Impacts of Large Vehicles on Traffic Safety in Freeway Interchange Merging Areas and Improvement Measures

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Abstract. In order to work out the characteristics of traffic operation on freeway interchange merging areas under different ratio of large vehicles, aerial photography technique based on unmanned aircraft and other observation device were used to investigate the merge section traffic data firstly. Based on survey data and actual traffic characteristics, the paper then established simulation models with VISSIM with calibrated car-following and lane changing behaviour models. Next, the paper analysed the influence of traffic volume and acceleration lane length under various traffic compositions to evaluate safety status of interchange merge sections by traffic conflict technique and speed consistency index. Finally, two kinds of safety promotion strategies, speed limit and setting forbidden line, were evaluated and the results indicated these measures can raise safety level by about 10%~15% under certain conditions, which were determined as the best applicable conditions.

1 Introduction

Freeway interchange merging area is the bottleneck and accident-prone spot. In general, at merging section, due to aggressive lane changing behaviours, vehicles on mainline may slow down or pull out to overtake, which increases the risk of traffic accident. Therefore, a well-functioning merging area has a significant effect on improving traffic safety [1].

Currently, large vehicles have increasingly become one of the research hotspots with construction of freeway and development of modern logistics industry. Owing to poor performance of large vehicles, there is serious interference in traffic flow, especially at interchange merging areas, which leads to a decline in stability of traffic flow. Agent et al. evaluated geometric alignment design of expressway with Heavy goods vehicle (HGV) as the objective [2]. Gazis and Herman first proposed the concept of "Moving Bottleneck" and attempted to explain it according to traffic flow wave theory when they found that a HGV may cause a slow motorcade in 1992 [3]. Later, numerous researches on formation mechanism of moving bottleneck have been conducted, and some traffic phenomena and experimental data were analysed from the perspective of moving bottleneck theory [4-8]. However, most of these findings focus on basic sections of highway, not on interchange areas.

Regarding merging area, many previous studies have focused on influence factors of traffic safety and capacity [9-11]. S. Li et al. established crash risk prediction model and defined HCRI index based on traffic conflict technique for freeway interchange merging area [12]. L. Lei analysed the gear-alternating control regulation based on FI cellular automaton model and concluded that gear-alternating control can improve traffic situation significantly under large traffic volume [13]. Sun et al. simulated the operation characteristics of merging area under open boundary condition by calibrated car-following model and lane changing model [14].

From the literature review, there seems to be three main issues in China: 1) few studies have linked large vehicles to interchange merging areas; 2) the models used to analyse merging segment in China are based on research results from other countries, but the differences of traffic composition and other conditions between China and other countries, isn't taken into consideration; 3) the research on merging areas is mainly focused on the capacity rather than safety.

In this paper, with regard to a directional on-ramp, simulations are conducted with the calibrated car following model and lane changing model in VISSIM. Then traffic conflict technique and velocity consistency index are selected to evaluate the impact of HGV on traffic safety at confluence area. Finally, some measures are proposed to improve safety status of merging section and their applicable conditions are given.

2 Methodology

2.1 Data collection

The traffic survey was conducted at a semi-cloverleaf interchange with a typical merging area, which is composed of a three-lane mainline and a one-lane ramp if emergency lane is neglected. The width of every lane is

3.75m. The horizontal curve radius of main line is 1500m and ramp radius is 650m. Unmanned aerial vehicle (UAV) photography was applied to shoot video in good conditions. Finally three hours high-precision video was obtained. Moreover, radar velocimeters were used to measure speed of gore nose, midpoint and end point of merge area, as shown in the Figure 1.

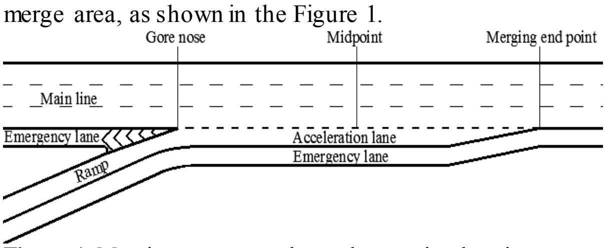

Figure 1. Merging segment and speed measuring locations.

2.2 Safety evaluation

Common traffic safety evaluation methods include three categories, namely accident-based method, conflict-based method and traffic flow characteristic based method. In this paper, the latter two methods are considered. The traffic conflict and traffic characteristic indicator are defined as follows.

2.2.1 Traffic conflict

Traffic conflict technique, as an approach that overcomes the lack of reliable accident records, is widely used for safety evaluation in China [15-17]. However, most previous studies on traffic conflict pay attention to the intersection rather than merging section. In fact, there exists great difference between them because of distinct traffic and road conditions. Therefore, the key of this method is how to identify the effective conflict at merging segments.

TTC (time to collision) is the critical parameter to determine a traffic conflict. In this paper, two typical types of conflicts are defined according to the angle between the vehicle travelling directions: 1) rear-end conflict, the angle is in [0°, 15°); 2) sideswipe conflict, the angle belongs to [15°, 85°]. Relevant studies pointed that the TTC thresholds of these two conflicts are 4.7s and 4.2s, respectively [16]. To make study convenient, this paper selects 4.2s as the TTC threshold for all conflicts.

2.2.2 Speed consistency

Based on traffic characteristics, some studies found that speed consistency can well reflect the traffic flow stability and safety situation of highway [18, 19]. Speed consistency indicators commonly used include the following two categories.

• SDI, speed difference index, can reflect directly safety of adjacent sections of highway, mainly including ΔV_{85} and $85(\Delta V)$.

• SSI, speed statistic index, reflect traffic safety by analysing distribution of velocity statistics such as σ and σ/μ, which is more applicable to a single segment.

As to confluence area, which is different from the basic section in traffic characteristics, SDI index may be more suitable. The equation of ΔV_{85} and $85(\Delta V)$ are listed as follows:

$$\Delta V_{85} = \left| |V_1|_{0.85} - |V_2|_{0.85} \right| \tag{1}$$

$$85(\Delta V) = |V_1 - V_2|_{0.85} \tag{2}$$

where V_1 and V_2 are respectively the speed of the same vehicle on different segments. In fact, ΔV_{85} overestimates the safety while $85(\Delta V)$ is more precise because the relationship and interaction of adjacent sections is taken into account [20]. Meanwhile, a novel indicator *SRC* based on $85(\Delta V)$ is proposed to reflect the reduction coefficient of speed.

$$SRC = \left| \frac{V_2 - V_1}{V_1} \right|_{0.85} \times 100\% \tag{3}$$

3 VISSIM-based merging area model

3.1. Model assumption

In this paper, the purpose is to investigate the safety situation under different ratio of HGV. Therefore, a freeway merge section model was established. Specific to the characteristics of merge sections and the functions of the software VISSIM，some assumptions are listed as follows.

• Assume that both the mainline and on-ramp are straight and the slope of merge section is zero.

• Assume that the angle of mainline and ramp is 30° and parallel type acceleration lane is adopted.

• Neglect the effect of weather conditions and lateral clear width on the traffic flow characteristics.

• Assume that the design speed of main line and ramp respectively are 100km/h and 60km/h.

• Assume that the traffic composition on the entrance ramp is the same as the main line.

3.2 Model calibration

3.2.1 Vehicle parameter calibration

We divide the vehicles into two types, cars and large vehicles (HGV), and their various parameters are shown in Table 1.

Table 1. Parameters of car and HGV in model.

Type	Length (m)	Width (m)	Maximum Acceleration	Maximum Deceleration
Car	4.11~4.34	1.5	3.5 m/s^2	6.0 m/s^2
HGV	7.0~14.0	2.5	2.5 m/s^2	5.5 m/s^2

3.2.2 Car following model calibration

In this paper, Wiedemann99 car-following model, which is widely used in highway, is adopted to simulate the car following behavior at on-ramp bottleneck. Table 2 gives the calibrated parameters of car following model.

Table 2. Parameters of car following model.

Parameter	Value	Parameter	Value
CC0	1.5m	CC5	0.35
CC1	1.50s	CC6	12
CC2	5.5m	CC7	0.25
CC3	-8.00	CC8	3.5m/s^2
CC4	-0.35	CC9	1.5m/s^2

3.2.2 Lane changing model calibration

In general, at a merging section, the lane changing behaviours have the most significant influence on the traffic flow. Due to aggressive lane changing behaviours, vehicles on the mainline may slow down or enter into another lane. Lane changing model in VISSIM includes mandatory and discretionary lane changing behaviours and thus it is adopted in this study. The parameters of model is calibrated as Table 3.

Table 3. Parameters of car following model.

Parameter		Value	Parameter		Value
Max. deceleration	own	-4.43 m/s^2	Accepted deceleration	own	-1.00 m/s^2
	Trailing vehicle	-3.00 m/s^2		Trailing vehicle	-0.50 m/s^2
-1m/s^2 per distance	own	200m	Waiting time before diffusion		60.0s
	Trailing vehcle	200m	Min. HeadWay (front/rear)		0.5m

3.3 Model verification

Table 4. Result of speed and conflict test.

	Vehicle type and Location		Survey value (km/h)	Mean of simulation (km/h)	Error
Speed test	Car	Gore nose	88.25	89.61	1.54%
		Midpoint	82.64	82.17	0.57%
		End point	77.38	75.51	2.42%
	HGV	Gore nose	70.44	72.16	2.44%
		Midpoint	64.37	62.65	2.67%
		End point	55.42	53.51	3.45%
	Conflict type and Time interval		**Survey value**	**Mean of simulation**	**Error**
Conflict test	Rear-end	0~1h	18	20.3	12.78%
		1~2h	42	38.6	8.10%
		2~3h	31	32.7	5.31%
	Sides-wipe	0~1h	22	23.6	7.27%
		1~2h	53	55.1	3.96%
		2~3h	40	35.3	11.75%

The merging segment model is built in VISSIM and the investigation and statistical results (traffic volume, ratio of HGV, etc.) were input into simulation model. For more stable output results and smaller random error, each simulation lasts for 3600s and simulation in the same condition is carried out 10 times, thus the average value of the total 10 simulations is adopted as final result.

To test the validity of the model, this paper compared the simulation results with the observations by two indicators, average speed of section and number of traffic conflicts. The verification results are shown in Table 4. It can be seen that Error of section speed and traffic conflict respectively are less than 5% and 15%, which are within acceptable range in terms of engineering application. Therefore the traffic simulation model is valid.

4 Simulation and results analysis

4.1 Simulation scheme

This paper aims to explore the influence of large vehicle mixing rate on traffic safety in freeway interchange merging areas. Nevertheless, the security situation is not only affected by large vehicles, but also by the traffic conditions (traffic volume, merging ratio, etc.), road conditions (acceleration lane length, curve radius, number of lanes, etc.) and control conditions (speed control, channelization, traffic markings, etc.).

This paper establishes kinds of sub-models of simulation by inputting different traffic conditions and road conditions, and thus the elements of different simulation scenarios are shown in Table 5.

Table 5. Conditions of traffic simulation.

Variable	Value
Ratio of HGV (%)	20, 30, 40, 50, 60
Mainline traffic volume (veh/h/ln)	500, 750, 1000, 1250, 1500, 1750
Merging ratio	0.25
No. of main lanes	One way and three lanes
No. of ramp lanes	1
Width of lanes (m)	3.75
Acceleration lane length (m)	200, 250, 300, 350, 400, 450

4.2 Relationship of ratio of HGV vs. mainline traffic volume

The relationship between the ratio of HGV and traffic volume at the merging area is studied in this section. The confluence area with the acceleration lane length of 250m and merging ratio of 0.25 was taken as an example. The simulation results are shown in Figure 2 and Figure 3.

From Figure 2, it can be observed that with the increase of mainline traffic volume, the conflict quantity at merge segment also increases obviously when the traffic volume is less than a critical value. When ratio of HGV is not greater than 30%, total amount of collisions increases roughly in proportion to traffic volume. Once the ratio of HGV reaches or exceeds 40%, the collisions will encounter a decline after a rapid growth. The difference is that the peak value of curve occurs at 1500veh/h/ln when proportion of HGV is 40% while it occurs at 1250veh/h/ln under 50%~60% of HGV. The decline is in line with expectations because the interaction and interference will increase when volume is large enough, which may cause larger traffic density, slower velocity and smaller possibility of collision. In addition, traffic conflicts also increases significantly with

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the increase of the rate of large vehicles under the traffic volume of 1000veh/h/ln~1500veh/h/ln, which means the large vehicles, as the moving bottleneck of merging area, exactly have great influence on safe operation of traffic flow, particularly when ratio of HGV arrived at 40%.

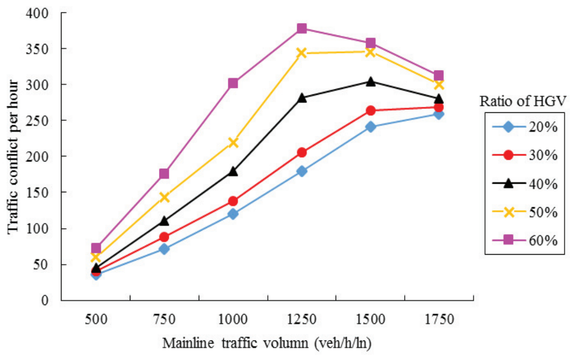

Figure 2. Relationship of traffic conflict vs. traffic volume.

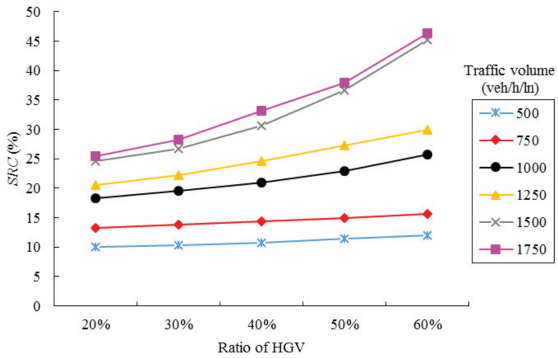

Figure 3. Relationship of *SRC* vs. traffic volume.

According to Figure 3, under the same traffic volume, the *SRC* increases along with the increment of the ratio of HGV as a whole, which implies the decline in security. Nevertheless, the curve showed different growth trend under different traffic volume. When volume is less than 750veh/h/ln, the SRC grows slowly, which suggests that the moving bottleneck caused by HGV has not yet formed. The SRC increases approximately in a line with the raise of ratio of HGV when the volume is between 1000~1250veh/h/ln. Specially, when volume continues to mount up, the SRC will increase exponentially which indicates HGV will have a greater impact on traffic stability under larger volume. Meanwhile, the curves under 1500veh/h/ln and 1750veh/h/ln have a similar shape and small spacing, indicating that the influence of traffic volume is weakened.

4.3 Relationship of ratio of HGV vs. acceleration lane length

To explore the relationship of HGV and acceleration lane length, the simulations under the situation that the mainline volume is 1250veh/h/ln, merging ratio is 0.25 and the acceleration lane length is between 200m and 450m were carried out with the results shown in the Figure 4 and Figure 5.

In Figure 4, it can be seen that the length of acceleration lane has significant influence over the traffic operation in the confluence area. In general, with the increase of the acceleration lane length, the number of traffic conflicts tends to decline when the length is less than a critical value and then it remains nearly stable. When the ratio of HGV is 20%, the conflicts are no longer reduced when acceleration lane length reaches 300m, while this critical value will climb to 350m when HGV account for 30%~40% and 400m when HGV exceed 50%. From another perspective, the acceleration lane exists a border, not the longer the better.

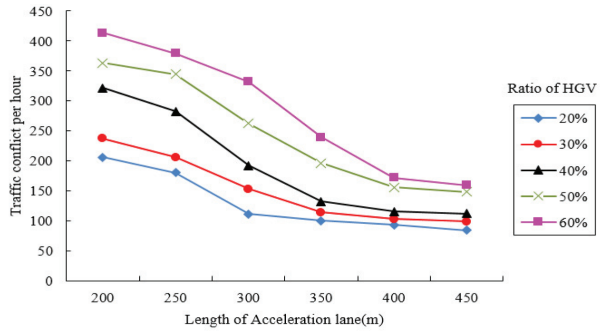

Figure 4. Relationship of conflict vs. acceleration lane length.

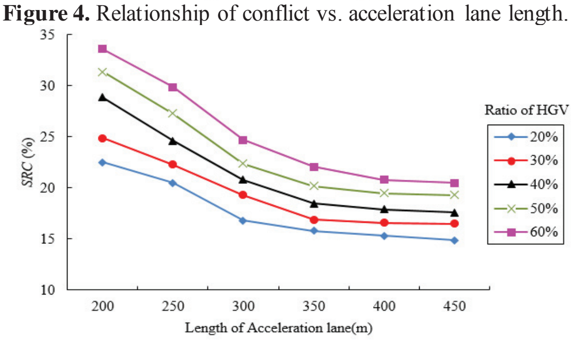

Figure 5. Relationship of *SRC* vs. acceleration lane length.

From Figure 5, it is found that the speed stability is improved with acceleration lane length increasing. Also, under the same length of acceleration lane and traffic volume, the more large vehicles, the lower the speed consistency and stability. This because the fact that large vehicles will cause more interference when changing lane at merging area.

4.4 The impact of speed limit measure

Under the same condition, a higher proportion of large vehicles may cause lower security on interchange on-ramp joints. By the analysis of section 4.3, setting reasonable length of acceleration lane can significantly improve traffic conditions. However, there are great difficulties in reconstructing an acceleration lane for an existing freeway interchange.

In addition to big size and poor performance of HGV, the main reason for the safety problems is that the vehicle enter into the main line too early, which cause large speed difference between ramp vehicles and mainline vehicles due to inadequate acceleration. Thus, a possible measure is limiting the mainline speed to reduce speed difference.

Because the design speed of mainline and ramp are respectively 100km/h and 60km/h, the speed of inner, middle and outer lane of mainline are respectively limited as 90km/h, 80km/h and 70km/h in this paper. Then the simulations under different conditions were conducted when merging ratio and acceleration lane length were fixed to 0.25 and 300m. The reduction rate of traffic conflicts is selected as the indicator to evaluate effcts and the result is shown in Figure 6.

From Figure 6, at the same traffic volume, a better improvement effect of sub-lane speed limit measure is observed at the condition of enhanced HGV proportion. And this measure can be implemented for optimum results when traffic volume is 1000veh/h/ln~1500veh/h/ln and ratio of HGV isn't less than 40%.

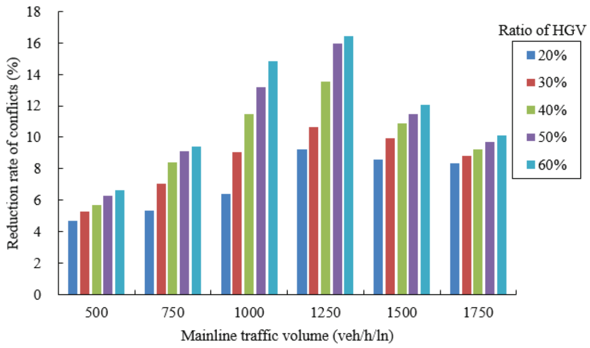

Figure 6. The effect of speed limit at merging area.

4.5 The impact of forbidden line

Regarding the parallel type acceleration lane, too large merging angle also may increase driving risk. Therefore MUTCD points out that the solid white line, namely forbidden line, setting at the end of optional diagonal or chevron approach markings on gore nose (Figure 7), can avoid premature merging into mainline [21]. However, the length of forbidden line and its adaptability in China and implementation effect have not been proven and evaluated.

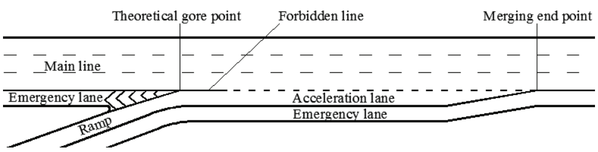

Figure 7. Forbidden line at merging area.

Taking the merge section under the condition that mainline volume arrives at 1250veh/h/ln, merging ratio is 0.25, acceleration lane is 300m long and HGVs account for 40% as an example, the simulation was carried out to study the effectiveness of forbidden line, with the results shown in Figure 8. Obviously, when forbidden line is 15m long, the best improvement has been achieved. And the effectiveness will decline when continuing to increase the length because this actually reduces acceleration lane length and the choice of merging space.

The merge section with forbidden line length of 15m, acceleration lane length of 300m, merging rate of 0.25, traffic volume of 500veh/h/ln~1750veh/h and HGV ratio of 20%~60% was taken as an example to compute the reduction rate of traffic conflicts. And the K-means cluster analysis method was applied for the effectiveness evaluation of the data obtained. The final clustering result obtained from ten iterations is shown in Table 6.

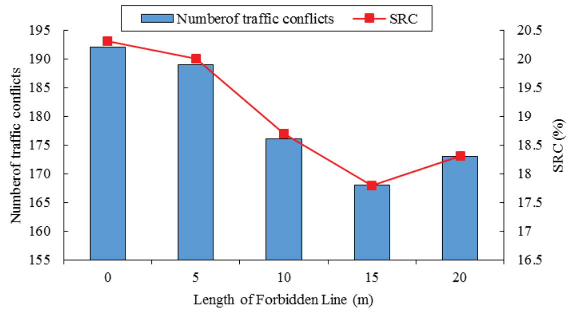

Figure 8. The effect of forbidden line at merging area.

According to the cluster results, the effectiveness of forbidden line is divided into four levels, excellent, good, medium and poor. The effectiveness under various conditions is shown in Table 7.

Table 6. Final cluster centres in simulation.

Level	Poor	Medium	Good	Excellent
Reduction Rate of Conflicts （%）	2.85	5.56	8.08	11.15

Table 7. Effect analysis for the setting of the forbidden line.

Traffic Volume (veh/h/ln)	Ratio of HGV	Reduction Rate of Conflicts	Level
500	20%	2.08%	Poor
	30%	5.33%	Medium
	40%	7.10%	Good
	50%	6.24%	Medium
	60%	4.27%	Medium
750	20%	3.34%	Poor
	30%	5.67%	Medium
	40%	8.36%	Good
	50%	6.91%	Good
	60%	5.02%	Medium
1000	20%	6.11%	Medium
	30%	8.43%	Good
	40%	10.05%	Excellent
	50%	8.81%	Good
	60%	6.67%	Medium
1250	20%	9.03%	Good
	30%	11.02%	Excellent
	40%	12.50%	Excellent
	50%	10.57%	Excellent
	60%	8.61%	Good
1500	20%	7.59%	Good
	30%	9.43%	Good
	40%	11.62%	Excellent
	50%	9.26%	Good
	60%	7.11%	Good
1750	20%	5.15%	Medium
	30%	7.08%	Good
	40%	7.33%	Good
	50%	3.83%	Poor
	60%	2.16%	Poor

From Table 7, when the large vehicle ratio is 30%~50% and mainline traffic volume is 1000veh/h/ln~ 1500veh/h/ln, setting forbidden line has excellent or good effect. When the traffic volume is relatively small or large, setting forbidden line has poorer effect along with the increment of the large vehicle ratio. The reasons are following: when the traffic volume is relatively small, the traffic flow is under free state and large vehicles slightly influence small vehicles. However, when the traffic volume is relatively large, the traffic flow is under saturated state, and forbidden line cannot effectively reduce traffic conflicts.

5 Conclusion

On the freeway interchange merging area, the moving bottleneck caused by large cars is not independent, which may affect traffic safety when lateral lane changing behavior and longitudinal car-following behavior occur. The impact of large vehicles and the improvement measures were systematically researched in this paper with the goal of traffic safety.

The influence of the moving bottleneck caused by large vehicles on the traffic flow is significant. With the increment of large vehicle ratio, traffic safety decreases for the traffic conflicts and *SRC* increases significantly. When traffic volume is less than 750veh/h/ln or more than 1500veh/h/ln, the impact of HGV is relatively small. This indicates that moving bottleneck has not yet formed at merging area at that time.

Setting appropriate length of acceleration lane can enhance traffic safety level effectively. Under the condition of traffic volume of 1250veh/h/ln, the length of acceleration lane should be set to 300m, 350m and 400m when large vehicle ratio are 20%, 30%~40% and 50%~ 60%, respectively.

Besides, speed limit is an effective method to improve traffic operetion at merge sections, especially when traffic volume of mainline is 1000veh/h/ln~1500veh/h/ln and ratio of HGV is less than 40%. Forbidden line proposed by MUTCD is also considered in this paper and we conclude that 15m long forbidden line may have better improvement effect under medium traffic volume condition. Meanwhile, by K-means cluster analysis, when traffic volume is 1000veh/h/ln~1500veh/h/ln and the ratio of HGV is 30%~50%, setting forbidden line on freeway interchange merging area can effectively promote the traffic safety; especially, when the large vehicle ratio is about 40%, the positive effect is the most obvious.

However, this paper was limited to analyzing data from the perspective of part of road and traffic conditions. In reality, merging ratio, number of lanes, ramp radius, type of acceleration lane and other traffic control or environment conditions should be taken into account. Future studies may look into these influencing factors as variables for modeling.

Acknowledgments

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