Proceedings of the 2020 4th CAA International Conference on Vehicular Control and Intelligence (CVCI), Hangzhou, China, December 18-20, 2020

A Comparison of Mode Switching Strategies for Adaptive Cruise Control

Yang Liu
School of Automotive Engineering
Chongqing University
Chongqing, China
liu_yang@cqu.edu.cn

Chunyun Fu
School of Automotive Engineering
Chongqing University
Chongqing, China
fuchunyun@cqu.edu.cn

Xiaolin Tang
School of Automotive Engineering
Chongqing University
Chongqing, China
tangxl0923@cqu.edu.cn

Cong Guo
School of Automotive Engineering
Chongqing University
Chongqing, China
cquguocong@cqu.edu.cn

Minghui Hu
School of Automotive Engineering
Chongqing University
Chongqing, China
hu_ming@cqu.edu.cn

2020 4th CAA International Conference on Vehicular Control and Intelligence (CVCI) | 978-1-7281-8497-5/20/$31.00 ©2020 IEEE | DOI: 10.1109/CVCI51460.2020.9338575

***Abstract*—Adaptive Cruise Control (ACC) systems have been implemented successfully in production vehicles primarily for improving driving comfort and reducing workload. As the core of all ACC systems, the mode switching strategy directly affects the performance of the ACC system. This paper presents a brief comparison of mode switching strategies for existing ACC solutions in the literature. The current mode switching strategies can be classified into three major types according to their required information, including the distance-based switching strategy, distance-speed-based switching strategy, and distance-speed-acceleration-based switching strategy. Their characteristics are carefully reviewed and explained. Besides, future works for improving the existing mode switching strategies are also presented.**

Keywords—Adaptive cruise control, mode switching strategy, spacing control

I. Introduction

Nowadays, advanced driver assistance systems (ADASs) have received extensive attention for their great potential in improving safety, traffic efficiency, fuel economy, emissions, and comfort [1, 2]. As a typical type of ADAS, adaptive cruise control (ACC) systems have been commercially implemented on vehicles [3]. ACC is an extension of the traditional cruise control (CC) systems [4]. An ACC system operates by maintaining a certain cruise speed or a desired distance with respect to the preceding vehicle, via automatically adjusting throttle or brake [5, 6].

In the ACC control process, two important switching logics are usually involved: switching between different control modes (such as cruise mode and follow mode) [7], and switching between throttle and brake [8, 9]. In common hierarchical ACC control systems [10] (see Fig. 1), the former belongs to the upper-level control and the latter belongs to the lower-level control. This paper focuses on the former one and investigates a variety of switching strategies.

In a typical ACC system, there exists at least two basic operating modes: cruise mode and follow mode [11, 12]. Since the control algorithms for these modes are different, a switching strategy must be developed to ensure that the ACC system operates in an appropriate operating mode according to the instantaneous driving condition. As the core of all ACC systems, the mode switching strategy directly affects the overall performance of the ACC system [13].

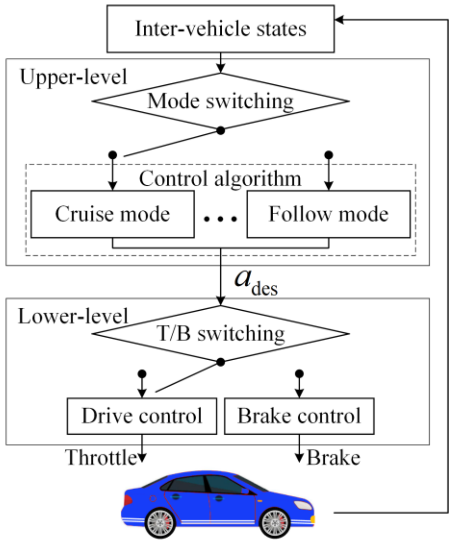

Fig. 1. Hierarchical ACC control system

II. Various Mode Switching Strategies

A. Distance-Based Switching Strategy

The most common switching strategy is the distance-based switching strategy. This strategy compares the actual distance with the desired distance and activates the follow mode if the actual distance is less than the desired one, otherwise, the ACC system operates in the cruise mode [14-16]. This switching strategy is schematically shown in Fig. 2, where the terms d_{act} and d_{des} represent the actual and desired inter-vehicle distances respectively, v_h and v_p are the speeds of the host and preceding vehicles respectively.

The advantage of this strategy lies in its low computation load, however, it also presents several obvious drawbacks:

- Firstly, this strategy may lead to frequent mode switching when the actual inter-vehicle spacing is close to the desired spacing. The reason is that the ACC vehicle longitudinal dynamics is described by a first-order system, which in turn results in a delay in the response of the ACC vehicle [17, 18].
- Secondly, this strategy increases the likelihood of collisions in an emergency. Based on this strategy, the ACC system switches to the follow mode only

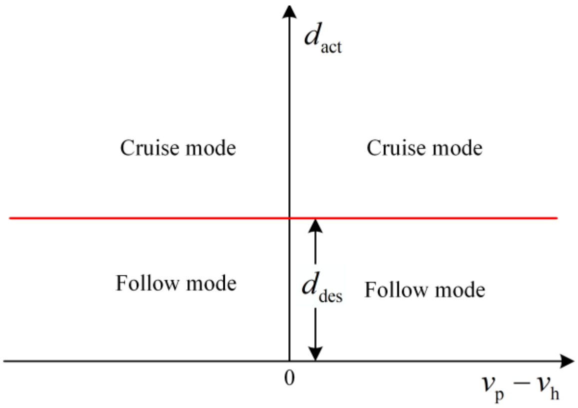

Fig. 2. Distance-based switching strategy

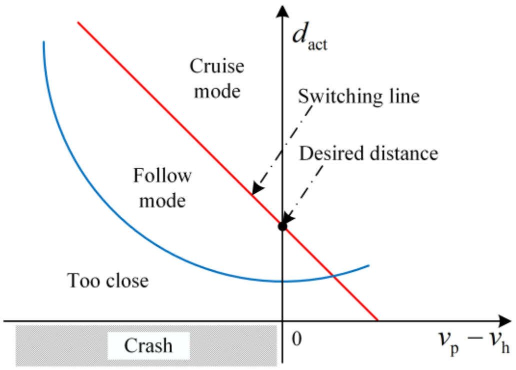

Fig. 3. Distance-speed-based switching strategy

when the actual inter-vehicle spacing is less than the desired spacing. If the host vehicle is faster than the preceding vehicle, the actual distance will be further reduced in the initial stage of follow mode.

- Thirdly, the driving comfort during the switching process is neglected in this strategy. It has been pointed out that a mode switching strategy should take into account not only safety performance, but also comfort performance [19].The rate of change of acceleration is an important criterion for evaluating driving comfort [20], however, it is not considered in this mode switching strategy.
- Lastly, the switching logic can result in unreasonable mode switching for certain driving scenarios. For instance, the host vehicle may experience unnecessary mode switching when another vehicle cuts in at a high speed.

To overcome the first drawback, Shladover et al. [21] proposed a modified mode switching strategy which includes a hysteresis region. In this hysteresis region, the ACC system maintains the current operating mode, thereby avoiding frequent mode switching.

B. Distance-Speed-Based Switching Strategy

As mentioned above, the distance-based switching strategy may lead to unnecessary mode switching in certain driving conditions. To tackle this shortcoming, the vehicle speed information should be introduced in the mode switching strategy design. Fancher and Bareket [22] first proposed a mode switching strategy using the distance and relative velocity diagram, as shown in Fig. 3. So far, this

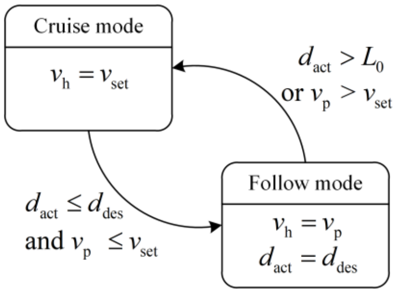

Fig. 4. Adaptive mode switching strategy

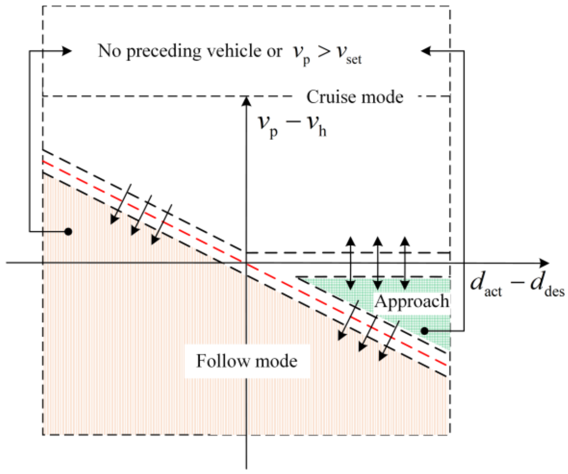

Fig. 5. Switching strategy based on zero-expectation acceleration curves

strategy has been widely adopted in various ACC systems [23]. The Delphi company designed an ACC system in which the distance error and relative velocity are used to determine the mode switching rules [24].

Based on the findings in [22], Haspalamutgil and Adali [7] proposed an adaptive switching strategy to avoid frequent mode switching. The relative velocity v_{set} and a constant L_0 are employed in this strategy as the switching thresholds. Note that the constant L_0 is greater than the desired distance. This strategy is shown in Fig. 4.

All the above switching strategies have not taken into consideration the acceleration continuity during the switching process. Apparently, discontinuous accelerations (i.e. abrupt acceleration changes) inevitably jeopardize the driving comfort during the mode switching process. Zhang et al. [25] proposed a switching strategy based on zero-expectation acceleration curves for tackling this shortcoming. In this strategy, the zero-expectation acceleration curves and the horizontal axis are used as the switching line, as shown in Fig. 5. The smooth change of acceleration is realized by a weighted average algorithm.

C. Distance-Speed-Acceleration-Based Switching Strategy

Gao et al. [13] proposed a multi-argument switching strategy to avoid violent acceleration changes during the mode switching process. This strategy is schematically shown in Fig. 6. Apart from the distance error and relative velocity, the desired acceleration is also considered in this strategy. If the vehicle states fall in the switching region of Fig. 6, the ACC operating mode is determined by the minimum desired acceleration computed in each mode.

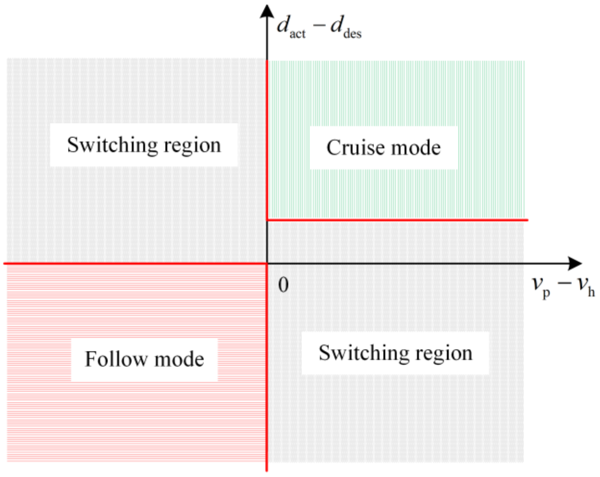

Fig. 6. Multi-argument switching strategy

It is seen that the existing ACC switching strategies are generally based on thresholds [26-28], and the switching lines used in these strategies are required to be clear. However, the determination of these switching lines is normally difficult. For this reason, Gao et al. [19] proposed a novel switching strategy based on intuitionistic fuzzy set, in which no clear switching lines are involved. The information required in this strategy includes distance, speed and acceleration. Safety, comfort, and economy are selected as attributes of the alternative modes. The optimal mode is determined by weighting the attributes of the alternative modes. Road tests proved that this strategy is superior to the traditional switching strategies based on distance and relative velocity.

The above three types of mode switching strategies are focused on the switching process itself. Indeed, simplifying the ACC control structure is also a feasible way to improve system performance. Kim et al. [29] simplified the ACC structure by introducing a virtual preceding vehicle. In this approach, no mode switching is needed because only the distance control algorithm is used in the ACC system, and undesired transients during the switching process are eliminated.

III. COMPARISON BETWEEN MODE SWITCHING STRATEGIES

In the previous section, a variety of mode switching strategies have been reviewed. To further reveal the differences between these strategies, in this section, the performances of three common mode switching strategies (i.e. distance-based switching strategy [16], distance-speed-based switching strategy [7], distance-speed-acceleration-based switching strategy [13]) are discussed and compared through simulation. The vehicle models and simulation scenarios were established in CarSim and the associated control law was implemented in MATLAB. In the simulation studies, three vehicles are involved in total, including host vehicle 1, preceding vehicle 2, and vehicle 3 in the adjacent lane. In the first 160 s of simulation, preceding vehicle 2 follows a predetermined speed profile, and host vehicle 1 operates either in cruise or follow mode, according to the inter-vehicle states. During 160 s – 200 s, preceding vehicle 2 accelerates and leaves the region of interest, and vehicle 3 in the adjacent lane cuts into the front of host vehicle 1. After driving ahead of vehicle 1 for a period of time, vehicle 3 cuts

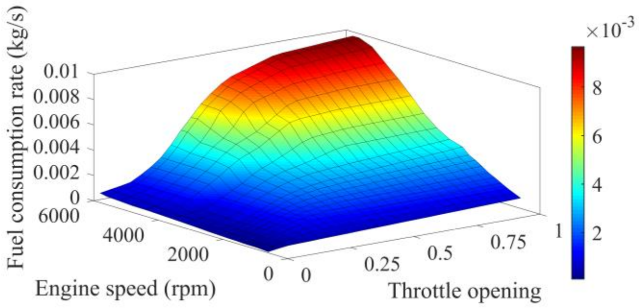

Fig. 7. Fuel consumption rate look-up table

out of the lane. In the three simulation tests, the simulation conditions (including control methods and vehicle models) are exactly the same, except for the mode switching strategies used.

This paper discusses and compares the performances of the mode switching strategies in terms of four criteria: rationality, safety, comfort, and economy. For rationality, a well-designed mode switching strategy should be able to select an appropriate operating mode for the current driving condition. In terms of safety, the distance error (i.e. difference between the actual –desired inter-vehicle distances) is selected for safety evaluation. It is known that safety is an important criterion in the design of desired inter-vehicle distance [30]. If the actual distance is less than the desired distance, then a collision may occur. When it comes to comfort, it is evaluated by acceleration and jerk in this paper [20]. As for fuel consumption, the fuel consumption rate is employed for economy evaluation in this paper. The fuel consumption rate is obtained through a 3D look-up table, as shown in Fig. 7.

A. Distance-Based Switching Strategy

Figure 8 shows the performance of the distance-based switching strategy in the simulation. It is seen in Figs. 8 (a) and 8 (b) that from 10 s to 160 s, host vehicle 1 maintains the cruise speed (65 km/h) or follows preceding vehicle 2 at a desired distance, according to the inter-vehicle states. However, as shown in Fig. 8(e), frequent mode switching occurs during this period. Between 160 s and 200 s, vehicle 3 in the adjacent lane cuts into the front of host vehicle 1. Although vehicle 3 drives faster than the cruise speed of host vehicle 1, the inter-vehicle distance is smaller than the desired distance (i.e. the distance error is negative), which activates the follow mode of host vehicle 1. Operating in this mode, host vehicle 1 accelerates to 80 km/h and follows vehicle 3. Then, vehicle 3 cuts out at 180 s, and host vehicle 1 switches to cruise mode.

In the above process, it is apparently unnecessary for host vehicle 1 to switch to follow mode and then accelerate to over the cruise speed. Therefore, the switching logic of distance-based switching strategy is unreasonable. As for safety, as shown in Fig. 8 (a), the distance error becomes negative during some time when approaching the preceding vehicle, and the minimum distance error is -4.0951 m. Therefore, the safety performance of this strategy is unsatisfactory. Besides, due to frequent mode switching, the vehicle acceleration also presents high frequency changes (as shown in Figs. 8(c) and 8(d)). During this process, the

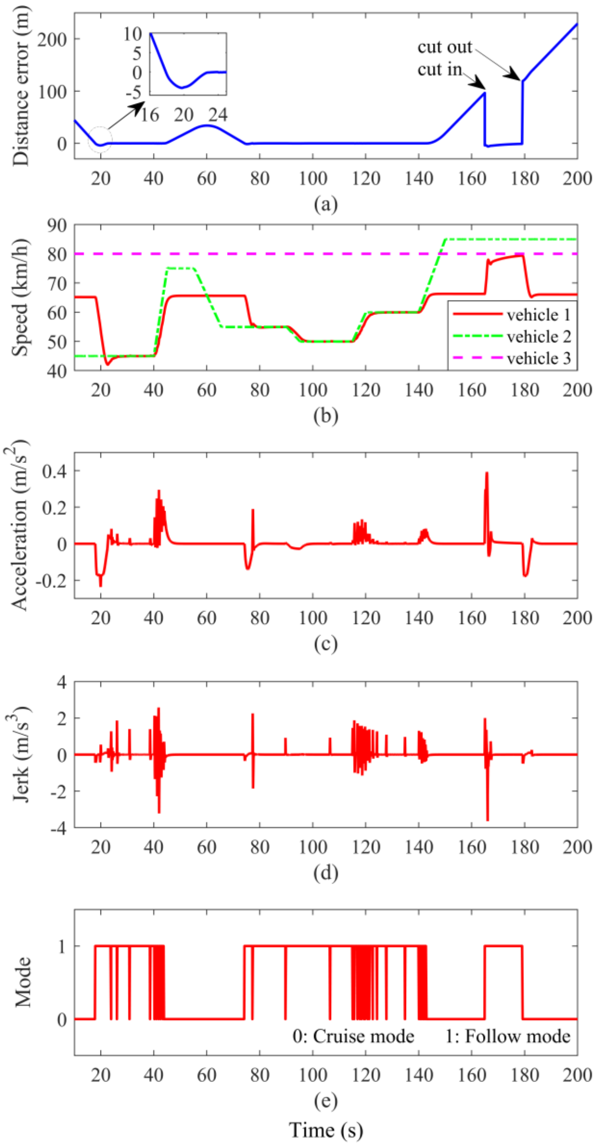

Fig. 8. Simulation results of Distance-Based Switching Strategy

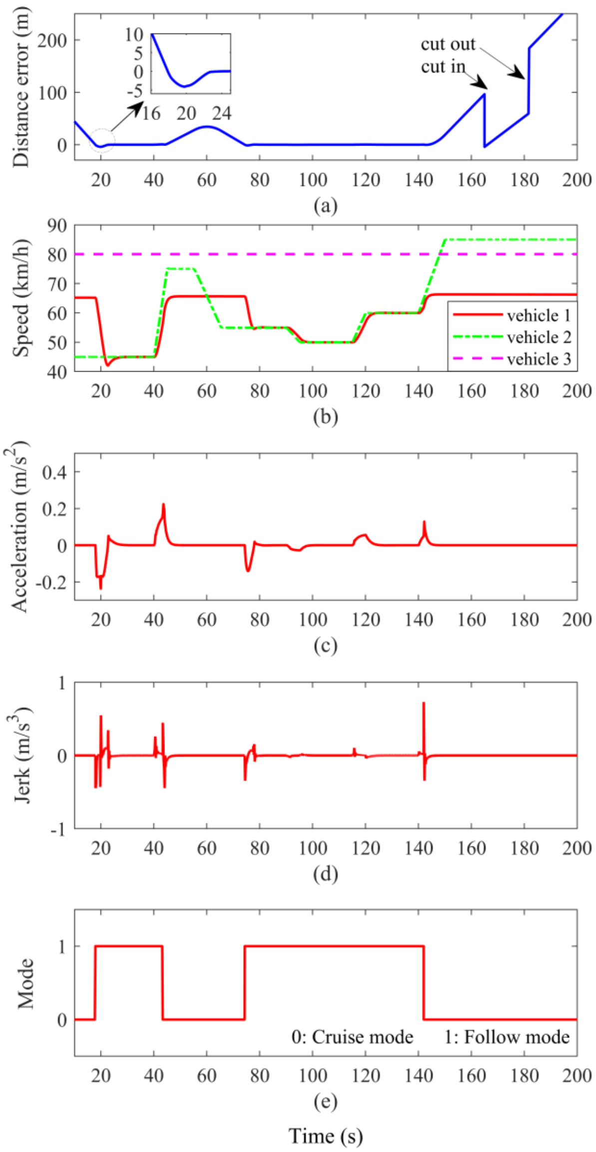

Fig. 9. Simulation results of Distance-Speed-Based Switching Strategy

maximum amplitude of acceleration is 0.3929 m/s^2, and the maximum amplitude of jerk is 3.6436 m/s^3. In terms of economy, the fuel consumption resulting from this mode switching strategy is 0.1004 kg for the entire simulated process.

B. Distance-Speed-Based Switching Strategy

Figure 9 shows the simulation results of the distance-speed-based switching strategy. As shown in Figs. 9(a) and 9(b), during 10 s – 160 s, this strategy always selects the appropriate operating mode and the ACC system performs well. Unlike the distance-based switching strategy, this strategy effectively avoids frequent mode switching during this period, as shown in Fig. 9(e). Between 160 s and 200 s, even though vehicle 3 cuts into the main lane, this strategy does not activate the follow mode due to the introduction of speed information. Therefore, the switching logic of this strategy is more reasonable compared to the previous one. However, this switching strategy also presents some safety issues under certain circumstances. For example, when approaching preceding vehicle 2, the distance error becomes negative during some time and the minimum distance error reaches -4.0951 m. As for comfort, this strategy effectively avoids frequent mode switching, which in turn significantly enhances driving comfort. Besides, the maximum amplitudes of acceleration and jerk are 0.2368 m/s^2 and 0.7304 m/s^3, respectively. During the entire simulation process, the fuel consumption reaches 0.0968 kg, which is less than that of the previous strategy.

C. Distance-Speed-Acceleration-Based Switching Strategy

Figure 10 shows the simulation results of the distance-speed-acceleration-based switching strategy. As shown in Figs. 10 (a), 10 (b), and 10 (e), between 10 s and 160 s, this strategy also performs very well and avoids frequent mode switching. During 160 s – 200 s, this strategy does not activate the follow mode of host vehicle 1 when vehicle 3 cuts in, which proves the rationality of the mode switching logic. Note that this switching strategy is seen to be safer than the previous two strategies, since the distance error never becomes negative when approaching the preceding vehicle. This is because an operating mode with a stronger deceleration is selected by this strategy. For comfort performance, this strategy is slightly better than the distance-speed based switching strategy, but the improvement is not

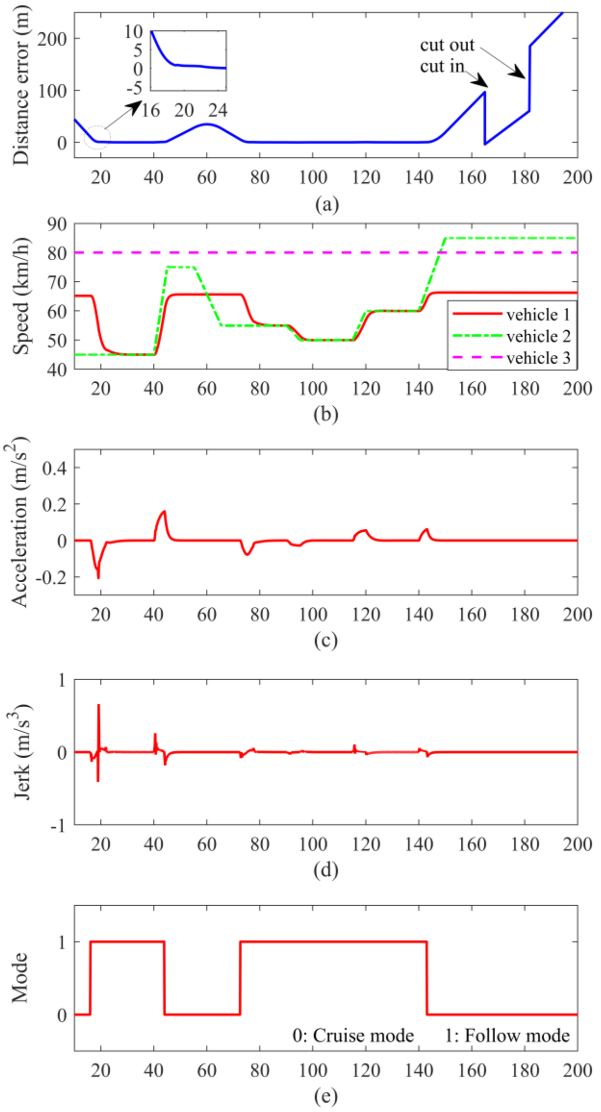

Fig. 10. Simulation results of Distance-Speed-Acceleration-Based Switching Strategy

TABLE I. SWITCHING STRATEGY SIMULATION RESULTS

Evaluation criteria	Quantitative indicators	Switching strategy		
		I	*II*	*III*
Rationality	/	Low	High	High
Safety	Distance error (m)	-4.0951	-4.0951	0
Comfort	Acceleration (m/s^2)	0.3929	0.2368	0.2064
	jerk (m/s^3)	3.6436	0.7304	0.6600
Economy	Fuel consumption quality (kg)	0.1004	0.0968	0.0944

Ⅰ refers to distance-based switching strategy, Ⅱ refers to distance-speed-based switching strategy, Ⅲ refers to distance-speed-acceleration-based switching strategy.

obvious. Among the three competing strategies, the fuel consumption of this strategy is the lowest, reaching 0.0944 kg for the simulated process.

The above comparison results between the three mode switching strategies are given in Table I. As seen from this table, the distance-speed-based switching strategy and the distance-speed-acceleration-based switching strategy provide more reasonable mode switching and better comfort, compared to the distance-based switching strategy. Besides, the distance-speed-acceleration-based switching strategy is superior to the other two strategies, in terms of safety and economy performances.

IV. SUMMARY

ACC systems are designed to provide longitudinal assistance for safety enhancement and workload reduction. The mode switching strategy employed in an ACC system plays a crucial role in ACC operation and significantly influences the overall performance. To provide a clear understanding of the current ACC mode switching strategies, in this article, we reviewed and compared several typical mode switching strategies in the existing literature. These strategies can be categorized into three major types: distance-based switching strategy, distance-speed-based switching strategy and distance-speed-acceleration-based switching strategy. The characteristics of each mode switching strategy are explained in detail, and both their pros and cons are discussed by means of comparisons.

A modern ADAS normally includes several subsystems for different purposes, such as collision avoidance (CA) and lane change assist (LCA). Namely, an ADAS is indeed an integrated control system, and the inevitable interactions between the subsystems bring about challenges for ADAS designers. Thus, devising appropriate mode switching strategies for integrated control systems is an extremely important topic to be investigated in the future.

ACKNOWLEDGMENT

This work was supported by the National Key R&D Program of China under Grant 2018YFB0106100.

REFERENCES

[1] J. Marzbanrad and I. T.-z. Moghaddam, "Self-tuning control algorithm design for vehicle adaptive cruise control system through real-time estimation of vehicle parameters and road grade," *Vehicle System Dynamics,* vol. 54, pp. 1291-1316, Sep 2016.

[2] C. Desjardins and B. Chaib-draa, "Cooperative Adaptive Cruise Control: A Reinforcement Learning Approach," *IEEE Transactions on Intelligent Transportation Systems,* vol. 12, pp. 1248-1260, Dec 2011.

[3] S. Cheng, L. Li, M. M. Mei, Y. L. Nie, and L. Zhao, "Multiple-Objective Adaptive Cruise Control System Integrated With DYC," *IEEE Transactions on Vehicular Technology,* vol. 68, pp. 4550-4559, May 2019.

[4] A. Rosenfeld, Z. Bareket, C. V. Goldman, D. J. LeBlanc, and O. Tsimhoni, "Learning Drivers' Behavior to Improve Adaptive Cruise Control," *Journal of Intelligent Transportation Systems,* vol. 19, pp. 18-31, Jan 2015.

[5] J. Pauwelussen and P. J. Feenstra, "Driver behavior analysis during ACC activation and deactivation in a real traffic environment," *IEEE Transactions on Intelligent Transportation Systems,* vol. 11, pp. 329-338, 2010.

[6] S. Wei, Y. Zou, T. Zhang, X. Zhang, and W. Wang, "Design and Experimental Validation of a Cooperative Adaptive Cruise Control System Based on Supervised Reinforcement Learning," *Applied Sciences-Basel,* vol. 8, pp. 1-21, Jul 2018.

[7] K. Haspalamutgil and E. Adali, "Adaptive switching method for Adaptive Cruise Control," in *21st International Conference on System Theory, Control and Computing, ICSTCC 2017, October 19, 2017 - October 21, 2017*, Sinaia, Romania, 2017, pp. 140-145.

[8] L. Luo, P. Li, and H. Wang, "Vehicle adaptive cruise control design with optimal switching between throttle and brake," *Journal of Control Theory and Applications,* vol. 10, pp. 426-434, 2012.

[9] J. C. Gerdes and J. K. Hedrick, "Vehicle speed and spacing control via coordinated throttle and brake actuation," *Control Engineering Practice,* vol. 5, pp. 1607-1614, 1997/11/01/ 1997.

[10] R. Rajamani, *Vehicle dynamics and control*: Springer Science & Business Media, 2011.

[11] W. Prestl, T. Sauer, J. Steinle, and O. Tschernoster, "The BMW active cruise control ACC," in *SAE 2000 World Congress, March 6, 2000 - March 9, 2000*, Detroit, MI, United states, 2000, pp. 1-7.

[12] P. Nilsson, O. Hussien, A. Balkan, Y. Chen, A. D. Ames, J. W. Grizzle*, et al.*, "Correct-by-Construction Adaptive Cruise Control: Two Approaches," *IEEE Transactions on Control Systems Technology,* vol. 24, pp. 1294-1307, Jul 2016.

[13] Z. Gao, J. Wang, H. Hu, W. Yan, D. Wang, and L. Wang, "Multi-argument Control Mode Switching Strategy for Adaptive Cruise Control System," in *Green Intelligent Transportation System and Safety, GITSS 2015*, Beijing, China, 2016, pp. 581-589.

[14] K. Yi, J. Hong, and Y. Kwon, "A vehicle control algorithm for stop-and-go cruise control," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 215, pp. 1099-1115, 2001.

[15] K. Yi, N. Ryu, H. Yoon, K. Huh, D. Cho, and I. Moon, "Implementation and vehicle tests of a vehicle stop-and-go cruise control system," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* vol. 216, pp. 537-544, 2002.

[16] J. Zhang and P. A. Ioannou, "Longitudinal control of heavy trucks in mixed traffic: Environmental and fuel economy considerations," *IEEE Transactions on Intelligent Transportation Systems,* vol. 7, pp. 92-104, 2006.

[17] K. Santhanakrishnan and R. Rajamani, "On spacing policies for highway vehicle automation," *IEEE Transactions on Intelligent Transportation Systems,* vol. 4, pp. 198-204, 2003.

[18] V. L. Bageshwar, W. L. Garrard, and R. Rajamani, "Model predictive control of transitional maneuvers for adaptive cruise control vehicles," *IEEE Transactions on Vehicular Technology,* vol. 53, pp. 1573-1585, 2004.

[19] Z. Gao, J. Wang, H. Hu, and Y. Sun, "Control mode switching strategy for ACC based on intuitionistic fuzzy set multi-attribute decision making method," *Journal of Intelligent & Fuzzy Systems,* vol. 31, pp. 2967-2974, 2016.

[20] J.-J. Martinez and C. Canudas-de-Wit, "A safe longitudinal control for adaptive cruise control and stop-and-go scenarios," *IEEE Transactions on control systems technology,* vol. 15, pp. 246-258, 2007.

[21] S. E. Shladover, D. Su, and X.-Y. Lu, "Impacts of cooperative adaptive cruise control on freeway traffic flow," *Transportation Research Record,* vol. 2324, pp. 63-70, 2012.

[22] P. Fancher and Z. Bareket, "Evaluating headway control using range versus range-rate relationships," *Vehicle System Dynamics,* vol. 23, pp. 575-596, 1994.

[23] Y. Zhai, L. Li, G. R. Widmann, and Y. Chen, "Design of switching strategy for adaptive cruise control under string stability constraints," in *Proceedings of the 2011 American Control Conference, ACC 2011*, San Francisco, 2011, pp. 3344-3349.

[24] G. R. Widmann, M. K. Daniels, L. Hamilton, L. Humm, B. Riley, J. K. Schiffmann*, et al.*, "Comparison of lidar-based and radar-based adaptive cruise control systems," in *SAE 2000 World Congress, March 6, 2000 - March 9, 2000*, Detroit, MI, United states, 2000.

[25] D. Zhang, J. Wang, J. Liu, K. Li, and X. Lian, "Switching strategy for adaptive cruise control modes for continuous acceleration," *Journal of Tsinghua University Science and Technology,* vol. 50, pp. 1277-1281, 2010.

[26] P. Shakouri and A. Ordys, "Nonlinear model predictive control approach in design of adaptive cruise control with automated switching to cruise control," *Control Engineering Practice,* vol. 26, pp. 160-177, 2014.

[27] P. Shakouri, A. Ordys, D. S. Laila, and M. Askari, "Adaptive cruise control system: Comparing gain-scheduling PI and LQ controllers," in *Proceedings of the 18th IFAC World Congress*, Milano ,Italy, 2011, pp. 12964-12969.

[28] J. Z. Chen, Y. Zhou, and H. Liang, "Effects of ACC and CACC vehicles on traffic flow based on an improved variable time headway spacing strategy," *Iet Intelligent Transport Systems,* vol. 13, pp. 1365-1373, Sep 2019.

[29] S. G. Kim, M. Tomizuka, and K. H. Cheng, "Mode switching and smooth motion generation for adaptive cruise control systems by a virtual lead vehicle," in *12th IFAC Symposium on Transpotaton Systems, CT'09 - Final Program*, Redondo Beach, CA, USA, 2009, pp. 490-496.

[30] C. Wu, Z. Xu, Y. Liu, C. Fu, K. Li, and M. Hu, "Spacing Policies for Adaptive Cruise Control: A Survey," *IEEE Access,* vol. 8, pp. 50149-50162, 2020.