Optimal Variable Speed Limit Control in a Connected Autonomous Vehicle Environment for Relieving Freeway Congestion

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INTRODUCTION

- Traffic congestion has become a major problem around the world.
- Active traffic management (ATM) is a scheme which can be used to relieve congestion and improve traffic flow on freeways.
- Variable speed limit (VSL) belongs to the ATM strategy, which enables one to change the posted speed limits dynamically on the basis of the real-time traffic and/or weather conditions.
- VSL has been widely implemented around the world (including Germany, England, Sweden, and the United States).
- With the development of autonomous vehicles (AVs), various novel methods on the basis of such technologies have been developed accordingly during recent years.
- Enhanced outcomes can be achieved through integrating VSL control with AVs.

DESIGN OF CONTROL ALGORITHM

- The modified cell transmission model (CTM) is used. The fundamental diagram (FD) is simplified as having a triangular relationship between flow and density.
- The CTM has been adopted in many studies to develop a first-order VSL control strategy. However, the control model failed to involve heavy vehicles.
- When modeling mixed traffic flows, the other classes of vehicles are converted to the passenger car equivalents (pce). A dynamic pce value that involves physical characteristics of vehicles and prevailing speeds on freeways is used

$$\eta_{i,j}(k)=\eta\left(sd_j,HW_j,v_{i,j}(k)\right)=\frac{sd_j+HW_j v_{i,j}(k)}{sd_{car}+HW_{car}v_{i,car}(k)}$$

CTM for VSL Control

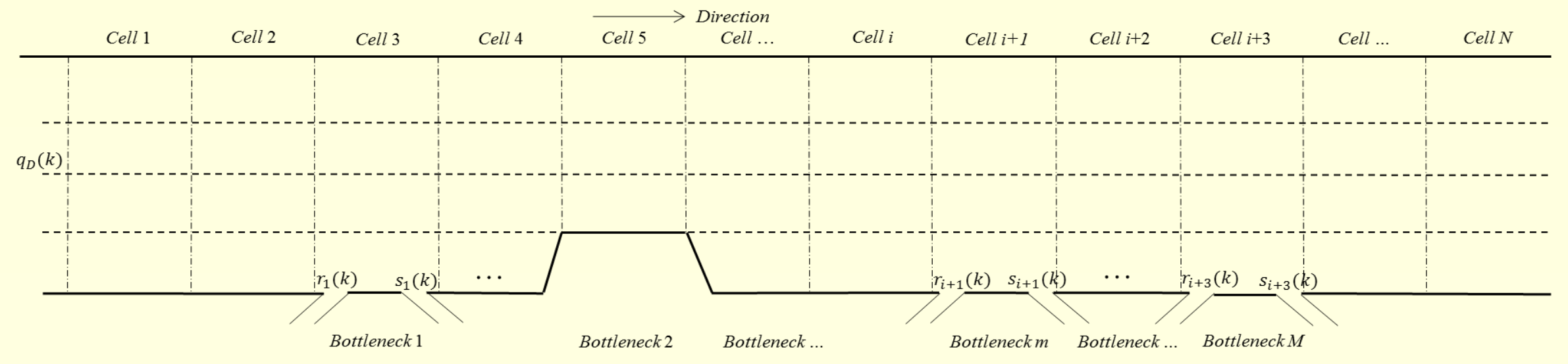


Fig. 1. An Illustration of A Freeway Stretch with Multiple Bottlenecks

During the high demand period, more than one bottleneck might be activated because of the ramp weaving effects, lane drops, accidents, and/or work zones.

For simplicity purpose, the following assumptions are made:

1. Under free flow traffic conditions, the average speeds of trucks are less than cars'; while in congested traffic conditions, the trucks' speeds equal to cars' speeds;
2. Traffic flow parameters, such as the free flow speed, might be different at different bottlenecks, but it is assumed that the values of such parameters on the cells upstream of the nearest

The average space mean speed of vehicle type *j* on cell *i* during time interval *k* is determined according to the following traffic conditions.

(1). If $\sum_{j=1}^{J}\frac{\rho_{i,j}(k)}{\rho_{j,m,c}}\le 1$, all the vehicle types are in free flow conditions. The average speed of vehicle type *j* on cell *i* during time interval *k* is $v_{i,j}(k)=min\left(v_{j,m,f},u_i(k)\right)$.

(2). If $\sum_{j=1}^{J}\frac{\rho_{i,j}(k)}{\rho_{j,m,c}}>1$ and $\sum_{j=1}^{j'}\frac{\rho_{i,j}(k)}{\rho^{*}_{j'+1,m,c}}+\sum_{j=j'+1}^{J}\frac{\rho_{i,j}(k)}{\rho_{j,m,c}}\le 1$, vehicle type 1… j' are in congested traffic conditions, and vehicle type $j'+1$… *J* are in free flow traffic conditions. The average speeds of vehicle class 1 … j' on cell *i* during time interval *k* are $v_{i,j}(k)=\frac{w_m\left(\rho_{m,jam}-E\rho_i(k)\right)}{E\rho_i(k)}$. The average speeds of vehicle type $j'+1$… *J* on cell *i* during time interval *k* are estimated by $v_{i,j}(k)=min\left(v_{j,m,f},u_i(k)\right)$.

(3). If $\sum_{j=1}^{J-1}\frac{\rho_{i,j}(k)}{\rho^{*}_{J,m,c}}+\frac{\rho_{i,J}(k)}{\rho_{J,m,c}}>1$ and $\sum_{j=1}^{J}\frac{\rho_{i,j}(k)}{\rho_{j,m,jam}}\le 1$, all the vehicle types are in congested traffic conditions, where $\rho_{j,m,jam}=\frac{\rho_{m,jam}}{\eta_{j,jam}}$, $\eta_{j,jam}=\frac{sd_j}{sd_{car}}$. The average speed of vehicle type *j* on cell *i* during time interval *k* is estimated by $v_{i,j}(k)=\frac{w_m\left(\rho_{m,jam}-E\rho_i(k)\right)}{E\rho_i(k)}$.

Autonomous Vehicle

The intelligent driver model (IDM) developed by Treiber et al. (2000) is adopted to model the car-following characteristics of AVs. The acceleration $a(k)$ during time interval *k* can be computed by

$$a(k)=a\left[1-\left(\frac{v(k)}{v_0}\right)^4-\left(\frac{s^*(k)}{s(k)}\right)^2\right]$$

$$s^*(k)=max\left(0,s_0+v*HW+\frac{v(k)\Delta v(k)}{2\sqrt{ab}}\right)$$

An AV is formulated by adopting the IDM with its headway being smaller than the human-driven vehicle's. If an AV is following another AV, a smaller headway will be used. If an AV is following a human-driven vehicle, this AV will be acting as a regular AV.

By using the External Driver Model DLL Interface of VISSIM, the IDM can be implemented. In other words, the IDM model is implemented in a DLL written in C++.

Objective Function and Constraints

$$\boldsymbol{min}\ J=w_1T\sum_{k=1}^{T_p}\sum_{i=1}^{N}\sum_{j=1}^{J}\rho_{i,j}(k)l_i+w_2\sum_{j=1}^{J}\sum_{k=1}^{T_p}\sum_{s=1}^{S}\sum_{i=vsl_{s-1}+1}^{vsl_s}\left[u_i(k)-\left(\frac{vsl_s-i}{N_s}v_{vsl_{s-1},j}(k)+\frac{i-vsl_{s-1}}{N_s}v_{vsl_s,j}(k)\right)\right]+\sum_{s=1}^{S-1}\left(u_{vsl_s}(k)-u_{vsl_s+1}(k)\right)^2$$

s.t.

$$v_{min}\le u_i(k)\le v_{max}$$

$$u_i(k)\in V\quad V=\{15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70\text{ mph}\}$$

$$|u_i(k+1)-u_i(k)|\le 10\quad |u_i(k)-u_{i-1}(k)|\le 10$$

- The first term of the objective function is the total travel time spent by all types of vehicles on the studied freeway corridor.
- The second term is the speed variation between speed limits on cell *i* and the traveling speeds of vehicle type *j* on the most upstream and most downstream cells.
- The third term is a penalty function used to ensure that the speed differences between two consecutive cells that are not in a same VSL control system will not be too large.

SOLUTION ALGORITHM

- Genetic algorithm (GA) is selected to optimize the speed limits during each and every control horizon.
- Two modules are included for determining the optimal speed limit set during the control period: GA and VISSIM simulation

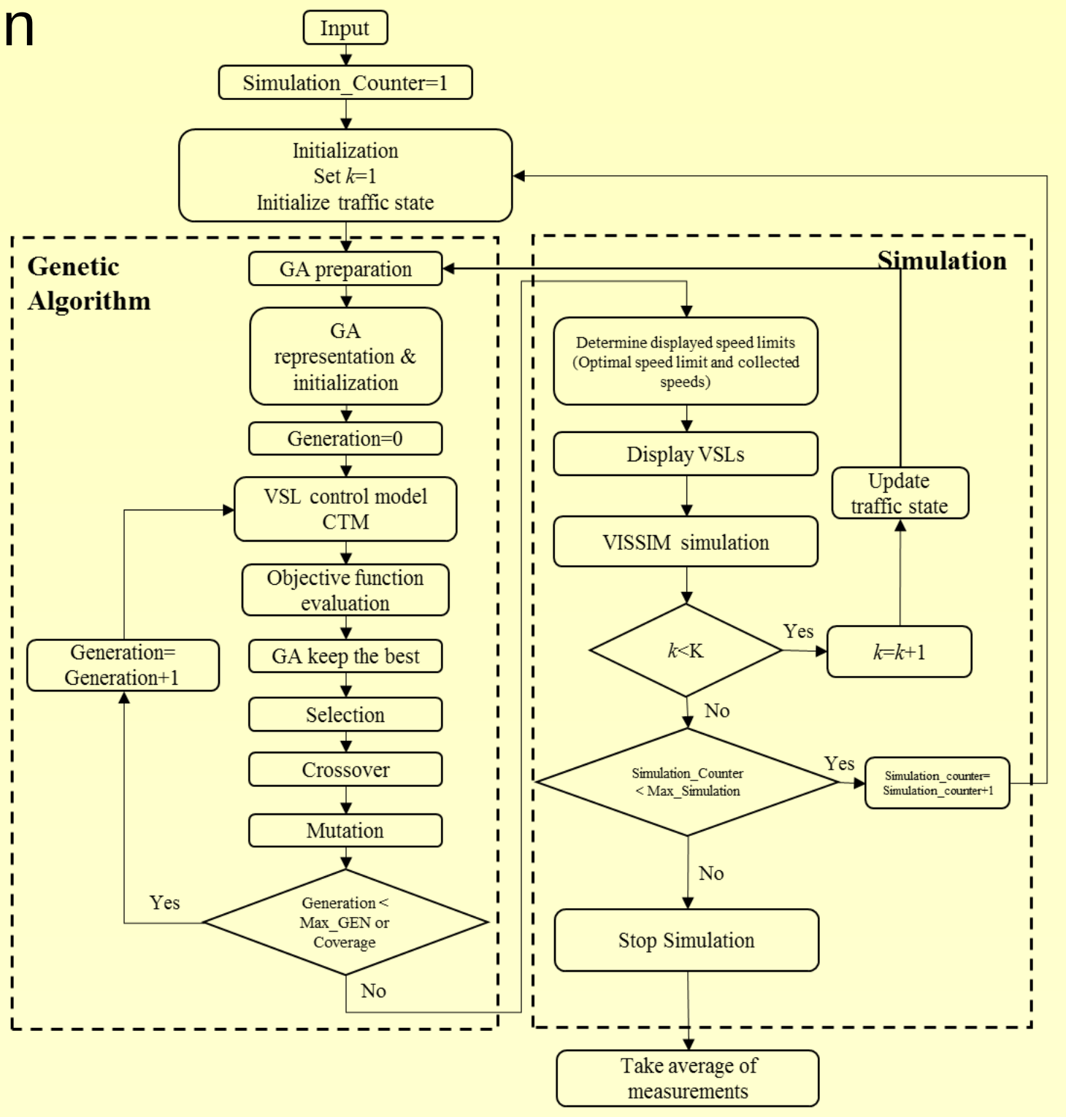


Fig. 2. GA Flow Chart for Determining Optimal Speed Limit Set

CASE STUDY

- A real-world freeway corridor is selected.
- The studying period is from 5:30 am to 9:00 am on weekdays.
- The field data is aggregated into 5-min counts.
- The length of the selected freeway corridor is about 5 miles.

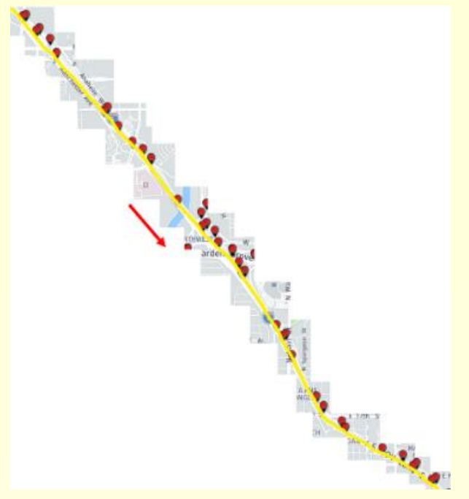


Fig. 3. Map of the Case Study from PeMS

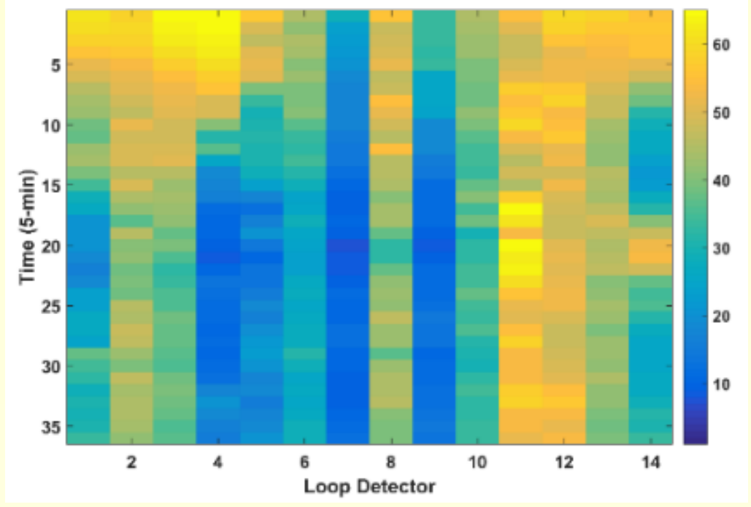


Fig. 4. Speed Profiles

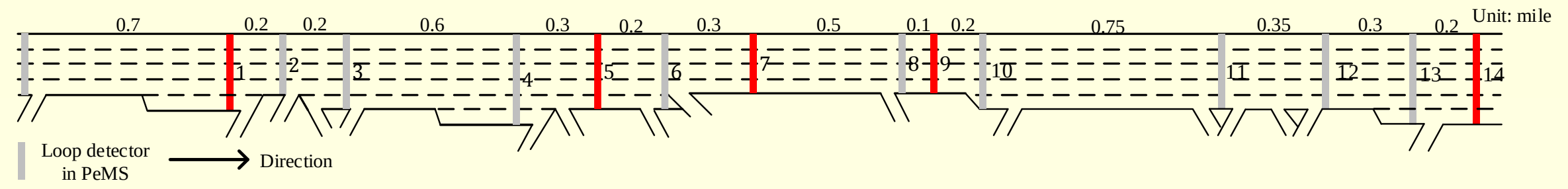


Fig. 5. Detailed Information about the Freeway Stretch

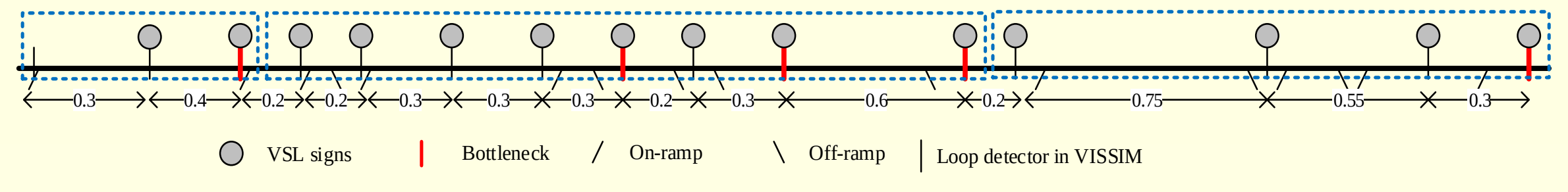


Fig. 6. Deployment of VSL Signs

- Five bottlenecks can be seen in Fig 4, i.e., at detectors 1, 5, 7, 9, and 14 (see Fig. 5).
- The freeway stretch is re-divided into 14 cells so that the CTM can be easily implemented (see Fig. 6.).
- Three VSL control systems are deployed in this study (see Fig. 6).

RESULTS

Calibration Parameters of CTM

Three types of vehicles (i.e., human-driven cars, trucks, and autonomous cars) are included, i.e., *J*=3.

The traffic parameters (e.g., capacity, jam density, and shock wave speed) at the five bottlenecks are computed first using the collected traffic data.

Table 1. Computation Results of the CTM at each Bottleneck

Parameters		Bottleneck 1	Bottleneck 2	Bottleneck 3	Bottleneck 4	Bottleneck 5
Capacity (pce/h/lane)		2232	1749	1797	1733	1702
Drop Capacity (pce/h/lane)		2023	1517	1669	1528	1630
Magnitude of Capacity Drop (%)		10.35	15.28	7.66	13.45	4.41
Shock Wave Speed (mph)		10.99	7.26	8.67	8.62	9.24
Critical Density (pce/mile/lane)		34.34	26.33	27.33	26.6	25.66
Jam density (pce/mile/lane)		214.39	235.3	219.86	203.81	202.08
Car (human-driven and AVs)	Free Flow Speed (mph)	64.99	66.42	65.74	65.16	66.32
	Critical Density (veh/mile/lane)	34.34	26.33	27.33	26.6	25.66
Truck	Free Flow Speed (mph)	59.99	61.42	60.74	60.16	61.32
	Critical Density (veh/mile/lane)	20.52	15.12	15.45	15.20	14.45

The driver behavior parameters of VISSM, such as standstill distance (CC0) and headway time (CC1), are calibrated. Parameters that are used to model the car-following characteristics of AVs are selected on the basis of existing studies.

Table 2. The IDM's Parameter Value

Vehicle Types	HW_j	a	b	s_0
Human-driven vehicle	1.6 s	3.28 ft/s^2	-6.56 ft/s^2	4.13 ft
AV	1.1 s	3.28 ft/s^2	-6.56 ft/s^2	0
CAV	0.6 s	3.28 ft/s^2	-6.56 ft/s^2	0
References	Treiber et al. 2000; Shladover et al. 2012; Milanés and Shladover 2014; Khondaker and Kattan 2015; Grumert et al. 2015; Li et al. 2017			

Simulation Results

- A 3.5-hour simulation with a 30-minute (from 5:30 am – 6:00 am) warm up period is conducted.
- The speed limit set that minimizes the objective function over a given prediction horizon (i.e., T_p=5 min).
- The speed limit changes every minute (i.e., T_c=1min).
- The discrete time step used in the control model is *T*=10s
- w_1=0.9 and w_2=0.1 are selected for the simulation.
- The length human-driven cars, autonomous cars, and trucks are set to be 15.62ft, 15,12ft, and 33.15 ft.

Table 3. Simulation Scenarios and Descriptions

Scenarios	Description
Scenario 1	With 100% human-driven vehicles and without VSL control
Scenario 2	With 10% CAVs and without VSL control
Scenario 3	With 100% human-driven vehicles, VSL control, and the CTM without considering mixed traffic flows
Scenario 4	With 100% human-driven vehicles, VSL control, and the extended CTM
Scenario 5	With 10% CAVs and VSL control, and the extended CTM
Scenario 6	With 10% CAVs and VSL control, V2I, and the extended CTM
Scenario 7	With 10% CAVs, I2V, V2I, VSL control, and the extended CTM

Table 4 shows the simulation results under the five designed scenarios, in which the TTT, average delays, average number of stops, and emission are computed.

- Improving the operating efficiency
- Reducing the greenhouse gas emissions

Table 4. Performance Comparison under Different Scenarios

Scenario	TTT (veh-h)	Average delays (s)	Average number of stops	Emission (g)			Improvement (%)					
				CO$_2$	NOx	Particulate	TTT	Delays	Number of stops	CO$_2$	NOx	Particulate
Scenario 1	8140.51	400.76	67.58	650.33	1734.2	1951	-	-	-	-	-	-
Scenario 2	7988.12	385.75	61.77	641.59	1730.57	1950.45	1.87	3.75	8.59	1.34	0.21	0.03
Scenario 3	5469.65	170.59	26.99	608.91	1585.7	1851.3	32.81	57.43	60.06	6.37	8.56	5.11
Scenario 4	5337.68	158.71	25.74	605	1583.5	1846.12	34.43	60.4	61.91	6.97	8.69	5.38
Scenario 5	5328.65	139.81	25.33	600.32	1578.54	1838.54	34.54	65.11	62.52	7.69	8.98	5.76
Scenario 6	5229.3	128.85	23.38	600.05	1577.99	1836.52	35.76	67.85	65.40	7.73	9.01	5.87
Scenario 7	5211.97	128.74	23.05	599.63	1576.54	1835.98	35.97	67.88	65.89	7.8	9.09	5.9

Fig. 7 presents the speed contours on each cell during the whole study period under scenario 4.

- The gradual change of color indicates that a smoother transition of speeds on each cell has been achieved

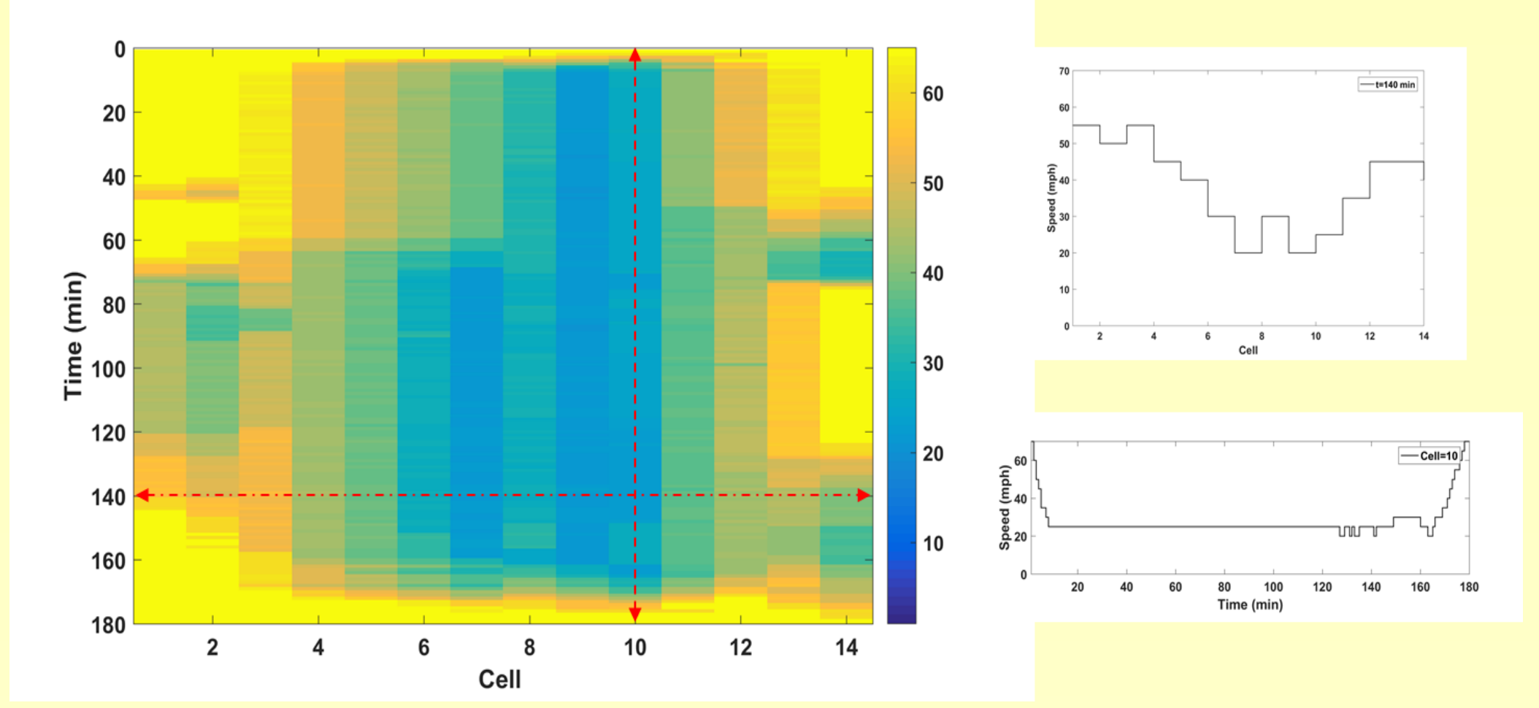


Fig. 7. Contour of Speed Limit under Scenario 4

The equilibrium flow (pce/h/lane) profiles during the entire simulation period at bottlenecks 2 and 3 under scenario 1, scenario 4, and scenario 5 are depicted.

- The equilibrium flow with VSL control can remain steady and a relative high discharge value can be achieved as well compared to that without VSL control.

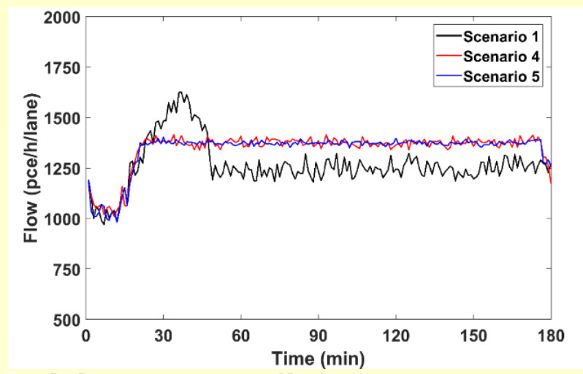


Fig. 8(a) Flow Profiles at Bottleneck 2

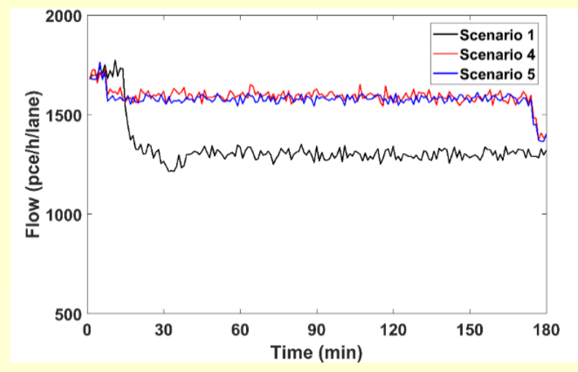
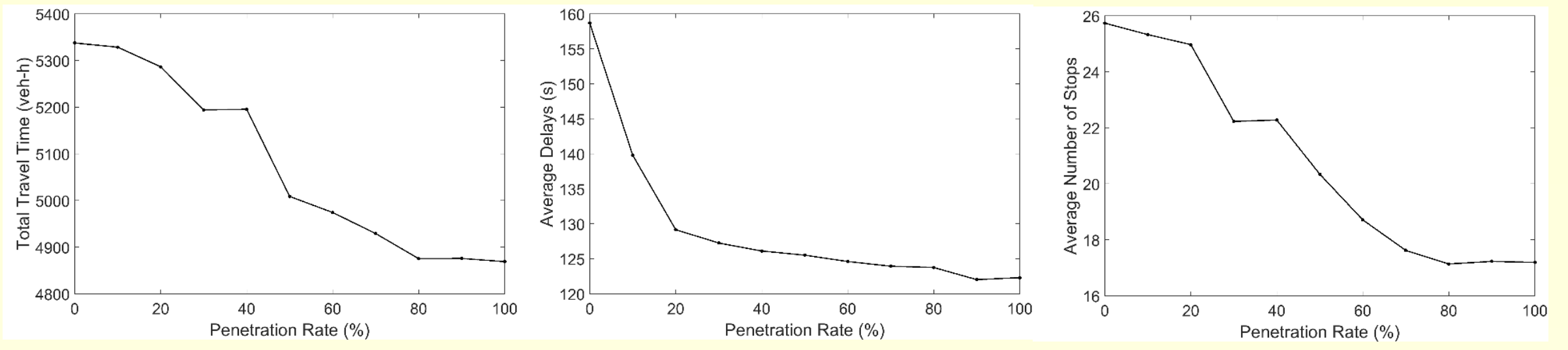


Fig. 8(b) Flow Profiles at Bottleneck 3

The effect of penetration rate is explored by varying it from 0% to 100%

- When the penetration rate is increased by 10%, it is assumed that the bottleneck capacity is increased by 1%
- As the penetration rate increases, the TTT, average delays, and average number of stops all decrease



CONCLUSION

- A proof-of-concept study on developing a VSL control strategy in a CAV environment for a freeway corridor is performed.
- The VSL control is developed on the basis of the extended CTM.
- The proposed VSL control model takes the mixed traffic flow (including human-driven cars, trucks and AVs) into consideration.
- The simulation results demonstrate that the developed VSL control can be used to greatly improve the operational efficiency, freeway mobility, and reduce the emissions of greenhouse gases.