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Placement distance of freeway exit advance guide sign and its safety impacts

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Abstract: To remedy the empirical pitfalls of current chinese specifications and MUTCD 2009 guidelines in determining the placement distance of freeway exit advance guide signs, the driving maneuver of exiting traffic is analyzed and the factors influencing placement distance are explored. Variables including the number of lanes, lane width, lane-changing time, driver's visual characteristics, sign installation methods and operating speeds on both freeway mainlines and exit ramps are found significant in explaining exit safety. Three different installation methods, namely ground installation, overhead installation and median installation, are introduced and their applicable conditions are given. Models, with the same structure among the three installation methods, are developed to compute the placement distance under different roadway geometric and traffic conditions. Taking overhead installation as an example, simulation results in TSIS-CORSIM show that the proposed distance reduces the number of lane changes in the area from the ramp nose to 500 m upstream by 58.93% compared with current Chinese specifications and 27.35% compared with MUTCD 2009 guidelines. Thus, the distances recommended in this paper have a better safety performance.

Key words: freeway; advance guide sign; placement distance; safety impact; lane change

Advance guide signs (AGSs) play a crucial role in informing drivers of the exits, directing them to destinations, and giving such general information as to help them drive in the most simple and direct manner. The major emphases of freeway AGSs are laid on destinations and distances, which are repeatedly provided in advance of exit ramps[1]. Among these repeated AGSs, the one closest to the exit is the most important due to the fact that if a careless driver misses this sign, there are no more signs informing him of his target exit. Proper location and installation of AGSs are important in helping drivers find their exact exits on unfamiliar freeways and avoid problems such as missing the exit, swerving abruptly, changing lanes sharply and other erratic maneuvers.

According to MUTCD 2009, there are three installation methods of AGSs, namely ground installation, overhead installation and median installation, among which the former two are often used and the other occasionally[2]. Where and how to install the AGS depends on land use, geometric design and traffic condition[3-4]. If there are more than three lanes on a freeway mainline, overhead installation is desirable. If the requirement for sight distance cannot be met using ground installation, overhead or median installation is preferable. Median installation is particularly suitable for left-side exit ramps[5-6].

As for the placement distance, there is little research to refer to. On the freeways of China, AGSs are repeatedly placed three times, generally 500, 1 000, and 1 500 m in advance of the ramp nose[7]. In MUTCD 2009, interchanges are classified into two categories: major/intermediate interchange and minor interchanges. The placement distances and repeated times of AGSs are determined according to the sizes of the interchanges. For major/intermediate interchanges, three AGSs should be installed, with the first sign 0.5 mile (0.8 km), the second sign 1 mile (1.5 km), and the third 2.0 miles (3.0 km) in advance of the ramp nose. For minor interchanges, only one AGS is required to be installed with 0.5 to 1.0 mile (0.8 to 1.5 km) in advance of the ramp nose[2]. From the current specifications in China and the guidelines in MUTCD 2009, one can see the following three weaknesses: 1) Both the guidelines are empiricism-based; 2) In China, placing AGSs at a fixed distance in advance of the ramp nose is lack of flexibility; 3) In MUTCD 2009, determining the placement distance and the number of AGSs according to the size of an interchange is arbitrary.

Aiming at minimizing the weaknesses mentioned above, we present models for the placement distance of three different AGS installation methods, considering lane-changing behavior, geometric design, and traffic conditions.

1 Analysis of Exiting Driving Maneuver

In Fig. 1, an east-west bound freeway on a level terrain intersects a north-south bound arterial by an exit ramp, with the rightmost lane directing an exit ramp to the crossroad. There is an exit sign indicating the distance from the ramp nose to the first AGS, which is the closest one to the ramp nose. The primary objective of this paper is to determine this placement distance, labeled with D_p in Fig. 1. The sign locations of three different installation methods are shown in Fig. 1, ① for ground installation, ② for overhead installation and ③ for median installation.

While modeling the AGS placement distance, we should consider the most adverse scenario to ensure safety. In the proposed model, we assume that the driver who expects to leave the freeway mainline is on the leftmost lane indicating

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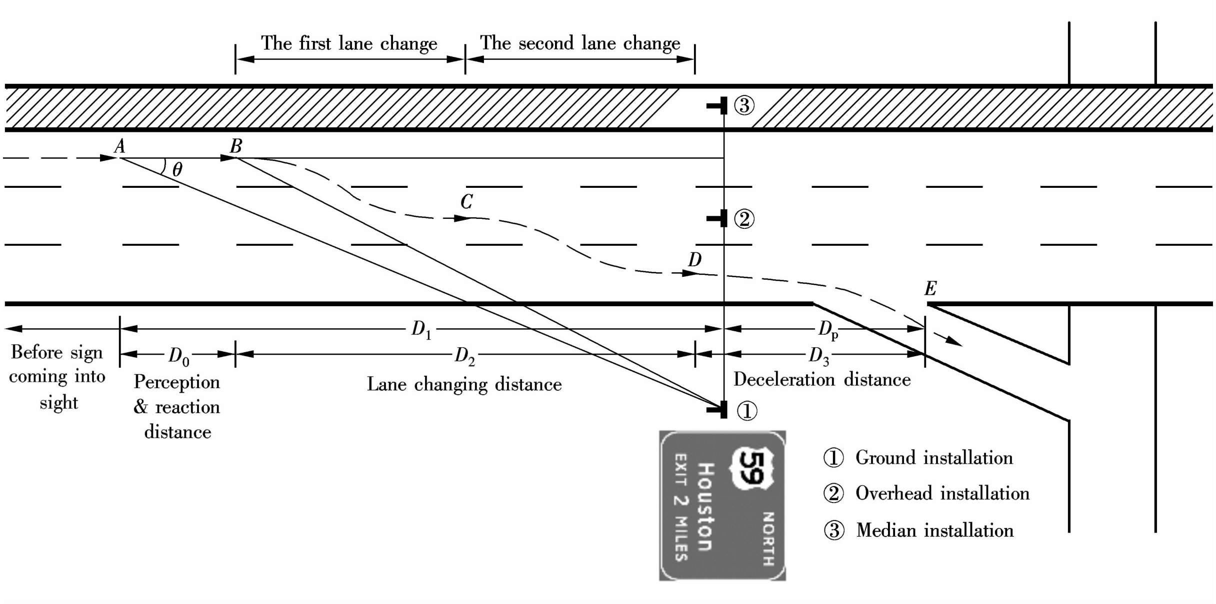

Fig. 1 Schematic diagram of driving maneuver after seeing the first advance guide sign

that he needs to make the maximum number of lane changes[8]. During the exiting process, there are five critical points, which are labeled with *A*, *B*, *C*, *D* and *E*. The dashed curve represents the driver's driving trajectory. Before reaching point *A*, the driver does not see the AGS informing him of the exit. He is driving in his normal desired pattern. At point *A*, the AGS comes into his sight. After seeing the AGS, he perceives that he is approaching his destination exit and he makes his decision to change lane. D_0 represents the distance traveled during the perception-reaction process.

After passing point *B*, the driver begins to look at his rearview mirror and right side-view mirror to search for an acceptable gap to make his lane change. Three different types of behavior, namely, normal, aggressive and courtesy lane-change, are often expected in diverging areas[9]. The average time required for a single lane change varies among these driving behaviors. In Fig. 1, the driver completes a single lane change during his driving from point *B* to point *C*. If there are more than two lanes on the freeway mainline, the drive needs to make more than one lane change to reach his target lane. We assume that after finishing his first lane change the driver does not need any more perception reaction time to start up his second lane change. If the number of lanes on the freeway mainline is N, $N-1$ lane changes is required. If the driving distance during a single lane change is L, $(N-1)L$ is the total driving distance from the leftmost lane to the rightmost lane. In Fig. 1, D_2 represents the driving distance during the whole lane-changing maneuver.

After moving onto the rightmost lane, the driver slows down and adjusts his speed to coordinate with the speed on the ramp. Given the operating speed V_1 on the mainline and V_2 on the exit ramp, the distance traveled during the deceleration process is D_3 as shown in Fig. 1.

2 Influential Factors

Important factors affecting the placement distance of an AGS include lateral offset, vertical offset, the number of lanes, lane-changing time, driver perception-reaction time, driving speed, and the driver's visual characteristics. Assumptions on these parameters are verified as follows.

Proper lateral and vertical placement of an AGS can improve sign visibility and reduce the probability of being hit by vehicles leaving the roadway[10]. In practice, the guide signs should be installed at a safety location to satisfy both lateral offset and vertical offset requirements to minimize possible impact forces. According to MUTCD 2009, Section 2A. 19 and 2E. 26, the minimum lateral clearance for ground or overhead guide signs shall be 6 ft (1. 8 m). Section 2A. 18 states that overhead signs shall provide a vertical clearance of not less than 17 ft (5. 2 m)[2]. However, none of the offsets is specified for China freeways.

The perception-reaction process consists of four distinct behaviors: detection, identification, decision and response, which the driver must perform after seeing the sign and before taking lane-changing action. The total amount of time needed is called perception-reaction time T_{PR}, which is affected by the driver's age, the driver's fatigue, driving speed, traffic conditions, etc. Previous study shows that an increase of 5 mile/h (8 km/h) results in a decrease of 0. 2 s of reaction time. To some engineers' experience, T_{PR} is about 2. 5 s while driving at 70 mile/h (110 km/h), which is the most common speed limit on the freeways in the USA[11]. Tab. 1 shows the relationship between T_{PR} and V_1. The corresponding driving distance D_0 is also given.

Lane-changing time is also important in designing the placement distance of an AGS. Finnegan and Green[12] conducted research on lane-changing behavior and found that the average visual search time for preparing a lane change is as much as 3. 7 s without traffic and as much as 6. 1 s with

Tab. 1 Relationship between perception-reaction time and speed

Driving speed on freeway V_1/(km · h^{-1})	Perception-reaction time T_{PR}/s	Perception-reaction distance D_0/m
60	3. 80	63. 33
70	3. 55	69. 03
80	3. 30	73. 33
90	3. 05	76. 25
100	2. 80	77. 78
110	2. 55	77. 92
120	2. 30	76. 67

traffic. They suggested that 6.6 s should be allowed for the visual search associated with a single lane change and 1.5 s to execute the lane-change. Salvucci et al.[13] also studied the driving behavior before, during and after the lane-changing based on driver eye-moment behavior and concluded that the time averaged 5.14 ± 0.86 s per lane change.

Drivers' visual characteristics are also considered while modeling. We assume that sign reading and comprehension need to be completed before the maximum degree of the cone of fairly clear vision expires, and then lane-changing could take place. Most people have clear vision within a conical angle of 3° to 10° and fairly clear vision within a conical angle of 10° to 12°. Here, the cone of vision of 10° is assumed for convenience[11].

3 Methodology

According to Fig. 1, the placement distance D_p can be calculated by

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

where D_0, D_2 and D_3 represent the perception-reaction distance, the lane-changing distance and the deceleration distance, respectively, m; D_1 is the distance between the AGS and the driver's position right after the cone vision angle is developed in reading the sign.

According to Tab. 1, we can deduce the relationships among D_0, T_{PR} and V_1 as follows:

$$T_{PR} = 2.80 - \frac{0.2(V_1 - 100)}{8} = 5.300 - 0.025V_1 \tag{2}$$

$$D_0 = V_1 \frac{T_{PR}}{3.6} = 1.472V_1 - 0.00694V_1^2 \tag{3}$$

To determine D_2, we simply assume that successive lane changes have a uniform time distribution with a mean value of T, and that the speed is constant as of V_1. So the length for $(N-1)$ lane changes is

$$D_2 = (N-1)V_1 \frac{T}{3.6} \tag{4}$$

The deceleration distance D_3 travelled while speed reduces from V_1 on the mainline to V_2 on the ramp is

$$D_3 = \left(\frac{1}{3.6}\right)^2 \frac{V_1^2 - V_2^2}{2g(f+G)} = \frac{V_1^2 - V_2^2}{254(f+G)} \tag{5}$$

where g is the gravitational constant (9.8 m/s^2); f represents the coefficient of the skidding friction between tires and the road pavement; and G stands for the grade, positive for upward and negative for downward.

Different installation methods have the same D_0, D_2 and D_3 but different D_1.

1) For ground installation,

$$D_1 = ((N-0.5)L_w + L_o)\cot\theta \tag{6}$$

2) For overhead installation, D_1 should meet the requirements for both lateral offset and vertical offset. For convenience, we assume that drivers have a uniform vision distribution within the conical angle.

Considering lateral offset to meet vision requirement,

$$D_1^1 = (N-1)L_w\cot\theta \tag{7}$$

Considering vertical offset to meet vision requirement,

$$D_1^2 = V_o\cot\theta \tag{8}$$

If $D_1^1 \geqslant D_1^2$, $D_1 = D_1^1$; otherwise, $D_1 = D_1^2$.

3) For median installation,

$$D_1 = (0.5L_w + 0.5M_w)\cot\theta \tag{9}$$

In Eqs. (6) to (9), L_w and M_w denote lane width and median width, respectively, m; L_o and V_o represent lateral offset and vertical offset, respectively, m; θ is the cone vision angle for the driver to read the sign clearly. After obtaining the value of D_0, D_2, D_3, and D_1, we can obtain the placement distance using Eq. (1). Thus, the first AGS should be mounted at least $(D_0 + D_2 + D_3 - D_1)$ m in advance of the ramp nose.

4 Case Study

Assume that there are four lanes on a freeway mainline with a lane width of 3.75 m and a median width of 3.0 m. The lateral offset for the ground mounted AGS is 2.0 m and the vertical offset for the overhead installation is 5.0 m, which is warranted by MUTCD 2009. The speed limit on the mainline and the exit ramp are 120 and 50 km/h, respectively. We suggest 8.1 s for a single lane change, which is supported by Finnegan's research. A cone of vision of 10° is assigned for convenience. All the model parameters are summarized as follows: $N=4$; $L_w = 3.75$ m; $M_w = 3.00$ m; $L_o = 2.00$ m; $V_o = 5.00$ m; $V_1 = 120$ km/h; $V_2 = 50$ km/h; $\theta = 10°$; $T_{PR} = 2.30$ s, $T = 8.10$ s; $G = 0.00$; $f = 0.28$ for a speed at 120 km/h.

According to the models and parameters proposed above, D_0, D_2 and D_3 are the same as follows for the three installation methods:

$$D_0 = V_1 \frac{T_{PR}}{3.6} = 76.67 \text{ m}$$

$$D_2 = (N-1)V_1 \frac{T}{3.6} = 810.00 \text{ m}$$

$$D_3 = \frac{V_1^2 - V_2^2}{254(f+G)} = 167.32 \text{ m}$$

For ground installation, $D_1 = 85.78$ m. According to Eq. (1), the AGS should be mounted at least 968.21 m in advance of the ramp nose. For an overhead installation, $D_1^1 = 63.80$ m; $D_1^2 = 28.36$ m. As $D_1^1 > D_1^2$, $D_1 = 63.80$ m. So the AGS should be placed at least 990.19 m in advance of the ramp nose. For a median installation, $D_1 = 19.14$ m. The AGS should be installed at least 1 031.85 m in advance of the ramp nose.

The minimum placement distances of the three installation methods under different scenarios (V_1 ranges from 60 to 120 km/h; V_2 ranges from 30 to 60 km/h; and the number of lanes ranges from 2 to 5) are given in Tabs. 2 to 4. The values in the parentheses (rounded up to hundreds of meters)

Tab. 2 Minimum placement distance of AGS for ground installation m

N	Operating speed on freeway/(km·h^{-1})	Operating speed on ramp/(km·h^{-1})						
		60	70	80	90	100	110	120
2	30	193(200)	240(300)	287(300)	337(400)	387(400)	440(500)	493(500)
	40	183(200)	230(300)	278(300)	327(400)	378(400)	430(500)	483(500)
	50	171(200)	217(300)	265(300)	314(400)	365(400)	417(500)	471(500)
	60	155(200)	202(300)	249(300)	299(300)	350(400)	402(500)	455(500)
3	30	307(300)	376(400)	446(500)	518(600)	591(600)	666(700)	742(800)
	40	297(300)	366(400)	436(500)	508(600)	581(600)	656(700)	732(800)
	50	284(300)	353(400)	424(500)	495(500)	569(600)	643(700)	719(800)
	60	269(300)	338(400)	408(500)	480(500)	553(600)	628(700)	704(800)
4	30	421(500)	512(600)	605(700)	699(700)	795(800)	892(900)	991(1 000)
	40	411(500)	502(600)	595(600)	689(700)	785(800)	882(900)	981(1 000)
	50	398(400)	489(500)	582(600)	677(700)	772(800)	870(900)	968(1 000)
	60	383(400)	474(500)	567(600)	661(700)	757(800)	854(900)	953(1 000)
5	30	534(600)	648(700)	764(800)	880(900)	999(1 000)	1 118(1 200)	1 239(1 300)
	40	524(600)	638(700)	754(800)	871(900)	989(1 000)	1 109(1 200)	1 230(1 300)
	50	512(600)	626(700)	741(800)	858(900)	976(1 000)	1 096(1 100)	1 217(1 300)
	60	496(500)	610(700)	726(800)	842(900)	961(1 000)	1 080(1 100)	1 201(1 300)

Tab. 3 Minimum placement distance of AGS for overhead installation m

N	Operating speed on freeway/(km·h^{-1})	Operating speed on ramp/(km·h^{-1})						
		60	70	80	90	100	110	120
2	30	208(300)	254(300)	302(400)	352(400)	402(500)	455(500)	508(600)
	40	198(200)	245(300)	292(300)	342(400)	393(400)	445(500)	498(500)
	50	185(200)	232(300)	280(300)	329(400)	380(400)	432(500)	486(500)
	60	170(200)	216(300)	264(300)	314(400)	364(400)	417(500)	470(500)
3	30	329(400)	398(400)	468(500)	540(600)	613(700)	688(700)	764(800)
	40	319(400)	388(400)	458(500)	530(600)	603(700)	678(700)	754(800)
	50	306(400)	375(400)	446(500)	517(600)	591(600)	665(700)	741(800)
	60	291(300)	360(400)	430(500)	502(600)	575(600)	650(700)	726(800)
4	30	442(500)	534(600)	627(700)	721(800)	817(900)	914(1 000)	1 013(1 100)
	40	433(500)	524(600)	617(700)	711(800)	807(900)	904(1 000)	1 003(1 100)
	50	420(500)	511(600)	604(700)	699(700)	794(800)	892(900)	990(1 000)
	60	405(500)	496(500)	589(600)	683(700)	779(800)	876(900)	975(1 000)
5	30	556(600)	670(700)	786(800)	902(1 000)	1 021(100)	1 140(1 200)	1 261(1 300)
	40	546(600)	660(700)	776(800)	893(900)	1 011(1 100)	1 130(1 200)	1 252(1 300)
	50	534(600)	648(700)	763(800)	880(900)	998(1 000)	1 118(1 200)	1 239(1 300)
	60	518(600)	632(700)	748(800)	864(900)	983(1 000)	1 102(1 200)	1 223(1 300)

Tab. 4 Minimum placement distance of AGS for median installation m

N	Operating speed on freeway/(km·h^{-1})	Operating speed on ramp/(km·h^{-1})						
		60	70	80	90	100	110	120
2	30	217(300)	264(300)	312(400)	361(400)	412(500)	464(500)	517(600)
	40	207(300)	254(300)	302(400)	351(400)	402(500)	454(500)	508(600)
	50	195(200)	241(300)	289(300)	338(400)	389(400)	441(500)	495(500)
	60	179(200)	226(300)	274(300)	323(400)	374(400)	426(500)	479(500)
3	30	352(400)	421(500)	492(500)	563(600)	637(700)	711(800)	787(800)
	40	342(400)	411(500)	482(500)	554(600)	627(700)	701(800)	778(800)
	50	330(400)	399(400)	469(500)	541(600)	614(700)	689(700)	765(800)
	60	314(400)	383(400)	454(500)	525(600)	599(600)	673(700)	749(800)
4	30	487(500)	579(600)	672(700)	766(700)	862(900)	959(1 000)	1 057(1 100)
	40	477(500)	569(600)	662(700)	756(700)	852(900)	949(1 000)	1 048(1 100)
	50	465(500)	556(600)	649(700)	743(700)	839(900)	936(1 000)	1 035(1 100)
	60	449(500)	541(600)	634(700)	728(700)	824(900)	921(1 000)	1 019(1 100)
5	30	622(700)	736(800)	852(900)	968(1 000)	1 087(1 100)	1 206(1 300)	1 327(1 400)
	40	612(700)	726(800)	842(900)	959(1 000)	1 077(1 100)	1 196(1 200)	1 318(1 400)
	50	600(600)	714(800)	829(900)	946(1 000)	1 064(1 100)	1 184(1 200)	1 305(1 400)
	60	584(600)	698(700)	814(900)	930(1 000)	1 049(1 100)	1 168(1 200)	1 289(1 300)

are recommended for engineering practice.

5 Comparison Analysis of Safety Impact

The parameter named off-ramp reaction point in TSIS-CORSIM makes it possible to simulate the safety impact of the placement distance of the AGS. Taking the number of lane changes as a measure of effectiveness, we compare the safety performance of three placement distances: the distance proposed in this paper, the distance specified in China, and the distance recommended in MUTCD 2009.

We assume four lanes on the freeway mainline and one lane on the exit ramp. During the peak hour from 17:00 to 18:00, a total volume of 7 200 veh/h is assigned to the network, with 1 800 veh/h on each lane for simplicity. The free flow speed on the mainline and the ramp is 110 and 50 km/h, respectively. We take the most commonly used installation method, overhead, as an example. According to Tab. 3, the first AGS should be mounted at least 900 m in advance of the ramp nose. The placement distance is specified as 500 m in current China and 800 m (0.5 mile) in MUTCD 2009. Three corresponding freeways, named "proposed", "China" and "MUTCD", are created with the only difference being in placement distance. In TSIS-CORSIM, we set the value of the off-ramp reaction point equal to the placement distance, which is 900, 800, and 500 m for "proposed", "China", and "MUTCD", respectively. The "MUTCD" freeway is a 500 m segment plus a 300 m segment, and the "proposed" freeway is the sum of a 500 m segment and a 400 m segment. By doing this we can compare not only the total number of lane changes but also the number of lane changes within the area 500 m upstream of the ramp nose. The number of lane changes occurring on each segment are summarized in Tab. 5 and Fig. 2.

Tab. 5 Number of lane changes generated by different AGS installation methods

Time	China (500 m)	MUTCD (800 m)			Proposed (900 m)		
	500 m	500 m	300 m	Total	500 m	400 m	Total
17:00	0	0	0	0	0	0	0
17:06	284	183	148	331	112	161	273
17:12	347	153	154	307	150	199	349
17:18	367	183	151	334	142	220	362
17:24	368	187	121	308	130	233	363
17:30	300	207	163	370	127	166	293
17:36	320	170	145	315	135	229	364
17:42	318	172	157	329	138	215	353
17:48	300	183	172	355	142	204	346
17:54	310	193	162	355	98	230	328
18:00	332	190	150	340	149	189	338
Total	3 246	1 821	1 523	3 344	1 323	2 046	3 369

One can see that the three freeways produce almost the same total number of lane changes, although the distances vary from 500 to 900 m. On average, the number of lane changes occurring on a 100 m segment is 3.74, 4.18 and 6.49 for "proposed", "MUTCD", and "China" freeways, respectively. The AGS, installed overhead according to the distance proposed in this paper, generates the least number of lane changes per 100 m, which is 89.47% and 57.62% of that from the "MUTCD" and the "China" freeways. On the segment from the ramp nose to 500 m upstream, the number of lane changes produced by "proposed", "MUTCD" and "China" freeways are 1 323, 1 821 and 3 246. If the AGS installed based on the distances suggested in this paper, the number of lane changes will be reduced by 27.35% compared with the MUTCD guidelines and 58.93% compared with China specifications. The "proposed" freeway still possesses superiority over the other two.

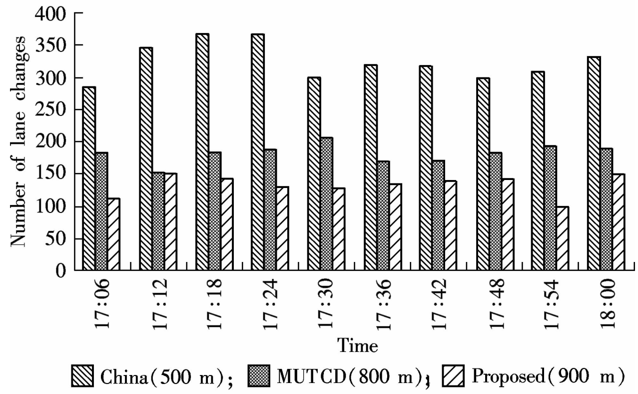

Fig. 2 Number of lane changes on segment from ramp nose to 500 m in advance

More lane changes concentrating on a shorter freeway segment not far away from the exit ramp nose increase the probability of a crash occurrence, together with worse operational performance, such as lower speed, more delay, lower fuel efficiency and higher exhaust emission. To improve this situation, installing more than one AGS is a highly recommended alternative.

6 Discussion and Conclusions

Regardless of geometric conditions, traffic conditions and drivers' visual characteristics, the guidelines currently applied in China and MUTCD 2009 do not satisfy the minimum distance requirement when the number of lanes and the speed increases. From Tabs. 2 to. 4, when the number of lanes is 2, almost all the placement distances are less than 500 m. When the number of lanes is 3, and the operating speed on the mainline is over 80 km/h, the minimum placement distances range from 500 to 800 m. When the number of lanes is more than 3, and the operating speed on the mainline is over 100 km/h, the minimum placement distances exceed 800 m.

Based on the proposed models and the comparison analysis above, we can draw the following conclusions:

1) The placement distances suggested by current Chinese specifications and MUTCD 2009 guidelines may fail to meet the minimum distance requirements when the number of lanes is more than 3 and the operating speed on the freeway mainline exceeds 100 km/h.

2) The placement distance of the AGS relates to roadway geometry, operating speed, drivers' visual charateristics and installation methods. The required minimum distance increases with the increase in the number of lanes and the increase in the operating speed on the freeway mainline.

3) Adoption of the placement distance as summarized in Tabs. 3 to 5 lessens the number of lane changes occurring on the segment from the ramp nose to upstream 500 m by

27.35% compared with MUTCD 2009 guidelines and 58.93% compared with current China specifications.

4) Installation of repeated AGSs improves the safety performance in diverging areas.

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高速公路前置指路标志设置距离及其安全影响

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摘要: 为弥补我国现行规范和美国 MUTCD 2009 关于高速公路前置指路标志设置距离经验主义的缺陷,首先分析了驾驶员驶离主线驾驶行为及前置指路标志设置距离的影响因素.车道数、车道宽度、车道变换时间、驾驶员的视觉特性、标志牌的架设方式以及主线和匝道上的运行速度对出口匝道安全性有显著影响.介绍了前置指路标志的 3 种架设方式,即路边直立式、路上横跨数和中央架设式,并给出了各自的适用条件.然后建模计算了不同道路几何条件和交通条件下各安装方式的设置距离,3 种安装方式具有相同的模型结构.最后以路上横跨式为例,TSIS-CORSIM 模拟结果表明,所给模型计算的设置距离在分流鼻上游 500 m 范围内产生的车道变换数较少,比我国的现行规范少 58.93%,比 MUTCD 推荐值少 27.35%,因而具有更好的安全性能.

关键词: 高速公路;前置指路标志;设置距离;安全影响;车道变换

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