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Traffic Engineering
Original Scientific Paper
Submitted: 30 Nov. 2020
Accepted: 10 Mar. 2021

PLACEMENT DISTANCE OF EXIT ADVANCE GUIDE SIGN ON AN EIGHT-LANE EXPRESSWAY CONSIDERING LANE CHANGING BEHAVIOUR IN CHINA

ABSTRACT

The reasonable placement of the advance guide signs (AGSs) is important in improving driving efficiency and safety when exiting an expressway. By analysing the lane-changing process when approaching an exit on new two-way eight-lane expressways, we modified the traditional AGS model lane-change distance formula. To this end, a field experiment was designed to explore the lane-change traversal time at the free flow condition (LOS 1). Considering the limitations of the experimental equipment, lane change distance at the worst levels of service was explored using VISSIM simulation. The results show that the eight-lane changing distance based on modified theoretical calculations, revealed a minor difference with VISSIM simulation in free flow condition. Furthermore, placement distance at the worst levels of service are discussed. Then placement distance of all-level AGSs is recommended to be 3 km, 2 km, 1.2 km, and 0.8 km, considering the driver's short-term memory attenuation calculation formula. Determining the two-way eight-lane AGS placement distance from the perspective of LOS can provide a basis on which to supplement the existing standards and references for the AGS placement distance after the expressway expansion in China.

KEYWORDS

advance guide sign; lane change distance; field driving experiment, levels of service; traffic simulation.

1. INTRODUCTION

The expressway advance guide sign (AGS) which is generally placed before an upcoming exit provides directional information and the distance for drivers to the upcoming exit for drivers [1]. Reasonable design and placement of the AGS help the driver select the driving route far enough in advance to avoid unsafe lane change behaviour, which improves driving operation efficiency and safety on expressways [2].

Previous research on expressway guide signs has mostly focused on how physical parameters, such as sign materials, structure, and guide information presentation including format, font, colour, and volume influence the driver's recognition and attention [3–7]. Particularly, the excessive amount of information on guide signs influences drivers' reaction time and increase the driver's visual load and mental stress, so the screening and stratification of guide sign information were also widely explored [8–10]. Besides, when the front and rear guide sign information remains consistent and continuous, the driver can quickly read and accurately identify relevant guide information, so as to improve driving efficiency [11, 12].

Placement distance of advance guide sign is also exceedingly worth exploring. In China, a considerable part of the two-way four-lane expressways with high functional positioning and large traffic volume will be broadened to two-way eight-lane expressways due to the expanding demand for transportation and economic development. The expanded expressway will increase the number of lane changes and extend lane change distance when exiting an expressway. Unreasonable AGS placement distance on expanded expressways may result in a negative impact on the driver's perception and judgment, and further increase driver’s travel cost or risk of casualties [13, 14].

However, the impact of lane expansion has not been considered with respect to the distance at which AGSs are placed before the actual exit. There is no related modification or supplement in the current Chinese national standards and specifications, which includes one rule for all types of expressways [9, 15]. There are few helpful references for determining the placement distance of exit AGSs on eight-lane expressways, while most countries do not specify a difference in the number of lanes but in interchanges types. The MUTCD [16] stipulates three-level AGSs for large and medium-sized interchanges, and two-level AGSs for small interchanges. The “Standard for Highway Guide” in Germany (FGSV 329/2) [17] and “Road Sign Handbook” in Japan [18] classify interchanges as hub and general interchanges; the AGS levels in Germany are distinguished as three and two, respectively, but Japan still employs three-level AGSs.

In the two-way eight-lane expressway, it is necessary to quantitatively determine the placement distance of the AGS before the upcoming exit according to the driver lane-change process. However, in the national standards, no specific calculation method is given for the AGS distance; the interchange type is specified, but there is no distinction in terms of the driver characteristics in different traffic environments. When it comes to the multi-level AGSs, the one closest to the ramp exit (noted as the final one) is essential and has the most significant impact on driver safety and operational behaviour [19]. Qiao et al. [20] used a driving simulator to estimate the final AGS location and took into account influential factors such as traffic flow rate, operating speed, and number of lanes. Guo et al. [21] proposed an AGS placement distance model for three types of sign installations, considered expressway geometry design, and driving behaviour, and then discussed the AGS placement distance at several posted speeds. However, this model still simplifies the lane changing process, which is quite different from reality. Based on this situation, Liu et al. [22] considered lane-change waiting time based on the characteristics of the expressway diversion area approaching an exit and the driver's visual-discontinuation behaviour, and provided a modified calculation model of the lane-change distance based on the probable angle. Zhu et al. [23] modified the AGS model based on the difference in lane-change distance under different types of AGS installations. However, in the above-referenced AGS placement distance model corrections, the calculations of the lane-change distance still tend to be ideal, and do not take into account the speed difference before and after the lane change, the traversal distance of the vehicle when changing lanes, and the specific traffic environment. Therefore, it is necessary to synthesize the traffic environment and driving characteristics, and further analyse the lane-change distance to determine the AGS placement distance.

In the existing model, when determining the placement of the AGS before the exit, speed is the most popular indicator to distinguish traffic conditions [24, 25]. Volume density reflects the degree of driving freedom and vehicle proximity in expressway traffic, and should also be considered [26], but is rarely considered in AGS distance calculations. The level of service (LOS) is an integration of the speed, traffic flow density, and traffic flow rate, and can fully and intuitively reflect the expressway traffic environment and driver satisfaction. Therefore, taken as an indicator of traffic flow and driver experience, LOS is of great significance in exploring the AGS placement distance.

Analysing the lane change process of exiting an eight-lane expressway, this paper classifies two periods of vehicle lane change that reflect the traffic environment and speed differences before and after the lane change, and corrects the lane change distance formula of an typical traditional AGS distance placement model. At the free flow condition, a field experiment is conducted to explore the lane change traversal time and determine the lane change distance. Considering the limitations of the experiment equipment, VISSIM simulation is employed to discuss the difference in lane changing distance under all levels of service. Taking into account the driver's memory attenuation, the AGS distance from the exit at each LOS is proposed to provide reference for the placement distance of the AGS on an eight-lane expressway.

This paper is divided into three parts: the first part deals with the change distance correction of AGS model, the second part considers the experimental method and VISSM simulation, and the third part contains research conclusion.

2. LANE CHANGE DISTANCE MODEL

2.1 A traditional placement distance model for AGS

The driver travelling on an eight-lane expressway decides to pull out of the main lane to enter the ramp when noticing the exit AGS. The overall process can be classified into three periods after the driver notices the AGS.

1) Perception and reaction. The driver notices the final exit AGS and then recognises the information on the sign; the driving distance in the period is set as D_1.
2) Lane changing. The driver decides to shift to the outermost lane with a maximum of three lane changes; the driving distance in the period is set as D_2.
3) Deceleration. After completing the lane changes, the driver slows down to a limited speed and enters the ramp; the driving distance in this period is set as D_3.

The advance distance D ranges from the final AGS location to the exit ramp shunt nose, and the D_0 of the AGS ranges from the driver noticing the final AGS to the final AGS location. *Figure 1* illustrates a theoretical calculation diagram of the lane-change process in the most unfavourable situation with three lane changes. The starting point of the reaction period, the first lane change, the second lane change, the third lane change, and the deceleration period are set as *a, b, c, d,* and *e,* while the exit ramp shunt nose is set as *f*.

According to *Figure 1*, an AGS placement distance model can be determined based on the following assumptions: (1) all drivers drive safely and the driving characteristics are similar for all drivers conforming to the same lane change rule; (2) vehicles with no need of exiting the expressway will not change lanes and will travel in a constant headway distribution pattern. V_1 and V_2 are the driving speed of the main lane and the ramp, respectively.

The advanced distance D is

$$D = D_1 + D_2 + D_3 - D_0 \tag{1}$$

The perception and reaction distance D_1 is

$$D_1 = V_1 \cdot \frac{PRT}{3.6} \tag{2}$$

where PRT is the Perception and Reaction Time, which is related to driving speed.

The lane changing distance D_2 with three lane changes is

$$D_2 = V_1 \cdot T \cdot \frac{3}{3.6} \tag{3}$$

where T is the average time for each lane change.

The deceleration distance D_3 from V_1 to V_2 is

$$D_3 = \frac{V_1^2 - V_2^2}{254 \cdot (f + G)} \tag{4}$$

where f is the coefficient of friction, generally from 0.29 to 0.44, and G is the slope of the expressway.

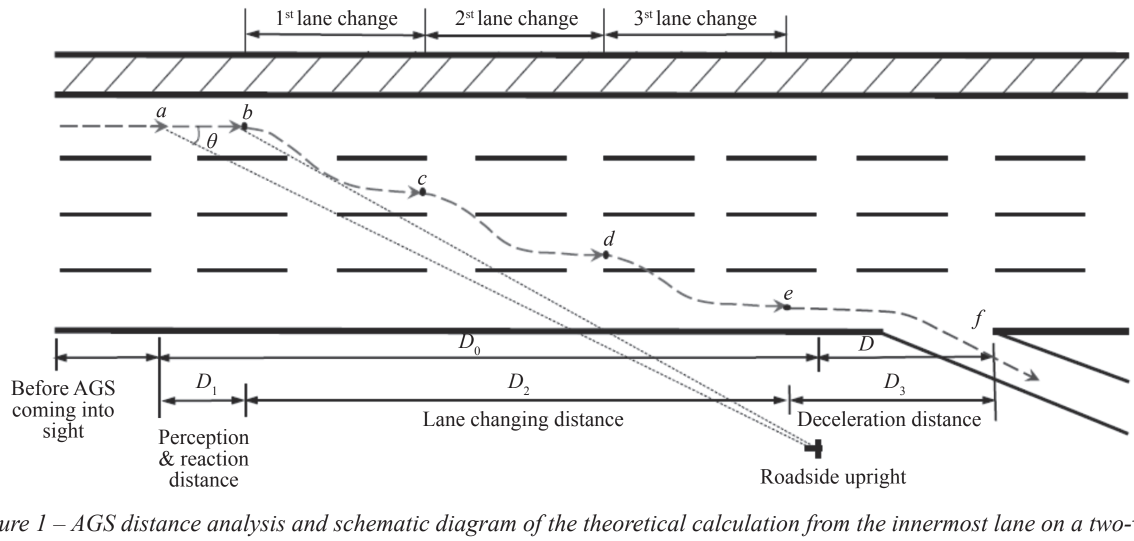


Figure 1 – AGS distance analysis and schematic diagram of the theoretical calculation from the innermost lane on a two-way eight-lane expressway

The visual distance D_0 is

$$D_0 = ((4 - 0.5) \cdot L_w + L_0) \cdot \cot\theta (3^\circ < \theta < 12^\circ) \quad (5)$$

where L_w denotes the width of the lane, L_0 denotes the horizontal offset of the guide sign, and θ denotes the angle between the driver and the exit guide sign. Based on the driver's visual field clarity on an eight-lane expressway, θ is set as 10°.

Lane changing distance of outgoing vehicles D_2 is

$$D_2 = \frac{1}{3.6} V_1 \cdot T \cdot (N - 1) \quad (6)$$

where V_1 is the main line design speed T is the average time of each lane change N is the number of motorway lanes.

In the traditional AGS model, the speed of each lane change is considered to be the same in the calculation of D_2. In fact, the driving speed varies at the beginning and the end of each lane change, which contributes to the difference in lane-change distance. In addition, there is a waiting period during which the driver looks for an acceptable gap in traffic to enter the target lane. Therefore, it is essential to modify the lane-change distance calculation formula for exiting the expressway.

2.2 Modification of the lane change distance formula

D_2 can be decomposed into three single lane change distances. This is similar for each single lane change distance L, which can be divided into three periods, waiting an acceptable gap, reaction, and execution.

1) Waiting Period. Drivers who are determined to change lanes from the current lane should wait for an acceptable gap in the target lane, where the waiting time t_w depends on the vehicle's headway distribution pattern and V_c denotes the average vehicle speed in the current lane.
2) Reaction Period. There exists a reaction time t_2 when an acceptable gap occurs. With reference to the proposed AASHTO, combined with the vehicle composition of expressways in China, traffic conditions, and driver characteristics, we take the reaction time t_2 as 2.5s [27].
3) Traversal Period. The travel distance from the current lane to the target lane is determined by the traversal time t_3 needing to be explored. The driving speed in the period is V_T, which is almost the speed of the target lane.

A single lane change distance L can be described by the following equation.

$$L = \frac{V_c \cdot t_w + V_c \cdot t_2 + V_T \cdot t_3}{3.6} \quad (7)$$

In the above equation, traversal time t_3 needs to be explored. Generally, there are two methods – field experiment and driving simulation – used to determine the traversal time t_3. Driving simulation allows the driver to experience a visual and auditory car driving experience in a virtual driving environment, regardless of time, climate, or location. However, compared with the field experiment, the driving simulation does not reflect the real comprehensive traffic flow environment, so a field experiment was chosen to explore the traversal time t_3.

3. A FIELD EXPERIMENT

The 'Traversal time' is the average waiting time for lane-changing vehicles to wait for an acceptance gap.

At present, most expressways are subject to full-closed toll management in China, but the distance between two adjacent exits can generally be more than 10 kilometres. This distance is excessive and increases the difficulties and time costs of successfully observing a vehicle exiting an expressway, due to the randomness of the vehicle departure and the limitation of the experiment equipment. Compared with general expressways that pass by many cities, the city's suburban expressway has excellent characteristics and is more convenient for data collection; it has more transition points, a relatively shorter distance between two adjacent exits, and many opportunities for vehicles to exit the expressway. Furthermore, the drivers' lane-changing behaviour between two adjacent lanes is similar in six-lane and eight-lane expressways, so the suburban expressway of Xi'an City with six lanes is employed for the field driving experiment.

3.1 The field experiment scheme

Xi'an suburban expressway (G3001), as the pivotal section of the main skeleton in Xi'an City, Shaanxi Province, China, has a total length of 88 kilometres at a designed speed of 120 km h-1. It is a fully enclosed six-lane expressway with full interchanges, and is connected to G30 in the west, G30 and G40 in the east, G70, G65, and G5 in the north, and G5 and G65 in the south. In this experiment, the south section of the expressway was selected for repeated observation due to shorter exit spacing and a larger proportion of vehicles exiting the expressway. The investigation route includes six interchanges totalling 106 km, namely Apanggong Interchange (No. 1), Hechizhai Interchange (No. 2), Xigaoxin Interchange (No. 3), Chang'an Interchange (No. 4), Qujiang Interchange (No. 5), and Fangzhicheng Interchange (No. 6), as shown in *Figure 2*. Furthermore, Interchanges No. 1, 3, 4, and 5 have a large number of vehicles exiting the expressway, which is convenient for collecting data.

The experiment was conducted on the morning of 15 January 2017 at approximately 8.00–11.15 in the morning. The installation and debugging of the equipment, including the Hi-Drive 10 car-following driving behaviour system and a driving recorder, were performed before the experimental data collection to ensure the smooth completion of the experiment. This experiment was also performed by one driver, two observers, and one equipment operator. The Hi-Drive 10 system depends on the following sensors to obtain the data: ranging lasers to collect the relative distance between the front and rear vehicle, MSE dynamic radar to collect the front and rear vehicle speeds, and a GPS module to collect the vehicle speed and driving route. The driving recorder is used to collect video data during the driving process.

Before starting the experiment, the Hi-Drive 10 system and driving recorder were installed on the hood of the car and the windshield inside the car at the entrance of the Chang'an interchange, and further debugged. At the beginning of the experiment, the data entry of the driving recorder and Hi-Drive 10 were started synchronously. At this point, the observers and the equipment operator simultaneously pressed "record" to ensure that the entered data was synchronised, which is required for later processing of the data. Once the test car entered the main lane of the expressway, observers began to look for the target vehicle and followed the vehicle to obtain its lane-change data. In this process, the dynamic radar MSE captured the vehicle and the driving recorder recorded the video. The target vehicle had to be able to change lanes toward the upcoming exit and the test car needed to exclude the effects of cut-off vehicles to complete a successful follow-up for the target vehicle. There are two main difficulties in this experiment: (1) the radar detection MSE is always limited by the distance and affected by the surrounding vehicles during the data acquisition process and

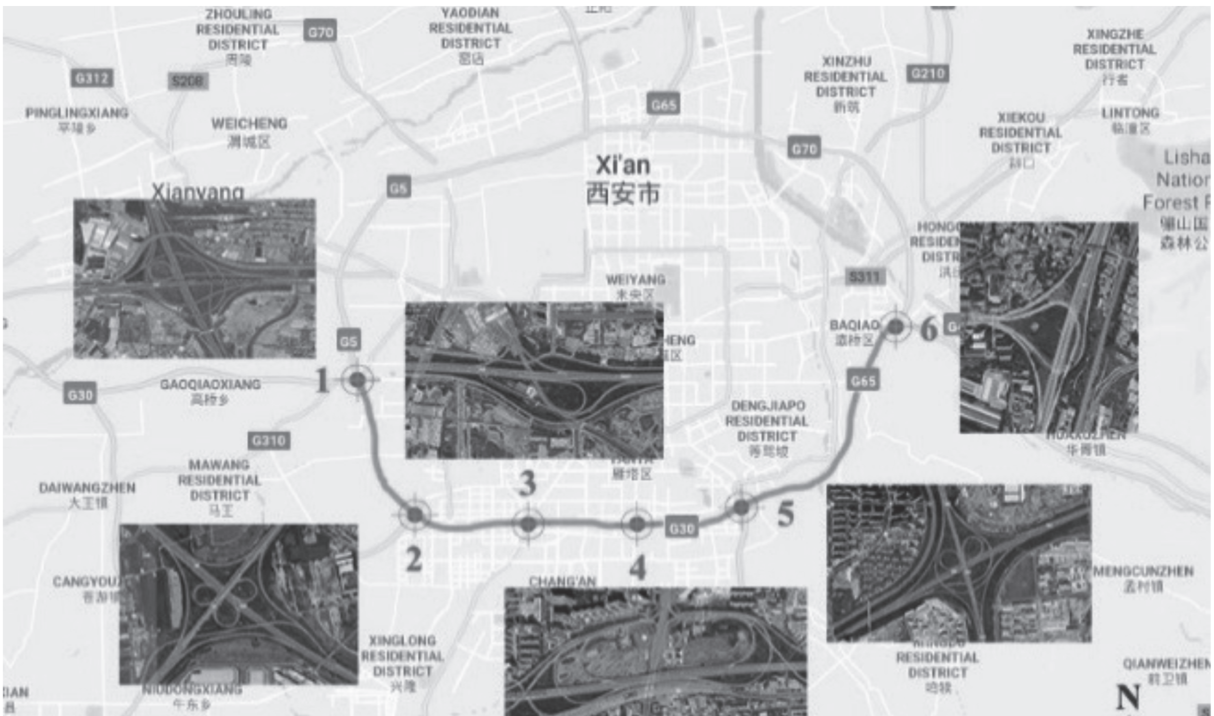


Figure 2 – Investigation route

Table 1 – Observed vehicle distribution

Route name	Length [km]	Route	Vehicles observed cues
Chang'an(4)-Apanggong(1)	18	4-3-2-1	3
Apanggong(1)-Fangzhicheng(6)	35	1-2-3-4-5-6	7
Fangzhicheng(6) – Apanggong(1)	35	6-5-4-3-2-1	8
Afanggong(1) - Chang'an(4)	18	1-2-3-4	2

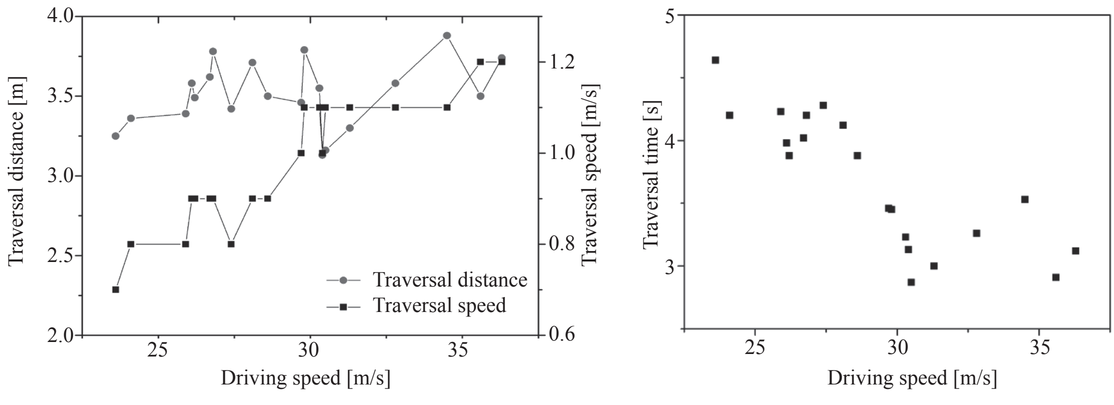
is therefore rarely able to capture all vehicles changing lanes to the upcoming exit; (2) the tracked vehicle does not necessarily exit the expressway, so considerable driving distance of the test car is required. Therefore, the test car needs to be shuttled multiple times to successfully obtain valid data. At the end of the investigation, the actions of the driving recorder and the Hi-Drive 10 system were stopped simultaneously to complete the data collection. The distribution of the vehicles that were successfully observed is shown in *Table 1*.

3.2 Traversal time of lane change

The determination of traversal time t_3 requires an extraction analysis from the raw data obtained in the experiment. When extracting valid data, the data recorded by the MSE dynamic radar needs to be coordinated with the video recorded by the driving recorder. Because the recording time of the MSE dynamic radar software is synchronised with the driving recorder, the lane changing vehicle recorded in the MSE dynamic radar software can be found by time positioning, according to the time when each lane changing vehicle started to change lanes. The collected data is extracted and analysed by the MSE dynamic radar software, where 1 second is divided into 20 frames in the study. The differences of the extracted parameters as driving speed develops are shown in *Figure 3*.

Pearson correlation analysis was performed on the above variables at the confidence level of 0.01. It was found that there was a significant negative correlation between vehicle traversal time and driving speed, and vehicle traversal time and vehicle traversal speed with the correlation coefficients -0.828 and -0.930, respectively. The vehicle traversal speed is significantly positively correlated with the driving speed, with a correlation coefficient of 0.929. This means that the greater the driving speed of the vehicle, the greater the traversal speed of the vehicle will be and the shorter the traversal time of the vehicle. Because driving speed is the most observable and obtainable variable and contributes to the vehicle traversal speed, the relationship between the driving speed and the traversal time were explored. It was found that the two are roughly linear; the abscissa is the driving speed and the ordinate is the traversal time of the vehicle (see *Figure 3b*).

Taking the driving speed V as the independent variable and the traversal time t_3 as the dependent variable, SPSS is used for linear regression, and the functional relationship is shown in *Equation 8*. In the regression coefficient test, the independent coefficient and the constant term Sig are both less than 0.001, indicating that the linear fit is excellent.



a) Traversal parameters difference *b) Traversal time development with driving speed*

Figure 3 – Parameters in the execution period of the lane change

$$t_3 = -0.123 \cdot \frac{V}{3.6} + 7.272 \quad (8)$$

The distance L_3 that the vehicle travels during the execution period can be expressed as *Equation 9* by combining *Equations 7 and 8*.

$$L_3 = V \cdot \frac{t_3}{3.6} = \frac{-0.123V^2}{12.96} + 2.02V \quad (9)$$

4. RESULTS AND DISCUSSION

4.1 Placement distance for the final AGS

Lane-change distance at free flow condition

Currently, the lane division rule of the eight-lane expressway is related to vehicle types. At a designed speed of 120 km/h discussed in this paper, the lane function division is characterised as follows: the first lane noted as car lane has speeds ranging from 120 km/h to 110 km/h; the second lane noted as coach lane has speeds from 120 km/h to 90 km/h; the third lane noted as truck lane has speeds from 100 km/h to 80 km/h; the fourth lane noted as truck lane has speeds from 100 km/h to 60 km/h. In the calculation, the average speed of each lane is taken as 110 km/h, 100 km/h, 90 km/h, and 70 km/h.

At the first LOS, the driver is traveling in the innermost lane with a free-flow condition. The maximum traffic volume at LOS 1 is 750 veh h^{-1} ln^{-1}, and the headway distribution can be represented by the shifted exponential distribution. The average waiting time t_w of the lane changing vehicle while waiting for an acceptable gap can be expressed as *Equation 9*, where t and τ are the critical clearance of the vehicle and minimum headway time, generally taken as 4.0 seconds and 1.5 seconds, respectively; μ is the average vehicle arrival rate, which is calculated to be 750/3600 veh s^{-1} at the first LOS. The waiting time t_w is calculated to be 0.78 s.

$$t_w = \frac{e^{\mu(t-\tau)} - \mu(t-\tau) - 1}{\mu} \quad (10)$$

The lane change distance with three lane changes can be calculated according to *Equation 7*. As the result, the first lane change distance is 207 m, the second lane change distance is 196 m, and the third lane change distance is 176 m. Therefore, the lane change distance D_2 that the vehicle shifted from the innermost lane to the outermost lane is 579 m at the free flow condition (LOS 1).

Perception distance and deceleration distance

Johansson mentioned that for every 8-m/h increase in speed, the driver's cognitive response time is shortened by 0.2 s [28]. When the driving speed V_1 is 120 km/h, it follows

$$PRT = 5.3 - 0.025V_1 \quad (11)$$

The relevant parameters in the AGS model and the calculated D_0 and D_3 values are presented in *Table 2*.

D_0, D_1, D_2, and D_3 substituted into *Equation 1* produced a value of 748 m of D at LOS 1. At the first LOS, the driver is travelling in the innermost lane at a free-flow condition, and the distance required to see the AGS and exit to the outermost lane is 748 m. However, the current placement distance in China is 500 m, which obviously cannot meet the driver's lane change needs, so the placement distance of the final AGS on an eight-lane highway is recommended to be 800 m. The determination of the placement distance of the rest of AGSs requires consideration of the lane change distance of the vehicle at the worst service levels.

4.2 Lane change distance at all levels of service

The lower the LOS, the higher the traffic density, and the longer the lane-change distance the driver needs to traverse. However, the field experiment can rarely obtain the data at the worst levels of service. On the one hand, it is difficult for the test car to follow the lane-change vehicle constantly in a higher traffic volume density. On the other hand, the MSE radar is exceedingly limited in capturing the lane-change vehicle due to the interference of surrounding vehicles, especially in a more complex traffic environment. Therefore, VISSIM simulation was used to simulate the vehicle lane-change behaviour at the worst service levels by setting relevant parameters.

Table 2 – Parameter values in the AGS placement distance model

Parameters	D_0			D_3			
	L_w	L_0	θ	f	G	V_1	V_2
Value	3.75 m	2.0 m	10°	0.29	0	120	60
	88.6 m			173.8 m			

At the beginning, VISSIM should be calibrated to conform real driving environment by setting a reasonable lane changing scheme and adjusting relevant parameters. Considering the most unfavourable situation, a vehicle in the innermost lane needs to make three lane changes in succession to shift to the outermost lane. The continuous lane change of the vehicle from the first lane is realised through the connector between four parallel lanes. *Figure 4* represents only one special case in the VISSIM simulation. The vehicle stops moving forward in the simulation, waiting for an acceptable clearance to change lanes, as shown in the connector in *Figure 4a*. In practice, however, the vehicle will always move forward when an acceptable gap is encountered before the lane change behaviour occurs through the connector) as shown in *Figures 4b and 4c*.

To characterise the behaviour of the vehicle changing lanes to find an acceptable gap to traverse a routing rule is established that between the lane and the connector, junction section vehicles give way to main lane vehicles. The detector is placed at the entrance and exit of each connector so that the number of vehicles, the driving speed, and the two time points of the vehicle entering and exiting the connection segment were recorded, respectively. The difference between the two time points represents the waiting time for the vehicle to find an acceptable gap to traverse. The total lane-change

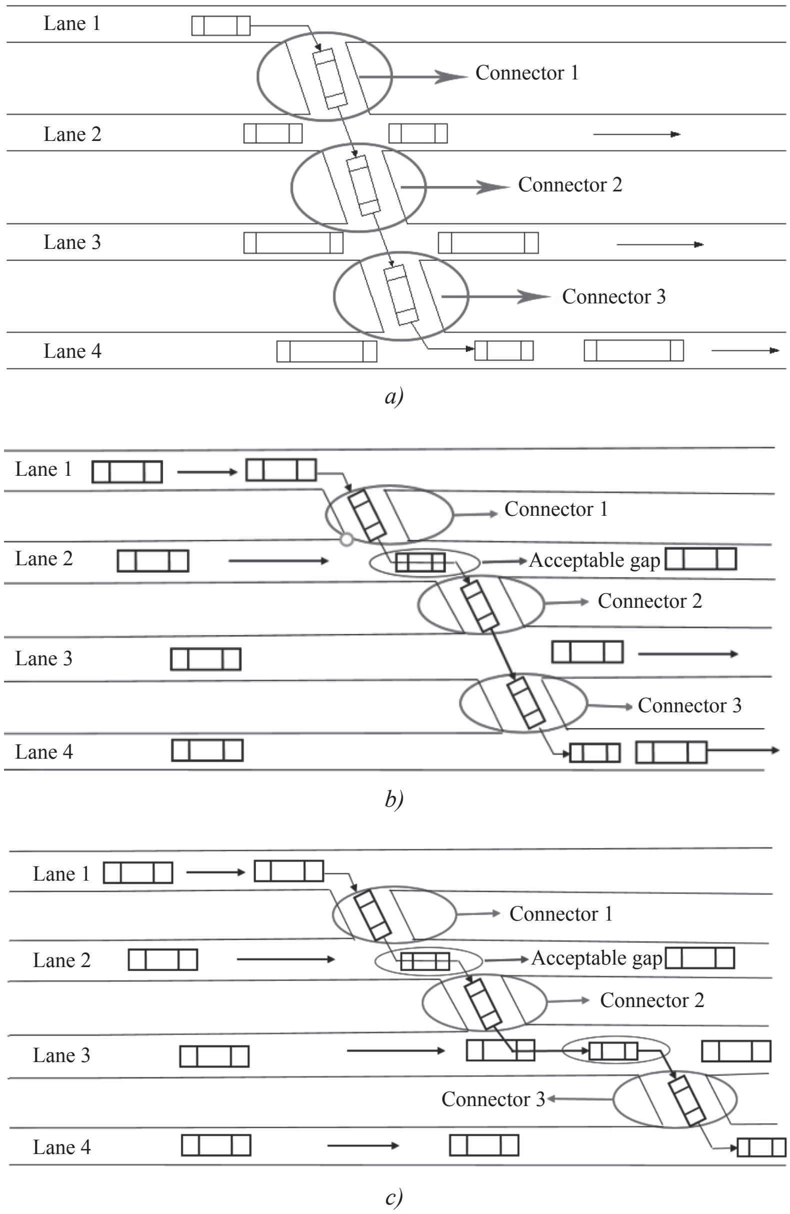


Figure 4 – Schematic diagram of lane changes on an eight-lane expressway in the VISSIM

Table 3 – The placement distance of AGS (meter)

AGS order	Recommended value	China	Japan*	America*	Germany*	The Netherlands*
Information signs	3000	none	none	none	2000	1800
1st	2000	2000	2000	3200	1000	1200
2nd	1200	1000	1000	1600	500	600
3rd	800	500	500	800	none	none

distance can be calculated according to *Equation 12*, in which V_i' indicates the vehicle running speed in the *i*th lane to the (*i*+1)th lane connector, and t_i indicates the beginning time difference from the *i*th lane to the (*i*+1)th lane, *i*=1, 2, 3.

$$S = \sum_{i=1}^{3} V_i' \cdot t_i \tag{12}$$

Consistent with the lane division rule in section 4.1, the lane division rule works in the VISSIM simulation by setting the vehicle composition and the vehicle speed limits in each lane. The distinction of the innermost lane exit rate and the maximum traffic volume of the lane under different levels of service are considered. According to the "Design Specification for Highway Alignment" (JTG D20-2017) [29], at a design speed of 120 km/h, the maximum traffic volume under the first to fifth LOSs are 750 veh/h/ln, 1200 veh/h/ln, 1650 veh/h/ln, 1980 veh/h/ln, and 2200 veh/h/ln, respectively. Considering that the exit rate of the innermost lane vehicle ranges from 10% to 90% with 10% taken as a step, the simulation of the combination scheme is performed according to the change value of the parameter, with the simulation time of one hour.

At the first LOS, the average value of the vehicle lane change distance under different exit rates in the VISSIM simulation was 590 m, which is exceedingly close to 579 based on the theoretical correction. The validity of the results based on lane change distance formula is also proved. On this basis, by setting the traffic volume of each lane under all levels of service, with the parameters of *Table 2* adopted, the placement distance of AGSs under the first to fifth LOSs are, respectively, 748 m, 920 m, 1320 m, 2060 m, and 2743 m.

4.3 Placement distance for all levels of AGS

According to a study on the short-term memory attenuation of driver recognition of traffic signs, when the memory time of drivers is 25 s, the memory is relatively clear [30]. The speed limit of vehicles on the expressway is 60 km/h~120 km/h, so the repeated spacing of exit signs required by the driver should range from 250 m to 1000 m. According to the repeated spacing of two exit signs, two repeated signs should be set between the first AGS and the last AGS to transmit the guide information repeatedly and continuously, and the spacing should be set as 1000 m, 800 m, and 400 m, respectively. The placement distance of all AGSs on an eight-lane expressway is recommended in hundreds of meters, compared with other countries as shown in *Table 3*. The number of lanes is not distinguished in the national standards in the table, but most countries classify interchange types, and the AGS placement distance of large and medium-sized or hub interchanges are listed (see countries with *). For convenience of comparison, miles are converted to meters.

As shown in *Table 3*, Germany and the Netherlands distinguished interchanges and setting an information sign. Although Japan classifies the interchange as a hub and general interchange, the placement distance is similar to China. The recommended placement distance of advance guide signs in this paper on an eight-lane expressway for exits has certain commonalities with American large and medium-sized interchanges and the Netherlands hub interchanges. In addition, the 3-km information sign draws on the practice of the consulting sign such as Germany and the Netherlands. LOS 4 and 5 on an expressway always appears at the beginning and end of the holidays. To prevent the driver from missing the sign and forcibly changing lanes at the exit, 3 km taken as a variable consultation sign is recommended. When the LOS reaches the fourth level, the advance guide information should be pushed to remind the driver to change lanes in advance, reducing the anxiety of the driver and inducing the driver to travel safely and effectively.

5. CONCLUSION

In this paper, the traditional lane change distance formula of the AGS model was modified and a field experiment was conducted to explore the traversal time in the lane changing process at the free flow condition, and both were used to determine the placement distance of the final AGS on an eight-lane expressway at a designed speed of 120 km/h^{-1}. VISSIM simulation was employed to discuss the lane change distance at worse service levels, which contributes to the placement distance of all-level AGSs.

1) A modified lane change distance formula is proposed that takes into account that the lane change process consists of the driver's waiting, reaction, and execution period, for which a linear function between the vehicle's traversal time and driving speed is proposed according to a field experiment. Further, considering the headway distribution characteristic at the first LOS, the lane change distance is calculated to be 579 m and the placement distance of the final AGS is 748 m, which is longer than the 500-m value in current Chinese national standards.
2) Considering the innermost lane exit rate and the difference in traffic volume under each LOS, VISSIM simulation calibrated was used to discuss lane change distance. Under the first LOS, the simulation results reveal conformity with the theoretically calculation results, so lane change distance at different LOSs were further explored.
3) Considering the short-term memory attenuation of the driver, placement distances based on VISSIM results of 3 km, 2 km, 1.2 km, and 0.8 km are proposed, which are similar to the United States and the Netherlands. Referring primarily to the placement distances in Germany and the Netherlands, 3 km at the fifth LOS is recommended to be a variable consultation sign, so when the service level reaches 4, distance and direction information for the upcoming exit can be released to induce drivers to change lanes in advance.

However, there are still limitations in two aspects: (1) lane-change distance at the high-density flow condition still needs to be further improved; (2) the difference of design speed and lane division rules may affect the range of AGS placement distances. Nevertheless, all of the above should be further explored in the future.

DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

ACKNOWLEDGEMENTS

The authors would like to thank Zhiqian Chen, M.S. from Chang'an University for the contribution to the manuscript. This work was supported by the Fundamental Research Funds for the Central Universities of China [300102210204]; the Shaanxi Natural Science Basic Program Research Grant in China [2020JM-222]; and a Xi'an Science and Technology Plan Project Grant [2019111913RKX-003SF007-9].

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基于换道行为的双向八车道高速公路出口指路标志设置距离研究

合理设置超前导向标志对提高高速公路行车效率和行车安全具有重要意义。通过对新建双向八车道高速公路的变道过程进行分析，对传统的*AGS*模型变道距离公式进行了改进。为此，设计了现场实验，探讨了自由流条件下变道穿越时间*(LOS 1)*。考虑实验设备的限制，利用*VISSIM*仿真研究了服务最差水平下变道距离。结果表明，在自由流条件下，基于修正理论计算的八车道变距与*VISSIM*仿真结果有微小差异。此外，还讨论了最差服务水平的安置距离。根据驾驶员短时记忆衰减计算公式，建议各级*AGSs*放置距离分别为*3 km*、*2 km*、*1.2 km*、*0.8 km*。从*LOS*角度确定双向八车道*AGS*放置距离可为我国高速公路扩建后*AGS*放置距离补充现有标准和参考提供依据。

关键词

前置指路标志；车道换道距离；实地驾驶试验；服务水平；交通仿真

REFERENCES

[1] Lu JJ, et al. *Safety and operational performance evaluation of four types of exit ramps on Florida's Freeways*. TechReport 1-192, 2010.

[2] Khalilikhah M, Heaslip K. The effects of damage on sign visibility: An assist in traffic sign replacement. *Journal of Traffic and Transportation Engineering (English edition)*. 2016;3(6): 571-581. doi: 10.1016/j.jtte.2016.03.009.

[3] Funkhouser D, Chrysler S, Nelson A, Park ES.

Traffic sign legibility for different sign background colors: Results of an open road study at freeway speeds. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. 2008;52(23): 1855-1859. doi: 10.1177/154193120805202305.

[4] Meeker DT, Pietrucha MT, Garvey PM. Proportion-based format system for freeway and expressway guide signs. *Journal of Transportation Engineering*. 2010;136(3): 267-275.

[5] Qiao F, Zhang R, Yu L. Using NASA-Task Load Index to assess drivers' workload on freeway guide sign structures. *ICCTP 2011: Towards Sustainable Transportation Systems*. 2011. p. 4342-4353. doi: 10.1061/41186(421)428.

[6] Pankok C Jr, Kaber DB, Rasdorf W, Hummer J. Effects of guide and logo signs on freeway driving behavior. *Journal of the Transportation Research Board*. 2015;2518: 73-78. doi: 10.3141/2518-10.

[7] Zahabi M, et al. Driver performance and attention allocation in use of logo signs on freeway exit ramps. *Journal of Applied Ergonomics*. 2017;65: 70-80. doi: 10.1016/j.apergo.2017.06.001.

[8] Yang MJ, Zhou ZW, Wang CH, Li Y. Research on relationship between information load of freeway combined guide signs and reaction time. *Journal of China Safety Science*. 2014;24(5): 15-20.

[9] Ministry of Transport of the People's Republic of China. *Guidelines for Design of Highway Safety Facilities*. China Communication Press; 2017.

[10] Zhao N, Zhao X, Lin Z, Song Y. Advance guide sign design considering the guidance demand of indirect reached freeway information. *Journal of Beijing University of Technology*. 2018;44(8): 1129-1135. doi: 10.11936/bjutxb2017050037.

[11] Chiu YC, Huynh N. Location configuration design for dynamic message signs under stochastic incident and ATIS scenarios. *Transportation Research Part C: Emerging Technologies*. 2007;15(1): 33-50. doi: 10.1016/j.trc.2006.12.001.

[12] Stasi LLD, et al. Congruent visual information improves traffic signage. *Transportation Research Part F: Traffic Psychology & Behaviour*. 2012;15(4): 438-444. doi: 10.1016/j.trf.2012.03.006.

[13] Shao F, Guo T, Liu Y, Hu Q. A disaggregate speed consistency measure for safety evaluation at freeway diverge areas. *Proceedings 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE), 16-18 Dec. 2011, Changchun, China*; 2011. p. 633-638. doi: 10.1109/TMEE.2011.6199283.

[14] Chen YX, Quddus M, Wang XS. Impact of combined alignments on lane departure: A simulator study for mountainous freeways. *Transportation Research Part C: Emerging Technologies*. 2018;86: 346-359. doi: 10.1016/j.trc.2017.11.010.

[15] National Bureau of Quality and Technical Supervision. *Specification for Layout of Highway Traffic Signs and Markings*. China Communications Press; 2009.

[16] Federal Highway Administration of the U.S. Department of Transportation. *Manual on Uniform Traffic Control Devices*. 2009. p. 12, 137-236.

[17] Forschungsgesellschaft fuer Strassen-und Verkehrswesen. *Regulations for Expressway Directional Signs in Germany*. FGSV 329/2; 2005.

[18] Japan National Road Marking Committee. *Road Sign Manual*. Japan Construction Provincial Road Bureau, Police Department Traffic Bureau; 2004.

[19] Brown JA. *Signing for dual exit lanes*. Florida Department of Transportation, Tallahassee. Letter report, 1991.

[20] Qiao F, Liu X, Yu L. Using driving simulator for advance placement of guide sign design for exits along highways. *Proceedings of the Driving Simulator Conference (DSC) 2007 North America in Iowa City*; 2007. p. 12-14.

[21] Guo TY, Deng W, Hou J, Lu J. Placement distance of freeway exit advance guide sign and its safety impacts. *Journal of Southeast University (English Edition)*. 2010;26(4): 622-627.

[22] Liu WM, Deng RF, Zhang Y, Zhuang YH. Setting model of safe distance of advance guide signs at highway exits. *Journal of South China University of Technology (Natural Science Edition)*. 2013;41(2): 37-43.

[23] Zhu ZB, Guo TY, Pan S. A placement distance model for advance guide signs to expressway exits. *Journal of Transport Research*. 2018;4(1): 44-50.

[24] Roess RP, Prassas ES, Mcshane WR. *Traffic Engineering*. 3rd ed. Upper Saddle River, NJ: Pearson Education; 2004. p. 19-23.

[25] National Bureau of Quality and Technical Supervision. *Highway Technical Standard*. China Communications Press; 2014.

[26] Transportation Research Board. *Highway Capacity Manual*. Washington, D.C.: National Research Council; 2010.

[27] American Association of State Highway & Transportation Officials. *Geometric Design of Highways and Streets*; 2004.

[28] Johansson G, Rumar K. Drivers' brake reaction times. *Human Factors: The Journal of the Human Factors and Ergonomics Society*. 2007;13(1): 23-27. doi: 10.1177/001872087101300104.

[29] Ministry of Transport of the People's Republic of China. *Design Specification for Highway Alignment (JTG D20-2017)*. China Communication Press; 2017.

[30] Chen J, Shao HP. A study on fading pattern of drivers' short-term memory of traffic signs. *Journal of Highway (Chinese Edition)*. 2011;29(7): 32-37.