A Situation-Aware Collision Avoidance Strategy for Car-Following

Li Li, *Fellow, IEEE*, Xinyu Peng, Fei-Yue Wang, *Fellow, IEEE,* Dongpu Cao, *Member, IEEE,*

and Lingxi Li, *Senior Member, IEEE*

***Abstract*—In this paper, we discuss how to develop an appropriate collision avoidance strategy for car-following. This strategy aims to keep a good balance between traffic safety and efficiency while also taking into consideration the unavoidable uncertainty of position/speed perception/measurement of vehicles. Both theoretical analysis and numerical testing results are provided to show the effectiveness of the proposed strategy.**

***Index Terms*—Collision avoidance, safety, traffic efficiency, uncertainty**

I. Introduction

COLLISION avoidance is a basic function of Advanced Driver Assistant Systems (ADAS) and automated vehicles [1]-[2]. Different collision avoidance strategies have been designed over the last 30 years. However, no strategy is currently guaranteed to be collision free due to several difficulties in producing these strategies.

In many situations, driving safety and traffic efficiency do not coincide with each other. If we want to ensure 100% collision-free conditions, the gaps between two consecutive vehicles should be sufficiently large. However, to increase traffic efficiency, we are required to reduce the gap between vehicles. So, we need to design appropriate strategies to handle such a dilemma.

Manuscript received on June 30th, 2018. This work was supported in part by the National Natural Science Foundation of China (Grant No. 61790565), the Beijing Municipal Science and Technology Commission Program under Grant D171100000317002, the Beijing Municipal Commission of Transport Program under Grant ZC179074Z. (Corresponding author: *Fei-Yue Wang*)

L. Li is with Department of Automation, BNRist, Tsinghua University, Beijing, China 100084 (email: li-li@tsinghua.edu.cn).

X. Peng is with Department of Automation, Tsinghua University, Beijing, China 100084.

F.-Y. Wang is with State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100080, China (email: feiyue.wang@ia.ac.cn).

D. P. Cao is with the Driver Cognition and Automated Driving Laboratory, University of Waterloo, Waterloo N2L 3G1, Canada (e-mail: dongpu.cao@uwaterloo.ca).

L. X. Li is with the Department of Electrical and Computer Engineering, Purdue School of Engineering and Technology, Indiana University-Purdue University Indianapolis, Indiana 46202-5132, USA (e-mail: LL7@iupui.edu).

Unideal position/speed perception/measurement needs to be considered too. The failure probability of the derived strategy should also be estimated in advance.

Recently, researchers in Mobileye proposed a new concept of Responsibility-Sensitive Safety (RSS) to derive the collision avoidance condition for automated vehicles [3]. Different driving scenarios, including car-following and ramp merging, were analyzed. Specially, the collision avoidance condition for car-following scenarios are quite similar to the classic collision avoidance car-following model NETSIM which was originally released in 1971 and was updated in late 1970s [4]-[6]. However, NETSIM model does not well consider traffic efficiency and received less attention in the new century [7].

Following these ideas, we focus on car-following scenario and discuss how to design a more efficient collision avoidance strategy to solve the aforementioned problems. We summarize the assumptions made in different papers for these problems and propose a more reasonable multi-state collision avoidance strategy which allows us to cope with uncertainty in position/speed perception/measurement of vehicles. Both theoretical analysis and numerical testing results are provided to show the effectiveness of the proposed strategy.

To better present our findings, the rest of this paper is arranged as follows. *Section II* presents the problem and reviews the RSS strategy. *Section III* proposed the new strategy and give theoretical comparison analysis. *Section IV* provides numerical study results. Finally, *Section V* concludes the paper.

II. Problem Presentation and the RSS Strategy

The nomenclatures used in this paper are given in Table 1 and are also illustrated in Fig.1.

This is the author's manuscript of the article published in final edited form as:
Li, L., Peng, X., Wang, F., Cao, D., & Li, L. (2018). A situation-aware collision avoidance strategy for car-following. IEEE/CAA Journal of Automatica Sinica, 5(5), 1012–1016. https://doi.org/10.1109/JAS.2018.7511198

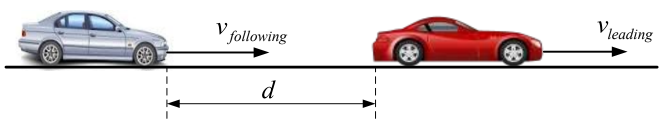

Fig.1 An illustration of the car-following scenarios

Table 1. The nomenclature list

Symbol	Definition
$a_{\max,\text{accel}}$	the maximum acceleration rate of the follower
$a_{\max,\text{brake}}$	the maximum deceleration rate of the follower
$a_{\min,\text{brake}}$	the minimum deceleration rate of the follower
$b_{\max,\text{brake}}$	the maximum deceleration rate of the leader
a_{accel}	a general acceleration rate of the follower
a_{brake}	a general deceleration rate of the follower
ρ	the response time lag
l_{leading}	the length of the leader
v_{leading}	the initial speed of the leader
$v_{\text{following}}$	the initial speed of the follower
$v_{\max}$	the maximum speed of vehicles
$d_{\min}$	the minimum gap between two vehicles
$h_{\min}$	the minimum headway between two vehicles

In [3], the following collision avoidance rule is set as follows.

Lemma 1. Suppose two consecutive vehicles are moving on the same lane in the same direction. The minimal safe longitudinal gap between the front-most point of the following vehicle and the rear-most point of the leading vehicle should be

$$d_{\min} = \left[v_{\text{following}}\rho + \frac{a_{\max,\text{accel}}\rho^2}{2} + \frac{\left(v_{\text{following}} + a_{\max,\text{accel}}\rho\right)^2}{2a_{\min,\text{brake}}} - \frac{v_{\text{leading}}^2}{2b_{\max,\text{brake}}} \right]^+ \quad (1)$$

which means two vehicles will not collide, if the leading vehicle brake by at most $b_{\max,\text{brake}}$ until a full stop, and the following vehicle accelerate by at most $a_{\max,\text{accel}}$ during the response time ρ, and then brake by at least $a_{\min,\text{brake}}$ until a full stop.

Remark 1. Similar collision avoidance rules (e.g. the one used in NETSIM model) had been adopted in literatures and researchers directly replace $a_{\min,\text{brake}}$ with $a_{\max,\text{brake}}$ in models [4]-[6].

Remark 2. The original RSS model assumes that the leading vehicle and the following vehicle have the same deceleration capability [3]; that is, $a_{\max,\text{accel}} = b_{\max,\text{brake}}$. However, this may not be true. The maximum deceleration rates of some heavy goods vehicles are significantly smaller than some sports cars, for example [7], [12].

Remark 3. The response time ρ implicitly characterizes the updating time interval length of the car-following models, though the two variables may be considered individually. In this paper, we assume that they are equal. In other words, the vehicle will check and possible update its ac/deceleration rate every ρ seconds.

III. The New Collision Avoidance Strategy

A. The New Strategy

As pointed out in [7], one major shortcoming of the above collision avoidance rule is its conservation in the determination of safety gap. It was shown in [8]-[12] that human drivers keep a much smaller gap in many practical situations.

One widely used measure of empirical gap is the so called headway, which is defined as "the time, in seconds, between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles" (on page 48 of [13]). In other words, we have

$$h(t) = \frac{d_{\min}(t) + l_{\text{leading}}}{v_{\text{following}}} \quad (2)$$

Fig.2 shows the distributions of empirical headway collected from the NGSIM trajectory data [14]. We can see that headways kept by human drivers are usually small than 3s when driving with fast speeds. The headways kept by RSS strategy are usually much larger than empirical ones; see discussions in Section IV.

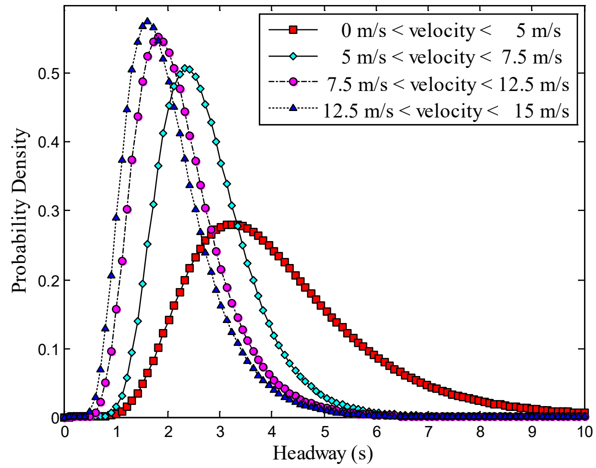

Fig.2 The smoothed empirical headway distributions collected from the NGSIM trajectory data (reproduced with courtesy from [11])

As suggested in [15]-[16], [6], one improving method for collision avoidance is to adopt multi-state rules that capture the characteristics of human drivers' car-following behaviors.

In this paper, we categorize the possible states of car-following into the following three kinds:

1) Following State: the following vehicle has already maintained a close gap from the leading vehicle. The speeds between two vehicles should be nearly identical at time t; i.e., $v_{\text{following}} = v_{\text{leading}}$. There is no reason to accelerate during the time range $(t, t+\rho]$. So, the safety gap at time t should be

$$d_{\min}^{1}(t) = \left[v_{\text{following}}\rho + \frac{v_{\text{following}}^2}{2a_{\text{brake}}} - \frac{v_{\text{leading}}^2}{2b_{\max,\text{brake}}} \right]^{+} \quad (3)$$

Correspondingly, the safety time headway between these two vehicles can be defined and calculated as

$$h_{\min}^{1}(t) = \left[\frac{l_{\text{leading}}}{v_{\text{following}}} + \rho + v_{\text{following}} \left(\frac{1}{2a_{\text{brake}}} - \frac{1}{2b_{\max,\text{brake}}} \right) \right]^{+} \quad (4)$$

Empirical observations indicate that human drivers tend to adopt large deceleration rate when braking if their speeds are large. As a result, the empirical mean time headway observed for a high speed range is larger than the empirical mean time headway observed for a slow speed range [11]-[12]. So, in this paper, we set the deceleration rate when braking as

$$a_{\text{brake}} = a_{\min,\text{brake}} + \frac{v_{\text{following}}}{v_{\max}} \left(a_{\max,\text{brake}} - a_{\min,\text{brake}} \right) \quad (5)$$

2) Departing State: the following vehicle slows down to depart from the leading vehicle and usually changes lane soon after. In such situations, the following vehicle will immediately brake with the minimum decelerating rate to complete the departure. No collision will occur if the following safety gap is satisfied at time t

$$d_{\min}^{2}(t) = \left[\frac{v_{\text{following}}^2}{2a_{\min,\text{brake}}} - \frac{v_{\text{leading}}^2}{2b_{\max,\text{brake}}} \right]^{+} \quad (6)$$

3) Approaching States: the following vehicle accelerates to catch up with the leading vehicle before it enters the Following state. This is a transition state. Empirical observations show that human drivers prefer to keep a special gap toward their leaders. When the following vehicle has a gap larger than the desired gap, it will accelerates to reduce the gap. However, different drivers take different actions to reduce the gap. Some human drivers will take a certain risk to approach their leaders by hypothesizing that the leading vehicle will not decelerate during the time range $(t, t+\rho]$. The accelerating rate a_{accel} should guarantee that the corresponding following safety gaps both be satisfied at time t and $t+\rho$

$$d_{\min}^{3}(t) = \left[v_{\text{following}}\rho + \frac{a_{\text{accel}}\rho^2}{2} + \frac{\left(v_{\text{following}} + a_{\text{accel}}\rho\right)^2}{2a_{\text{brake}}} - v_{\text{leading}}\rho - \frac{v_{\text{leading}}^2}{2b_{\max,\text{brake}}} \right]^{+} \quad (7)$$

$$d_{\min}^{3}(t+\rho) = d_{\min}^{3}(t) - v_{\text{following}}\rho - \frac{a_{\text{accel}}\rho^2}{2} + v_{\text{leading}}\rho \geq \left[\frac{\left(v_{\text{following}} + a_{\text{accel}}\rho\right)^2}{2a_{\max,\text{brake}}} - \frac{v_{\text{leading}}^2}{2b_{\max,\text{brake}}} \right]^{+} \quad (8)$$

B. *A Comparison between Two Models*

To compare the difference between the RSS model and the new model, we discuss three kinds of states respectively.

1) Following State. We obtain that

$$d_{\min} - d_{\min}^{1}(t) = \frac{a_{\max,\text{accel}}\rho^2}{2} + \frac{\left(v_{\text{following}} + a_{\max,\text{accel}}\rho\right)^2}{2a_{\min,\text{brake}}} - \frac{v_{\text{following}}^2}{2a_{\text{brake}}} \quad (9)$$

2) Departing State. We obtain that

$$d_{\min} - d_{\min}^{2}(t) = v_{\text{following}}\rho + \frac{a_{\max,\text{accel}}\rho^2}{2} + \frac{\left(v_{\text{following}} + a_{\max,\text{accel}}\rho\right)^2}{2a_{\min,\text{brake}}} - \frac{v_{\text{following}}^2}{2a_{\min,\text{brake}}} \quad (10)$$

3) Approaching State. We obtain that

$$d_{\min} - d_{\min}^{3}(t) = \frac{a_{\max,\text{accel}}\rho^2}{2} + \frac{\left(v_{\text{following}} + a_{\max,\text{accel}}\rho\right)^2}{2a_{\min,\text{brake}}} - \frac{a_{\text{accel}}\rho^2}{2} - \frac{\left(v_{\text{following}} + a_{\text{accel}}\rho\right)^2}{2a_{\min,\text{brake}}} + v_{\text{leading}}\rho \quad (11)$$

Clearly, the safety gap required by the new model will be smaller than that required by the original RSS model. This is mainly because the new model further analyzes the driving scenarios and make more reasonable assumptions. In the following *Section IV*, we will numerically show that the new model helps to improve traffic efficiency noticeably.

C. Considering Uncertainty

The major uncertainty of collision avoidance problems lie in the incorrect position/speed perception/measurement. Here, we can divide the uncertainty into two groups.

First, the underestimate of the maximum deceleration rate of the leading vehicle and the overestimate of the speed of the leading vehicle may lead to an increase of desired safety gap. To solve this problem, we can replace v_{leading} by $\lambda_1 v_{\text{leading}}$ in the above calculations with a pre-selected scale coefficient $\lambda_1 < 1$, and replace $b_{\text{max,brake}}$ by $\lambda_2 b_{\text{max,brake}}$ in the above calculations with a pre-selected scale coefficient $\lambda_2 > 1$.

Second, the underestimate of an existing gap may lead to an increase in the desired safety gap. As suggested in [17], we can directly add a positive coefficient μ to the calculated minimal safe gap to counteract the effect.

IV. NUMERICAL TESTING RESULTS

To check the difference between the RSS model and the new model, we design the following two experiments. Particularly, we set $a_{\text{max,accel}} = a_{\text{max,brake}} = b_{\text{max,brake}}$=2m/s^2, $a_{\text{min,brake}}$=2m/s^2, ρ=1s, $v_{\max}$=30m/s, l_{leading}=5m in the rest tests.

The first experiment calculates the required safety gaps by different models, when two vehicles are already in following state. Here, we set λ_1=0.95, λ_2=1.05, μ=5m.

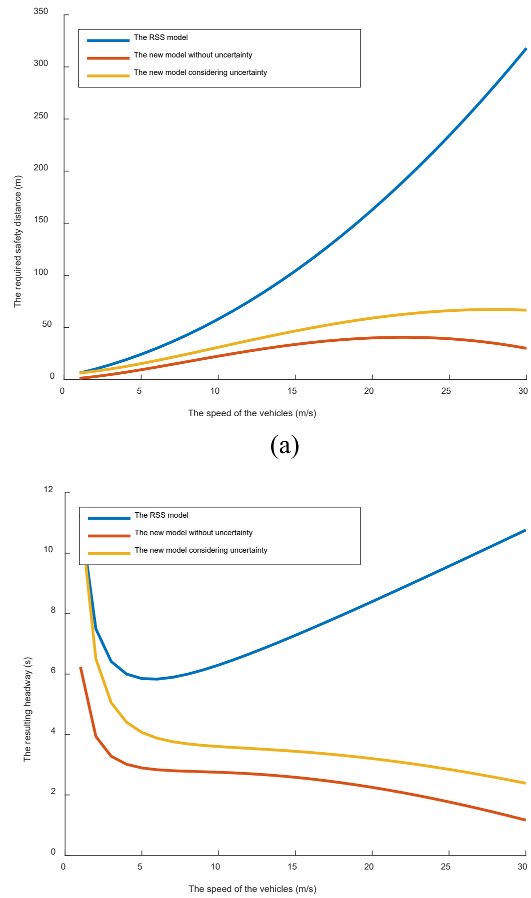

Fig.3 An illustration of (a) the required safety gaps and (b) the resulting headways by different models for following state.

As shown in Fig.3(a), the original RSS model requires much larger safety gaps then the new model when the speed is large, even when the uncertainty of position/speed measurement are considered. Fig.3(b) shows that the resulting headways when we apply the RSS model and the new model. Noticing that flow rate is reciprocal to the headway, the road capacity could be boosted when we use the new model instead of the RSS model.

The second experiment simulates a special approaching case for two vehicles. The speed of the leading vehicle is kept as 15m/s. The initial speed of the following vehicle is set as 30m/s and the initial gap is set as 550m. We use the following rules to adjust the speed of the following vehicle for both the RSS model and the new model.

If the current gap is larger than the require safety gap, we accelerate according to the following rules

$$v_{\text{following}}(t+\rho) = \min\left\{v_{\text{following}}(t) + a_{\text{max,accel}}\rho, v_{\max}\right\} \quad (12)$$

Otherwise, we decelerate by

$$v_{\text{following}}(t+\rho)=\max\left\{v_{\text{following}}(t)-a_{\text{min,brake}}\rho, v_{\text{leading}}, 0\right\} \quad (13)$$

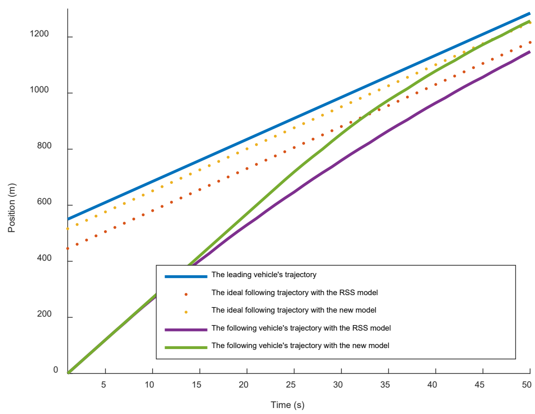

Fig.4 The trajectories of the following vehicle calculated by different models for a special approaching case.

Fig.4 shows the trajectories of the following vehicle obtained from different models, and the trajectories of virtual vehicles which are assumed to follow the leading vehicle (with ideal safety gaps calculated by different models) from the beginning. We can see that the new model can make the following vehicle quickly approach the leading vehicle and appropriately switch from Approaching State to Following State.

The RSS model is too conservative and leaves a larger gap than needed. The safety gap required by the RSS model is 104.25m; while the safety gap required by the new model is 33.75m. Since the speed is set as 15m/s, the flow rate derived by the RSS model is around 518veh/hour and the flow rate derived by the new model is 1600veh/hour (which is over 3 times larger than 518veh/hour). Thus, we can conclude that the conservation property of the RSS model leads to a significant waste of limited road capacity.

V. Conclusion

In this paper, we propose a new collision avoidance strategy for car-following, aiming to keep a good balance between traffic safety and efficiency. We discuss how to handle the unavoidable uncertainty of vehicles' position/speed perception in decision. Theoretical analysis and numerical tests show that a better categorization of the driving state could help reduce the required safety gap and thus make a better of road resources.

It should be pointed out that researchers show increasing interests in cooperatively organization of vehicles' movements [17]-[20]. The required safety gap can be further reduced in such settings.

References

[1] C. Little, "The Intelligent Vehicle Initiative: Advancing 'Human-Centered' smart vehicles," *Public Roads*, vol. 61, no. 2, 1997.

[2] L. Li, F.-Y. Wang, *Advanced Motion Control and Sensing for Intelligent Vehicles*, Springer, New York, NY, 2007.

[3] S. Shalev-Shwartz, S. Shammah, A. Shashua, "On a formal model of safe and scalable self-driving cars," https://arxiv.org/abs/1708.06374

[4] *Network Flow Simulation for Urban Traffic Control Systems: Phase II*. Federal Highway Administration, U.S. Department of Transportation, vols. 1-5, 1977.

[5] M. F. Aycin, R. F. Benekohal, "Comparison of car-following models for simulation," *Transportation Research Record*, no. 1678, pp. 116-127, 1999.

[6] L. Li, R. Jiang, B. Jia, X. Zhao, *Modern Traffic Flow Theory and Applications, Vol. I, Highway Traffic*, Tsinghua University Press, Beijing, China, 2010, (in Chinese).

[7] M. T. Parker, "The effect of heavy goods vehicles and following behaviour on capacity at motorway roadwork sites," *Traffic Engineering and Control*, vol. 37, no. 9, pp. 524-531, 1996.

[8] J. Ch. Hayward, Near miss determination through use of a scale of danger. Report no. TTSC 7115, The Pennsylvania State University, Pennsylvania, 1972.

[9] A. R. A. van der Horst, *A Time-Based Analysis of Road User Behaviour in Normal and Critical Encounters*. PhD Thesis, Delft University of Technology, Delft, 1990.

[10] W. V. Winsum, A. Heino, "Choice of time-headway in car-following and the role of time to collision information in braking," *Ergonomics*, vol. 39, pp. 579-592, 1996.

[11] X. Chen, L. Li, Y. Zhang, "A Markov model for headway/spacing distribution of road traffic," *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 4, pp. 773-785, 2010.

[12] L. Li, X. Chen, "Vehicle headway modeling and its inferences in macroscopic/microscopic traffic flow theory: A survey," *Transportation Research Part C: Emerging Technologies*, vol. 76, pp. 170-188, 2017.

[13] *Highway Capacity Manual*, Transportation Research Board, National Research Council, Washington, DC, 2000.

[14] US Department of Transportation, NGSIM-Next Generation Simulation, http://www.ngsim.fhwa.dot.gov

[15] W. Leutzbach, R. Wiedemann, "Development and application of traffic simulation models at Karlsruhe Institut fur Verkehrwesen," *Traffic Engineering and Control*, vol. 27, no. 5, pp. 270-278, 1986.

[16] H. T. Fritzsche, "A model for traffic simulation," *Traffic Engineering and Control*, vol. 35, no. 5, pp. 317-321, 1994.

[17] Y. Meng, L. Li, F.-Y. Wang, K. Li, Z. Li, "Analysis of cooperative driving strategies for nonsignalized intersections," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 4, pp. 2900-2911, 2018.

[18] L. Li, F.-Y. Wang, "Cooperative driving at blind crossings using intervehicle communication," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 6, pp. 1712-1724, 2006.

[19] L. Li, D. Wen, D.Yao, "A survey of traffic control with vehicular communications," *IEEE Transactions on Intelligent Transportation Systems*, vol. 15, no. 1, pp. 425-432, 2014.

[20] Q. Wang, L. Li, H. Li, Y. Zhang, J. Hu, "Discussion on parameter setting of adaptive cruise control," *Proceedings of Youth Academic Annual Conference of Chinese Association of Automation*, pp. 1045-1048, 2018.