A Flexible Control Study of Variable Speed Limit in Connected Vehicle Systems

Abstract. Traffic congestion has already been a distinctly serious problem in both developed and developing countries. Among the proposed methods to solve the traffic congestion problem, Variable Speed Limit (VSL) is considered as one of the most promising methods. But to the traditional VSL, the speed limit sign and the control distance is fixed, which makes VSL lack deployment and control flexiblity. Whereas, in Connected Vehicle (CV), which is a crossing field of Intelligent Transportation Systems (ITS) and Internet of Things (IoT), control and deployment flexibility can be achieved both. Furthermore, a big data environment is formed in CV to solve the traffic problems. In this paper, Connect Vehicle based Variable Speed Limit (CV-VSL) is proposed, and a simulation platform SimIVC is used to study the influence of control distance. The results show that the improvement of traffic performance increases 0.72% when the control distance is 270 meters than that of 250 meters, which means that the traffic performance can be further improved by CV-VSL.

Keyword: Connected Vehicle, Variable Speed Limit, VISSIM, OMNeT++

1 Introduction

With the growing number of vehicles, bad traffic condition causes traffic congestion, accident, traffic delay, additional fuel wastage, excessive air pollution, and productivity and efficiency loss. Especially in bottleneck areas, problems become worse. In recent years, a lot of studies have been done in this field. Among the proposed solutions, Variable Speed Limit (VSL) is considered to be one of the most promising technologies to make traffic more efficient and safer based on existing road networks.

VSL is an Active Traffic Demand Management (ATDM) method that adjusts posted limit speed based on traffic flows, real-time road, and weather conditions [1]. Lin et. al. presented two online algorithms for VSL, which improved traffic performance in bottleneck areas [2]. Hegyi et. al. used a model-based predictive control (MPC) approach to suppress shock waves in freeway traffic [3]. A VSL control through in-vehicle systems is implemented to expand the MPC approach by Lu, et. al. [4]. However, to the best of our knowledge, almost all traditional VSL scheme focus on fixed speed limit signs, which has the following defects: 1) VSL control lacks flexibility which means drivers can only react to the speed limit sign at the fixed location generally. 2) VSL deployment lacks flexibility. 3) Influence of environmental factors is serious, for example, drivers have a high possibility to ignore the speed limit sign in heavy fog.

Meanwhile, Connected Vehicle (CV), a crossing field of Intelligent Transportation Systems (ITS) and Internet of Things (IoT), has the potential to solve the critical problem of traffic congestions. In CV, Vehicles are equipped with wireless communication devices and can communicate with other vehicles and roadside equipment, which forms a big data environment to address traffic problems. In this paper, Connect Vehicle based Variable Speed Limit (CV-VSL) is proposed, which apply CV into VSL. CV-VSL combines VSL and CV with the following advantages: 1) Variable control distance leading to a more efficient control of traffic condition. 2) Flexible deployment since the speed limit sign is not required. 3) Low influence of environment due to the wireless communication technology. Many new features have been brought into CV-VSL, which need further studies.

The contribution of this paper is :1) proposing a new concept of CV-VSL, 2) giving a simulation experiment of CV-VSL using a high level simulation platform SimIVC [5] with a calibrated road network, and 3) discussing the influence of control distance to CV-VSL quantitatively.

The remainder of this paper is organized into sections: Section 2 introduces the basic background of CV and VSL. Section 3 describes the scheme design of CV-VSL. For the convenience of discussion, Control Distance (CD) is defined, which will be used in Section 4. The comparison of advantage and disadvantage between VSL and CV-VSL is also introduced. Section 4 presents the experiment setup, including configurations of the simulation platform SimIVC, road network model, VSL strategy, communication protocol, and Control Distance. Section 5 analyzes and discusses the simulation results. Finally, conclusions are given and future work is discussed in Section 6.

2 Background

2.1 Connected Vehicle

Connected Vehicle is a significantly important portion of Internet of Things (IoT). With advanced technologies like vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and sensor technology, a car can communicate to other cars, to traffic lights, to other Road Side Unit (RSU), and the roadway can also communicate to the car. CV is architected as a network for real-time, short-range wireless data exchange between vehicles and it will provide safety, mobility and environmental benefits. CV is considered to be a very promising strategy to solve traffic congestion problem. An over view of Connected Vehicle System is showed in Fig. 1. There are three RSUs which can broadcast information to vehicles within the range of communication. Vehicles send information to RSU by V2I. RSU also can communicate with each other by wire or wireless communication. Using V2V technology, information can be transformed among vehicles, which can further expand the range of communication.

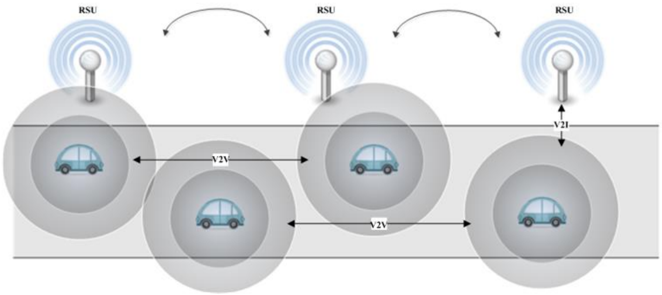


Fig. 1. Connected Vehicle System

2.2 Variable Speed Limit

Variable Speed Limit is a representative application of ITS which gives a limited driving speed to control traffic flow entering bottleneck area. On different conditions of traffic flow, weather information and road condition, the limited driving speed will be changed. As showed in Fig. 2, there are three lanes in upstream and only two lanes in downstream. The upstream of bottleneck area is a highly congested section where the discharge flow of three lanes will be larger than the flow capacity of bottleneck. To increasing the mobility in bottleneck, a variable limited speed is given to drivers to avoid the downstream growing too fast and blocking the ramps. A speed limit sign is fixed in the upstream of the bottleneck area.

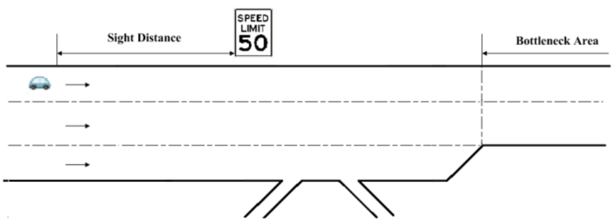


Fig. 2. Bottleneck area

Generally, a VSL system is composed of three subsystems: 1) a real-time traffic data collection system, 2) a data processing center, and 3) a fixed dynamic speed limit sign. The fundamental traffic data, such as traffic speed, counts, and occupancy, are collected by traffic data collection system, which could be inductive loop detectors, overhead radar, and visibility sensor [6]. Then the useful data is summarized in the data processing center and extracted to get the current traffic conditions. By operating a VSL algorithm, the road speed limit is calculated based on the current traffic conditions and displayed on the speed limit sign. Drivers, who catch the sight of the speed limit sign, change the speed to limit smoothly as soon as possible. The working process is showed in Fig. 3.

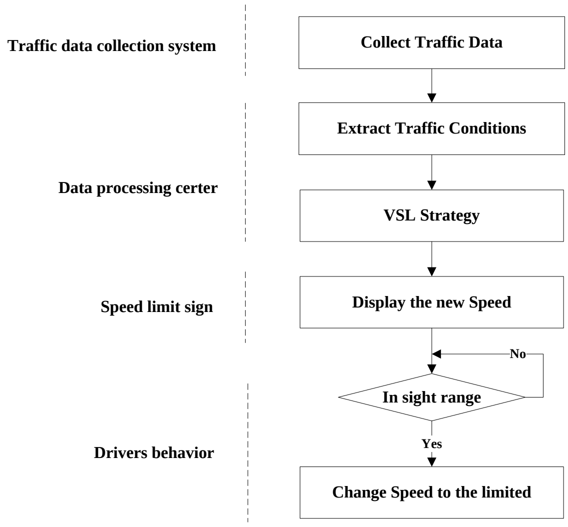


Fig. 3. VSL working process

3 CV-VSL

3.1 Overview

In CV-VSL, RSUs broadcast traffic information in real-time. OBUs inside vehicles receive the information and display the road speed limit to drivers. So when to inform drivers about the speed limit can be decided by OBU according to the current situation.

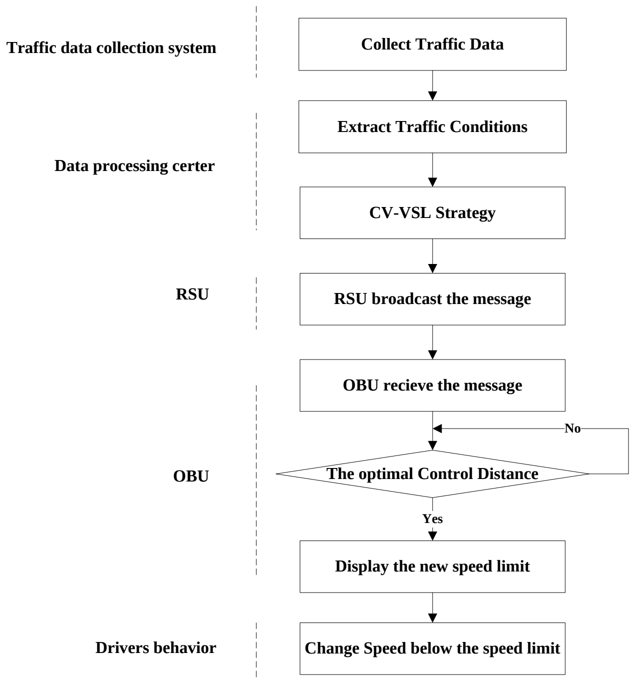


Fig. 4. **CV-VSL working processing**

As showed in Fig. 4, a RSU obtains all the traffic information sent by vehicles around, and forwards the information to the data processing center to extract the current traffic conditions. After all the required data is collected, the CV-VSL strategy is applied in the data processing center to calculate the limit speed. Then the data center sends the speed message to every RSU. Then RSU periodically broadcast the limit speed to vehicles around. Receiving the message doesn't mean changing speed immediately. Only if the vehicles are within the optimal control distance, drivers will be informed by in-car display equipment, then change speed below the speed limit. Among the process above, how to get the optimal control distance is also a big issue, which will be discussed in the next section.

3.2 Control Distance

Control distance is defined as the distance on-road from the point where OBU displays the speed limit message to the traditional speed limit sign, as shown in Fig. 5. When the distance from the vehicle to the traditional speed limit sign is blow the control distance, the driver will be informed of the speed limit message. If the vehicle is in the upstream of the speed limit sign, the control distance is positive, otherwise negative. "Distance on- road" means the distance is calculated along the road rather than air line distance. In traditional VSL, when the drivers see the speed limit sign, they will react to change the speed immediately. That is to say, the receiving distance equals to the control distance. But in CV-VSL, the control distance has nothing to do with the receiving distance. If V2I and V2V are all implemented in the scenario, the vehicle will forward the speed message to its destination, which means the receiving distance can be as large as several kilometers as shown in the below figure. If the receiving distance is large, the deployment of RSU can be rather flexible to meet the need that vehicles must receive speed message before the control distance point. In the traditional VSL, speed limit signs and the control distance is fixed. But in CV-VSL, the control distance can be flexibly changed. Different control distances will be configured to find the optimal solution of CV-VSL.

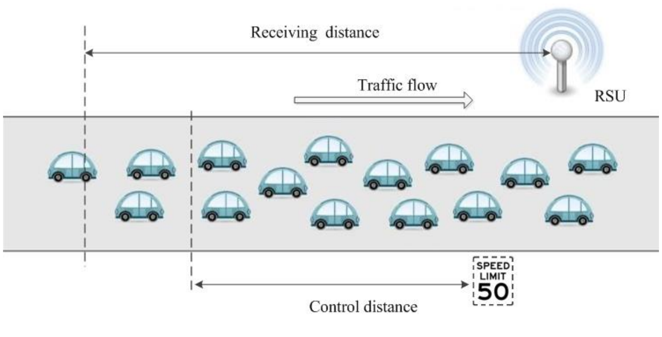


Fig. 5. CV-VSL

3.3 Advantages of CV-VSL

Compared with traditional VSL, CV-VSL has three advantages:

1. Variable control distance

To VSL, the control distance is the visible distance, which is usually about 100-250 meters. Nevertheless, CV-VSL uses wireless communication to spread information. Generally speaking, one-hop propagation distance can reach 300-900 meters [14]. By using V2V technology, communication distance can be extended to several kilometers. Wireless communication makes CV-VSL more flexible to control the vehicles entering the bottleneck area, which means the speed can be adjusted smoothly. This brings the potential to improve both safety and mobility to the road network.

2. Flexible deployment

To VSL, each of bottleneck areas needs a speed limit sign. Once the speed signs are installed, it will be quite difficult to change the signs distribution along the road network. But for CV-VSL, informations' transmission is completely different. RSU broadcasts traffic information in real-time. OBU receives and displays the speed limit. The physical speed limit sign is not required, and the deployment of RSU is flexible. So the deployment of CV-VSL has more flexibility.

3. Low influence of environment

To traditional VSL, the speed limit sign is usually fixed, which means drivers can react to the speed limit information only when they get close to the bottleneck area and see the sign. But drives' sight will be easily influenced by weather factors, especially in rainy, snowy, or other extreme conditions. However, to CV-VSL, information will be directly transmitted to the car which makes it convenient for drivers to get speed limit information.

4 Experiment Setup

4.1 Simulation Platform

The simulation platform used in this paper is a high level simulation platform—SimIVC [5][7], as showed in Fig. 6. VISSIM [8], which is a state-of-the-art commercial traffic simulator, uses C2X module to collect and control the traffics' status, like speeds, accelerations, positions etc. With this vehicle information, VSL strategy analysis the optimal value of limit speeds, than feedback this speed to VISSIM to control the vehicles. OMNeT++ [9], which is an open-source wireless network simulator, controls the network simulation. Traffic data and network data is exchanged between the two simulators periodically.

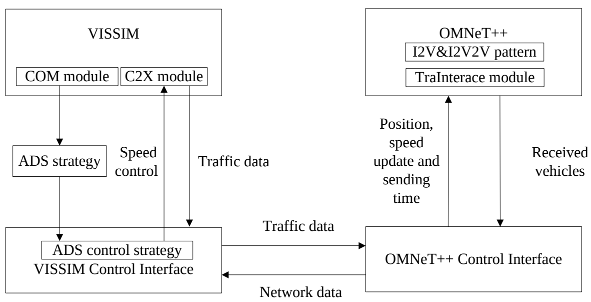


Fig. 6. CV-VSL simulation platform

4.2 Road network model

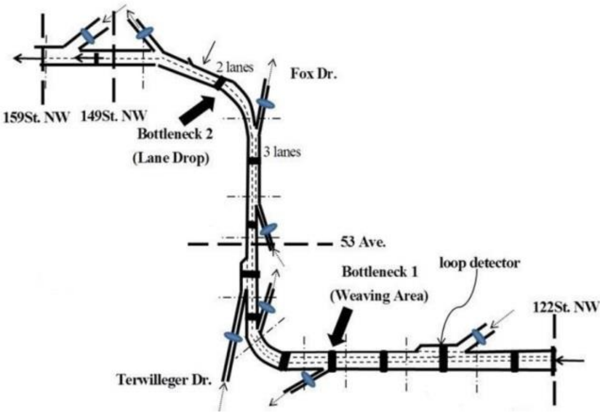


Fig. 7. Whitemud Drive road model

As shown in Fig. 7, the road network model simulated in VISSIM is a westbound 11-km (between 122 St. and 159 St.) urban freeway corridor of the Whitemud Drive (WMD), which is located in the south of Edmonton, Canada. It has six interchanges and a static posted speed limit of 80 km/h. According to statistics, the directional 24 average annual daily traffic (AADT) is approximately 100,000 vehicles. The road network model has been carefully calibrated with VISSIM according to the feedback of realistic traffic data [10][11].

4.3 VSL Strategy

A VSL strategy is used to control the cars' behavior in the VISSIM model, which is presented by Md. Hadiuzzaman et al [12]. The object function of this VSL strategy takes Total Travel Time (TTT) and Total Travel Distance (TTD) into consideration as shown below.

$$obj = \alpha_{TTT} T_{TTT} + \alpha_{TTD} T_{TTD} \qquad (1)$$

α_{TTT} and α_{TTD} are weight factors, T_{TTT} and T_{TTD} are TTT and TTD, respectively. TTT and TTD are also carefully discussed in the experiments.

4.4 DSRC Configurations

In this simulation, Dedicated Short Range Communication (DSRC) is selected as the communication protocol. DSRC is reported in 2011 by American Association of State Highway and Transportation Officials (AASHTO) [13], and the wide spectrum band of DSRC is 75MHz at 5.9GHz allocated by the U.S. Federal Communication Commission (FCC) exclusively [14]. The simulation configurations are shown in Table 1.

Table 1. DSRC Configurations.

Application layer	ADS packet size	64B
	Contention packet size	32B
Media Access Control (MAC) layer	Channel number	2
	Switching mode	CCH(50ms),SCH1(50ms)
Physical layer	Transmission power	3mW
	Communication distance	352m
	Receiving sensitivity	-94dBm
	Thermal noise	-110dBm
	Data rate	18Mbps

4.5 Control Distance Configurations

After the simulation platform is already completed, a series of simulations is conducted to study the influence of control distance. In this paper, the factor of control distance is taken into account. The test range of control distance is from 150 meters to 350 meters with 10 intervals, each of which is 20 meters. And the control distance of 250 meters corresponds to the situation of the traditional VSL. In the experiment, the TTT and TTD in different control distances are discussed.

5 Result and Discussion

To evaluate the traffic performance in CV-VSL, the improvement of object function value is introduced, which is calculated below:

$$improvement = \frac{V_{noVSL} - V}{V_{noVSL}} \qquad (2)$$

V_{noVSL} is the object function value when there is no VSL control. And V is the object function value in CV-VSL. The improvement of object function value is showed in Fig. 8.

The improvement is 108.31% when the control distance is 270 meters, which increase 0.72% than that when the control distance is 250 meters. According to the experiment, the scenario when the control distance is 250 meters can reflect the performance of traditional VSL which equals to the sight distance. So it can be easily concluded that the traffic performance can be further improved by CV-VSL.

Control distance of 230 meters and 270 meters show better performance. When the control distance is much larger or smaller than 250 meters, the performance trends to be worse. It means that the optional solution is around 250 meters, which verifies the correctness of traditional speed limit sign's location.

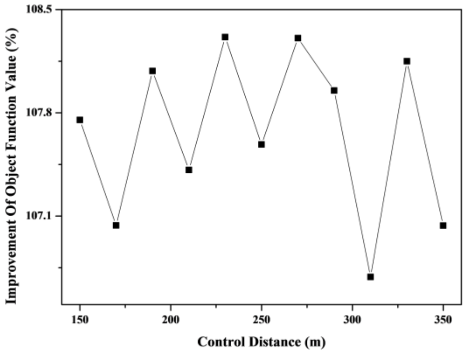
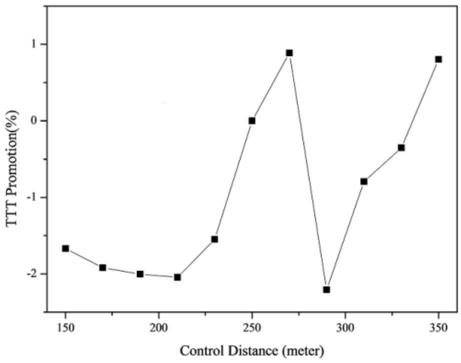
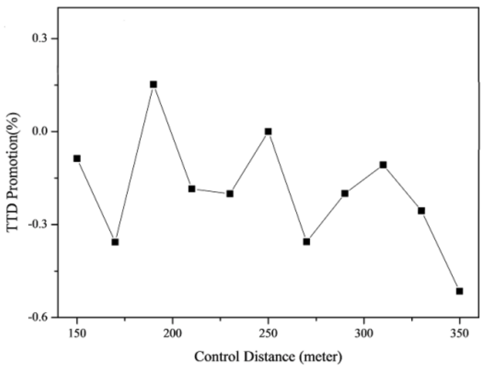


Fig. 8 The improvement of object function value

And Fig. 9 shows that TTD and TTT vary with control distance, which reflect the same tendency as the object function. When the control distance is 230 meters, the TTD and TTT are both lower than that of 250 meters.



(a) TTD



(B) TTT

Fig. 9 The total travel distance and the total travel time

The object function is a weighted summation of TTT and TTD. Lower the object function value, better the traffic performance is. The less delay time brings a more comfortable travel feeling. The curves of the object function waves may due to several reasons: a) the performance is very sensitive to the control distance and b) simulation with ten different random seeds may lack accuracy. Ten different random seeds are enough for traffic applications usually, so there is a high possibility that the performance is sensitive to the control distance, which means that there are some other factors involved. These factors may be traffic volumes, the condition of the bottleneck area and so on, which need more work.

6 Conclusion and Future work

Traffic congestions have been a critical problem in city development. The traditional VSL have played an important role in improving traffic performance, but still with many limitations. In this paper, CV is applied to VSL, bringing into being CV-VSL. The influence of control distances to CV-VSL is analyzed quantitatively with high lever architecture simulator—SimIVC. A group of experiments are conducted with a calibrated road network while changing control distances.

For simplification, all the vehicles in the simulations are equipped with OBU, and all the drivers change speed immediately when they receive the speed limit message displayed by OBU. The results show that:

- The traditional position of speed limit sign is not the optimal one.
- The optional solution is around 250 meters.
- The traffic performance can be further improved by CV-VSL.

The factors that have influenced the performance of CV-VSL may be traffic volumes, the condition of the bottleneck area and so on, which needs more work.

Our future works will focus on developing a control distance model of traffic flow, considering the condition of bottleneck area and so on to give a more efficient control of CV-VSL. Penetration rates and compliance rates will also be taken into considerations in simulation.

Acknowledgements

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