Study on Merging Sign Installation in work zone of Expressway Based on Changeable Critical Headway

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Abstract

The purpose of this research was to consider the vehicles' changeable critical headway when driving along the upper work zone, and reducing conflicts and risks by merging in the end of the warning area, via installation of merging signage. A merging probability model was established by differential methods according to the M3 model and headway acceptance theory. According to the model, the appropriate position of merging signs was calculated in different traffic conditions. The influence of the merging probability by traffic parameters was analyzed, which indicated that the distance of merging signs had a positive correlation with the traffic volume; the distance of merging signs had a negative correlation with the proportion of free flow in the major lane; the distance of merging signs had a positive correlation with the vehicles' speed in the major lane; the establishing of merging signs should be combined with the speed limiting.

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1. Introduction

The accident ratio in work zones of expressway is rising in recent years in China, rising from 1.5% to 5~7% in all traffic accidents in 2010. Closing part of the roadway is commonly applied in surface maintenance of expressway, which is at high safety risk because of heavy traffic flow and complicated field environment. Pigman and Agent (1990) noted that the traffic accidents were mainly due to the poor sign and management of work zones on the expressway. Ha and Nemeth (1995) claimed that the unnecessary traffic accident can be avoided by improving the traffic control facilities according to the studies on the characteristics of traffic accidents in work zones.
zones. HE Xiao-zhou (2005) divided the control areas of the work zone on the expressway and clarified the functions and characteristics of these control areas.

In recent safety control for work zone on expressway, the “construction ahead”, “lane close” and “speed limit” signs were established to advise the drivers to move and choose the lane. The vehicles in the closed lane (called minor lane in the paper) will change the lane into the accessible lane (called major lane in the paper) when approaching the end of the alarm area, where the drivers seek an acceptable headway to merge. Due to indeterminate direction for merging, the drivers can only make the decision according to his observation and experience. The merging will be difficult if the decision is too late, which will increase the risk of accidents. The concept of merging sign was proposed, for direct the drivers to start observing and merging as illustrated in Fig. 1:

![Diagram of merging sign establishing in work zone of expressway](image)

**Fig. 1 Merging Sign Establishing in Work Zone of Expressway**

2. Vehicles’ Merging Model and Probability Distribution

The headway acceptance theory is widely applied in the traffic capability and merging model of the unsignalized intersections and roundabouts, which supposes that the vehicles in the minor lane will make merging when the headway in the major lane becomes more than an certain value (called critical headway), or the vehicles will wait for the headway. The bunched exponential distribution (M3) is a traditional distribution model of the headway in the major lane, which divides the traffic flow into two parts: free flow and bunched flow. The negative exponential distribution and shifted negative exponential distribution can be regarded as specific form of the bunched exponential distribution. The Cowan M3 model is applied in this paper and the distribution of the model is: (R. Tapio Luttinen, 1999)

\[
F(t) = \begin{cases} 
1 - \varphi e^{-\lambda(t-\tau)} & t \geq \tau \\
0 & t < \tau 
\end{cases}
\]

In the Equation (1), \( \lambda = \varphi q / (3600 - q \tau) \); \( q \) is the traffic volume of the major lane, veh/h; \( \varphi \) is the proportion of free flow in the major lane; \( \tau \) is the minimum headway, s. The model is a shifted negative exponential distribution when \( \varphi = 1 \); The model is a negative exponential distribution when \( \varphi = 1 \) and \( \tau = 0 \).

The choice of drivers' critical headway will be influenced by many factors, and in this paper it is supposed that all the driving’s estimation of safety merging headway is unified in the merging area. When the vehicle approaches the end of the warning area, a preliminary estimation of merging headway will be made by the driver,
called as the initial critical headway. The driver will decide to drive into the major lane when headway is more than the critical headway, otherwise he will move on, waiting for an acceptable headway. If the traffic is light, the driver can easily gain an acceptable headway to merging, but when the traffic is heavy, the probability of the same headway occurring will be reduced and the drivers have to move farther to gain the opportunities. As the vehicle approaching to the transition area, the driver will be more and more worried that the vehicle cannot merge into the major lane. In this case, the drivers’ acceptable critical headway will be reduced gradually. When the vehicles have arrived the end of alarm area, there will be a minimum headway for the drivers to make merging, which is called as minimum critical headway \( T_0 \) (equals to \( T \)), and it is supposed that the critical headway varies linearly along the distance of \( l \). (GUAN Yu and ZHANG Ning, 2010) It is supposed that the initial acceptable headway is \( T_c \), and the relationship of critical headway \( t_c \) and the distance from the vehicle to the end of alarm area \( l \) is illustrated in Fig.2:

![Figure 2](image_url)

Fig.2 Relationship between driving distance in minor lane and critical headway

The equation of the relationship of \( t_c \) and \( l \) is following:

\[
t_c(l) = \left( \frac{T_c - T_0}{L} \right) l + T_0
\]  

(2)

Let \( \beta = \left( \frac{T_c - T_0}{L} \right) \) and the equation can be modified as following:

\[
t_c(l) = \beta l + T_0
\]  

(3)

According to the M3model of Equation (1), the probability that the merging headway in \( l \) is more than the critical headway \( t_c \) is following:

\[
P(t \geq t_c(l)) = 1 - P(t < t_c(l)) = 1 - F(t_c(l)) = \varphi e^{-\beta l}
\]  

(4)

It is proposed that the merging probability of the vehicles in \( x = l - \Delta l \) is \( P(l - \Delta l) \), and the differential method is applied: (LI Shuo and ZHANG Yang, 2000)

\[
P(l - \Delta l) = P(l) - (1 - P(l)) \cdot P(t \geq t_c(l)) \cdot \Delta t
\]  

(5)

In the Equation(5), \( \Delta t \) is the time for the vehicles moving from \( l \) to \( (l - \Delta l) \), s. It is supposed that the vehicles are moving at speed of \( v \) (m/s), so \( \Delta l = v \cdot \Delta t \), and Equation (5) can be modified as following:

\[
\frac{P(l - \Delta l) - P(l)}{-\Delta l} = (1 - P(l)) \cdot \frac{P(t \geq t_c(l))}{v}
\]  

(6)

Equation (6) was calculated by a limit of \( \Delta l \to 0 \) as following:
After solving the first order linear differential equation (7), the probability function in Equation (3) was applied. According to the physical explanation that when the distance \( l \rightarrow L \), the merging probability \( P(L) = 0 \), the expression of the accumulated merging probability \( P(l) \) is following:

\[
P(l) = 1 - \exp\left[ -\frac{\varphi}{\nu \lambda \beta} (e^{-\lambda \beta l} - e^{-\lambda \beta L}) \right]
\]  

(8)

3. Application and Discussion

According to the cumulative probability model, the merging results on different traffic conditions can be calculated and analysed, and the model relates to these following parameters: the proportion of free flow in the major lane, \( \varphi \); the traffic volume of the major lane, \( q \); the minimum critical headway, \( T_0 \); changeable critical headway, \( T_c \); the distance from the merging sign to the end of alarm area, \( L \); the vehicles’ speed in the major lane, \( v \). \( T_0 \) and \( T_c \) were the driving parameters, which can be determined by tests; \( \varphi \) and \( q \) were the traffic characters, varying according to the road and time; \( L \) and \( v \) is the work zone parameters, according to the work zone design. Therefore the merging probability of different position \( l \) can be calculated according to the work zone conditions, which is illustrated in the Fig.3. \( q = 1200 \text{veh/h}, \ T_c = 5 \text{s}, \ T_0 = 2 \text{s}, \ \nu = 22.2 \text{m/s (80km/h)}, \ \varphi = 0.5: \)

![Graph showing merging probability of different positions](image)

Fig.3 Merging probability of different positions

As is shown in Fig.3, the merging probability in position \( l \) will increase as the establishing distance \( L \) expands. However, a large value of \( L \) will cause drivers to forget and ignore, which has a similar character with the design of the warning area. Considering the service effect, what is more focused on by the engineers is that weather the merging sign meets the traffic requirements, as to decrease the conflicts and accident risks.

So the focus is not the prediction of merging possibility but the suitable distance for merging in the design of work zone on different traffic conditions, according to the safety management. The establishing criterion in this
paper is that the merging probability in the end of the alarm area should be 0.85 \( P(0) = 0.85 \). According to this criterion, the calculated equation of establishing distance \( L \) should be this:

\[
P(0) = 1 - \exp\left[\frac{v}{\nu\lambda} \left(1 - e^{-\lambda L}\right)\right] = 0.85
\]

\[
\exp\left\{ -\frac{vL}{\nu\lambda (T_c - T_0)} \left[1 - e^{-\lambda (T_c - T_0)}\right] \right\} = 0.15
\]

\[
L = -\frac{\ln 0.15}{[1 - e^{-\lambda (T_c - T_0)}]v\lambda (T_c - T_0)}
\]

\[
L = \frac{1.897v\nu q(T_c - T_0) / (3600 - q\tau)}{[1 - e^{-\nu q(T_c - T_0)/3600 - q\tau}] v\nu}
\]

As defined that \( T_c = 5s \) and \( T_0 = 2s \), the calculated results according to the different value of parameters is illustrated in the Fig.3:

As is shown in Fig.4, when the proportion of free flow and the vehicles’ speed are the same, the distance of merging sign had a positive correlation with the traffic volume; when the traffic volume and the vehicles’ speed are the same, the distance of merging sign had a negative correlation with the proportion of free flow in the major lane; when the proportion of free flow and the traffic volume are the same, the distance of merging sign had a positive correlation with the vehicles’ speed in the major lane. Considering that the speed limit is the common control method to regulate the traffic flow, we should determine the establishing distance as well as the speed limit.
4. Conclusion

In this paper, the merging behavior in the end of alarm area of work zone was analysed, and a merging sign was proposed. According to the M3 distribution model and the acceptable headway theory, the merging possibility was calculated and the advised distance of the merging sign was given under different traffic conditions. The establishing was on the basis of a possibility of 85% and an acceptable headway of 2~5s, which should be determined in further research.

References

HE Xiao-zhou. Research on the traffic organization and simulation of work zone of expressway[D]. Southeast University. 2005