Research Article

Successive-Stage Speed Limit on Exit Ramp Upstream of Direct-Type Freeway in China

Hongwei Li,[1] Jian Lu,[2] Yongfeng Ma,[1] and Yuanlin Liu[1]

[1] *School of Transportation, Southeast University, Nanjing 210096, China*
[2] *School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*

Correspondence should be addressed to Hongwei Li, lihongwei-2008@163.com

The first objective of this study is to analyze a successive-stage speed limit model developed for vehicles along the exit upstream ramp of direct-type freeway in China. This paper (1) explains the necessity to implement speed limit to the exit ramp upstream, (2) analyzes whether speed limit is related to the length of the deceleration lane, vehicle type, saturation, and turning ratio and (3) proposes a speed prediction model and calibrates speed-limit sign validity model and establishes successive-stage speed limit model. *The results.* $\Delta v_{85} \geq 10$ illustrates the necessity of the using speed limit on the exit ramp. Speed-deceleration lane length curve presents two trends bounded by 200 m, so the speed limit should be in accordance with the deceleration length. Speed-small vehicle curve closing to speed-large vehicle curve presents that the vehicle type is not the factor of the speed limit. After curve fitting and polynomial regression, saturation is considered to be the most influential factor of speed. Speed-saturation prediction model and calibrated speed-limit sign validity model are built through linearization. According to the above results, successive-stage speed limit model is established. An exit ramp was implemented to verify the feasibility and validity of the model.

1. Introduction

Ramps provide the connections between freeway and roads and influence traffic efficiency and safety of the freeway and ground roads. In USA, 20% to 30% of freeway truck accidents occur at or near ramps (excluding an additional 10% to 15% that occur at weaving section and surface streets), despite the fact that weaving section account for less than 5% of all freeway lane-miles [1]. Kloeden et al. have provided direct evidence that speeds just 5 km/h above the average in urban (60 km/h) areas, and 10 km/h above average in rural areas, are sufficient to double the risk of a casualty crash [2]. It can be seen that the speed of vehicles, even with minor changes, will have a significant influence on freeway safety. *World Prevent Road Traffic*

Injuries Report [3] pointed out that speed is the first risky influence of collisions. Therefore, controlling vehicle speed and reducing speed dispersion is the key to reduce accident rates on the freeway.

2. Literature Review

According to speed limit determinant factors, speed limit control methods are divided into four categories:

(1) Road grade and geographic feature: The United States [4] use a legal speed limit method for certain types of road infrastructure. The value of the speed limit is mainly determined according to highway classification and alignment elements. Meanwhile, design speed, operating speed, historical accident records and law enforcement experience, and other factors are considered.

(2) Δv_{85}: Research on the speed limit on the exit ramp of the freeway has focused on one single limit for a long time. *U.S. Institute of Transportation Engineers* [5] recommended the speed limit to be 5 mph higher than v_{85} (the 85% speed) and accident rates is recommended for making speed limits. Milliken [6] proposed a speed limit model using Δv_{85} (the 85% speed difference) on free flow modified by accident rates. A study in the US [7] mentioned that the speed limit should be obtained by Δv_{85} on the freeway main line and the small vehicle and large vehicle should use different speed limit on the freeway main line. The Poisson specification was applied to characterize the relationship between traffic speeds and crash rates under free-flow conditions in two different areas. The results suggested that the proportion of heavy vehicles is inversely associated with the crash rate, and mean speed contributes to crash rates [8]. Park [9] established the speed limit value model by road alignment, traffic flow, and surrounding environment collected under low accident rate and free traffic flow.

(3) Driver physiological characteristics: *National cooperative highway research program* [10] studied the relationship between the speed limit, accident rate, and vehicle speed. Data was collected from a questionnaire and traffic accident record. *Georgia Department of Driver Services* [11] evaluated driver's feeling of vehicle speed limit and safety using drivers' tolerance degrees to exceed speeds.

(4) The comprehensive influential factors: In Australia, ARRB [12] developed a road safety software—XLIMITES with a complex decision-supporting method. The method determines speed limits by speed limit already in use, land type, road characteristics, and historical accidents.

The disadvantages in above mentioned methods are:

(1) Application scope of legal speed limit method is limited: In some sections, the actual situation on the freeway does not match the range of the legal limit speed and, therefore, legal speed limit method cannot be used under some situation.

(2) Single speed limit is not related with the speed of change and accident data is not easy to obtain. Solomon [13] found that the number of accidents has a U-curve shape related with V_{speed}—$\overline{V}$ using data of 970 kilometers roads and 1000 drivers. Accident rate is low when vehicles are traveling at a speed within one standard deviation around the average speed. When speed reaches 10 km/h more

than the average speed (V85), accident rate reaches minimum. U-curve is suitable for steady flow and it is the theoretical basis of Δv_{85} limit method. However, a single speed limit is not accorded with the normal speed trend. In addition, accident data requires long-term accumulation. It means that accident data is not easy to obtain.

(3) Driving behavior is complex: When driver approaches the exit ramp from the main line, they need to finish a series of complex driving behaviors, such as looking for acceptance gap, slowing down, and change lanes in the slow lane. Driver's driving habits and reflections are different in the different area or on different roads [14]. Since different researchers developed different models, it is necessary to know whether the value of the speed limit designed for a particular freeway can be applied to another freeway in the same area and whether the value of the speed limit determined for one specific road in specific areas could imply in another road in another area.

(4) Consider geometry parameters only: The comprehensive influential factors method only considers geometric parameters, such as the slope and curve radius. McLean [15] studied the level of the expected speed and radius regression curve according to the data from Australia and New Zealand. The conclusion shows that when the curve radius is greater than 1000 m, 85% of the expectation speed is not affected by geometry parameters. In China, JTG/T B05-20049 (Guidelines for Safety project on Highway) [16] proposed that the sections whose curve radius is less than 1000 m and the absolute value of slope is less than 3% can be considered as a straight-line. Above studies illustrated that in some sections, geometry parameters should not be the only parameter in consideration.

3. Research Goal

In this paper, the primary goal is to develop a successive-stage speed limit model for vehicle speed along the exit upstream ramp of direct-type freeway in China. The specific tasks of this paper can be summarized as follows:

(1) State the necessity of operating successive-stage speed limit control on the exit ramp upstream.

(2) Analyze the relationship between operation speed and deceleration lane length on the exit ramp upstream, and prove that the speed limit should be in accordance with the deceleration lane length.

(3) Determine whether the speed limit needs to be set for the small vehicle and large vehicles separately on the exit ramp upstream.

(4) Analyze the main factor of the speed limit from saturation, turning ratio, and vehicle type using double-factors curve fitting and polynomial regression.

(5) Build speed-prediction model according to the result of factor analysis.

(6) Calibrate speed-limit sign validity model by linearization

(7) Establish successive-stage speed-limit model based on a speed-prediction model and a speed-limit sign validity model.

(8) Verify the validity of the successive-stage speed-limit model by a case study.

4. Hypothesis and Research Objective

4.1. Hypothesis

The research is based on three hypotheses.

(1) The speed limit for the exit ramp nose is reasonable. This research focuses on developing a successive-stage speed limit model on the exit ramp upstream. The value of the speed limit of the exit ramp nose is not studied in this paper; therefore assume that the speed limit on the exit ramp nose is reasonable.

(2) 90% of right-turn drivers have finished lane change at 2/3 location of deceleration lane in China [17]. To simplify driver behavior, all vehicles are assumed to have finished lane change.

(3) Except mountainous freeway, geometric line of freeway meets freeway design standard. Combining with the actual situation, as well as the result of McLean [15] study, and JTG/T B05-2004 [16], the line of the exit ramp upstream recognized as the line.

4.2. Research Objective

The type of an exit ramp has influences on the traffic flow of the exit ramp, speed distribution and driver behavior. So the exit ramp type should be determined firstly. 428 exit ramps from 11 provinces in China were observed by Google Earth. Statistically, 93.5% of the ramps fell into the above 4 categories by the change of lanes number in the main line of upstream and downstream, the setting of the deceleration lane, the number of ramp lane, and the separation situation of ramp. 55.8% of them were direct-type exit ramp. Hence, direct-type exit ramp is the research objective in this study. Characteristics of direct-type exit ramp are as follows:

(1) The number of lanes in the main line of upstream and downstream is constant.

(2) The area of ramp upstream is broadened properly and has a deceleration lane.

(3) The number of lane on the ramp is 1.

(4) The exit ramp lanes are not separated.

5. Data Collection and Process

5.1. Site Selection

Sites are selected as follows:

(1) Safeguard facilities at the road side are in normal condition.

(2) Has a good visual space.

(3) Service level is A or B (to ensure that speed is not significantly affected by other vehicles in the flow).

(4) The freeways selected in this study should include two lanes, three lanes, and four lanes in one direction in the main line.
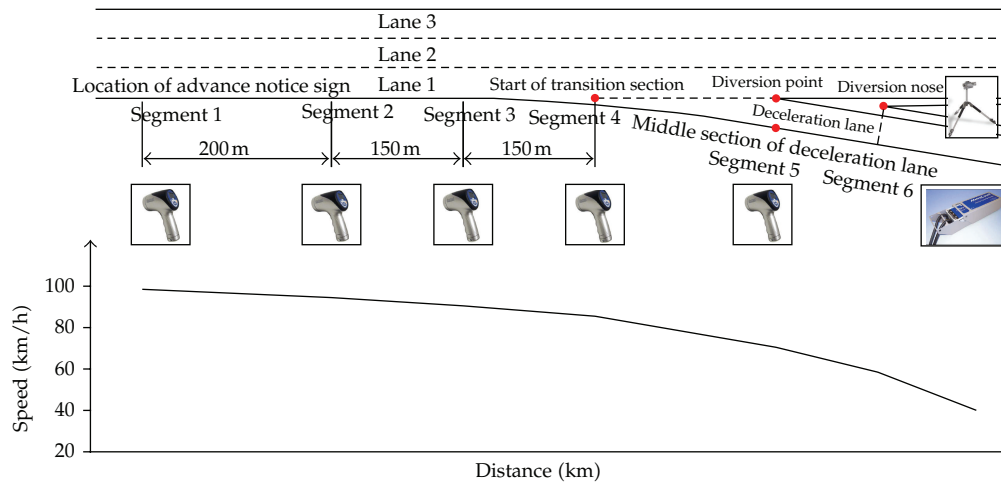
(5) The range of deceleration lane length is 150–250 m.

Figure 1: Speed profile of the exiting flow.

(6) The values of the speed limit on the main line are 100 km/h and 120 km/h; the values of the speed limit on exit ramp are 40 km/h and 60 km/h, respectively.

(7) No congested traffic phenomenon.

As a result, seven exit ramps in Nanjing, China were chosen as candidate sites.

5.2. Investigation Segments

The exit ramp impact area is within 500 meters upstream of nose, according to HCM, as length 500 m from the nose [18]. So the research area is from the location of the advance notice sign to nose and is divided into six segments according to deceleration trend. As shown in Figure 1, Segment 1 is the location of the advance notice sign; segment 4 is the start of the transition section; segment 5 is the middle section of the deceleration lane; Segment 6 is cross-sectional on the nose. Data collection area is the upstream of main road lanes. The curve shows the speed-change trend in this section in Figure 1.

5.3. Data Collection

Data in this study includes geometric parameters, traffic-flow parameters and traffic-control parameters.

Geometric parameters include alignment elements and lane number in the main lanes and deceleration lane length. It is known that the alignment is not considered in above studies. Therefore, geometric parameters refer to the lanes number in the main lanes and deceleration lane length. The main traffic control parameter is main lane speed limit and exit ramp speed limit. Deceleration behavior on the main line mainly happens on the outside lane. Traffic-flow parameter includes traffic volume and point speed of the outside lane.

Traffic flow parameters are collected during the peak hour from 8 to 11 a.m or 2 to 5 p.m on a clear, well visibility, and regular-temperature day.

The procedures of data collection are designed as follows:

(1) *Preparation*: Train 8 investigators; prepare 2 radar guns (LaiSai Bushnell), 1 MetroCount 5600 and 1 camera (Sony Handcam). Investigators should be familiar with the investigation plan, the survey locations, and can use the guns, MetroCount 5600, and camera. Radar gun and MC5600 are applied to collect point speed and camera is applied to collect traffic volume.

(2) *Arrangement equipments*: Put 4 radar guns, MC5600, and Sony Handcam camera at the location of Sections 1 to 6 respectively, as shown in Figure 1.

(3) *Observer assignment*: Assign two observers at each location of Sections 1, 2, 3, and 4, respectively. One is the radar-gun holder and the other one is the recorder.

The radar-gun holder is in charge of shooting speed, reading the last three digits of the plate number, and informing the recorder of the information.

Observers are hidden from traffic to minimize the effect of their presence on passing vehicles.

5.4. Data Process

The data collected from the camera were sorted into small-vehicle and large-vehicle categories. The small vehicle has less than 20 seats for passenger vehicles or less than 2 tons in weights for freight vehicles.

It was found that Δv_{85} is a major parameter used by traffic engineers and transport planners from literature. Point speed will be transformed to Δv_{85}.

Discard nonnormal data that does not conform to normal distribution using statistic software SPSS [19].

6. Data Analysis

6.1. Δv_{85} Characteristics Analysis

Fitzpatrick [20] divided Δv_{85} into 3 groups: $\Delta v_{85} \leqslant 10 \,\text{km/h}$, $10 \,\text{km/h} < \Delta v_{85} < 20 \,\text{km/h}$, and $\Delta v_{85} \geqslant 20 \,\text{km/h}$.

(1) $\Delta v_{85} \leqslant 10 \,\text{km/h}$ means that operation speed is well and accident rate is low.

(2) $10 \,\text{km/h} < \Delta v_{85} < 20 \,\text{km/h}$ means that the coordinated of operation speed becomes bad, and the accident rate has increased.

(3) $\Delta v_{85} \geqslant 20 \,\text{km/h}$, means that the coordinated operation speed becomes worse, and the accident rate is high.

It is worth noticing that the accident rate of observations with $\Delta v_{85} \geqslant 20 \,\text{km/h}$ is 6 times more than that of $\Delta v_{85} \leqslant 10 \,\text{km/h}$. We can see that the higher the Δv_{85} is, the more the accident rate is. Hence, Δv_{85} should be lower than $10 \,\text{km/h}$. If $\Delta v_{85} \geqslant 10 \,\text{km/h}$, successive-stage speed limit should be applied. Figure 2 shows the Δv_{85} curves of the exit ramp upstream.

In Figure 2, the Δv_{85} of all sites are less than $10 \,\text{km/h}$ in segments 1–4. It reveals that the trend of speed is gentle and the accident rate is low in segments 1–4. In segments 4–6, the Δv_{85} of Sites 1, 2, 3, and 7 are more than $10 \,\text{km/h}$. Especially, the Δv_{85} of Site 2 is close
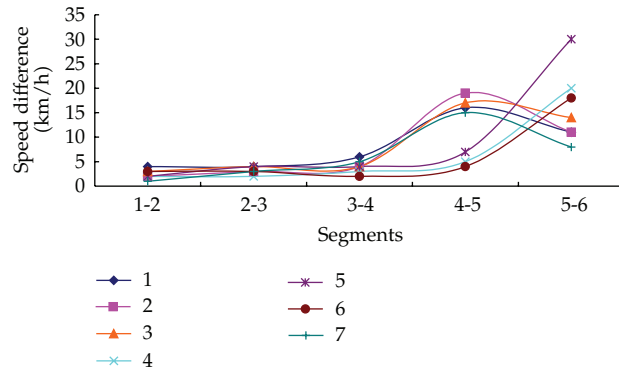
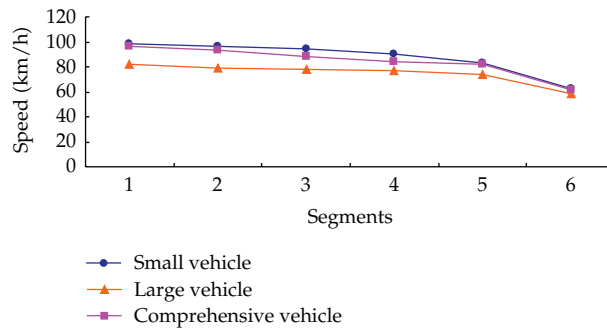**Figure 2:** Δv_{85} curve on the exit ramp upstream.

Figure 3: v_{85} curve of small, large, and comprehensive vehicles.

to 20 km/h. It shows that the accident rate has increased in segments 4–6. Δv_{85} of Sites 4, 5, and 6 are higher than 20 km/h as in segments 5-6. In this scope, the accident rate increases significantly. Δv_{85} of Sites 1, 2, 3, and 7 increase from 5 km/h to 15 km/h approximately from segments 3-4, then decreases from 15 km/h to 10 km/h approximately. For Sites 4, 5, and 6, Δv_{85} dramatically increases from 5 km/h to 20 km/h approximately from segments 4–6.

Through the above analysis, we can conclude that it is necessary to operate successive-stage-speed limit control on the exit ramp upstream.

6.2. The Speed of Vehicle Type Characteristics Analysis

The v_{85} curves of small, large and comprehensive vehicles are shown in Figure 3.

There are three-speed curves in Figure 3. The above curve is small vehicles; the middle curve is comprehensive vehicles; and the below curve is large vehicles. Comprehensive vehicle represents the speed level for the small vehicle and the large vehicle. In Figure 3, curves of small vehicles and large vehicles have a similar trend. Specific performance is that they all decrease slowly in segments 1–4 and a rapid decline in segments 4–6. Meanwhile, difference of v_{85} does not exceed 10 km/h in segments 1–4 and 5 km/h in segments 4–6. The curve of the comprehensive vehicle is between the small vehicle curve and large vehicle curve. In segments 4–6, v_{85} curves of the small vehicle and large vehicle approach v_{85}
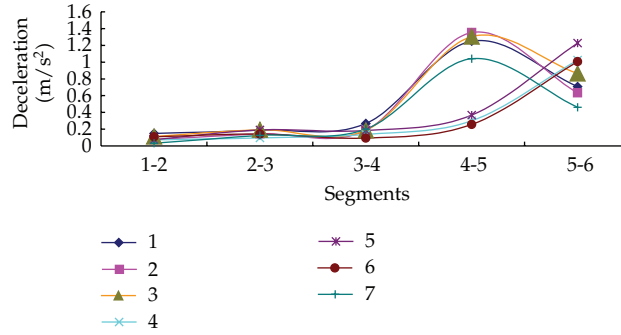
Figure 4: v_{85} speed-deceleration-lane-length curve.

curves of comprehensive vehicle simultaneously. Finally, three curves intersect on 65 km/h at segments 7. Hence, speed limits of small vehicles and large vehicles are same.

It is not needed to design different speed limits for small vehicles and large vehicles, respectively, on the exit ramp upstream, as the speed limit control pattern on the main line.

6.3. The Deceleration Lane Length Characteristics Analysis

According to hypothesis 3, the only difference of the seven sites in terms of geometric aspect is the deceleration lane length. Speed-deceleration-lane-length curve is used to judge whether the speed limit needs to be determined according to deceleration lane length.

The range of deceleration lane length used in this paper is 150–250 m. The range almost covers all deceleration-lane-length of freeway in China. If there are different trends in speed-deceleration lane length curves in Sites 1, 2, 3, 4, 5, 6, and 7, the speed limit should be determined due to the differences of the deceleration lane length.

Figure 4 is the speed-deceleration-lane-length curve.

In segments 1–4, curves of all 7 sites are nearly flat. In segments 4–6, however, there are two opposite trends. The curves of Sites 1, 2, 3, and 7 rise in segments 4-5, and then drop in segments 5-6. The trends of the curve 4, 5, 6 are opposite. The common characteristics of 1, 2, 3, and 7 is that their deceleration lane length are more than 200 m. The lengths of the deceleration lane of 4, 5, and 6 are less than 200 m.

Hence, deceleration lane length is related to v_{85} and the speed limit should be different according to the deceleration lane length.

6.4. The Speed of Lanes Number of Main Line Characteristics Analysis

In order to analyze whether the number of lanes of main line affect speed, speed-lane number curve is displayed in this section. The numbers of lanes in the main line for one direction are 2, 3, 4 in this study.

Speed-lane number curves are shown in Figure 5.

In segment 1 to segment 4, the curves are similar to each other. The difference of the curve is manifested in 4–6. The highest speed level appears in four lanes, and then in three lanes and two lanes. The trend of the curve is similar with the curve in Figure 4. It can be explained that the difference of speed-lane number curve is caused by different deceleration lane lengths.
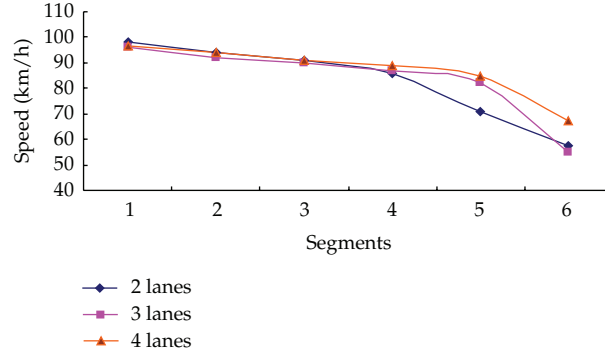
Figure 5: Speed-lane number 10urves.

We can deduce that the lane number in the main line does not relate to speed, and lane number in the main line has not been considered when we determine the speed limit.

$\Delta v_{85} \geq 10$ illustrates the necessity of speed limit on the exit ramp. Speed-deceleration-lane-length curve presents two trends bounded by 200 m, so the speed limit should be in accordance with the deceleration length.

7. Successive-Stage Speed Limit Model

7.1. The Frequency of the Speed Limit

Many drivers become irritated by frequency of slow speed. Considering the maneuverability of the speed limit sign, the number of successive-stage speed limit should not be more than two stages.

7.2. Model Choice

The speed limit has a certain impact on operational speed, but not all vehicles travel under the speed limit. In 1986, Anders and Arne [21] analyzed the relationship between initial speed under different speed limits and drivers' behavior. A speed limit influential model is developed under free flow circumstance and shown as follows:

$$V_T = \frac{V_0}{1 + c \cdot d^{z^2}},$$
$$z = \frac{V_g}{V_0},$$

(7.1)

where V_T is the operational speed limit area (km/h), V_0 is the operational speed in the upstream of the speed limit area (km/h), V_g is the speed limit (km/h), c, d, are influential coefficients.

Equation (7.2) is the linearization of (7.1)

$$\frac{V_0}{V_T} - 1 = c \times d^{z^2},$$
$$\ln\left(\frac{V_0}{V_T} - 1\right) = \ln c + z^2 \ln d.$$

(7.2)

Set $Y = \ln(V_0/V_T - 1)$, $a = \ln c$, $b = \ln d$, $X = z^2$, it can be obtained that

$$Y = a + bX. \tag{7.3}$$

It is can be found that R Square (goodness of fit) is 0.839, Adjusted R Square (Coefficient of Determination) is 0.838, and Sig. (significant indicators) are less than 0.05. The results meet the statistical requirements. So that can be obtained that

$$Y = 0.903 - 3.657X,$$

$$V_T = \frac{V_0}{1 + 2.467 \times 0.026^{z^2}}. \tag{7.4}$$

V_0 can be obtained by field investigation. For new freeway, V_0 can only be obtained through speed prediction model. The building process of speed-prediction model is studied in the next section.

7.3. Speed Prediction Model

7.3.1. Influence Factors Analysis

It is widely believed that influence factors of speed include geometric parameters, traffic-flow parameters, and traffic control parameters. Traffic-flow parameters include traffic volume, speed, density, average time headway, average space headway, turning ratio and vehicle type, and so forth. Traffic flow parameters comprise density, average time headway, and average space headway. Therefore, traffic volume, turning ratio and vehicle type are chosen in this paper. To increase the universality of the model, traffic volume is converted to saturation.

7.3.2. Speed Prediction Model

Double-factor curve fitting is used to analyze the correlation between various factors and speed by *SPSS*. From test results, the R^2 value and P value of the quadratic curve and cubic curve based on saturation and large vehicles rate meet statistical requirement and these are used as independent variables. But models of turning ratio and operational speed do not meet statistical requirement, so turning ratio is removed. The form of the quadratic curve is simple, so quadratic curve is selected as the basic model in this paper.

A two-factor multinomial model is developed to compare how saturation and percentage of large vehicles affects operational speed. Independent variables are selected by the stepwise regression method. Every variable selected by the stepwise regression method is tested. Percentage of large vehicles is eliminated in SPSS.

Saturation is selected as the main factor affecting operational speed. Step length needs to be decreased to increase model fit. The Adjusted region of saturation is p [0.3, 0.7] with a step length of 0.5 and 9 levels. Stepwise regression is analyzed in SPSS. Variation of saturation is eliminated in regression, and the calibrated model is as follows:

$$V = 104.788 - 13.465S^2, \tag{7.5}$$

where S is saturation.

Table 1: Average deceleration in each section.

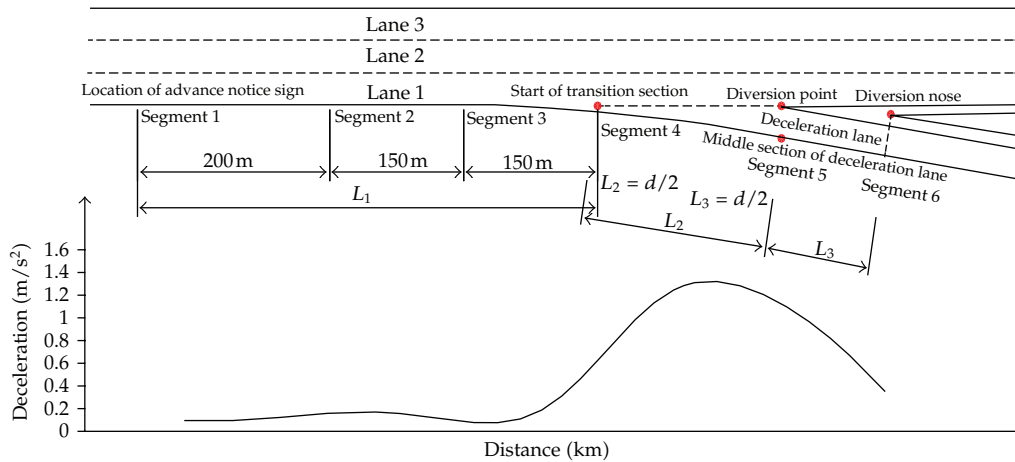| Deceleration lane length (m)	a_t (m/s^2)	a_{02} (m/s^2)	a_{01} (m/s^2)
<200 m		1.30	0.73
	0.15		
>200 m		0.31	1.09

Figure 6: Segments of research scope divided by deceleration.

Hypothesis tests are carried out in SPSS. Outputs are R square is 0.844, Sig. is 0.000, these manifest that the goodness-of-fit and coefficients test is statically satisfied. The residuals and dependent variable are distributed as normal distribution approximately. All of the results prove that the speed-prediction model proposed in this paper is statistically significant.

7.4. Deceleration Value

It can be concluded that the variation of deceleration is more significant than speed difference and speed. The research scope is divided into three sections according to the variation of the deceleration. The entire exiting process is divided into three sections below, as shown in Figure 6. The curve shows the deceleration change trend in this section in the following Figure 6.

In Figure 6, speed difference in L_1 section is low and barely changes. Suppose that vehicles in L_1 travel by the average deceleration are denoted as a_t from Sections 1 to 4. Decelerations on L_2 and L_3 are denoted as a_{01} and a_{02} which are average field decelerations. Average deceleration in each section is illustrated in Table 1.

7.5. The Speed Limit Value

Denote V_t' as the reasonable speed of the middle section of the deceleration lane and V_{go} as the speed limit at the exit ramp painted nose. During constant deceleration (a_{01}), the speed of

vehicles changes from V_{go} to V'_t in L_3. V'_t can be derived according to the kinematics principle, and the expression is

$$V'_t = 3.6\sqrt{a_{01}d + \left(\frac{V_{go}}{3.6}\right)^2},\qquad(7.6)$$

where V'_t is the reasonable speed at the middle section of deceleration lane (km/h); V_{go} is the speed limit at the exit ramp painted nose (km/h); a_{01} is the average deceleration at L_3 in the exit ramp area (m/s^2).

In L_2, it is known that vehicles move with a constant acceleration of a_{02}. Define V_t as a reasonable speed of the start of the transition section. It can be expressed as

$$V_t = 3.6 \times \sqrt{a_{02}d + \left(\frac{V'_t}{3.6}\right)^2},\qquad(7.7)$$

where V_t is the reasonable speed of the start of transition section (km/h); a_{02} is average deceleration at L_2 in the exit ramp area (m/s^2).

Combine (7.6) and (7.7), V_t can be calculated using a_{01} and a_{02}.

$$V_t = 3.6 \times \sqrt{(a_{01} + a_{02})d + \left(\frac{V_{go}}{3.6}\right)^2}.\qquad(7.8)$$

At L_1, vehicles move with a constant acceleration of a_t. Define V_T as reasonable speed at the start of the outside lane of deceleration. During constant deceleration a_{01}, the speed of vehicles changes from V_T to V_t. V_T can be expressed as

$$V_T = 3.6\sqrt{2a_tL_1 + \left(\frac{V_t}{3.6}\right)^2} = 3.6\sqrt{2a_tL_1 + (a_{01} + a_{02})d + \left(\frac{V_{go}}{3.6}\right)^2},\qquad(7.9)$$

where, V_T is reasonable speed at the start of the outside lane of the deceleration (km/h); a_t is average deceleration at L_1 in the exit ramp area (m/s^2); L_1 is the length of the exit ramp upstream section (500 m).

Define V'_g as the successive-stage speed limit at the outside lane in the main line. The successive-stage speed limit was deduced based on V_0 of a field investigation or of the speed-saturation prediction model and V_T of speed-limit sign validity model.

$$V'_g = V_0\sqrt{\frac{0.903 - \ln(V_o/V_t - 1)}{3.650}},\qquad(7.10)$$

where, successive-stage speed limit at the outside lane of main line (km/h); V_0 is operational speed at the outside lane in the exit ramp upstream gained though a field investigation or speed-saturation prediction model.

7.6. The Placement of Speed-Limit Sign

At present, the placement of the speed-limit sign is determined by the basis of the psychical process of drivers perceiving and reacting to signs. The determinant of the perception-reaction process is the placement of the danger point. Thus, the paper is focused on a danger point to confirm the placement of successive-stage speed limit in this section.

By analyzing deceleration characteristics curves, we found drivers began to slow down in segment 1. Between segment 1 and segment 2, curves decreased smoothly and steadily. A significant change in deceleration happened in segment 2–4. According to *Investigation segments* section, we can find that advance notice sign is located at segment 1. It can explain the trend of deceleration in segment 1–4 commendably. So the location of segment 1 is identified as a danger point.

The placement and clear height of successive-stage speed limit sign are determined according to *Traffic Engineering Manual* [22].

8. Case Study

Yang Dongfang exit ramp along Nanjing Round Freeway is chosen to verify the feasibility and validity of the successive-stage speed limit model.

After investigation, we got the information about *Yang Dongfang* exit ramp. The length of the deceleration lane is 170 m. From Table 1, this paper takes the values of a_{01}, a_{02} and a_t to be 0.73 m/s^2, 1.3 m/s^2, and 0.15 m/s^2, respectively. Vehicles speed in the main line is controlled below 120 km/h and exit line is controlled under 40 km/h. So, $V_{g0} = 40$ km/h. Operational speed in the outside lane on the exit ramp upstream is 98 km/h. So, $V_0 = 98$ km/h.

Using successive-stage speed limit model, the value of successive-stage speed limit can be gained.

$$V_t' = 3.6 \times \sqrt{a_{01}d + \left(\frac{V_{go}}{3.6}\right)} = 3.6 \times \sqrt{0.73 \times 170 + \left(\frac{40}{3.6}\right)^2} = 56.6 \,\text{km/h},$$

$$V_t = 3.6 \times \sqrt{a_{02}d + \left(\frac{V_t'}{3.6}\right)^2} = 3.6 \times \sqrt{1.3 \times 170 + \left(\frac{56.6}{3.6}\right)^2} = 77.9 \,\text{km/h},$$

$$\text{(8.1)}$$

$$V_T = 3.6 \times \sqrt{2a_t L_1 + \left(\frac{V_t}{3.6}\right)^2} = 3.6 \times \sqrt{2 \times 0.15 \times 500 + \left(\frac{77.9}{3.6}\right)^2} = 89.5 \,\text{km/h},$$

$$V_g' = V_0 \sqrt{\frac{0.903 - \ln(V_0/V_T - 1)}{3.650}} = 98 \times \sqrt{\frac{0.903 - \ln(98/89.5 - 1)}{3.650}} = 92.6 \,\text{km/h}.$$

Combined with engineering experience, get the value of successive-stage speed limit is 90 km/h. This result suggests that successive-stage speed limit is not determined for the small vehicle and large vehicle, respectively, on the exit ramp upstream.

9. Discussion and Conclusions

v_{85} is a major parameter used by traffic engineers and transport planners. Generally, speed limits are set at or below the Δv_{85} [23]. A bill to raise Texas highway speed limit to 85 mph could have motorists getting there faster but shelling out much more money at the gas pump [24]. The paper uses the "85th percentile speed" to determine the successive-stage speed limit.

The previous studies show when the curve radius is greater than 1000 m, 85% of the desired speed is not affected by horizontal alignment. JTG/T B05-2004 [16] proposed that the sections which the curve radius are less than 1000 m and slope of absolute value small than 3% may be handled as a straight-line section. Except the mountainous freeway, geometric alignments of most freeways meet freeway design standard. Above studies illustrated that geometry parameters should not be the only parameter in consideration.

In segments 4–6, the Δv_{85s} of Sites 1, 2, 3, and 7 are more than 10 km/h. Especially, the Δv_{85} of Site 2 is close to 20 km/h. Δv_{85s} of Sites 4, 5, and 6 is more than 20 km/h in segments 5-6. These show that accident rate has increased in segments 4–6. Through the above analysis, it is necessary to set successive-stage speed limit control on the exit ramp upstream.

Curves of the small vehicle and large vehicle have a similar trend. Meanwhile, difference of v_{85} does not exceed 10 km/h in segments 1–4 and 5 km/h in segments 4–6. The curve of the comprehensive vehicle is between curves of the small vehicle and the large vehicle. In segments 4–6, v_{85} curves of the small vehicle and large vehicle approach the curve of comprehensive vehicle simultaneously. Finally, three curves intersect on 65 km/h at segment 7. Hence, speed limits of the small vehicle and large vehicle are same. Case study also tests this conclusion. So, successive-stage speed limit is needed to be developed for the small vehicle and large vehicle, respectively, on the exit ramp upstream.

In segments 4–6, deceleration curves show two opposite trends. The curve of Sites 1, 2, 3, and 7 rise in segments 4-5, and then drop in segments 5-6. The trend of the curve of 4, 5, and 6 is opposite. The common characteristic of 1, 2, 3, and 7 is that their deceleration lane length is more than 200 m. The length of the deceleration lane about 4, 5, and 6 is less than 200 m. Hence, deceleration lane length is related with v_{85} and the speed limit should be in accordance with the deceleration lane length. This means deceleration lane length is an important factor for successive-stage speed limit.

Speed-lane number curves in the main line are similar with deceleration curves. The similarity suggests that the difference of speed-lane number curves is caused by different deceleration lane length. We can deduce that lane number in the main line does not relate with speed and the lane number of the main line has not been considered when determine the speed limit.

Double-factor curve fitting is used to analyze the correlation between saturation, turning ratio, and large vehicles rate and speed. Based on test results of models, saturation is selected as the main factor of operational speed. As a result, the paper built speed-saturation prediction model.

The research scope is divided into three sections according to the variation of the deceleration. Based on field investigation speed or speed-saturation prediction model and the speed-limit sign validity model, the value of successive-stage speed limit is deduced according to kinematic principles.

The conclusions are summarized as follows:

(1) It is necessary to set successive-stage speed limit control on the exit ramp upstream. The successive-stage speed limit is not needed to be developed for small vehicles and large vehicles, respectively, on the exit ramp upstream.

(2) Geometry parameters are not considered in building successive-stage speed limit model.

(3) Deceleration lane length is related to v_{85}, and the speed limit should be in accordance with the deceleration lane length.

(4) Lane number in the main line does not relate to speed and cannot be considered when determining the speed limit.

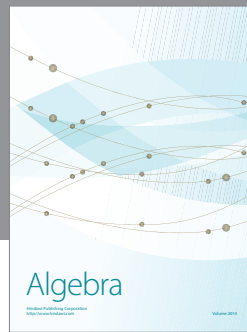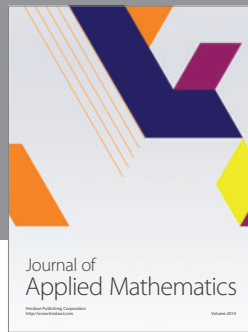(5) Saturation is the main factor affecting speed, and the paper built a speed-saturation prediction model.

Acknowledgments

References

[1] M. Firestine, H. McGee, and P. Toeg, "Improving truck safety at interchanges: final report to the Federal Highway Administration," FHWA IP-89-024, U.S. Department of Transportation, Washington, DC, USA, 1989.

[2] C. N. Kloeden, A. J. McLean, and G. Glonek, "Reanalysis of travelling speed and the risk of crash involvement in Adelaide South Australia," Report CR207, Australian Transport Safety Bureau, Canberra, Australia.

[3] M. Peden, R. Scurfield, D. Sleet et al., *World Report on Road Traffic Injury Prevention*, World Health Organization, Geneva, Switzerland, 2004.

[4] G. Milliken, "Managing speed: review of current practice for setting and enforcing speed limits," *Transportation Research Board*, pp. 36–70, 1998.

[5] W. C. Taylor, *Speed Zoning Guidelines: A Proposed Recommended Practice*, Institute of Transportation Engineers, Washington, DC, USA, 1990.

[6] G. Milliken, "Managing speed: review of current practice for setting and enforcing speed limits," Special Report 254 [R], Transportation Research Board, Washington, DC, USA, 1998.

[7] K. R. Agent, J. G. Pigman, and J. M. Weber, "Evaluation of speed limits in Kentucky," *Transportation Research Record*, no. 1640, pp. 57–64, 1998.

[8] A. A. M. Aljanahi, A. H. Rhodes, and A. V. Metcalfe, "Speed, speed limits and road traffic accidents under free flow conditions," *Accident Analysis and Prevention*, vol. 31, no. 1-2, pp. 161–168, 1999.

[9] J. Park, *Modeling of setting speed limits on urban and suburban roadways [Ph.D. thesis]*, University of South Florida, 2003.

[10] NCHRP, "Safety impacts and other implications of raised speed limits on high speed roads," Contractors Final Report, 2006.

[11] DDS, *2011 Driver's Manual*, The Department of Driver Services, 2011, http://www.dds.ga.gov/docs/forms/fulldriversmanual.pdf.

[12] A. Edgar and M. Tziotis, "Computerizing Road Safety," in *Australia Road Research Board*, pp. 46–51, 1999.

[13] D. R. Solomon, *Accidents on Main Rural Highways Related To Speed, Driver and Vehicle*, US Department of Commerce, Federal Bureau of Highways, Washington, DC, USA, 1964.

[14] W. H. Wang, W. Zhang, H. W. Guo et al., "A sfety-based behavioural approaching model with various driving characteristics," *Transportation Research Part C-Emerging Technologies*, vol. 19, no. 6, pp. 1202–1214, 2011.

[15] J. McLean, "Driver speed behavior and rural road alignment design," *Traffic Engineering & Control Magazine*, pp. 208–211, 1981.

[16] CHELBI Engineering Consultants. INC., *Guidelines for Safety Project on Highway (JTG/T B05-2004)*, Communications Press, 2004.

[17] R. H. Rong, *Research on Traffic Characteristic of Interchange Diverging Area [D]*, Southeast University, 2006.

[18] National Research Council Washington, *D.C. Highway Capacity Manual 2000*, Transportation Research Board, 2000.

[19] C. Henry Jr. and Thode, *Testing For Normality*, Marcel Dekker, New York, NY, USA, 2002.

[20] K. Fitzpatrick, "Evaluation of design consistency methods for two-lane rural highways," Publication FHWA-RD-99-174. FHWA, U.S. Department of Transportation, 1999.

[21] B. Anders and C. Arne, *The VTI Traffic Simulation Model*, Swedish Road and Traffic Research Institute, 1986.

[22] Transportation Research Board, *Traffic Engineering Manual*, Department of Transportation, 2000.

[23] Speed Zoning Information, "Institute of transportation engineers[DB/OL]," 2004, http://www.ite.org/standards/speed_zoning.pdf.

[24] Lyneka, "Texas may raise speed limit to 85 MPH," http://abcnews.go.com/Business/texas-moves-raise-speed-limit-85-mph/story?id=13319173.