A flexible control study of variable speed limit in connected vehicle systems

Lu Pu, Xiaowei Xu, Han He and Hanqing Zhou

School of Optical and Electronic Information,
Huazhong University of Science and Technology,
Wuhan, China
Email: pulu.lskm@gmail.com
Email: xuxiaowei@hust.edu.cn
Email: hehan_hust@gmail.com
Email: zhq199139@gmail.com

Zhijun Qiu

Department of Civil and Environmental Engineering,
University of Alberta,
Edmonton, Canada
Email: qiuzhijun@ualberta.ca

Yu Hu*

School of Optical and Electronic Information,
Huazhong University of Science and Technology,
Wuhan, China
Email: bryanhu@hust.edu.cn
*Corresponding author

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 flexibility. 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 both be achieved. 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 metres than that of 250 metres, which means that the traffic performance can be further improved by CV-VSL.

Keywords: connected vehicle; variable speed limit; VSL, VISSIM; OMNeT++.

Reference to this paper should be made as follows: Pu, L., Xu, X., He, H., Zhou, H., Qiu, Z. and Hu, Y. (2015) 'A flexible control study of variable speed limit in connected vehicle systems', *Int. J. Embedded Systems*, Vol. 7, No. 2, pp.180–188.

Biographical notes: Lu Pu received her BS from the Department of Electronic Science and Technology, Huazhong University of Science and Technology, Wuhan, China in 2012. She is currently working toward her MS in the School of Optimal and Electronic Information, Huazhong University of Science and Technology, Wuhan, China. Her research interests include intelligent transportation systems, connected vehicles, and data mining. She is the recipient of the Outstanding Graduate Thesis from Hubei Province, China.

Xiaowei Xu received his BS and MS from the Department of Electronic Science and Technology, Huazhong University of Science and Technology, Wuhan, China, in 2011 and 2013, respectively. He is currently working toward his PhD in the School of Optimal and Electronic Information, Huazhong University of Science and Technology, Wuhan, China. His research interests include intelligent transportation systems, connected vehicles, and embedded computing. He is the recipient of the Outstanding Graduate Thesis from Hubei Province, China.

Han He received her BS from Department of Control Science and Engineering, Huazhong University of Science and Technology, Wuhan, China in 2012. She is currently working toward her MS in the School of Optimal and Electronic Information, Huazhong University of Science and Technology, Wuhan, China. Her research interests include intelligent transportation systems and vehicles detection.

Hanqing Zhou received his BS from the School of Optimal and Electronic Information, Huazhong University of Science and Technology, Wuhan, China in 2013. He is currently working toward his MS in the School of Optimal and Electronic Information, Huazhong University of Science and Technology, Wuhan, China. His research interests include intelligent transportation systems, vehicles detection, and field-programmable gate arrays (FPGAs).

Zhijun (Tony) Qiu received his BEng and MEng from the Control Science and Engineering Department, Tsinghua University, Beijing, China, in 2001 and 2003, respectively, and his PhD from Department of Civil and Environmental Engineering, the University of Wisconsin – Madison, USA, in 2007. From 2007 to 2008, he was a Post-Doctoral Researcher in Transportation Operation and Safety Lab, University of Wisconsin Madison, USA. From 2008 to 2009 he was a Post-Doctoral Researcher in California PATH Program, University of California Berkeley, USA. Science 2009, he has been an Assistant Professor in University of Alberta, Canada. His research interests include intelligent transportation systems, traffic modelling and simulation, traffic operation and control, traffic state detection, estimation and prediction, urban traffic safety analysis and wireless sensor network (WSN).

Yu Hu received his BEng and MEng degrees from the Computer Science and Technology Department, Tsinghua University, Beijing, China, in 2002 and 2005, respectively, and PhD degree from the Department of Electrical Engineering, University of California, Los Angeles (UCLA) in 2009. From 2010 to 2012, he was an Assistant Professor in the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Canada. Since 2012, he has been a Professor in the School of Optimal and Electronic Information, Huazhong University of Science and Technology, Wuhan, China. His research interests include intelligent transportation systems, connected vehicles, and embedded computing, and general aspects of field-programmable gate arrays (FPGAs). He is the co-recipient of the Best Contribution Award at International Workshop of Logic and Synthesis 2008. His work has been nominated for the Best Paper Award multiple times at the International Conference on Computer-Aided Design and Design Automation Conference.

This paper is a revised and expanded version of a paper entitled ‘A flexible control study of variable speed limit in connected vehicle systems’ presented at The International Workshop on Mobile Internet Big Data, Wuhan, China, 26–28 May 2014.

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 flow, real-time road information, and weather conditions (Balaji et al., 2013). Lin et al. (2004) presented two online algorithms for VSL, which improved traffic performance in bottleneck areas. Hegyi et al. (2003) used a model-based predictive control (MPC) approach to suppress shock waves in freeway traffic. A VSL control through in-vehicle system is implemented to expand the MPC approach by Lu et al. (2006). However, to the best of our knowledge, almost all the traditional VSL scheme focus on fixed speed limit sign, which has the following three defects:

1. VSL control lacks flexibility which means that drivers can only react to the speed limit sign at the fixed location generally.
2. VSL deployment lacks flexibility. Once the speed limit sign is placed, it will be not easy to change its position.
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 a great potential to solve the critical problem of traffic congestion. In CV, vehicles are equipped with wireless communication devices and can communicate with other vehicles and roadside equipments, which forms a big data environment to address traffic problems. In this paper, connected 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 the variable control distance (CD) leads to a more efficient control of traffic condition

2 the deployment of the CV-VSL system is flexible since the speed limit sign is not required

3 the influence of environment is lower owing 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 (Xu et al., 2013) with a calibrated road network

3 discussing the influence of CD to CV-VSL quantitatively.

The remainder of this paper is organised 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, CD is defined, which will be presented in Section 4. The comparison of advantages and disadvantages 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 CD. Section 5 analyses and discusses the simulation results. Finally, conclusions are given and future work is discussed in Section 6.

2 Background

2.1 Connected vehicle

CV is a typical application of ITS (Gupta et al., 2012; Lurie et al., 2006), which is a significantly important portion of 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 problems. An overview of CV system is showed in Figure 1. There are three RSUs which can broadcast information to vehicles within the range of communication. Vehicles send information to RSU by V2I. RSUs 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.

2.2 Variable speed limit

VSL 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, road condition and weather information, the limited driving speed is different. As showed in Figure 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 of bottleneck, a variable limited speed in upstream is necessary to avoid the traffic flow of downstream growing too fast and blocking the ramps.

Figure 1 CV System (see online version for colours)

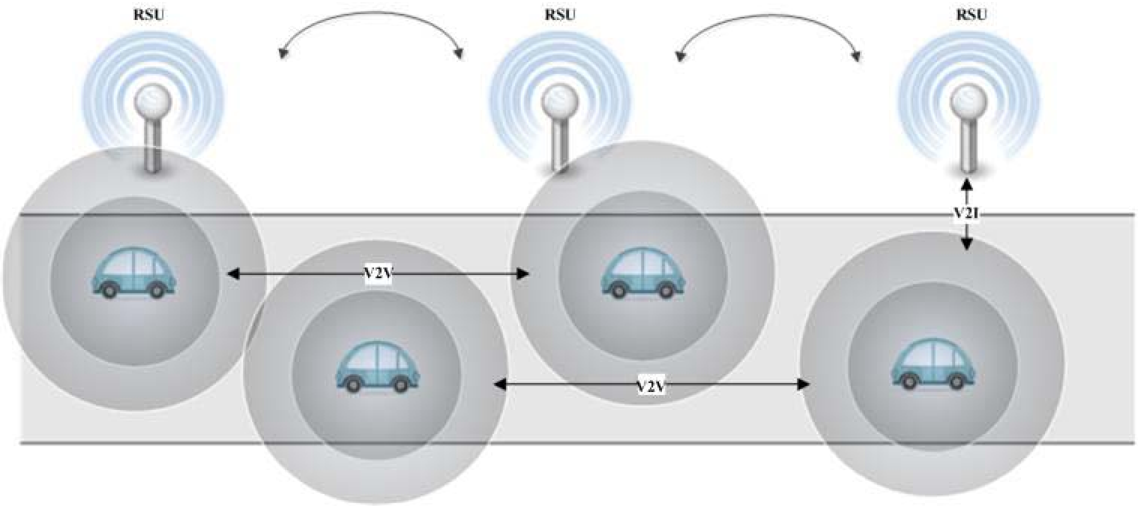
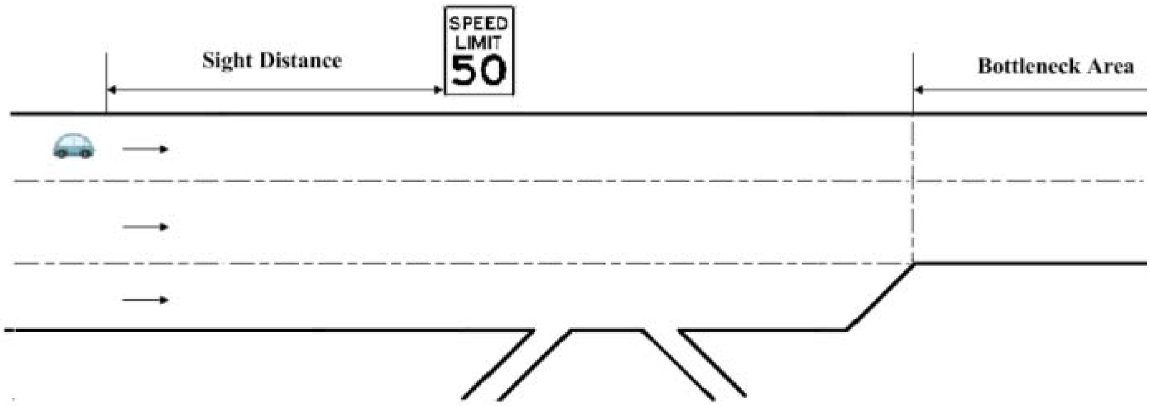


Figure 2 Bottleneck area (see online version for colours)



Generally, a VSL system is composed of three subsystems:

1 real-time traffic data collection system

2 data processing centre

3 fixed dynamic speed limit sign.

And the working process is showed in Figure 3. The fundamental traffic data, such as traffic speed, counts, position, and occupancy, are collected by traffic data collection system, which could be inductive loop detectors, overhead radar, and visibility sensor (Sisiopiku, 2001). Then the useful data is summarised in the data processing centre 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.

3 CV-VSL

3.1 Overview

In CV-VSL, RSUs broadcast traffic information in real-time. On board units (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.

As showed in Figure 4, the traffic data collection system collects traffic data from loop detectors, vehicles, roadside units and so on, which will be sent to data processing centre. The data processing centre will extract traffic conditions from the traffic data and apply the CV-VSL strategy to calculate the limit speed. The limit speed is sent to RSUs. And RSUs will periodically broadcast the limit speed to vehicles around. Once receiving the limit speed message, the OBU will check its position with GPS. If the CD is below the optimal CD, the OBU will display the limit speed to the driver. The drivers who see the limit speed message will determine to change the speed or not. Among the process above, how to get the optimal CD is also a big issue.

3.2 Control distance

CD 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 Figure 5. When the distance from the vehicle to the traditional speed limit sign is below the CD, the driver will be informed of the speed limit message by the display equipment in-car. If the vehicle is in the upstream of the speed limit sign, the CD is positive, otherwise negative. ‘Distance on-road’ means the distance is calculated along the road rather than the straight 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 CD. But in CV-VSL, the CD 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 kilometres as shown in the Figure 5. If the receiving distance is long, the deployment of RSU can be rather flexible to meet the need that vehicles must receive speed message before the CD point. In the traditional VSL, speed limit sign and the CD is fixed. But in CV-VSL, speed limit sign is replaced by RSU and OBU, and the CD can be flexibly changed. Different CDs will be configured to find the optimal solution of CV-VSL.

Figure 3 VSL working process

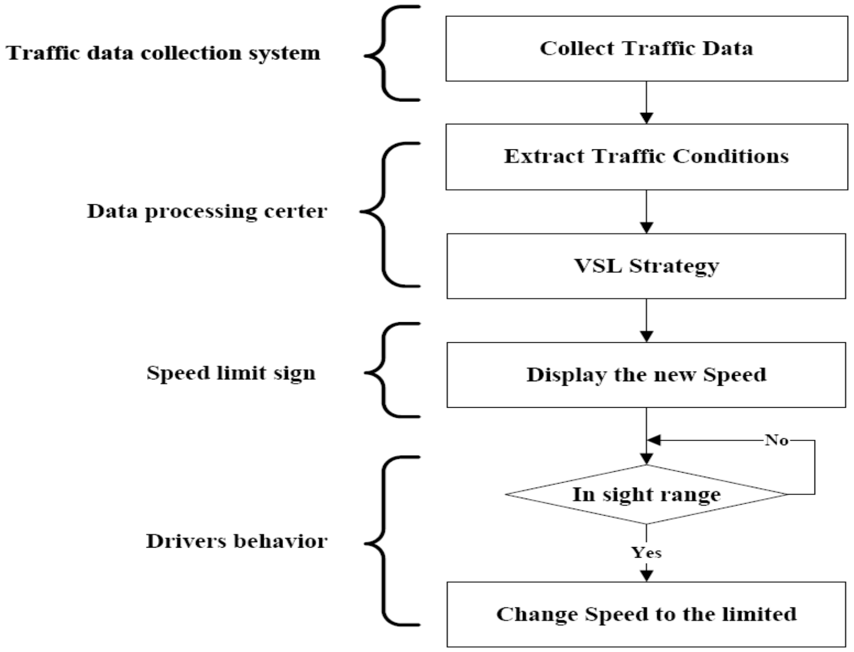


Figure 4 CV-VSL working process

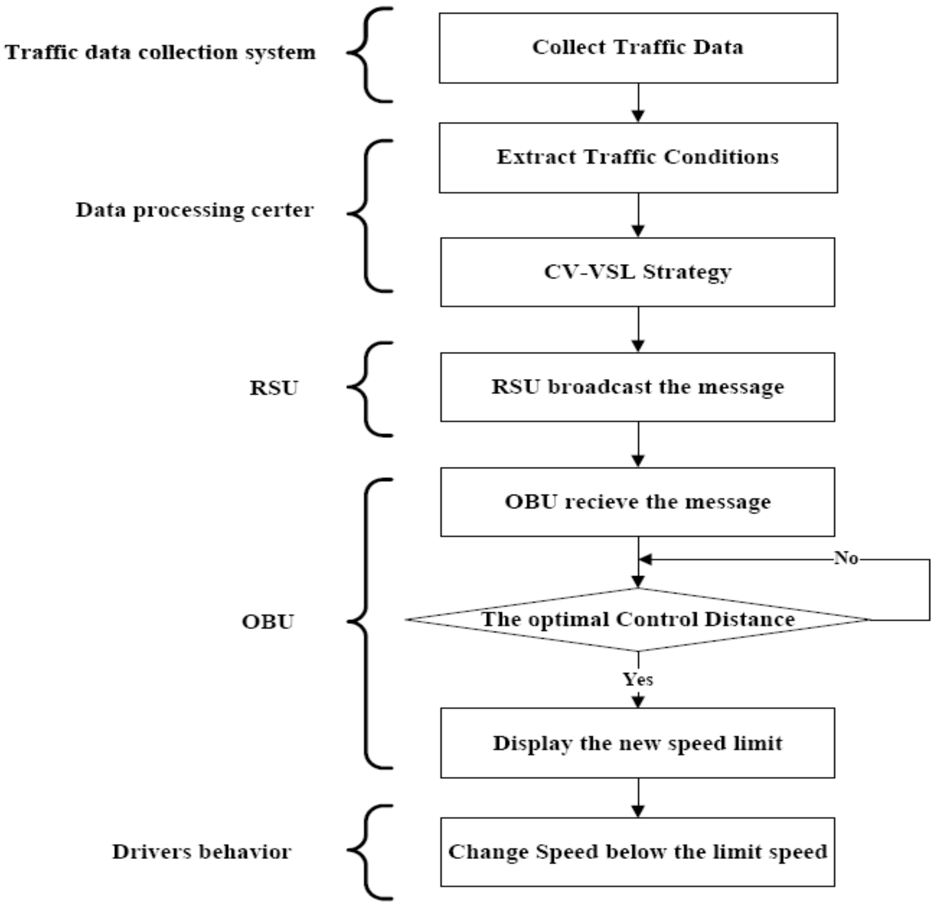
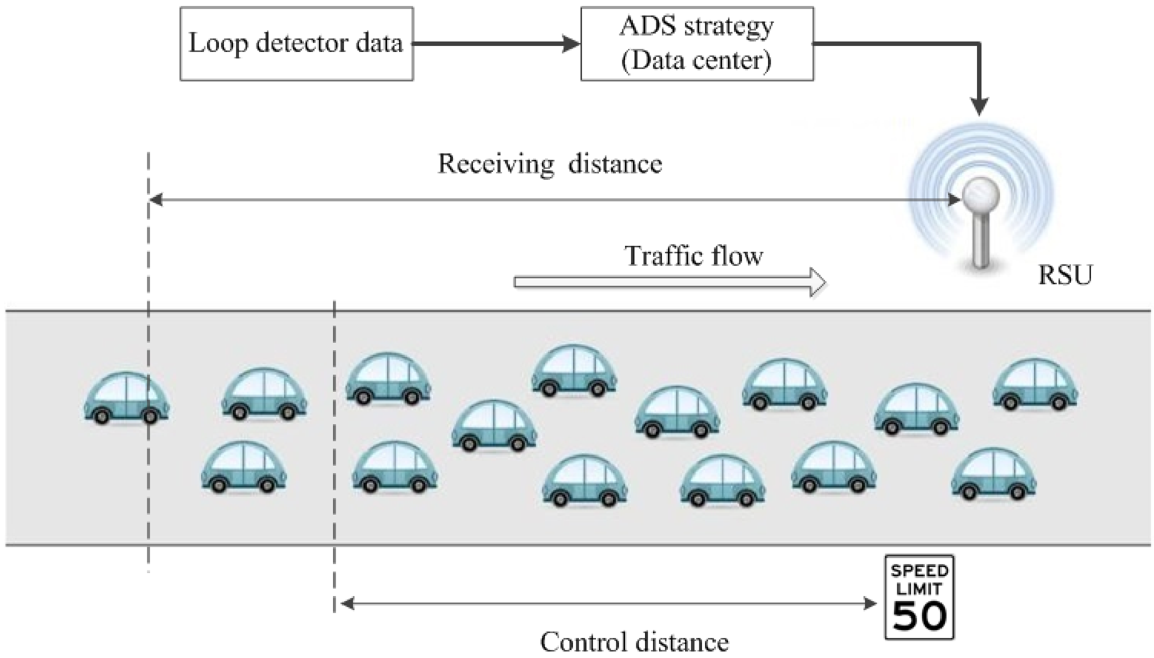


Figure 5 CV-VSL (see online version for colours)



3.3 *Advantages of CV-VSL*

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

1 *Variable CD*

To VSL, the CD is the visible distance, which is usually about 100–250 metres. Nevertheless, CV-VSL uses wireless communication to broadcast information. Generally speaking, one-hop propagation distance can reach 300–900 metres (Hadiuzzaman et al., 2012). By using V2V technology, communication distance can be extended to several kilometres. 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 speed limit signs' distribution along the road network. But for CV-VSL, information's 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 drivers' 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 (Xu et al., 2013; Jiang et al., 2013), as showed in Figure 6. VISSIM (http://www.ptvamerica.com/support/vissim/), 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 analyses the optimal value of limit speed, then feedback this speed to VISSIM to control the vehicles. OMNeT++ (http://www.omnetpp.org/), which is an open-source wireless network simulator, controls the network simulation. Traffic data and network data is exchanged between the two simulators periodically.

4.2 *Road network model*

As shown in Figure 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 (Qiu, 2012; Karim and Qiu, 2012).

4.3 VSL strategy

A VSL strategy is used to control the cars' behaviour in the VISSIM model, which is presented by Hadiuzzaman et al. (2012). The object function of this VSL strategy takes total travel time (TTT) and total travel distance (TTD) into consideration as shown below.

$$obj = \alpha_{TTT} T_{TTT} + \alpha_{TTD} T_{TTD} \tag{1}$$

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) (Hill and Kyle, 2011), and the wide spectrum band of DSRC is 75 MHz at 5.9 GHz allocated by the US Federal Communication Commission (FCC, 2006) exclusively. The simulation configurations are shown in Table 1.

Figure 6 CV-VSL simulation platform

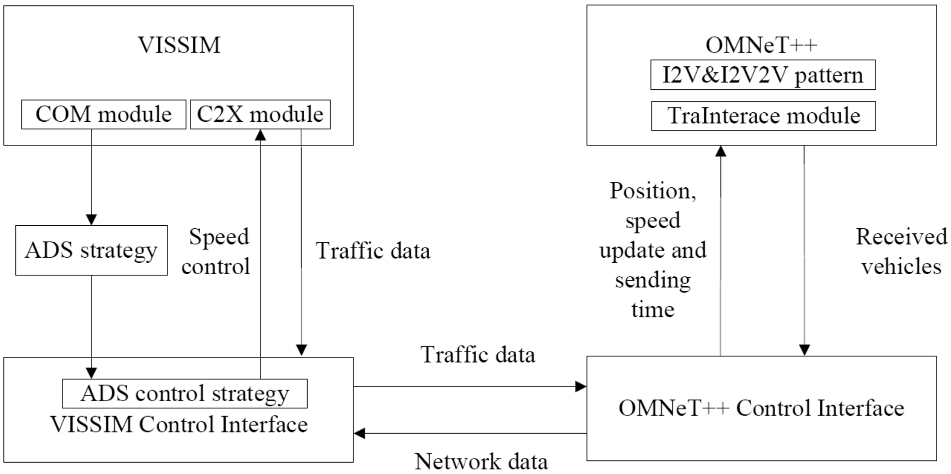


Figure 7 WMD road model (see online version for colours)

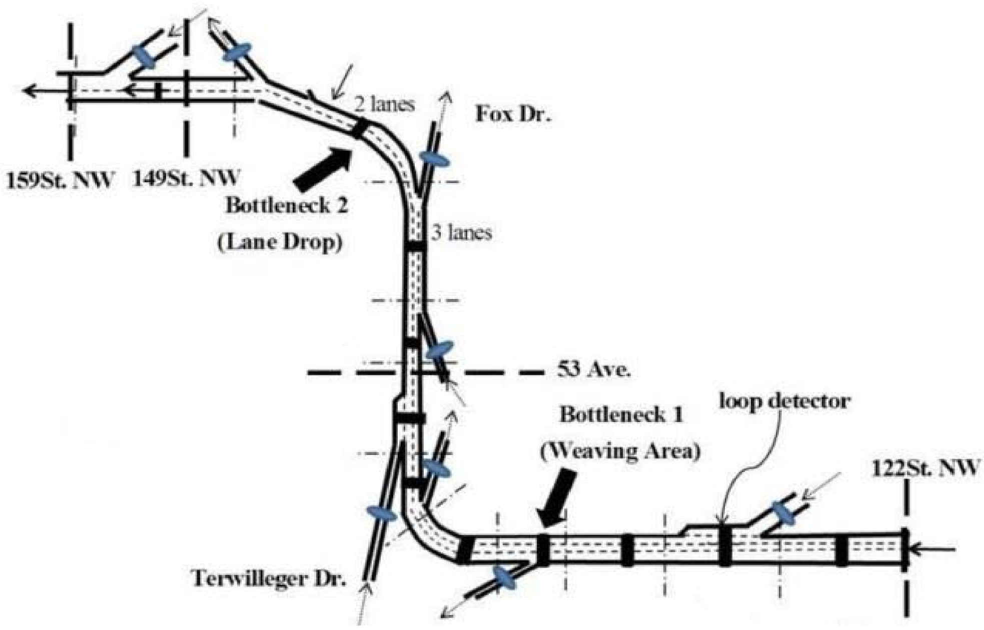


Table 1 DSRC configurations

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

4.5 CD configurations

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

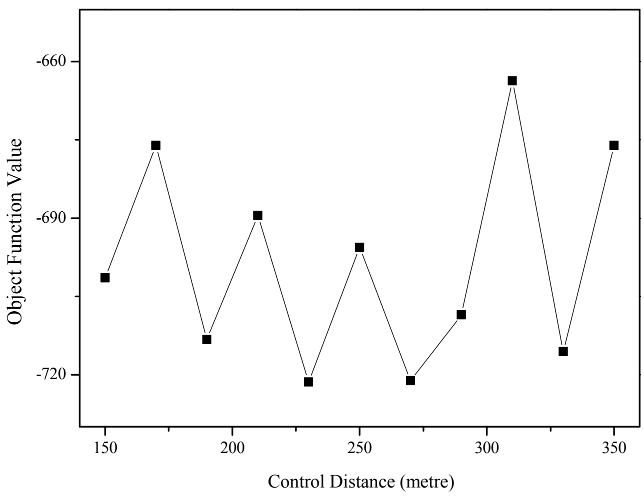
5 Result and discussion

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

$$improvement = \frac{V_{noVSL} - V}{V_{noVSL}} \tag{2}$$

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

Figure 8 The improvement of object function value

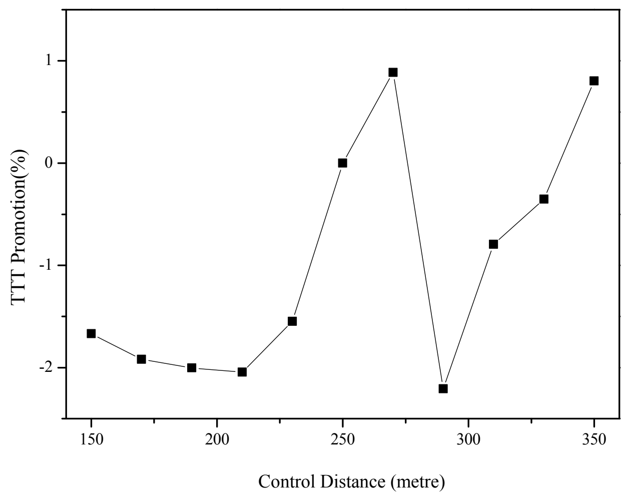


The improvement is 108.31% when the CD is 270 metres, which increase 0.72% than that when the CD is 250 metres. According to the experiment, the scenario when the CD is 250 metres can reflect the performance of traditional VSL which equals to the sight distance. So it can be easily concluded that the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

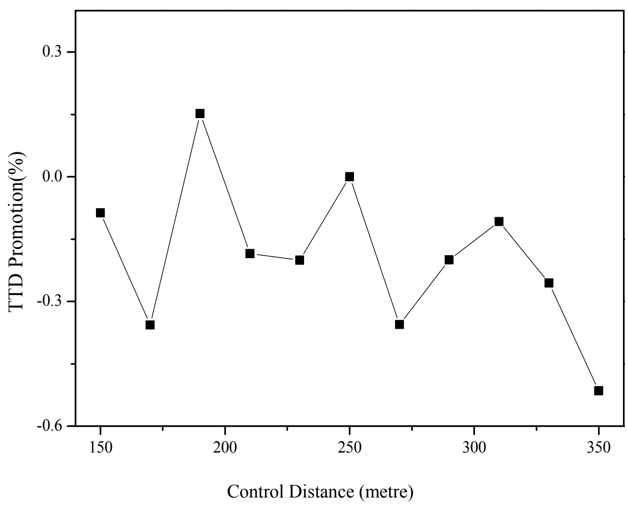
CDs of 230 metres and 270 metres show better performance. When the CD is much larger or smaller than 250 metres, the performance trends to be worse. It means that the optional solution is around 250 metres, which verifies the correctness of traditional speed limit sign's location.

Figure 9 shows that TTD and TTT vary with CD, which reflects the same tendency as the object function. It also proves that it is not the optimal CD where the traditional VSL's speed limit sign is.

Figure 9 The total travel distance and the total travel time, (a) TTD (b) TTT



(a)



(b)

The object function is a weighted summation of TTT and TTD. The lower the object function value, the better the traffic performance is. The shorter 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 CD

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 CD, 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 Conclusions and future work

Traffic congestions have been a critical problem in city development. The traditional VSL has 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 CD to CV-VSL is analysed quantitatively with high level architecture simulator – SimIVC. A group of experiments are conducted with a calibrated road network while changing CD.

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 best solution is around 250 metres
- 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 CD 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 consideration in simulation.

Acknowledgements

This work is partially sponsored by National Science Foundation of China (61272070).

References

Balaji, Y., Sashank, S., Swapnil, R. and Booz, A.H. (2013) *Active Transportation and Demand Management (ATDM) Foundational Research*, Technical report, US Department of Transportation, No. FHWA-JPO-13-022.

FCC (2006) *Amendment of the Commission's Rules Regarding Dedicated Short-Range Communication Services in the 5.850-5.925 GHz Band*, FCC Report and Order 06-110.

Gupta, P., Purohit, G.N. and Dadhich, A. (2012) 'Approaches for intelligent traffic system: a survey', *International Journal on Computer Science and Engineering*, September, Vol. 4, No. 9, pp.1570–1578, ISSN : 0975-3397.

Hadiuzzaman, M., Qiu, T.Z. and Lu, X.Y. (2012) 'Variable speed limit control design for relieving congestion caused by active bottlenecks', *Journal of Transportation Engineering*, Vol. 139, pp.358–370, ISSN (print): 0733-947X.

Hegyi, A., Schutter, B. and Hellendoorn, J. (2003) 'MPC-based optimal coordination of variable speed limits to suppress shock waves in freeway traffic', *American Control Conference*, Denver, Colorado, pp.4083–4088.

Hill, C.J. and Kyle, G.J. (2011) *AASHTO Connected Vehicle Infrastructure Deployment Analysis*, US Department of transportation, USA, Technical report FHWA-JPO-11-090.

Jiang, T., Xiaowei, X., Lu, P., Yu, H. and Zhijun, Q. (2013) 'A simulation study of connected vehicle systems using named data networking', *4th International Conference on Cloud Computing*, Wuhan.

Karim, M. and Qiu, T.Z. (2012) 'Study on calibration and validation of fundamental diagram for urban arterials', in *Transportation Research Board 91st Annual Meeting*, No. 12-0637.

Lin, P-W., Kang, K-P. and Chang, G-L. (2004) 'Exploring the effectiveness of variable speed limit controls on highway work-zone operations', *Int. J. of Intelligent Transportation Systems*, Vol. 8, pp.155–168, ISSN: 1547-2450 (print), 1547-2442 (online).

Lu, M., Hegyi, A. and Wevers, K. (2006) 'Perspective of mitigating shock waves by temporary in vehicle dynamic speed control', *Transportation Research Board 85th Annual Meeting*, No. 06-1753.

Lurie, S.A., Hui, D., Kireitseu, M.V. et al. (2006) 'Computational mechanics modelling of nanoparticle-reinforced composite materials across the length scales', *International Journal of Computational Science and Engineering*, Vol. 2, Nos. 3–4, pp.228–241, ISSN :1742-7185 (print), 1742-7193 (online).

OMNeT++ [online] http://www.omnetpp.org/ (accessed 7 March 2014).

Qiu, Z.T. (2012) *Online Simulation of Networked Vehicle based Active Traffic Management for Freeway Operation*, Final report, University of Alberta.

Sisiopiku, V.P. (2001) 'Variable speed control: technologies and practice', *Proceedings of the 11th Annual Meeting of ITS America*, pp.1–11.

VISSIM, PTV America [online] http://www.ptvamerica.com/support/vissim/ (accessed 7 March 2014).

Xu, X., Jiang, T., Li, P., Tony Qiu, Z. and Yu, H. (2013) 'A high-level architecture SimIVC for simulating the traffic network', *2nd International Conference on Transportation Information and Safety*.