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Research of Integrated Control Methods and its Simulation for Freeway Mainline and Related Ramp

***Abstract**. To relieve traffic congestion during peak hours on freeways, various ramp metering models have been attempted for regulation of the inputs to freeway from entry ramps. Integrated control is a new development to find the combination of control measures for the best road performance and control effectiveness. In consideration of some weaknesses of current intelligent metering, this study proposes an innovative concept and associated local ramp metering approach. From results of a comparative case study with real world traffic flow data in Beijing, the new Intelligent control approach of freeway mainline and related ramp that is proven to significantly output from traditional models, particularly in regards to its effectiveness in minimizing the waiting time of multiple cycles.*

***Streszczenie.** W artykule przeanalizowano słabości obecnie stosowanych metod do kontroli przepełnienia w czasie ruchu drogowego i zaproponowano nowa metodę oceny zwalniania tego ruchu. Zaproponowano też inteligentne metody kontroli tego ruchu w tym wjazdu na autostrady. (**Zintegrowana metoda kontroli ruchu na autostradzie**)*

Keywords: Traffic control; Integrated Control; Freeway mainline and Related Ramp; Junction Network.
Słowa kluczowe: kontrola ruchu drogowego, autostrada.

1 Introduction

Road congestion has been a very serious worldwide problem for many metropolises. The problem has also caused additional social, economic, and environmental costs due to higher fuel consumptions, emission, and delay. In general, the principal causes of freeway congestion are: (1) incidents/accidents; (2) queues from exiting vehicles that spill over onto the mainline; (3) bottlenecks; (4) entering demand that exceeds exiting demand; and (5) mainline flow disrupted by platoon entering demand. The problem can be tackled from various points of view, such as implementing traffic management system (ATMS), including ramp metering, and mainline speed control. One of the most effective freeway control measures is ramp metering [1,2]. By regulating ramp access to the mainline, the on-ramp metering seek to eliminate, or at least reduce operational problems resulting from [3]. Ramp metering has been used for over forty years and is presently employed in a number of cities, including Beijing, the capital of China.

A ramp metering method can be defined by its objective, strategy, method, and control range. Ramp metering strategies can be either fixed-time or traffic-responsive [3]. The former is derived off-line using historical road traffic flow information to build the control rules, and the later is based on real-time measurements from sensors located on freeway and the on/off ramps. Previous studies demonstrated various ramp metering algorithms for volume calculation since 1970s originated from seeking the trade-off of mainstream flow and queuing length [4]. Whereas feed-forward is the demand-capacity strategy and its variations [5], feedback is ALINEA strategy and its variations [6], as well as artificial neural network (ANN)[7], and the albeit approaches method of ANN and Fuzzy in theory and in control application .The other representative strategies or methods are: queue control algorithms[8]; Diamond Interchange Control System[9],et al. At present, the ANN is a hot research area of ITS.

Although research results of previous ramp metering studies are encouraging, a number of issues are worthy of further investigation. Current methods focus primarily on the efficiency of total flow but neglected the balance of efficiency and equity. For example, the total waiting time of a vehicle on the ramp is not reflected in any of the current methods. As a result, in particular cases, some vehicles in the ramp may need to wait for a very long time or even indefinitely in the worst scenario [10].Considering balance between efficiency and equity in local ramp metering, we propose a new parameter, the accumulative waiting time, in ramp queuing model. The study develops ramp metering and traffic control models with the use of this new parameter. For model calibration, we subscribe to the principle of structure risk minimization by adopting a Support Vector Machine (SVM) algorithm to overcomes the problems of globally optimal control structure selection and the over-learning, which are common to the ANN. The applications of the SVM in transportation have been very limited and they have not been seen in ramp metering literature.

2 Freeway Mainline and Related Ramp Queuing Model

This section presents the theoretical framework of the developed freeway traffic control model for local traffic management of any freeway on-ramp area.

(1)A Revised General Ramp Queuing Length Model

To model the process of on-ramp receiving and forwarding traffic into the freeway mainline, current practices use a simple queue model as shown in Equation (1). By applying ramp metering, the outflow r(j), the flow that is allowed to leave the ramp during period k, is a portion of the total incoming flow that would leave in the absence of ramp metering. The volume of r(j) depends on the dynamic traffic conditions of the corresponding mainstream and the existence of ramp metering control measures. A variety of models have been developed to calibrate the control measures, each with consideration of unique combination of traffic variables. According to the conservation idea in the LWR model, the simple ramp queuing length model considers the traffic variables including queuing length l and flow demand d, as shown in the following equation.

$$l(k) = l(k-1) + [d(k) - r(k)] = \sum_{j=0}^{k} [d(j) - r(j)] \quad (1)$$

where l(k) is the queue length(represented by number of vehicles in queue) in the on-ramp at time k, d(k) is the demand (veh/h) at the same time period.

In this study, we revise and extend the abovementioned simple queue model to a more general ramp queuing length model. The revised general model considers more constraints to describe the dynamic nature of traffic conditions more faithfully. The additional variables include the maximal ($\max R_{ramp}^{T}$)and minimal ($\min R_{ramp}^{T}$) ramp metering volumes and the maximum permissible storage (Lmax) under the condition that Lmax≥l(k)=l(k-1)+T[d(k)-r(k)] ≥0). The general ramp queuing length model r(k) is described in Equation (2):

(2) $\min[d(k)+\frac{l(k-1)}{T}, \max R_{ramp}^{T}, f_{\max}(q_p(k))] \geq r(k)$

$\geq \max[d(k)+\frac{l(k-1)}{T}, \min R_{ramp}^{T}, f_{\min}(q_p(k))] > 0$

(2) A Novel Ramp Queuing Waiting Time Model

(a) Tt Past research typically uses the ramp queuing waiting time (Tt) for ramp queuing model. It is the total waiting time of all vehicles in the current waiting cycle. Computationally, it is the product of number of vehicles in the queue and the cycle time, as expressed in Equation (3)

(3) $$T_t = T\times[d(k)-r(k)] = T\times\sum_{j=0}^{k}[d(j)-r(j)]$$

Based on Equation 3, Tt is solely determined by the number of waiting vehicles in time period k and the cycle length (T). The time of those vehicles in the ramp that has been waiting for more than one cycle (reduplicated waiting time hereafter) are ignored. This, however, causes the problem that severe reduplicated delay can happen to some vehicles in the ramp. This is the major shortcoming of the current models.

(b) Ts For the above reason, this study propose a novel parameter, Ts, which represents the accumulative waiting time of all the vehicles waiting in the ramp. Based on the queuing theory, Ts can be modeled by the following conservation equations.

(4) $$\sum_{j=k+1}^{n} r_j T = \sum_{j=0}^{k}(d_j - r_j)T + 1$$

(5) $$T_s = (n-k-1)\times T$$

From the equations, it is clear that Ts is solely determined by l(k), r(j) (for j>k) and T, and is independent of d(j) (for j>k). For example, under the condition that l(j) and qp(j) are both small, a portion of the traffic demand in the ramp will be permitted to move forward into the freeway mainline, Tt will thus keep constant and Ts will increase gradually which means a vehicle has to wait at least one cycle. If so, r(j) can't be determined computationally by the model where only Tt is used This implies that some vehicles may have to have to wait in the ramp for unknown amount of time or in the worst scenario indefinitely. This is clearly in conflict with the principle of equality.

(c) Ts-Tt In comparison, Tt can be viewed as waiting time in current waiting cycle and Ts as the accumulative waiting time of current vehicles over all relevant waiting cycle. The difference between them, Ts-Tt , , relates to the amount of repeated waiting cycles. Therefore, it is a good indicator of the degree of the reduplicated waiting time which we want to minimize for equity consideration. In this study, we will use this new parameter in the formulation of control model.

3 Formulation of the Integrated Control Problem

(1) Control Evaluation Criteria

Ramp metering seeks to improve the freeway traffic conditions by regulating the inflow from the on-ramp to the mainline compulsorily. Through explicit signals of traffic light that changes self-organization behavior of mass drivers, ramp metering observes and traffic conditions of the mainline and the ramp. Appropriate selection of control evaluation criteria is fundamental for the clear description and monitoring of real traffic conditions. In prior research, system times (total time spent of all vehicles in the road and in the ramp queues-TTS), freeway travel times (FTT), freeway queuing times(FQT), ramp delays(Tt), downstream traffic flow volume(Qdown), mainline density ρ, and space speed ν, etc., were often chosen as on-ramp control parameters.

Although the above control parameters or any combination of them can lead to control at various levels of efficiency, effectives, and equity, how to choose them deserves careful research. Discussed below are a few important considerations that have been neglected in the past.

(a) Information redundancy among these parameters must be avoided. Speed and density follow rules under continuum traffic flow, the parameters of TTS, FTT, FQT and qdown contain essentially the same information.

(b) There should be appropriate and impartial consideration of both efficiency and equity. Efficiency and equity are partially competitive criteria. Previous traditional control considers efficiency only. But in consideration of equity, we argue that a good control strategy should be flexible enough to accommodate a particular trade-off between mainstream and ramp users. The issue of equity has not yet been addressed in the literature of ramp metering strategy, in spite of an important characteristic of a particular ramp metering application.

(c) Constraints in real life must be considered. Ramp storage capacity must be considered because it is critical to accommodating the initial excess demand and avoiding congestion, and overlong queue will interface with the adjacent street traffic.

To address the above concerns, we selected Qdown(k), L(k) and Ts-Tt as parameters for control modeling in this study. Qdown(k) indicates the mainline traffic condition, L(k) is the ramp queuing length, and Ts-Tt measures the degree of repetitive ramp waiting time.

(2) Control Function

The objective of ramp control is to maintain a desirable level of service for the freeway system being controlled, such that the freeway system is utilized as fully as possible. Qdown(k), L(k) and Ts-Tt are selected to evaluate the control result. The discrete-time formulation of the control problem is expressed in Equation (6):

(6) $$\max P = \sum_{j=0}^{k}[Q.q_{down}(k)^T - S.l(k)^T - R.(Ts\text{-}Tt)^T]$$

where Q, S and R is the weighting factors of qdown(k), l(k) and Ts-Tt , respectively. And the control function is Equation (7):

(7) $$\vec{X}(k+1) = f(\vec{X}(k), r(k), \vec{D}(k))$$

The three-dimensional vector variable $\vec{X}(k) = [\rho_{down}(k), l(k), t_s]$ are the input to the two proposed ramp queuing models as expressed by (9) and (10), r(k) is the output variable, and $\vec{D}(k) = [q_{up}(k), d(k)]$ are the robust variables.

4 Integrated Control Optimization Algorithm

4.1 Methodology

SVM is a new machine learning method based on the statistical learning theory and the principle of the structure risk minimization. It can be used for classification, calibration of regression models, and other tasks. The use of SVM in this study is for calibration of a nonlinear regression model for local ramp control. To deal with the nonlinear problem, SVM applies a kernel function to map training data into a high-dimensional feature space where the regression is implemented. The SVM algorithm can calibrate parameters by constructing an optimal hyperplane that can separate most distant clusters of data apart. The optimization problem can be constructed and solved as a quadratic programming problem:

(8) $$\min_{w,b,\xi}\frac{1}{2}\|w\|^2 + C\sum_{i=1}^{l}\xi_i$$

$$y_i(w\times\phi(x_i)+b) \geq 1-\xi_i, \xi_i \geq 0, i=1,2,...,l.$$

where $w \times \phi(x_i) + b$ is the hyperplane, C is the penalty function, b* is classification threshold, ξ_i is the non-negative slack variable,

It can be solved by Lagrange multiplier method as follows:

(9) $$\max_{\ell}\{L_D = \sum_{i=1}^{l} \ell_i - \frac{1}{2}\sum_{i=1}^{l}\sum_{j=1}^{l} \ell_i \ell_j y_i y_j \phi(x_i)\phi(x_j)\}$$

$$= \sum_{i=1}^{l} \ell_i - \frac{1}{2}\sum_{i=1}^{l}\sum_{j=1}^{l} \ell_i \ell_j y_i y_j K(x_i.x_j)\}$$

$$0 \le \ell_i \le C \quad \sum_{i=1}^{l} a_i y_i = 0$$

where $K(x_i x_j) = \phi(x_i)\phi(x_j)$ is the kernel function meets Mercer requirement. Then the distinguish function $f(x) = sign[w.\phi(x) + b]$ can be described as the following:

(10) $$f(x) = sign(\sum_{i=1}^{n} \ell_i y_i K(x_i, x) + b^*)$$

where ℓ is Lagrange multiplier and $sign(.)$ is the distinguish function.

4.2 Design of Implementation Procedures

(a) Data Training:

Real world traffic flow data in Beijing are collected and classified into groups. The classification is done by standardizing the flow data first, and get Yi using GP algorithm to calculate the insert dimension of m, then construct $\{x_i, y_i\}_{i=1}^{l}$ make use of ri=xi=(Yi; Yi=1,…,Yi=m-1) and yi=Yi+m, where l=N-m.

(b) Kernel Function Selection. The RBF, $K(x, x_i) = \exp(-|x - x_i|^2 / \sigma^2)$, is selected as the kernel function.

(c) Output Function for ramp metering volume

The training data are fed to the ramp metering models to calculate ℓ and b*. Then use then to get the output function as defined in Equation (11).

(11) $$f(r) = \sum_{i=1}^{l} \ell_i K(x, x_i) + b^*$$

where x_i is the ramp metering volume of certain cycle(same to r(k)).

(d) Fine-tuning the Output. According to the result from step (c) and the set error space, if the value exceed, then go back to step (b) and regulate.

(e) Condition Test. If not, then return to step b.

5 Case Study and Simulation Results Analysis

5.1 Data and Scenario

A one-week in-situ traffic flow data from June 2nd to June 8th, 2011 were obtained. The part of the dataset that covers peak hour traffic flow is selected for this study. Figure 1 shows the area in Beijing where the traffic flow data were collected and shows the volume profile of ramp and freeway during peak hours in the study area.

5.2 Simulation Results Analysis

(1) Application of Integrated Control

Finally the model developed in this study is applied. As illustrated in Fig 2, congestion occurs after the 19th cycle and maintains within a certain degree after ρ_{down} meets the 1.8ρ_{cr}. In sum, the Qdown for this scenario is 4090pcu in one hour, accumulative L is 1390pcu and TR is 780minutes.

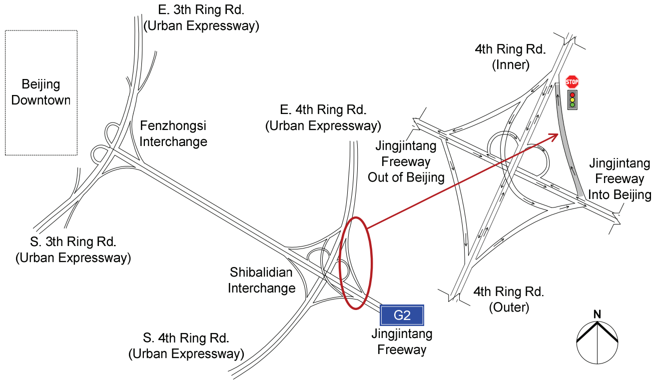

Fig.1. Controlled ramp and location in road network shown.

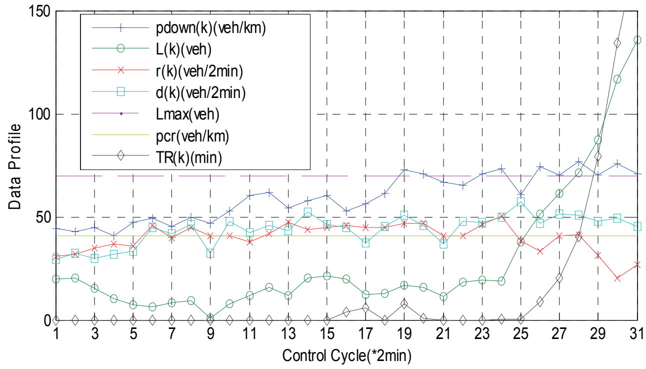

Fig.2. RBF-SVM ramp control profile

(2) Comparison and discussions of results

For comparison of the results from the four models, results are plotted against each other in Fig 3, 4,and 5. Fig 3 depicts the on-ramp queuing vehicle number of each model.

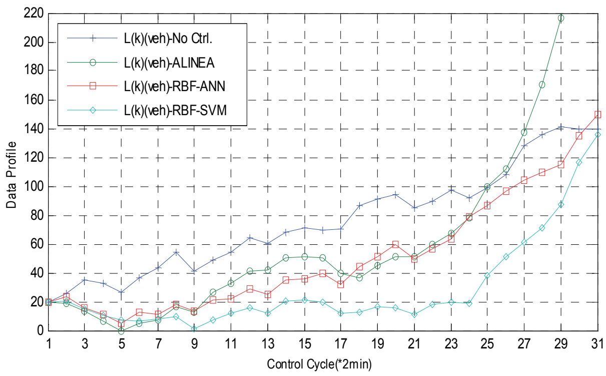

Fig.3. Ramp queues length comparison profile

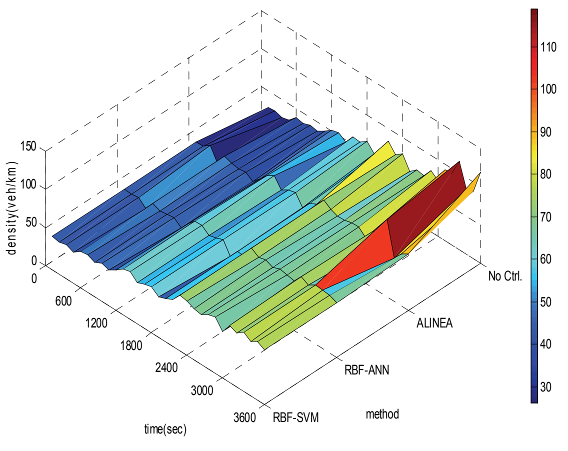

Fig.4. Evolution and comparison of downstream density

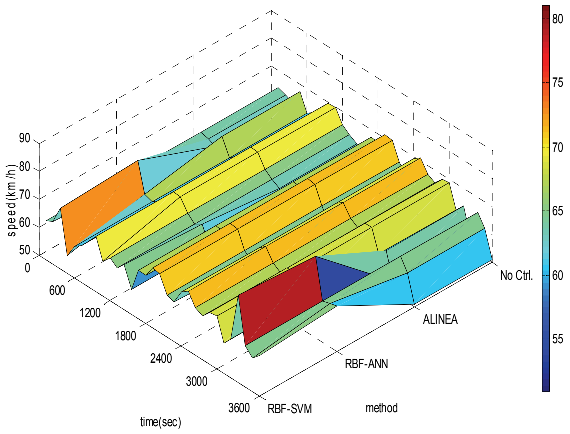

Fig.5. Evolution and comparison of downstream speed

The related downstream vehicle volume evolution and the corresponding downstream vehicle density stereogram are displayed in Fig 4 and 5.

Set WQ, WL and WT as 0.6, 0.2 and 0.2 respectively, Z represents as control value of each objective, and P represents as comprehensive control value of each algorithm. After data standardization, control value of various methods can be obtained as follows Table 1.

Table 1. Standard values of integrated control objectives with various methods during peak hour

	Q_{down} (pcu/h)	$Z_{Q\ down}$	L (pcu)	Z_L	T_R (min)	Z_{TR}	P
Min value	2000	0	800	0	0	0	0
No-Ctrl.	3549	0.62	2351	0.97	2057	0.69	0.041
ALINEA	3890	0.76	2135	0.83	2113	0.70	0.146
RBF-ANN	4025	0.81	1570	0.48	1094	0.36	0.317
RBF-SVM	***4093***	0.84	***1094***	0.18	***483***	0.16	***0.433***
Max value	4500	1	2400	1	3000	1	1

In total, the result shows integrated control methods that RBF-SVM exhibits more steady control quality and leads to a significant amelioration of the traffic conditions for effectively reducing the reduplicated waiting time.

6 Conclusion

This study focuses on two shortcomings of current ramp metering methods. The first one is that the accumulative waiting time of particular vehicles is ignored. As a result, we argue that the issue of equality is neglected by the omission of the above consideration. The second shortcoming is that information redundancy appears in many methods by including parameters that essentially convey the same information. In response to the two shortcomings of concern, we introduce a novel concept, the accumulative waiting time, and use it to generate new parameters in ramp control modeling. We further develop two ramp metering models and propose a new RBF-SVM algorithm for model calibration. In a case study, the two developed models are compared against two other models under exactly the same scenario. The results suggest both of our two models clearly outperform existing models by significantly increase total downstream flow volume, reduce queue length, and greatly reduce the multiple waiting cycles for any single vehicle. Particularly, our model (RBF-SVM) with the use of newly introduced concept, accumulative waiting time, is the overall winner in all respects. Therefore, we recommend the use of the accumulative waiting time as a parameter in future ramp metering practices.

Further study on the selection of parameters and the kernel function model is necessary. Other research avenues include the design of ramp coordinated metering system and its empirical implementation.

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