Spacing Policies for Adaptive Cruise Control: A Survey

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ABSTRACT Adaptive cruise control (ACC) systems are designed to provide longitudinal assistance for drivers to enhance safety and reduce workload. As the core of all ACC control algorithms, the spacing policy plays a crucial role in various aspects. This paper presents a comprehensive survey on spacing policies for existing ACC solutions in the literature. The objectives of this paper are to clarify the operating mechanisms and characteristics of the common spacing policies, and to reveal their advantages and shortcomings by means of a comparative study. In this survey, the general evaluation criteria for spacing policies are first introduced. Then, the existing spacing policies are categorized into different types according to their operating mechanisms, and their characteristics are carefully reviewed and explained. A comparative study is followed to analyze the performances of five typical spacing policies in the literature, including the constant spacing policy, constant time headway, traffic flow stability, constant safety factor and human driving behavior spacing policies. The contents provided in this paper serve as a tool for understanding current ACC spacing policies, and pave the way for future ACC enhancement.

INDEX TERMS Adaptive cruise control, spacing policy, traffic flow stability, string stability, time headway.

I. INTRODUCTION

In recent decades, advanced driver assistance systems (ADAS) have attracted significant attention from both academia and automotive industry [1]. The existing ADAS on the market are designed to assist drivers in many different ways. As a typical type of ADAS, the adaptive cruise control (ACC) systems assist with driving in one of the most important aspects – vehicle longitudinal control [2]. ACC is an extension or enhancement of the traditional cruise control (CC) systems [3], [4]. An ACC system maintains a certain cruise speed or a desired distance with respect to the preceding vehicle by automatically adjusting throttle or brake [5], [6]. The first generation ACC systems were mainly developed for improving driving comfort [7], [8]. Indeed, ACC systems also have the potential to improve other performance such as traffic efficiency, safety, fuel economy and emission [9]–[14]. Furthermore, as the fast development of electric vehicles and hybrid electric vehicles, complex power systems [15], [16] and regenerative braking [17], [18] have brought about new potential and challenges to the next generation of ACC systems.

The core of any ACC systems is the spacing policy. In other words, all ACC designs begin with the selection of an appropriate spacing policy [19]. The spacing policy refers to the desired steady state spacing between two consecutive vehicles during vehicle following. The spacing policy of an ACC system plays an important role in various aspects such as traffic capacity, fuel/energy consumption, driver's subjective acceptance, and safety [20]–[24]. Previous research on spacing policy was mainly focused on the longitudinal control of the personal rapid transit (PRT) system [25], [26] and automated highway systems (AHS) [27], [28]. Along with the fast development of ACC systems, these preliminary results and findings are successfully applied to ACC systems.

In recent years, a lot of efforts have been made for improving spacing policies, and many interesting results have

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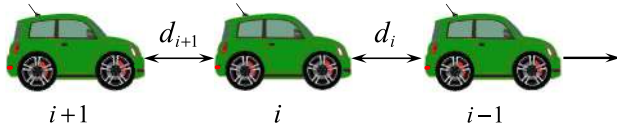
FIGURE 1. Adaptive cruise control vehicles.

FIGURE 2. String stability of two ACC platoon examples. (a) unstable platoon; (b) stable platoon.

been produced in the literature. In this survey, we categorize existing spacing policies according to their operating mechanisms, and carefully review the characteristics of each policy. The rest of this paper is organized as follows: Section II describes the evaluation criteria for spacing policies, Section III discusses the details of various spacing policies, Section IV compares the performances of five typical spacing policies, and Section V summarizes the contents in this survey and provides recommendations for future work.

II. EVALUATION CRITERIA FOR SPACING POLICIES

In the existing literature, the following criteria are used to evaluate the spacing policies:

1) The spacing policy and its associated control law must guarantee individual vehicle stability. Mathematically, this criterion implies that the spacing error of the host vehicle δ_i should converge to zero if the preceding vehicle is operating at a constant speed v_{i-1} [29]–[31], namely:

$$\delta_i = d_i - d_{\text{des}} \qquad \dot{v}_{i-1} \to 0 \Rightarrow \delta_i \to 0 \tag{1}$$

where i is an index representing the order of a vehicle in a platoon, d_i denotes the actual inter-vehicle spacing between the $i - 1$th vehicle and the ith vehicle, and d_{des} represents the desired inter-vehicle spacing. Note that the host vehicle is normally identified by index i in the literature (see Figure 1). The individual vehicle stability is a basic requirement [32], which guarantees the fundamental functions of an ACC system.

2) The selected spacing policy should have a companion ACC controller that ensures string stability [33], [34]. The string stability of a platoon of ACC vehicles is a property that constrains the spacing errors from diverging as the errors propagate towards the tail of the platoon [35], [36]. Unlike the individual stability which describes the behavior of a single vehicle, the string stability is a group property that describes the interaction between vehicles in a platoon [37]. The concept of string stability is graphically demonstrated in Figure 2. We see in Figure 2(a) an unstable ACC platoon in which the spacing error increases as it propagates towards the tail, in other words, the string stability of this platoon is not maintained. On the other hand, Figure 2(b) shows that the spacing error smoothly decreases along the platoon, indicating that the string stability is guaranteed.

It is claimed in [38] that the string stability of a platoon is directly related to the spacing policy selected. Normally, the following condition is used to determine if a platoon is
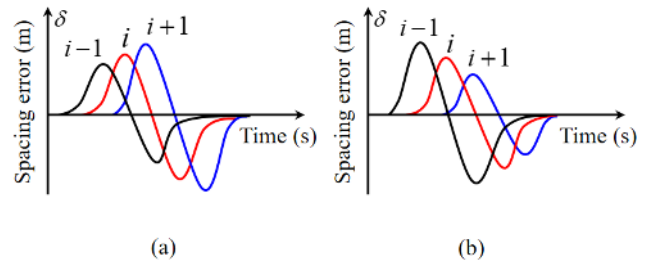
string stable [39], [40]:

$$\left\| \widehat{H}(s) \right\|_\infty \leq 1, \quad \widehat{H}(s) = \frac{\delta_i}{\delta_{i-1}} \tag{2}$$

where $\widehat{H}(s)$ is the transfer function relating the spacing errors of consecutive vehicles.

3) The traffic flow stability should be guaranteed by the selected spacing policy. The traffic flow stability associated with a specific spacing policy refers to a macroscopic property of the traffic flow which would be obtained if all vehicles on a highway adopted this particular spacing policy [41], [42]. It reflects the variations of traffic flow in response to small disturbances in traffic density [43]. The following condition is normally employed to determine if a system is traffic stable [44]:

$$\frac{\partial Q}{\partial \rho} > 0 \tag{3}$$

where Q denotes the traffic volume flow rate, and ρ represents the traffic density. Indeed, no matter what spacing policy is chosen, it is impossible to guarantee the traffic flow stability for all traffic density [45]. However, measures should be taken to ensure the traffic flow stability for a largest possible traffic density range.

4) The spacing policy should enable the host vehicle to avoid any possible collisions, under unpredictable actions of the preceding vehicle. This criterion imposes comprehensive security constraints on a spacing policy. Although criteria 1) and 2) are also related to safety [46], they are only necessary conditions for avoiding collisions, as opposed to sufficient ones [8], [47]. The main objective (or priority) of criteria 1) and 2) is stability performance as opposed to safety, and they do not necessarily provide absolute collision avoidance. To guarantee collision avoidance under unpredictable actions of the preceding vehicle, this important safety-oriented criterion must be introduced.

5) The spacing policy should provide similar driving patterns to human driving behaviors, in order to avoid possible discomfort for the driver and passengers.

In fact, the selection of spacing policy is a highly complex problem, as many design objectives are inherently contradictory. For example, a smaller inter-vehicle spacing can increase traffic throughput, however, the safety may be jeopardized if the inter-vehicle spacing is chosen too small.

Hence, a successful spacing policy often requires careful trade-offs between multiple design goals.

III. DIFFERENT TYPES OF SPACING POLICIES

The current spacing policies can be classified into two major categories: constant spacing policy and variable spacing policies [48]. The characteristics of these spacing policies are summarized in the following sections.

A. CONSTANT SPACING POLICY

The ACC vehicle using the constant spacing policy (CSP) always keeps a constant inter-vehicle spacing from the preceding vehicle during ACC operation, which is independent of the driving environment [49]–[51]. This spacing policy can be simply expressed as [52], [53]:

$$d_{des} = L \qquad (4)$$

where d_{des} denotes the desired inter-vehicle spacing, and L represents a fixed positive constant.

The computation load of the CSP is low, and it provides high traffic capacity if a small L is chosen [54]. Specifically, it is suggested in [42], [43] that the value of L be chosen as 1 m. However, it has been proven that when linear controllers are used, the CSP cannot guarantee string stability [55]–[58]. It is claimed in [59] that the unstable platoon is not only likely to provide poor ride quality but also could result in collisions. To tackle this issue, a solution is proposed in [60]–[63] to achieve string stability with CSP, by means of maintaining continuous inter-vehicle communication. Some existing studies on string stability using CSP are summarized in Table 1. Once the string stability is achieved, the CSP provides the potential to enhance traffic capacity by choosing a small L [35], [64]. This idea is employed in the design of CSP-based cooperative adaptive cruise control (CACC) systems [65]–[67]. It is not practical to maintain high-quality inter-vehicle communication for long platoons [68]. As a result, in practice, no ACC system on the market has adopted CSP.

B. VARIABLE SPACING POLICIES

In variable spacing policies, the desired inter-vehicle spacing is treated as a function of the ACC vehicle's speed. In this survey, the existing variable spacing policies in the literature are categorized into four major types, according to their underlying operating mechanism: time headway-based spacing policy, traffic flow stability spacing policy, constant safety factor spacing policy, and human driving behavior spacing policy.

1) TIME HEADWAY-BASED SPACING POLICY

The most typical variable spacing policy is the time headway-based spacing policy. In some existing works the phrase 'time gap' is employed instead of 'time headway' [69]–[71]. Strictly speaking, the time gap refers to the period during which the rear bumper of the preceding vehicle and the front bumper of the host vehicle pass a fixed position on
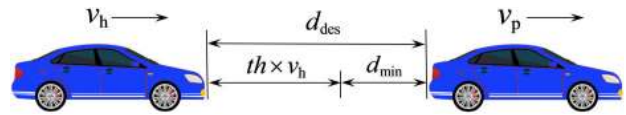
the road, while the time headway refers to the period during which the front bumper of the preceding vehicle and the front bumper of the host vehicle pass a fixed position on the road. Although these two are different in quantity, they lead to the same vehicle behavior from a qualitative perspective [36]. In this paper, these two types of spacing policies are no longer distinguished, but are uniformly classified as the time headway-based spacing policy. Time headway-based spacing policy can be mathematically expressed as a function of the host vehicle's speed:

$$d_{des} = th \times v_h + d_{min} \qquad (5)$$

where th represents the time headway, v_h denotes the host vehicle speed, and d_{min} is the minimum clearance allowed when both the preceding and host vehicles stop completely. Two types of time headways are commonly used: constant time headway (CTH) and variable time headway (VTH). The th in equation (5) is a constant in CTH while a variable in VTH.

Alternatively, the time headway-based spacing policy can also be expressed as a function of the preceding vehicle's speed (instead of the host vehicle's speed), namely [74]–[76]:

$$d_{des} = th \times v_p + d_{min} \qquad (6)$$

where v_p denotes the preceding vehicle speed. However, this policy increases the likelihood of collisions in an emergency [77]. Figure 3 shows a schematic of the time headway-based spacing policy.

The time headway-based spacing policy was proposed based on the kinematic relationship between the preceding and host vehicles, which is mathematically expressed by [78]–[80]:

$$d_{des} = \lambda_1(v_h^2 - v_p^2) + \lambda_2 v_h + \lambda_3 \qquad (7)$$

where the terms v_h and v_p represent the speeds of the host and preceding vehicles respectively, and λ_1, λ_2 and λ_3 are three constant coefficients. For tight vehicle following conditions, where v_h is close to v_p, equation (7) simplifies to the form of equation (5) by neglecting the first term.

As mentioned above, the th in the CTH spacing policy is a constant, which indicates that the desired inter-vehicle spacing must be proportional to the vehicle speed. This spacing policy is consistent with the driving intuition of slowing down as the inter-vehicle spacing decreases [81]. The selection of time headway has a significant impact on subjective driver states [22], including risk rating, task difficulty, effort and comfort [82], [83]. The values of th and d_{min} can be determined based on the driving test data [21], [84]. Commercial ACC systems normally employ a selectable th

TABLE 1. A summary of existing studies on string stability based on CSP.

Reference	Information obtained from inter-vehicle communication	Control law	String stability
[60]	/	$u_i = -k_v \dot{\delta}_i - k_p \delta_i$	unstable
[56], [72]	lead vehicle speed v_L and lead vehicle acceleration a_L	$u_i = c_p \delta_i + c_v \dot{\delta}_i + c_a \ddot{\delta}_i + k_v (v_L - v_i) + k_a (a_L - a_i)$	stable
[57], [73]	lead vehicle position x_L	$u_i = k_p \delta_i + k_l [x_L - x_i - (i-1) \times (d_{des} + L_V)]$	stable
[55]	lead vehicle speed v_L and lead vehicle position x_L	$u_i = k_D [\dot{\delta}_i + (v_L - v_i)] + k_P [\delta_i + (x_L - x_i - iL_V - id_{des})]$	stable

"/" means "only radar information is used, and no inter-vehicle communication is available".

between 1 s - 2 s [85]. Unlike the CSP, the CTH spacing policy can achieve string stability without inter-vehicle communication [19], [35], [37]. Since a very small th may jeopardize the string stability regardless of the spacing policy, an appropriate th should be selected when adopting the CTH spacing policy. Indeed, the CTH spacing policy has become the most common spacing policy in both academia and automotive industry [45]. As the development of inter-vehicle communication technology, current ACC systems will most likely evolve into CACC systems in the near future [86], with CTH chosen as the spacing policy [87]–[90].

However, the CTH spacing policy is not suitable for high-density traffic conditions [2]. The reason is two-folds: Firstly, the CTH spacing policy increases the inter-vehicle spacing, thereby reducing traffic throughput [91]–[93]. Secondly, this spacing policy cannot guarantee the traffic flow stability [43], [45].

To overcome the first drawback of the CTH spacing policy, the VTH spacing policy was firstly proposed by Yanakiev and Kanellakopoulos [94] in 1995. Broqua et al. [95] proposed a VTH spacing policy in which the th is a variable dependent on the host vehicle speed. This spacing policy can be expressed as:

$$d_{des} = th \times v_h + d_{min} \quad th = h_1 + h_2 \times v_h \quad (8)$$

where h_1 and h_2 are two positive constants. Note that this time headway th increases with the host vehicle speed v_h. In practice, the vehicle speed is bounded by an upper limit v_{max}. Hence, the time headway th is written as follows:

$$th = \begin{cases} h_1 + h_2 \times v_h, & v_h < v_{max} \\ h_1 + h_2 \times v_{max}, & \text{otherwise} \end{cases} \quad (9)$$

The VTH spacing policy proposed in [94] is formulated based on relative speed, which is mathematically given by:

$$th = h_0 - c_1 v_r \quad v_r = v_p - v_h \quad (10)$$

where $h_0 > 0$ and $c_1 > 0$ are two constants. The time headway has to be always positive, however, a too large time headway is undesirable as it decreases the traffic through-put [96]. Therefore, the time headway is limited within the

interval [0, 1], as follows [94]:

$$th = sat(h_0 - c_1 \times v_r)$$
$$= \begin{cases} 1, & \text{if } h_0 - c_1 \times v_r \geq 1 \\ h_0 - c_1 \times v_r, & \text{if } 0 < h_0 - c_1 \times v_r < 1 \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

In addition to the VTH spacing policy, the introduction of a speed parameter in equation (5) is also an effective approach to reduce the inter-vehicle spacing of the CTH spacing policy. Ali et al. [97] proposed a spacing policy for decreasing the inter-vehicle spacing of CTH, which can be expressed by:

$$d_{des} = th \times (v_h - v^*) + d_{min} \quad (12)$$

where v^* is a reference speed shared by all vehicles in the platoon. Note that v^* can be chosen as the speed of the lead vehicle or the minimum speed in the platoon.

In [98], [99], the reference speed v^* in equation (12) is defined as follows:

$$v^* = \begin{cases} 0, & e_i < S_1 \\ \bar{v}^*, & S_1 \leq e_i \leq S_2 \\ v'_{max}, & e_i > S_2 \end{cases} \quad (13)$$

where S_1 and S_2 are two positive constants, v'_{max} denotes the maximum speed in the platoon, e_i is defined as $e_i = d_i - d_{min}$, and $\bar{v}^*$ takes the following form:

$$\bar{v}^* = \frac{v'_{max}}{2}[1 - \cos(\pi \frac{e_i - S_1}{S_2 - S_1})] \quad (14)$$

2) TRAFFIC FLOW STABILITY SPACING POLICY

As mentioned above, one of the drawbacks in the CTH spacing policy is that the traffic flow stability cannot be guaranteed. The traffic flow stability (TFS) spacing policy is a possible approach for tackling this shortcoming. One TFS spacing policy was designed based on the Greenshield's relation, and it has been proven to provide better traffic flow stability while ensuring safety [45], [48], [100]. This TFS spacing policy is mathematically given by [45]:

$$d_{des} = \frac{1}{\rho_{max}(1 - v_h/v_f)} \quad (15)$$

where v_f denotes the free speed of the traffic and ρ_{max} represents the jam density. In [45], v_f is equal to the cruise speed and ρ_{max} is chose as $1/L_0$, where L_0 is the sum of the inter-vehicle spacing at rest and the vehicle length. It should be pointed out that the vehicle length is included in the result calculated from equation (15). Indeed, the vehicle length should be subtracted from equation (15) to obtain the following accurate expression:

$$d_{des} = \frac{1}{\rho_{max}(1 - v_h/v_f)} - L_V \qquad (16)$$

where L_V is the uniform vehicle length. Based on the findings in [45], Chen *et al.* [101] proposed an enhanced TFS spacing policy which takes into account relative vehicle speed and preceding vehicle's acceleration.

Santhanakrishnan and Rajamani [8] developed a TFS spacing policy based on the traffic volume flow rate curve (i.e. the $Q - \rho$ curve), in which the desired spacing d_{des} is a nonlinear function of the host vehicle speed. The traffic volume flow rate curve is in the form of a piecewise function, which ensures traffic flow stability and leads to higher traffic flow capacity. Zhou and Peng [33] proposed another TFS spacing policy through a constrained optimization procedure. This policy can be expressed as follows:

$$d_{des} = 3 + 0.0019v_h + 0.0448v_h^2 \qquad (17)$$

Compared with the CTH spacing policy, this policy provides smoother traffic flow, better string stability and lower energy consumption [20].

3) CONSTANT SAFETY FACTOR SPACING POLICY

Safety is one of the major concerns for ACC systems [102]. Constant safety factor (CSF) spacing policy was proposed to improve safety and minimize the possibility of collisions [103]. The CSF spacing policy can be obtained by analyzing the emergency braking process [25]. This spacing policy is normally expressed as [54], [104]:

$$d_{des} = K \times D_{stop} \qquad (18)$$

where D_{stop} denotes the safe stopping distance, and K is a safety factor. To avoid collisions in an emergency, K is generally a constant greater than 1 [105]. The values of K for different vehicles are available in [106]. In earlier works, the safe stopping distance D_{stop} was usually defined as [107]–[109]:

$$D_{stop} = v_h^2 / (2\alpha_{max}) \qquad (19)$$

where α_{max} is the maximum deceleration of the host vehicle. Hence, the CSF spacing policy in equation (18) is rewritten as [109]:

$$d_{des} = K \times \frac{v_h^2}{2\alpha_{max}} \qquad (20)$$

In recent literature, a modified CSF spacing policy was proposed in [52], [110]:

$$d_{des} = d_{min} + \sigma v_h + K \times D_{stop} \qquad (21)$$

where d_{min} represents a constant distance, and σ is the time delay of the vehicle longitudinal control system. According to [111], σ may range from 10 ms to 80 ms. Flores *et al.* [112] developed a new spacing policy by combining the CTH and CSF spacing policies. This policy is able cover the entire vehicle speed range for ACC and CACC systems.

Compared with the CTH spacing policy, the CSF spacing policy can also guarantee string stability without inter-vehicle communication [113]. However, as its name suggests, the CSF spacing policy operates with higher emphasis on safety and it is more conservative safety-wise. In addition, some evidence indicates that the CFS spacing policy can achieve traffic flow stability [110].

4) HUMAN DRIVING BEHAVIOR SPACING POLICY

Previous research on spacing policy has been mostly focused on stability and safety [114]. However, in order to enhance comfort and customer acceptance, apart from stability and safety, the effects of human driving behaviors should be taken into considerations. In other words, advanced ACC systems need to operate in a similar fashion to human drivers to reflect their physical and mental capabilities [115]. It is stated in [33] that an ACC spacing policy should be similar to human driver's spacing behavior. To this end, real human driving data has been employed to develop ACC spacing policies in recent works [21], [116], [117].

Fancher *et al.* [117] proposed a spacing policy based on human driving behavior (HDB). In this study, driving behaviors of 107 drivers were recorded. This HDB spacing policy can be expressed in a quadratic form, as follows:

$$d_{des} = A + Tv_h + Gv_h^2 \qquad (22)$$

where A represents the inter-vehicle spacing at rest, and T and G are the coefficients of the first and second order terms, respectively. Note that the values of T and G can be determined by curve fitting. The value of T for individual drivers lies within the range of 1 s to 2.5 s, and these two coefficients are approximately related by $G = -0.0246T + 0.010819$.

The HDB spacing policy can improve driver's acceptance and system utilization by introducing characteristics of human drivers [118]. However, the drawback of this spacing policy is that the traffic flow stability cannot be guaranteed [52].

IV. COMPARISONS BETWEEN TYPICAL SPACING POLICIES

In the previous section, a variety of spacing policies have been reviewed. To further understand the differences between these spacing policies, in this section, the performances of five typical spacing policies are discussed and compared in terms of individual vehicle stability, string stability, traffic flow stability, safety and comfort, i.e. the five evaluation criteria introduced in Section II.

Figure 4 presents the desired inter-vehicle spacing curves resulting from different spacing policies, including CSP (equation (4)), CTH spacing policy (equation (5)), TFS
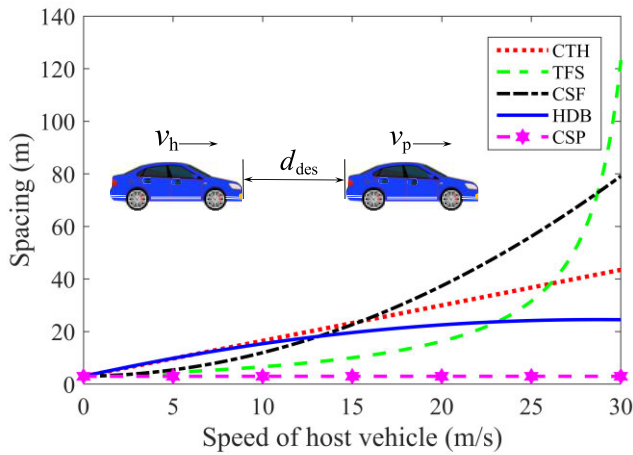
FIGURE 4. Desired inter-vehicle spacing of various spacing policies.

FIGURE 5. ACC platoon model established in CarSim.

TABLE 2. Parameters used for various spacing policies.

Symbol	Description	Value	Unit
L	Constant spacing	3	m
th	Time headway	1.35	s
d_{min}	Minimum clearance	3	m
L_v	Uniform vehicle length	5	m
ρ_{max}	Jam density	0.125	vehicle/m
v_f	Free speed of the traffic	32	m/s
σ	Time delay	0.08	s
K	Safety factor	1.2	-
α_{max}	Maximum deceleration	7.32	m/s^2
A	Distance at standstill	3	m
T	Curve parameter	1.5	s
G	Curve parameter	-0.026081	s^2/m

FIGURE 6. Actual speed curve of lead vehicle.

spacing policy (equation (16)), CSF spacing policy (equation (21)), and HBD spacing policy (equation (22)). It is necessary to emphasize that only CSP produces a constant desired spacing, and the others provide variable desired spacings as the host vehicle speed changes. The cruise speed used in the simulation studies in this paper is 115 km/h (32 m/s). Other parameters are determined according to [33], [45], [110], [119], and they are given in Table 2.

Typical ACC systems operate above a minimum speed. For example, the minimum operating speed for Bosch's ACC system is 30 km/h (8.33m/s). Therefore, in Figure 4, we are only interested in the region with a speed of 10 m/s or greater.

The CSP, as its name suggests, always maintains a constant inter-vehicle spacing (3 m in our simulation) during ACC operation. Intuitively, to ensure safety, a larger spacing is required for higher vehicle speed. However, the CSP cannot meet this requirement and in turn endangers the involved vehicles at high speed. Among the five competing spacing policies, only the CTH generates a linear desired inter-vehicle spacing (i.e. proportional to the host vehicle speed). Besides,
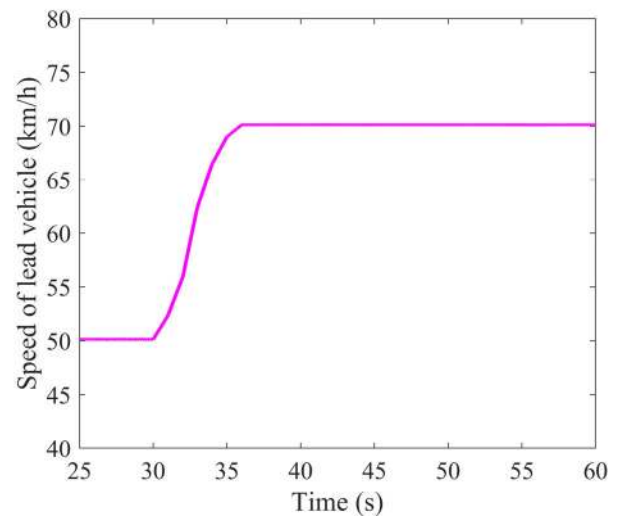
the spacing resulting from the CTH is larger than the others at low speed. For the TFS spacing policy, in the low to medium speed range, the desired inter-vehicle spacing grows very slowly with the host vehicle speed. However, at high speed, the spacing becomes highly nonlinear and increases rapidly with the host vehicle speed, especially near the cruise speed. Not only can this rapid change at high speed lead to frequent cut-ins, but also drastic spacing change in response to a small speed variation. As a result, drivers may experience discomfort and engineers may encounter troubles when designing the ACC controller. As for the CSF spacing policy, the desired inter-vehicle spacing is larger than the others in the medium to high speed range. The larger spacing well ensures safety but results in loss of traffic capacity. Regarding the HDB spacing policy, the slope of the spacing curve is smaller than the others, indicating that the desired inter-vehicle spacing is not sensitive to the host vehicle speed. Besides, the spacing of HDB is the lowest among the four variable spacing policies at high speed, which gives rise to the highest collision possibility among these four.

	Spacing policy	ACC upper-level control law	Reference
CSP	$d_{\text{des}} = L$	$\ddot{x}_{i\_\text{des}} = -k_{\text{v}}\dot{\delta}_i - k_{\text{p}}\delta_i$	[60]
CTH	$d_{\text{des}} = th \times v_{\text{h}} + d_{\min}$	$\ddot{x}_{i\_\text{des}} = -\dfrac{1}{h}(\dot{\varepsilon}_i + \lambda\delta_i)$	[79]
TFS	$d_{\text{des}} = \dfrac{1}{\rho_{\max}(1 - v_{\text{h}}/v_{\text{f}})}$	$\ddot{x}_{i\_\text{des}} = -\rho_{\text{m}}(v_{\text{f}} - v_i)(1 - \dfrac{v_i}{v_{\text{f}}})(\dot{\varepsilon}_i + \lambda\delta_i)$	[44]
CSF	$d_{\text{des}} = d_{\min} + \sigma v_{\text{h}} + K \times D_{\text{stop}}$	$\ddot{x}_{i\_\text{des}} = -(\dot{\varepsilon}_i + \lambda\delta_i) \Big/ (t_{\text{d}} - \dfrac{\gamma}{j_i}\dot{x}_i)$	[123]
HDB	$d_{\text{des}} = A + Tv_{\text{h}} + Gv_{\text{h}}^2$	$\ddot{x}_{i\_\text{des}} = (1 - \dfrac{\tau T_v}{T_a})a_i + \dfrac{\tau}{T_a}\dot{R}_i + \dfrac{\tau\lambda}{T_a}\varepsilon_i$	[33]
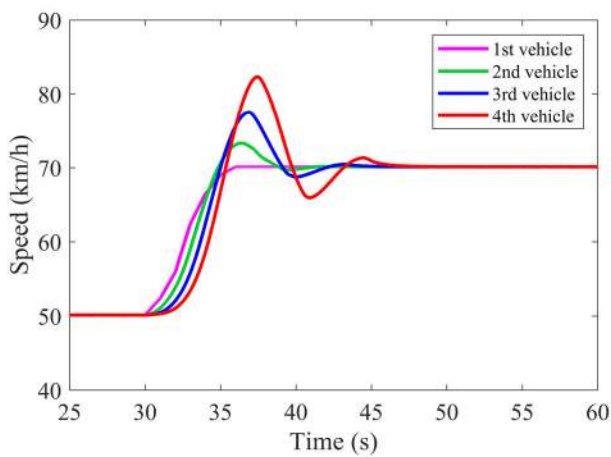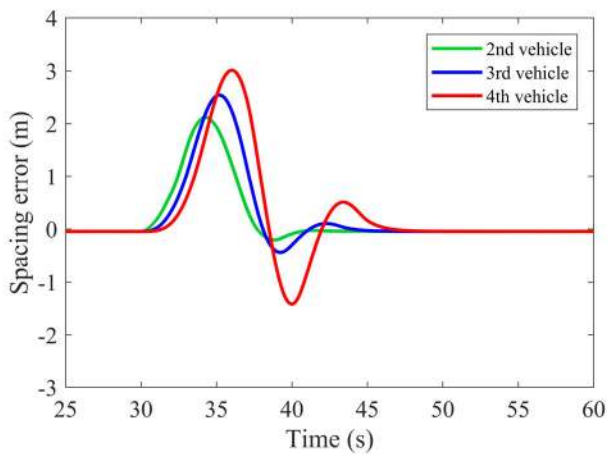
FIGURE 7. ACC platoon stability performance of CSP.

To discuss individual stability and string stability, a complete ACC platoon model is necessary for simulation analyses. For this purpose, an ACC platoon model was built in CarSim and its associated control law was designed in MATLAB in this study. Figure 5 shows the established platoon that includes four identical vehicles. A complete ACC controller is usually designed to be a hierarchical structure containing an upper-level controller and a lower-level controller [120]. The upper-level controller determines the desired acceleration for the ACC vehicle [71], [121], while the lower-level controller determines the throttle or brake command to track the desired acceleration sent from the upper-level controller [93]. In this study, the upper-level control laws corresponding to each spacing policy are given in Table 3, and the lower-level control laws are all PID control.

To investigate the string stability of the platoon, in the simulation study a typical disturbance (i.e. velocity variation of the lead vehicle) was applied to the platoon [122]. Specifically, the simulation condition is designed as follows: the four simulated vehicles are driven in a compact ACC platoon, and the actual speed curve of the lead vehicle (1st vehicle) is shown in Figure 6. During the simulation period of 25 s − 30 s, the lead vehicle is maintained at 50 km/h. Starting from 30 s, the lead vehicle begins accelerating until it reaches 70 km/h at 36 s. Afterwards, the lead vehicle is maintained at 70 km/h. Each of the following vehicles follows its own preceding vehicle based on the designed ACC control law.

Figure 7 shows the ACC platoon stability performance with the CSP onboard. During 25 s − 30 s, the lead vehicle is maintained at 50 km /h, and the spacing errors of the three following vehicles are 0. This indicates that the CSP and its associated control law can guarantee individual vehicle stability. During 30 s − 36 s, the lead vehicle accelerates to 70 km/h, and both the speed (see Figure 7(a)) and spacing error (see Figure 7(b)) of the following vehicles start to amplify towards the tail of the platoon. This implies that the string stability cannot be achieved by using CSP.

Figure 8 shows the ACC platoon stability performance resulting from the four variable spacing policies. We see from the results during 25 s − 30 s that the individual stability of each vehicle in the platoon is guaranteed using these four variable spacing policies. Besides, it is also seen that when the
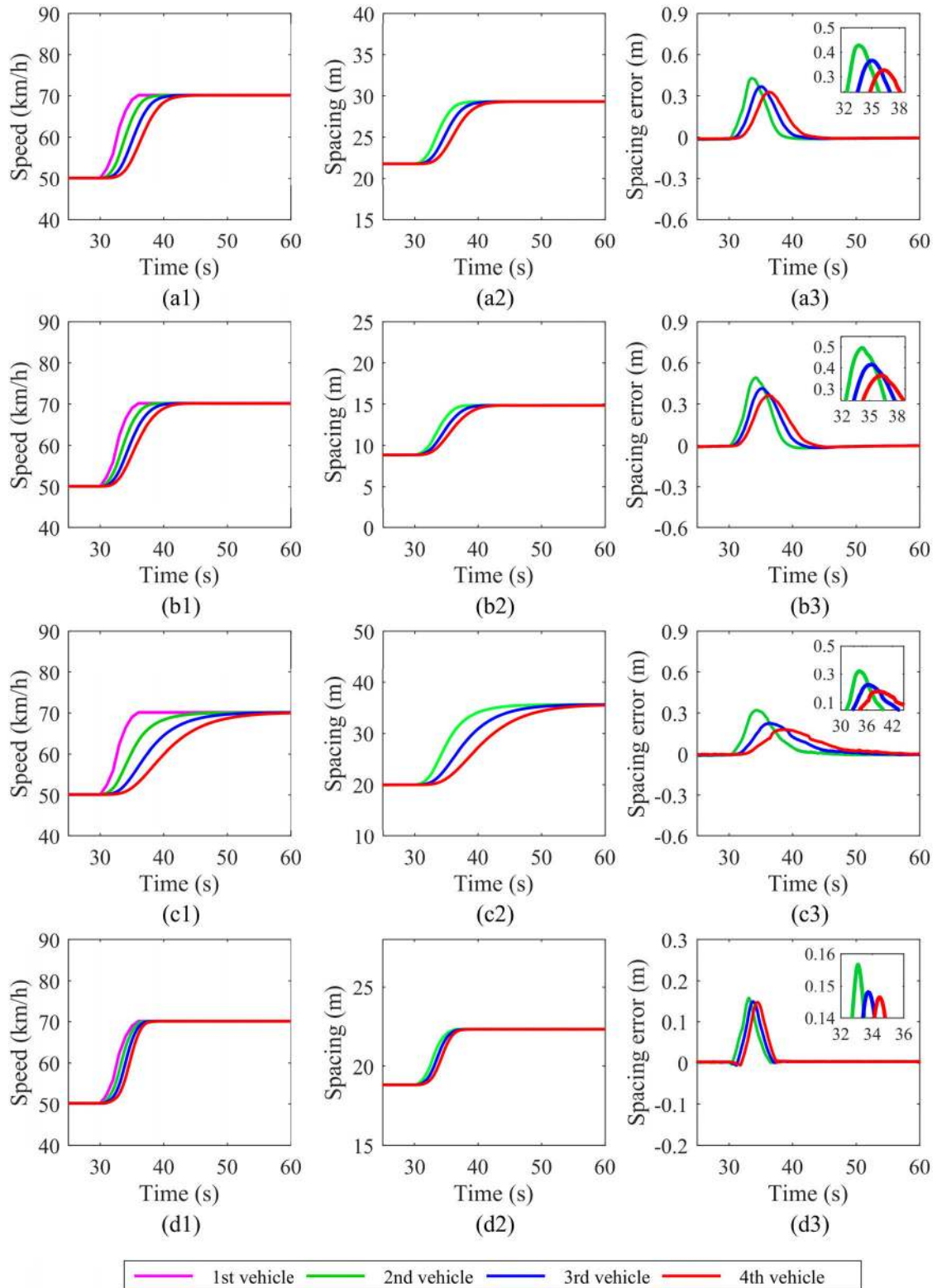
FIGURE 8. ACC platoon stability performance of variable spacing policies. a(1)- a(3) based on CTH; b(1)- b(3) based on TFS; c(1)- c(3) based on CSF; d(1)- d(3) based on HDB.

speed of the lead vehicle increases, each of the three following vehicles can smoothly trace its own preceding vehicle, and the spacing error gradually decreases towards the tail of the platoon. Compared to the CSP, although the spacing performances of the four variable spacing policies are different, yet all of them can achieve string stability.
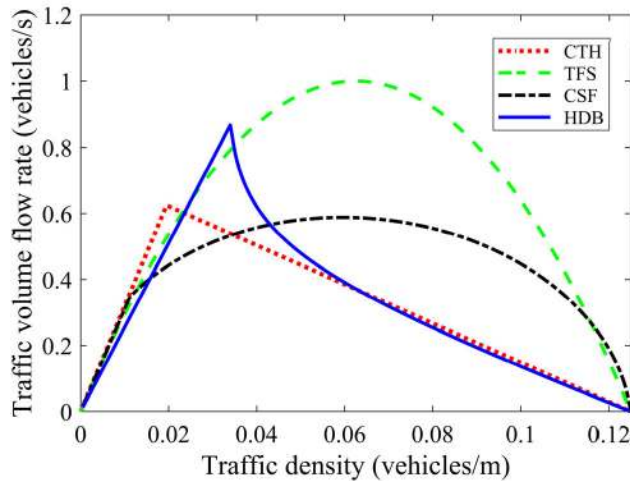
FIGURE 9. Traffic volume flow rate curves of various variable spacing policies.

As for the traffic flow stability, only the performances of the four variable spacing policies are discussed in this paper. The CSP is not considered in this topic as it always maintains a constant inter-vehicle spacing, which makes the discussion of traffic flow stability inapplicable. In Figure 9, the traffic volume flow rate curves resulting from different variable spacing policies are compared. These curves describe the relationship between the traffic volume flow rate and the traffic density for a certain spacing policy.

In Figure 10, two types of critical densities are clearly observed: the first critical density and the second critical density. The former one is used to differentiate the cruise mode and the follow mode, based on the different traffic flow characteristics of these two modes. The cruise mode operates if the traffic density is less than the first critical density. Otherwise, the follow mode is activated. When the vehicle is cruising at the cruise speed v_{set} and the desired inter-vehicle spacing based on a spacing policy is d_{cri}, then the first critical density ρ_1 can be expressed as follows:

$$\rho_1 = \frac{1}{L_V + d_{cri}} \tag{23}$$

where L_V is the uniform vehicle length. The second critical density refers to the maximum traffic density that maintains traffic flow stability. When the traffic density is equal to the second critical density, we have $\partial Q / \partial \rho = 0$ and the traffic volume flow rate reaches its peak. This peak can be used to evaluate the traffic capacity of a certain spacing policy. In this paper, we stipulate that the second critical density is always greater than the first critical density.

As a matter of fact, all existing spacing policies have a first critical density. Despite the fact that the spacing resulting from the TFS policy is infinite as the host vehicle approaches the cruise speed, in practice the TFS spacing policy still has a first critical density due to the range limitation of radar. For operations below the first critical density, all ACC vehicles are maintained at the cruise speed which does not change as

the traffic density increases. Hence, the traffic volume flow rate Q ($Q = v\rho$) always increases linearly with the traffic density. In other words, below the first critical density, the slope of the traffic volume flow rate curve is always positive, and the traffic flow stability is achieved (see criterion 3) in Section II).

The second critical density is closely related to the traffic flow stability. As seen from Figure 10, not all spacing policies have a second critical density. The underlying reason is that in the follow mode, there exists a correlation between vehicle speed and traffic density. If a spacing policy possesses a second critical density, this spacing policy can guarantee the traffic flow stability in a certain range under the follow mode. A higher second critical density reflects better traffic flow stability in terms of traffic density.

It is shown in Figure 10 that the TFS and CSF spacing policies can achieve traffic flow stability, while the CTH and HDB spacing policies cannot. To demonstrate this fact quantitatively, the characteristic values of various policies are shown in Table 4.

As for the CTH spacing policy, it has only a first critical density which can be expressed as:

$$\rho_1 = \frac{1}{L_V + th \times v_{set} + d_{min}} \tag{24}$$

We see in Table 4 that the first critical density of the CTH is 0.0195 vehicles/m. This means that when the traffic density is less than 0.0195 vehicles/m, the traffic flow increases linearly with the traffic density. The slope of the traffic volume flow rate becomes negative (i.e. $-(d_{min} + L_V)/th$) once the traffic density is over 0.0195 vehicles/m. This indicates that the CTH spacing policy cannot guarantee traffic flow stability.

Likewise, the HDB spacing policy has only a first critical density which is expressed as:

$$\rho_1 = \frac{1}{L_V + A + T v_{set} + G v_{set}^2} \tag{25}$$

The value of this first critical density is 0.0341 vehicles/m, which is greater than that of the CTH spacing policy. Since the spacing produced by the HDB is generally smaller than that by the CTH, the first critical density of the HDB is greater than that of the CTH, and the traffic volume flow rate at the first critical density is also higher.

The TFS spacing policy has both the first and second critical densities, and this spacing policy is able to achieve traffic flow stability. The first critical density of the TFS is determined by the mode switching distance. When the actual inter-vehicle spacing is less than the mode switching distance, the vehicle operates in the follow mode. Otherwise, the cruise mode is activated. The second critical density of the TFS, $\rho_{max}/2$, is obtained when $\partial Q / \partial \rho = 0$, and its value is 0.0625 vehicles/m. When the traffic density is less than 0.0625 vehicles/m, the traffic flow stability can be guaranteed. The peak traffic volume flow rate at the second critical density is 1 vehicles/s.
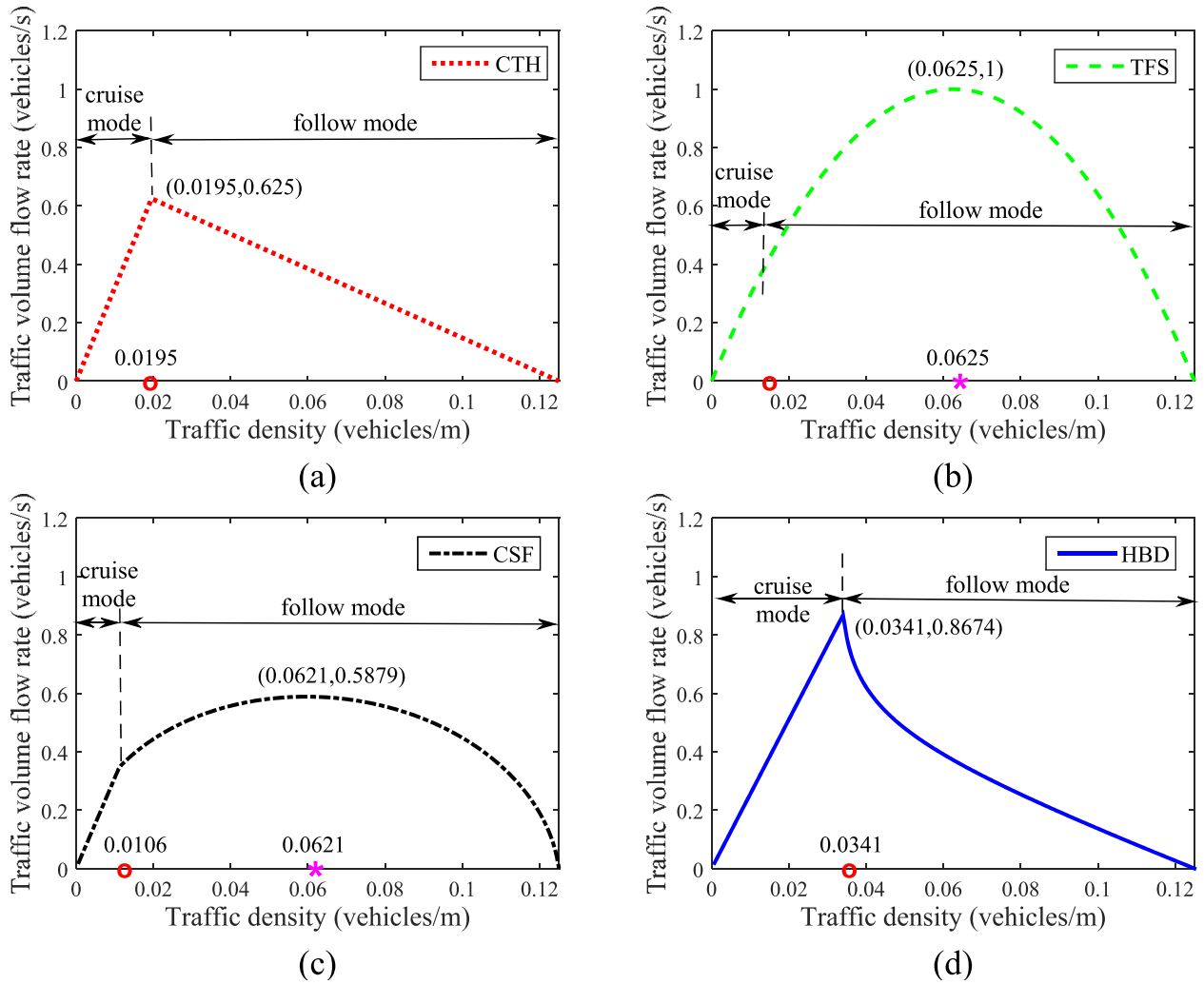
FIGURE 10. Traffic volume flow rate curves of various variable spacing policies (○ denotes the first critical density, ＊ denotes the second critical density).

TABLE 4. Characteristic values of different spacing policies.

Spacing policy	First Critical Density	Second Critical Density	Maximum Traffic Volume Flow Rate	Traffic Flow Stability
CTH	0.0195 vehicles/m	/	0.625 vehicles/s	unstable
TFS	-	0.0625 vehicles/m	1 vehicles/s	stable
CSF	0.0106 vehicles/m	0.0621 vehicles/m	0.5879 vehicles/s	stable
HBD	0.0341 vehicles/m	/	0.8674 vehicles/s	unstable

" / " means "does not exist", and " - " means "determined by the mode switching distance".

As for the CSF spacing policy, it also has both the first and second critical densities. The first critical density of the CSF can be expressed as:

$$\rho_1 = \frac{1}{L_V + d_{\min} + \sigma v_{\text{set}} + K \times D_{\text{stop}}} \quad (26)$$

As shown in Table 4, the value of its first critical density is 0.0106 vehicles/m. Since the inter-vehicle spacing resulting from the CSF spacing policy is generally large, the first critical density is small compared to other spacing

policies. The second critical density of the CSF is 0.0621 vehicles/m, which is close to that of the TFS (0.0625 vehicles/m). However, the peak traffic volume flow rate of the CSF is only 0.5879 vehicles/s, which is much smaller than that of the TFS (1 vehicles/s). In other words, although the CSF spacing policy ensures traffic flow stability, its traffic capacity is significantly lower than that of the TFS. The underlying reason is that the first priority of the CSF spacing policy is safety, which makes the inter-vehicle spacing too large.

V. SUMMARY

As an important type of ADAS, the ACC systems have been extensively studied by academia and are currently available in a wide range of passenger vehicles on the market. It is known that the spacing policy is the core of all ACC control algorithms, and the performance of an ACC system hinges on the choice of the spacing policy. Although various spacing policies are available in the literature, detailed explanation on their operating mechanisms and comparative studies on different spacing policies are still lacking. In this paper, a comprehensive survey on various ACC spacing policies is presented. The general evaluation criteria for spacing policies are first introduced. Then, the existing spacing policies are categorized into two major types: constant spacing policy and variable spacing policies. The latter type can be further divided into four sub-types: time headway-based spacing policy, traffic flow stability spacing policy, constant safety factor spacing policy and human driving behavior spacing policy. The characteristics of each spacing policy are discussed in detail, and both the pros and cons are analyzed. Then, a comparative study is conducted to analyze the performances of five spacing policies (i.e. CSP, CTH, TFS, CSF and HDB) by means of graphical and numerical simulation results, which clearly illustrates the differences, advantages and disadvantages of each spacing policy.

Besides, based on the above analyses, it is also revealed that the current spacing policies cannot guarantee the stability, safety and comfort at the same time, and an inevitable trade-off must be made when using the existing spacing policies. Hence, it is recommended that the future work be focused on developing strategies for achieving appropriate performance trade-off to satisfy multiple and complex design goals for next generation of ACC systems. The contents given in this survey not only lay the foundation for enhancing existing ACC systems, but also providing insights for designing future advanced ACC solutions.

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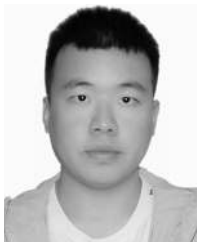
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