Variable Speed Limit Control on Highway Work Zone
Considering Large Vehicle Mix Rates

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Abstract

Due to the difference of vehicle type and power performance between large vehicles and cars, large vehicle mix rate will have an important impact on traffic flow of work zone and lead to the decrease of driving safety. Through a survey of Shanghai outer ring highway work zone, this article analyzes the influence of large vehicles to traffic flow speed and speed variance, and then put forward a variable speed limit (VSL) strategy based on gap acceptance theory for highway work zone considering large vehicle mix rate. The simulated analyses showed that this strategy can reduce speed variance which can contribute to improving the overall traffic safety in work zone. The research results can provide a powerful technical support for highway work-zone speed management.

Keywords: highway; work-zone; large vehicle mix rate; variable speed limit

1. Overview

Improving safety and operational efficiency of traffic flows at work zone has been one of the major challenges in traffic engineering. The research of work zone mainly focused on merge control and speed management.

Speed management has a positive effect on improving the safety of traffic flow (WU Xinkai, 2004). A common practice over the past several decades for work zone operations is to recommend or enforce a reduced speed limit using posted speed limit (PSL), which can improve the smoothness of traffic flow but may not respond to fluctuation in approaching traffic demand (Wang Qiang, 2010). In order to improve traffic safety and increase the compliance rate of drivers, traffic professionals in recent years have experimented using variable speed limits (VSL) in work zones, which are designed to be adjusted in response to traffic conditions.
speed limit (VSL) controls in highway work zones. Most such field studies have indicated that by properly regulating traffic flow speeds with VSL, the potential risk of traffic accidents in work zone can be reduced (Coleman, J.A, 1996; Abdel-Aty, 2006). A model-based optimization approach with VSL was also tried by Lin P-W (2004), who showed the potential benefit of a work zone VSL control in maximizing throughput while minimizing the delay.

The mixture of large vehicles and cars is one of the basic characteristics in highway of China. Due to the difference of vehicle type and power performance, large vehicles and cars show different characteristics in course of driving and interfere with each other seriously. The mixture of large vehicles will inevitably have an important impact on traffic flow of work-zone, especially for speed variance, and then increase the probability of accidents (Liu Weizheng, 2007). Overseas scholars including Hurber (1986) and Gazis (1992) had found that the mixture of large vehicles will cause the car-following with low speed and they first put forward the concept of “Moving Bottleneck” for this phenomenon. At home, some researchers, such as Lianyu Wei (2008), have studied the influence of large vehicle mix rate to traffic flow speed variance and then discuss the relationship between large vehicle mix rate and traffic safety. As highway work zone usually have some lane closure and have a poor driving condition, the mixture of large vehicles will lead to further traffic chaos.

Throughout the study, most VSL calculate the limit speed from macroscopic perspective without considering the lane changing behavior and at the same time, traffic composition is single, not involving the influence of large vehicle mix rate.

2. A New VSL Based on Gap Acceptance Theory (VSL-GA)

The core concept of VSL-GA algorithm aims to minimize the difference between the volume on closed lane and the acceptable gaps provided by the open lane with a proper dynamic control of speed over the entire area impacted by work zone.

VSL-GA algorithm steps (take 3-1 type work zone for example):

Step 1: Detecting the traffic flow rate of section $S_{L1}$ and $S_{L2,3}$ for interval $k$, vehicle speed, the passing time and vehicle coordinate (figure 1). Where $S$ stands for section, $L1$ for lane 1 and similar as $L2,3$.

![FIGURE 1 the VSL-GA model diagram](image)

Step 2: According to the passing time of each vehicle through $S_{L2,3}$, determine the headway distribution of incoming traffic flow. Considering that Erlang distribution can have a good reflection of traffic flow (Wang wei.2004), we adopt it to estimate the incoming traffic flow headway distribution. The Erlang distribution formula is described as shown in Equation (1):
\[ P(h \geq t) = \sum_{i=0}^{t-1} (\lambda t)^i e^{-\lambda t} t! \] (1)

Where \( P(h \geq t) \) stands for the probability of headway greater than \( t \) seconds; \( \lambda \) is the average arrival rate of vehicles during unit time interval; \( \lambda \) is the Erlang distribution parameter and reflect the random levels of traffic flow.

Step 3: Determine the target arrival rate \( \lambda \)

Situation 1: When the traffic flow is less than 600 vph each lane, Erlang distribution comes down to negative exponential distribution (Zhao Chun 2005), namely, Erlang distribution parameter \( \lambda = 1 \). In this case, acceptance gap can be so big that it can allow more than one car merge. So, at this point, the control aim is to make lane 2 and 3 have the capacity to allow all the vehicles in lane 1 to merge into.

The merging capacity of lane 2 and 3 can be approximated as Equation (2):

\[ q_s = q_{s,1,3} (k) \frac{e^{-\lambda t_0}}{1 - e^{-\lambda t}} \] (2)

Where \( q_s \) is the merging capacity of lane 2 and 3; \( q_{s,1,3} (k) \), traffic flow rate through section \( S_{1,2,3} \) for interval \( k \); \( t_0 \) stands for the gap for vehicles in lane 1 to merge into; \( t \), minimum headway for vehicles of lane 1 passing the merge point continuously.

When meet Equation (3):

\[ S \geq q_{s,1} (k) \] (3)

Where \( q_{s,1} (k) \) is the traffic flow rate through section \( S_{1,1} \) for interval \( k \). Then, lane 2 can meet the merge requirement of lane 1 and we can calculate the target arrival rate \( \lambda \) from Equation (3).

Situation 2: When the traffic flow is more than 600vph each lane, the control goal is just to let the acceptance gaps approximately equal to the volume on lane 1 because it is too hard to get traffic capacity of Erlang distribution in this situation (Chang, 1998; Xu Jian-min, 2002). At this time, the traffic flow of work zone upstream is more crowded and would not exists the situation that the vehicle headway is so big that it can allow more than one car to merge into. Namely,

\[ q_{s,1,3} (k) \cdot P(h \geq t) \geq q_{s,1} (k) \] (4)

Step 4: Calculate the traffic density around section SL2, 3 according to vehicle coordinates

\[ d_{s,1,3} (k) = \frac{n}{L} \] (5)

Where \( d_{s,1,3} (k) \) stands for the traffic density around section \( S_{1,2,3} \) for interval \( k \); \( L \), the segment length under test; \( n \) is the vehicle number in corresponding segment.

Step 5: Calculate the target control speed

At first, we divide work zone upstream into some small segments (1...... N) (Figure 2). Based on the assumption that within a short distance and a short time period, the density remains approximately constantly, the target control speed for the 1st segment during interval \( k \) can be approximated as Equations (6) according to the basic traffic flow relationship:
\[ Q = 3600 \lambda = V_s(k)d_{s123}(k) \]  

(6)

Where, \( V_s(k) \) stands for the control speed for section S in interval k.

At the point far from work zone upstream, traffic flow speed is free flow speed (\( u_n(k) \)) because it have not been influenced by the work zone. As shown in Figure 2, the \( V_s(k) \) to \( u_n(k) \) line represents the speed reduction process under ideal conditions. The ideal target flow speed of each segment can be approximated as follows:

\[ V_i(k) = V_s(k) + \left[ u_n(k) - V_s(k) \right] \frac{I_i}{L_g} \]  

(7)

Where, \( V_i(k) \) stands for the control speed for segment I during interval k; \( I_i \) stands for the distance between speed limit sign and section S; \( L_g \) stands for the length of entire control area at work zone.

3. The influence of large vehicle mix rate on VSL-GA

3.1. The influence of large vehicle mix rate on traffic flow

Shanghai S20 outer ring highway had road maintenance work from September to December of 2012 with a lane closed. This article collected the traffic operating data by video from 12:00 to 22:00.

Figure 3 gives the distribution relationship between large vehicle mix rate and traffic flow speed by hour. We can find that as the increase of large vehicle mix rate, traffic flow speed decreases gradually.
Figure 4 gives the relationship between large vehicle mix rate and traffic flow speed variance. As the increase of large vehicle mix rate, speed variance increase first and then decreases. When the large vehicle mix rate exceeds 30%, traffic speed variance declines steadily.

3.2. The correction of large vehicle mix rate on VSL-GA

If we can have a correction on VSL-GA according to the real-time detection or history large vehicle mix rate data, we will reduce the probability of traffic accident effectively by controlling the speed difference.

By clustering the traffic flow data in hours, we can establish the relationship between large vehicle mix rate and traffic speed standard deviation. We find that 4 times Polynomial fitting is the most appropriate and the R²=0.97 which indicates that model fitting result is ideal.

Polynomial fitting model is as follow:

\[ Y = -742X^4 + 1480X^3 - 1062X^2 + 315X - 28 \]  

(8)

Where Y stands for traffic flow variance; X stands for large vehicle rate.

Through the data analysis we found that the speed variance stabilized at 2.1km/h and the highest point is 5.2km/h. As the average speed difference between large vehicle and car is 20km/h, so the correction of control speed is as follow:

\[ f'_{\text{truck}} = \frac{Y - 2.1}{5.2 - 2.1} \times 20 \]  

(9)

The final control speed of VSL is as follow:

\[ VSL = f'\left[f'(PSL_{\text{max}}), f'_{\text{truck}}\right] \]  

(10)

Where \( f'(PSL_{\text{max}}) \) stands for the legal maximum speed; \( f'_{\text{truck}} \) stands for the correction of control speed by large vehicle mix rate.
4. Model Evaluation with Simulation Experiments

4.1. Design of experiments and calibration

The first step for simulation experiments is to design a simulated work-zone system that can replicate real-world work-zone traffic conditions. This study has selected ShangHai outer ring highway work zone as simulation objects (Figure 5, 6). Large vehicle mix rate is 30%. To ensure the reliability and the quality of the simulated results, this study has calibrated the simulation program with the field data collected on non-control days. The vehicle acceptance gap is 3.5s, the minimum headway for vehicles passing the merge point continuously is 2s (Huang Sunjun, 2007). The car-following model is Wiedemann 99. Lane change model is free lane selection: allow vehicles change lane at any lane.

![Field work zone](image1)

**FIGURE 5** field work zone

After speed limit has been given to the drivers in VISSIM, "desired speed" setting of vehicle object is changed. This can be done by its .COM interface through second development (PTV AG, 2007). This paper supposes that the driver compliance rate was 100%.

![Simulation architecture](image2)

**FIGURE 6** simulation architecture
4.2. Analysis of simulation result

A large number of home and abroad studies have shown that vehicle speed deviation and traffic safety are closely associated (Vivian Robert R, 2004) and traffic safety is worse at the point where speed deviation is larger. In order to eliminate the influence of vehicles average speed, this study has used CV value as the measure of effectiveness.

\[ CV = \frac{\text{speed deviation}}{\text{average speed}} \]  

In simulation, we collected vehicle speed every 50m to have an observation of vehicle speed variance. FIGURE 7 shows the CV result:

![FIGURE 7 the CV results (1600vph)]

Before: VSL-GA without considering large vehicle mix rate
After: VSL-GA with considering large vehicle mix rate

We can see from Figure 7 that these three situations have similar variation trend. But in summary, the CV values under VSL-GA control with considering large vehicle mix rate are lower than those two others. This indicates that the vehicle speed variation under VSL-GA with considering large vehicle mix rate is smaller, which can indirectly contribute to improving the overall traffic safety in work zone.

5. Conclusions

Through above research, the conclusions of this article are as follows:
1) Put forward the gap acceptance theory based variable speed limit control strategy with considering large vehicle mix rate;
2) Through field observation, this article finds that when large vehicle rate is 30%, the traffic flow speed difference is the largest;
3) Based on VISSIM and its .COM interface, we evaluated the VSL-GA strategy with considering large vehicle mix rate and the results show that it can reduce speed variance and improve safety.

Further studies along this line will focus on considering the compliance rate of drivers.

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