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Integrated Spacing Policy Considering Micro- and Macroscopic Characteristics

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Abstract

An appropriate spacing policy improves traffic flow and traffic efficiency while reducing commuting time and energy consumption. In this paper, the integrated spacing policy that combines the benefits of the constant time headway (CTH) and safety distance (SD) spacing policies is proposed in an attempt to improve traffic flow and efficiency. Firstly, the performance of the CTH and SD spacing policies is analyzed from the perspective of the microscopic characteristics of human-vehicle and the macroscopic characteristics of traffic flow. The switching law between CTH and SD spacing policies and the integrated spacing policy are then proposed to increase traffic efficiency according to the traffic conditions, and the critical speed for the proposed integrated spacing policy is derived. Using the proposed switching law, the integrated spacing policy utilizes the safety redundancy difference between the CTH and SD spacing policies in a flexible manner. Simulation tests demonstrate that the proposed integrated spacing policy increases traffic flow and that the traffic flow maintains string stability in a wider range of traffic flow density.

Keywords Integrated spacing policy · Critical speed · Critical traffic flow density · String stable · Traffic efficiency

Abbreviations

a_{bmax}	Maximum deceleration
C	Stability factor
CTH	Constant time headway
D_{CTH}	Following space of CTH spacing policy
D_{com}	Following space of integrated spacing policy
d_{min}	Minimal following space when vehicle stopped
D_{SD}	Following space of SD spacing policy
L	Vehicle length
q	Traffic flow
s	Braking distance
SD	Safety distance
th	Time headway
V_{c}	Critical vehicle speed
V_{r}	Relative vehicle speed
V_{max}	Maximum speed
ρ	Traffic density
ρ_{c}	Critical traffic density
τ	Equivalent braking system response time

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1 Introduction

Congestion is a common problem in urban traffic environments, and the spacing policy applied in vehicles has a considerable influence on traffic flow and efficiency. Many researchers have studied spacing policies from micro- or macroscopic perspectives. The main objects of research are the car-following safety, driver habits, and stability performance of the spacing policy.

The constant time headway (CTH) and safety distance (SD) spacing policies have been widely studied. Based on the vehicle dynamics, Ioannou [1] concluded that the safety distance between preceding and following vehicles was

$$S = \lambda_1 \left(v_i^2 - v_{i-1}^2\right) + \lambda_2 v_i + \lambda_3 \tag{1}$$

where $\lambda_1, \lambda_2, \lambda_3$ are constants and v_i, v_{i-1} denote the ego and preceding vehicle speed, respectively.

The CTH policy results in a long car-following space in the steady state. To reduce the following space, Yanakiev

[2–4] proposed the spacing policy given by Eq. (2), in which the time headway th varies linearly with the relative speed to enhance traffic efficiency

$$th = \text{sat}\left(h_0 - c_1 v_r\right) = \begin{cases} 1, & h_0 - c_1 v_r > 1 \\ h_0 - c_1 v_r, & 0 < h_0 - c_1 v_r < 1 \\ 0, & h_0 - c_1 v_r < 0 \end{cases} \tag{2}$$

where h_0, c_1 are constants and v_r is the relative vehicle speed.

Driver behavior and habits are the core factors of spacing policy research. Han [5] analyzed real-world data obtained from 125 participants under normal driving conditions and used these human drivers' characteristics to develop a spacing policy for an adaptive control strategy via a recursive least-squares algorithm. The proposed adaptive control strategy [5] is similar to drivers' maneuvering and is readily accepted by human drivers. Treiber [6, 7] proposed the intelligent driver model (IDM) to imitate the car-following behavior of individual drivers in real city traffic based on trajectory datasets. The IDM can be written as follows:

$$S(v, \Delta v) = s_0 + s_1 \sqrt{\frac{v}{v_0}} + Tv + \frac{v \Delta v}{2\sqrt{ab}} \tag{3}$$

where s_0, s_1, a, b, T, v_0 are model parameters that should be calibrated.

Stability performance is another important feature of spacing policies. Swaroop [8–10] defined the concept of string stability, i.e., spacing errors should not become amplified as they propagate upstream from vehicle to vehicle. In his research [8], the CTH policy and constant headway (CH) policy were analyzed and compared. The CTH policy does not need inter-vehicle communication to ensure string stability, whereas the CH policy requires speed and acceleration information of the ego and preceding vehicles. Shrivastava [11, 12] defined the stability of macroscopic traffic flow, i.e., the traffic flow stability induced by traffic flow density, and found that a critical traffic flow density exists when the spacing policy is a function of speed: below this critical density, traffic flow decreases as traffic flow density increases. Zhou [13] proposed the nonlinear spacing policy to improve traffic flow stability and string stability through the optimization of traffic flow and stability constraints and the proposed nonlinear spacing policy maintains a stable traffic flow under higher traffic flow density than the CTH policy. Santhanakrishnan [14] developed the design and evaluation framework for adaptive cruise control spacing policies, including string stability, traffic flow stability, and traffic flow capacity. This framework was used to determine the "ideal" spacing policy. Considering the parasitic time delay in vehicle platoons and the actuator lags in the vehicle longitudinal dynamics model, Xiao [15] concluded that traffic flow with the CHT policy exhibited string stability under the constraint in Eq. (4). Rödönyi [16] proposed an adaptive spacing policy in which the leader and predecessor follow a certain control strategy to guarantee the string stability of a platoon

$$th > 2\left(\Delta + \tau'\right) \tag{4}$$

where Δ is the vehicle's delay in a platoon and τ' is the lag in responding to command signals.

Most of the above studies considered traffic string stability or driver behavior separately. A synthesized consideration of both the micro- and macroscopic characteristics is needed to promote traffic flow and efficiency. To reduce traffic congestion and simultaneously achieve a good tradeoff between traffic efficiency and human behavior, an integrated spacing policy is proposed in this article. The proposed policy combines the benefits of the CTH and SD spacing policies. The proposed integrated spacing policy considers both micro- and macroscopic characteristics and has the following three main features:

1. The critical speed of the integrated spacing policy is derived, and the safety redundancy differences between the CTH and SD spacing policies is used to improve traffic efficiency. When the vehicle speed is lower than the critical speed, the SD spacing policy is applied to shorten the car-following space; when the vehicle speed is greater than the critical speed, the CTH spacing policy is applied to promote traffic efficiency.
2. As the traffic flow density varies from sparse to dense, the proposed integrated policy always maintains a large traffic flow to improve traffic efficiency.
3. Compared with the CTH and SD spacing policies, the proposed integrated policy broadens the range of traffic flow density that ensures string stability.

The remainder of this paper is organized as follows. In Sect. 2, the microscopic characteristics and stability performance of the CTH and SD spacing policies are analyzed. In Sect. 3, a switching law is proposed and the critical speed is derived for an integrated spacing policy that combines the advantages of the CTH and SD spacing policies. In Sect. 4, the characteristics of the integrated spacing policy are compared with those of the CTH and SD spacing policies. Finally, the conclusions to this study are summarized in Sect. 5.

2 Microscopic Characteristics and Stability Analysis

2.1 CTH and SD Spacing Policies

The CTH spacing policy [1, 5] is analogous to human car-following behavior, and for a stable vehicle following process,

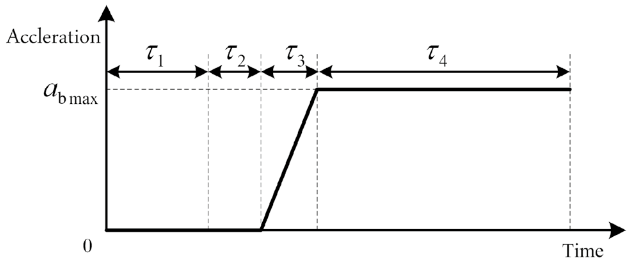

Fig. 1 Acceleration curve during braking process

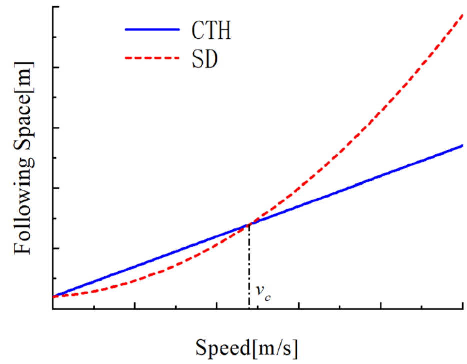

Fig. 2 Following characteristics of CTH and SD spacing policies

the CTH car-following space D_{CTH} is an approximately linear function of vehicle speed [1]:

$$D_{\mathrm{CTH}} = v \cdot th + d_{\min} \tag{5}$$

where $d_{\min}$ is the minimum distance to the preceding vehicle when the following vehicle has stopped completely, *th* is the time headway (generally 1–2 s), and v is the ego-vehicle initial speed.

The SD spacing policy [1] can be obtained by analyzing the braking process in an emergency situation. The safety distance prevents the ego-vehicle from colliding with the preceding vehicle in any condition. The acceleration curve of a vehicle during the whole process is shown in Fig. 1.

In Fig. 1, τ_1 is the driver reaction time, τ_2 is the time to eliminate the clearance of braking system, τ_3 is the braking force build time, τ_4 is the braking time to stop the vehicle completely, and a_{bmax} is the maximum braking deceleration.

The braking distance s in the above braking process is

$$s = v\left(\tau_1 + \tau_2 + \frac{\tau_3}{2}\right) + \frac{v^2}{2a_{\mathrm{bmax}}} - \frac{a_{\mathrm{bmax}}\tau_3^2}{24} \tag{6}$$

where v is the ego-vehicle initial speed, $\frac{a_{\mathrm{bmax}}\tau_3^2}{24}$ can be ignored because τ_3 is very small in hydraulic brake, and τ_1 is zero when inter-vehicle communication is applied. Thus, s can be rewritten as

$$s = v \cdot \tau + \frac{v^2}{2a_{\mathrm{bmax}}} \tag{7}$$

where $\tau = \tau_2 + \frac{\tau_3}{2}$ is called the equivalent braking system response time in this paper. From the above, the SD car-following space D_{SD} can be written as

$$D_{\mathrm{SD}} = s + d_{\min} \tag{8}$$

where $d_{\min}$ is the minimum distance to the preceding vehicle when the following vehicle has stopped completely.

2.2 Microscopic Characteristics and Critical Speed

The microscopic characteristics of humans, the ego-vehicle, and the preceding vehicle mainly include car-following safety, human driver car-following habits, and stability performance. Car-following safety refers to the ability to ensure there is no collision with the preceding car under any condition during the car-following process. From the analysis in Sect. 2.1, the CTH and SD spacing policies have different car-following performance.

The SD car-following space in Eq. (8) prevents vehicles from colliding in emergency situations, except when the preceding vehicle reverses or drives backwards. When the following space is no less than the safety distance D_{SD}, the vehicle is protected from collisions and remains absolutely safe. In other word, the vehicle with SD spacing policy is "absolutely safe." When the vehicle following space is longer than the safety distance, there exists too much safety redundancy and the vehicle is "over-safe."

Figure 2 shows the following characteristics of the CTH and SD spacing policies in terms of the ego-vehicle speed. Usually, $th > \tau$, and from Eqs. (5) and (7), there exists the critical speed v_{c} that is the intersection of the CTH and SD spacing policies, as shown in Fig. 2, to let $D_{\mathrm{SD}} = D_{\mathrm{CTH}}$, and the critical speed v_{c} is derived as

$$v_{\mathrm{c}} = v = 2a_{\mathrm{bmax}}(th - \tau) \tag{9}$$

Equations (5) and (8) demonstrate that the CTH and SD spacing policies are both safe, but have different safety redundancies, as shown in Fig. 2. In this paper, these safety redundancy differences are used to improve traffic efficiency. When the vehicle speed is no more than the critical speed v_{c}, $D_{\mathrm{SD}} \le D_{\mathrm{CTH}}$ and the vehicle following the CTH spacing policy is "over-safe." In this case, the SD spacing policy is applied. When the vehicle speed is greater than the critical speed v_c, $D_{\mathrm{SD}} > D_{\mathrm{CTH}}$ and the vehicle following the SD spacing policy has too much safety redundancy. In this case, the CTH spacing policy is set. In short, the policy with less safety redundancy is set to improve traffic efficiency while satisfying the given safety requirements.

2.3 Stability Analysis

2.3.1 Traffic Flow Stability

Two of the most important macroscopic characteristics of traffic flow system are the traffic flow stability and string stability. Vehicles in the same lane can be seen as a one-dimensional model of compressible fluid flow. Let x be somewhere in the traffic flow, and let the direction that x is moving in be "downstream"; the opposite direction is "upstream." Let x_u be the lane length and $\rho(x,t)$ and $v(x,t)$ be the traffic flow density and traffic flow speed located at x at time t, respectively. Hence, the traffic flow q at point x and time t is

$$q(x,t) = \rho(x,t)v(x,t) \tag{10}$$

When the traffic flow density ρ is sparse, the traffic flow speed v is constrained by the upper speed limit and the traffic flow q is unbalanced. As ρ increases, $v(x,t)$ becomes a function of $\rho(x,t)$ and can be described as

$$v(x,t) = f(\rho) \tag{11}$$

In this situation, the traffic flow q is balanced.

Let $\rho_p(x,t)$ and $v_p(x,t)$ represent the density disturbance and speed disturbance of the traffic flow, respectively. The "string stability" term refers to the non-amplifying upstream propagation of vehicle speed perturbations through a string of vehicles.

A platoon is string stable [17] if, given $\varepsilon > 0$, there exists

$$\sup_{x \le x_u} \left\{ \left| v_p(x,0) \right|, \left| \rho_p(x,0) \right| \right\} < \delta \tag{12}$$

such that

$$\sup_{t \ge 0} \sup_{x \le x_u} \left\{ \left| v_p(x,t) \right|, \left| \rho_p(x,t) \right| \right\} < \varepsilon \tag{13}$$

and

$$\lim_{t \to \infty} \sup_{x \le x_u} \left\{ \left| v_p(x,t) \right|, \left| \rho_p(x,t) \right| \right\} = 0 \tag{14}$$

According to the continuity equation of one-dimensional fluid flow, the following must hold:

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \tag{15}$$

Let $C = \frac{\partial q(x,t)}{\partial \rho}$. Combining Eqs. (10) and (15), it follows that

$$\frac{\partial \rho(x,t)}{\partial t} + C\frac{\partial \rho(x,t)}{\partial x} = 0 \tag{16}$$

Then,

$$\begin{aligned} C &= \frac{\partial[\rho(x,t)v(x,t)]}{\partial \rho} \\ &= \rho(x,t)\frac{\partial f(\rho)}{\partial \rho} f(\rho) + f(\rho) \end{aligned} \tag{17}$$

where C is the stability factor. When $C > 0$, the solution to the partial differential Eq. (16), i.e., the perturbation $\rho_p(x,t)$, is a right-moving single-wave, which means that the perturbation propagates downstream. When $C < 0$, the perturbation $\rho_p(x,t)$ is a left-moving single-wave, which means that the perturbation propagates upstream. Dimensional analysis indicates that the stability factor C has units of km/h, which represents the propagation speed.

2.3.2 String Stability

According to the definition of string stability [15], if the perturbation $\rho_p(x,t)$ propagates downstream, the spacing and speed errors of vehicles in a platoon will remain small for all time. In contrast, the perturbation will not weaken if it propagates upstream. This means that the traffic flow can maintain string stability when the stability factor $C > 0$. However, from Eqs. (10) and (15), it is clear that C is not always positive, i.e., traffic flow cannot always be string stable. Hence, the ideal spacing policy should have the following two characteristics:

1. Maintain large traffic flow over a wide range of traffic flow density and promote traffic efficiency;
2. Maintain traffic flow string stability over a wide range of traffic flow density.

The effects of spacing policies on traffic flow and string stability are now examined.

(1) For the CTH spacing policy, the vehicle density ρ can be described as

$$\rho = \frac{1}{D_{\text{CTH}} + L} \tag{18}$$

where L is the vehicle length (all vehicles are assumed to have the same length), and the traffic flow q can be described as follows:

When $\rho \le \frac{1}{v_{\max} th + d_{\min} + L}$,

$$q = \rho v_{\max}, \tag{19}$$

When $\frac{1}{v_{\max} th + d_{\min} + L} < \rho < \frac{1}{d_{\min} + L}$

$$q = \frac{1 - \rho\left(d_{\min} + L\right)}{th}, \tag{20}$$

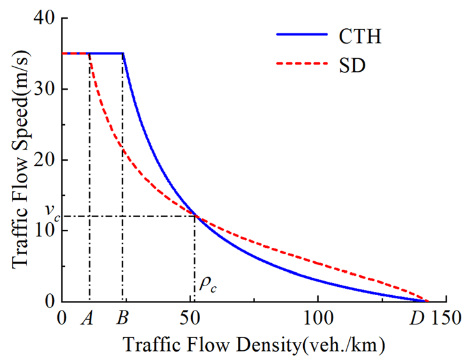

Fig. 3 Traffic flow speed of the CTH and SD policies

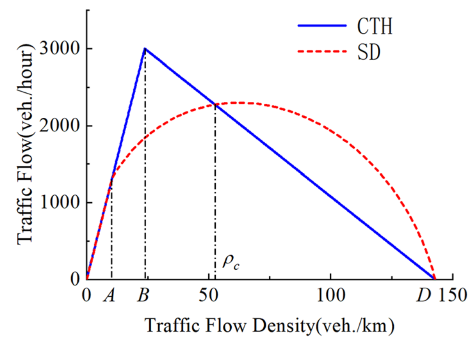

Fig. 4 Traffic flow of the CTH and SD policies

Here, the stability factor C is

$$C = -\frac{d_{\min} + L}{th} \tag{21}$$

(2) For the SD spacing policy, the vehicle density ρ can be described as

$$\rho = \frac{1}{D_{SD} + L}, \tag{22}$$

Then, traffic flow q can be described as follows:
When $\rho \le \frac{1}{v_{\max} th + \frac{v_{\max}^2}{2a_{b\max}} + d_{\min} + L}$,

$$q = \rho v_{\max}, \tag{23}$$

When $\frac{1}{v_{\max} th + \frac{v_{\max}^2}{2a_{b\max}} + d_{\min} + L} < \rho < \frac{1}{d_{\min} + L}$,

$$q = -\rho a_{bamx} \tau + \rho a_{bamx} \sqrt{\tau^2 + \frac{2D_v}{a_{b\max}}} \tag{24}$$

Here, the stability factor C is

$$C = -a_{b\max} \tau + \sqrt{\tau^2 + \frac{2D_v}{a_{b\max}}} - \frac{1}{\rho \sqrt{\tau^2 a_{b\max}^2 + 2D_v a_{b\max}}} \tag{25}$$

where $D_v = 1/\rho - d_{\min} - L$, which is the relation between the inter-vehicle spacing and speed.

According to [15, 17], let $L = 5$ m, $d_{\min} = 2$ m, $a_{b\max} = 7.5$ m/s^2, $\tau = 0.2$ s, $th = 1$ s, $v_{\max} = 35$ m/s. From Eqs. (14)–(19), the characteristics of traffic flow density, namely traffic speed, traffic flow, and the stability factor C, can be obtained. The results are shown in Figs. 3, 4, 5 and 6.

Figure 3 shows the relationship between the traffic flow speed and traffic flow density for the CTH and SD spacing policies. Generally, the traffic flow density increases as the traffic flow speed decreases. Point A indicates the maximum traffic flow density for the SD spacing policy with $v_{\max} = 35$ m/s,, and point B denotes the maximum traffic flow density for the CTH spacing policy with $v_{\max} = 35$ m/s. Point D is the maximum traffic flow density point, and ρ_c is defined as the critical density based on Eqs. (20) and (24), which is the intersection point (ρ_c, v_c) in Fig. 3. This is given by

$$\rho_c = \frac{1}{2a_{b\max}(th - \tau)th + d_{\min} + L} \tag{26}$$

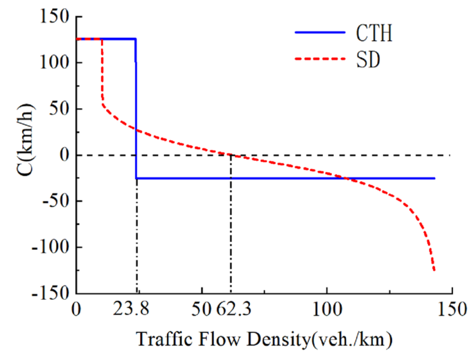

Fig. 5 Traffic stability factor of the CTH and SD policies

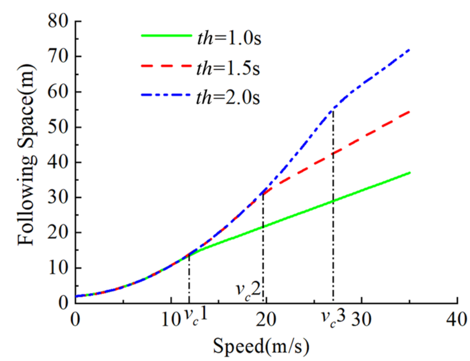

Fig. 6 Following space of the integrated policy

Figure 3 also shows that, when the traffic flow speed is no greater than the critical speed v_c or the traffic flow density is no less than the critical density ρ_c, the SD spacing policy improves traffic efficiency; when the traffic flow speed is greater than the critical speed v_c or the traffic flow density is less than the critical density ρ_c, the CTH spacing policy shows more benefits to improve traffic efficiency. Comparing the analytical solutions for the critical speed v_c in Eq. (9) and the critical density ρ_c in Eq. (26), it is apparent that the critical speed v_c and critical density ρ_c are at the same point as shown in Fig. 3. In other words, as a switching index, ρ_c and v_c are equivalent for the integrated spacing policy. For simplicity, only the critical speed v_c is set as the switch indicator, as this also reflects the critical density ρ_c.

Figure 4 shows the relationship between the traffic flow density and traffic flow. Points A, B, D indicate the same quantities as in Fig. 3, although the coordinate system in Fig. 4 is different. When the traffic flow density of CTH and SD is below point B and point A, respectively, the slope of the two curves is just $v_{\max}$, and $q = \rho v_{\max}$. When the traffic flow density of CTH and SD is greater than point B and point A, the two curves follow Eqs. (18) and (22), respectively, and $q = \rho v$. In this case, the two curves intersect at $(\rho_c, \rho_c v_c)$. Namely, when the traffic flow speed is no greater than the critical speed v_c, the SD spacing policy is applied; when the traffic flow speed is greater than the critical speed v_c, the CTH spacing policy is applied.

Figure 5 shows the traffic stability factor of the CTH and SD spacing policies. This figure indicates that the SD spacing policy can maintain string stability over a wide range of traffic flow density range. The SD spacing policy ensures string stability over a wider traffic flow density range of [0, 62.3] veh./km, whereas the CTH spacing policy ensures stability for [0, 23.8] veh./km.

3 Integrated Spacing Policy Considering Traffic Flow Characteristics

From the analysis in Sect. 2, it is clear that the CTH and SD policies are based on the microscopic system consisting of humans, the ego-vehicle, and the preceding vehicle. The CTH policy emphasizes human drivers' habits from the microscopic perspective, whereas the SD policy considers the inter-vehicular kinematics from the macroscopic perspective. Moreover, both policies have advantages and limitations in terms of traffic flow efficiency and traffic flow stability. Generally, the CTH spacing policy ensures larger traffic flow at high speed, whereas the SD spacing policy realizes larger traffic flow at low speed and maintains string stability over a wider traffic flow density range.

The integrated spacing policy that combines the CTH and SD spacing policies is now proposed to improve traffic efficiency and provide a better tradeoff between safety and traffic stability. As shown in Eq. (27), when the vehicle speed is no greater than the critical speed v_c, the SD spacing policy is applied; when the vehicle speed is greater than the critical speed v_c, the CTH spacing policy is applied

Table 1 Critical speed v_c for various *th*

th (s)	1.0	1.5	2
v_c (m/s)	12	19.5	27

$$\begin{cases} D_{\mathrm{com}} = v \cdot \tau + \frac{v^2}{2a_{\mathrm{bmax}}} + d_{\min}, & v \le v_c \\ D_{\mathrm{com}} = v \cdot th + d_{\min}, & v > v_c \end{cases} \tag{27}$$

where D_{com} is the following space in the integrated spacing policy, v is the ego-vehicle speed, and τ is the time constant of the braking system.

As shown in Fig. 6, the integrated spacing policy has different critical speeds depending on the time headway *th*. Critical speeds v_c1, v_c2, v_c3 correspond to $th = 1.0\ \mathrm{s},\ 1.5\ \mathrm{s},\ 2.0\ \mathrm{s}$ respectively. The critical speed increases with the increasing time headway *th*, i.e., the speed range over which the SD spacing policy is applied increases as the time headway *th* rises. Table 1 lists the critical speed v_c for different values of the time headway *th*.

The proposed integrated spacing policy uses the critical speed v_c as a switch law, and the safety redundancy differences are used to improve traffic efficiency. When the vehicle speed is no greater than the critical speed v_c, the vehicle is in the "over-safe" state and the SD spacing policy helps shorten the inter-vehicle distance and increase traffic flow. When the vehicle speed is above the critical speed v_c, the CTH spacing policy is applied to reduce the excessive safety redundancy of SD and keep the following space within a suitable range for improving the traffic efficiency.

4 Simulation Test

The following parameters were used to compare the performance of the integrated spacing policy with that of the CTH and SD spacing policies from the perspective of traffic flow efficiency and stability: $L = 5$ m, $d_{\min} = 2$ m, $a_{\mathrm{bmax}} = 7.5\ \mathrm{m/s^2}$, $\tau = 0.2$ s, $v_{\max} = 35$ m/s [15, 17]. The results presented in Figs. 7, 8, 9 and 10 show the characteristics of traffic flow speed, traffic flow, and the stability factor C with respect to the traffic flow density, respectively.

Figure 7 shows that the traffic flow density varies with time headway *th*. As the traffic flow density reflects the traffic congestion situation, a smaller time headway *th* achieves better traffic efficiency with the same traffic flow speed;

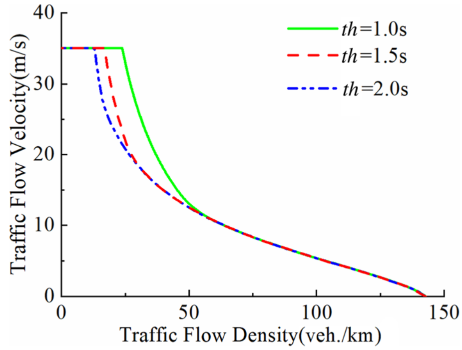

Fig. 7 Traffic flow speed of the integrated policy

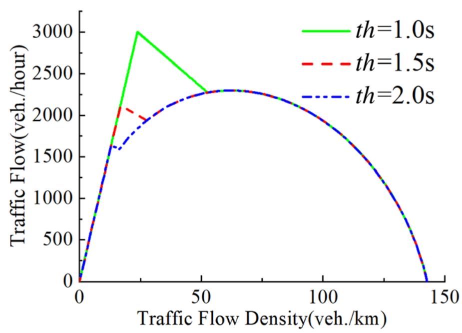

Fig. 8 Traffic flow of the integrated policy

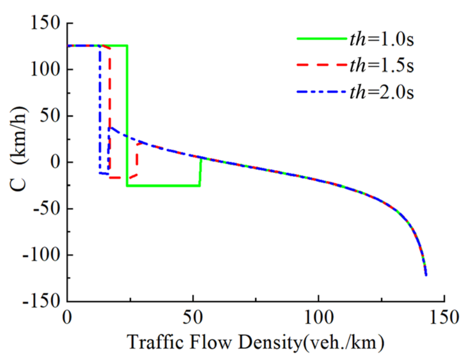

Fig. 9 Traffic flow stability factor of the integrated policy

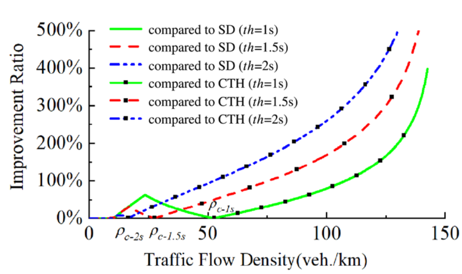

Fig. 10 Improvement ratio of traffic flow

Fig. 8 shows similar results. The integrated policy with a smaller time headway *th* results in better traffic flow for the same traffic flow density.

The range of string stability offered by the integrated policy with different time headway *th* is illustrated in Fig. 9. Specifically, taking $th = 1.0$ s as an example, analysis of the stability factor C shows that the SD spacing policy ensures traffic flow string stability in the density range [0, 62.3] veh./km (Fig. 5); for the integrated spacing policy, the range is [0, 23.8] veh./km and [52.6, 62.3] veh./km; for the CTH policy, the range is [0, 23.8] veh./km. From these results, it can be concluded that the integrated policy broadens the traffic flow density range that has string stability compared with the CTH policy. Thus, the traffic flow remains string stable at high traffic flow density, which is a significant benefit for low-speed conditions in high-traffic-density urban scenarios.

Figure 10 shows the traffic flow improvement ratio of the integrated policy compared with the CTH and SD spacing policies. When the traffic flow density is lower than ρ_c, the integrated policy uses CTH spacing policy and is much better than the SD spacing policy; when the traffic flow density is no less than ρ_c, the integrated policy uses SD spacing policy and performs significantly better than the CTH spacing policy.

Overall, the proposed integrated spacing policy can be used to improve traffic efficiency and string stability, as it combines the benefits of the CTH and SD spacing policies to reduce the excessive safety redundancy. When the vehicle speed is no more than the critical speed v_c, compared with the CTH spacing policy, the integrated policy shows significant improvements in traffic efficiency and broadens the range of string stability. When the vehicle speed is greater than the critical speed v_c, compared with the SD spacing policy, the traffic efficiency is improved, and the integrated spacing policy avoids the large following spaces that cause driver anxiety, thus making the proposed policy more acceptable to human drivers.

5 Conclusions

The integrated policy combined the advantages of the CTH and SD policy is proposed via utilizing the safety redundancy and the switching law is presented with the derived critical speed of CTH and SD spacing policies. Simulation tests show that the proposed spacing policy can improve traffic efficiency and achieve better performance in terms of traffic flow string stability and car-following safety.

Compared with the CTH spacing policy, when traveling at less than the critical speed, the integrated policy produces significant benefits in terms of traffic efficiency and broadens the range of string stability. Compared with the SD spacing policy, when traveling at greater than the critical speed, the traffic efficiency is improved, and the integrated spacing policy avoids the large following spaces that cause driver anxiety, making the proposed method more acceptable to human drivers. Furthermore, the integrated spacing policy can maintain efficient traffic flow and stability over a wide traffic flow density range.

The results presented in this paper can be integrated with other spacing policies, and vehicle tests will be extended to calibrate the effectiveness of the integrated spacing policy.

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Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interest.

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