A New Approach for Combined Freeway Variable Speed Limits and Coordinated Ramp Metering

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Abstract—Freeway corridor traffic flow is limited by bottleneck flow. A possible approach for maximizing recurrent bottleneck flow is to create a discharge section immediately upstream of the bottleneck. This paper proposes a control strategy for combining Variable Speed Limits (VSL) and Coordinated Ramp Metering (CRM) design to achieve this objective when the bottleneck can be modeled as a lane drop (or virtual lane drop) and/or weaving section. The control design strategy is to design VSL first and then use Finite Time Horizon Model Predictive Control to design Coordinated Ramp Metering. Microscopic simulation results showed that the control strategy could improve traffic throughput significantly.

I. INTRODUCTION

Ramp metering is the most widely practiced strategy to control freeway traffic in the US, particularly in California. It is recognized that ramp metering can directly control the flow into the freeway and the average density immediately downstream of the onramp. After entering the freeway, the collective behaviors of the drivers are not controlled. This is why using ramp metering alone to control freeway traffic has limited performance if the flows from onramps and the upstream mainline are high. In addition, from the perspective of equity among the onramps along a corridor and the ramp queue length limit due to road geometry, ramp metering has to be switched off if the demand from that onramp is too high to avoid traffic spilling back onto arterials. Therefore, from a systems and control viewpoint, using ramp metering alone cannot fully control the freeway traffic in practice. This is the motivation for investigating other control strategies such as Variable Speed Limits. VSL attempts to control the collective vehicle speed (or driver behavior) of mainline traffic, which is complementary to RM.

The following acronyms are used throughout the paper: VSL – Variable Speed Limit; RM – Ramp Metering; CRM – Coordinated RM; CTM – Cell Transmission Model; FD – Fundamental Diagram; TOPL (Tools for Operational Planning); SWARM - System Wide Adaptive Ramp Metering; TTT – Total Travel Time; TTS - Total Time Spent; TTD – Total Traveled Distance; MPC – Model Predictive Control; EB (WB) – East Bound (West Bound);

Several implementations have been conducted in the UK, France, Germany and Netherlands using VSL to harmonize the traffic mainly for safety rather than for mobility improvement. It is generally accepted that crashes and incidents can be reduced between 25–40 percent [1]. However, none of the VSL practice reported before was intended for maximizing traffic flow. This paper will focus on mobility improvements along a stretch of freeway using combined VSL and RM.

Freeway traffic flow is limited by bottleneck flow. The causes of bottleneck may vary from case to case. In general, bottlenecks can be classified as: recurrent - the location and congestion time are predictable; non-recurrent- location and time are non-predictable.

To maximize freeway traffic flow, one possible approach is to maximize the bottleneck flow. The main strategy to achieve this is to create a discharging section right before the bottleneck such that the feeding flow into the bottleneck could be closer its capacity flow. This consideration is based on previous works [2-7], which indicate that congested upstream traffic will reduce the bottleneck flow by about 5–20% depending on location and times.

There are several possible ways to combine VSL and RM depending on what model is adopted and how the control strategy is designed, classified as follows:

- Determine RM before determining VSL;
- Determine RM and VSL simultaneously with tightly coupled speed and density dynamics model;
- Determine VSL first before determining RM rate.

In the work of [8], RM was designed before VSL or assumed known. It has some practical implication since RM has been widely implemented in many states in the U.S., particularly in California.

This paper uses the third approach to design a combined traffic control strategy for maximizing the recurrent bottleneck flow. It determines VSL for each link/cell without a model while taking into account the following factors: maximizing the bottleneck flow, mainline and onramp demand variation, onramp length limit (storage
capacity), and limit on speed variation over time and space for driver acceptance. This is a higher level design which leaves spaces to the CRM design for further optimization. This approach considers the fact that VSL cannot change quickly but the CRM rate can. From this sense, it is practical but sub-optimal. With the designed VSL, the macroscopic model is linearized, which is then used for CRM design. With proper formulation of the constraints, the control design problem is formulated as a Sequential Linear Programming, which can be solved efficiently numerically.

The paper is organized as follows: Section II is for relevant literature review; Section III presents higher control strategy and an approach for combined VSL and RM; Section IV is for VSL design; Section V is for MPC CRM design with density dynamics; Section VI presents the results of Integrated Traffic Control Simulation; Section VII is for concluding remarks.

II. LITERATURE REVIEW

In recent years, model-based traffic control design has been becoming more and more popular. The analysis and control design of ramp metering based on the first order CTM [9] is one example [10]. Another example is use of a second order model for combined Variable Speed Limit and Coordinated Ramp Meter control design in [11 - 14].

A. Ramp Metering

A good review of model-based freeway ramp metering approaches is found in [15, 16]. Several RM strategies were also reviewed and compared in [17]. Reference [18] evaluated four ramp metering methods: ALINEA-local traffic responsive; ALINEAQ with onramp queue handling; FLOW - a coordinated algorithm that tries to keep the traffic at a predefined bottleneck below capacity; and the Linked Algorithm, which is a coordinated algorithm that seeks to optimize a linear quadratic objective function. The most significant result was that ramp metering, especially the coordinated algorithms, was only effective when the ramps are spaced closely together.

SWARM is based on linear regression of measured data for prediction of density instead of a model. A good review and implementation of SWARM is documented in [19].

B. VSL Strategies

Work in [20] presents two VSL algorithms for traffic improvement, which was combined with RM. The authors of [20] believe that VSL not only can improve safety and emissions, but also can improve traffic performance by increasing throughput and reducing time delay. Work in [13] identified two functions of VSL: speed homogenization and prevention of traffic breakdown. The former is the reduction of speed variance; and the latter avoids high density, which achieves density distribution control through VSL. As an example, it used a VSL strategy to suppress shock waves in a traffic network.

Work in [21] used an empirical approach to investigate the effectiveness of reducing congestion at a recurrent bottleneck and improving driver safety by using feedback to the driver with advisory Variable Message Signs (VMS) on a highway stretch (18 km). The feedback includes: (a) speed limit (piecewise constant with 12 km/h increment); and (b) warning information (attention, congestion, and slippery). The VSL strategy was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver response to the speed limit and messages on the VMS was reasonable, speed was regulated to some extent, and safety was improved by 20%~30% incident/accident reduction, more significant than mobility improvements.

The Dutch Experiment [1] intended to smooth or homogenize the traffic flow along a stretch of highway using enforced VSL. Only two speed limits, 70 and 90 km/h, were used, with 1 min update interval. Tests were conducted on multiple stretches totaling 200 km, showing that speed control was effective to some extent in reducing speed and speed variation and the number of shock waves.

Several empirical studies have been conducted in the U.S. since the 1960’s in several states with varying levels of development for different purposes (improving traffic safety, work-zone safety, or traffic flow) [22]. The outcomes were diverse, with some positive and most negative. The most impressive positive outcome was the work by the state of New Jersey, which was similar to the approach in Germany [23, 24], but with the speed enforced instead of advised.

Papageorgiou [25] evaluated implemented VSL strategies based on data analysis. The paper summarizes available information on the VSL impact on FD-aggregate traffic flow behavior as follows: (a) decrease the slope of the flow-occupancy diagram at under-critical conditions; (b) shift the critical occupancy to higher values; and (c) enable higher flows at the same occupancy values in overcritical conditions. It concluded that there was no clear evidence of improved traffic flow efficiency in operational VSL systems for the implemented VSL strategies.

A simple real-time merging traffic control concept is proposed [26] for efficient toll plaza management in cases where the total flow exiting from the toll booths exceeds the capacity of the downstream highway, bridge, or tunnel, leading to congestion and reduced efficiency due to capacity drop. The Merging Control strategy of Toll Plaza is similar to RM - ALINEA, which is different from the VSL physically since VSL do not completely stop the vehicles. RM using traffic lights decouples the platoon into individual vehicles while VSL intend to keep it.

C. Combined VSL and RM

Reference [27] considered both VSL and RM, which are believed to be the two key tools influencing conditions on congested freeways. Their combined effect was also studied in reducing the risk of crash and improving operational parameters such as speeds and travel times. Work in [28] refined METANET model to different vehicle classes for combined VSL and CRM design with MPC. [29] used a second order model for optimal VSL and RM plus extended Kalman filter for state estimation. Optimization is carried out by minimizing (or maximizing) an empirical mean cost function according to the Monte Carlo method. [30]
considered optimal combined VSL and RM based on the METANET model using MPC. It is believed that RM was effective only when the traffic demand from the combination of onramp and mainline does not significantly exceed downstream mainline capacity flow. Otherwise, flow would break down and RM has no use. Study in [12] considered combined VLS and CRM with an optimal control approach. It claimed an algorithm feasible for large scale systems. It showed by simulation that traffic flow significantly improved with combined VSL and CRM versus using each strategy alone.

In this paper, the combined VSL and CRM design takes into account mobility, safety, equity and driver acceptance instead of just for safety as most previous VSL practice. The approach of combination is for practice which dictates simplicity, efficiency, and robustness. However, results are sub-optimal from the overall system viewpoint.

The method for determine the Critical VSL in the link immediate upstream of the discharge link is to regulate the discharge link flow to the bottleneck capacity flow, similar to that used in [25]. Similarly, one could also regulate occupancy (density) of the discharge link to its critical occupancy (density). The catch here is that the occupancy (density) of the discharge link only indirectly related to the bottleneck capacity flow.

III. HIGHER LEVEL CONTROL STRATEGY

This section presents the main results, i.e., design of VSL based on a pre-specified RM strategy for a stretch of freeway as shown in Figure 1. The objective is to maximize the recurrent bottleneck flow to approach its capacity flow. The definition of “Cell” is referred to [14]. MPC terminologies are used in the discussion below, which are referred to [30].

![Figure 1](image1.png)

**Figure 1.** Upper: A stretch of freeway with recurrent bottleneck that can be modeled as lane drop; Lower: the discharge flow of 2 lanes will be lower than the bottleneck capacity flow due to conservation if upstream is congested: 
\[ q = 2q_{b}^{(u)} < Q_{b}; \quad q_{b}^{(u)} \] feeding flow per lane into the bottleneck; 
\[ Q_{b} \] total bottleneck capacity flow.

A. Recurrent Bottleneck Characteristics

This analysis applies to a recurrent bottleneck that can be modeled as a lane reduction or weaving section, such as a work-zone lane closure, geometric design, and freeway split, etc. To understand bottleneck flow characteristics, the following concepts are crucial:

**Bottleneck Capacity:** Physical capacity of the bottleneck or its observed maximum flow; assumed known

**Bottleneck Discharge flow:** The following cases are not distinguished: (a) upstream is congested but there is no queue within the bottleneck; and (b) both upstream and part of the bottleneck stretch are congested with queue.

**Bottleneck feeding flow:** the flow at the geometric starting point of the bottleneck.

B. Control Objective and Strategy

The control objective is to maximize the bottleneck flow. It can be proved that maximizing the bottleneck flow is equivalent to reducing the TTS under the assumption that all the traffic has to pass the bottleneck. Based on the traffic characteristics, the following control strategy is proposed for the following situation: if the demand is too high from both mainline upstream and onramp and congestion is unavoidable, then create a discharge section with adequate length (500~700 m) immediately upstream of the bottleneck by defining a critical VSL as shown in Figure 2 such that the feeding flow to the bottleneck is close to the bottleneck capacity flow. This is possible if there is a practical or virtual lane drop upstream of the bottleneck with weaving.

![Figure 2](image2.png)

**Figure 2.** Control strategy: to maximize bottleneck flow by creating a discharge section upstream of the bottleneck

A practical example of virtual lane drop is the split at I-80 West and I-880S & I-580E for PM peak traffic as shown in Figure 3. It means that some drivers to I-880S or I-580E intend to use I-80W until the last minute, then change left to the proper lane since the traffic on I-80W is light in PM peak hours except for times of special events in San Francisco.

![Figure 3](image3.png)

**Figure 3.** I-80 West PM peak: virtual lane drop and weaving
C. Control Strategies for Combined VSL and CRM

Equity needs to be taken into account in the design of combined VSL and CRM. The essence of equity could be interpreted as the following:

- Drivers from all the onramps along a corridor should have equal opportunity to use the freeway;
- TTS should be minimized – it includes the queue time at the onramps with or without ramp metering;
- TTD should be maximized – it is equivalent to saying that the freeway should accommodate more vehicles if congestion is unavoidable;
- The control strategy should minimize the possibility of traffic spilling back into the arterials causing gridlock – this is usually implemented as: once the queue length at the onramp reaches a certain level, ramp metering is switched off to allow vehicles to get into the freeway.

The following notations are used throughout the paper, which are grouped according to their functions:

**Model Parameters**

- \( m \) – link index; \( M \) – Critical VSL Control link index; \( M+1 \) discharge link index;
- \( k \) – time index
- \( L_m \) – length of link \( m \)
- \( m_b \) – index of the most upstream link affected by the bottleneck; \( m_b \) could be a negative integer;
- \( m_h \) – link index of the congestion head
- \( m_c \) – link index of the congestion tail
- \( \gamma \) – gain parameter to be determined in simulation
- \( N_p \) – prediction steps for each \( k \) in Model Predictive Control

**State and Control Variables**

- \( q_{m+1}, V_{m+1} \) – flow and speed at the discharge section
- \( u_m \) – desired VSL at link \( m \), to be designed
- \( q_m (k) \) – estimated main lane flow at time \( k \)
- \( \rho_m (k) \) – density of link \( m \) at time \( k \)
- \( u_{st} (k) \) – Critical VSL immediately above the discharge link, control variable
- \( r_m (k) \) – metering flow rate (veh/hr), control variable

**Measured or Estimated Traffic State Parameters**

- \( \bar{q}_m (k-1) \) – flow at time \( k-1 \), measured
- \( \bar{V}_m (k) \) – speed of link \( m \) at time \( k \), measured
- \( u_{st} (k) \) – speed in the most upstream link, measured
- \( \bar{L}_{m+1} \) – discharge link density, measured/estimated
- \( s_m (k) \) – total off-ramp flow rate (veh/hr), measured
- \( d_m \) – demand from onramp \( m \), measured or estimated
- \( V_c \) – speed of congested flow upstream of the Critical VSL, measured

\( Q_m \) - mainline capacity of link \( m \), known
\( Q_b \) – bottleneck capacity flow, known or estimated
\( Q_{m,r} \) – onramp \( m \) capacity, known
\( L_{m,r} \) – onramp \( m \) length, known;
\( V_f \) – free-flow speed, known
\( O_c \) – critical occupancy, known
\( \rho_c \) – critical density, known

In theory, it is possible to further divide a link into cells [12, 13]. In practice, unless there is more than one sensor in each link, such a division would not help. Implicitly, each link will have exactly one onramp but may contain more than one off-ramp. In case there are two or more off-ramps, \( s_m (k) \) represents the total flow of them.

IV. VSL Design

The VSL strategy is designed for two stages according to the traffic situation. It is clear that \( m_b \leq m \leq m_b \leq M \).

**Stage 1**: (congestion beginning) It can be characterized by the measured flow exceeding a threshold value. The congestion tail and head are the same \( m_b = m = M \) (Figure 4). The VSL for each link in the potential influence zone could be determined as:

\[
\begin{align*}
&u_{m-1} (k) = u_m (k) + \\
&\max \left\{ -5, \min \left[ \left( \eta \alpha_m (k) + (1-\eta) \beta_m \right) \left( u_m (k) - u_{m-1} (k) \right), 0 \right] \right\}
\end{align*}
\]

\( m_b < m_h = m = M \)

\( u_m (k) = V_f \)

\( R_m (k) = \min \left\{ d_m (k), Q_{m,r} - \bar{q}_{m-1} (k-1) \right\} \) (1)

\( q_m (k) = \bar{q}_{m-1} (k-1) + R_m (k) - s_m (k) \)

\( \alpha_m (k) = H \left( e_m - q_m (k) \right) \)

\( \beta_m = H \left( 1 / L_{m,r} \right) \)


where \( \eta \) is selected to balance the priorities between onramp demands and their lengths along the corridor. The recursive algorithm is the first in (1). -5 in the braces is for limiting VSL variation over time. The Harmonic function \( H (\cdot) \) is defined as: Let \( x = [x_1, x_2, ..., x_M] \) be a real vector. Then

\[
H (x_m) = \frac{1}{x_m^2} = \frac{1}{\sum_{\mu=1}^{M} x_{\mu}^2} = \frac{1}{\prod_{\mu=1}^{M} x_{\mu}^2} = \prod_{\mu=1}^{M} \frac{1}{x_{\mu}^2}
\]

(2)

The following properties are straightforward:

\[
\sum_{m=1}^{M} \alpha_m (k) = 1, \quad \sum_{m=1}^{M} \beta_m = 1
\]

(3)
VSL algorithm for Stage 2 (0 ≤ m ≤ m_f) only can be specified as:
\[
    u_{m}(k) = u_{m-1}(k) + \max \left\{ -5.0, \min \left[ (\eta \alpha_{m}(k) + (1-\eta) \beta_{m}) [u_{m}(k) - u_{m-1}(k)], 0 \right] \right\}
\]

\[
    u_{m}(k) = V_f
\]

\[
    R_{m}(k) = \min \{ d_{m}(k+1), Q_{m+1} - Q_{m-1}(k-1) \}
\]

\[
    q_{m}(k) = \bar{q}_{m-1}(k-1) + R_{m}(k) - \pi_m(k)
\]

\[
    \alpha_{m}(k) = H (Q_{m} - q_{m}(k))
\]

\[
    \beta_{m} = H \left( 1 / L_{m,o} \right)
\]

0 ≤ η ≤ 1

Determination of \( u_{m}(k) \) is based on the following Integral Controller (regulator) which intends to regulate the density of the discharging section to the critical density.

\[
    u_{m}(k) = u_{m-1}(k-1) + \begin{cases} 
    \varepsilon_1 \cdot (\rho_m - \bar{\rho}_{m,i}) & \text{if } \bar{\rho}_{m,i} < \rho_r \\
    \varepsilon_2 \cdot (\rho_m - \bar{\rho}_{m,i}) & \text{if } \bar{\rho}_{m,i} > \rho_r
    \end{cases}
\]

The two control gains may be different in value. Such flexibility can be used to improve control performance. In practice, the density here can be replaced with occupancy, and the critical density is replaced with critical occupancy.

V. CRM DESIGN WITH MPC

In MPC design, at time step k, RM rate is to be determined over the predicted time horizon k+1, ..., k+N_p:

\[
    Z = \begin{bmatrix} 
    r_{i}(k+1), ..., r_{N_p}(k), ..., r_{m}(k+1), ..., r_{m+N_p}\end{bmatrix}^T
\]

A. Modeling

The following linearized density and onramp queue dynamics model (8) is adopted for CRM design:

\[
    \rho_{m}(k+1) = \rho_{m}(k) + \frac{T}{L_m \bar{\lambda}_{m}} (\bar{\lambda}_{m} \rho_{m-1}(k) u_{m-1}(k) - \bar{\lambda}_{m} \rho_{m}(k) u_{m}(k) + r_{m}(k) - \pi_{m}(k))
\]

\[
    \pi_{m}(k+1) = \pi_{m}(k) + T \left[ d_{m}(k) - q_{m,o}(k) \right]
\]

The first equation is the conservation of flow [14]. It is linear since the speed variable is the designed VSL. This can be justified by arguing that (a) for strictly enforced VSL, the practical speed will be close to the designed VSL; (b) for advisory VSL, if the density is high enough, even 30% driver compliance will lead to almost 100% compliance. Such linearization greatly simplifies the control process.

B. Constraints

\[
    0 \leq w_{m}(k) \leq L_m \rho_f
\]

\[
    0 \leq r_{m}(k) \leq \min \{ d_{m}(k), Q_{m+1} \bar{\lambda}_{m} (Q_{m} - \bar{q}_{m-1}(k)) \} \alpha_{m}(k) \cdot (\rho_f - \bar{\pi}_m(k))
\]

\[
    0 \leq \rho_{m}(k) \leq \min \{ \rho_r, \varphi(u_{m}(k)) \}
\]

Figure 4. VSL control strategy at Stage 1

Figure 5. VSL control strategy 1 at Stage 2
The first is the onramp queue limit; the second is the direct constraints on RM rate, which is the minimum of the four terms in the braces: the onramp demand, onramp capacity; the last two terms are space left in the mainline traffic lanes:
\[ \lambda_n (Q_n - \bar{q}_n (k)) \] is likely assumed in free-flow case, and 
\[ \lambda_n u_n (k) \left( \rho_j - \bar{\rho}_n (k) \right) \] is likely assumed in congestion.
This consideration is motivated by [14]. The third is an indirect constraint on RM rate through the density dynamics. 
\[ \phi(u_n (k)) \] is curve of a specified traffic speed drop probability contour as indicated in Figure 6. The details for the empirical estimation of the contour are described in [31].

![Figure 6. Empirical traffic speed drop probability contour vs. flow contour](image)

**C. Objective Function**

The following objective function is used at time step \( k \) over the predictive time horizon:

\[
J = TTS - TTD \\
TTS = T \sum_{j=1}^{n} L_j \lambda_j \rho_j (k + j) \quad \text{(TTT)} \\
+ T \sum_{j=1}^{n} \sum_{n=1}^{N} w_n (k + j) \quad \text{(Time Delay Due to Onramp Queue)} \\
TTD = \alpha_{TTD,0} \sum_{j=1}^{n} \sum_{k=1}^{N} \lambda_j L_j \xi_j (k + j) + \alpha_{TTD,M} \sum_{j=1}^{N} \lambda_j L_j \xi_j (k + j) \\
\alpha_{TTD} \gg \alpha_{TTD,0} > 0
\]

The first term minimizes TTS (to maximize mainline flow); the second term maximizes the TTD (to accommodate more vehicles in mainline). To choose \( \alpha_{TTD,M} \gg \alpha_{TTD,0} \) is to emphasize maximizing the flow on link \( M \).

**VI. SIMULATION**

An Integrated Traffic Control Simulation Platform (ITCSP) has been preliminarily developed in Aimsun with API, which includes: (a) I-80 W from Carlson to the diverge of I-80 and I-580E & I-880S (with 7 links and HOV lane ignored) about 6.5 miles long including I-580 merging (Figure 7); (b) aggregated traffic speed, flow and density (occupancy) for feeding into calibrated macroscopic traffic model; (c) combined VSL and CRM design using the macroscopic model; (d) feedback control at the microscopic level with VSL and CRM; and (e) performance evaluation for comparison of different control scenarios. A virtual link has been added to each onramp to store the vehicle queue which cannot be accommodated by the onramp and the mainline in the cases with and without RM if both mainline and onramp demand are very high. Those vehicles will be considered as spilling back to arterials and accounted for when the TTS is calculated.

![Figure 7. Road Geometry from Carlson to I-80 Diverge](image)

The simulation is conducted for 5 hours. Demand is high in the first hour and drops afterwards. Figure 8 shows the accumulated demand for all the onramps and the most upstream mainline. The legend shows the onramp in the order from top to bottom as the traffic moving direction.

Different scenarios have been tested: status quo, CRM only, VSL only, and combination of VSL and CRM; and application of control from the very beginning, or switching it on only when traffic flow reaches a certain level. For those control scenarios, the driver compliance is assumed to be 100% (strictly enforced). Lastly, one simulation has been conducted with all-time combined control with 30% driver compliance. Due to the high enough density, other drivers are forced to follow the posted speed. Therefore the performance is very similar to the 100% compliance case. Figures 9 and 10 show the performance parameters: Total Delay and TTS for those scenarios with all the vehicles accounted for, including those stored in the virtual link. It can be observed that RM control only could improve system performance somehow but not significantly, while VSL only and combined VSL and CRM can improve system performance significantly. This can be explained as follows: since the lengths of those onramps are short RM control is switched off if the queue reaches 90% of the storage capacity.
As indicated in Figure 11, TTD is improved significantly in peak hours. Essentially, this would allow the freeway stretch to accommodate more vehicles in peak hours under control. Detailed development of ITCSP and simulation will be reported in the future due to limited paper length.

VII. CONCLUDING REMARKS

Freeway corridor traffic flow is determined by bottleneck flows. There may be multiple bottlenecks. The most critical one is that with the least capacity flow. To maximize the traffic flow needs maximizing the bottleneck flow. This paper uses combined VSL and CRM to achieve this purpose. The VSL design strategy is to create a discharge section immediately upstream of the bottleneck and regulating the feeding-flow into the bottleneck close to its capacity flow. After VSL design, the CRM is designed based on a linearized density model which is necessary to predict the spatiotemporal characteristics of density for optimal ramp metering. Such linearization greatly simplifies CRM design.

The VSL design is a higher level scheme which takes into account onramp demand and length, mainline flow, and driver acceptance such as VSL variation limit over time and space. The refined optimization is left to the CRM design. With Finite Time Horizon MPC approach, the control design problem can be formulated as linear optimization at each time step with proper constraints. The solution searching at each time step is simple and calculation is very efficient. Simulation has been conducted over the I-80W section from Carlson to the MacArthur Maze, showing that combined VSL and CRM could potentially improve traffic performance such as TTS and TTD significantly.

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