Optimal Variable Speed Limit Control under Connected Work Zone and Connected Vehicle Environment

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Abstract

Despite the long-term benefits gained through road maintenance projects, the work zone involved can cause serious traffic congestion and greatly increase traffic delay. Variable speed limit (VSL) enforcement provides a means to reduce the travel time and alleviate the traffic congestion in work zones. This paper presents a novel proactive VSL control algorithm for freeway work zone traffic management under connected work zone and connected vehicle environment. In a connected work zone environment, the estimated work zone capacity can be easily shared considering the work zone configuration factors such as number of lane closure, signal distance, presence of work activity, etc. After incorporating the estimated capacity which contributes to a better modeling of the traffic disturbance caused by work zone, the traffic flow predictive model was established to obtain preventive measures and avoid traffic breakdown. In addition, based on the trajectories of individual vehicles recorded and shared by connected vehicles, the objective function was developed for the VSL control algorithm to minimize the Total Travel Time which can be used to measure level of the traffic congestion. The VSL control was implemented and tested in a traffic simulator SUMO. The results showed that the designed VSL algorithm effectively decreased the total travel time with the reduction of the speed variance which potentially improved the traffic safety at work zones.

Keywords

Variable Speed Limit; Connected Work Zone; Connected Vehicles; Total Travel Time

1 Introduction

Traffic congestion frequently occurred in freeway has become a critical issue in modern societies. To improve the traffic condition, $66 billion are estimated to be invested into maintaining and repairing road infrastructure in Canada between 2013 and 2023 [1]. However, these projects such as resurfacing, lane widening, drainage realignment, etc. create numerous construction work zones in freeways and other urban arterial roads. Such work zones, which involve lane closure, will have serious impacts on traffic mobility. According to [2], in 2014 the estimated 888 million hours delay and the fuel loss of over 310 million gallon are attributed to work zones in the US. Therefore it is essential to develop an effective control strategy on freeway traffic operation to mitigate the traffic congestion caused by work zones.

Variable speed limit, one of the Intelligent Transportation System (ITS) control strategies, can dynamically change the posted speed limits along the upstream segments of a bottleneck. As such, VSL is able to reduce the traffic inflow or homogenize the traffic flow to avoid traffic breakdown, reduce the total travel time, achieve uniform distribution of traffic flow and improve the safety. However, the majority of the research developed the VSL control strategies based on macroscopic speed-limit model, which extracts the aggregate traffic states such as flow, density and average speed. This makes it difficult to accurately acquire and analyze the microscopic behavior (acceleration, merge location, etc.) of individual vehicles given the work zone disturbance.

Connected vehicle (CV) environment enables vehicle-to-vehicle and vehicle-to-infrastructure wireless communication to better share the traffic states of each CV-enabled vehicle. Few studies have considered making the work zone connected. Connected work zone enables a more accurate and timely assessment of the traffic impacts caused by the configuration factors of work zone such as work zone ahead warning signal distance, number of lane closure, work activity inside work zone, etc.

Since the microscopic vehicle behavior and work zone configuration have great impacts on traffic flow, the VSL control strategy should be developed given due consideration to such impacts. Therefore a microscopic traffic speed-limit model, capable of obtaining more accurate traffic states as the input of the VSL controller, is in need. Meanwhile, the work zone as the disturbance to the traffic also needs to be modeled in order to consider the work zone configuration.

This paper introduces a novel proactive VSL control strategy to optimize the VSL, minimize the impact on travel time and mitigate the traffic congestion under connected work zone and connected vehicle environment. The rest of this paper is organized as follows. Recent studies are reviewed in Section 2. The research objectives are described in Section 3. The development of a model predictive controller to optimize the VSL given the constraints of posted speed limit on the freeway is presented in Section 4.1. The connected work zone is analyzed in Section 4.2. After the introduction of experiment setup, the effectiveness of the designed VSL control was tested in the traffic simulator SUMO [3] as described in Section 5. Section 6 concludes this paper.

2 Literature Review

There are a number of studies on developing VSL control strategies to reduce the traffic congestion and improve traffic condition. The Model Predictive Control (MPC) was utilized by [4] to proactively coordinate VSL to eliminate the traffic shock waves. The macroscopic model METANET was modified to predict the traffic flow, density, average speed and queue length so that VSL controller would be able to reduce the effects of moving jams. The SPECIALIST algorithm was designed based on the shock wave theory by using the fundamental diagram (FD) [5]. The shock wave detection, resolve and assessment were proposed by analysing the traffic states on the FD. The FD was also employed in cell transmission model design to optimize the VSL control [6]. The modified FDs were proposed at the active bottleneck on the freeway to model the capacity drop and variable speeds. The optimization of VSL proved to improve the traffic flow and capacity. The VSL optimization was also proposed and developed to improve traffic safety by homogenizing the traffic flow given different driver compliance rates [7].

The control strategies adopted in the above-mentioned studies were able to optimize the VSL proactively to suppress the shock wave, improve the traffic flow capacity and enhance the traffic safety. However, the control method was developed under the macroscopic simulation environment. Therefore, the behaviour and trajectories of microscopic individual vehicles, which are vitally important to analyze the disturbance of traffic flow, were neglected. Inappropriate lane changing behavior can easily cause the shock wave. The vehicle sudden acceleration and deceleration behaviors due to velocity changes of the leading or following vehicles also greatly affect the traffic flow. To accurately analyze the traffic flow on the freeway and develop optimal VSL control strategy, it is essential to take the behavior of individual vehicle into consideration.

A number of VSL control strategies were also developed in work zone applications to mitigate the negative effects such as traffic congestion, green house emission, safety issue, etc. A multi-objective function was established to optimize the travel time, improve safety and reduce gas emission under microscopic simulation [8]. In this study, a MPC was implemented to predict the microscopic vehicle behaviors considered a hypothetical incident with speed limit on the freeway. In another study, a macroscopic traffic flow model was established to develop the VSL controller for the freeway work zone operations [9]. In [10], to study the effectiveness of VSL, a control logic was designed to determine the posted speed limits on the highway with a work zone.

The work zone applications of VSL have been explored to study the interaction between the traffic flow and work zone so as to optimize the VSL and reduce the negative impacts due to the presence of work zone. However, the details of work zone such as the number of lane closure and warning signal distance have not yet considered. Instead, the work zone disturbance was simplified as a static speed limit on the freeway. In reality, the different configuration factors of work zone will result in different capacity and have different impacts on traffic flow. Thus having a better understanding of work zone as the disturbance is of great importance to develop an effective VSL control strategy.

Though extensive studies have been conducted to develop VSL control strategies and explore the work zone applications, the lack of the behavior of each vehicle reacted to the work zone and understanding of work zone disturbance makes it difficult to obtain optimal VSL. Therefore, a proactive VSL control which is capable of incorporating the microscopic vehicle behavior and work zone configuration needs to be developed.

3 Research Objectives

Developing the optimal VSL control for freeway work zone traffic management to mitigate the traffic congestion and reduce travel time is the major objective of this study. The following objectives are included: (1) developing a predictive VSL control under connected vehicle environments to incorporate the behavior of individual vehicle, (2) analyzing the effects of connected work zone on VSL controller design and (3) evaluating the effectiveness of the designed control strategy in SUMO.

4 Methodology

To reduce the traffic congestion caused by work zone, a MPC is proposed to achieve optimal VSL control on the freeway under the connected work zone and connected vehicle environment. To obtain the traffic states and predict the behavior of each vehicle, the modified Krauß car-following model and 4-layer motivation lane changing model are adopted [11][12]. Since the freeway work zone can easily lead to non-recurring congestion and has significant influence on traffic flow, the work zone configuration factors are analyzed to establish the vehicle merge location model, estimate the work zone capacity and evaluate the effects of work zone disturbance. The comprehensive traffic data such as speed and position of individual vehicle and the work zone factors are available under connected environment.

To make full use of the traffic states and work zone information, the MPC is developed and connected work zone effects are analyzed in the following sections.

4.1 Model Predictive Control

To develop VSL control for traffic flow, MPC is proposed to follow the controller design procedures showed in Figure 1.

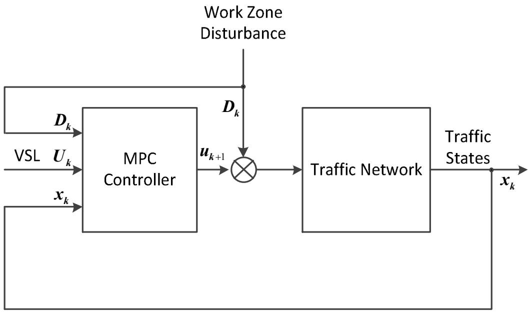


Figure 1. MPC Control for Traffic Network

The MPC controller is designed to control the traffic network through the control signal VSL u_{k+1} at next time step k+1. Three signals are input to MPC controller to optimize the VSL u_{k+1}. The work zone on the freeway is treated as D_k which consists of N_c controller time steps of disturbance from work zone. The VSL control signal U_k as the second input has the VSL solutions for N_c controller time steps. The traffic states x_k such as the velocity, position of each vehicle at time step k collected from the connected vehicle environment are fed back to the MPC controller for each simulation step as the third input signal. By taking the feedback traffic states x_k, together with the VSL U_k and work zone disturbance D_k, MPC controller is developed to optimize the VSL.

The components inside MPC controller are illustrated in Figure 2. The objective function is designed to optimize the next time step VSL control u_{k+1} by minimizing the total travel time. The travel time is calculated based on the predicted N_p time steps of traffic states. Specifically, the velocity and position of each vehicle are predicted for N_p time steps by using the car-following model. Thus in the designed MPC control, the traffic states are predicted in N_p prediction horizon while the control signals are predicted in N_c controller horizon. However, only the first optimal VSL control u_{k+1} is applied in traffic network. Then the prediction horizon shift one time step when the new traffic states are obtained. The VSL control action is optimized in this rolling horizon scheme considering the constraints of VSL in real world.

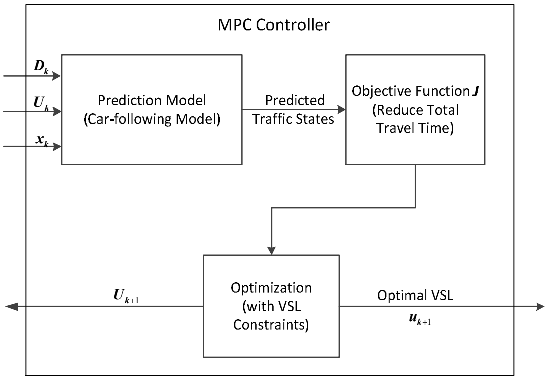


Figure 2. MPC Controller

4.1.1 Car-following Model

The car-following model is developed based on the modified Krauß model which has low computation complexity and was proved to have high validity [11].

There are three speed constraints needed to be considered for this car-following model. The first one is safe speed. The speed v of the vehicle which follows the leader vehicle whose speed is v_{leader} should not exceed the safe speed v_{safe} meaning the gap d_{gap} between the vehicle and its leader should be larger than the brake distance d_{brake}. This prevents the vehicle having the rear-end collision. The brake distance d_{brake} and safe speed are calculated as:

$$d_{brake} = \frac{{v_{safe}}^2}{2a_{\max dec}} \tag{1}$$

$$v_{safe} = \sqrt{(\tau * a_{\max dec})^2 + v_{leader}(t-1)^2 + 2 * a_{\max dec} * d_{gap}(t-1)} - \tau * a_{\max dec} \tag{2}$$

where the $a_{\max dec}$ is the maximum deceleration ability, τ is the driver reaction time, $v_{leader}(t-1)$ is the velocity of leader vehicle at previous time step t-1 and $d_{gap}(t-1)$ is the gap between the vehicle and its leader at previous time step t-1.

In addition to the constraint of vehicle deceleration ability, the speed of vehicle also needs to satisfy the acceleration ability showed in Equation (3).

$$v_{acc} = v(t-1) + a_{\max acc} \tag{3}$$

where $a_{\max acc}$ is the maximum deceleration ability and $v(t-1)$ is the speed of the vehicle at previous time step t-1. However, in reality when the speed is close to the maximum speed, the acceleration tends to be smaller. Therefore, a decay factor was applied to the acceleration in Equation (4).

$$a_{\max adjusted} = a_{\max acc}(1 - \frac{v}{v_{\max}}) \tag{4}$$

where $v_{\max}$ is the speed limit posted.

The third constraint is maximum speed $v_{\max}$ allowed on the freeway. This constraint reflects the VSL control action.

Therefore the vehicle speed which satisfied these three constraints is the desired speed showed in Equation (5).

$$v_{desire} = \min\{v_{safe}, v_{acc}, v_{\max}\} \tag{5}$$

When the driver's imperfection is considered, the desired speed will be reduced by a stochastic deceleration expressed by

$$v = \max\{0, v_{desire} - \lambda * a_{\max adjusted} * \delta\} \tag{6}$$

where λ is the imperfection factor of the driver and δ is a random number between 0 and 1.

4.1.2 Lane Changing Model

The lane changing model which has a low wrong-lane teleport rate in SUMO was adopted [12] in this study. This model analyzes four motivations to perform the lane changing behavior: (1) strategic change, (2) cooperative change, (3) tactical change and (4) regulatory change. In this study, the focus is on performing lane changing behavior due to the lane closure at the work zone area. Therefore, strategic change, which happens when the dead lane is in front, is mainly discussed.

Before analyzing the speed changes of vehicles, the some terms for the lane and vehicles will be briefly introduced in Figure 3. As it is showed, the ego vehicle is the vehicle which is performing the lane changing behavior to the target lane. The leader and follower vehicles potentially block the ego vehicle.

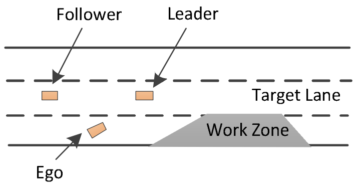


Figure 3. Lane Changing Behaviour

To successfully change to the target lane, the speed adjustment should be made based on the flow diagrams illustrated in Figure 4 and Figure 5.

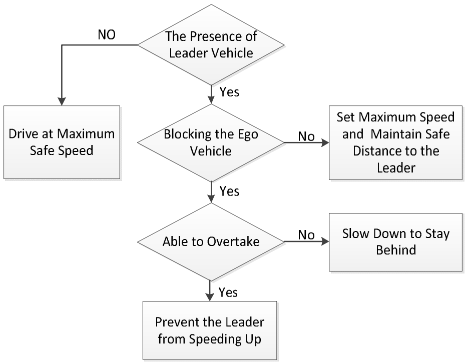


Figure 4. Speed Adjustment with the Presence of Leader

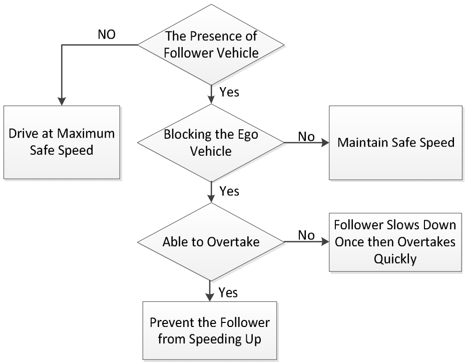


Figure 5. Speed Adjustment with the Presence of Follower

The speed of ego, leader, and follower vehicles should be adjusted to be complied with the basic rules set in the above flow diagrams when ego vehicle performs the lane changing behaviour.

4.1.3 Objective Function

The objective function is designed to optimize VSL by minimizing the total travel time spent in the upstream and work zone area. To calculate the total travel time, the velocity and position of each vehicle are predicted first. The velocity is updated based on the maximum safe speed discussed in car-following model. The VSL will affect the safe speed by setting the maximum speed limit $v_{\max}$. Once the speed of vehicle i is updated at time step t+1, the position of vehicle i is updated as:

$$x_i(t) = x_i(t-1) + \frac{v_i(t)^2 - v_i(t-1)^2}{2a_i} = x_i(t-1) + \frac{v_i(t) + v_i(t-1)}{2} \quad (7)$$

The total travel time J_{travel} is obtained using Equation (8). It can be seen that total travel time is calculated by taking the sum of vehicles in the upstream of work zone. Because one simulation time step in SUMO represents one second, then the N_p prediction horizon is N_p seconds. When N_p time steps of vehicle position are predicted, the total number of vehicle stays in the upstream segments will determine the total travel time.

$$J_{travel} = T\sum_{k=t}^{N_p} n_k \quad (8)$$

where T equals to one simulation time step which is one second and n_k is the total number of vehicle in the upstream work zone and work zone area at time step t.

The genetic algorithm was utilized to optimize the VSL. By changing the VSL, the maximum speed of each vehicle is changed. Correspondingly the predicted the position of each vehicle is changed. Then Equation (8) is utilized to find the optimal VSL with minimum total travel time.

4.1.4 Constraints

The three constraints showed in Equation (9) are considered during the optimization of VSL.

$$\begin{cases} \mathrm{v} \in \{50, 60, 70, 80, 90, 100\} \\ \left|\mathrm{v}_j(t) - \mathrm{v}_{j+1}(t)\right| \le 10 \\ \left|\mathrm{v}_j(t) - \mathrm{v}_j(t+1)\right| \le 10 \end{cases} \quad (9)$$

where the $\mathrm{v}_j(t)$ represents the posted speed limit in the position j at time step t.

The VSL should be in the set of speed limit from 50km/h to 100km/h with the increment of 10km/h. The 50km/h is set to ensure the travel efficiency of freeway and 100km/h is the maximum speed limit in free-flow status. Such numbers may differ for different jurisdictions. To avoid the sudden acceleration and deceleration, the difference between the posted speed limits on two consecutive VMS should be less than 10km/h and the speed limit at the same position for two consecutive controller time steps should be less than 10km/h too.

4.2 Connected Work Zone

The work zone is considered under connected environment in this study. By making the work zone connected, more information of work zone such as the approaching distance to work zone, number of lane closure, activity inside work zone, etc. will be shared with the vehicles in the upstream segment. This will help drivers make better decision before they approach the work zone and will reduce the possibility of traffic congestion. The merge location, capacity estimation and disturbance caused by work zone will be discussed under the connected environment.

4.2.1 Merge Location

The early merge location determines when the vehicle in the lane which will be closed due to work zone should change to the target lane earlier. The distance is more than 550 meters, where 50% of vehicles merge, away from work zone [13]. It will greatly affect the lane changing behavior when the lane changing model in 4.1.2 is utilized.

The early merging location model was adopted to consider the density and speed in the lane of work zone and target lane [14]. The merge location is calculated using Equation (10) and the obtained location will act as one input signal to the lane changing model.

$$\mathrm{L}_{\text{merge}} = \exp(\boldsymbol{\alpha} \bullet \boldsymbol{\omega} + \varepsilon) \quad (10)$$

where $\mathrm{L}_{\text{merge}}$ is the merge location, $\boldsymbol{\alpha}$ is the parameter vector, $\boldsymbol{\omega}$ consists of the variables of the speed and density and ε is the random error follows the normal distribution.

Under connected environment, the distance to the work zone and traffic states will be accessible to perform better lane changing behavior.

4.2.2 Capacity

The work zone capacity which is the traffic breakdown flow is an essential element to analyze the traffic congestion. However, the capacity estimation does not only depend on work zone layout and other geometry factors. It also correlates with the states of traffic flow near the work zone.

To estimate the capacity of the 3-to-2 type of work zone, the estimation model was established in [15] as:

$$\mathrm{C}_{\text{wz}} = \boldsymbol{\beta} \bullet \boldsymbol{\chi} \quad (11)$$

where $\boldsymbol{\beta}$ is the parameter vector and $\boldsymbol{\chi}$ consists of the variable of the distance of warning sign, the percentage of traffic on each lane, work activity in work zone, heavy vehicle percentage, etc.

Then the estimated work zone capacity under connect environment is utilized to analyze the disturbance of work zone in the following section.

4.2.3 Disturbance

The work zone acts as the disturbance in VSL control showed in Figure 1. Since the presence of work zone will greatly affect the traffic flow and cause traffic congestion in the upstream segments of work zone. It is essential to model this disturbance in microscopic simulation.

Before modeling the work zone disturbance, the traffic stages in which VSL will be applied will be discussed first. There are three stages (free flow, transition and congestion) to describe the traffic flow [16]. In free flow stage, there is a low traffic density and the traffic will flow stably. In transition stage, the small disturbance in the traffic flow will be disappeared. However, the large disturbance will cause the traffic breakdown. While in congestion stage, the traffic congestion has already happened or a small disturbance will lead to traffic congestion.

VSL control will only apply to the transit stage. In free flow stage, VSL control will restrict the traffic inflow and increase the time delays. While it will not have effective impacts on traffic control when the traffic is in congestion. However, in transit stage, VSL control will have the possibility to absorb the small disturbance and reduce or eliminate the effects caused by the disturbance.

Therefore the speed-flow relationships in transit stage will be utilized to analyze the work zone disturbance. This relationship is expressed as [16]:

$$v_{\text{limit}} = v_{\max} - (v_{\max} - 18.7) * (\frac{Q-900}{2182.2-4.3*v_{\max}})^{3.6} \quad (12)$$

where $v_{\max}$ is the maximum speed limit and Q is the work zone capacity.

The disturbance is modelled as the speed limit in the work zone area. Under connected environment, the speed limit will be obtained based on the calculated work zone capacity (section 4.2.2).

5 Experiment and Results Analysis

5.1 Experimental Setup

The effectiveness of the proposed VSL control was assessed in traffic simulator SUMO. A hypothetical three lanes of freeway traffic network was established under connected work zone and connected vehicle environment as showed in Figure 6. The upstream road of the work zone was divided into 5 segments. Each segment had 800 meters. There was a 3-to-2 type of work zone set in the 6th segment with the length of 100m. In addition, the 7th segment represented the downstream road of the work zone with 800 meters. It was assumed that work zone will not be removed during the simulation.

There were six VMSs set up to post the speed limits as presented in Figure 6. The first 5 VMSs along the upstream road will show the speed limits acquired from the VSL control and the 6th VMS will post the speed limit result from the work zone disturbance. The initial speed limit was set to be 100km/h for all the 6 VMSs before the VSL was applied. Once the vehicle travels to a new segment, it will set the posted speed limit in the new segment as its maximum speed limit.

The work zone in 6th segment was set up with the following configuration settings: heavy vehicle percentage was 5%; the warning signal distance was 3.2km; lateral clearance was 8ft; lane width was 12ft; there was no work activity presented inside the work zone.

The vehicle parameters in SUMO were set with maximum acceleration 2.6 m/s^2; maximum deceleration 4.5 m/s^2; the driver's imperfection 0.9. The traffic demand was 3500 vehicles/h which is close to the estimated work zone capacity 4000 vehicles/h by HCM 2000 [17]. The parameter vectors of merge distance and capacity estimation were adopted from [14] and [15]. The prediction horizon N_p was selected as 3.5 minutes which is an approximate to the time to travel the whole road network under free flow and the controller horizon N_c was selected as 2 minutes.

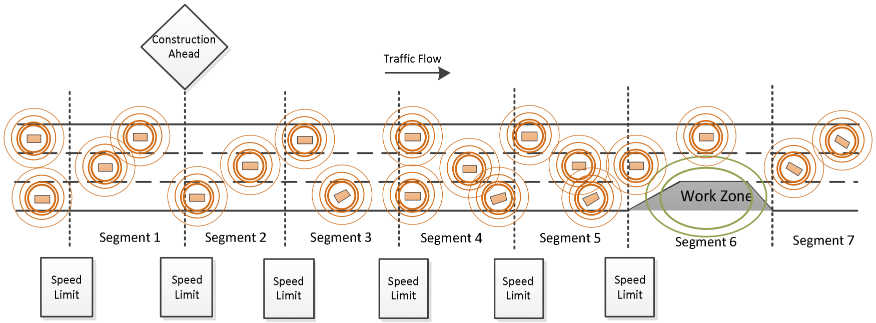


Figure 6. VSL for Freeway Traffic Control under Connected Work Zone and Connected Vehicle Environment

5.2 Results Analysis

To assess the impacts of connected environment and the effectiveness of VSL control, 4 scenarios are considered in the simulation: (1) VSL with connected environment; (2) VSL without connected environment; (3) uniform speed limit with connected environment and (4) uniform speed limit without connected environment.

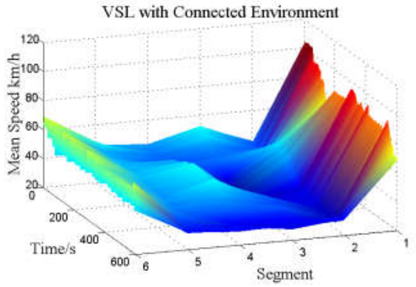
The simulation was run for 20 minutes with the assumption of 100% market penetration rate of the connected vehicle. Since it takes time for the traffic to arrive at the work zone area and have a stable traffic condition, the simulation data of the first 10 minutes was discarded.

The estimated average travel time of each segment are showed in Table 1.

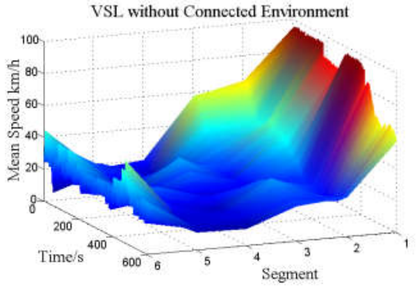
Table 1 Average Travel Time for Each Segment

Travel Time (s)	Scenario			
	VSL & Connected	VSL	Connected	Normal
Segment 1	30.2	30.2	30.2	30.2
Segment 2	33.7	35.3	35.8	37.2
Segment 3	89.5	101.5	89.1	97.6
Segment 4	92.6	117.2	130.5	151.4
Segment 5	68.4	182.2	209.1	217.2
Segment 6	66.4	177.2	181.0	193.7

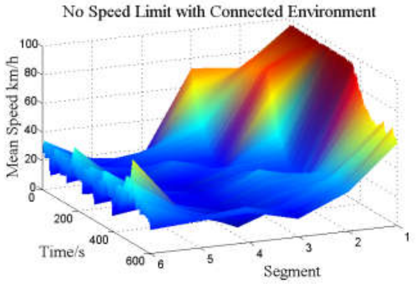
As we can see from Table 1, VSL with connected environment has the shortest travel time in all the six segments. Though scenario 2 has similar travel time to scenario 1 in the first 2 segments, the congestion happened in scenario 2 before the work zone delays the traffic significantly. Because the information of work zone is not shared with the vehicles earlier before they arrive at the work zone, the vehicle tends to perform inappropriate lane changing behavior which will easily lead to traffic congestion. The effects of earlier information are also showed in the uniform speed limit control between connected and non-connected environment. The outperformance of VSL is illustrated in both connected and non-connected environment as the average travel time of VSL is much less than that of uniform speed limit. Although this outperformance is not significant in the first 3 segments, it saves considerable time when the traffic is closed to work zone area. The improvement of homogenization of the traffic flow because of VSL control accounts for the less travel time compared with traffic network with uniform speed limit. This argument was also demonstrated in the speed profile of each segment in Figure 7.



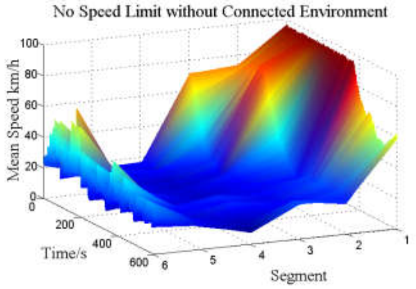
(a) Speed Profile in Scenario 1



(b) Speed Profile in Scenario 2



(c) Speed Profile in Scenario 3



(d) Speed Profile in Scenario 4

Figure 7. Speed Profile in Different Scenarios

As it can be seen from Figure 7, the vehicles in upstream segment maintain higher speed (40-60km/h) and experience less speed variance under VSL control with connected environment. Without connected environment, only VSL can achieve relatively small variance. However, the travel speed (20-40km/h) in segment 3, 4, 5 and 6 are much slower. A large speed variance exists at segment 6 which is the work area for VSL control without connected environment due to the lack of work zone information, which leads to more stop-to-go vehicle statuses and higher safety risk. The homogenization effects are also demonstrated between speed profiles of the VSL and uniform speed limit.

It can be seen from Table 1 and Figure 7, VSL control significantly decreases the travel time, enhances the speed homogeneity and reduces the speed variance which potentially improves the safety.

6 Conclusion and Future Work

To mitigate the traffic congestion and reduce the travel time, a VSL control strategy was proposed under connected work zone and connected vehicle environment. By optimizing the VSL using MPC and connected work zone, the proposed approach was able to significantly reduce the total travel time and decrease the speed variance which has the potential to improve the safety around the freeway work zone area.

In this study, the 100% market penetration of connected vehicle and perfect wireless communication were assumed. The driver compliance rate was not considered. In future work, the effects of low market penetration will be explored and the driver reaction to VSL will be incorporated to achieve optimal VSL control.

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