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Simulation-driven multi-segment variable speed limits on freeway

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***Abstract*—Variable Speed Limits (VSL) have great potential for increasing freeway traffic efficiency. This paper presents a multi-segment lane-level VSL system, in which speed limits of each lane can be adjusted respectively. In addition, a simulation-driven method is proposed to test and analyze different VSL strategies with respect of speed, occupancy and travel time. The simulation-driven method is based on the SUMO simulator and traffic control interface. Different commands can be applied to adjust speed limits of edges and lanes. The results show that multi-segment lane-level VSL strategies can significantly improve traffic efficiency. This approach can be applied to a long-distance freeway section with multiple variable message signs.**

***Keywords*—expressway, traffic control, traffic simulation, SUMO, cooperative system**

I. Introduction

Active Traffic Management (ATM) is an effective method to deal with growing traffic on freeways in modern times, without expanding the infrastructure. Growing traffic on freeways may cause safety hazards, delay and waste of fossils. ATM is used in modern transport facilities to minimize these problems. One of the strategies is Variable Speed Limits (VSL) in which speed limits of traffic stream are adjusted in order to harmonize the traffic flow before traffic breakdowns[1]. Values of speed limits play an important role in the performance of VSL.

There are various control algorithms which optimize the performance of VSL. The applied algorithms can be divided into: rule based, open-loop based, feedback based and reinforcement learning based[2]. In rule based algorithms, the strategy of VSL bases its logic for calculating speed limits on predefined thresholds for available traffic states. The traffic states mainly include density, flow, mean speed on a given freeway segment[3] and weather[4]. In open-loop based algorithms, accurate traffic models with the ability to predict the movement of traffic flow are used to determine values of speed limits [5],[6]. The strategy of feedback VSL controllers is based on the current traffic state and feedback deviations. In [7], an ALINEA-like feedback controller for VSL was proposed. In [8], a distributed feedback controller for VSL was adapted and tested via the METANET macroscopic traffic simulator. On the other hand, reinforcement learning provides great potential for optimizing VSL control strategies. In [9], a Q-Learning algorithm was applied to VSL considering traffic prediction. In [10], a novel actor-critic architecture was developed for the lane-level VSL. The results showed that the lane-level VSL can improve the safety, efficiency and environment friendliness of freeways.

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Traffic simulation software provides an excellent platform to develop, test and improve the performance of VSL. In [11], microscopic traffic simulation software VISSIM was used along with MATLAB to implement VSL algorithm based on volume, occupancy and mean speed. In [12], the scenario with VSL and the scenario without VSL were compared in efficiency, safety and environmental impact via VISSM. In [13], a new macroscopic model for VSL was proposed to analyze the effects of VSL on freeway traffic flow. The results showed that the proposed model delivered more accurate predictions in cases where speed limits were applied. In [14], a multi-segment VSL system based on the SUMO simulator was proposed to produce a series of speed limits. The results indicated that the multi-segment VSL had the potential to contribute to flow harmonization.

Few researchers have addressed the problem of lane-level VSL and the problem of multi-segment VSL. In this paper, we apply the SUMO simulator to analyze the effects of multi-segment lane-level VSL on freeway traffic flow. Values of speed limits for different lanes and segments are adjusted, which produces multiple strategies. Meanwhile, those strategies are evaluated via the SUMO simulator with respect of mean speed, occupancy, and travel time. The combination of lane-level VSL and multi-segment VSL can improve the traffic efficiency of freeways.

The rest of this paper is organized as follows. In Section 2, we describe a novel VSL system Then, we propose the simulation-based methods in Section 3. In Section 4, we give numerical examples to demonstrate the efficiency of the proposed method. We conclude this paper in Section 5.

II. A Novel Variable Speed Limits System

A. Lane-level VSL sign

The lane-level VSL sign can issue information for each line. As shown in Fig. 1, the lane-level VSL sign shows the information "100-90-80-80-X", which corresponds to "line1-line2-line3-line4-shoulder lane" respectively. In this way, the speed limits of each line can be set differentially based on the traffic states among lines.

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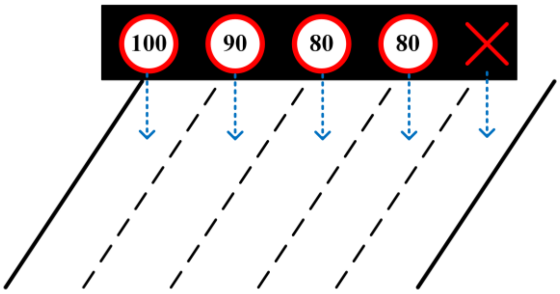

Fig. 1. Illustration of lane-level VSL sign

However, there are two significant challenges to achieve remarkable benefits in lane-level VSL. The first one is that the benefits of VSL strategies are limited by driver compliance [15]. Thus, VSL strategies are always discussed and analyzed under a connected and autonomous vehicles (CAV) environment, in which the message of dynamic speed limits can be sent to each individual vehicle. The second one is that it is a complex task to calculate the speed limits of multiple lanes. In comparison to the traditional VSL problem, there are decision variables, constraints and objectives in the lane-level VSL problem. The traditional VSL problem corresponds to the edge-level VSL problem, in which only one speed limit value should be calculated.

B. Multi-segment VSL system

The multi-segment VSL system contains multiple VSL signs among a section of freeway. Each VSL sign releases speed limits based on the states of the control area. In comparison to the single VSL system, the multi-segment VSL system can control a long-length section of freeway. In the multi-segment VSL system, the speed limits are decreased sequentially, not abruptly. Meanwhile, multiple speed limit values should be calculated in the multi-segment VSL problem, which is more complex than the single VSL problem.

C. Multi-segment lane-level VSL system

Combining the multi-segment VSL system and the lane-level VSL system, a multi-segment lane-level VSL system is proposed in this paper. As shown in Fig. 2, there are three different VSL strategies, including:

- Single edge-level VSL: the traditional VSL strategy, there is only one edge-level VSL sign.
- Multi-segment edge-level VSL: there are multiple edge-level VSL signs.
- Multi-segment lane-level VSL: there are multiple lane-level VSL signs. The speed limits of each lane can be adjusted.

Due to the complexity of the multi-segment lane-level VSL system, it is difficult to determine the speed limits of lanes among a multi-segment freeway section. Thus, a simulation-driven method is proposed to analyze the multi-segment lane-level VSL system.

III. Simulation-ddriven Method

A. SUMO simulator

The SUMO (Simulation of Urban MObility) is an open source, microscopic, multi-modal traffic simulation[16]. It allows to simulate how a given traffic demand which consists of single vehicles moves through a given road network. The simulation allows to address a large set of traffic management topics. It is purely microscopic: each vehicle is modelled explicitly, has an own route, and moves individually through the network. The applications based on the SUMO simulator mainly include: traffic lights evaluation, route choice and re-routing, evaluation of traffic surveillance methods, simulation of vehicular communications, traffic forecast.

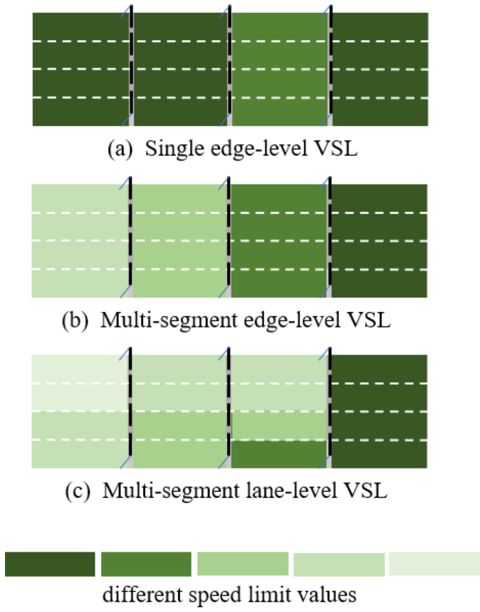

Fig. 2. Illustration of different VSL strategies

The usage of the SUMO simulator includes the following steps:

- Network building: the network in the SUMO simulator is composed of edges (including lanes), junctions and connections.
- Demand modelling: the demand determines the routes of vehicles, passengers and other transport modes.
- Simulation: the simulation performs each time step one-by-one, based on car-following, lane-changing models.
- Output analysis: the output of the SUMO simulator mainly includes trajectory, speed, occupancy, and etc.

B. Traffic control interface

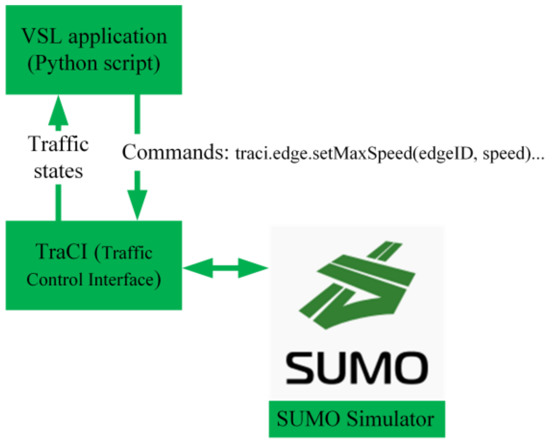

Fig. 3. Illustration of the structure of VSL application via TraCI in the SUMO simulator

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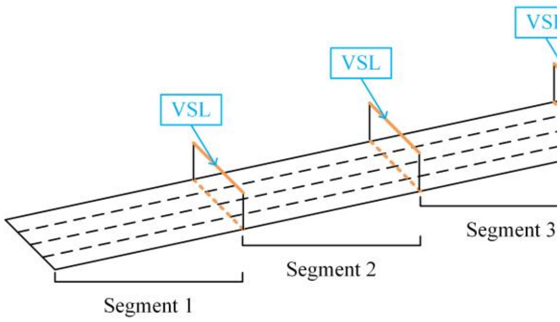

Fig. 4. The considered freeway section with 4 VSL signs (VSL: Variable Speed I

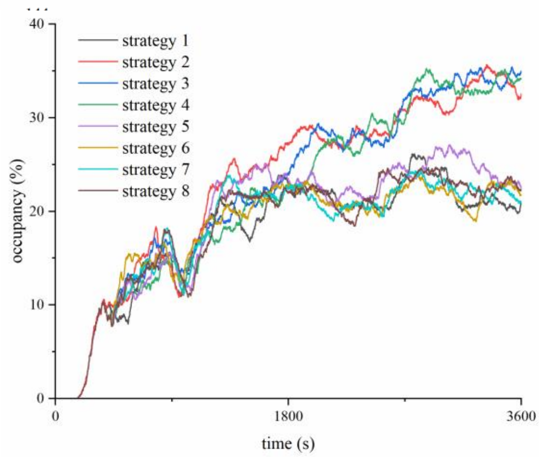

Fig. 7. Occupancy of segment 4 for VSL strategies

TABLE 1. SPEED LIMIT SCHE

No.	Type	*Segment 2*	*Segment 3*	*Segment 4*
1	single edge-level VSL strategy	120	120	100
2		120	120	80
3	multi-segment edge-level VSL	120	100	80
4		100	90	80
5		110	100	90
6	multi-segment lane-level VSL strategy	120	120	80-90-100-110
7		120	90-100-110-120	80-90-100-110
8		100-110-120-120	90-100-110-120	80-90-100-110

Multiple values represent the speed limit values of each line, which represent the speed limit values of "line4-line3-line2-line1".

Traffic Control Interface (TraCI) gives access to a running road traffic simulation, it allows to retrieve values of simulated objects and to manipulate their behaviour "on-line". TraCI uses a TCP based client/server architecture to provide access to the SUMO. Thereby, the SUMO simulator acts as a server listening for incoming connections. By using TraCI, states of vehicles and networks from the SUMO simulator can be obtained. Meanwhile, the states of vehicles and networks in the SUMO simulator can be changed.

In this paper, TraCI is used to get access to the SUMO during the simulation and a python script is used to communicate with the SUMO. VSL strategies are applied using the command "traci.edge.setMaxSpeed(edgeID, speed)" for changing the edge speed limit, and "traci.lane.setMaxSpeed(laneID, speed)" for changing the land speed limit. The modified speed limits are communicated to the SUMO simulator via TraCI, as shown in Fig. 3.

IV. NUMERICAL EXAMPLES

A. *Numerical example conditions*

In order to illustrate the effectiveness of the VSL strategies, one section of freeway is taken as an example to implement the numerical examples. The section includes 5 segments and 4 VSL signs, as shown in Fig. 4. The length of each segment is 2km, and the total length of the considered section is 10 km. The section is a two-way eight lane freeway with a designed speed of 120km/h, and each direction contains 4 lanes. The considered VSL signs are lane-level, which means that speed limits of each lane can be assigned.

The simulation is performed during one hour interval. The flow during simulation is 6000 vehicles per hour, which includes 4800 passenger cars (80%) and 1200 coaches (20%). In 400 s, a part of line 4 in segment 5 is closed due to a traffic accident, which causes a bottleneck. The closed part of line 4 starts at the beginning of segment 5 with a length of 400m. After 400 s, the reduction in capacity causes congestion on the segments upstream of the bottleneck. In addition, eight different VSL strategies, as shown in Table 1, are tested in this condition. The strategies 1 and 2 correspond to the single edge-level VSL strategy. The strategies 3 to 5 correspond to the multi-segment edge-level VSL. And, the strategies 6 to 8 correspond to the multi-segment lane-level VSL strategy. The VSL strategies 1 to 8 are compared from the perspectives of mean speed, occupancy, and travel time.

B. *Mean speed*

The mean speed reflects the average vehicle speed on the edge/lane. The mean speed of edges and lanes can be obtained using commands "traci.edge.getLastStepMeanSpeed(edgeID)" and "traci.lane.getLastStepMeanSpeed(laneID)" via TraCI. The

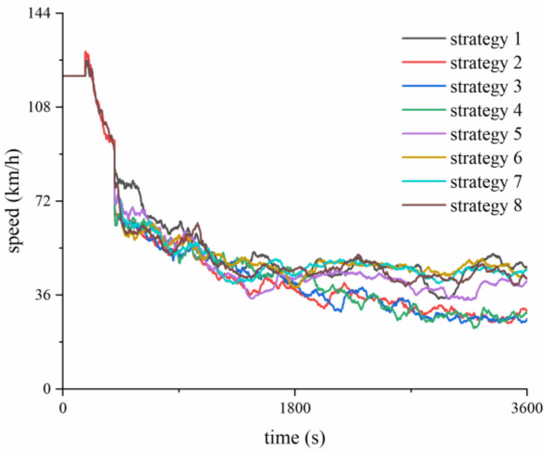

Fig. 5. Mean speed of segment 4 for VSL strategies

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mean speed of segment 4 for VSL strategies are shown in Fig. 5. The mean speed of lines in segment 4 for VSL strategy 6 are shown in Fig. 6.

From Fig. 5, we can observe that the mean speed of segment 4 for eight VSL strategies are different. The mean speed of strategies 2 to 4 is lower than the mean speed of strategies 1, 5 to 8. The speed limits of segment 4 in strategies 2 to 4 are 80 km/h. The lower speed limit reduces the traffic capacity of segment 4, which means that the speed limit 80 km/h is not suitable for the pre-designed situation. The speed limits of segment 4 in strategies 1, 5 to 8 are higher than 80 km/h. Correspondingly, the mean speed of segment 4 in strategies 1, 5 to 8 is higher. The value of variable speed limit strategy should not be chosen too low, as it will affect traffic capacity.

In addition, we analyze the mean speed of lines in segment 4 for VSL strategy 6. From Fig. 6, we can observe that the mean speed of line 1 (the leftmost line) is the highest. This is consistent with the driving rules of driving on the left. Specially, the condition that the mean speed equals to the speed limit indicates that there are no cars on the line. The significant speed fluctuations in lane 4 are due to that there are few vehicles running. Vehicles avoid running in lane 4 due to interruptions ahead.

C. Occupancy

The occupancy equals to the ratio of the total length of vehicles to the length of edge/lane, which reflects the degree of crowing. The occupancy of edge and lane can be obtained using commands "traci.edge.getLastStepOccupancy (edgeID)" and "traci.lane.getLastStepOccupancy (laneID)" via TraCI. The occupancy of segment 4 for VSL strategies are shown in Fig. 7. The occupancy of lines in segment 4 for VSL strategy 6 are shown in Fig. 8. The dynamic changes in occupancies of segments for VSL strategy 6 are shown in Fig. 9.

From Fig. 7, we can observe that occupancies of segment 4 for VSL strategies are different. The occupancies of strategies 2 to 4 are higher than the occupancies of strategies 1, 5 to 8. This corresponds to the mean speed difference of segment 4, as shown in Fig. 5. Vehicles are running slower under strategies 2 to 4, and the densities of strategies 2 to 4 are higher.

From Fig. 8, we can observe that the occupancy of line 4 is the lowest, it is due to that there are few vehicles running in line 4. Sometimes, the number of vehicles equals zero, which corresponds to the mean speed dynamics of line 4 in Fig. 5. In Fig. 9, the dynamic changes in occupancy of segments for VSL strategy 6 can be observed more obviously.

D. Travel time

The travel time can directly reflect the traffic efficiency of edge/line. The shorter the travel time, the faster the vehicle can pass through the freeway section. The average travel time for VSL strategies is shown in Fig. 10.

From Fig. 10, we can observe that the average travel time for VSL strategy 1 is the lowest, which indicates that the traffic efficiency of the considered section under VSL strategy 1 is the highest. The multi-segment lane-level VSL strategies (strategies 6 to 8) have great performances in traffic efficiency. Due to the speed limits of segment 4 setting as 80 km/h, the traffic efficiency under VSL strategies 2 to 4 are lower.

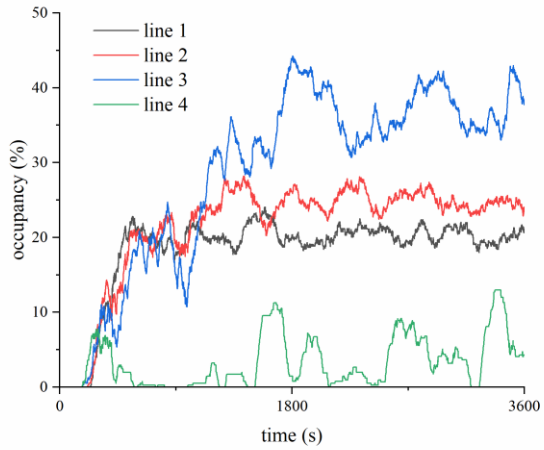

Fig. 8. Occupancy of lines in segment 4 for VSL strategy 6

strategy

Fig. 10. Average travel time for VSL strategies

V. CONCLUSION

In this paper, we studied the simulation-driven VSL problem. We introduced a novel multi-segment lane-level VSL system, in which speed limits of lanes among a long-length freeway section can be adjusted. In addition, based on the SUMO simulator and TraCI, we built a simulation-driven structure to test and analyze VSL strategies. In addition, numerical examples based on one section of freeway with 4 VSL signs were implemented to demonstrate the performance of VSL strategies. The computational results showed that the multi-segment lane-level VSL strategies can effectively improve traffic efficiency in comparison to other

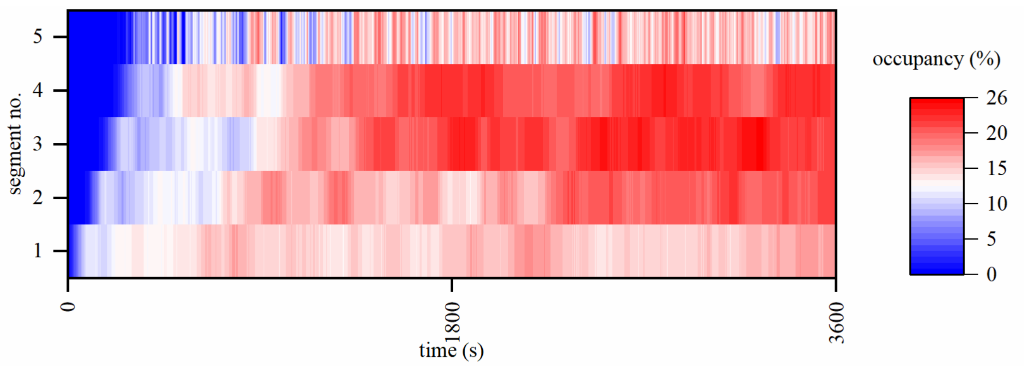

Fig. 9. Dynamic changes in occupancy of segments for VSL strategy 6

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types of VSL strategies.

Our future research will focus on the multi-segment lane-level VSL optimization problem. This paper only analyzes the pre-determined VSL strategies. The speed limits of VSL strategies should be optimized based on the dynamic traffic states. The simulation structure built in this paper can be used as a testing environment for optimization methods, and also a training environment for reinforcement learning.

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