Title

Traffic Flow Models and Impact of Combined Lane Change and Speed Limit Control on Environment in Case of High Truck Traffic Volumes

Authors
Ioannou, Petros
Zhang, Yihang
Zhao, Yanbo

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A Research Report from the National Center for Sustainable Transportation

Petros Ioannou, University of Southern California
Yihang Zhang, University of Southern California
Yanbo Zhao, University of Southern California

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ABSTRACT

This report presents the work performed in collaboration with University of California, Riverside (UCR) as part of a project to University of California, Davis funded by the California Energy Commission (CEC).

The aim of the project is to research intelligent traffic control strategies, which will have positive impact on the environment by reducing fuel consumption and pollution levels in areas where the truck volume is relatively high, using as an example for demonstration a network adjacent to the twin ports of Los Angeles and Long Beach.

The work is divided into two parts. The first part involves the development of a microscopic traffic simulation network in a selected area around the Ports of Long Beach/Los Angeles in collaboration with UCR to be used for simulation studies of different Intelligent Transportation Technologies for traffic flow control.

The second part deals with the evaluation of the impact of combined variable speed limit (VSL) and lane change control on the environment during highway incidents where the volume of trucks is relatively high. We use the simulation model developed in the first part to carry out microscopic Monte-Carlo traffic flow simulations of traffic in order to evaluate the benefits of combined VSL and lane change control during incidents on I-710 that involve closure of lanes and capacity drops. We demonstrated that this combined control strategy is able to generate consistent improvements with respect to travel time, safety, and environmental impact under different traffic conditions and incident scenarios.

CHAPTER 1: Microscopic Traffic Network Model

Under this effort we, developed a microscopic traffic simulation model using VISSIM software to be used for evaluation of different Intelligent Transportation System (ITS) technologies and traffic flow control techniques at the University of Southern California (USC) and University of California, Riverside (UCR).

The simulation model involves a traffic network that includes highways and arterial streets adjacent to the Port of Long Beach/Los Angeles. An arterial street is a high-capacity urban road that delivers traffic from smaller roads to freeways. In order to improve the speed of computations, the simulation model allows the user to split it into parts. For example, for highway traffic flow control the simulator models the highway traffic that interacts with some of the main arterial streets which feed into the respective highway, without exercising the full network. For traffic flow control strategies for arterial streets, the simulator focuses on traffic on arterial streets and treats the highway traffic as a source and sink of traffic interacting with the arterial network. The overall simulation model covers I-110, I-710, and SR-47 freeways, and arterial streets near the port as shown in Figure 1. The simulation model allows the implementation of traffic flow control algorithms in MATLAB/C++ software integrated with the simulation environment via a Component Object Model (COM) interface. The corresponding VISSIM diagram of the simulation model that focuses on highway traffic flow is shown in Figure 2.

Figure 1: Selected Freeway Network Area

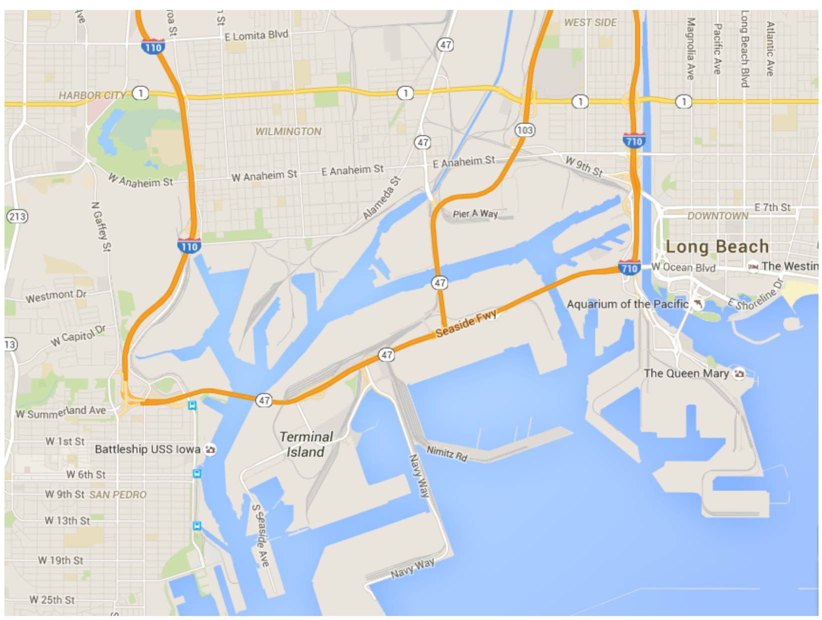

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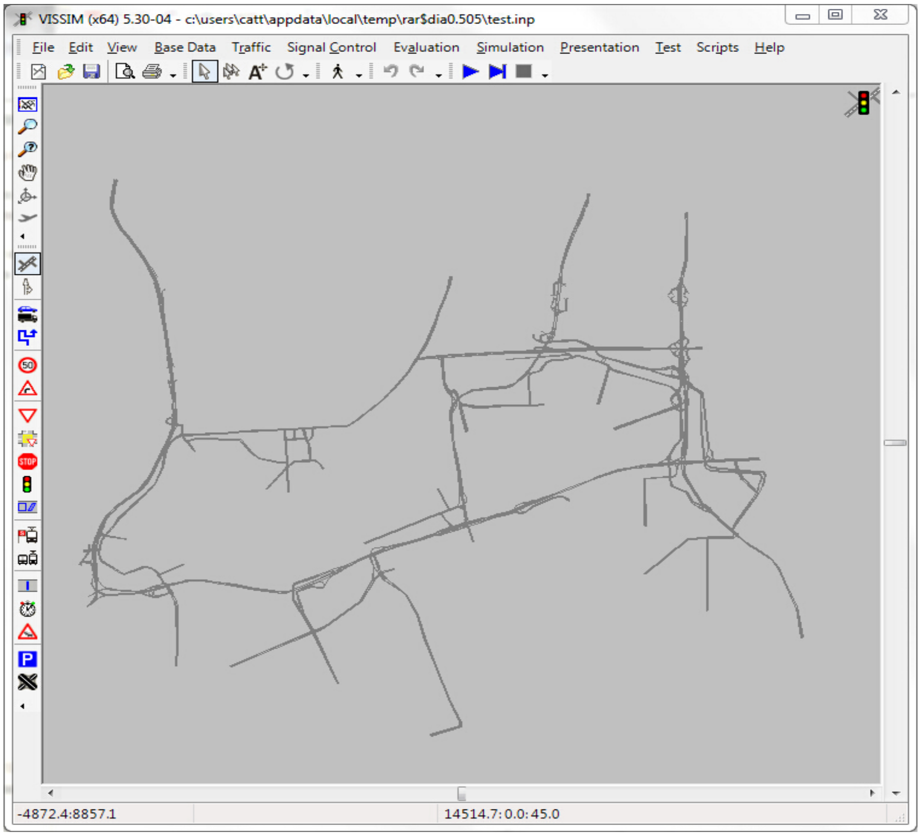
Figure 2: Traffic Simulator of Selected Freeway Network



The arterial road network adjacent to the Port of Long Beach is circled by Pacific Coast Highway, North Wilmington Blvd., West Anaheim St., and North Avalon Blvd., and consists of more than 100 intersections in total—15 of which have traffic signals as shown in Figure 3. The 15 intersections are controlled by 15 signal controllers, which can be designed using different approaches. The corresponding microscopic simulator of the selected road network in VISSIM is shown in Figure 4.

The designed microscopic traffic simulation network model is used to evaluate a combined variable speed limit and lane change control strategy under USC's part of the project. UCR considered the simulation model for traffic light control evaluations.

Figure 3: Selected Arterial Road Network

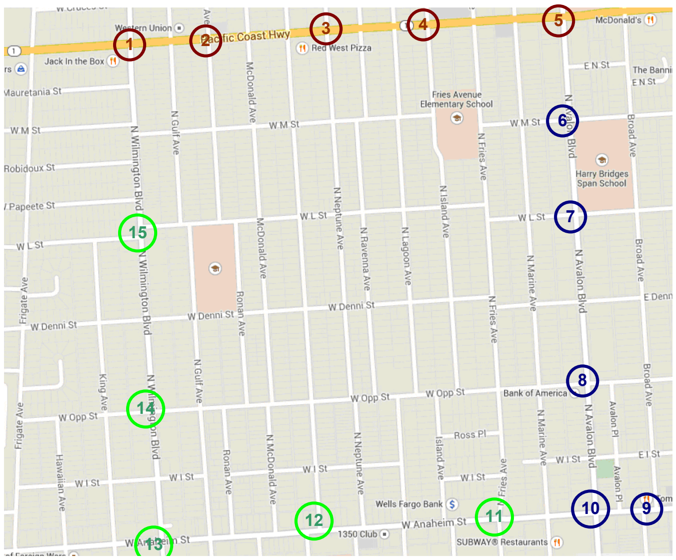
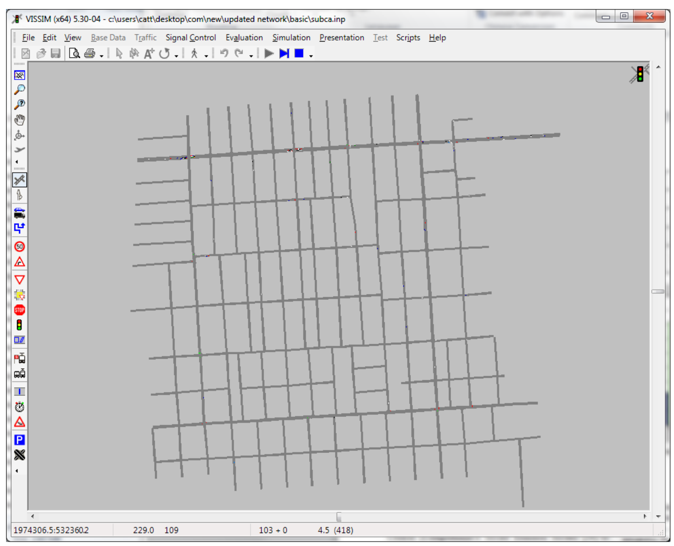


Figure 4: Traffic Simulator of Selected Arterial Road Network



CHAPTER 2: Impact of Combined Lane Change Speed Limit Control on Environment in Case of High Truck Traffic Volumes

Introduction

Trucks are important components of surface transportation in the United States and all over the world. In 2012, large trucks carried 67% of freight transportation by weight and 64% by value in the United States. The demand of truck transportation in 2040 is predicted to increase by 42.5% compared to 2012 (Strocko et al. 2014). Trucks have a detrimental effect on traffic flow due to their size and slower dynamics when compared with light duty vehicles. In addition, they pollute more and consume more fuel as individual vehicles. From 2003 to 2012, heavy trucks produced 22% of total congestion cost (value of travel time delay plus excess fuel consumption), 22% of traffic greenhouse gas emissions, and were involved in more than half of on-road crashes (Schrank et al. 2014, Environmental Protection Agency 2015, Toth et al. 2003). Especially in highway segments with high truck volume (e.g. highway segments going in and out of port areas, freight transportation hubs, and arterial truck corridors), the travel time delay, accident rates, and air pollutant emission rates of all types of vehicles are higher than the average level in other areas. Therefore, efficient traffic flow control strategies are needed at truck-dominant highway networks to regulate traffic flows, avoid or postpone congestions, and reduce accidents and emissions.

From the perspective of traffic flow control, there are two basic ideas to save energy and reduce emissions:

1. Reducing travel time of vehicles. The longer time that vehicles stay on roads with their engines on, the more emissions are produced and more energy is consumed. Therefore, reducing the total travel time of vehicles by improving traffic mobility has potential to benefit the environment.
2. Improving the engine efficiency. Vehicle engines gain higher efficiency under good operating conditions, and hence can travel longer distances with less energy and produce fewer emissions. Under certain road conditions, good operating conditions require moderate speed, low acceleration, and low number of stop-and-go traffic situations. Therefore, by smoothing the traffic flow we can improve engine efficiency and provide a positive environmental impact.

Variable Speed Limit (VSL) is an important highway control strategy which has long been studied and reported to be able to smooth traffic flows and dampen shockwaves (Van den Hoogen and Smulders 1994, Wang and Ioannou 2011, Lu and Shladover 2014). VSLs are speed limits that change based on road, traffic, and weather conditions. In truck-dominant highway networks, maneuvering of trucks such as accelerations and lane changes easily disturb the traffic flow, and increase travel time and tailpipe emissions. Therefore, it is intuitive that by smoothing and homogenizing the traffic flow in truck-dominant highway networks with VSL we could improve traffic mobility, safety, and environmental impact.

The benefits of VSL on traffic safety have been shown in simulations and field tests while numerous studies have also been conducted to design and evaluate different VSL control methods with respect to improvements in traffic mobility and environmental impact (Lu and Shladover 2014, Hegyi et al. 2005, Yang et al. 2013, Jin and Jin 2014). These VSL methods are reported to improve traffic mobility in macroscopic traffic simulations. However, in most cases, these improvements cannot be duplicated on the microscopic level and the performance varies among different traffic conditions due to many microscopic and stochastic factors, which are hard to measure or predict. The goal of this study is to find a control scheme that provides consistent improvements under different traffic conditions.

Highway congestion usually occurs at bottlenecks caused by incidents, lane drop, etc. In our study, we found out that one of the problems a VSL scheme is faced with is that most lane changes are taking place in the vicinity of the bottleneck at forced lane changes, creating congestion and deteriorating possible travel time improvements obtained by the use of VSL. Especially in truck-dominant highway segments, a lane change of a single truck can significantly affect traffic in other lanes. This observation motivated us to use a combined lane change (LC) and VSL control strategy where vehicles are recommended to change lanes upstream and reduce congestion in the vicinity of the bottleneck. We have demonstrated using Monte Carlo microscopic traffic simulations under different bottleneck scenarios that this combined LC and VSL control scheme guarantees consistent improvements with respect to travel time, safety, and environmental impact.

In this proposed combined control method, LC control provides lane change recommendations to upstream vehicles, which spreads lane changes along a long distance and hence mitigates the capacity drop at bottlenecks. A local feedback VSL controller is deployed to maintain downstream density and suppress traffic disturbance. Constraints are applied to VSL commands for driver acceptance.

Numerous studies have been conducted to evaluate VSLs on highway, but none of them takes the effects of large trucks into consideration. Abdel-Aty et al. (2006) evaluated the safety benefit of VSL on freeways. The author concluded that well-configured VSL strategies can decrease the crash likelihood, but large gaps of speed limit along time and space may increase it. No improvement in travel time is observed in this study.

Hegyi et al. (2005) modified the METANET model and adopted model predictive control (MPC) to determine optimal VSL control with total travel time (TTT) of all vehicles as the cost function. The study reported a 21% decrease in TTT with the method in macroscopic simulation.

However, this model-based control method is not robust to different traffic scenarios. Kejun et al. (2008) applied the same approach as in Hegyi et al. (2005) to highway work zone scenarios and found no significant improvement in TTT.

Yang et al. (2013) introduced a Kalman Filter algorithm to improve the prediction accuracy of MPCs, which therefore enhanced the performance of the MPC VSL control system. The method was evaluated with VISSIM and the simulation result shows TTT can be decreased by 16% during peak traffic hours.

In Jin and Jin (2014), Abdel-Aty et al. (2006), Kejun et al. (2008), and Baldi et al. (2014), two different static feedback controllers are proposed to maximize the flow rate at highway bottlenecks. Closed-loop stability is proved in both studies. However, the stability holds only if speed limits vary continuously, which is difficult for drivers to follow in reality, if not impossible. LC control or LC recommendation have been used in highway to deal with lane closure or help with merging. Jha et al. (1999) evaluated three different lane control signal settings for the tunnel of I-93 South. Yellow and red overhead signals were applied ahead of incident location and evaluated using the microscopic simulator MITSIM. The study showed that under incident condition, travel time is sensitive to upstream road geometry and driver compliance rate. Carelessly configured LC signal settings may result in increase of travel time.

Baskar et al. (2008) proposed a MPC approach to determine appropriate speed limits and lane allocations for platoons. The approach is simulated on a 2-lane highway segment and reported to improve travel time by 5% - 10%. However, this approach assumes all vehicles are controlled by road-side controllers, which is not implementable yet.

Combined LC & VSL Controller

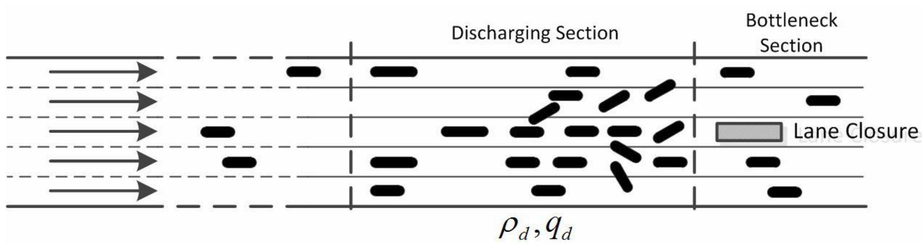
In this section, the design parameters and the procedure of designing a combined LC & VSL controller are introduced.

Description of LC System and VSL System

Congestion usually occurs at highway bottlenecks which can be introduced by road geometry, incidents, or construction events. When upstream flow rate exceeds the bottleneck capacity, congestion occurs.

As shown in Figure 5, the discharging section, which is the highway section immediately upstream of the bottleneck, usually has high vehicle density and low flow rate. A queue would establish in blocked lanes or merging lanes. Without LC control, no vehicle would have knowledge of when and which direction to change lanes until they stop in the queue. This raises the number of stops and forms a huge gap between the speed of vehicles waiting in the queue and the speed of vehicles moving in the open lanes, which makes the lane change very dangerous and introduces huge disturbances and shockwaves to the traffic flow. Applying LC recommendation, drivers would be informed of lane closure and lane change direction ahead of time and distance. LC recommendation allows drivers to continue in the previous lane if they cannot find a gap to merge. This control style provides higher road utilization rates and won’t make extra stops.

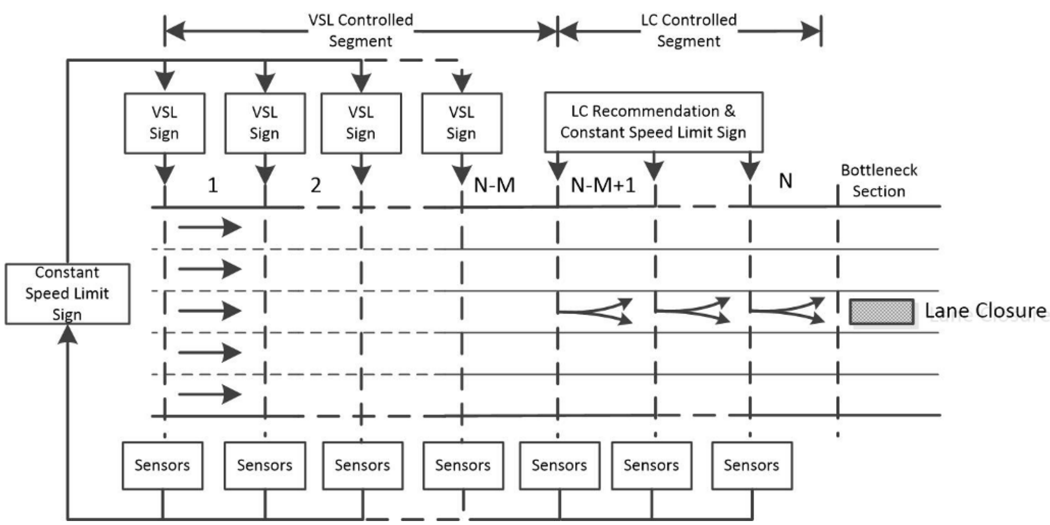
Figure 5: Highway Bottleneck



The proposed VSL control system is deployed at the highway segment upstream of the bottleneck and consists of on-road sensors, overhead, or roadside variable speed limit signs and central processing unit. An example of a combined LC & VSL control system is shown in Figure 6—the highway segment upstream of the bottleneck is divided into *N* sections with similar length to ensure homogeneity.

LC control uses overhead signs to make lane change recommendations at the beginning of *M* sections upstream of the bottleneck, i.e. section N-M+1 through section N. For each lane, there are 4 possible types of LC recommendations: "Straight Ahead", "Change to Left", "Change to Right", and "Change to Either Way". The length of the LC-controlled segment is a function of vehicle demand and bottleneck capacity. Vehicles are not forced to perform lane changes at where the LC signs appear, but are expected to be prepared and look for an appropriate chance to change lanes.

Figure 6: Configuration of LC & VSL Controller



An LC controlled segment works as the discharging section in Figure 5. The speed limits in this segment remain constant—usually the free flow highway speed limit—to ensure that vehicles can get through the bottleneck as fast as possible.

To help improve flow rate at the bottleneck, the VSL controller tends to maintain reasonable density in the discharge section. VSL signs, which are used to inform drivers of the enforced speed limits, are deployed at the beginning of Section 1 through Section N-M. It is assumed that sensors measure vehicle density at sections 1 to N and send the information to the VSL controller. The central processing unit receives the density signal in real-time and computes the desired VSL control command of each section for display.

Design of LC Control Strategy

In this study, the design of the LC controller includes decisions on the pattern of LC recommendations and the length of LC controlled segments according to bottleneck formation.

Lane Change Recommendation Patterns

Assignment of proper lane change recommendation type R_i in lane *i* should help upstream vehicles to leave the closed lane and evenly distribute traffic flow to open lanes. Therefore, the LC control pattern is a function of bottleneck formation. Suppose a general highway segment has *m* lanes, with Lane 1 (Lane m) being the right (or left) most lane. We select the LC recommendation type for each lane using the following rules:

1. For *i* = 1, 2, …, *m*, if Lane *i* is open, R_i="Straight Ahead".
2. For *i* = 1 (*i* = *m*), if Lane *i* is closed, R_i="Change to Left (Right)".
3. For 1<*i*<*m* if Lane *i* is closed, and Lane *i* -1 and Lane *i* +1 are both open, R_i="Change to Either Way".
4. For 1<*i*<*m*, if Lane *i* is closed, Lane *i*-1 (Lane *i*+1) is closed, and Lane *i*+1 (Lane *i*-1) is open, R_i="Change to Left (Right)".
5. For 1<*i*<*m*, if Lane *i* is closed, and Lane *i*-1 and Lane *i*+1 are both closed, then we check $R_{(i-1)}$ and $R_{(i+1)}$. If $R_{(i-1)} = R_{(i+1)}$, then $R_i = R_{(i-1)} = R_{(i+1)}$, else if $R_{(i-1)} \neq R_{(i+1)}$, R_i="Change to Either Way".

Rules (1) – (5) can always be applied from Lane 1 and Lane *m* to the middles lanes, which hence are well-defined and self-consistent.

Length of LC Control Segment

Decision on the length of the LC controlled segment is a trade-off between smooth lane changing and capacity utilization. A longer LC control segment gives upstream vehicles more space to change lanes and therefore further avoids the queue, but leads to road surface underutilization. Intuitively, if more lanes are closed at the bottleneck, more vehicles need to change lanes, and then longer LC control distance is required to provide enough space and time to change lanes. Therefore, the LC controlled segment length d_{LC} is decided by the following equation:

$$d_{LC} = \xi * n \qquad (1)$$

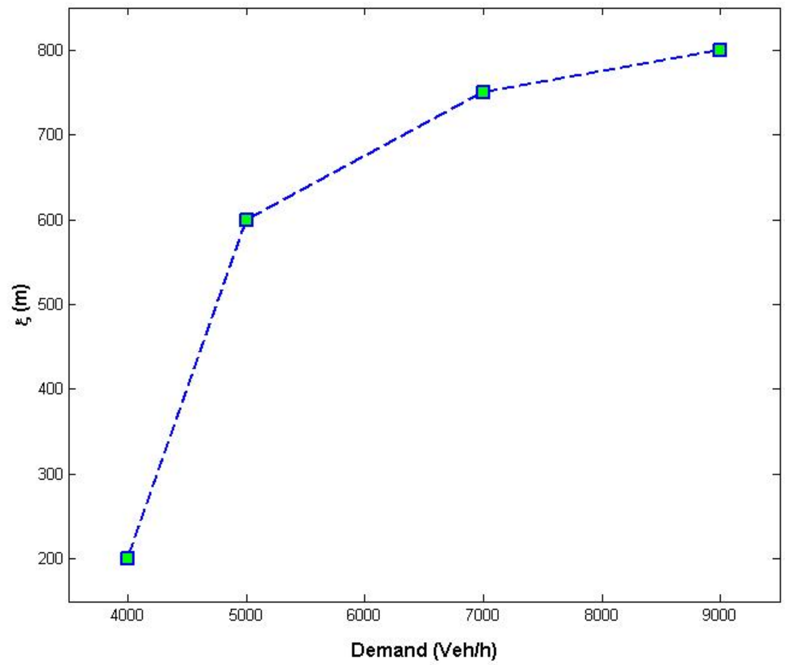
where *n* is the number of lanes closed at the bottleneck, and ξ is a design parameter related to the original capacity of the bottleneck section and the traffic demand. For specific highway segments, the minimum value of ξ required under different traffic demand can be found by simulation. Figure 7 shows the minimum ξ under different demand for the system shown in Figure 6.

In this system, LC signs are only deployed at the beginning of sections. The number of LC controlled sections M is chosen such that

$$M = min \left| \sum_{i=N-M+1}^{N} l_i - d_{LC} \right| \quad (2)$$

where l_i represents the length of section i.

Figure 7: ξ under Different Traffic Conditions



Design of VSL Control Law

In designing the VSL controller, we adopt the idea of a ramp metering algorithm, ALINEA. ALINEA adjusts the on-ramp flow rate to keep downstream density at a desired level (Papageorgiou et al. 1997). We generalize it to VSL control by regarding each highway section as the on-ramp of its downstream sections and regulating downstream density with VSLs. Unlike ramp metering, VSL cannot directly control the flow rate by stopping vehicles; therefore, a multi-section structure as shown in Figure 6 is applied to ensure control effect. The VSL controller in each section is expected to regulate the vehicle density of its downstream sections. The VSL control law is described as follows. Let

$$\eta_i(k) = \frac{\sum_{j=i}^{N} \rho_j(k) l_j}{\sum_{j=i}^{N} l_i} \quad (3)$$

denote the average vehicle density of section *i* through section *N* at time step *k*. For each $1 \leq i \leq N - M$, the VSL command of Section *i* at time step *k* can be expressed as:

$$V_i(k) = V_i(k-1) + K_I[\rho_c - \eta_i(k)] \qquad (4)$$

where $V_i(k)$ is the speed limit command of section *i* in control period k. K_I is the feedback gain and ρ_c denotes the critical density of the discharging section.

In Equation (4), VSL commands respond to the difference to a fixed reference density, in order to suppress shockwaves and maintain the density in the discharging section.

Constraints on VSL commands

To ensure safety, we apply the following constraints to VSL commands in Equation (4).

1. Finite Numbered Command Space. VSL commands would be hard to comply with if taking values from a continuous space. Hence, we round VSL commands $V_i(k)$ in Equation (4) to whole 5 mi/h numbers and apply lower/upper bounds to it. This makes the commands clear for drivers and adds dead-zone characteristics to the controller and therefore avoid control chattering.
2. Saturation of Speed Limit Variations. It is dangerous to decrease the speed limit too fast in both time and space. The decrease should be within some threshold $\mathrm{C_v} > 0$ between successive control periods and highway sections. We don't bound the speed limit variation if the speed limit increases. In this study, $C_v = 10\ mi/h\ (16\ km/h)\mathrm{C_v} = 10\mathrm{mi/h}(16\mathrm{km/h})$.

The above described constraints can be presented as follows

$$V_i(k) - V_i(k-1) < C_v, 1 \le i \le N - M \qquad (5)$$

$$V_i(k) - V_{i+1}(k) < C_v, 1 \le i \le N - M \qquad (6)$$

$$V_{min} \le V_i(j) \le V_{max}, 1 \le i \le N - M \qquad (7)$$

Hence, the virtual mainline ramp metering VSL controller can be formulated as follows:

$$\overline{V_i}(k) = V_i(k-1) + \big[K_I[\rho_c - \eta_i(k)]\big]_5 \qquad (8)$$

$$\widetilde{V_i}(k) = \max\{\overline{V_i}(k), V_i(k-1) - C_v, ⍰_{i-1}(k-1) - C_v\} \ (9)$$

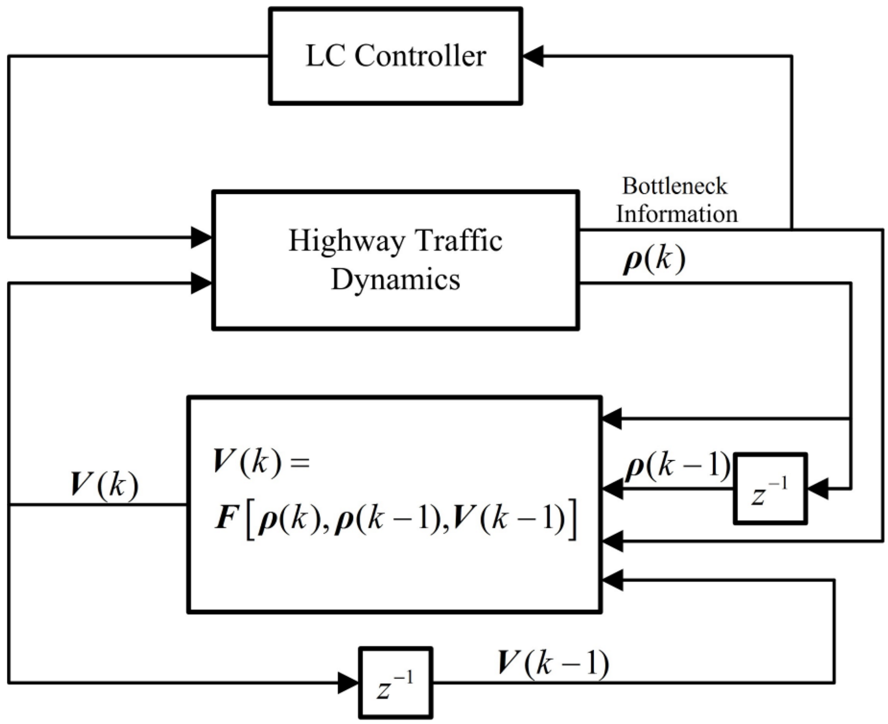
$$V_i(k) = \begin{cases} V_{max}, & \text{if } \widetilde{V_i}(k) > V_{max} \\ V_{min}, & \text{if } \widetilde{V_i}(k) > V_{min} \\ \widetilde{V_i}(k), & \text{otherwise} \end{cases} \qquad (10)$$

In Equation (9), $[\cdots]_5$ is the operator that rounds a real number to its closest whole multiple of 5. In Equation (10), V_{max} and V_{min} are the upper and lower bounds of VSL commands, respectively.

Combination of VSL Control and LC Control

As described in Section 2.2 and Section 2.3, the LC controller is designed based on bottleneck layout and traffic demand. The VSL controller takes an LC controlled segment as the discharging section and deploys VSL signs upstream of it to keep desired density and smooth the traffic flow. The effect of an LC controller helps the VSL controller to be more effective in generating the desired benefits. A block diagram of the combined VSL & LC control system is shown in Figure 8.

Figure 8: System Block Diagram



Evaluation

Simulation Network

We evaluate the combined VSL & LC control method on a 16 km-long southbound segment of I-710 freeway in California, United States (between I-105 junction and Port of Long Beach), which has a static speed limit of 65 mi/h (105 km/h). The Port of Long Beach is one of the largest seaports in the US and I-710 freeway carries high traffic demand with large truck volume. It is predicted that the peak hour demand of this segment would be about 9,000 vehicles per hour (veh/h) in 2035, 30% of which would be trucks (Systematics 2007). This is a very high ratio considering the large overall demand. We build this freeway network in VISSIM.

The studied highway segment has 3 – 5 lanes at different locations, as shown in Figure 9. We assume the bottleneck is introduced by an incident which blocked one lane. The upstream segment of the bottleneck is divided into ten 500 – 600 meter sections. The bars across the highway in Figure 9 are where VSL signs and LC signs are deployed. Near the indicated incident spot is a 3-lane/4-lane connection; therefore, different bottleneck conditions can be simulated by slightly changing the incident location. In VISSIM, incidents are simulated by placing a stopped bus in a certain lane.

Figure 9: Simulation Network

Traffic Demand and Composition

We redefined the vehicle types in VISSIM based on Federal Highway Administration (FHWA) vehicle classes and Environment Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) vehicle source types to apply the environmental evaluation models (Systematics 2007, Environmental Protection Agency 2010). The vehicle types and their proportion in the simulation traffic demand are listed in Table 1. Here, passenger trucks are classified as cars since their weight, power, and dynamics are very much similar to passenger cars according to FHWA.

Table 1: Vehicle Types

Vehicle Class	Vehicle Type	Average Weight (kg)	Proportion in Demand (%)
Cars	Passenger Car	1,400	40
	Passenger Truck	1,800	30
Trucks	Single-body Short Truck	6,800	5
	Single-body Long Truck	7,600	5
	Combined Short-hual Truck	29,000	1
	Combined Long-haul Truck	32,000	1

To simulate the worst case, the traffic demand of the highway and each ramp are calibrated with 2014 annual average peak hour data provided by California Department of Transportation (2015), but increased proportionally to make the highway demand 9,000 veh/h at the bottleneck, 30% of which are trucks as predicted in Los Angeles County Metropolitan Transportation Authority (2010). We assume that all passenger cars are gasoline-based and all trucks are diesel-based. Car following and lane change behavior in the VISSIM model is calibrated to be moderate. According to our study, the system performance is not sensitive to driving behavior with combined VSL/LC control.

Monte Carlo Simulation and Setup of Incident Scenarios

To verify that the proposed control method generates consistent results under different traffic conditions, we set up 3 different scenarios on the highway network to perform a general evaluation of the proposed method and take 10 sets of Monte Carlo simulation for each scenario. The final performance measurements are averages of the Monte Carlo simulation results. In the simulation, all lanes are open at the beginning of the simulation. At 20 min after the simulation begins, a certain lane is closed near the incident spot (as shown in Figure 9) and the controller is activated. The simulation terminates when 2,000 vehicles pass through the bottleneck. We held constant the total number of vehicles that passed through the bottleneck in each simulation, so that the measurements are comparable. The scenario configurations are listed in Table 2.

Table 2: Simulation Scenarios

Scenario Number	Total Number of Lanes	Bottleneck Pattern
1	3	Lane 2 Closed
2	3	Lane 3 Closed
3	4	Lane 3 Closed

Performance Measurements

We introduce the following measurements to evaluate the performance of the proposed control method. To be precise, all measures start when a lane closes and terminate at the end of the simulation.

Control effects on traffic mobility are evaluated by total travel time (TTT) of all vehicles that passed through the highway network (in hours). Let $t_{i,in}$ and $t_{i,out}$ denote the time instant vehicle *i* enters and exits the network, respectively. TTT is given by the equation:

$$TTT = \sum_{i=1}^{2000} \left(t_{i,out} - t_{i,in}\right) \tag{11}$$

Control effects on traffic safety are evaluated by total number of stops s_{tot} and total number of lane changes c_{tot}:

$$s_{tot} = \sum_{i=1}^{2000} s_i \tag{12}$$

$$c_{tot} = \sum_{i=1}^{2000} c_i \tag{13}$$

where s_i and c_i are number of stops and lane changes performed by vehicle *i*, respectively.

For environmental impact, we measure fuel consumption rate fr, carbon dioxide (CO_2) emission rate E_{CO_2}, and nitrogen oxide (NO_x) emission rate E_{NO_x} as follows:

$$fr = \frac{\sum_{i=1}^{2000} f_i}{2000 \cdot \sum_{i=1}^{2000} d_i} \tag{14}$$

$$E_{CO_2} = \frac{\sum_{i=1}^{2000} E_{CO_2,i}}{2000 \cdot \sum_{i=1}^{2000} d_i} \tag{15}$$

$$E_{NO_x} = \frac{\sum_{i=1}^{2000} E_{NO_x,i}}{2000 \cdot \sum_{i=1}^{2000} d_i} \tag{16}$$

where f_i, $E_{CO_2,i}$, and $E_{NO_x,i}$ are fuel consumption, CO_2 emission rate and NOx emission rate of vehicle *i* respectively. d_i is the distance travelled in the network of vehicle *i*.

Controller Parameters

In our simulation, the default speed limit when VSL controller is not active is v_f=65 mi/h (105 km/h). The VSL decrease threshold is C_v=5 mi/h. The lower and upper bounds of VSL are V_{min}=30 mi/h (48 km/h) and V_{max}=65 mi/h (105 km/h), respectively. Feedback gain is K_I=2.

Simulation Results

In scenario 1 – 3, we compare the simulation results under the following control modes:

1. No control.
2. LC control only.
3. VSL control only.
4. Combined VSL & LC control

Figure 10 and Figure 11 show the discharging section density and the bottleneck flow rate during the simulation in scenario 1. After the incident happens at 1,200s, the density of the discharging section increases dramatically to 250 veh/km and the bottleneck flow rate drops by 50% if LC control is not applied. When VSL control is applied alone, the density of the discharging section increases slower, but cannot be kept at a lower level. When LC control is applied, the bottleneck flow rate only deceased by about 30%. Since we lose 1 lane out of 3, the flow rate per lane has no drop. LC control ensures a high discharging rate of the bottleneck and therefore avoids the congestion. Comparing the flow rate and density curve with and without VSL control, system oscillation is dampened by VSL, and thus traffic safety improved. Fuel consumption and emissions also tend to be reduced, which is shown in Tables 3 – 8.

Figure 10: Flow Rate in Discharching Section

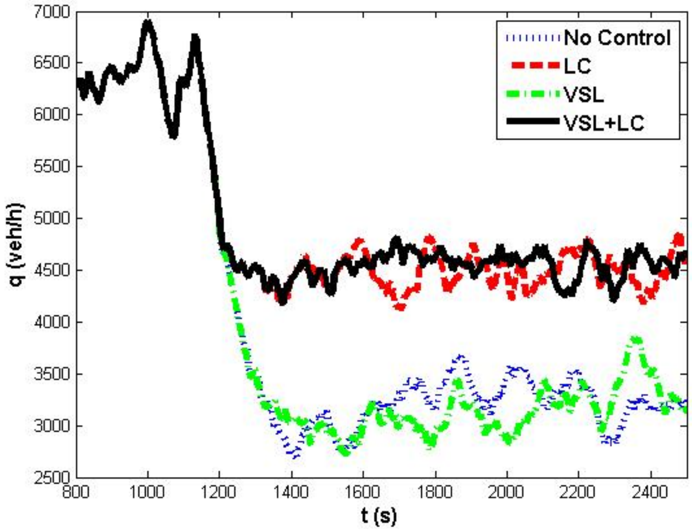
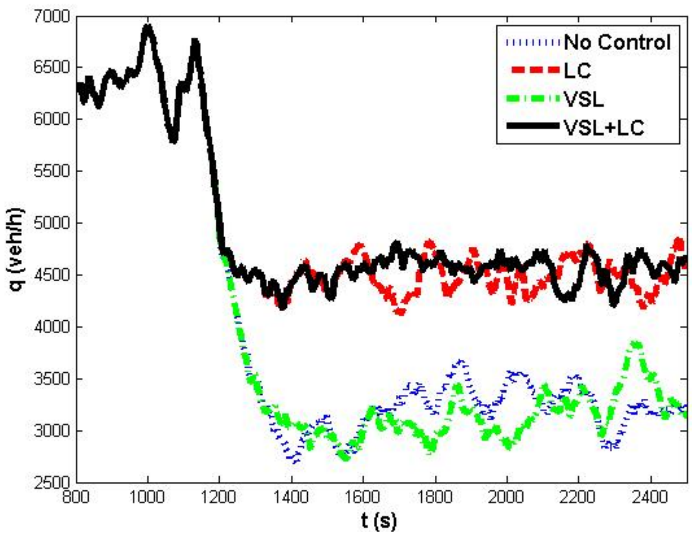


Figure 11: Density in Discharging Section



The effects of different control modes on performance measurements defined in the previous sections are shown in Tables 3 – 8. The environmental data in the tables are all evaluated with CMEM (Comprehensive Modal Emission Model) (Barth et al. 2000). We can observe that the combined control method provides significant improvement on each measurement, which is also consistent with respect to different scenarios. The combined VSL & LC control strategy reduces TTT by 26 – 32%, s_{tot} by about 90%, c_{tot} by 3 – 14%, fr and E_{CO_2} by 16 – 24%, and E_{NO_x} by 16 – 21%.

Table 3: Performance of Cars in Scenario 1

Performance Measurement	No Control	LC	LC Percentage Changed	VSL	VSL Percentage Changed	VSL+LC	VSL+LC Percentage Changed
Travel Time (min)	29,561	20,486	-31%	29,780	1%	20,574	-30%
Number of Stops	27,503	3,007	-89%	25,721	-6%	3,099	-89%
Number of LC	12,344	12,089	-2%	11,134	-10%	10,630	-14%
Fuel (g/mi/veh)	141.46	120.76	-15%	130.78	-8%	109.64	-22%
CO2 (g/mi/veh)	422.4	354.76	-16%	394.44	-7%	325.56	-23%
NOx (g/mi/veh)	0.49	0.47	-4%	0.42	-15%	0.39	-20%

Table 4: Performance of Trucks in Scenario 1

Performance Measurement	No Control	LC	LC Percentage Changed	VSL	VSL Percentage Changed	VSL+LC	VSL+LC Percentage Changed
Travel Time (min)	9,539	6,925	-27%	9,447	-1%	7,047	-26%
Number of Stops	6,757	719	-89%	6,344	-6%	783	-88%
Number of LC	1,245	1,314	6%	1,094	-12%	1,142	-8%
Fuel (g/mi/veh)	599.24	582.77	-3%	520.60	-13%	505.71	-16%
CO2 (g/mi/veh)	1,917.86	1,864.23	-3%	1,665.80	-13%	1,617.36	-16%
NOx (g/mi/veh)	22.10	20.38	-8%	20.03	-9%	18.65	-16%

Table 5: Performance of Cars in Scenario 2

Performance Measurement	No Control	LC	LC Percentage Changed	VSL	VSL Percentage Changed	VSL+LC	VSL+LC Percentage Changed
Travel Time (min)	29,076	19,914	-32%	28,403	-2%	19,854	-32%
Number of Stops	23,889	2,541	-89%	22,464	-6%	2,321	-90%
Number of LC	12,404	12,944	4%	11,254	-9%	11,585	-7%
Fuel (g/mi/veh)	141.60	120.67	-15%	128.50	-9%	109.67	-23%
CO2 (g/mi/veh)	421.32	353.24	-16%	386.03	-8%	323.71	-23%
NOx (g/mi/veh)	0.50	0.48	-5%	0.42	-17%	0.41	-19%

Table 6: Performance of Trucks in Scenario 2

Performance Measurement	No Control	LC	LC Percentage Changed	VSL	VSL Percentage Changed	VSL+LC	VSL+LC Percentage Changed
Travel Time (min)	9,273	6,862	-26%	9,280	0%	6,842	-26%
Number of Stops	7,206	573	-92%	6,665	-7%	535	-93%
Number of LC	1,354	1543	14%	1,233	-9%	1,373	1%
Fuel (g/mi/veh)	599.35	582.86	-3%	516.70	-14%	502.49	-16%
CO2 (g/mi/veh)	1,918.83	1,864.56	-3%	1,653.81	-14%	1,607.09	-16%
NOx (g/mi/veh)	22.22	20.37	-8%	19.94	-10%	18.56	-16%

Table 7: Performance of Cars in Scenario 3

Performance Measurement	No Control	LC	LC Percentage Changed	VSL	VSL Percentage Changed	VSL+LC	VSL+LC Percentage Changed
Travel Time (min)	30,033	20,378	-32%	30,033	0%	20,426	-32%
Number of Stops	27,544	2,797	-90%	25,763	-6%	2,681	-90%
Number of LC	12,475	12,380	-1%	11,295	-9%	11,084	-11%
Fuel (g/mi/veh)	143.37	120.71	-16%	132.38	-8%	110.05	-23%
CO2 (g/mi/veh)	427.21	354.32	-17%	398.29	-%7%	326.01	-24%
NOx (g/mi/veh)	0.51	0.47	-6%	0.43	-15%	0.40	-21%

Table 8: Performance of Trucks in Scenario 3

Performance Measurement	No Control	LC	LC Percentage Changed	VSL	VSL Percentage Changed	VSL+LC	VSL+LC Percentage Changed
Travel Time (min)	9,524	6,938	-27%	9,650	1%	6,914	-27%
Number of Stops	6,729	695	-90%	6,568	-2%	650	-90%
Number of LC	1,276	1,331	4%	1,152	-10%	1,162	-9%
Fuel (g/mi/veh)	601.58	583.50	-3%	523.66	-13%	506.20	-16%
CO2 (g/mi/veh)	1,925.31	1,866.57	-3%	1,675.56	-13%	1,618.96	-16%
NOx (g/mi/veh)	22.16	20.40	-8%	20.12	-9%	18.67	-16%

To study the roles of VSL control and LC control in the combined control strategy respectively, we also analyze the cases in which VSL control and LC control are applied to the traffic system individually. LC control considerably decreases travel time and number of stops, but cannot reduce number of lane changes. LC control only spreads forced lane changes along the LC controlled sections, instead of avoiding them. On the other hand, VSL control homogenizes the density and speed in each section. Drivers do not tend to change lanes if the density and speed are similar in all lanes; therefore VSL control is able to reduce number of lane changes in VSL

controlled sections. This is very important for traffic safety in truck-dominant highways. Trucks not only take a long time and large space to change lanes, their large size also blocks the eyesight of drivers, which makes lane changing much more dangerous than usual.
The evaluation of environmental impacts is interesting. VSL control and LC control have different performance effects on different measurements and vehicle types. For trucks, fr and E_{CO_2} are highly sensitive to accelerations. Large portions of fuel consumption and CO_2 emissions are produced by speeding up and slowing down in shockwaves. Therefore, although LC control reduced the travel time of trucks by 26 – 27%, fr and E_{CO_2} of trucks are only reduced by 3%. On the other hand, VSL control suppresses shockwaves and smooths the speed of all vehicles, which reduce fr and E_{CO_2} of trucks by 13 – 14%.

For cars, fr and E_{CO_2} are not as sensitive to accelerations as they are for trucks. Engine efficiency, which increases with vehicle speed, is also a major factor. LC control significantly increases the average speed and engine efficiency of cars, and therefore decreases fr and E_{CO_2} of cars by 15 – 17%. In the meantime, VSL control also reduces fr and E_{CO_2} of cars by 7 – 9%. NOx is a major toxic road traffic emission. Since we assume cars are all gasoline-based, the NOx emission of cars is very small compared to that of trucks. Both VSL control and LC control contribute to reducing NOx.

From the simulation results and analysis above, a combined VSL & LC control method can improve the bottleneck flow rate, smooth and homogenize the traffic flow simultaneously, and is hence able to provide significant and consistent improvement on traffic mobility, safety, and environmental impacts in truck-dominant highway networks.

Conclusion

This report proposed a combined variable speed limit (VSL) and lane change (LC) control strategy for truck-dominant highway traffic. In the proposed method, LC control provides lane change recommendations in an open loop manner based on bottleneck formation. A non-model based reactive proportional-integral (PI) VSL controller is designed which is robust with respect to traffic disturbance and is less computationally demanding than model-based proactive VSL controllers. Certain constraints on the output of the VSL controller are imposed by taking into account driver response to VSL commands. Simulations of the traffic along I-710 where the volume of trucks is relatively high are used to demonstrate improvements in travel time and the environment under different scenarios.

Combined lane change and variable speed limit control for highway traffic has a strong potential to improve traffic flow during incidents and bottlenecks by communicating lane change and speed limit recommendations to drivers. Using the traffic on I-710 as a demonstration example, we showed consistent benefits for different incident scenarios as follows:

- Reduced travel time on the order of 25 – 36%
- Reduced number of stops by 90%
- Fuel savings of about 20%

- Reduction of CO_2 and NOx emissions by about 16 – 20%

The implementation of combined lane change and variable speed control is feasible with today's available technologies and does not require major changes to existing highway infrastructure.

GLOSSARY

Term	Definition
CEC	California Energy Commission
CMEM	Comprehensive Modal Emission Model
CO_2	Carbon Dioxide
COM	Component Object Model
EPA	Environment Protection Agency
FHWA	Federal Highway Administration
ITS	Intelligent Transportation System
LC	Lane Change
MOVES	Motor Vehicle Emission Simulator
MPC	Model Predictive Control
NOx	Nitrogen Oxides
PI	Proportional-Integral
TTT	Total Travel Time
UCR	University of California, Riverside
USC	University of Southern California
VSL	Variable Speed Limit

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NOMENCLATURE

$[\cdots]_5$	operator that rounds a real number to its closest whole multiple of 5
C_v	variable speed limit decrease threshold
c_i	number of lane changes performed by vehicle *i*
c_{tot}	total number of lane changes
d_i	distance travelled in the network of vehicle *i*
d_{LC}	lane change controlled segment length
ξ	design parameter related to the original capacity of the bottleneck section and the traffic demand
E_{CO_2}	CO_2 emission rate
$E_{CO_2,i}$	CO_2 emission rate of vehicle *i*
E_{NO_x}	NOx emission rate
$E_{NO_x,i}$	NOx emission rate of vehicle *i*
fr	fuel consumption rate
f_i	fuel consumption of vehicle *i* respectively
i	incremental unit (e.g., for section number, vehicle number)
k	time step
K_I	feedback gain
l_i	length of section i
M	number of lane change controlled sections
N	total number of highway segments upstream of the bottleneck
n	number of lanes closed at the bottleneck
$\eta_i(k)$	average vehicle density of section *i* through section *N* at time step *k*
ρ_c	critical density of the discharging section
R_i	lane change recommendation type
s_i	number of stops performed by vehicle *i*
s_{tot}	total number of stops
$t_{i,in}$	time instant vehicle *i* enters the network
$t_{i,out}$	time instant vehicle *i* exits the network
v_f	default speed limit when variable speed limit controller is not active
$V_i(k)$	speed limit command of section *i* in control period k
V_{max}	upper bound of variable speed limit
V_{min}	lower bound of variable speed limit

APPENDIX A: Definitions

Arterial street: A high-capacity urban road that delivers traffic from smaller roads to freeways.

Model predictive control: An advanced method of process control that relies on dynamic models of the process. The main advantage of model predictive control is the fact that it allows the current time event to be optimized, while keeping future time events in account.

Monte Carlo method: A computational algorithm that relies on repeated random sampling to obtain numerical results. It is a technique in which a large quantity of randomly generated numbers are studied using a probabilistic model to find an approximate solution to a numerical problem that would be difficult to solve by other methods.

Proportional-integral controller: An algorithm that computes and produces an output at every sample time, while eliminating offsets. Proportional-integral controllers are widely used in process control applications.

Variable speed limit: Traffic speed limit that changes based on road, traffic, and/or weather condition.