Impacts of Reduced Visibility under Hazy Weather Condition on Collision Risk and Car-following Behaviour: Implications for Traffic Control and Management

Kun GAO[a], Huizhao TU[a,*], Lijun SUN[a], N.N. SZE[b], Ziqi SONG[c], Heng SHI[a]

[a] *College of Transportation Engineering, Tongji University, Key Laboratory of Road and Traffic Engineering of the Ministry of Education, 4800 Cao'an Road, JiaDing District, Shanghai, P. R. China 201804*

[b] *Department of Civil and Environmental Engineering, the Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

[c] *Department of Civil and Environmental Engineering*
Utah State University, Logan, UT, United States

Huizhao TU (corresponding author)
College of Transportation Engineering, Tongji University
Key Laboratory of Road and Traffic Engineering of the Ministry of Education
4800 Cao'an Road, JiaDing District, Shanghai, P. R. China 201804
Email: huizhaotu@tongji.edu.cn

Impacts of Reduced Visibility under Hazy Weather Condition on Collision Risk and Car-following Behaviour: Implications for Traffic Control and Management

Abstract

This paper examines the impacts of reduced visibility under hazy weather conditions on collision risk and car-following behaviour to enhance the understanding of relationships among weather conditions, driving performance and road safety. A high-fidelity driving simulator is applied to collect vehicle trajectory data concerning a number of driving performance metrics under both clear and hazy weather conditions. The collision risks under different weather conditions as indicated by two surrogate measures - time exposed time-to-collision (TET) and time integrated time-to-collision (TIT) – are compared. Results indicate that hazy weather conditions have significant impacts on traffic safety in terms of increased collision risk and impaired car-following performance. The TET and TIT with a critical time-to-collision threshold value of 5s under hazy weather conditions are 35.9% and 43.0% higher, respectively, than those under clear weather conditions. The increase in the low collision risk is more noticeable than that of the high collision risk. For car-following behavior, under hazy weather conditions, the average reaction time is higher and the sensitivity to the change in car-following spacing is lower. In addition, the interaction effects of vehicular speed on the relationship between weather conditions and some driving performance metrics are significant. Both the distance and time headways under hazy weather conditions are lower than those under clear weather conditions when the vehicular speed is high. However, no significant evidence is found for the relationship between weather conditions and distance or time headways when the vehicular speed is low or medium. Moreover, the variations in speeds under hazy weather conditions are higher than those under clear weather conditions when the speed is high or medium. The plausible causal relationships among the weather conditions, driving performance changes and collision risk are analysed and discussed. Findings of this study contribute to effective traffic control and management to enhance road safety under hazy weather conditions.

Keywords：Road safety; Reduced visibility; Collision risk; Car-following behaviour; Hazy weather conditions.

1 Introduction

Excessive emissions, from both fixed and mobile sources, contribute to the prevalence of inclement weather conditions like hazy weather. Adverse hazy weather has been frequent in the central and eastern parts of China in the past decade. For example, the number of days with hazy weather in the Beijing–Tianjin–Hebei region reached 21.7 in January 2013. Reduced visibility due to hazy weather conditions can result in the high risk of crash and traffic congestion and, thus, high societal losses (Tu, Li, Li, Zhang, & Sun, 2015). Indeed, adverse weather conditions (e.g. rainy, hazy and snowy) have been correlated to 39% of the traffic crashes on China's motorways in 2015 (Ministry of Public Security of China, 2015). Therefore, it is important to investigate the relationships among hazy weather conditions, collision risk and driving performance to develop effective measures of traffic safety control.

The impact of inclement weather conditions on traffic crashes has been a major road safety concern. Evidence has established the association among reduced visibility under foggy or hazy weather conditions, crash rate and injury severity based on historical crash data (Abdel-Aty, Ekram, Huang, & Choi, 2011; Hamilton, Tefft, Arnold, & Grabowski, 2014; Meng, Zhang, Wong, & Au, 2016; Peng, Abdel-Aty, Shi, & Yu, 2017; Sze & Song, 2018; Tay, Choi, Kattan, & Khan, 2011; Wu, Abdel-Aty, & Lee, 2017). For instance, the risk of a fatal crash increased with the existence of fog and smoke (Hamilton, et al., 2014) and the likelihood of a severe injury crash under foggy weather conditions varied with geographic location (Edwards, 1998). Abdel-Aty et al. (2011) analysed the impacts of foggy weather conditions on traffic crashes using traffic accident data in Florida. They revealed that crashes under foggy weather conditions tended to be more severe and involve more vehicles, as compared to those under clear weather conditions. Wu et al. (2017)

proposed a crash risk increase indicator to reveal the differences in the crash risk between foggy and clear weather conditions. Wang et al. (2015) examined crashes occurring on highway ramps under low visibility conditions and demonstrated that the prevalence of single-vehicle and multi-vehicle crashes was significantly correlated with the visibility level. Peng et al. (2017) also found that the likelihood of rear-end crashes increased with a reduced visibility level based on data collected from the real-time traffic surveillance system. In summary, previous studies based on historical crash data have mostly suggested associations among crash risk, crash severity and reduced visibility caused by reduced visibility conditions. However, on the basis of historical crash data for analysis, it is difficult to analyse changes in drivers' driving behaviour due to an adverse environment and, thus, the mechanism of collision risk. The effects of reduced visibility under hazy weather conditions on the drivers' behaviour and collision risk are simultaneously examined in relation to vehicle-based driving data to shed light on the relationships of weather conditions, changes in safety-related driving behaviour and collision risk caused by reduced visibility. Indeed, it is dangerous and difficult to gather naturalistic driving data by field experiments. A viable approach is to examine collision risk and car-following behaviour under hazy weather conditions in a controlled manner such as by using a high-fidelity simulator as reported in the current study.

Several studies have been conducted to investigate driving behaviour under different weather conditions using the driving simulator approach. Commonly investigated driving performance indicators have included speed, distance headway and time headway (Cavallo, 2002; Tu, et al., 2015; Yan, Li, Liu, & Zhao, 2014). Some studies have indicated that the preferred driving speed tended to be lower when the visibility level decreased (Cavallo, 2002; Tu, et al., 2015). Hawkins (1988) and Brooks et al. (2011) suggested that a significant reduction in driving speed could be observed only if the visibility level dramatically fell below a certain threshold limit (e.g. 100

meters). Generally, both distance and time headways decreased with the reduced visibility level (Boer, Caro, Cavallo, & Arcueil, 2007; Caro, Cavallo, Marendaz, Boer, & Vienne, 2009; Cavallo, 2002; Saffarian, Happee, & Winter, 2012; White & Jeffery, 1980). Broughton et al. (2007) found that variations in car-following behaviour across drivers were noticeable under foggy weather conditions. Some drivers adopted active behaviour to maintain smaller headways to follow up, while others lagged behind and gave up following the lead vehicle for the sake of safety. Cavallo (2002) demonstrated that reductions in car-following distance and time headways could be attributed to drivers' overestimation of vehicle spacing. Likewise, Caro et al. (2009) suggested that headway reduction under a poor visibility environment could be ascribed to the drivers' desires for better recognition of relative motion between vehicles. Moreover, when the visibility level dropped, the maximum acceleration rate also dropped and the maximum deceleration rate increased in contrast to clear weather conditions (Hoogendoorn, Hoogendoorn, Brookhuis, & Daamen, 2011; Hoogendoorn, 2012; Tu, et al., 2015). The interaction effects of the vehicular speed (i.e. traffic density) on the association between visibility level and driving performance has also been evaluated (Gao, Tu, & Shi, 2018). However, the effects of reduced visibility under hazy weather conditions on other driving performance indicators, including speed variance, drivers' sensitivity to the changes in vehicle spacing and relative speed, have often been overlooked. It is indeed worth exploring the safety implications of changes in these driving performance metrics due to haze and, consequently, effective safety countermeasures can be developed. Moreover, the interaction effects of the vehicular speed (i.e. traffic density) on the association between visibility level and driving performance should be further evaluated as well.

This study aims to examine the effects of reduced visibility caused by hazy weather on traffic safety and safety-related car-following behaviour based on vehicle trajectory data collected by driving simulator experiments. The considered performance metrics are distance headway, time headway, speed variance, reaction time, drivers' sensitivity to vehicle spacing and sensitivity to relative speed. In particular, the association between changes in driving performance metrics and collision risk will be discussed to analyse the mechanism of collision risk under hazy weather conditions from behavioural perspectives. Note that the focuses of the current study are rear-end collision risk and car-following behaviour. The findings can enhance the understanding regarding the effects of hazy weather conditions on traffic safety and driving performance and suggest implications for effective traffic control countermeasures.

The rest of this paper is structured as follows: Section 2 describes the process of data collection and experiment design of the driving simulator study. The methodology of analysis is presented in Section 3. The analysis results and their implications are provided and discussed in Section 4. Section 5 offers concluding remarks and suggestions for future works.

2 Experiments and Data Collection

In this study, a high-fidelity driving simulator system was used to collect vehicle trajectory data on driving performance metrics. The simulator system consisted of a fully instrumented car and high-fidelity visual system. The immersive cylindrical projection system produced a front view of horizontal 250 degrees and vertical 40 degrees. The immersive driving forces were generated using an 8-degrees-of-freedom motion system. SCANeR™ studio software was employed to set up experimental scenarios under clear and hazy weather conditions in the daytime, as shown in **Figure 1**. The sight distance under clear weather conditions was greater than 10,000m and that of hazy weather conditions was at most 80m (Tu, et al., 2015). The threshold limit of sight distance for hazy weather conditions was set in accordance with Chinese meteorological classifications regarding hazy weather conditions (Chinese Standard Council, 2011).

A dual-carriageway four-lane urban motorway was simulated in the experiments. In each trial, the participant was asked to drive to follow a leading vehicle, with freely selected headways in accordance with his or her own conventional driving habit. The speed profile of the leading vehicle was prescribed, and the leading vehicle would not make any lane change throughout the experiment for simulating car-following behaviour. To imitate a realistic driving environment, several vehicles around the subject vehicle were randomly generated. Duration of each trial was about seven minutes. **Figure 2** illustrates the speed profiles of a leading vehicle and corresponding subject vehicle in a typical simulation trial.

In the current study, 23 participants were recruited for the driving simulator experiments. The participants were in good health and had held a full driving license for at least three years. Informed consent for participation was obtained, and a monetary reward of 100 RMB (equivalent to US$16) for each trial was given. The average age of the participants was 36.2 (range [26, 44]), and the average driving experience was 10.3 years (range [4, 18]). Six of the participants were female.

Each participant was asked to complete two driving simulator trials, one under clear and another under hazy weather conditions. The order of trial was randomly assigned in case of effects of the experimental order. A practice section was provided to the participants before the actual experiments. A five-minute break between trials was also provided. The driving performance metrics including the displacement, vehicular speed, acceleration rate, distance headway, throttle and brake pedal force were recorded by the system at the frequency of 10Hz.

3 Methodology

3.1 Extended Time-to-collision Measures

Time-to-collision (TTC) is a well-established surrogate measure for evaluating traffic safety risk. The TTC is determined by Eq. (1). One consideration for the application of TTC is the thresholds stratifying the different risk levels. Various threshold limits have been set out in previous studies (Hecht, Landwehr, Baur, & Xe, 2009; Ossen & Hoogendoorn, 2007; Vogel, 2003). In this study, referring to the thresholds from the recognised literature, the collision risk is stratified into three categories: (i) negligible collision risk (TTC>5s), (ii) low collision risk (2s<TTC≤5s) and (iii) high collision risk (TTC≤2s). Also, Minderhoud and Bovy (2001) extended the conventional TTC to more complicated surrogate indicators for assessment: time exposed time-to-collision (TET) and time integrated time-to-collision (TIT). TET refers to the duration of exposure to critical TTC over a specific period *H,* as shown in Eq. (2). TET can represent the duration with noticeable collision risk. Critical TTC is the threshold limit of TTC for potential collision risk. However, TET does not consider the severity of the potential collision. Therefore, TIT is established. TIT denotes the integral of severity of potential collision risk (depicted by the difference between real-time and critical TTCs) with respect to time, as specified in Eq. (3). The two extended surrogate indicators are widely applied for reflecting collision risk. According to the definitions, larger TET and TIT demonstrate larger collision risk.

$$\boldsymbol{TTC}_n(t) = \frac{X_{n-1}(t) - X_n(t) - l_n}{V_n(t) - V_{n-1}(t)} \quad \forall\ V_n(t) > V_{n-1}(t) \tag{1}$$

$$\boldsymbol{TET} = \sum_{t=0}^{H} \delta_n(t) * \tau \quad \delta_n(t) = \begin{cases} 0 & else \\ 1 & 0 \le TTC_n(t) < TTC^{\#} \end{cases} \tag{2}$$

$$\boldsymbol{TIT} = \int_0^H [TTC^{\#} - TTC_n(t)]dt \quad \forall\ 0 \le TTC_n(t) < TTC^{\#} \tag{3}$$

where $X_n(t)$, $V_n(t)$ and l_n denote the displacement, speed and length of vehicle *n* at time *t*, respectively. τ is the time step. $TTC^{\#}$ means the critical TTC. $\delta_i(t)$ is a dummy variable that equals 1 while the actual TTC is less than $TTC^{\#}$.

Both TET and TIT will be estimated in this study with two $TTC^{\#}$ of 5s and 2s, indicating the stratified risk levels. TET_5 and TIT_5 ($TTC^{\#}$ of 5s) denote the overall collision risk, including low and high collision risk, and TET_2 and TIT_2 ($TTC^{\#}$ of 2s) represent the high collision risk.

3.2 Car-following Behaviour Metrics

The investigated car-following performance metrics in this paper are distance headway, time headway, speed variance, response time, sensitivities to the change in spacing and relative speed between the leading and the subject vehicles. To examine the intervention effects by traffic conditions (i.e. vehicular speed) on the relationship between weather conditions and driving behaviour, the car-following behaviour at different speed stages is analysed separately. For instance, driving behaviour metrics including distance headway, time headway and speed variance in three different stages (high-speed (70-80 km/h for simulating low traffic density), medium-speed (40-50km/h for simulating medium traffic density) and low-speed (5-15km/h for simulating traffic density) stages, are evaluated. In addition, the reaction time in acceleration and deceleration stages are diagnosed separately as well (Gao, et al., 2018).

The formulation proposed by Zhang and Bham (2007) is applied to estimate the reaction time. The reaction time is defined as the difference between T_e (the moment at which the leading vehicle starts to accelerate or decelerate) and T_s (the moment at which the change in the acceleration rate of the subject vehicle exceeds the threshold of A_t=0.15m/s^2), while the time headway is less than

10 seconds (Zhang & Bham, 2007). To evaluate the sensitivities to changes in spacing and relative speed between subject and leading vehicles, Helly’s (1959) model as specified in Eq. (4) is employed. In particular, the genetic algorithm (GA) is applied to calibrate Helly’s model based on trajectory data. The objective function of optimisation is the root mean square percentage error (RMSPE) of the spacing, as illustrated in Eq. (5) (Punzo & Montanino, 2016). More details of the calibration process can be referred to the reference (Gao, et al., 2018).

$$\textbf{Helly}: \quad a_n(t) = \begin{cases} C_1 \Delta V_n(t-\tau_n) + C_2[\Delta X_n(t-\tau_n) - \overset{\square}{\Delta} X_n(t-\tau_n)] \\ \overset{\square}{\Delta} X_n(t-\tau_n) = a + b^* V_n(t-\tau_n) \end{cases} \qquad (4)$$

$$\textbf{RMSPE} = \quad \sqrt{\frac{1}{N} * \sum_{i=1}^{N} (\frac{S_i^{obs} - S_i^{sim}}{S_i^{obs}})^{2}} \qquad (5)$$

where $a_n(t)$ is the acceleration rate of vehicle *n* at time *t*. τ_n is the reaction time. C_1 and C_2 are the sensitivity parameters in response to the changes in relative speed and spacing, respectively. $\Delta X_n(t-\tau_n)$ and $\overset{\square}{\Delta} X_n(t-\tau_n)$ are the actual and desired spacing. *a* and *b* are the coefficients to be estimated. $V_n(t-\tau_n)$ and $\Delta V_n(t-\tau_n)$ are the speed of vehicle *n* and the speed difference at time $t-\tau_n$. S_i^{obs} and S_i^{sim} denote the observed and simulated values of spacing at time *i*, respectively. *N* is the size of dataset.

In this study, statistical tests, including the parametric *T-test* and non-parametric *Wilcoxon test*, are used to evaluate the difference in the mean values and distributions of the investigated variables under different weather conditions.

4 Results and Discussion

4.1 Collision Risk

Table 1 illustrates the results of the differences in the mean evaluation and coefficient of variation (COV) for the collision risk between clear and hazy weather conditions. As shown in **Table 1**, the difference in the collision risk between clear and hazy weather conditions is significant at the 5% level. In particular, the average TET_5 and TIT_5 under hazy weather conditions are 35.9% and 43.0% higher, respectively, than those under clear weather conditions. In addition, the average TET_2 and TIT_2 under hazy weather conditions are 8.1% and 3.2% higher, respectively, than those under clear weather conditions. Nevertheless, no evidence is found for the significant difference in the high collision risk (i.e. TET_2 and TIT_2). The results demonstrate that the overall collision risk (TTC≤5s) under hazy weather conditions is significantly higher than that under clear weather conditions. However, the high collision risk (TTC≤2s) under hazy weather conditions is not significantly larger (even though larger on average) in contrast to clear weather conditions. This implies that the reduced visibility level under hazy weather conditions can mainly be correlated with the noticeable increase in the low collision risk (2s<TTC≤5s).

The COVs of TET and TIT are both above 50% under clear and hazy weather conditions. This indicates the remarkable variations in safety performance among drivers. Furthermore, the COVs of TET and TIT under hazy weather conditions are more substantial as compared to clear weather conditions, demonstrating that the reduction in visibility leads to the increase in the variances of drivers' safety performance.

4.2 Car-following Behaviour

4.2.1 Distance headway, time headway and speed variance

Table 2 summarises the results of the differences in mean tests and COV estimates for car-following behaviour metrics including distance headway, time headway and speed variance in different speed stages. In the high-speed stage, differences in time headways and speed variances between hazy and clear weather conditions are both significant at the 5% level in the *T-test* and the *Wilcoxon test*. The distance headways under hazy weather conditions are significantly smaller in comparison to clear weather conditions in the *Wilcoxon test* (at the 5% level) and *T-test* (at the 10% level). The average distance headway and time headway under hazy weather conditions are 16.6% and 17.0% lower, respectively, in contrast to clear weather conditions. In contrast, the standard deviation of speeds under hazy weather conditions is 34.1% higher than that under clear weather conditions.

In the medium-speed stage, the standard deviation of speeds under hazy weather conditions is 36.1% higher than that under clear weather conditions and the difference is significant at the 5% level. However, no significant evidence is established for the association among distance headways, time headways and weather conditions in both medium-speed and low-speed stages. Moreover, the COVs of distance headways, time headways and standard deviation of speeds are all greater than 35%. This again implies the remarkable variations in car-following behaviour across drivers.

The car-following performance in terms of distance and time headways is degraded under hazy weather conditions, especially in the high-speed stage. This can be attributed to the impairment of visual perception under adverse weather conditions. Compensatory manoeuvers, such as smaller distance and time headways, would be required to assist the driver to recognise the movement (e.g. relative speed and spacing) of the leading vehicle (Caro, et al., 2009). However, reductions in distance and time headways under hazy weather conditions lead to reduction in the values of TTC and, therefore, an increase in the risk of collision. Note that heterogeneities exist among drivers concerning driving behaviour adaptions and risk perceptions (Wild, 1988) under low visibility conditions. Some drivers might slow down and give up following the leading vehicle due to their serious concerns regarding potential risk under hazy weather conditions, while others might choose to accept the potential risk (or even suppose it is not risky at all), follow up the leading vehicle and be compelled to adapt smaller headways because of the impaired visual perception (Broughton, et al., 2007). Another reason for the smaller headways under hazy weather conditions might be that the drivers have a dramatically increased sense of severe collision risk without awareness when the lead vehicle is not clearly visible (Saffarian, et al., 2012) and, consequently, compromise to accept the risk due to smaller car-following headways. Higher speed variance has been associated with an increase in crash risk (Garber & Gadirau, 1988; Stuster, Coffman, & Warren, 1998). An increase in the speed variance under hazy weather conditions, as indicated in this study, contributes to an increase in the risk of potential collision as well.

However, no evidence is found for the difference in distance and time headways between different weather conditions in the medium-speed and low-speed stages. The main reason might be that the impact of the impairment of visual perception is marginal if the distance headways are short in the medium-speed and low-speed stages. Therefore, the degradation of car-following behaviour is less sensitive to the reduction in visibility levels. The intervention by vehicular speed (namely, traffic density) on the impacts of hazy weather conditions on distance and time headways should be noted in the analysis. Such findings are indicative of the effective traffic control and management measures (e.g. variable speed limit) to improve the safety level under adverse hazy weather conditions. For instance, a temporary lower speed limit can be imposed when the visibility level is severely reduced or time headway is lower than a certain threshold limit based on real-time weather conditions and traffic surveillance.

4.2.2 Reaction time, sensitivity to spacing and relative speed

Table 3 illustrates the results of difference-in-mean tests for reaction times of acceleration and deceleration, sensitivities to changes in speed difference and spacing. The acceleration reaction time under hazy weather conditions is on average 11.4% higher in comparison to clear weather conditions, and the difference is significant at the 5% level. This indicates that the drivers respond in a less timely manner to the acceleration of the leading vehicle under the reduced visibility conditions. Likewise, the reaction time of deceleration under hazy weather conditions on average increases by 5.1% compared to that under clear weather conditions. However, the associations among deceleration reaction time, sensitivity to change in speed difference and weather conditions are not statistically significant in the *T-test* and *Wilcoxon test*. However, the difference in the sensitivity to change in spacing between hazy and clear weather conditions is significant at the 1% level. The sensitivity to spacing under hazy weather conditions is 40.4% lower than that under clear weather conditions, indicating that drivers react less actively to changes in spacing under hazy weather conditions. Moreover, the COV of sensitivity to spacing under hazy weather conditions is 57% higher, compared to clear weather conditions, implying that the reduced visibility under hazy weather conditions amplifies the variations across drivers in sensitivity to change in spacing during car-following.

The reduction in the sensitivity to the change in spacing and the increase in the response time of deceleration might echo the estimated increase in the overall collision risk under hazy weather conditions. The degraded performance may be ascribed to the reduced visual perceptions caused by the haze. The stimulus to which drivers respond is the looming visual stimuli (proportional to $\Delta V / \Delta X^2$) (Michaels, 1963) and the haze would reduce drivers' cognitive ability to identify the motion changes. The reduction in sensitivity to spacing and the increase in reaction time could both impair the capability of defensive driving manoeuvers in an emergency (e.g. sudden braking of a leading vehicle) and, thus, result in an increase in the potential collision risk. Therefore, variable message signs (e.g. warning the driver to maintain an adequate distance and time headway under adverse weather conditions) can be implemented. Moreover, variations in driving performance across drivers are remarkable under hazy weather conditions. It is worth exploring the possible factors contributing to the heterogeneities in drivers' behaviour in an extended study.

5 Conclusions

In this study, the impacts of reduction in the visibility level under hazy weather conditions on the collision risk and car-following behaviour are examined using the driving simulator approach. The main findings are: (1) Overall collision risk under hazy weather conditions is significantly higher than that under clear weather conditions, (2) distance and time headways under hazy weather conditions are significantly lower than those under clear weather conditions in the high-speed stage, (3) speed variance under hazy weather conditions is higher than that under clear weather conditions in the high-speed and middle-speed stage and (4) the sensitivity to vehicle spacing under hazy weather conditions is lower as compared to clear weather conditions. The relationships among collision risk, car-following behaviour changes and weather conditions are causally discussed to understand the mechanism of collision risk under hazy weather conditions. The findings have implications for the development of effective traffic management and control measures, such as variable speed limits and variable message signs, for real-time risk prevention under hazy weather conditions.

In further research, the population of participants for the experiments can be enlarged. It is also worth exploring the interaction effects by driver characteristics (e.g. age, driving experience) and traffic composition (e.g. proportion of heavy vehicles) on the associations among traffic safety, car-following behaviour and weather conditions.

Acknowledgements: This project is supported by Science and Technology Commission of Shanghai Municipality (STCSM, 17DZ1205302), the National Key Research and Development Program of China (2017YFC0803902), National Natural Science Foundation of China (NSFC, 51578414), and the Research Grants Council of the Hong Kong SAR Government (25203717).

6 References

Abdel-Aty, M., Ekram, A. A., Huang, H., & Choi, K. (2011). A study on crashes related to visibility obstruction due to fog and smoke. *Accident analysis and prevention, 43*(5), p 1730.

Boer E R, Caro S, Cavallo V, *et al.* (2007) *A cybernetic perspective on car following in fog*. Proceedings of the fourth international driving symposium on human factors in driver assessment, training and vehicle design. Washington, US, pp. 9-12.

Brooks, J. O., Crisler, M. C., Klein, N., Goodenough, R., Beeco, R. W., Guirl, C., Grygier, J. (2011). Speed choice and driving performance in simulated foggy conditions. *Accident analysis and prevention, 43*(3), pp. 698-705.

Broughton, K. L., Switzer, F., & Scott, D. (2007). Car following decisions under three visibility conditions and two speeds tested with a driving simulator. *Accident Analysis & Prevention, 39*(1), pp. 106-116.

Caro, S., Cavallo, V., Marendaz, C., Boer, E. R., & Vienne, F. (2009). Can headway reduction in fog be explained by impaired perception of relative motion? *Human Factors: The Journal of the Human Factors and Ergonomics Society, 51*(3), pp. 378-392.

Cavallo V. (2002) Perceptual Distortions When Driving in Fog. *International Conference on Traffic and Transportation Studies*. American Society of Civil Engineers, Beijing, pp.965-972.

Chinese Standard Council (2011). Grade of Fog Forecast: *Classification of fog level* (pp.1-4). Beijing: Chinese Standard Council.

Edwards, J. B. (1998). The Relationship Between Road Accident Severity and Recorded Weather. *Journal of Safety Research, 29*(98), pp. 249-262.

Gao, K., Tu, H., & Shi, H. (2018). Stage-specific impacts of hazy weather on car following. In *Proceedings of the Institution of Civil Engineers-Transport* pp.1-13.

Garber, N. J., & Gadirau, R. (1989). Speed Variance and Its Influence on Accidents. *Transportation Research Record Journal of the Transportation Research Board, 1989*(1), pp 69.

Hamilton, B., Tefft, B., Arnold, L., & Grabowski, J. (2014). *Hidden Highways: Fog and Traffic Crashes on America's Roads*. Montana, 40, pp.1-87.

Hawkins R K. (1988) *Motorway traffic behaviour in reduced visibility conditions.* in Vision in Vehicles II. Second International Conference on Vision in Vehicles. Elsevier Science Ltd, Nottingham, Amsterdam, pp. 9–18

Hecht, H., Landwehr, K., Baur, & Xe, R. (2009) *Discrimination thresholds for time-to-collision*. Paper presented at the European Conference on Visual Perception, Regensburg, Germany.

Helly W (1959) Simulation of bottlenecks in single-lane traffic flow. *In Proc. Symposium on Theory of Traffic Flow*, Elsevier,General Motors. New York, pp. 207-238.

Hoogendoorn, R., Hoogendoorn, S., Brookhuis, K., & Daamen, W. (2011). Adaptation longitudinal driving behaviour, mental workload, and psycho-spacing models in fog. *Transportation Research Record: Journal of the Transportation Research Board*(2249), pp. 20-28.

Hoogendoorn, R. G. (2012). *Empirical research and modeling of longitudinal driving behaviour under adverse conditions*: TU Delft, Delft University of Technology.

Meng, M., Zhang, J., Wong, Y., & Au, P. (2016). Effect of weather conditions and weather forecast on cycling travel behaviour in Singapore. *International journal of sustainable transportation, 10*(9), pp. 773-780.

Michaels R. (1963) Perceptual factors in car following. *Proceedings of the 2nd International Symposium on the Theory of Road Traffic Flow (London, England),* OECD, London, England, pp. 44–59

Minderhoud, M. M., & Bovy, P. H. (2001). Extended time-to-collision measures for road traffic safety assessment. *Accident analysis and prevention, 33*(1), pp 89.

Ossen, S., & Hoogendoorn, S. P. (2007). Driver Heterogeneity in Car Following and Its Impact on Modeling Traffic Dynamics. *Transportation Research Record Journal of the Transportation Research Board, 1999*(1), pp. 95-103.

Peng, Y., Abdel-Aty, M., Shi, Q., & Yu, R. (2017). Assessing the impact of reduced visibility on traffic crash risk using microscopic data and surrogate safety measures. *Transportation Research Part C Emerging Technologies, 74*, pp. 295-305.

Punzo, V., & Montanino, M. (2016). Speed or spacing? Cumulative variables, and convolution of model errors and time in traffic flow models validation and calibration. *Transportation Research Part B: Methodological, 91*, pp. 21-33.

Saffarian, M., Happee, R., & Winter, J. d. (2012). Why do drivers maintain short headways in fog? A driving-simulator study evaluating feeling of risk and lateral control during automated and manual car following. *Ergonomics*, 55(9), pp. 971-985.

Stuster, J., Coffman, Z., & Warren, D. (1998). Synthesis of safety research related to speed and speed management (No. FHWA-RD-98-154).

Sze, N., & Song, Z. (2018). Factors contributing to injury severity in work zone related crashes in New Zealand. *International journal of sustainable transportation*, pp. 1-7.

Tay, R., Choi, J., Kattan, L., & Khan, A. (2011). A multinomial logit model of pedestrian–vehicle crash severity. *International journal of sustainable transportation, 5*(4), pp. 233-249.

The Ministry of Public Security of China (2015). *Road Traffic Accidents Annual Statiscal Report of China 2015*. Beijing: The Ministry of Public Security of China.

Tu, H., Li, Z., Li, H., Zhang, K., & Sun, L. (2015). Driving Simulator Fidelity And Emergency Driving Behaviour. *Transportation Research Record: Journal of the Transportation Research Board*(2518), pp. 113-121.

Vogel, K. (2003). A comparison of headway and time to collision as safety indicators. *Accident; analysis and prevention, 35*(3), pp. 427-433.

Wang, L., Shi, Q., & Abdel-Aty, M. (2015). Predicting Crashes on Expressway Ramps with Real-Time Traffic and Weather Data. *Transportation Research Record Journal of the Transportation Research Board, 2514*, pp. 32-38.

White M & Jeffery D (1980). Some aspects of motorway traffic behaviour in fog. TRRL Laboratory Report 958. Crowthorne, U.K.

Wild, G. J. S. (1988). Risk homeostasis theory and traffic accidents: propositions, deductions and discussion of dissension in recent reactions. *Ergonomics, 31*(4), pp. 441-468.

Wu, Y., Abdelaty, M., & Lee, J. (2017). Crash risk analysis during fog conditions using real-time traffic data. *Accident analysis and prevention*

Yan, X., Li, X., Liu, Y., & Zhao, J. (2014). Effects of foggy conditions on drivers' speed control behaviours at different risk levels. *Safety Science, 68*, pp. 275-287.

Zhang, X., & Bham, G. H. (2007). Estimation of driver reaction time from detailed vehicle trajectory data. *Moas*, pp. 574-579.