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Research Article

Exploring the Impact of Differentiated Per-Lane Speed Limits on Traffic Safety of Freeways with Considering the Compliance Rate

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This is a subsequent study of a two-lane cellular automata (CA) traffic simulation model proposed by the authors. The current study focused on understanding the impacts of the configuration of the differentiated per-lane speed limit (DPLSL) and its compliance rate on traffic safety indexes, including lane-changing frequency, the coefficient of variation of speed, and incident rate of dangerous situations. The results indicate that freeway sections with DPLSL, especially the ones with complex DPLSL, have potentials to reduce the speed variation, lane changing frequencies, and chances of dangerous situations, resulting in higher traffic safety levels. Furthermore, under DPLSL configurations, the compliance rate of the lane of slow vehicles could positively affect the traffic safety levels. Specifically, as the decrease of the compliance rate, lane changing frequency slightly increases, the coefficient variation of speed especially of the outer lane increases, and the incident rate of the overtaking-on-the-right circumstances increases. In contrast to the simple DPLSL, freeway segments with the complex DPLSL configuration are more sensitive to the influence of the compliance rate.

1. Introduction

The differentiated per-lane speed limit (DPLSL) is a type of speed control for freeway traffic management, which is commonly adopted in China and certainly applied or studies in some other countries [1]. Under DPLSL, each lane could apply an exclusive maximum speed limit, minimum speed limit, or both for regulating traffic speed. Usually, the speed limit of the inner lane is set at a higher value than the one of the outer lane to push slow vehicles to the outer lane and in turn reduce the influence of slow vehicles on the overall traffic. By doing so, the speed variation is expected to decrease for each lane and the motivation for lane changes could also be constrained. In fact, the two resulting changes in traffic flow characteristics due to the DPLSL have potentials to benefit traffic safety levels [2–5]. In practice, there are two typical DPLSL configurations, i.e., the simple DPLSL and the complex DPLSL. Regarding the simple DPLSL, the adjacent lanes have the same maximum speed limit but different minimum speed limits, while under the complex DPLSL, both the maximum and minimum speed limits are different for adjacent lanes.

In fact, the existing studies in the field of speed limit settings paid heavy attention to variable speed limits [6–10] including the cooperative variable speed limit system [11, 12], speed limit strategies [13–15], speed limit compliance [16], and the impact of speed limits on traffic safety [17–19] and traffic performance [20]. In recent years, the studies focusing on variable speed limits under connected-vehicle environments are also highlighted [21, 22]. Those studies have made a tremendous contribution to the state of the art, but none of them allowed the speed limit values varying across different lanes. The influence of DPLSL on traffic flow characteristics and traffic safety levels has been rarely investigated. In addition, the existing traffic simulation methods and behavioral analyses [13, 23, 24] capable of considering such speed limit configuration are limited.

For the above reasons, this study seeks to analyze the impact of DPLSL on freeway traffic safety through a recently proposed traffic flow simulation model [1]. Several safety

indexes including lane changing frequency, the speed variation of each lane, and incidence rate of dangerous situations were investigated with respect to different traffic densities. This study considers the situation that slow vehicles [23] in the outer lane could violate the speed limit and enter the inner lane. The simulation was further conducted for situations having different speed compliance [25–27] rate of slow vehicles.

2. Methods

2.1. The Traffic Simulation Model. The recent study [1] established a traffic simulation model that allows the speed limit configuration to vary across different lanes. Using this model, three simulation scenarios according to different speed-limit configurations were built, named as scenario 1, scenario 2, and scenario 3. The specifications of speed limit values for the inner and outer lanes under those scenarios are presented in Table 1. In more detail, scenario 1 is the regular uniform speed limit setting, scenario 2 is the simple DPLSL setting, and scenario 3 is the complex DPLSL setting.

Besides the different settings of speed limit values, all the other parameters and simulation environmental characteristics were designed to be the same for the three scenarios. The simulation adopted a two-lane ring road CA model in which each lane has 2,000 cells with a length of 25/9 m for each cell. Specifically, the lane changing rules under the DPLSL settings, which were calibrated using a driving simulator data and a back-propagate neural network, were proposed in one of our previous studies [1]. For the background vehicles, 40% of them were set as slow vehicles which have a lower expectation of speed than other vehicles, representing the group of drivers tending to maintain a slower speed in real driving situations. The expectation of speed of regular vehicles was set to twelve cells/s (120 km/h), while one of the slow vehicles was set to eight cells/s (80 km/h).

For analyzing the general impact of speed-limit configurations on traffic safety indexes, slow vehicles were set to completely comply with the speed limits and hence they did not enter the inner lane for the scenarios having DPLSL configurations (scenario 2 and scenario 3). The slow vehicles were allowed to enter the inner lane for the scenario having the uniform speed limits (scenario 1) because in this scenario the minimum speed limit is 60 km/h greater than the expected speed of the slow vehicles.

For further analyzing the impact with respect to different compliance rates of the slow vehicles, some slow vehicles would enter the inner lane and be chosen randomly according to the predefined compliance rates.

2.2. Traffic Safety Indexes. Several traffic safety indexes were adopted to represent the risk of being in a traffic accident for freeways, including lane changing frequency, coefficient of variation of speed, and incident rate of dangerous situations. The lane changing frequency was defined as the average number of lane changes per second, which was counted for each simulation trial. The coefficient of variation of speed was defined as the ratio between the standard deviation σ and the mean μ of the speed observed for a specific spot, i.e., σ/μ.

There were two dangerous situations considered for this study. DS 1: the first dangerous situation DS 1 corresponds to the situation that the time-to-collision is less than five seconds [28] between the subject vehicle and the lead vehicle in the current lane, the lead vehicle in the target lane, or the lag vehicle in the target lane. DS 2: the second dangerous situation DS 2 corresponds to the overtaking-on-the-right situation. For the countries using the right-hand-traffic, like China, the driver sits on the left. For the vehicles trying to overtake, taking the action from the right would experience a higher risk of accidents than doing from the left because, in the former situation, the driver has a smaller field of view than the one of the latter situation. In addition, the driver is also to be injured in the former situation as he/she is nearer to the impact area of collision. Note that an overtaking was counted as long as there are two successive lane changes making the vehicle return back to its original lane and the whole process was finished within a predefined amount of time.

3. Results and Analysis

3.1. Impacts of DPLSL on Traffic Safety Indexes under the Full Compliance of Slow Vehicles. This section focuses on the impacts of DPLSL scenarios and several other factors including vehicle density and inner/outer lane indicator on the three traffic safety indexes, under the full compliance of slow vehicles. Table 2 reports the ANOVA results of those traffic safety indexes. Most relationships between the traffic safety indexes and influential factors were significant. The exception would be that the DPLSL scenario does not have a significant impact on the incident rate of both the dangerous scenarios 1 and 2.

3.1.1. Lane Changing Frequency. Figure 1 illustrates the observed lane changing frequencies under different vehicle densities. In general, drivers are more likely to change lanes for a lower-density situation as changing lanes become difficult when the traffic density is higher resulting in smaller gaps between vehicles. Drivers were also more inclined to change lanes under scenario 1 than the two other scenarios. Scenarios 2 and 3 restricted the slow vehicles in the outer lane, reducing their influence on regular vehicles running in the inner lane. Between the two scenarios applying the DPLSL configurations, the complex DPLSL scenario (scenario 3) provides a smaller overlap of the legitimate range of speed for the two lanes than the one of the simple DPLSL scenario (scenario 2). Thus, vehicles would have the least motivation to make a lane change under scenario 3.

3.1.2. Coefficient of Variation of Speed. Figure 2 illustrates the coefficient of variation of speed under different vehicle densities for each lane. For both the inner and outer lanes and all the different densities, the corresponding coefficient of variation of speed is consistently smaller for the DPLSL scenarios than scenario 1. For the outer lane, such a pattern is more obvious. Comparing scenario 2 and scenario 3, the

Table 1: Specifications of speed limit values under different speed-limit configurations (unit: km/h).

No.	Inner lane		Outer lane	
	Max. speed limit	Min. speed limit	Max. speed limit	Min. speed limit
Scenario 1	120	60	120	60
Scenario 2	120	90	120	60
Scenario 3	120	90	100	60

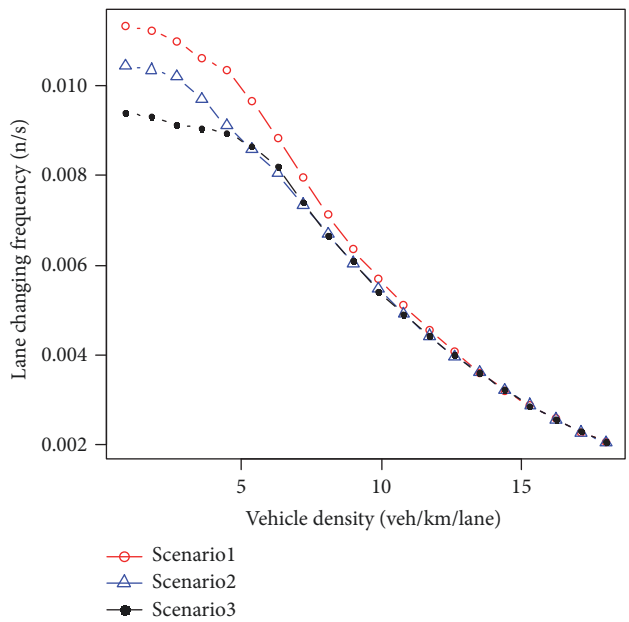

Figure 1: Lane changing frequency under different vehicle densities.

former illustrates higher coefficient of variation of speed under most of these traffic densities. Such results indicate that applying DPLSL for freeways could reduce the speed variation for both the two lanes as the slow vehicles were largely constrained to run only in the outer lane.

3.1.3. Incident Rate of DS 1 and DS 2. Figure 3 illustrates the incident rate of dangerous situations DS 1 and DS 2 under different vehicle densities. Although the ANOVA results cannot reveal a significant impact of the DPLSL scenarios on the incident rate of DS 1 and DS 2, minor patterns still exist as shown in Figure 3. Under low-density situations, scenario 3 exhibits a lower incident rate of DS 1 than scenario 1 and scenario 2. The overall incident rate of DS 1 is 33.8% less than scenario 1, indicating that the strict DPLSL setting would be beneficial to raise the safety level of freeways. With the increase of the traffic density, the incident rates of DS 1 tend to be the same for the three scenarios.

The speed of vehicles is higher under a low-density situation than a high-density situation. However, the vehicle was difficult to take an overtaking action on the right because the speed limit is low for the DPLSL scenarios. Therefore, the incident rate of DS 2 under scenario 3 is less than the ones under scenario 1 and scenario 2. The overall incident rate of DS 1 is 43.2% less than scenario 1. Thus, scenario 3 has a higher level of traffic safety. With the increase of the traffic density, the incident rates of DS 2 tend to be the same for the three scenarios.

3.2. Impacts of DPLSL on Traffic Safety Indexes with respect to Different Compliance Rates. The analysis in the previous section considered the situation that all slow vehicles obey the speed limits for each lane and hence they are not allowed to enter the inner lane. In reality, a portion of slow vehicles may not fully abide by the speed limits settings due to purposed or unpurposed lane changing activities. Enlightened by the results in the previous section, these illegal lane changes performed by the slow vehicles are expected to have impacts on those traffic safety indexes. In this section, the simulation was performed under different compliance rates of slow vehicles ranging from 0 to 0.8, and the resulting lane changing frequency, coefficient of variation of speed, and incident rate of dangerous situations are reported (in Figures 4, 5, and 6) using a relative magnitude as a ratio to the corresponding situation with full compliance of slow vehicles. Note that the compliance rate represents the proportion of slow vehicles that are allowed to enter the inner lane in the simulation. Such chosen slow vehicles may not perform a lane change if the trigger conditions of making lane changes did not meet.

Table 3 reports the ANOVA results of those traffic safety indexes. Most relationships between the traffic safety indexes and influential factors were significant. The exceptions would

Table 2: ANOVA results of the traffic safety indexes under the full compliance of slow vehicles.

Source	Lane changing frequency			Coefficient of variation of speed			Incident rate of DS 1			Incident rate of DS 2		
	Df	F value	Pr(>F)	Df	F value	Pr(>F)	Df	F value	Pr(>F)	Df	F value	Pr(>F)
Vehicle density	1	2036.099	< 2e-16	1	155.552	<2e-16	1	6.708	0.0164	1	4.595	0.0429
DPLSL scenario	2	8.137	0.00079	2	85.882	<2e-16	2	0.063	0.9394	2	0.098	0.9070
Inner/outer lane	NA	NA	NA	1	6.468	0.0123	NA	NA	NA	NA	NA	NA

Table 3: ANOVA results of the traffic safety indexes under different compliance rates of slow vehicles.

Source	Lane changing frequency			Coefficient of variation of speed			Incident rate of DS 1			Incident rate of DS 2		
	Df	F value	Pr(>F)	Df	F value	Pr(>F)	Df	F value	Pr(>F)	Df	F value	Pr(>F)
Vehicle density	1	64.005	3.38e-12	1	7.853	0.00559	1	2.341	0.1294	1	44.41	1.86e-09
DPLSL scenario	1	147.342	< 2e-16	1	0.660	0.41770	1	4.726	0.0323	1	18.33	4.51e-05
Inner/outer lane	NA	NA	NA	1	143.545	< 2e-16	NA	NA	NA	NA	NA	NA
Compliance rate	4	4.774	0.00151	4	32.043	< 2e-16	4	3.308	0.0140	4	25.82	2.10e-14

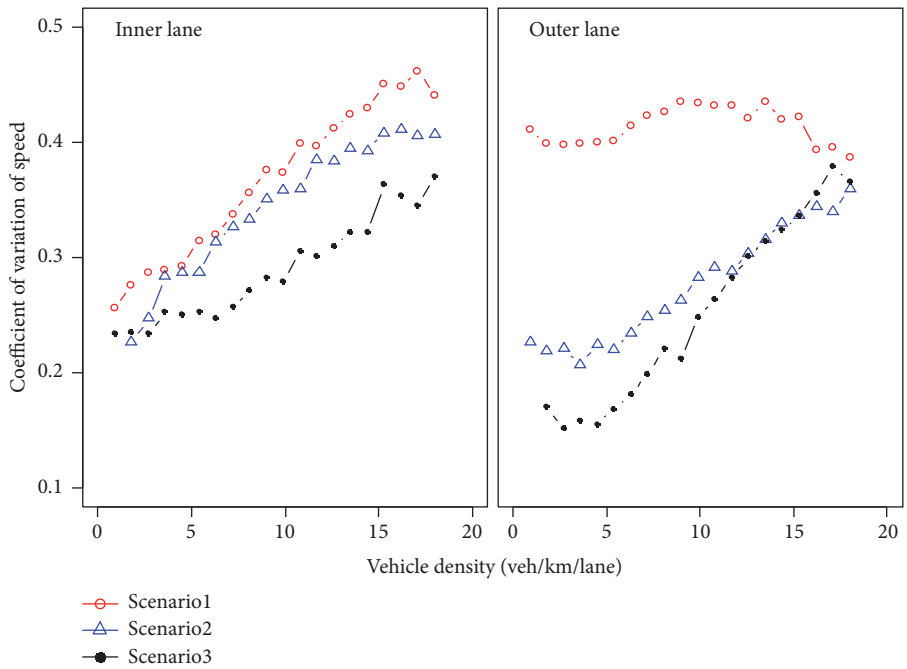

Figure 2: Coefficient of variation of speed under different vehicle densities for each lane.

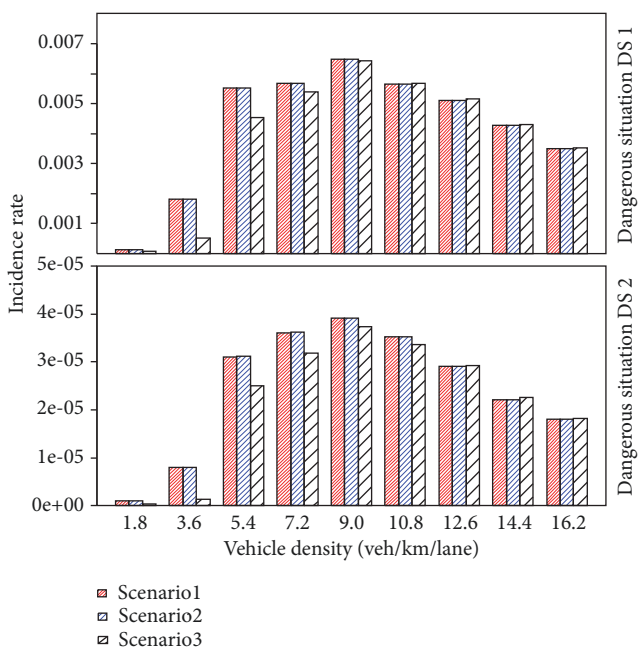

Figure 3: Incident rates of DS 1 and DS 2 under different vehicle densities.

be that the DPLSL scenario does not have a significant impact on the coefficient of variation of speed and the vehicle density does not have a significant impact on the incident rate of DS 1.

3.2.1. Lane Changing Frequency. Figure 4 illustrates the variation of lane changing frequency under different vehicle densities and compliance rates. In Figure 4, the red solid line is the average ratio to the results under fully compliance situation (compliance rate=1) in different scenarios. Broadly, having some unruly slow vehicles (compliance rate<1) will result in a larger lane changing frequency than the one under the full compliance situation (compliance rate=1). With the increase of the compliance rate, there are two variation stages for the averaged level of lane changing frequency. For the compliance rates 0, 0.2, and 0.4, there is no substantial variation of the averaged lane changing frequency, while when the compliance rate is 0.6, the averaged lane changing frequency started to drop and approach the level with respect

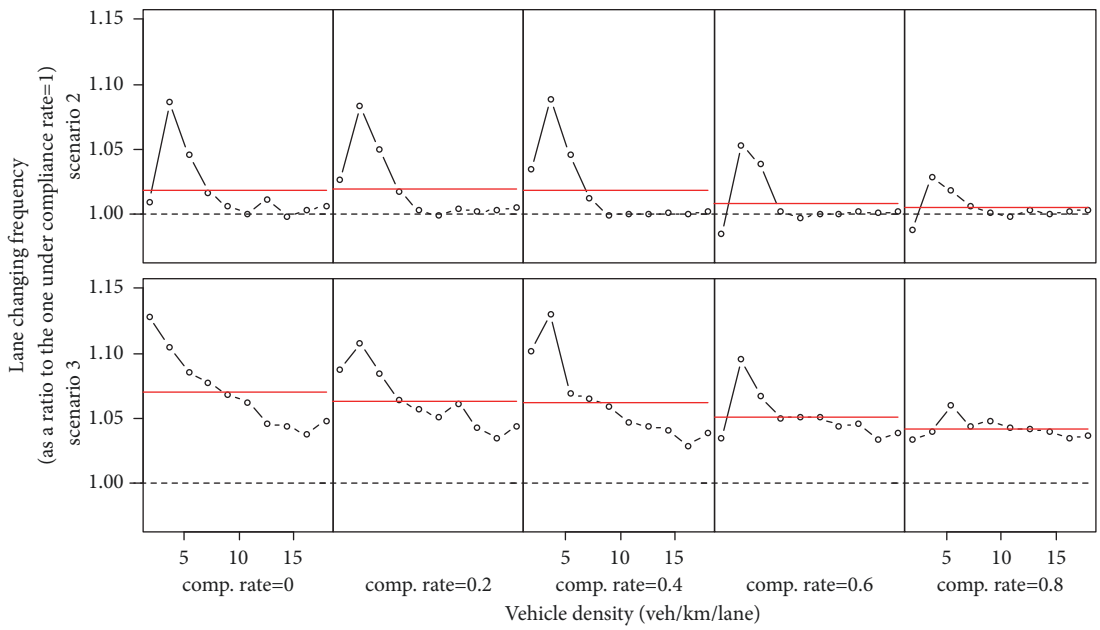

Figure 4: Lane changing frequency under different vehicle densities and compliance rates.

to the situation of full compliance of slow vehicles. Thus, a small proportion of unruly slow vehicles may not be able to execrate substantial interference to the overall lane changing behaviors of the system. Between scenario 2 and scenario 3, the latter still has more lane changes than the former consistently for all traffic densities and compliance rates.

Interestingly, the gap of lane changing frequency between the situation with unruly slow vehicles and the full compliance situation is relatively small under small and large densities in contrast to middle-ranged densities. For the situation with small traffic densities, the expected speed of the slow vehicles was more likely to achieve leading to a reduced motivation of making lane changes for the unruly slow vehicle. For the situation with large traffic densities, the sufficient gap between vehicles in the target lane for making a lane change is usually difficult to search for.

3.2.2. Coefficient of Variation of Speed. Figure 5 illustrates the coefficient of variation of speed under different vehicle densities and compliance rates. The results are also reported individually for the inner and outer lanes in scenario 2 and scenario 3. Broadly, with the increase of the compliance rate, the averaged level of the coefficient of variation of speed continues to drop. Those slow vehicles that violate the speed limits would disturb the traffic flow and in turn enlarge the speed variations of both the inner and outer lanes, but in different ways. Regarding the inner lanes, the variation of speed originated from the unruly slow vehicles being mainly due to the additive slow vehicles entering the inner lanes. The resulting coefficient of variation of speed is not significantly large, because the actual number of slow vehicles that entered the inner lane is small even under the situations with low compliance rates. In fact, the motivation for the unruly slow vehicles to make lane changes is not as strong as the traffic flow in the inner lane running far faster than the speed those slow vehicles expected. Regarding the outer lane, there are two major sources contributing to the variation of speed. First, the slow vehicles that violated the speed limits essentially enlarge the variation of speed. Second, the unruly slow vehicles, even a small number, would inevitably reduce the speed of the regular vehicles running behind them and hence increase the motivation of making a lane change for the regular vehicles being blocked. The consequent lane changes and overtaking made by the regular vehicles would heavily increase the coefficient of variation of speed for the outer lanes. Therefore, we see that the coefficient of variation of speed for the outer lane is more sensitive to the compliance rate of slow vehicles in contrast to the one for the inner lane. Although the ANOVA model indicates that the DPLSL scenario does not have a significant impact on the coefficient of variation of speed, minor patterns exist, worthy of being discussed. These patterns are slightly stronger under the complex DPLSL scenario (scenario 3) than the ones of the simple DPLSL scenario (scenario 2). In average, the coefficient of variation of speed increases by about 12% and 99%, respectively, for the inner and outer lanes under scenario 2, and increases by about 13% and 128%, respectively, for the inner and outer lanes under scenario 3.

3.2.3. Incident Rate of DS 1 and DS 2. According to the ANOVA model, the vehicle density does not have a significant impact on the incident rate of DS 1. All other impacts were verified to be significant, especially on the incident rate of DS 2, which corresponds to higher significant levels. Figure 6 illustrates the incidence rates under different vehicle densities, compliance rates, and dangerous situations. Overall, the impact of compliance rate of slow vehicles on the occurrence of the DS 1situation is limited, especially under scenario 2. It

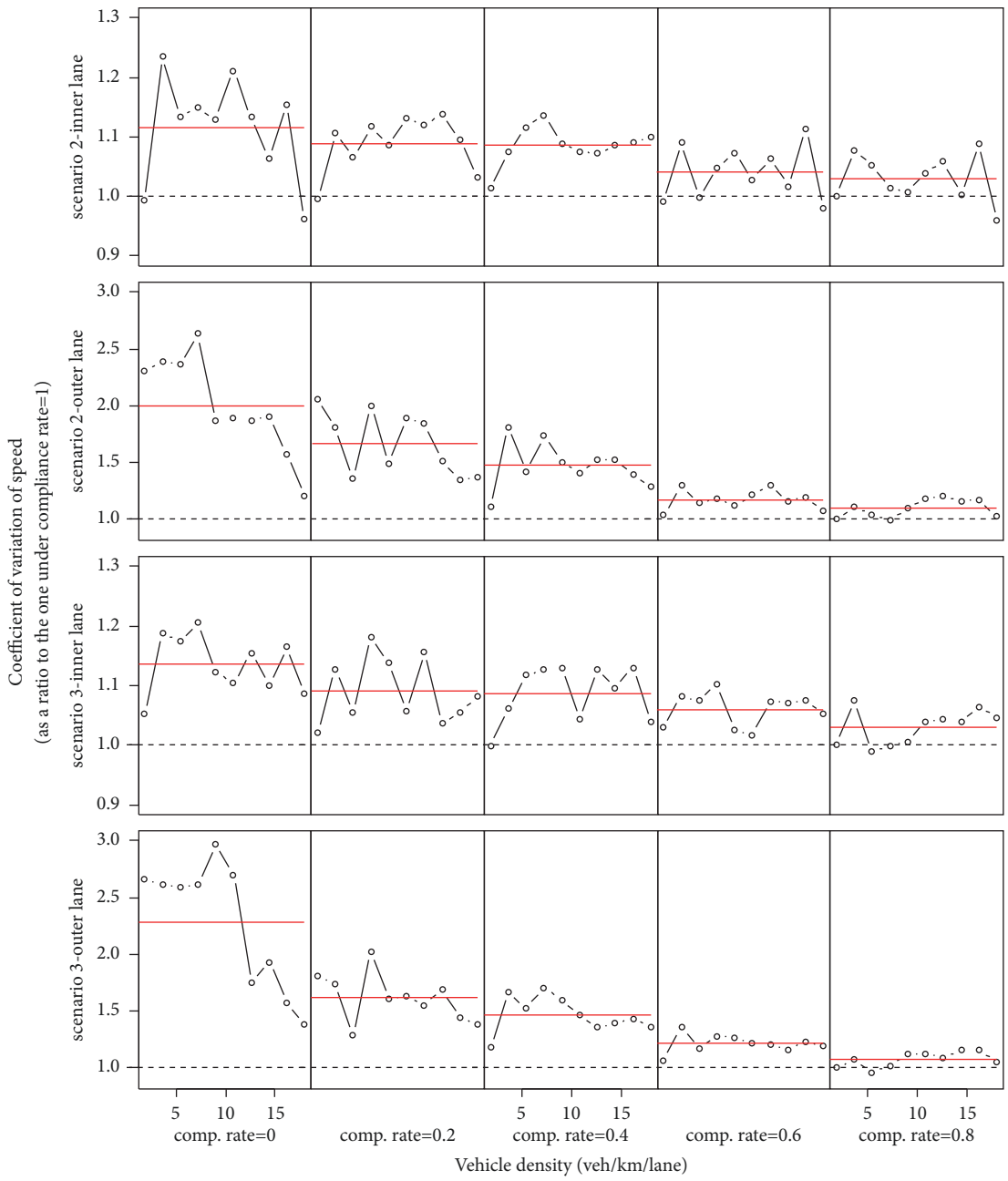

Figure 5: Coefficient of variation of speed under different vehicle densities and compliance rates.

is plausible that there are no direct connections between the compliance rate and the incident rate of the DS 1 situation. In contrast, the compliance rate would alter the behavior of vehicles overtaking. With the decrease of the compliance rate, the incident rate of the DS 2 situation (overtaking on the right) substantially increases. Under scenario 2, the largest increase of the DS 2 situation is about 14.9% while under scenario 3, the largest increase of the DS 2 situation is about 21.7%. As aforementioned, the unruly slow vehicles entered the inner lane affecting the regular vehicles behind them. These regular vehicles in the inner lane were motivated to overtake using the outer lane resulting in the increased incidence rate of the DS 2 situation.

4. Discussion and Conclusions

Two advantages motivate the application of the differentiated per-lane speed limit in freeway segments. First, certain drivers tend to maintain a slow speed while driving on freeways because of the compound aspects including age, gender, mood, and extra task. Those slow vehicles are easy to formulate bottlenecks that interfere with the traffic of vehicles running at normal or high speeds, especially under the circumstance that all lanes within a small range are occupied by slow vehicles. The DPLSL was developed to confine the slow vehicles onto a designated lane (usually the outer lane). By doing so, the normal-speed traffic would

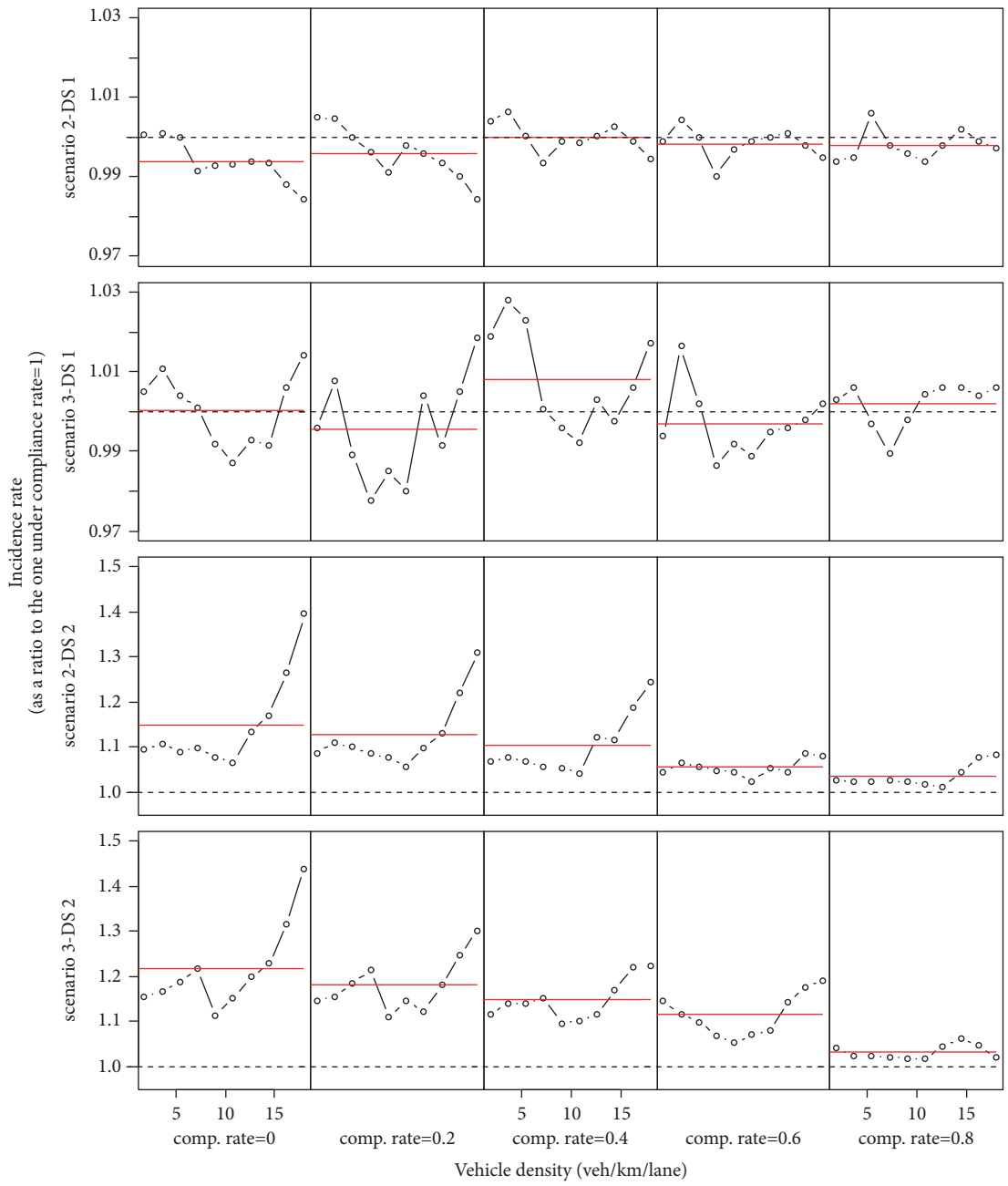

Figure 6: Incidence rates under different vehicle densities, compliance rates, and dangerous situations.

not be blocked for most of the situations. Second, with the DPLSL, the motivation of changing lanes could be suppressed to some extent, leading to a reduced chance of traffic conflicts. Besides, the speed variances for all lanes could be turned down.

Thus, traffic safety levels of freeway segments could be influenced by the per-lane speed limit configurations as this leads to drivers' different driving behaviors. In general, the DPLSL, especially the complex configuration, is able to effectively raise the safety levels of freeways. Such a pattern was conjectured as under the DPLSL scenarios, the lane changing frequency is smaller than that of the regular scenario with uniform speed limits for both lanes. Under DPLSL scenarios, drivers might need to process more information when making a lane change compared to regular speed limit control. In this situation, drivers would adopt special safety-prone driving strategies to compensate for the potential threat of traffic crashes [29–31] and therefore reduce the lane changing frequency. Such infrequent lane changing behavior in the complex DPLSL scenario, in fact, has the potential to raise the overall traffic safety levels [32] by reducing potential vehicle conflicts resulting from lane changes. In the meantime, the variation of speed is smaller under the DPLSL scenarios especially for the outer

lane, which indicates a higher traffic level. There are two possible reasons. One is that the slow vehicles are fully or partly constrained to run only in the outer lane under the DPLSL scenarios. The other one is that the legitimate range of speed is smaller than that of the regular scenario. More importantly, the complex DPLSL setting could reduce the chance of dangerous situations (DS 1 and DS 2) under low-density situations. Under the complex DPLSL scenario, the vehicle is difficult to take an overtaking action on the right because the speed limit is low for the DPLSL scenarios; therefore the incident rate of DS 2 is less than the ones in other scenarios.

The compliance rate of slow vehicles has a substantial impact on the traffic safety levels of freeways under the DPLSL scenarios. In general, reducing compliance rates would reduce safety levels. Specifically, the lane changing frequency increases along with the decrease of the compliance rate. Similarly, the variation of speed increases along with the decrease of the compliance rate. And between the inner and outer lanes, the latter was more sensitive to the compliance rate. Besides, the impact of the compliance rate on the occurrence of the DS 1 situation is limited. It is plausible that there are no direct connections between the compliance rate and the incident rate of the DS 1 situation. However, the compliance rate has some influence on the incident rate of the DS 2 (overtaking on the right). With the decrease of the compliance rate, the incident rate of the DS 2 substantially increases. More unruly slow vehicles entering the inner lane would affect the regular vehicles behind them with the decrease of the compliance rate. These regular vehicles in the inner lane were motivated to overtake using the outer lane resulting in the increased incidence rate of the DS 2. In a word, reducing compliance rates would reduce the safety levels of freeways under the DPLSL scenarios.

One limitation of this study is that the analyses are highly relying on simulations. Conducting such a study has a very high requirement for data. In particular, the precise positions of all vehicles during a giving time are needed in order to extract the speed data and check the two dangerous scenarios. On the other hand, real traffic flow is nonrecurrent. It means the impossibility to repeat a given traffic scenario by observing data in real freeways. The two aspects are the most critical impediments of using real data.

The results in this paper imply the existence of different traffic safety levels for different DPLSL configurations, which can be referenced for policy-makers. This study suggests considering complex DPLSL configurations with both nonuniform maximum and minimum speed limits which can effectively raise the safety levels of freeways. In the meantime, increasing the compliance rate of slow vehicles can further improve the traffic safety levels of freeways under the DPLSL scenarios.

Data Availability

The [traffic simulation results] data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] M. Liu and J. Shi, "A cellular automata traffic flow model combined with a BP neural network based microscopic lane changing decision model," *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, pp. 1–10, 2018.

[2] Y. Zhang, Q. Huang, M. Zhang, and X. Yu, "Lane change behavior character and its influence to traffic safety on urban roads," in *Proceedings of the Ninth International Conference of Chinese Transportation Professionals (ICCTP '09)*, pp. 1–7, 2009.

[3] R. C. Carlson, I. Papamichail, M. Papageorgiou, and A. Messmer, "Optimal mainstream traffic flow control of large-scale motorway networks," *Transportation Research Part C: Emerging Technologies*, vol. 18, no. 2, pp. 193–212, 2010.

[4] M. Quddus, "Exploring the relationship between average speed, speed variation, and accident rates using spatial statistical models and GIS," *Journal of Transportation Safety & Security*, vol. 5, no. 1, pp. 27–45, 2013.

[5] R. Chen, K. D. Kusano, and H. C. Gabler, "Driver Behavior During Overtaking Maneuvers from the 100-Car Naturalistic Driving Study," *Traffic Injury Prevention*, vol. 16, pp. 176–181, 2015.

[6] Y. Zhang and P. A. Ioannou, "Stability analysis and variable speed limit control of a traffic flow model," *Transportation Research Part B: Methodological*, vol. 118, pp. 31–65, 2018.

[7] E. R. Müller, R. C. Carlson, W. Kraus, and M. Papageorgiou, "Microsimulation analysis of practical aspects of traffic control with variable speed limits," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 1, pp. 512–523, 2015.

[8] H. Liu, L. Zhang, D. Sun, and D. Wang, "Optimize the Settings of Variable Speed Limit System to Improve the Performance of Freeway Traffic," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 6, pp. 3249–3257, 2015.

[9] Y. Zhang and P. A. Ioannou, "Combined Variable Speed Limit and Lane Change Control for Highway Traffic," *IEEE Transactions on Intelligent Transportation Systems*, vol. 18, no. 7, pp. 1812–1823, 2017.

[10] Y. Bie, M. Seraj, C. Zhang, and T. Z. Qiu, "Improving traffic state prediction model for variable speed limit control by introducing stochastic supply and demand," *Journal of Advanced Transportation*, vol. 2018, Article ID 7959815, 12 pages, 2018.

[11] E. Grumert, X. Ma, and A. Tapani, "Analysis of a cooperative variable speed limit system using microscopic traffic simulation," *Transportation Research Part C: Emerging Technologies*, vol. 52, pp. 173–186, 2015.

[12] Y. Zhang and P. A. Ioannou, "Coordinated Variable Speed Limit, Ramp Metering and Lane Change Control of Highway Traffic," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 5307–5312, 2017.

[13] F. Soriguera, I. Martínez, M. Sala, and M. Menéndez, "Effects of low speed limits on freeway traffic flow," *Transportation*

Research Part C: Emerging Technologies, vol. 77, pp. 257–274, 2017.

[14] J. You, S. Fang, L. Zhang, J. Taplin, and J. Guo, "Enhancing freeway safety through intervening in traffic flow dynamics based on variable speed limit control," *Journal of Advanced Transportation*, vol. 2018, Article ID 3610541, 10 pages, 2018.

[15] J. R. Frejo and B. D. Schutter, "SPERT: A speed limit strategy for recurrent traffic jams," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–12, 2018.

[16] I. M. Harms and K. A. Brookhuis, "Dynamic traffic management on a familiar road: Failing to detect changes in variable speed limits," *Transportation Research Part F-Traffic Psychology and Behaviour*, vol. 38, pp. 37–46, 2016.

[17] X. Xu and Ž. Šarić, "Investigation into interactions between accident consequences and traffic signs: A bayesian bivariate tobit quantile regression approach," *Journal of Advanced Transportation*, vol. 2018, Article ID 5032497, 10 pages, 2018.

[18] A. Vadeby and Å. Forsman, "Traffic safety effects of new speed limits in Sweden," *Accident Analysis & Prevention*, vol. 114, pp. 34–39, 2018.

[19] C. M. Farmer, "Relationship of traffic fatality rates to maximum state speed limits," *Traffic Injury Prevention*, vol. 18, no. 4, pp. 375–380, 2017.

[20] X. Li and J.-Q. Sun, "Effects of vehicle-pedestrian interaction and speed limit on traffic performance of intersections," *Physica A: Statistical Mechanics and its Applications*, vol. 460, pp. 335–347, 2016.

[21] B. Khondaker and L. Kattan, "Variable speed limit: a microscopic analysis in a connected vehicle environment," *Transportation Research Part C: Emerging Technologies*, vol. 58, pp. 146–159, 2015.

[22] A. Mittal, E. Kim, H. S. Mahmassani, and Z. Hong, "Predictive Dynamic Speed Limit in a Connected Environment for a Weather Affected Traffic Network: A Case Study of Chicago," *Transportation Research Record*, 2018.

[23] S. Masukura, T. Nagatani, K. Tanaka, and H. Hanaura, "Theory and simulation for jamming transitions induced by a slow vehicle in traffic flow," *Physica A: Statistical Mechanics and its Applications*, vol. 379, no. 1, pp. 263–273, 2007.

[24] W. Jin, "Macroscopic Characteristics of Lane-Changing Traffic," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2188, no. 1, pp. 55–63, 2018.

[25] B. Hellinga and M. Mandelzys, "Impact of driver compliance on the safety and operational impacts of freeway variable speed limit systems," *Journal of Transportation Engineering*, vol. 137, no. 4, pp. 260–268, 2011.

[26] M. J. Giles, "Driver speed compliance in Western Australia: A multivariate analysis," *Transport Policy*, vol. 11, no. 3, pp. 227–235, 2004.

[27] A. Bhowmick, T. Z. Qiu, and M. Hadiuzzaman, "Driver compliance analysis of variable speed limit based freeway traffic control," *American Society of Civil Engineers National Natural Science Foundation of China*, pp. 4181–4192, 2011.

[28] E. C. B. Olsen, S. E. Lee, W. W. Wierwille et al., "Analysis of distribution, frequency, and duration of naturalistic lane changes," *Human Factors & Ergonomics Society Annual Meeting Proceedings*, vol. 46, no. 22, pp. 1789–1793, 2002.

[29] V. Cantin, M. Lavallière, M. Simoneau, and N. Teasdale, "Mental workload when driving in a simulator: Effects of age and driving complexity," *Accident Analysis & Prevention*, vol. 41, no. 4, pp. 763–771, 2009.

[30] A. Calvi, A. Benedetto, and F. D'Amico, "Investigating driver reaction time and speed during mobile phone conversations with a lead vehicle in front: A driving simulator comprehensive study," *Journal of Transportation Safety & Security*, vol. 10, no. 1-2, pp. 5–24, 2018.

[31] R. Hoogendoorn, S. P. Hoogendoorn, K. Brookhuis, and W. Daamen, "Mental workload, longitudinal driving behavior, and adequacy of car-following models for incidents in other driving lane," *Transportation Research Record*, vol. 2188, pp. 64–73, 2010.

[32] Z. Zheng, "Recent developments and research needs in modeling lane changing," *Transportation Research Part B: Methodological*, vol. 60, no. 1, pp. 16–32, 2014.