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Car-following model featured with factors reflecting emergency evacuation situation

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Abstract: A new emergency evacuation car-following model (EECM) is proposed. The model aims to capture the main characteristics of traffic flow and driver behavior under an emergency evacuation, and it is developed on the basis of minimum safety distances with parts of the drivers' abnormal behavior in a panic emergency situation. A thorough questionnaire survey is undertaken among drivers of different ages. Based on the results from the survey, a safety-distance car-following model is formulated by taking into account two new parameters: a differential distributing coefficient and a driver's experiential decision coefficient, which are used to reflect variations of driving behaviors under an emergency evacuation situation when compared with regular conditions. The formulation and derivation of the new model, as well as its properties and applicability are discussed. A case study is presented to compare the car-following trajectories using observed data under regular peak-hour traffic conditions and theoretical EECM results. The results indicate the consistency of the analysis of assumptions on the EECM and observations.

Key words: emergency evacuation; car-following; minimum safety distance; driving behavior

In areas threatened by disasters emergency evacuation contingency plans are required to prepare for an efficient evacuation. The problem of determining optimal evacuation routes out of a dangerous or harm zone can be modeled as a roadway network flow problem and can be integrated into a simulation system to exhibit the effects of the routing plan[1−2]. A variety of strategies have been developed to increase the speed of evacuation. Often this involves the use of evacuation simulation models. At the macroscopic level, NETVACI, MASSVAC, along with its successors (MASSVAC 3.0, MASSVAC 4.0 and TEDSS) developed in the 1980s and 1990s, are embedded with some static traffic assignment models to project the flow distribution during an evacuation[3−6]. From the mid 1980s, microscopic simulators emerged to be a widely used tool for evacuation planning. Examples of such systems include CEMPS, IMDAS, OREMS, and other practices[7−11]. The models supporting the development of microscopic evacuation analysis systems are used to describe individual vehicle travel behaviors and interactions between vehicles in a traffic stream under various scenarios. The car-following model is one of such supportive models. Despite tremendous efforts and considerable interest in the development of car-following models, they are generally refer to the understanding of traffic flow characteristics in general and observed phenomena in motorway traffic under regular traffic conditions[12−16]. Little research has been reported on car-following behaviors in emergency evacuation situations.

Car-following models are concerned with inter-vehicular dynamics in a single stream of traffic. In other words, a single-lane car-following model addresses speed-spacing relationships of vehicles following one another where there is no passing (neglecting all other subsidiary tasks such as steering, routing, etc.)[16]. It describes the movements of a following vehicle in response to the actions of the lead vehicle. The car-following models are conventionally classified into three categories: 1) Stimulus-based models; 2) Safety distance models; 3) Action point models[16]. The hypothesis of a stimulus-based model is based on the assumption that the acceleration of a following vehicle is determined by the driver's reaction to the speed and position differences to the vehicle in front[15]. The general motors (GM) models are typical stimulus-based models, which have been developed and improved since the late 1950s. One of the latest revised models was proposed by Ozaki[15]. The safety distance models are based on the assumption that the driver of the following vehicle adopts a speed and keeps at a distance at which he could bring his vehicle to a safe stop if the front vehicle maneuvers a sudden stop. The Gipps car-following model[17] is a typical safety-distance model. The action point models are based on the assumption that a driver's driving behavior vary depending upon the traffic state he is in for the concerned time step: whether he is driving freely, or approaching a vehicle in front, or following the vehicle in front or braking. The boundary conditions that define different states are usually indicated by a function of speed difference and relative distance to the vehicle ahead[18−19].

The literature review indicates that existing car-following models cannot really reflect drivers' abnormal reactions or behaviors under unusual traffic conditions. Some drivers will obtain different safety distances during an emergency situation, such as following too closely and the inability to control harmoniously. As a consequence, the space between preceding and following vehicles decreases while time headway between them increases. Mostly traditional car-following models are developed on the basic hypothesis that the space between preceding and following vehicles and time headway of each of them increases or decreases simultaneously. However, this hypothesis does not very well represent true traffic flow states and microscopic attributes of vehicles under

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emergency evacuation conditions. This paper aims to propose a new car-following model to better depict traffic flow and driver behavior characteristics under emergency evacuation conditions.

As a result of the literature review on analyses of the characteristics of normal car-following traffic situations and a questionnaire-based survey on driver responses and behaviors under an emergency evacuation, the emergency evacuation car-following model (EECM) is developed to depict the car-following behaviors under emergency situations. This paper presents the formulation and derivation of the new model, and discusses its properties and applicability. A case study is presented to compare the car-following trajectories using observed data on peak-hour traffic conditions and to validate the hypothesis and theoretical results of the EECM. The results effectively support the rationality of the EECM and the analysis of the questionnaires.

1 Development of Car-Following Featured with Evacuation Features

1.1 Analysis of car-following state under emergency evacuation traffic flow

Under the emergency evacuation situation, the car-following behavior refers to the driving behavior of the following vehicles. Apparently, the following vehicles will adjust their safety distances through closely observing the action taken by the preceding vehicles. The process can be depicted with a heuristic model, as illustrated in Fig. 1, and details are described as follows.

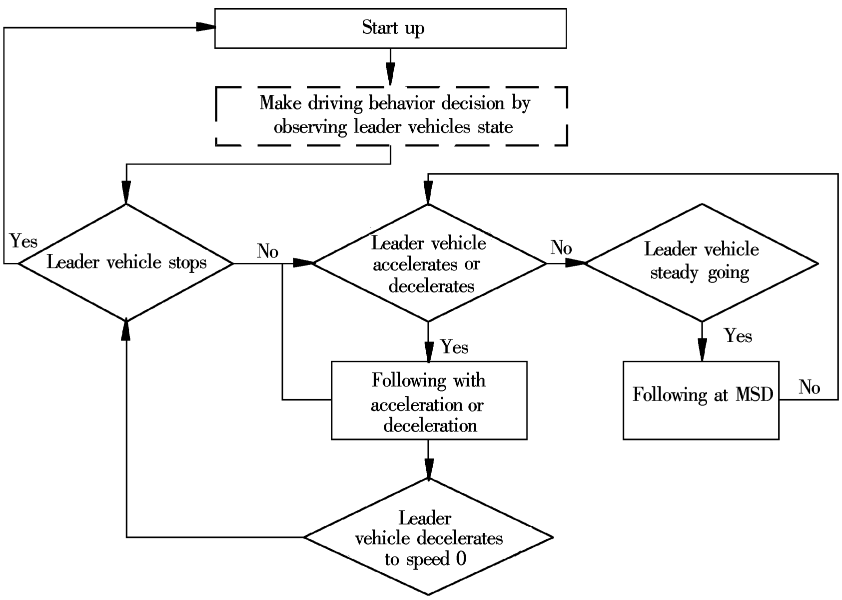

Fig. 1 Analysis of car following state during emergency evacuation

1) When a car-following process begins, the driver uses his/her experience to anticipate whether the space from the preceding vehicle is at a satisfactory safety distance. If the space is greater than the minimum safety distance, the driver will accelerate to be closer to the preceding vehicle until reaching the minimum safety distance and continue such a car-following maneuver.

2) If the preceding vehicle stops, the following vehicle will continue following at the minimum safety distance.

3) When the preceding vehicle accelerates or decelerates, the following vehicle will follow it with a similar acceleration or deceleration after short time interval to react and harmoniously maneuver. If the preceding vehicle decelerates until zero, the following vehicle will decelerate and stop at the minimum safety distance (back to state 1).

4) If the preceding vehicle is running at a steady speed, the following vehicle will follow it at the same steady speed in order to maintain the minimum safety distance from the preceding vehicle.

1.2 Car-following behaviors under emergency evacuation conditions

Traditional car-following models are mostly focused on the depiction of car following states through indicating the dynamics of a vehicle's movement in terms of speed, acceleration and position, few of them take into account the traffic environment and the influence of driver behavior differentia during the car-following state. When an emergency evacuation occurs, a severe increase in traffic demand may concentrate on the impacted roadways and invite unbearably heavy traffic. Under such conditions, the freedom of car-following maneuvers may become more constrained while aggressive driving behavior may increase. The preceding vehicles and/or following vehicles are suffering from the overload of traffic , and they cannot achieve their desired accelerations or decelerations under such conditions. As a consequence, a driver's ability to maintain desirable reaction time, driving behavior, and decision-making will be influenced by the panic due to emergency traffic constraints. The study of Li et al. [20] indicates that abruptness and indeterminism may be featured in more driving behaviors in an emergency traffic situation. This has great potential to cause traffic jams and arouse a driver's instincts to countermine the situation utilizing their common sense. Under such a situation, about 32% of the drivers would behave unusually or even extremely so while driving. Regarding car-following behavior, the following vehicle will very possibly be considerably close to the preceding vehicle while contending to scramble on the roadway. In this situation, the probability of traffic accidents caused by such "abnormal" driving behaviors would increase.

During a course of car-following, the spacing or headway from the preceding vehicle is controlled and determined by a driver's experience, which varies with the driver's driving habits and aggressiveness associated with his/her personality. When drivers were exposed in an emergency environment, most of them wanted to leave the emergency area as fast as possible while being influenced by panic and anxiety, and other negative psychological factors. Consequently, the level of a driver's ability to control his emotions and to maneuver will be much different from that under normal traffic conditions.

For the sake of avoiding the difficulties in conducting observations of emergency evacuation cases, a driving behavior survey was conducted via a questionnaire among 2 000 eligible drivers in Beijing. This survey was designed for the need of preparing emergency traffic plans for the Beijing 2008 Olympic Games. As a result, 1 800 valid respondents have been received, among which 1 370 are male drivers, and 430 are female drivers. The drivers' ages are from 18 to 60, and 95% of the age distributes within [36. 13, ± 8. 34]. The driving history ranges from 1 to 41 years, and 95% of them fall into the range of [8. 67, ± 6. 52]. There are three types of vehicles that are driven by respondent drivers: 303 coach drivers, 211 truck drivers, and 1 286 car drivers. The statistical results of the survey are shown in Tab. 1.

Tab. 1 Statistic collection table for questionnaire survey

Contents of investigation	Statistics of options			
	A	B	C	D
Gender	1 370	430		
Age	90	1 440	234	36
Years of driving	144	1 548	72	36
Vehicle type	303	211	1 286	
Panic	270	360	1 170	
Evacuation mode	770	540	490	
Route choice	774	306	720	
Destination	720	162	918	
Information	1 476	324	0	
Drastic driving	1 692	90	18	
Following distance	180	270	648	702
Influence of lane change	846	162	792	
Go-aheadism	900	594	306	

Note: The contents of options A, B, C and D are derived from Ref. [21].

The results of emergency evacuation driving reactions and behaviors are summarized in Tab. 2. The survey results show that 65% of the drivers would be influenced and change their normal driving behavior because of panic; 73% of the drivers are willing to evacuate by driving vehicles, while 27% of drivers would plan to leave on foot; 40% of the drivers would intend to take an emergency service vehicle (such as a specially assigned bus, police car, or ambulance); 49% of the drivers are likely to go to a familiar safety place; 51% of respondents would have no idea where to go and they would just want to leave the dangerous area as quickly as possible; 83% of the drivers think that they would try to seek useful information during the evacuation process while 17% do not believe that evacuation information is so important if they are familiar with the surrounding roadways; 83% of the drivers think they should obey the emergency traffic regulations to evacuate the emergency area under specific traffic control and management plans; 36% of the drivers are likely to drive at considerably close distance; 47% of the drivers believe that total evacuation time would be prolonged if any driver tries to change lanes under the circumstance of high occupancy of roadways.

Through the literature review and the aforementioned survey results we have a better understanding of contributing factors to car-following behaviors under evacuation in urban areas. Two factors are defined in this paper to adapt an existing car-following model into a model reflecting differences in emergency situations. K is defined as the differentia distributing coefficient about a driver's behavior differentia in an emergency situation ($K \leqslant 1$). Based on the survey results, it is proposed that K fall into the range of [0. 3, 0. 4] under the circumstances of an emergency evacuation, meaning that about 30% to 40% of the drivers driving under the circumstances of an emergency evacuation would take smaller spacing headways than under normal traffic conditions.

Another factor β is the driver's experiential decision coefficient. β is determined based on the driver's driving aggressiveness, driving experience, self-control ability of external stimuli, and type and capabilities of the vehicle that the driver drives. It is proposed that, under the circumstance of greater ranges of emergency evacuation, the β value falls into the range of [0. 6, 0. 7], which means that about 60% to 70% of the drivers whose driving behavior under the circumstances of an emergency evacuation would be influenced to a different extent in the evacuation situation. Both K and β are equal to zero under normal traffic conditions.

Tab. 2 Questionnaire survey on emergency evacuation driving reactions and behaviors

Contents of investigation	Drivers quantity	Male drivers quantity	Female drivers quantity	Percentage of total valid sample/%
Panic	1 170	803	367	65
Hitching vehicles to evacuate	1 310	933	377	73
Following wrecking car to evacuate	720	465	255	40
Going to planned shelter	882	630	252	17
Seeking information	1 494	1 137	357	83
Close following driving	648	583	65	40
Influence of lane change	846	744	102	47

Note: Total samples 1 800: 1 370 male and 430 female.

1.3 Development of safety-spacing-based car-following model under evacuation

Under normal traffic conditions, if the preceding vehicle's speed is much lower than the desired speed of the following vehicle, the following vehicle will tend to end the current state and search for an opportunity to change lanes or overtake the preceding vehicle. When an emergency evacuation is implemented, clustered vehicles in a traffic stream of higher density will increase the difficulty in making a lane change. The length of the roadway that is occupied by such traffic streams is estimated by the following expression:

$$L_{\mathrm{v}} = \sum_{i=1}^{n} S_{i-1} + \sum_{i=1}^{n} d_i \tag{1}$$

where L_v is the length of occupied vehicular traffic stream in a concerned roadway lane (m); S_{i-1} is the body length of the preceding vehicle $i-1$(m); d_i is the minimum desired safety distance between the front bumper of the following vehicle i and the preceding vehicle i (m).

According to kinematics, the normal minimum safety distance d_i(m) is

$$d_i = V_i T + \frac{V_i^2 - V_{i-1}^2}{2a_{i,t+T} + G} + L_i \tag{2}$$

where V_{i-1} is the speed of the ahead vehicle $i-1$(m/h); V_i is the speed of the following vehicle i (m/h); T is the time needed for the following vehicle to take to adjust its speed as the same as that of the preceding vehicle (s); a is the acceleration/deceleration of the vehicle I(m/s^2); G is the grade of the concerned roadway lane; and L_i is the length of vehicle i(m).

As analyzed above, the primary feature of the emergency car-following behavior is that all the drivers trapped in the evacuation area hope to leave the area as fast as possible; however, their freedom of maneuvering is more constrained by the "chaos" of the traffic and there may be little space to maneuver as they desire compared to normal conditions. A speed observation undertaken during the peak hours and off-peak hours of the Third Ring Road(i. e., Olympic Boulevard) in Beijing discloses that if the relative speed between a preceding vehicle and a following vehicle is less than 10 km/h, there is almost no acceptable gap available for other vehicles to merge from the adjacent lanes. The acceleration or deceleration of the following vehicle is therefore assumed to be similar to that of the preceding vehicle as a result of car-following maneuvers in the evacuation traffic stream. In other words, the primary hypothesis of the emergency evacuation car-following model is $a_{i,t+T} \approx a_{i-1,t}$(acceleration), or, $d_{i,t+T} \approx d_{i-1,t}$(deceleration); i. e., at time $(t+T)$ the following vehicle n can achieve an acceleration/deceleration that is close to the preceding vehicle's acceleration/deceleration at time t. Integrating K and β factors into Eq. (2), the minimum safety distance between two vehicles can be expressed as

$$D_{\min} = (1-K) V_{i,t} T + \frac{V_{i,t}^2 - V_{i-1,t+T}^2}{2a_{i,t} + G} e^{-K\beta} + L_i \tag{3}$$

Assuming that $G = 0$ for level terrain, then Eq. (3) becomes

$$D_{\min} = (1-K) V_{i,t} T + \frac{V_{i,t}^2 - V_{i-1,t+T}^2}{2a_{i,t}} e^{-K\beta} + L_i$$

Then, the following vehicle i's acceleration/deceleration at time t can be derived from Eq. (3) as

$$a_{i,t} = \frac{(V_{i,t}^2 - V_{i-1,t+T}^2) e^{-K\beta}}{2[D_{\min} - (1-K) V_{i,t} T - L_i]} \tag{4}$$

where $a_{i,t}$ is vehicle i's accessible maximum acceleration at the time t or during the period of $(t+T)$(m/s^2). If $a_{i,t} < 0$, it is the vehicle i's accessible maximum deceleration during the period of $(t+T)$(m/s^2); $D_{\min}$ is the minimum safety distance (m); K is the differentia distributing coefficient regarding a driver's behavior differentia in an emergency situation, 0.30 to 0.40; β is the driver's experiential decision coefficient, 0.60 to 0.70.

When $K = 0$ and $\beta = 0$, Eqs. (3) and (4) represent the minimum safety distance between two vehicles under normal traffic conditions.

According to the results of Ref. [22], the minimum safety distance $D_{\min}$ between evacuating vehicles can be defined by

$$D_{\min} = \begin{cases} S_{i-1} + L_i & V_{i,t} \leqslant 10 \text{ km/h} \\ 0.278 V_{i,t} + 1 & 10 < V_{i,t} \leqslant 40 \text{ km/h} \\ 0.417 V_{i,t} + 1 & V_{i,t} > 40 \text{ km/h} \end{cases} \tag{5}$$

After $D_{\min}$ is solved by using Eq. (5), the acceleration or deceleration of vehicles at different speeds at time $(t+T)$ can be computed by Eq. (4). Then, the following vehicle's speeds and location at time $(t+T)$ can be figured out through the principles of kinematics.

2 Case Study

Based on the field investigations at major segments of expressways in Beijing, the Jing-Song Segment of the East Third Ring Road is selected as one of major sites for data observation and case study. It features heavy traffic loads, high occupancy of lanes, and high density of vehicles over the segment, which multiplies the difficulties for drivers to maneuver in making lane changes or overtaking preceding vehicles. The traffic condition at this site is therefore assumed to be similar to an evacuation situation. A global positioning system(GPS) technique with high accuracy is utilized to collect vehicle trajectory data. Actual car-following trajectories and theoretical evacuation trajectories($K = 0.3$ and $\beta = 0.6$) are analyzed. Fig. 2 and Fig. 3 show an example of comparisons of trajectory data between the preceding and following vehicles in terms of acceleration and space, respectively.

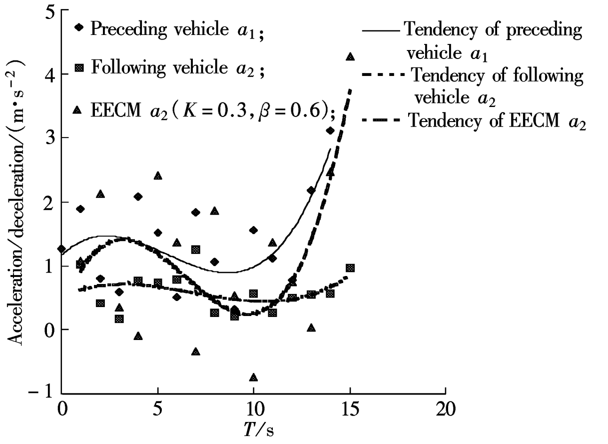

Fig. 2 Comparison between actual and EECM's acceleration/deceleration

From Fig. 2, it is observed that the following vehicle keeps close accelerations with the preceding vehicle during evacuation all the time while a margin always exists between the two vehicles in regular peak-hour traffic flows. This difference explains the primary distinct travel behaviors be-

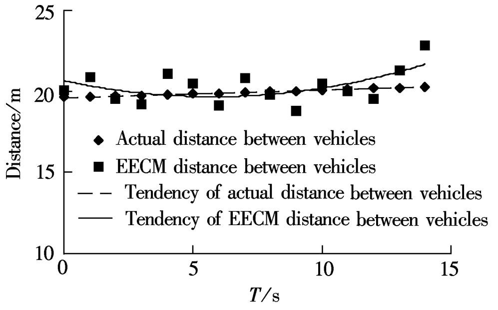

Fig. 3 Comparison between distances of actual and EECM's vehicles

tween regular peak hours and an evacuation period. Because of emergency conditions, the driver may feel panic or anxiety and then strongly tend to leave the dangerous site. At the same time, the high density traffic condition does not allow the drivers to freely change lanes. As a consequence, the following vehicles will try to keep as close a space from the preceding vehicle as possible during the evaluation. When their space is near the minimum safety distance, the following drivers will adjust acceleration/deceleration in a timely manner to avoid any possible collision. When the preceding vehicle speeds up, the following vehicle may follow up with a much bigger acceleration than regular traffic condition. Meanwhile, the space may be wanted keeping as closer as he/she can, as shown in Fig. 3, but driver behavior may not as consistent as they drive under normal traffic conditions, so the minimum distance under emergency evacuation can be greatly influenced by drivers' abnormal estimates or unharmonious behaviors.

3 Conclusion

This paper aims to capture the main traffic flow characteristics and driver behavior under emergency evacuation situations. A new car-following model EECM is the key contribution used to reflect the reality of emergency traffic phenomena. The model is developed based on the investigation of driver behavior and control ability under hypothesis of emergency circumstances. A thorough questionnaire is given to drivers of different ages, and about one quarter of the informants are female drivers. According to the results of the questionnaire, this paper modifies the traditional safety-distance car-following model by presenting and verifying two new parameters. This paper also presents the formulation and derivation process of the model which is discussed. A real field of car-following survey data is compared with the data derived from the EECM, the result shows that the EECM can reflect both closer car-following and driver behavior characteristics under the emergency evacuation situation. It is hoped that the EECM can be more applicable for emergency traffic planning and management than those traditional models which are developed under normal traffic conditions. Further studies of this model will be given by developing the algorithmic program, and making a case study by simulation under emergency evacuation.

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基于应急疏散交通特征的车辆跟驰模型

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摘要:提出了一个应急交通疏散车辆跟驰模型(EECM),模型首次在车辆最小安全间距的动力学推导过程中纳入驾驶员心理行为影响因素,使得跟驰过程更客观地反映在紧急疏散状态下的交通流和疏散驾驶行为特性. 通过文献研究分析传统跟驰理论与应急交通疏散跟驰特性的区别,并进一步进行驾驶员问卷调查对应急交通疏散条件下的驾驶心理行为特性进行统计分析,提炼出驾驶员行为差异分布系数和经验判断系数 2 个参数,并将其纳入车辆安全间距的动力学推导过程,建立了基于驾驶行为特性和最小安全间距的应急交通疏散车辆跟驰模型. 应用 GPS 技术对北京东三环劲松路段高峰小时交通流跟驰数据,对 EECM 进行了比较验证,结论有力地支持了 EECM 模型及问卷量化分析的合理性.

关键词:应急疏散;车辆跟驰;最小安全距离;驾驶行为
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