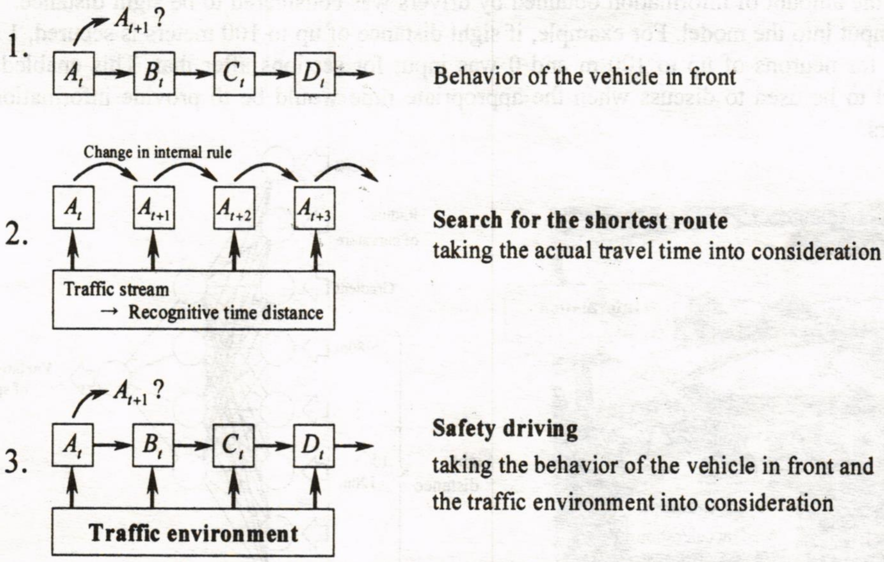

Figure 3. Conceptual drawing of a traffic simulator

4.2 Method of inputting traffic information

Traffic information presented here is characterized by the fact that it is linear information concerning the running section. By providing this information to the driver in advance, changes in the vehicle's running speed was analyzed. Interesting points regarding this method of providing information are (1) how people recognize continuous information and react to it and (2) consideration of ways to provide continuous sectional information. The proposed traffic simulator will be established to analyze these two points. More specifically, an attempt will be made to construct a model to reproduce the traffic stream conditions in different road traffic environments by dividing each road traffic environment into the "existence of vehicles in front (traffic flow volume)" and the "method of providing traffic information (including the existence of such information)." Although this idea has already been presented by FHWA, the implementation of modeling is unique to this study.

5. CASE STUDY (SOCIAL EXPERIMENT AT NAKAYAMA PASS)

5.1 Preliminary social survey

Based on the measurement data obtained in the study of Iimura et al. conducted at Nakayama Pass in 1999, two samples with or without information under the same running conditions were used.

5.2 Construction of a traffic simulator

Using the above two types of data, an NN-CA simulator was prepared. As shown in Fig. 4, explanatory variables of the NN model were the speed, road factors and sight distance with the target variable as the variation of speed.

Here the amount of information obtained by drivers was considered to be sight distance. This was input into the model. For example, if sight distance of up to 100 meters is secured, 1 was input for neurons of up to 100 m and 0 was input for sections after that. This enabled the model to be used to discuss when the appropriate time would be to provide information to drivers.

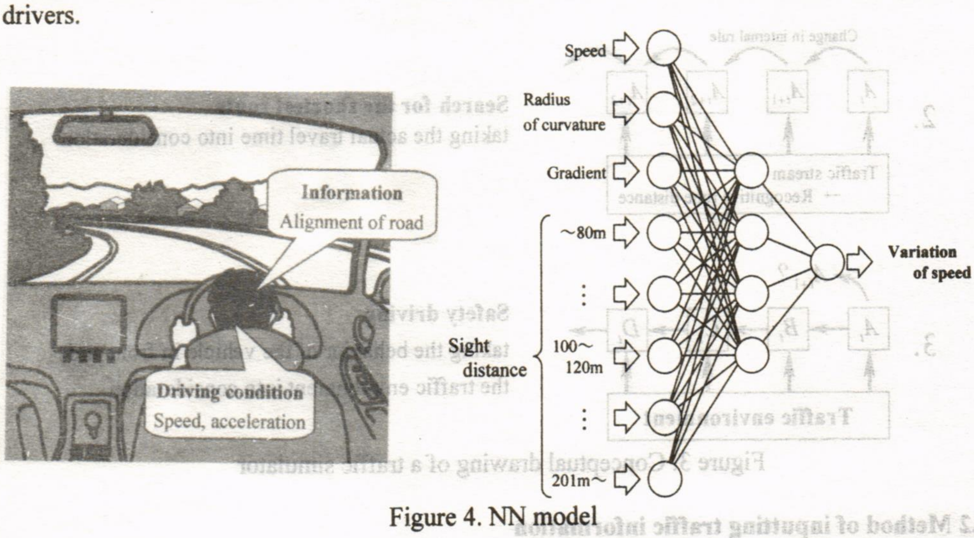

Figure 4. NN model

As shown in Fig. 5, the structure of the CA traffic simulator is such that the speed (position) at time $t+1$, which was determined by the running environment factors, reciprocal factors among vehicles and ITS and other information technology factors at time t, is mapped in a space and re-mapped in the relationship among drivers. In other words, it means that the above NN model is running on the CA that includes the road environment. This was a concept to represent the effectiveness of linear information. Figure 6 shows the results of an NN-CA simulator using this. Also, a video monitor to plot the hourly NN-CA simulation results on a map was produced and used for provision of linear information.

Although the results of the actual running and the simulator were consistent in the case with information, divergence was observed in the case without information, as shown in Figs. 5 and 6. This was thought to be caused by the reproduction of information by the NN model on the supposition that drivers already had information on the entire section (12-km) in the results with the simulator. In other words, actual drivers are driving using information on limited parts. The other reason is that they are driving only with information on sight distance of 100 meters or less when receiving information.

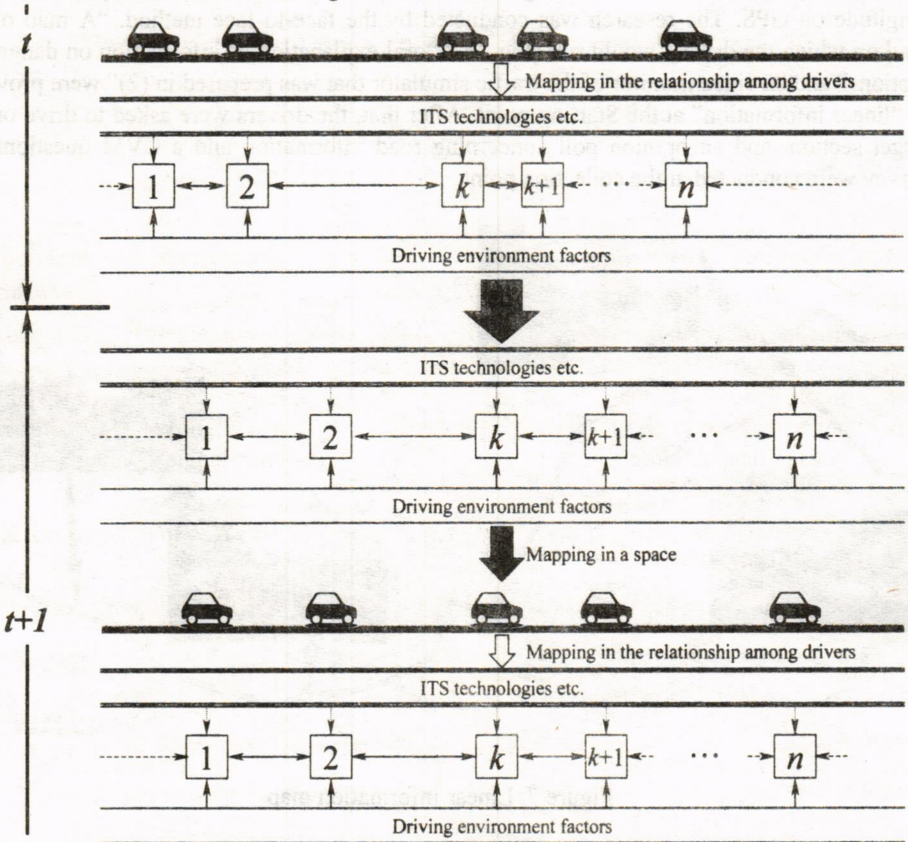

Figure 5. Conceptual drawing of CA traffic simulator

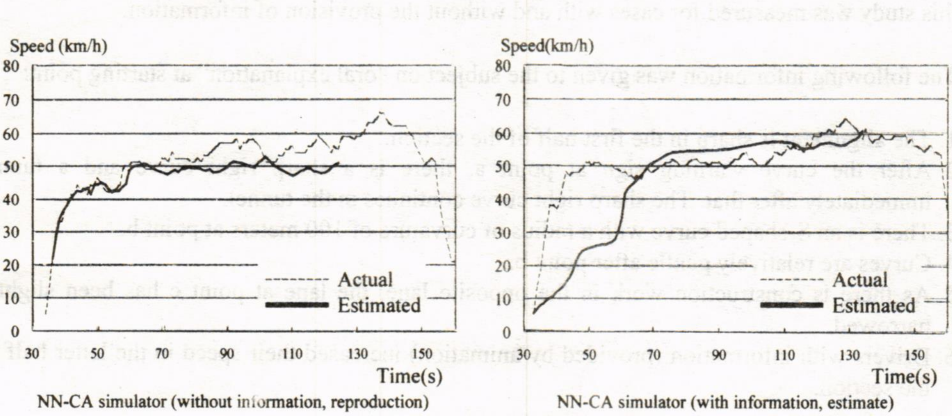

Figure 6. Results of NN-CA simulation

5.3 Social experiment

The social experiment was conducted from October 30 to November 2, 2000. The research site was a section of National Route 230, approximately 12-km long, starting from the Michinoeki at the summit of Nakayama Pass toward Kimobetsu Town. The subjects of the research were ordinary drivers who visited the Michinoeki. A Safety Recorder was automatically used to measure driving behavior; velocity, accelerated velocity and latitude-longitude on GPS. The research was conducted by the face-to-face method. "A map of the road on which the drivers would run (Fig. 7)," "oral explanation of information on dangerous sections" and "a video monitor of the traffic simulator that was prepared in (2)" were provided as "linear information" at the Starting point. After that, the drivers were asked to drive on the target section, and an opinion poll concerning road information and a CVM questionnaire survey were conducted at the collection point.

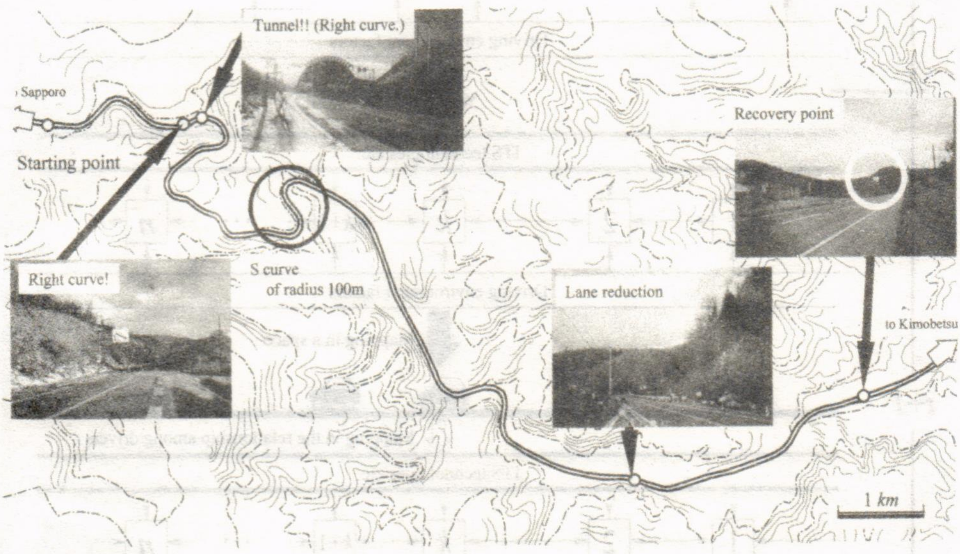

Figure 7. Linear information map

To measure the effect of "linear information" on drivers, driving behavior of the subjects of this study was measured for cases with and without the provision of information.

The following information was given to the subject on "oral explanation" at starting point:

1. The alignment is sharp in the first half of the section.
2. After the curve warning sign at point a, there is a sharp right curve and a tunnel immediately after that. The sharp right curve continues in the tunnel.
3. There is an S-shaped curve with a radius of curvature of 100 meters at point b.
4. Curves are relatively gentle after point b.
5. As there is construction work in the opposite lane, the lane at point c has been slightly narrowed.
6. Drivers with information (provided by animation) increased their speed in the latter half of the section.

5.4 Research results

Data collected from 52 subjects in three days were totaled for each question. Fig. 8-1 shows age of driver, and Fig. 8-2 shows years of driving experience. From these figures, we can find out that our survey sampling was conducted randomly. Fig. 8-3 shows number of times the driver has passed Nakayama Pass, 80% of the drivers has passed 4 times or more per week. So, the rate of using car navigation and other systems was relatively low here, no one was having difficulty driving. This was probably because many of the subjects were frequent drivers due to the high dependency on automobiles in Hokkaido and because it is not necessary to use systems that only provide routine information for frequent users of National Route 230. It was thus thought that the amount of information provided was small and navigation systems were not used enough on frequently traveled roads in rural areas.

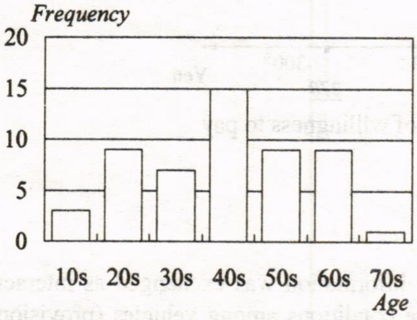

Fig. 8-1 Questionnaire results (Age)

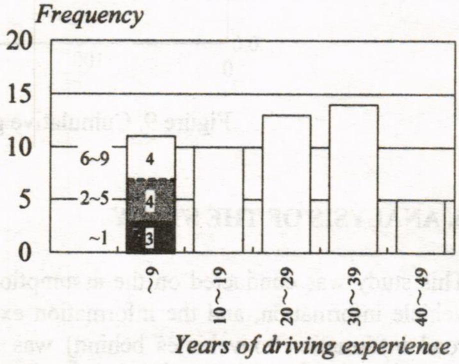

Fig. 8-2 Questionnaire results (Years of driving experience)

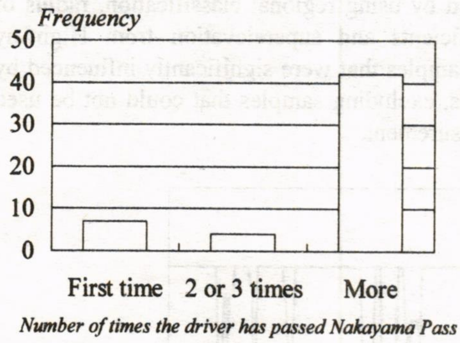

Fig. 8-2 Questionnaire results (Num. of times the driver has passed Nakayama Pass)

5.5 CVM results

The following CVM questionnaire survey was conducted in this study:

"If alignment of road, dangerous points and other real-time traffic information becomes available in the future by car navigation or other systems as in this experiment, would you like to use such an information service?
What is the maximum charge you would be willing to pay for such an information service? (Ref: information service for portable terminals is ¥100 to 200 a month.)"

As a result, the willingness to pay was estimated to be as shown in Fig. 9 by cumulative total. Fifty percent showed a willingness to pay ¥270, which was larger than the reference amount.

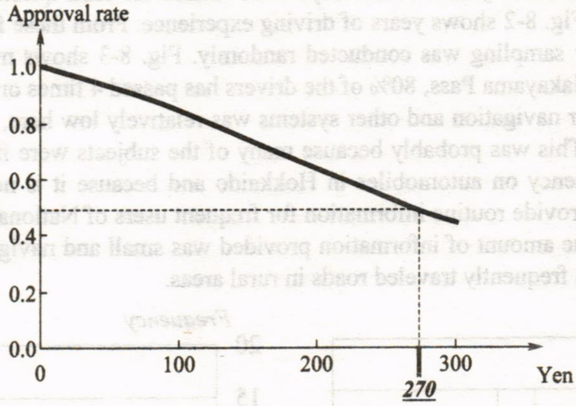

Figure 9. Cumulative graph of willingness to pay

6. ANALYSIS OF THE STUDY

This study was conducted on the assumption that information was exchanged as interactive vehicle information, and the information exchange conditions among vehicles (provision of road information to vehicles behind) was simulated as a provision of linear information. Changes in driving behavior with the provision of information were therefore clarified by comparative analysis with driving behavior of vehicles without information using an NN model. The ideal speed (Fig. 10) was determined by using regional classification, radius of curvature, sight distance, cornering slip coefficients and superelevation from Highway Capacity Manual in JAPAN to randomly select samples that were significantly influenced by the existence of information from the 52 samples, excluding samples that could not be used due to their running after state or mistakes in measurement.

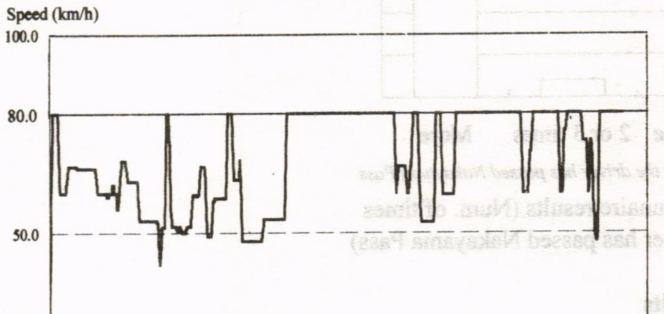

Figure 10. Ideal speed

With information *Without information*

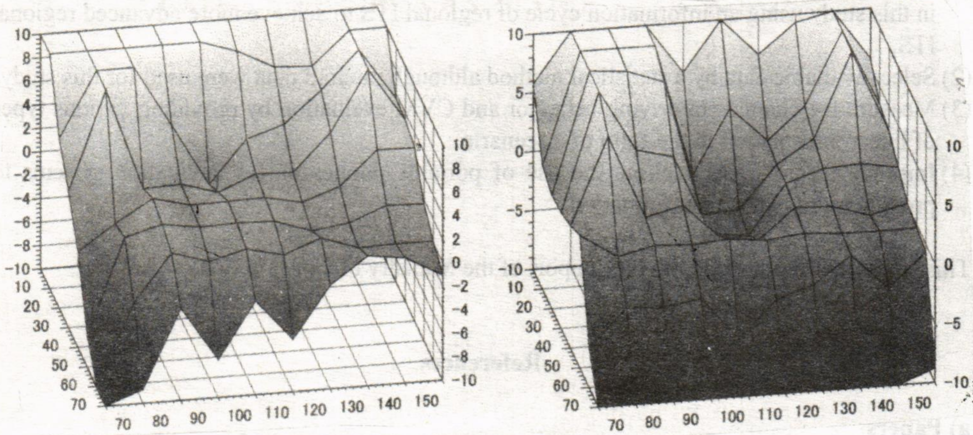

Figure 11. Difference in acceleration by sight distance and speed
Horizontal axis: sight distance (m), Vertical axis: speed change (km/h), Depth axis: speed (km/h), Top: with information, Bottom: without information

The graphs of Fig. 11 show the results of implementing NN using representative examples with or without provision of information based on the ideal speed. On the graph with information, a gentle downward line can be seen from the condition with high speed and long sight distance to the lower and shorter condition. It was presumed that the subjects could secure a certain amount of information regardless of sight distance at a certain driving condition and showed appropriate reaction to alignment changes at the time because the alignment on the route had been given to them. On the graph of drivers without information, however, the line is sinking in the middle even though the subjects were driving every day and had passed Nakayama Pass many times. They probably did not increase their speed as they were worried about changes in sight distance and losing visibility at some parts due to the lack of accurate information on route alignment and the inability of securing a certain amount of information necessary for safe driving. This was considered to have occurred when the sight distance was 100 to 120 (m) and the speed was 30 to 50 (km/h) at Nakayama Pass.

7. CONCLUSION

The following three results were attained in this study:

(1) The concept of interactive vehicle information was established as an ITS platform.
(2) The method of providing interactive vehicle information in ITS was examined.
(3) Based on the data obtained by social experiment, a driving simulator taking into account interactive vehicle information was developed.

In the social experiment, it was proved that application of linear information by NN-CA on markets of portable terminals and other information services was possible. It was also indicated in comparative analysis of the test results that provision of information caused great changes in driving behavior.

There are following four future challenges:

(1) Continue information provision experiments based on the results of the social experiment in this study using an information cycle of regional ITS to achieve more advanced regional ITS.
(2) Select available data by a statistical method although random data were used for this study.
(3) Measure the changes in driving behavior and CVM evaluation by providing various types of linear information in the form of a scenario.
(4) Improve technologies such as the use of portable phones or car navigation systems to provide more real-time information.

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OPTIMAL RAMP METERING STRATEGY WITH DYNAMIC ROUTE CHOICE BEHAVIOR

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Abstract: To efficiently control the ramp metering rates entering expressway, a combined optimal ramp metering method with dynamic traffic assignment model is introduced. Optimal ramp metering method is derived from optimal control theory. In the paper a linear quadratic regulator(LQR) is developed for optimal metering. With regard to route choice behavior we assume that drivers follow Wardrop's principle(1952) well adopted in equilibrium assignment model. This implies that they try to only minimize their travel cost and choose their routes according to this criterion with considering ramp metering strategy. The model is formulated as bi-level approach: the upper level try to optimize ramp control, the lower level minimize travel cost. Its solution algorithm is also presented. With a contrived network, the model is tested.

Key words: Optimal ramp metering, Dynamic traffic assignment, LQ regulator, Bi-level problem

1. INTRODUCTION

This paper presents a new combined optimal ramp control method with dynamic traffic assignment model in road network, which consists of freeway and arterial. Ramp metering has been recognized as an effective tool of reducing freeway congestion, in particular during peak commuting hours or incidents. Ramp metering is very effective if the traffic volume on the mainline freeway at the section immediately upstream of the ramp is less than the capacity. Under such condition, metering can be used not to create a bottleneck and to divert the traffic to adjacent surface streets.

Existing models developed to date have determined the metering rate based mainly on the traffic condition of freeway. The methods have been derived from traffic flow theory in traffic engineering and focused on corridor control, not in road network dimension, thus they have limits to take into account the route choice behavior of the users. This implies that drivers may divert their routes to alternatives when traffic congestion occurs in freeway. In practice to efficiently control the freeway traffics entering from ramps, it is necessary to consider the drivers' route choice behavior. Regarding this respect, however, there have been not enough studies yet. The reasons come from the fact that if we include the drivers' behaviors within the freeway ramp metering model, mathematical formulation is to be very complicated. Such complexity may lead the formulation to nonlinear and nonconvex mathematical programming, thus it is necessarily difficult to solve and its solution algorithm has not fully developed yet. If we consider real-time traffic situation, it make us more difficulty in attaining a solution.

In this paper, a combined optimal ramp metering method with dynamic traffic assignment model is introduced. Optimal ramp metering method is derived from optimal control theory widely used in mechanical engineering for automatic control. In the paper a linear quadratic regulator(LQR) is developed for optimal metering. With regard to route choice behavior we assume that drivers follow Wardrop's principle(1952) well adopted in equilibrium assignment model. This implies that they try to only minimize their travel cost and choose their routes according to this criterion. The model is formulated as bi-level approach: the upper level try to optimize ramp control, the lower level minimize travel cost. Its solution algorithm is also presented. With a contrived network, the model is tested.

2. EXISTING STUDIES

2.1 Responsive ramp metering strategies

Ramp metering has proven to be the most widely used form of freeway traffic control. Freeway ramp metering control is also known to be useful for congestion prevention. With the ramp metering control, traffic operator may manage a freeway section at the optimal state. Ramp metering regulates the number of vehicles entering the freeway, so that traffic demand does not exceed capacity. Some traffic desiring access to the freeway mainline will wait on the ramps before receiving a signal to enter. Instead of waiting, some vehicles may choose alternative routes or other ramps to enter. Thus ramp metering tends to maintain uninterrupted, non-congested flow on the freeway.

The determination of metering rates depends on the metering strategies. If the purpose of ramp metering is intended to minimize congestion, demand must be kept below capacity. In many cases, ramp metering provides a smoother ramp merging operation for safety. Collisions are caused by platoons of vehicles on the ramp competing for gaps in the freeway traffic stream, thus metering breaks up the platoons and facilitates single-vehicle entry. The main stream of ramp metering strategies is to minimize total travel. time of freeway and ramp section. This leads to maximize metering rates without interrupting mainline traffics.

However, these existing metering controls have been focused only on freeway. The methods does not consider alternative roads, thus have a limit of analyzing route-changing behaviors. The first research on the ramp metering is that of Wattleworth(1965) who proposed a linear model for ramp control in the freeway. The method was formulated to maximize ramp rates under the circumstances of below capacity of mainline. Texas A&M model(Messer,et.al, 1969) added a ramp capacity constraint to Wattleworth model. Later May(1973) suggested a constraint for describing traffic transition to alternative road, but it could not fully depict it. In additions, Yuan et al. (1971), Chen et al.(1974) developed linear metering models.

On the other hand, some combined methods with traffic assignment model have been developed. Iida et al. (1989) and Yang et al. (1994) proposed the models to optimize some objective functions with constraint of user equilibrium condition proposed by Wardrop(1952). They try to minimize total travel time or to maximize ramp metering rates with considering route choice of drivers simultaneously. Although they include route choice behaviors of drivers, these methods, however, also have a limit of describing real world because of static traffic assignments adopted in the model.

2.2 Dynamic equilibrium traffic assignment models

Traditional static network equilibrium models were developed for long range transportation planning. They are not suitable for analyzing and evaluating dynamic route choice, which need the capacity to solve transportation problems in real time. Since late 1970th, several approaches have been developed for formulating dynamic route choice behaviors. These approaches are classified into two categories; flow-based models and vehicle-based models. Flow-based models are based on traffic flow theory, thus flow-based models are more applicable for large-scaled transportation networks. Vehicle-based models are derived from micro-simulation model, therefore they can describe more details of vehicle movements.
Urban traffic assignment models are usually associated with network equilibrium concepts. Most static user equilibrium(UE) models are formulated to be consistent with the Wardrop's principle(Wardrop, 1952). This principle is that for a given origin-destination pair, all used route costs are equal and at least less than those of unused routes. This user equilibrium has been employed as the key behavioral assumption in most static transportation network models. In dynamic transportation networks, the static assumption needs revision to consider short-term variations of traffic. Expanded user equilibrium condition for dynamic case is that for an origin-destination pair and for each departure time slice, all used route costs are equal and at least less those that of unused routes. This condition can be written in mathematical equations as follows.

dynamic user equilibrium conditions

$$\begin{aligned} &If\ C_p^{rs}(t) = C^{rs}(t)\ ,then\ f_p^{rs}(t) > 0 \\ &If\ C_p^{rs}(t) \geq C^{rs}(t)\ ,then\ f_p^{rs}(t) = 0 \quad \forall\, r, s, p \end{aligned}$$

Where $C_p^{rs}(t)$ is the cost on route p at time t between origin r and destination s, $C^{rs}(t)$ is minimum cost at time t between origin r and destination s. $f_p^{rs}(t)$ is route flow of p at time t between origin r and destination s.
Based on the dynamic user equilibrium, many dynamic traffic assignments have been developed. The study of dynamic route choice models over a general road network was begun by Merchant and Nemhauser(1978) who formulated a dynamic system-optimal model. Subsequently Carey(1987) reformulated the Merchant and Nemhauser model as a convex nonlinear program which has analytical advantages over the original one. Recently Friesz et al (1989) proposed a dynamic user optimal traffic assignment model by considering the equilibrium of instantaneous route costs. A generalized dynamic user optimal model over a multiple origin-destination network was presented by Wie et al (1990). More recently Ran et al (1996) formulated two new dynamic user optimal models; instantaneous and ideal models with flow propagation constraints. Basic constraints for a dynamic network model were also described in Ran et al. (1996).

3. DEVELOPMENT OF COMBINED RAMP CONTROL MODEL WITH DTA

In this paper Linear Quadratic Regulator(LQR) ramp metering model is developed from optimal control theory widely used in mechanical engineering. LQR has a simple linear relation (via a gain matrix) between measurement from field and on-ramp volumes required in order to achieve a desired traffic state. Since the elements of the gain matrix are constant, the LQR appears particularly simple and easy to implement as compared with other control techniques. It is the scope of this paper to combine the LQR with dynamic traffic assignment model for describing traffic behaviors of drivers. Before explaining the model, we define some principal variables and notations in first.

$x_a(t)$: number of vehicles on link a at time t
$f^{rs}(t)$: departure flow rate from origin r toward destination s at time t
$u_a(t)$: inflow into link a at time t
$v_a(t)$: exit flow from link a at time t
$x_{ap}^{rs}(t)$: number of vehicles on link a and route p between OD pair rs at time t
$v_{ap}^{rs}(t)$: exit flow on link a and route p between OD pair rs at time t
$u_{ap}^{rs}(t)$: inflow on link a and route p between OD pair rs at time t
$e_p^{rs}(t)$: arrival flow at destination s from origin r at time t through path p
$e^{rs}(t)$: arrival flow at destination s from origin r at time t
$E_p^{rs}(t)$: cumulative number of vehicles arriving at destination s from origin r at time t through path p
$\pi^{ri*}(t)$: minimal actual route travel time between origin r and node i at time t
$\tau_a(t)$: actual travel time over link a for flows entering link a at time t
$\overline{\tau_a}(t)$: estimated actual travel time over link a for flows entering link a at time t
$\overline{\pi^{ri*}}(t)$: estimated minimal actual route travel time between origin r and node i at time t

3.1 Linear Quadratic Regulator(LQR)

Since Linear Quadratic Regulator(LQR) was developed by Kalman in 1960th, LQR has been adopted in engineering for optimal control. In order to formulate LQR, we define a state equation as follows.

$$\frac{dx(t)}{dt} = \dot{x}(t) = Ax(t) + Bu(t) \tag{3.1}$$

Where, $x(t)$ is state variable $x(t) = [x_1(t), x_2(t), \ldots, x_n(t)] \in R^n$ and initial state variable $x(0)$ is given. $u(t) = [u_1(t), \ldots, u_m(t)] \in R^n$ is control variable and A, B are constant matrices.
In order to evaluate the performance of a system quantitatively, the system controller needs to select a performance measure or objective function. We assume that the performance of a system can be evaluated by a measure J in LQR.

$$J = \int_0^\infty [x^T(t)Qx(t) + u^T(t)Ru(t)]dt \tag{3.2}$$

Where, Q is positive definite(or, positive semi-definite) matrix and R is positive definite. Control variable that minimize the objective function J can be written as,

$$u(t) = -G\,x(t) \tag{3.3}$$

and the system is stable. Where G is a gain matrix, $G = R^{-1}B^TK$. K is positive semi-definite matrix and if K satisfy CARE(Continuous-time Algebraic Riccati Equation) condition, K has an unique solution in Riccati equation. The CARE condition is found in related books.
To design a LQR problem, we have to determine the values of Q and R matrices. Unfortunately it has not been known to determine Q and R analytically. Thus most studies use heuristic method to attain satisfying results by adjusting the values iteratively.

3.2 Development of combined ramp metering model

In the paper a combined optimal ramp metering method with dynamic traffic assignment model is developed. LQR described in previous section is used for optimal ramp metering method and variational inequality formulation proposed by Ran et al.(1996) is adopted for describing dynamic route choice behaviors. In dynamic user equilibrium state, for each origin-destination pair at each time slice, the actual travel times experienced by travelers departing at the same time are equal and minimal. The developed model in this paper may be formulated as follows.

$$\min\ J = \int_0^{\infty} [\sigma(t) Q \sigma(t) + u(t) R u(t)] \qquad (3.4)$$

Subject to,

$$\int_0^T \sum_{rs}\sum_{a} \Omega_a^{rj*}(t)\ \{u_a^{rs}[t+\pi^{ri*}(t)] - u_a^{rs*}[t+\pi^{ri*}(t)]\}\ dt \geq 0$$

where,

$$\Omega_a^{rj*}(t) = \pi^{ri*}(t) + \tau_a[t+\pi^{ri*}(t)] - \pi^{rj*}(t)$$

Relationship between state and control variable;

$$\frac{dx_{ap}^{rs}}{dt} = u_{ap}^{rs}(t) - v_{ap}^{rs}(t) \qquad \forall a, p, r, s;$$

$$dE_p^{rs}(t) = e_p^{rs}(t) \qquad \forall p, r, s \neq r;$$

Flow conservation constraints;

$$f^{rs} = \sum_{a \in A(r)} \sum_p u_{ap}^{rs}(t) \qquad \forall r, s;$$

$$\sum_{a \in B(j)} v_{ap}^{rs}(t) = \sum_{a \in A(j)} u_{ap}^{rs}(t) \qquad \forall j, p, r, s;\ j \neq r, s;$$

$$\sum_{a \in B(s)} \sum_p v_{ap}^{rs}(t) = e^{rs}(t) \qquad \forall r, s;\ s \neq r;$$

Flow propagation constraints;

$$x_{ap}^{rs}(t) = \sum_{b \in p} \{x_{bp}^{rs}[t+\tau_a(t)] - x_{bp}^{rs}(t)\} + \{E_r^{rs}[t+\tau_a(t)] - E_p^{rs}(t)\}$$

$$\forall a \in B(j);\ j \neq r;\ p, r, s;$$

Definitional constraints;

$$\sum_{rsp} u_{ap}^{rs}(t) = u_a(t) \qquad \forall a;$$

$$\sum_{rsp} v_{ap}^{rs}(t) = v_a(t) \qquad \forall a;$$

$$\sum_{rsp} x_{ap}^{rs}(t) = x_a(t) \qquad \forall a;$$

Nonnegativity constraints;

$$x_{ap}^{rs}(t) \geq 0, \quad u_{ap}^{rs}(t) \geq 0, \quad v_{ap}^{rs}(t) \geq 0, \qquad \forall a, p, r, s;$$

$$e_p^{rs}(t) \geq 0, \quad E_p^{rs}(t) \geq 0 \qquad \forall p, r, s;$$

Boundary conditions;

$$E_p(0) = 0, \qquad \forall p, r, s;$$

$$x_{ap}^{rs} = 0, \qquad \forall a, p, r, s;$$

State equation for optimal control;

$$\frac{d\sigma(t)}{dt} = A\sigma(t) + Bu(t)$$

Where,
$x(t) = x^*(t) + \sigma(t)$,
$x^*(t)$: *Optimal state density(or, desired density)*

Ramp metering rates ;
$q_{in}(t) = q^*(t) + u(t)$, $q^*(t)$: *optimal ramping rates*
where, $\sigma'(t)$, $u'(t)$ are state variation and control variation respectively.

Objective function of equation (3.4) is to be formulated for minimizing the sum of variations of state variable and control variable. The model yields an optimal ramp metering rates when the objective function is minimized within the constraints. In the paper we follow the constraints of Ran et al.(1996). More detailed explanation of the constraints are given in Ran. et al.
This kind of minimization problem has been known to be non-convex, and it is difficult to solve simultaneously. Thus, in general the original problem is split into two subproblems such as upper-level problem and lower-level problem. Where we set ramp metering problem as upper-level problem and dynamic route choice problem as lower-level problem. Then, it is possible to solve such a bi-level problem independently. The upper-level problem can be easily solved on the condition that CARE condition is satisfied. The lower-level problem is also tackled by diagonalized algorithm of Ran et al.(1996). These two subproblems calculate interactively until mutually consistent flows are attained. Where we skip the explanation about the diagonalized algorithm because it is the same of Ran et al.

4. MODEL ASSESSMENT THROUGH AN EXAMPLE NETWORK

4.1 Numerical example analysis

To assess the model, in this paper we use an example network consisting of 1 expressway and arterials as shown in Figure 1. Where we assume the link connecting from node 3 to node 4 as expressway. We also assume that the link connecting from node 2 to node 3 is ramp to enter expressway and the link from node 4 to node 5 is exit ramp out of expressway. Only one origin-destination pair from node 1 to node 6 exists in the example. Six time slices, 300 seconds per time slice, are simulated. Origin-destination traffic demand and network data such as length of link, free flow speed and link capacity are shown in Table 1 and Table 2. The link impedance in the paper is a linear function as follows.

$$C_a(t) = C_{\min} + (C_{jam} - C_{\min}) \times (\frac{V_a(t)}{X_{jam}}) \tag{4.1}$$

This cost function of equation (5) has some merits,
- Easy to calculate
- Satisfying first in first out(FIFO) rule
- Keeping consistence of the model

Table 1. Origin-destination trip demands

Time slice	Trip demand(Vehicles/time slice)
1	120
2	120
3	100
4	100
5	100
6	100

Table 2. Network Data for example network

Link number	From node → to node	Length of link(km)	Free flow speed (km/hour)	Link capacity (vehicle/hour)	Link type
1	1→3(j-1)	4	60	1800	arterial
2	1→2	6	60	1800	arterial
3	2→3	0.3	30	720	on-ramp
4	2→5	20	60	1800	arterial
5	3→4(j)	15	100	2200	expressway
6	4→5	0.3	30	720	exit-ramp
7	4→6(j+1)	5	60	1800	arterial
8	5→6	5	60	1800	arterial

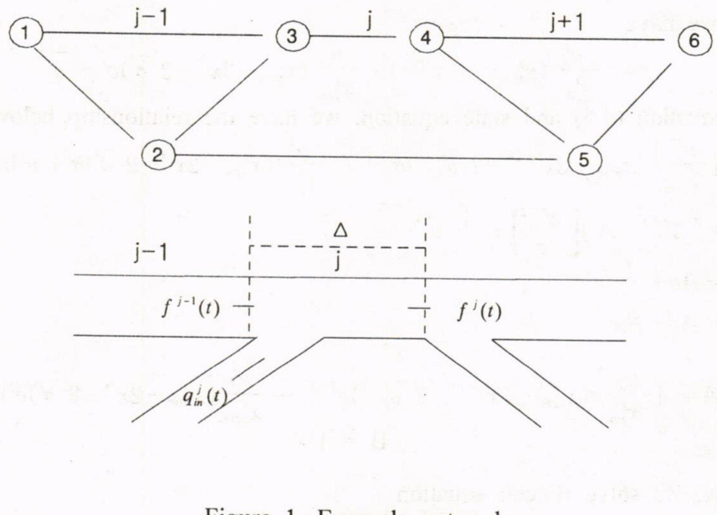

Figure 1. Example network

For assessing the model, optimal ramp metering function should be specified for the example network. State equation on section j at time t may be written as follows.

$$\frac{dx^j(t)}{dt} = [f^{j-1}(t) + q^j_{in}(t) - f^j(t)]/\triangle$$

Where, $\triangle$ is section length. We set x^{j*}, q^{j*}_{in} as follows.

$$x_j = x^{j*} + \sigma^j \quad (4.2)$$

$$q^j_{in} = q^{j*}_{in} + u^j \quad (4.3)$$

Where x^{j*}, q^{j*}_{in} are optimal density on section j and optimal ramp metering rates entering section j . σ^j and u^j are perturbation vectors.
From Greenshield equation, we can calculate the flows on section j. Greenshield equation is as follows(note that skip the time variable t for convenience).

Greenshield equation(Basic formula) : $f = u_f(x - \frac{x^2}{x_{jam}})$

$$\begin{aligned} f^j &= \frac{u^j_f}{x^j_{jam}}(x^j_{jam}x^j - x^{j^2}) \\ &= \frac{u^j_f}{x^j_{jam}}[(x^j_{jam}(x^{j*} + \sigma^j) - (x^{j*} + \sigma^j)^2] \\ &= \frac{u^j_f}{x^j_{jam}}[x^j_{jam}x^{j*} - x^{j*^2} + (x^j_{jam} - 2x^{j*})\sigma^j - \sigma^{j^2}] \end{aligned} \quad (4.4)$$

Then, we expand the equation (4.4) at $\overline{\sigma}^j$ with Taylor series,

$$f(\overline{\sigma}^j) = \frac{u^j_f}{x^j_{jam}}[x^j_{jam}x^{j*} - x^{j*2} + (x^j_{jam} - 2x^{j*}) \times \overline{\sigma}^j - \overline{\sigma}^{j2}] \quad \text{-----} \ ①$$

$$f'(\overline{\sigma}^j) = \frac{u^j_f}{x^j_{jam}}(x^j_{jam} - 2x^{j*} - 2\overline{\sigma}^j) \quad \text{-----} \ ②$$

$$f^j = ① + ② \times (\sigma^j - \overline{\sigma}^j)$$

Therefore, we have

$$f^j \simeq \frac{u^j_f}{x^j_{jam}}(x^j_{jam}x^{j*} - x^{j*^2}) + \frac{u^j_f}{x^j_{jam}}(x^j_{jam} - 2x^{j*} - 2\overline{\sigma}^j)\sigma^j + \overline{\sigma}^{j2} \quad (4.5)$$

From the equation (4.5) and state equation, we have the relationship below.

$$\begin{aligned} \frac{dx^j(t)}{dt} &= [\frac{u^{j-1}_f}{x^{j-1}_{jam}}(x^{j-1}_{jam} - 2x^{j-1*} - 2\overline{\sigma}^{j-1})\sigma^{j-1} - \frac{u^j_f}{x^j_{jam}}(x^j_{jam} - 2x^{j*} - 2\overline{\sigma}^j)\sigma^j + u^j]/\triangle \\ &= [A^{j-1} \quad A^j]\begin{bmatrix}\sigma^{j-1} \\ \sigma^j\end{bmatrix} + \frac{1}{\triangle}u^j \\ &= A\sigma + \frac{1}{\triangle}u^j \\ &= A\sigma + Bu^j \end{aligned}$$

Where,

$$A = [\frac{u^{j-1}_f}{x^{j-1}_{jam}}(x^{j-1}_{jam} - 2x^{j-1*} - 2\overline{\sigma}^{j-1})\sigma^{j-1} - \frac{u^j_f}{x^j_{jam}}(x^j_{jam} - 2x^{j*} - 2\overline{\sigma}^j)\sigma^j]/\triangle \quad (4.6)$$

$$B = 1/\triangle \quad (4.7)$$

At this time, we solve Riccati equation.

$$KA + A^T K + Q - KBR^{-1}B^T K = 0 \quad (4.8)$$

$$A = [\frac{u^{j-1}_f}{x^{j-1}_{jam}}(x^{j-1}_{jam} - 2x^{j-1*} - 2\overline{\sigma}^{j-1}) - \frac{u^j_f}{x^j_{jam}}(x^j_{jam} - 2x^{j*} - 2\overline{\sigma}^j)]/\triangle$$

$$B = 1/\triangle$$

Where, we have to set the values of parameters for further calculation. In the paper we set the values below.

x_{jam}^{j-1} = 60 vehicles/km (jam density on section j-1)
x_{jam}^{j} = 44 vehicles/km (jam density on section j)
x^{j-1*}= 30 (1800vehicles/hour= $x^{j-1*}\times$60km/hour) for arterial
x^{j*} = 22 (2200vehicles/hour= $x^{*}\times$100km/hour) for expressway
$\overline{\sigma}^{j-1}$ = -2, $\overline{\sigma}^{j}$ = 2
Q = $(1/x_{jam})^2$, R = 1

Where, the values of Q and R are not specified by analytic method, thus we set appropriate values by inspection. Accordingly the values of A and B are calculated from these parameters.

A = 0.873
B = 1/15 = 0.0667
$Q = (\frac{1}{44})^2 = 0.0005165$
R = 1

With the values above, we solve Riccati equation below.
$-0.0044K^2+1.746K+0.0005165=0$
We obtain as
$K=0,\ or\ 396.82$

Therefore, Gain matrix is
$G=R^{-1}B^{T}K=1\times\frac{1}{15}\times396.82=26.45$
With the gain matrix, we determine the perturbation vector of $u(t)^j$.
$u^j(t)=-G\sigma^j(t)=-26.45\sigma^j(t)$

Conclusively, ramp metering rates $q^j_{in}(t)$ is as follows.

$$q^j_{in}(t) = q^{j*}_{in}+u^j(t) = q^{j*}_{in}-26.45[x^j(t)-x^{j*}(t)] \quad (4.9)$$

In ALINEA model(Papageorgiou,1991), the value of Gain matrix(G) is 16 or 70. It has been known that if the value of Gain matrix is larger, the LQ regulator is unstable and has fluctuation

4.2 Test results

The test results from the application of the model to the example network are as follows. Figure 2 shows the comparison of ramp metering rates between LQR and Do-nothing cases. Where, Do-nothing case is that no ramp metering control is executed. As shown in the figure there exists the difference of ramp metering rates each other.
Figure 3 depicts the total travels of expressway in the cases. We found that the total travel time reduced when LQR executed as expected. As shown in Table 3, there exist differences of reduced travel times according to each time slice; from maximum 27.63% of reduction to minimum 1.31%, compared with Do-nothing case. These figures show that 15961 seconds of total travel time(7.09% of average travel time) can be reduced as LQR execute.
Compared with existing ramp metering strategies, however, the time saving ratio is

relatively small. There are some reasons. One of them is that we assume the traveler to have perfect knowledge of traffic condition and to follow Wardorp's principle. The assumption leads to a gap between the results of this work and the existing controls to real world. This implies that due to the existence of difference between perceived travel cost and perfect travel cost adopted in the paper, the efficiency of LQR is relatively small as shown in Table 3.

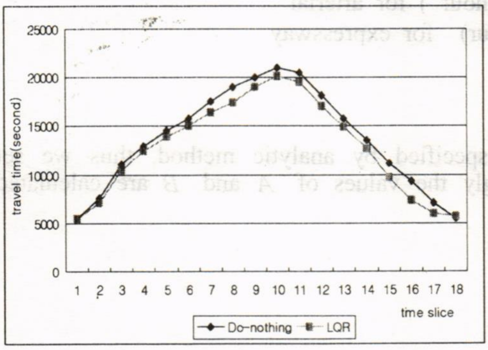

Figure 2.Comparison of ramp metering rates

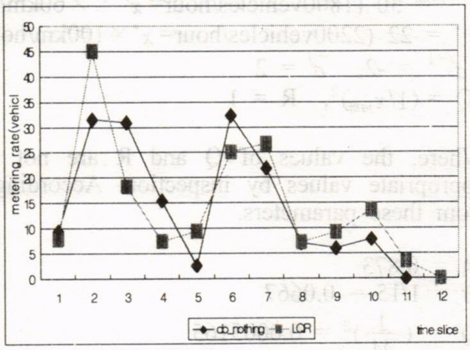

Figure 3. Comparison of travel times of expressway

Table 3. Comparison of total travel times of expressway

Tim slice	Do-nothing (sec) ①	LQR(sec) ②	Efficiency of LQR(%) $\frac{① - ②}{②} \times 100$
1	5485.2	5414.1	1.31
2	7621.8	7114.4	7.132014
3	11090.6	10476.4	5.862701
4	12997.2	12479	4.152576
5	14579.5	13886.3	4.991971
6	15813.5	15089.9	4.79526
7	17497.2	16393.9	6.729942
8	19056.7	17450.9	9.201818
9	20064.9	19004.3	5.580842
10	21042.8	20191	4.218711
11	20512.6	19557.4	4.884085
12	18135.5	17045.2	6.396522
13	15814.3	14966.8	5.662533
14	13502.3	12739.8	5.98518
15	11218.8	9706.5	15.580281
16	9307	7320.9	27.129178
17	7053.4	5996	17.63509
sum	240793.3	224832.8	7.098831

5. CONCLUSION

In this paper we proposed an optimal ramp metering model with considering dynamic route choice simultaneously. The results from the numerical test are expected valuable for further works, although the example network is very simple. The model developed in the paper will be contributed to the ramp metering research area in that it takes into account dynamic route choice behavior explicitly.

Further studies related to this research include the following issues: Firstly, as described above, deterministic dynamic traffic model has some limits for simulating the behaviors of travelers, thus stochastic dynamic model needs to embed in. Secondly, Comparisons are needed between the model and other existing ramp metering methods. Finally, we also remain to develop a global searching technique for the model.

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