A jam-absorption driving system based on moving jam propagation speed estimation with camera sensors

Siyu Li, Ryosuke Nishi, Daichi Yanagisawa, and Katsuhiro Nishinari

Abstract In this study, a real-time control system is developed to operate the novel jam-absorption driving (JAD) strategy against single moving jams on freeway sections. Mixed traffic (human-driven vehicles and connected and automated vehicles (CAVs)) and heterogenous traffic (cars and trucks) are considered. The system calculates the moving jam propagation speed using vehicular trajectory data collected by camera sensors covering the entire control zone. The central controller selects a suitable CAV as an absorbing car in traffic through vehicle-to-infrastructure communication for performing JAD. Simulation results show that the system effectively enhanced traffic safety under a low market penetration rate of CAVs (approximately 1% to 10%). The investigation also shows the robustness of the proposed JAD system under various inflow rates.

Keywords: jam-absorption driving, moving jam estimation, camera sensor, vehicular trajectory data, heterogeneous traffic

1 Introduction

Freeway traffic usually experiences moving jams. Vehicles are compelled to decelerate and accelerate when going through a moving jam, causing adverse effects (i.e., crash risk) on traffic [1]. Jam-absorption driving (JAD) is a state-of-the-art connected and automated vehicles-based (CAVs-based) strategy for clearing moving

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jams by employing a single actuator (i.e., the absorbing car) in traffic [2–7]. Thus, infrastructure investment required for conventional traffic regulation strategies, e.g., variable speed signs for the variable speed limit (VSL) [1, 8] becomes unnecessary. Meanwhile, thanks to CAV technologies, control location is variable, and control accuracy is higher than that of conventional traffic regulation strategies. Additionally, unlike most CAVs-based strategies (e.g., Adaptive Cruise Control [9, 16] and FollowerStopper [10]), JAD focuses on mitigating moving jams based on spatiotemporal geometric traffic dynamics rather than improving car-following behavior or optimizing traffic state.

However, previous JAD investigations assumed that the control is operated employing non-error future traffic state prediction with well-calibrated car-following models. This leads to i) control failure [3] may occur when miscalibration occurs or traffic characteristics vary; ii) many computer resources are required for predicted trajectory data computation, transmission, and storage. In this study, a practical real-time operating system to perform JAD based on the spatiotemporal geometry of wave speed estimation is proposed. Therefore, detailed traffic states reproduction with well-calibrated traffic models is not required. Moreover, researchers integrated the camera sensors system into VSL (i.e., the SPECIALIST), reducing jams detection delay and enhancing control effects [11]. For the JAD strategy, the performance of camera sensor–based JAD systems needs to be developed and investigated, e.g., the appropriate market penetration rate (MPR) of CAVs.

2 Methodology

2.1 The system

In the proposed JAD system, the central controller processes vehicular trajectory data to detect the moving jam and estimate the moving jam propagation speed. The central controller designates a suitable CAV as the absorbing car after detecting a moving jam. Meanwhile, control commands are sent to the absorbing car for performing the “slow-in” to avoid rushing into the moving jam. The control commands switch to the “fast-out” to guide the absorbing car to merge into its downstream traffic flow when it avoids rushing into the moving jam or when the moving jam disappears.

The proposed JAD system requires the following equipment: (i) CAVs are available to receive control commands; (ii) roadside units (RSUs) allow vehicle-to-infrastructure (V2I) communication between CAVs and the central controller; (iii) camera sensors [12, 13] are installed at the roadside to collect high-resolution vehicular trajectory data.

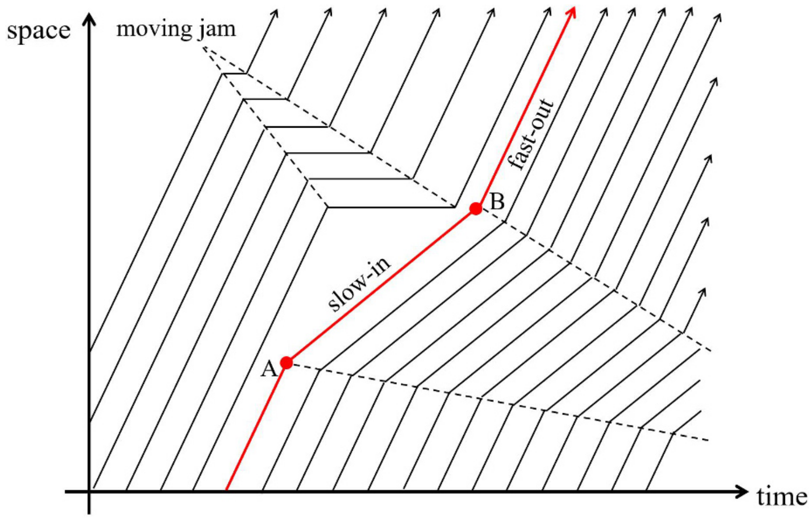

Fig. 1 The concept of JAD [2].

2.2 Moving jam propagation speed estimation

This study proposes a practical microscopic method for moving jam propagation speed estimation based on trajectory data collected by camera sensors. When v_n (i.e., the speed of vehicle n) < 4 m/sec and $v_n(t) < v_n(t - \Delta t)$, the system detects that vehicle n is entering a moving jam; then, when $v_n \geq 8$ m/sec and $v_n(t) > v_n(t - \Delta t)$, the system detects that vehicle n is exiting the moving jam. Such deceleration–acceleration spatiotemporal points $(t_{\mathrm{dw}}, p_{\mathrm{dw}})$ and $(t_{\mathrm{aw}}, p_{\mathrm{aw}})$ are respectively stored in $\Omega_{\mathrm{dw}} = (T_{\mathrm{dw}}, P_{\mathrm{dw}})$ and $\Omega_{\mathrm{aw}} = (T_{\mathrm{aw}}, P_{\mathrm{aw}})$ for further estimation.

Empirical studies have demonstrated that moving jams propagate upstream at a certain wave speed [14]. Thus, our wave speed estimator assumes that the shockwave is a straight line. Therefore, Ω_{dw} and Ω_{aw} are employed to estimate the deceleration wave speed and acceleration wave speed using the least squares method [15], respectively.

2.3 The JAD model

As illustrated in Fig. 1, the concept of JAD is to guide an absorbing car to move from point A (the absorbing start point) to point B (the absorbing end point) at an absorbing speed before it reaches the downstream moving jam (i.e., "slow-in"); and then it accelerates when it avoids the jam to merge into its downstream traffic (i.e., "fast-out") [2]. The following describes the detailed models.

Absorbing car designation. First, the system searches among CAVs from downstream to upstream to designate the absorbing car to conduct "slow-in". CAV i is determined to absorb the moving jam at time t with the absorbing speed threshold $v_{\text{ad,thre}}$ and the distance threshold $L_{\text{ad,thre}}$ by the following expressions:

$$v_{\text{ad},i}(t) \geq v_{\text{ad,thre}} \text{ or } L_{\text{ad},i}(t) \geq L_{\text{ad,thre}}, \tag{1}$$

$$v_{\text{ad},i}(t) = \min\{v_{\max}, \max\{\underline{v_{\text{ad}}}, \frac{p_{\text{ep},i}(t) - p_i(t)}{t_{\text{ep},i}(t) - t}\}\}, \tag{2}$$

$$L_{\text{ad},i}(t) = p_{\text{aw}} - p_i(t), \tag{3}$$

where $v_{\max}$ represents the maximum speed limit, $\underline{v_{\text{ad}}}$ represents the lower bound of absorbing speed, $p_i(t)$ represents the rear-end position of CAV i, $p_{\text{ep},i}(t)$ and $t_{\text{ep},i}(t)$ are the position and time of the absorbing end point computed using Eqs. (4) and (5), respectively.

"Slow-in". The time-updated spatiotemporal absorbing end point $(t_{\text{ep},i}(t), p_{\text{ep},i}(t))$ of CAV i is predicted by traffic count approach during the "slow-in".

$$p_{\text{ep},i}(t) = p_{\text{aw}}^{M} - (s_{\text{car}} + d_{\text{car}})\chi_{\text{car}}(n^M, i) - (s_{\text{truck}} + d_{\text{truck}})\chi_{\text{truck}}(n^M, i), \tag{4}$$

$$t_{\text{ep},i}(t) = f^{-1}(\alpha_{\text{aw}}(t), \beta_{\text{aw}}(t), p_{\text{ep},i}(t)), \tag{5}$$

where p_{aw}^{M} represents the position of the latest (i.e., M) acceleration spatiotemporal point, n^M represents the vehicle number of the latest acceleration spatiotemporal point, s_{car} and s_{truck} represent inter-vehicular distances for the car (both human-driven vehicle (HDV) and CAV) and truck inside the jam, and d_{car} and d_{truck} are the lengths of the car (both HDV and CAV) and truck, respectively. Variables $\chi_{\text{car}}(n^M, i)$ and $\chi_{\text{truck}}(n^M, i)$ represent traffic count for cars (both HDV and CAV) and trucks between vehicle n^M and CAV i, respectively. The parameters $\alpha_{\text{aw}}(t)$ and $\beta_{\text{aw}}(t)$ are time-intercept and space-intercept of the linear equation $p_{\text{ep},i}(t) = f(\alpha_{\text{aw}}(t), \beta_{\text{aw}}(t), t_{\text{ep},i}(t))$ of the acceleration wave of the moving jam. $f^{-1}(\bullet)$ is the inverse function of $f(\bullet)$. The control input of the acceleration rate for reaching $v_{\text{ad},i}(t)$ is given by:

$$a_i(t) = \begin{cases} \max\{\underline{a_{\text{ad}}}, a_{\text{ad},i}(t), \frac{v_{\text{ad},i}(t) - v_i(t)}{\Delta t}\} & \text{if } v_{\text{ad},i}(t) < v_i(t), \\ \min\{a_{\text{ad},i}(t), \overline{a_{\text{ad}}}, \frac{v_{\text{ad},i}(t) - v_i(t)}{\Delta t}\} & \text{if } v_{\text{ad},i}(t) > v_i(t), \\ 0 \quad \text{else}, \end{cases} \tag{6}$$

where $a_{\text{ad},i}(t) = k_1(v_{\text{ad},i}(t) - v_i(t))$, $\underline{a_{\text{ad}}}$ and $\overline{a_{\text{ad}}}$ are the lower and upper bounds, and k_1 is the parameter. However, the "slow-in" will be shut down for avoiding a rear-end collision, when detects $s_i < s_{\text{safe}}$ and $\Delta v_i < 0$ and $a_{\text{cf},i} < a_i < 0$. Here, $s_i = p_{i-1} - p_i - d_{\text{car}}$, $\Delta v_i = v_{i-1} - v_i$, $a_{\text{cf},i}$ is the desired acceleration of car-following behavior, and s_{safe} is the safe gap.

"Fast-out". Finally, the control system will shut down the "slow-in" and perform the "fast-out" by B-ACC (Basic Adaptive Cruise Control) [16] when detects $t > t_{\text{ep},i}$ or $p_i > p_{\text{ep},i}$. Additionally, if the system does not detect $(t_{\text{dw}}, p_{\text{dw}})$ and $(t_{\text{aw}}, p_{\text{aw}})$

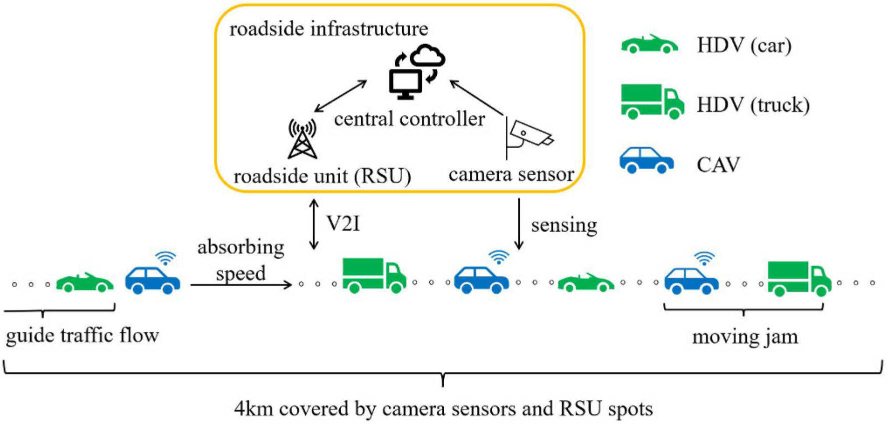

Fig. 2 Illustration of the JAD system on a test road section.

within the specific time-space regions from vehicle n ($1 < n < i$), it will decide that the target moving jam disappeared, and will switch to perform the "fast-out". The "fast-out" will be shut down finally when $s_i < s_{\text{safe}}$ and $v_i \geq v_{\text{rec}}$. Here, v_{rec} is the speed threshold.

3 Simulation results

3.1 Settings

For evaluation, the proposed JAD system is assessed on a hypothetical 4 km single-lane road section (Fig. 2). For simplicity, camera sensors and RSU spots covered the entire road section. Furthermore, no communication or detection errors are considered in the simulation. To consider the communication delay, we update the control inputs of JAD every $\Delta t_{\text{ad}} = 1$ sec. The intelligent driver model plus (IDM+) with stochastic noise is employed for HDVs, while the deterministic IDM+ is employed for CAVs not performing JAD [16, 17]. Vehicle 1 (a HDV) is forced to decelerate from $v_{\max}$ to V_{ip} with constant acceleration $-a_{\text{ip}}$ at time t_{ip} to generate a moving jam. Then, it remains at V_{ip} for time interval T_{ip} (Here, ip means initial perturbation, and V_{ip} and T_{ip} reflect the moving jam scale). Finally, it returns to normal car-following driving. Inverse time-to-collision (iTTC) is used as the surrogate measure of crash risk for measuring performance [18]. ΔAiTTC represents the measure of safety improvement.

Other parameters employed in the simulation are as follows: $v_{\max} = 17$ m/sec, $\underline{v_{\text{ad}}} = 16.5$ km/h, $v_{\text{ad,thre}} = 35$ km/h, $L_{\text{ad,thre}} = 2000$ m, $s_{\text{safe}} = 50$ m, $\overline{a_{\text{ad}}} = 1$ m/sec^2, $\underline{a_{\text{ad}}} = -1$ m/sec^2, $v_{\text{rec}} = 4.5$ m/s, $d_{\text{car}} = 4$ m, $d_{\text{truck}} = 12$ m, $k_1 = 0.2$, and $\Delta t = 0.1$ sec. Other parameters related to the IDM+ are the same as [16].

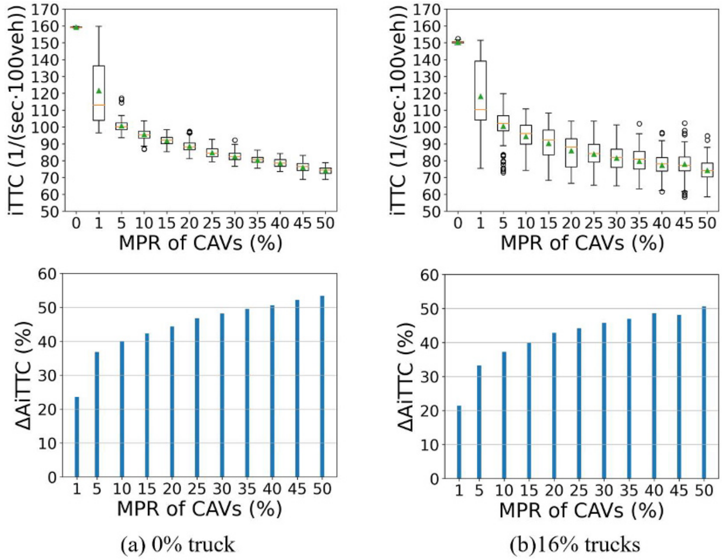

Fig. 3 Sensitivity analysis on MPR of CAVs.

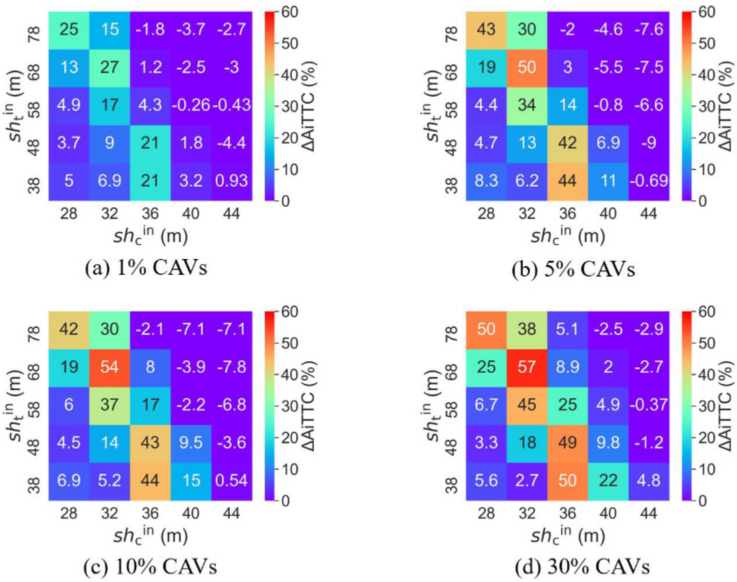

Fig. 4 Sensitivity analysis on inflow rate (the ratio of trucks is set to 16%).

3.2 Results

MPR of CAVs. Figure 3 demonstrates that the crash risk generally decreases with the increase in the MPR of CAVs. Additionally, the heterogeneous traffic scenario shows similar performance. The situation of 1% CAVs can even enhance about 20% of traffic safety; however, there is a significant fluctuation since no proper absorbing car is found in some cases. Additionally, only a few CAVs (around 5% to 10%) enhanced roughly 30% or more of traffic safety. Figure 3 also demonstrates that 5% MPR of CAVs is fairly sufficient for removing the moving jam since the improvements are close from 5% to 50% MPR of CAVs. This indicates that our JAD system can effectively reduce moving jams under low MPRs of CAVs in the near future.

Inflow rate. In the simulation, we consider two variables of inflow rate, i.e., the inflow space headway of cars (both of HDVs and CAVs) $sh_{\mathrm{c}}^{\mathrm{in}}$ and the inflow space headway of trucks $sh_{\mathrm{t}}^{\mathrm{in}}$. The higher value of space headway represents a lower inflow rate and vice versa. Traffic safety is enhanced with JAD under various inflow rates for the truck ratio of 16%, as shown in Fig. 4. The enhancement in the scenario of 5% CAVs is very close to 10% and 30% CAVs. This indicates that the 5% MPR of CAVs is fairly sufficient for conducting JAD. However, the enhancement decreases at both extremely low inflow rates and extremely high inflow rates. The safety enhancement is reduced because the moving jam does not tend to appear, or it may disappear spontaneously under low inflow rates; however, the secondary jam induced by JAD is more serious under higher inflow rates than under lower inflow rates. Moreover, JAD slightly deteriorates traffic performance under extremely low inflow rates because the initial perturbation tends to decay and disappear, while the deceleration of the JAD leads to minor adverse effects on the upstream traffic.

4 Conclusions

This study proposed a non-traffic model JAD system to reduce single moving jams with mixed traffic (HDVs and CAVs) and heterogeneous traffic (cars and trucks) on freeway sections. The system operates based on the moving jam propagation speed estimation with vehicular trajectory data collected by roadside camera sensors. The proposed JAD system effectively increases traffic safety under conditions of low MPRs of CAVs (approximately 1% to 10%). Particularly, we found that the scenario of 5% CAVs substantially reduced the moving jam, indicating that this scenario is sufficient for conducting JAD. Furthermore, the sensitivity analysis showed the robustness of the JAD system with variations in the inflow rate. Future work should consider more realistic conditions (i.e., partial coverage of camera sensors and RSUs, and communication and detection errors) to examine the robustness of the proposed JAD system. Additionally, in the future, we would like to improve our current JAD system to address multilane and multiple moving jams problems for real-world applications.

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