Get More Out of Variable Speed Limit (VSL) Control: An Integrated Approach to Manage Traffic Corridors with Multiple Bottlenecks

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16. Abstract
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About the Pacific Southwest Region University Transportation Center

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The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education, and technology transfer aimed at *improving the mobility of people and goods throughout the region*. Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

U.S. Department of Transportation (USDOT) Disclaimer

Disclosure

Principal Investigator, Michael Zhang, and Graduate Student Researchers Hang Gao and Shenyang Chen conducted this research titled, "Get More Out of Variable Speed Limit Control: An Integrated Approach to Manage Traffic Corridors with Multiple Bottlenecks," at the Department of Civil and Environmental Engineering, College of Engineering, University of California, Davis. The research took place from October 2018 to December 2019 and was funded by a grant from the U.S. Department of Transportation in the amount of $116,813.00. The research was conducted as part of the Pacific Southwest Region University Transportation Center research program.

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Abstract

The model based variable speed limit (VSL) control has been proven effective to resolve capacity-drop and time delay at a single recurrent bottleneck in previous studies. This project applies VSL controls to the traffic corridors with multi-segment and multi-bottleneck with the objective of reducing fuel consumption and greenhouse gas emissions. Based on a comprehensive review of existing methods, we develop and compare two fuel consumption centered VSL control (FC-VSL) strategies: flow-based control versus density-based control. These control strategies are implemented in SUMO, a microscopic traffic simulation package, on a 10-mile long freeway section. Results show that the density-based control reduces fuel consumption and gas emissions significantly at the cost of slight increase of travel time. The flow-based control, in contrast, reduces congestion and emissions in the downstream segments but transfers the congestion to the segments upstream of the controlled segments, resulting in an overall performance that is worse than the density-based FC-VSL, and no better than imposing static speed limits.

Get More Out of Variable Speed Limit (VSL) Control: An Integrated Approach to Manage Traffic Corridors with Multiple Bottlenecks

Executive Summary

This project investigates the potentials of fuel consumption centered variable speed limit (FC-VSL) control in the freeway corridor with multiple segments and multiple bottlenecks. The FC-VSL strategies are designed based on the model predictive control that has been studied extensively to resolve capacity drop and reduce time delay at the single recurrent freeway bottleneck (lane drop or ramp). Despite previous study confirming the environmental benefit of VSL in non-congested conditions, this study focuses on the case where traffic can be congested.

Emission model choice and benchmark

we select the HBEFA v3.1 emission model of SUMO to estimate the fuel consumption and gas emissions. Like other microscopic emission models, it uses vehicle's instantaneous speed and acceleration as input. The cubic functional form yields adaptation to calibration from the HBEFA database that keeps updating. A numerical benchmark shows that the optimal speed for fuel consumption ranges around 30 mph to 45 mph.

The FC-VSL strategies

While most variable speed limit control strategies aim to improving safety and reducing congestion, the goal of the FC-VSL strategy is to reduce fuel use and certain emissions. We develop and evaluate FC-VSL control strategies for freeways with multiple interacting bottlenecks: flow-based FC-VSL and density-based FC-VSL.

<u>Flow-based strategy:</u>

This strategy is designed to maximize throughput at the congested bottleneck. Previous studies have implemented it at single bottleneck to reduce the effect of capacity drop such that the overall vehicle delay is reduced. In the multi-bottleneck context, the strategy is implemented with three key components:

- ✓ A demand control VSL segment upstream of all the bottlenecks to prevent congestion;
- ✓ A fuel-efficient operating speed assigned in all the segments downstream the demand control segment;
- ✓ The activation/deactivation criteria of demand control.

<u>Density-based strategy:</u>

This strategy is designed to keep the density of freeway segment around an exogenous optimal density. It aims to minimize the so-called "cost" from the difference between optimal density

and actual density. As a result, it prevents flow breakdown and formation of queue. An LQR controller is applied to choose speed limit based on the measured density.

Simulation and results

SUMO, an open-source microscopic simulator, is selected to build the testbed for FC-VSL strategies. The source code of lane change model is modified to enable queue propagation from right-hand lanes to the middle lanes. Moreover, we develop external modules to aggregate detection data and implement VSL control actions via TraCI API. A 10-mile-long freeway network of Interstate 80 Eastbound near Davis, CA is modeled for case study in SUMO, divided into 19 segments. It contains 6 junctions where 4 of them are all "critical" bottlenecks. We compare the scenarios of three types of control: static speed limit, flow-based and density-based control with different optimal speed settings. Results show that:

- Flow-based VSL transfers congestion to upstream, whose overall performance is no better than that of static speed limits, and is worse than density-based VSL.
- Density-based VSL produces more reduction in fuel consumption and carbon emissions with less travel time increase than the other two VSL control strategies. Furthermore, its performance is not sensitive to the choice of optimal target speed as long as it falls in the fuel-efficiency range (35-50 mph based on SUMO's HBEFA v3.1 model).

Introduction

Variable speed limit (VSL) has been extensively studied as an effective tool for active traffic management and operation. Originally, VSL is designed to improve safety. Via active assignment of travel speed in a proper range, it significantly reduces the crash likelihood in the case of medium-to-high speed regimes on the freeway (Abdel-Aty, Dilmore et al. 2006). Specifically, a fine-tuned VSL strategy near recurrent bottlenecks can lower the rear-end collision potential over 50% as well as travel time saving over 30% (Islam, Hadiuzzaman et al. 2013, Li, Liu et al. 2014). Yet, many existing VSL systems in practice are associated with extreme weather and work zones (Al-Kaisy, Ewan et al. 2012, Edara, Sun et al. 2013, Choi and Oh 2016). Even though low speed limits may cause larger speed difference, it still increases the vehicle storage capacity and lane utilization of freeway segments (Soriguera, Martínez et al. 2017).

Recent studies have treated VSL as more than an advisory speed limit system. Many scholars have been exploring the impact of VSL as a control method for managing freeway bottlenecks (Bertini, Boice et al. 2006). It is widely recognized that flow breakdowns at bottlenecks and the resulting shockwaves cause “capacity-drop”, an approximately 5% to 20% reduction of throughput (Cassidy and Bertini 1999, Bertini and Leal 2005). The “capacity-drop”, caused by the gaps created by lane changes and vehicle’s bounded acceleration (Leclercq, Laval et al. 2011, Chen and Ahn 2018), further intensifies the congestion, energy consumption and emissions of freeway traffic. Analysis using traffic data in the UK indicates that VSL control substantially improves the maximum flow rate (Heydecker and Addison 2011).

Various studies have developed VSL control strategies to resolve capacity-drop along with flow breakdown at a recurrent bottleneck. Some of them develop analytical models for an isolated yet recurrent bottleneck (Chen, Ahn et al. 2014, Han, Chen et al. 2017); others introduce multiple VSL-controlled segments (Zhang and Ioannou 2017, Zhang and Ioannou 2018). Despite the minor difference in the context, their methodologies are essentially the same, that is, to apply the VSL as a (mainline) traffic demand controller. Even though Lu, Varaiya et al. (2011) treat multiple bottlenecks in their studied segments, the “critical bottleneck” is always located at the end of VSL-controlled segments and all the other bottlenecks. None of them consider the common cases that bottlenecks downstream the critical bottleneck nullify the gains of VSL control.

While most work contribute to the VSL control strategies to reduce time delay, some other studies explore its application in reducing fuel consumption and emissions of highway traffic. Stevanovic, Stevanovic et al. (2009) tests heuristic algorithms using fuel consumption, CO2 emissions and delay on an integrated platform. Despite the substantial improvement in the final results, lengthy computational time prevent the methods to be applied for practical use. In contrast, a model predictive control performs more efficient (Asadi and Vahidi 2011). From the studies that attempt to reduce fuel consumptions and emissions using VSL control, it is concluded that fuel consumption centered VSL control on freeways does reduce environmental externality under the non-congested conditions (Liu, Ghosal et al. 2012); but may not be as

effective as travel time centered VSL control (Zegeye, De Schutter et al. 2009). Overall, the benefit of VSL is limited if it cannot significantly reduce congestion (Soriguera, Torné et al. 2013).

Under the model predictive control (MPC) framework, the existing VSL control methods can be categorized into two families.

1. Flow-based control. This kind of control logic attempts to maintain the maximum flow rate in the downstream of VSL-controlled segments. As is demonstrated in the literature (Chen, Ahn et al. 2014, Zhang and Ioannou 2018), the optimal speed limit is estimated based on the expected flow rate at the steady state. The outcome of speed limit is relatively stable.
2. Density-based control. This kind of control logic keeps the density of controlled segment around the target density estimated from the expected flow rate and flow-density diagram. It determines the speed limit by the difference between target density and measured density(Lu, Varaiya et al. 2011, Zhang and Ioannou 2017). By frequently shifting speed limit, the VSL control facilitates flow discharge of dense segments, thereby preventing the flow from breaking down. Unlike the steady state demand control which considers only the long-term response of VSL, the short-term response is not negligible for feedback control.

In this study, we will apply VSL control strategies to a multi-segment and multi-bottleneck corridor with extra bottlenecks downstream of the “critical bottleneck”. Via the specific design for the studied corridor and implementation in an integrated platform based on SUMO, an open source microscopic simulator, we will test and compare the effectiveness of aforementioned control strategies. Given the existing studies that optimize traffic throughput and queueing delay, our efforts will be focused on the fuel-consumption-aware variable speed limit (FC-VSL) strategies that prioritizes reducing fuel consumption and greenhouse gas emissions, which does not intend to recover the traffic to free flow speed but to maintain the traffic speed in the fuel-efficient range.

Three major assumptions are made as listed below for simplification:

1. The studied freeway network is virtually segmented and equipped with variable speed signs. Each segment can have its own speed limit.
2. All the vehicles follow the speed limit with some speed control error.
3. The traffic simulated contains only passenger cars (trucks are converted to equivalent passenger cars with PCE values).

Review of emission models

Various emission models have been developed to evaluate the exhausts of road traffic. They utilize different data inputs, functional forms, and pollutant coverage to meet with different

application contexts. Some popular models like MOVES and MOBILE, its predecessor, known as "inventory" or macroscopic model, are developed for the purpose of calculating the automotive performance in a predefined driving cycle (EPA 2014). Despite wide pollutant coverage, their major inputs are travel distance and average speed, which is not accurate enough to capture the variability of emissions due to complex traffic flow dynamics. In contrast, a "instantaneous" model using vehicle's instant speed and acceleration as input second by second is necessary to evaluate the operational-level problem.

Since 1990s, scholars have developed a variety of instantaneous emission models for academic use, among which CMEM and VT-Micro are the two popular representatives following different philosophy. As a physical model that modularizes the emission process, CMEM can predict emissions for light duty vehicles in various operating states; but exhibits abnormal behaviors in high speed range. In contrast to the complex structure of CMEM, VT-Micro, as a cubic regression model, has been proven to be able to produce consistent outputs when compared with field measurement data (Rakha, Ahn et al. 2003).

In this project, we select the HBEFA v3.1 emission model of SUMO to estimate the fuel consumption and emissions. With a polynomial functional form that is similar to VT-Micro and being calibrated using HBEFA database that is frequently updated, it delivers reliable results and has been extensively used in various investigations (Krajzewicz, Behrisch et al. 2015).

A benchmark of SUMO's HBEFA emission model

A numerical benchmark is set up to approximate the fuel consumption with speed limit. The general form of emission and fuel consumption with respect to instant speed v and acceleration a is given as Eq. 1:

$$e(v,a) = \max\{0, c_0 + c_1 va + c_2 va^2 + c_3 v + c_4 v^2 + c_5 v^3\} \qquad \text{Eq. 1}$$

In general, a vehicle entering a road segment with length L with initial speed v_0 and being imposed with new speed limit v_t experiences an acceleration/deceleration phase (Phase One) and a uniform speed phase (Phase Two) before it passes through. Assuming a constant acceleration rate a^+ and deceleration rate a^- in Phase One, we derive the cumulative emission or fuel consumption as shown in Eq. 2:

$$E(v_0, v_t) = \int_0^T e\big(v(t; v_0, v_t), a(t)\big)\, dt$$

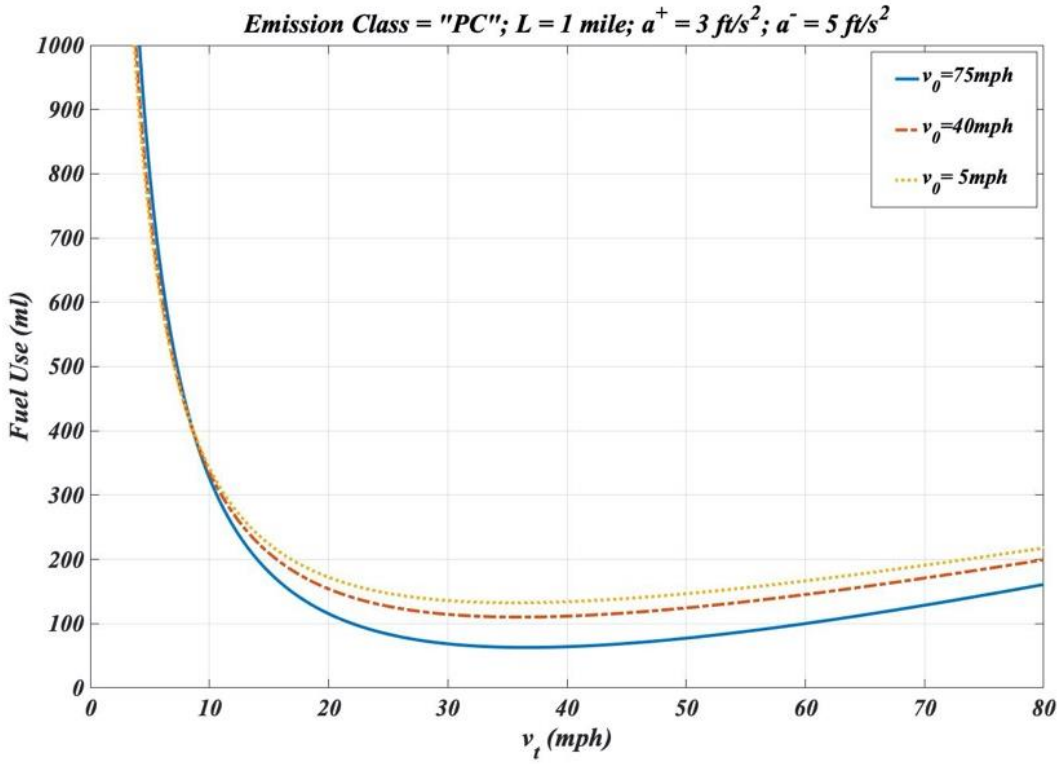
$$a(t) = \begin{cases} a^+ & v(t; v_0, v_t) < v_t \\ 0 & v(t; v_0, v_t) = v_t \\ -a^- & v(t; v_0, v_t) > v_t \end{cases} \qquad \text{Eq. 2}$$

$$v(t; v_0, v_t) = \begin{cases} v_0 + at & t < \dfrac{v_t - v_0}{a} \\ v_t & otherwise \end{cases}$$

where T is solved by equation $\int_0^T v(t; v_0, v_t)\, dt = L$.

Figure 1 is the benchmark of an average passenger car (emission class "PC" in SUMO) with acceleration rate $3\ ft/s^2$ and deceleration rate $5\ ft/s^2$ passing through a 1-mile-long road segment. We plot three curves using different sample initial speed $v_0 = 5, 45, 75\ mph$. The results imply that the optimal fuel-efficient speed limit is approximately around $40\ mph$, either with low or high initial speed. It should be pointed out that the fuel-use curve shown in Figure 1 is rather flat in the speed range of [30pmh, 50mph], and therefore any speed in this range can be chosen as the target "optimal" speed in the subsequent VSL control strategies.

Figure 1. Fuel use versus speed limit on a 1-mile-long road segment



Fundamental diagram of a single-segment road

Although early studies propose nonlinear VSL-aware diagram of flow-density relation to represent the benefit of VSL control (Hegyi, Deschutter et al. 2005, Carlson, Papamichail et al. 2010), it is hard to pair these flow-density diagrams with specific car following and lane change models. These models are necessary only if evaluation of VSL strategy stays at macroscopic level. In contrast, we select a piecewise linear flow-density diagram to approximate the value of speed limit, such that the flow-density relation is easy to calibrate with simulation models. Consider an arbitrary road section with infinitesimal length, the traffic flow volume q is a function of density ρ, denoted as

$$q = f\left(\rho; v^f, c_j, \rho_j, \bar{q}\right) = \min\left\{v^f \cdot \rho, c_j \cdot \left(\rho_j - \rho\right), \bar{q}\right\} \qquad \text{Eq. 3a}$$

where the parameters are defined as follows:

v^f: the free flow speed of the road section;
c_j: the backpropagate wave speed;
ρ_j: the jam density;
$\bar{q}$: the capacity of road section.

With $q = \rho \cdot v$, we derive the flow q as a function of speed v:

$$q = g(v;\ c_j, \rho_j, \bar{q}) = \min\left\{\frac{c_j \rho_j v}{c_j + v}, \bar{q}\right\}, 0 < v \leq v^f \qquad \text{Eq. 3b}$$

For a road segment with finite number M homogeneous road sections with unit length, on-ramp and off-ramp, the steady state maximum inflow with respect to density of section i's inflow is calculated as

$$q_i^{in} = \min\left\{\min_i\{f_i(\rho_i) + q_i^{off} - q_i^{on}\}, q_{i+1}^{in}\right\}\ \forall\ i = 1, \dots, M \qquad \text{Eq. 4}$$

Here, q_{M+1}^{in} represents the maximum throughput constrained by downstream segments; and flow conservation gives the constant equations $q_{i+1}^{in} = q_i^{out}\ \forall\ i = 1, \dots M$.

Eq. 4 illustrates the constraints of adjacent road sections and segments, which is consistent with Eq. 3a in all cases, where $\bar{q}$ can be determined by downstream mainline capacity, on-ramp flow and off-ramp flow.

Because real-time measurement of traffic flow is available at limited stations, it is necessary to estimate traffic condition given limited detection of a road segment. For a road segment with detectors at the entry and exit only, and no inner bottleneck, the steady state maximum inflow is estimated based on real-time detected inflow $\tilde{q}^{in}$, outflow $\tilde{q}^{out}$, on-ramp flow $\tilde{q}^{on}$ and off-ramp flow $\tilde{q}^{off}$ with Eq. 5a:

$$q^{in} \approx \min\{\tilde{q}^{out} + \tilde{q}^{off} - \tilde{q}^{on}, \tilde{q}^{in}\} \qquad \text{Eq. 5a}$$

Given the speed limit u_k of segment k and fundamental diagram at entry and exit, we can further estimate the maximum inflow of road segment k using Eq. 5b:

$$q_{k,max}^{in} = \min\{g_{k+1,in}(v_k) + \tilde{q}_k^{off} - \tilde{q}_k^{on}, g_{k,in}(v_k)\} \qquad \text{Eq. 5b}$$

Eq. 5b is a recursive form that helps to estimate the mainline throughput of any segment in the upstream, which is the key to our flow based VSL strategy.

Congestion dynamics of adjacent bottlenecks

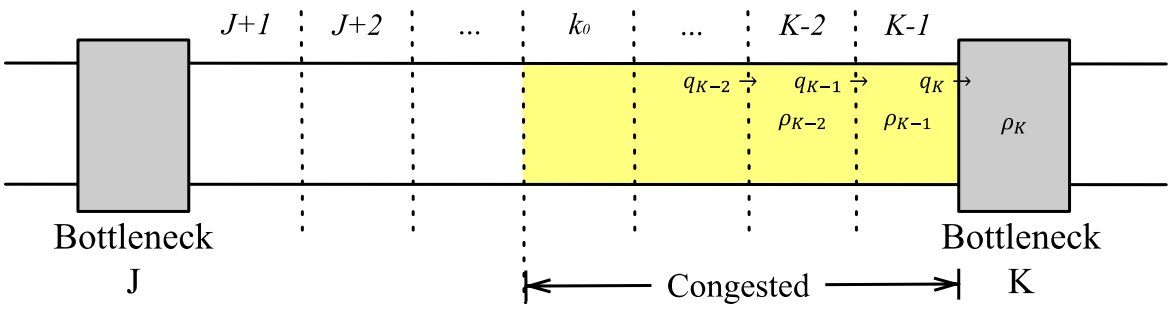
The existing literatures of flow based VSL strategies on recurrent bottlenecks so far have introduced similar components. As we see in Figure 2a, segment K contains a recurrent bottleneck with maximum inflow q_k. After flow breakdown occurs, the congested flow spills back to segment $K-1$, $K-2$ and so forth. Denote the downmost congested segment $K-1$ as "congestion head"; and the upmost congested segment k_0 as "congestion tail". Then VSL is activated at segment $K-1$ with speed limit v_{k-1}, which allows segment K to discharge at speed limit v_k, which performs as a "demand controller". An adjacent bottleneck in segment J is located in the upstream with finite segments in between. Assuming there is no lane drop or ramp in these segments, the discharge flow of segment J, q_{J+1} equals the demand of segment K.

As is clearly summarized by Lu, Varaiya et al. (2011), the dynamics of congested segments are determined by discharge flow downstream (outflow of segment K, q_{K+1}) and feeding flow upstream (outflow of segment J, q_{J+1}). The congestion tail k_0 moves forward if $q_{J+1} < q_K$ and backward if $q_{J+1} > q_K$. $q_{J+1} = q_K$ is the maximum flow rate to keep the downstream segments out of congestion after the congested segments are fully discharged.

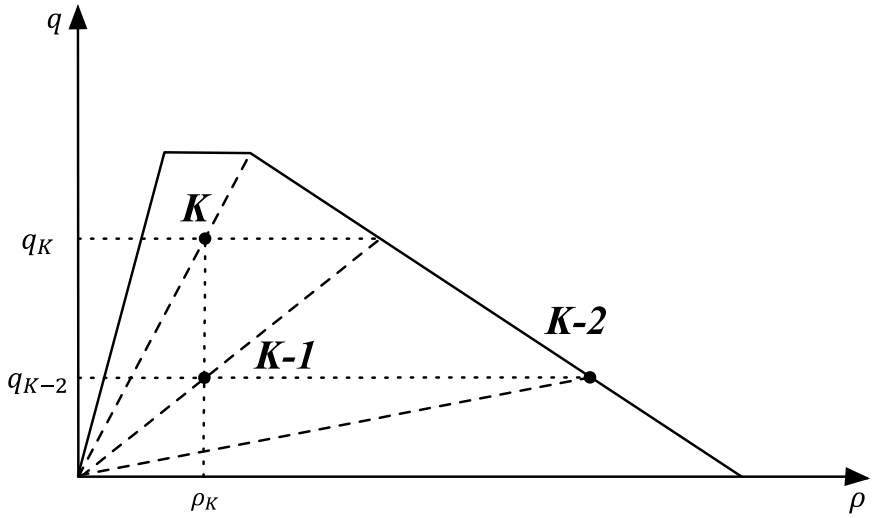
Moreover, we analyze the possible movement of congestion head and its outcome using the fundamental diagram. Given constant road capacity of segment K for discharge, the VSL control guarantees that congestion head at $K-1$ won't move forward. Yet, moving congestion head backward is costly and inefficient. As is shown in Figure 2b, it is necessary that $\rho_{k-1} \leq \rho_k$ such that the flow rate won't exceed q_k when the state of segment $K-1$ changes from congestion head to discharge with speed limit raised from u_{k-1} to u_k. This condition requests further suppression of throughput in segment $K-2$ and upstream further. Both throughput and speed limit must be restricted extremely low. Therefore, we conclude that the most efficient way to operate demand controller is to set up a fixed location and leave it unmovable after VSL is activated.

Figure 2. Congestion dynamics of adjacent bottlenecks

a) VSL components related to adjacent recurrent bottlenecks



b) Necessary conditions that congestion head moves upward from $K-1$ to $K-2$



FC-VSL Control Strategies

We propose two FC-VSL control strategies in this research: the flow-based FC-VSL control and the density-based FC-VSL control. The former is developed based on how congestion shockwaves generated by bottlenecks propagate and controls the inflow to the bottlenecks from a so-called demand-control segment upstream of the bottlenecks. The latter attempts to maintain a target density (hence a target fuel-efficient operating speed) through controlling the speed limits of each segment through linear quadratic regulator feedback control.

Flow-based FC-VSL strategy

The flow-based FC-VSL strategy for a multi-segment and multi-bottleneck freeway zone is designed based on the analysis above on the characteristics of shockwaves between adjacent bottlenecks. It consists of three key decision components to suppress the negative effects of

the shockwaves created by the bottlenecks and maintain a fuel-efficient speed in the controlled segments:

- A demand control VSL segment upstream of all the bottlenecks to prevent congestion;
- A fuel-efficient operating speed assigned to all the segments downstream the demand control segment;
- The activation/deactivation criteria of the demand control.

In a VSL zone with N segments and segment m selected for demand control, a universal fuel-efficient speed v^e is set for all the downstream segments $k = m+1, m+2, \dots, N$. Then the maximum inflow of segment m, $q_{m,max}^{in}$ is calculated recursively with Eq. 6a modified from Eq. 5b:

$$q_{N,max}^{in} = \min\{g_{N,out}(v^e) + \tilde{q}_N^{off} - \tilde{q}_N^{on}, g_{N,in}(v^e), C_d\};$$
$$q_{k,max}^{in} = \min\{q_{k+1,max}^{in} + \tilde{q}_k^{off} - \tilde{q}_k^{on}, g_{k,in}(v^e)\} \ \forall k = m, m+1, \dots, N-1 \qquad \text{Eq. 6a}$$

where C_d is the flow capacity downstream.

The value of demand control speed limit is then calculated inversely based on the fundamental diagram:

$$v_m^{in} = g_{m,in}^{-1}(q_{m,max}^{in}) \qquad \text{Eq. 6b}$$

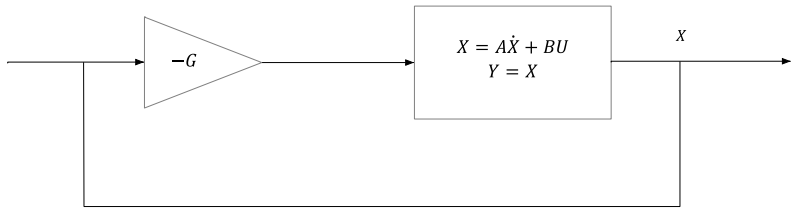
The demand control is activated if the measured speed of any segment $\tilde{u}_k < 0.9u^e, \forall k = m+1, \dots, N$; and is deactivated if the measured density of demand control segment $\tilde{\rho}_m \leq \frac{q_{m,max}^{in}}{v^e}$.

Density-based FC-VSL strategy

The density based VSL strategies are usually applied in the feedback control together with ramp metering. Studies have commonly demonstrate the effectiveness of integrated VSL and ramp metering feedback control for a single-ramp recurrent bottleneck with different traffic flow model (Hegyi, De Schutter et al. 2005, Carlson, Papamichail et al. 2010). Furthermore, the PID control method has been tested on a multi-segment and multi-bottleneck ring-road (Carlson, Papamichail et al. 2014). In comparison, the linear quadratic regulator (LQR), a control that has been proven to be smoother, simpler and more robust (Prasad, Tyagi et al. 2014), will be applied to the density-based FC-VSL feedback control to improve the mainline fuel consumption and emissions in a multi-segment and multi-bottleneck zone.

Linear quadratic regulator control is a well-known technique to design a full state feedback gain G to form a closed-loop system (Figure 3). It is an optimal controller that provides automated design procedure for generating only stabilizing control systems for Multiple Input Multiple Output (MIMO) plants. In the sense, it is a proper control strategy for VSL, specifically for multi-segments and multi-bottlenecks scenario.

Figure 3. The designed feedback control system



Denote $e_i(t) = \rho_i - \rho_i^e, u_i(t) = v_i - v_i^e$

$$e_i(t) = \alpha e_i(t-1) + \beta e_{i+1}(t) + u_i(t) \qquad \text{Eq. 7}$$

- $e_i(t)$ represents the density error between the optimal density ρ_i^e and measured density ρ_i at i^{th}segment in time step t.
- $u_i(t)$ represents the velocity error between the optimal velocity v_i^e and measured velocity v_i at i^{th}segment in time step t.
- α & β are just two parameters as constants.

Notably, the i^{th}segment is correlated with $(i+1)^{th}$ segment. The optimal speed of each segment $v_i^e = v^e$ is set universally in the range of fuel-efficient zone based on the emission model. Then the optimal density is calculated based on the fundamental diagram $\rho_i^e = \frac{g_{i,in}(v^e)}{v^e}$.

For N segments forming a long distance, we have our state-space model:

$$E(t) = A \cdot E(t-1) + B \cdot U(t) \qquad \text{Eq. 8}$$

$E(t) = [e_1, e_2, \dots, e_n]^T, U(t) = [u_1, u_2, \dots, u_n]^T$ Namely, the vector form of all density error and velocity error for multiple segments. B is just an identity matrix $I_{n\times n}$. A is a Toeplitz matrix with elements α & β:

$$A = \begin{bmatrix} \alpha & \beta & 0 & \cdots & 0 \\ 0 & \alpha & \beta & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & 0 \\ \vdots & \vdots & \cdots & \ddots & \beta \\ 0 & \cdots & \cdots & \cdots & \alpha \end{bmatrix}$$

The cost function of the discrete system could be constructed below:

$$\begin{aligned} J &= \sum_{\tau=1}^{N} \|e(\tau)\|^2 + \rho \sum_{\tau=1}^{N} \|u(\tau)\|^2 \\ &= E^T Q E + U^T R U \end{aligned} \qquad \text{Eq. 9}$$

$\sqrt{\rho}$ gives relative weighting of density error Euclidian norm and velocity error Euclidian norm which is the control variable. The requirement $J \geq 0$ implies both Q and R are positive definite. The compared eigenvalues of Q and R determines the sensitiveness between the road system and VSL control speed. Technically, if $Q \gg R$, it indicates the system cost ρ_i^e dominates the cost function and if not, the control cost v_i^e dominates the cost function. In most cases, the former is preferred over the latter for smooth control.

With the prerequisite of Q and R being positive definite, the regulator G is obtained through solving:

$$\dot{\lambda} = -QE - A^T\lambda \qquad \text{Eq. 10}$$

$$RU + B^T\lambda = 0 \qquad \text{Eq. 11}$$

From Eq. 10, the systems are clearly linear, we introduce a connection $\lambda = PE$ inserting into the first condition Eq.11 with a substitution for U, we obtain

$$PAE + A^TPE + QE - PBR^{-1}B^TPE + \dot{P} = 0 \qquad \text{Eq. 12}$$

It holds for all e_i the steady-state solution satisfies the matrix $Riccati\ equation$ where:

$$A^TS + SA - SBR^{-1}B^TS + Q = 0 \qquad \text{Eq. 13}$$

Through this process, the VSL speed control $U(k)$ is determined:

$$U(t) = -GU(t-1) \qquad \text{Eq. 14}$$

$$G = R^{-1}B^TS \qquad \text{Eq. 15}$$

Simulation platform

Various simulation platforms have been applied to VSL related tests, either the macroscopic simulators like METANET or the microscopic simulators like VISSIM, AIMSUM and PARAMICS. Among these commercial microscopic simulators, the preset car-following and lane-change models cannot represent the process of flow breakdown and propagation either backward or to median lanes. Therefore, we choose SUMO, an open-source microscopic simulator to build our testbed for FC-VSL strategies. Thanks to the open source code of SUMO's lane change model, we are able to reproduce the flow breakdown and backpropagation in all lanes by slightly modifying the lane change model. The platform has an external library that is connected to the SUMO simulation model via TraCI API. Based on the basic components of "detector" and "vehicle", the platform can process data retrieval, aggregation, strategic computation and control update in each time step (Figure 4).

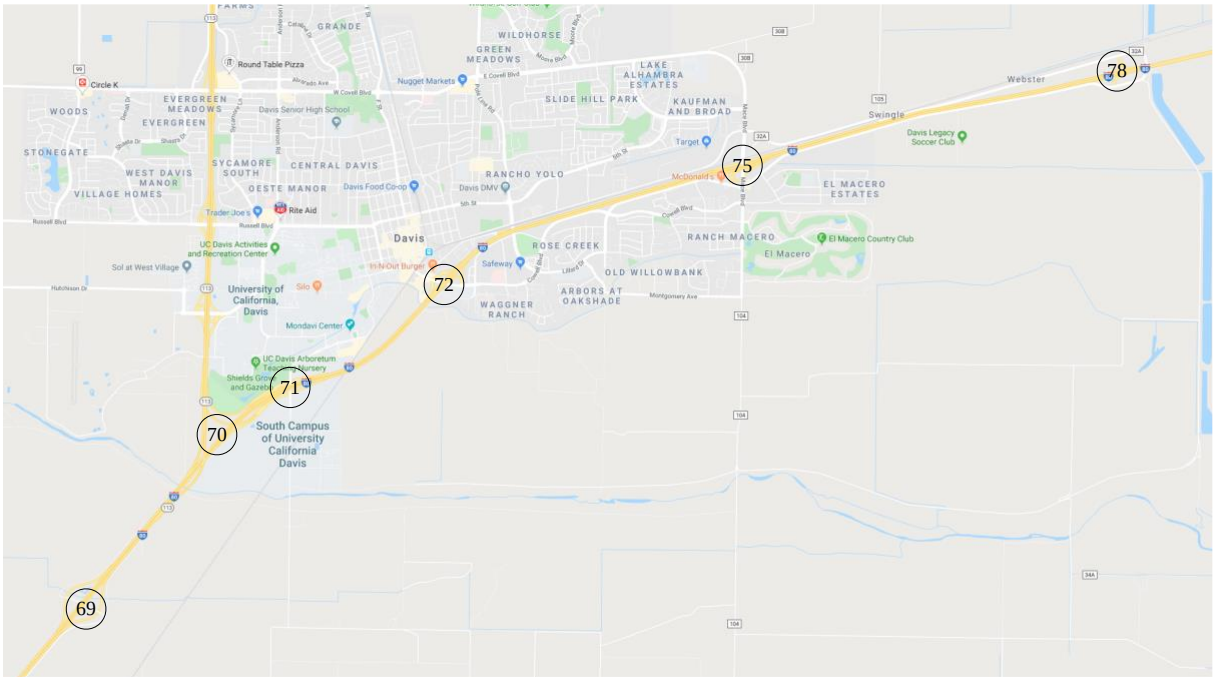
Figure 4. Data exchange via TraCI API

In the external library, we construct VSL components that facilitate data aggregation and strategic computation as is listed below:

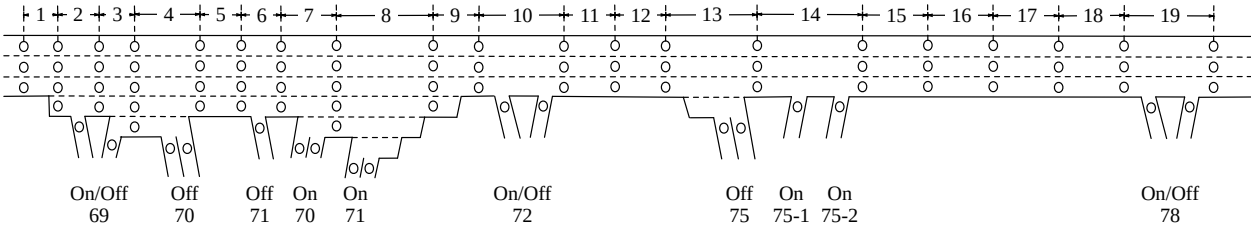
- An all-lane flow detector that covers multiple lanes at a certain detector station, where speed, flow and density is aggregated over time and lane;
- A fundamental diagram per flow detector to calculate speed limit;
- A variable speed sign paired with a detector to set new speed limit to the vehicles passing though (SUMO doesn't offer dedicated speed sign object that can be modified via TraCI API);
- A VSL segment that aggregate all the components at entry and exit that have been listed above.

Figure 5. Simulation network topology

a) Studied freeway section and contained junctions



b) Detector locations and VSL segmentation



A 10-mile-long freeway section of Interstate-80 Eastbound, with 6 junctions across the city of Davis, CA is selected to evaluate our VSL control strategies. This section has a series of recurrent bottlenecks and severe congestion occurs almost every day in the afternoon peak hours. These multiple bottlenecks are all "critical" along the path. As is shown in Figure 5a, Junction 70 is interconnected with SR-113, another freeway from the north. It introduces heavy merging traffic without metering. A vast lane drop from 6 to 3 lanes exists between Junction 71 and 72. With saturated mainline flow and extra ramp demand at Junction 75 and 78, the downstream traffic flow is sensitive to breakdown even with ramp metering activated in peak hours.

The corridor is partitioned into 19 segments. Each segment is approximately 0.5-mile-long, as is shown in Figure 5b. Segment 1 is selected as the critical VSL segment for demand control. Based on the public database from PeMS, we configure three typical demand sets (light, medium and heavy, see Tab. A1. in Appendix); and calibrate the traffic flow parameters. In this scenario, we use the Krauss car-following model with critical headway $\tau = 1.3\ sec$, maximum

acceleration rate $acc = 1.8\ m/s^s$, maximum deceleration rate $dec = 2.8\ m/s^2$ and driving imperfection $\sigma = 0.5$. The model is calibrated using the peak hour traffic volume data for this segment obtained from the PeMS database. From these parameters, we further estimate the parameters of fundamental diagram listed below:

$$\begin{cases} v^f = 75mph, c_j = 12.5mph, \rho_j = 600vpm, \bar{q} = 6000vph & if\ lane\ number = 3 \\ v^f = 75mph, c_j = 12mph, \rho_j = 800vpm, \bar{q} = 7000vph & if\ lane\ number \geq 4 \end{cases}$$

The vehicle demand input lasts for 5 hours, which consists of the demand sets in sequence of $light \times 1h \rightarrow medium \times 1h \rightarrow heavy \times 1h \rightarrow medium \times 1h \rightarrow light \times 1h$. The first hour is the warmup phase and VSL control starts in the second hour.

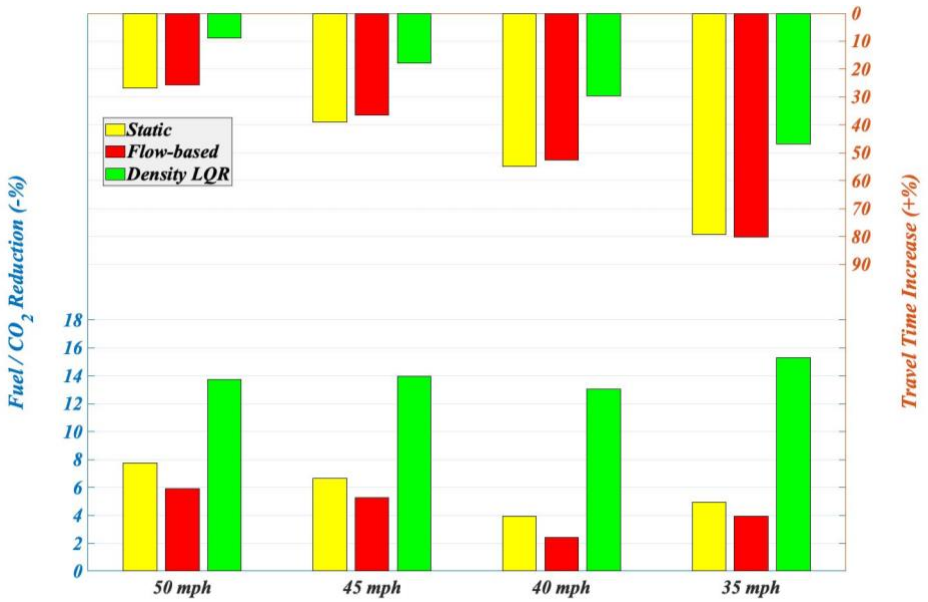
Simulation Results

We test the flow-based and density-based strategy and compare the results with the scenarios of static speed limit in the VSL segments. Each scenario is implemented using optimal speed limit $50mph, 45mph, 40mph, 35mph$. The aggregated average travel time, fuel consumption and carbon emissions are listed in Tab. A2. In Appendix.

From Tab.A2., it is clear that imposing lower speed limits than free flow speed does improve the fuel efficiency and carbon emissions as well as increase the travel time. The absolute volume CO_2 emissions are dominant to CO and HC. All the carbon emissions are proportional to fuel consumption. Therefore, fuel consumption centered control also contributes to reducing carbon emissions. The percentage of fuel use reduction versus travel time increase compared to the scenario of no VSL control is listed in Figure 6.

In Figure 6, we see that density-based LQR control has better performance than the flow-based control and static speed limits. With optimal target speed set to 50 mph, the LQR control yields about 14% reduction of fuel use and CO_2 emissions with only 9% of travel time increase. Lower optimal target speed settings result in extra travel time but not necessarily further fuel reduction. Static speed limit works effectively in fuel saving only for non-congested conditions. The flow-based control mitigates downstream congestion but transfers the congestion to upstream, which doesn't improve the overall performance since some segments downstream are not fully utilized. Figure 6 shows that the fuel saving of flow-based control cannot even match that of the static speed limit control. Clearly it is not worth the extra effort to implement such a more complicated control when its performance is worse than the much simpler static speed limit control. From these simulation results, it is clear that the density-based LQR control is the most effective strategy to reduce fuel consumption and carbon emissions on a multi-segment and multi-bottleneck corridor.

Figure 6. Fuel/CO_2 reduction vs. travel time increase



Conclusion and future work

This study investigates the use of VSL strategies on a multi-segment and multi-bottleneck corridor to reduce fuel consumption and emissions. Under the framework of model predictive control, all the calculation of the target speed limits is based on the fundamental diagrams. Based on the selected fuel consumption/emissions model and the analysis of bottleneck dynamics, we propose a flow-based and a density-based VSL strategy, which are implemented and tested in the SUMO simulation software. While both flow-based and density-based control work in the scenarios where single critical bottleneck is targeted at the end of VSL segments, the simulation results indicate that only density-based control strategy can be extended to effectively control multi-bottlenecks to reduce fuel use and emissions. The flow-based VSL strategy optimizes only the segments downstream the critical VSL segment, which is not adequate to improve overall efficiency. Choice of optimal speed is a tradeoff between travel time and environmental cost, which is subjective problem.

For future study, we will combine the FC-VSL together with ramp metering as others have done. Meanwhile, we will explore the model-free reinforcement learning for speed limit control considering the fact that traffic flow in real world are heterogeneous. These efforts will augment the FC-VSL strategies that we proposed in this research.

References

Abdel-Aty, M., et al. (2006). "Evaluation of variable speed limits for real-time freeway safety improvement." Accident analysis & prevention **38**(2): 335-345.

Al-Kaisy, A., et al. (2012). Evaluation of a variable speed limit system for wet and extreme weather conditions: phase 1 report, Oregon. Dept. of Transportation. Research Section.

Asadi, B. and A. Vahidi (2011). "Predictive Cruise Control: Utilizing Upcoming Traffic Signal Information for Improving Fuel Economy and Reducing Trip Time." IEEE Transactions on Control Systems Technology **19**(3): 707-714.

Bertini, R. L., et al. (2006). "Dynamics of variable speed limit system surrounding bottleneck on german autobahn." Transportation Research Record **1978**(1): 149-159.

Bertini, R. L. and M. T. Leal (2005). "Empirical study of traffic features at a freeway lane drop." Journal of Transportation Engineering **131**(6): 397-407.

Carlson, R. C., et al. (2014). "Integrated feedback ramp metering and mainstream traffic flow control on motorways using variable speed limits." Transportation research part C: emerging technologies **46**: 209-221.

Carlson, R. C., et al. (2010). "Optimal motorway traffic flow control involving variable speed limits and ramp metering." Transportation Science **44**(2): 238-253.

Cassidy, M. J. and R. L. Bertini (1999). "Some traffic features at freeway bottlenecks." Transportation Research Part B: Methodological **33**(1): 25-42.

Chen, D. and S. Ahn (2018). "Capacity-drop at extended bottlenecks: Merge, diverge, and weave." Transportation Research Part B: Methodological **108**: 1-20.

Chen, D., et al. (2014). "Variable speed limit control for steady and oscillatory queues at fixed freeway bottlenecks." Transportation Research Part B: Methodological **70**: 340-358.

Choi, S. and C. Oh (2016). "Proactive strategy for variable speed limit operations on freeways under foggy weather conditions." Transportation Research Record **2551**(1): 29-36.

Edara, P. K., et al. (2013). Evaluation of variable advisory speed limits in work zones, Iowa. Dept. of Transportation.

EPA, U. (2014). Motor vehicle emission simulator (MOVES), user guide for MOVES2014.

Han, Y., et al. (2017). "Variable speed limit control at fixed freeway bottlenecks using connected vehicles." Transportation Research Part B: Methodological **98**: 113-134.

Hegyi, A., et al. (2005). "Model predictive control for optimal coordination of ramp metering and variable speed limits." Transportation research part C: emerging technologies **13**(3): 185-209.

Hegyi, A., et al. (2005). "Optimal coordination of variable speed limits to suppress shock waves." IEEE transactions on intelligent transportation systems **6**(1): 102-112.

Heydecker, B. and J. D. Addison (2011). "Analysis and modelling of traffic flow under variable speed limits." Transportation research part C: emerging technologies **19**(2): 206-217.

Islam, M. T., et al. (2013). "Assessing mobility and safety impacts of a variable speed limit control strategy." Transportation Research Record **2364**(1): 1-11.

Krajzewicz, D., et al. (2015). Second Generation of Pollutant Emission Models for SUMO. Modeling Mobility with Open Data**:** 203-221.

Leclercq, L., et al. (2011). "Capacity drops at merges: An endogenous model." Procedia-Social and Behavioral Sciences **17**: 12-26.

Li, Z., et al. (2014). "Development of a control strategy of variable speed limits to reduce rear-end collision risks near freeway recurrent bottlenecks." IEEE transactions on intelligent transportation systems **15**(2): 866-877.

Liu, B., et al. (2012). "Reducing Greenhouse Effects via Fuel Consumption-Aware Variable Speed Limit (FC-VSL)." IEEE Transactions on Vehicular Technology **61**(1): 111-122.

Lu, X.-Y., et al. (2011). "Novel freeway traffic control with variable speed limit and coordinated ramp metering." Transportation Research Record **2229**(1): 55-65.

Prasad, L. B., et al. (2014). "Optimal control of nonlinear inverted pendulum system using PID controller and LQR: performance analysis without and with disturbance input." International Journal of Automation and Computing **11**(6): 661-670.

Rakha, H., et al. (2003). "Comparison of MOBILE5a, MOBILE6, VT-MICRO, and CMEM models for estimating hot-stabilized light-duty gasoline vehicle emissions." Canadian Journal of Civil Engineering **30**(6): 1010-1021.

Soriguera, F., et al. (2017). "Effects of low speed limits on freeway traffic flow." Transportation research part C: emerging technologies **77**: 257-274.

Soriguera, F., et al. (2013). "Assessment of Dynamic Speed Limit Management on Metropolitan Freeways." Journal of Intelligent Transportation Systems **17**(1): 78-90.

Stevanovic, A., et al. (2009). "Optimizing Traffic Control to Reduce Fuel Consumption and Vehicular Emissions." Transportation Research Record: Journal of the Transportation Research Board **2128**(1): 105-113.

Zegeye, S. K., et al. (2009). "Model-based traffic control for balanced reduction of fuel consumption, emissions, and travel time." IFAC Proceedings Volumes **42**(15): 149-154.

Zhang, Y. and P. A. Ioannou (2017). "Combined Variable Speed Limit and Lane Change Control for Highway Traffic." IEEE transactions on intelligent transportation systems **18**(7): 1812-1823.

Zhang, Y. and P. A. Ioannou (2018). "Stability analysis and variable speed limit control of a traffic flow model." Transportation Research Part B: Methodological **118**: 31-65.

Data Management

Products of Research

As a simulation-based study, the project generates the simulation related data listed below:

1) SUMO input data, including network topology, detector position, vehicular demand and routine definition;
2) SUMO output data, including aggregated traffic measurement data (speed, flow and density), mainline travel time and emissions;
3) Python script for external modules, including aggregated detection, VSL component integration and control algorithms.

Data Format and Content

SUMO input data are stored in .XML format; SUMO output data are stored in .XML and .TXT format. Python script are in .PY format.

Data Access and Sharing

All the data used and produced in this research do not contain personal information, and most of them are from public data sources. They will be stored in a project Box folder during the research and transferred to ITS's data repository after the project is completed. They can be shared with the public upon request to the data repository.

Reuse and Redistribution

The intellectual property rights of the data belong to the researchers of the project, who also manage the data before the data are transferred to a data archive (the Dryad data repository). Once the data are transferred to the data archive, the researchers retain intellectual property rights but delegate the data management to the data archive. Public agencies such as Caltrans have free and complete access to the archived dataset.

The team allows for the use of the data with the proper citation and attribution to the research team and project.

Dataset DOI: https://doi.org/10.25338/B8QD04

Appendix A1

The OD demand sets are listed in Table A1.

Table A1. Simulation OD demand sets

Origin	Destination	Demand Set		
		Light	Medium	Heavy
Up	70	200	250	300
Up	71		50	100
Up	72	100	50	
Up	75	100		
Up	Down	1720	3000	4600
69	70	100	300	600
69	Down			200
70	72			400
70	75			400
70	Down	500	600	700
71	Down	50	400	600
72	Down	150	250	450
75-1	Down	80	150	300
75-2	Down	70	150	300
78	Down	20	300	550

Appendix A2

The simulation results of comparison between no VSL, static speed limit, flow-based control and density-based control are listed below:

Table A2. Aggregated mainline travel time and emissions

Optimal Speed	Control	Travel Time	Fuel use (ml/veh)	CO (g/veh)	CO2 (ton/veh)	HC (mg/veh)
No VSL		779.74	1937.20	72.39	4.507	440.77
50 mph	Static	988.64	1787.05	56.98	4.157	352.60
	Flow-based	979.53	1822.88	62.85	4.241	382.25
	Density LQR	848.16	1671.36	42.96	3.888	282.88
45 mph	Static	1084.16	1808.57	59.29	4.207	361.55
	Flow-based	1063.67	1834.67	63.91	4.268	385.05
	Density LQR	919.48	1666.89	41.51	3.878	273.23
40 mph	Static	1207.56	1860.96	64.17	4.329	384.68
	Flow-based	1188.92	1890.35	69.66	4.398	412.37
	Density LQR	1010.94	1684.83	41.68	3.920	273.21
35 mph	Static	1398.15	1841.06	69.48	4.283	403.34
	Flow-based	1404.84	1860.63	73.78	4.435	406.05
	Density LQR	1144.81	1640.92	40.62	3.817	262.80

Appendix A3

Since we conduct a simulation-based project, there is only modeling and simulation data which includes SUMO input, SUMO output and python script for modeling. The SUMO input mainly contains the case study network components. The SUMO output generates total travel time and emissions to do simulation analysis and the python script constructs functions to do modeling.

Data Files and Contents

SUMO Input Data		
File Name	**File Format**	**Contents**
vsl_I-80.net	xml	It's the traffic-related part of a map for Interstate-80 Eastbound. It defines the edges, junctions and connections to form a road network.
vsl_I-80.flow	xml	It defines the vehicular demand for SUMO like vehicle type, compliance, car-following model and flow of I-80
vsl_I-80.rou	xml	It automatically computes and builds vehicle routes from demand information
vsl_I-80.additionals	xml	It includes a wide range of network elements like detector definitions, variable speed signs and traffic light information for mainline and ramp
vsl_I-80.sumocfg	xml	It glues every input data file into a configuration file

SUMO Output Data		
File Name	**File Format**	**Contents**
emissions	xml	It generates unaggregated emission values for every vehicle and time step
scenario	xml	It is generated by python file named scenario. SUMO will not read the python script. Instead, TraCI generates the xml file for SUMO as executable file

Python Script		
File Name	**File Format**	**Contents**
embedded	Python	It guarantees the interaction between python and SUMO through TraCI which gives the complete flexibility of doing cross-platform, cross language and networked activities as a server
traci_main	Python	It constructs the modeling framework to run the simulation properly
variable_speed_limit	Python	It contains functional modules to update vsl speed. Variable speed sign: detect and update speed limit for each vehicle in every time step. VSLSegment: compute flow, capacity, density for mainline and ramp, check the congestion. Control_static and control_lqr: two vsl control strategies
flow_measure	Python	It contains functional modules to detect flow. FlowDetector: detect number of vehicles, compute flow rate and average speed. TrafficDiagram: Draw the fundamental diagram for each edge. EdgeFlowMeasure: compute critical density and corresponding discharging speed for each edge based on the diagram.
scenario	Python	It sets up the parameters of the simulation case study for detectors, edges and traffic diagrams
results	Python	It generates the aggregated emission and travel time results for emissions (xml)