A jam-absorption driving strategy for mitigating traffic oscillations

Zhengbing He, Liang Zheng, Liying Song and Ning Zhu

Abstract—To mitigate traffic oscillations usually sustainably propagating upstream, this paper proposes a jam-absorption driving (JAD) strategy in the framework of Newell’s car-following theory. The basic idea of the JAD strategy is to guide a vehicle slowly move before being captured by an oscillation, and terminate the slow movement when the vehicle would begin to leave the jam if no such a JAD strategy was implemented. To practically achieve the idea, a two-step method is proposed to estimate the time-space ending point of the strategy, and a proper vehicle is selected to implement the JAD strategy based on a given expected absorbing speed and current traffic conditions. To test the JAD strategy, two simulated traffic scenarios are constructed based on a realistic simple data-driven car-following model. The first scenario, which only reproduces one oscillation, directly shows the effectiveness of the JAD idea in preventing wave propagation and capacity drop. The second scenario, which contains a series of traffic oscillations induced by the rubbernecking behavior, validates the proposed JAD strategy in a more complicated and realistic conditions. These results show that the JAD strategy works well in absorbing traffic oscillations, and the side effects brought by the oscillations can be subsequently mitigated.

Index Terms—Jam-absorption driving, traffic oscillation, trajectory, capacity.

I. INTRODUCTION

Traffic oscillations or stop-and-go waves are common phenomena in freeway traffic. “Drifting” with the oscillations, vehicles accelerate and decelerate alternatively, and the side effects are mainly threefold: First, capacity drop maybe spontaneously occur and traffic efficiency is thus reduced [1]–[3]; Second, considerable fuel is consumed, and more emissions are discharged; Third, potential risk of traffic accidents significantly increases. More seriously, once a traffic oscillation forms, it usually propagates against congested traffic as kinematic waves without losing their structures [4]–[6]. It means that the side effects persistently affect the traffic and environment.

Since the well-known trajectory dataset was published ten years ago by Next Generation Simulation Project (NGSIM), a number of researches were dedicated to investigate the features of the formation and propagation of the traffic oscillations. For example, Ref. [7] proposed an asymmetric microscopic driving behavior theory in order to study the trigger of the traffic oscillation. Based on Newell’s car-following theory [8], [9] modeled driver’s timid and aggressive car-following behavior, and the traffic oscillations were well reproduced consequently. Ref. [10] later extended the model in Ref. [9] by taking into account more behavior parameters in different periods of experiencing an oscillation. Ref. [2] defined and analyzed all stages of the traffic oscillation, namely, precursor, growth, stable, and decay. Most of the researches took Newell’s car-following theory as the theoretical foundation. It, in return, implied the soundness and the importance of the Newell’s theory.

As more and more characteristics of the traffic oscillations have been understood, how to mitigate the oscillations becomes a natural subsequent question. An interesting driving strategy, i.e., slowly moving in advance of being captured by a jam, recently attracts our attention. Although many drivers may have the idea in daily life, Ref. [11] and [12] may be the first ones that clearly introduced the idea as a driving technique, which was composed of two sequential actions: “slow-in”, i.e., slowly moving and taking a longer headway in advance of reaching a leading vehicle in a standstill, and “fast-out”, i.e., after the “slow-in” action, following the leading vehicle and accelerating quickly. More recently, Ref. [13] named the strategy as jam-absorption driving (JAD), and theoretically addressed the two actions, and additionally focused on the condition that no secondary jam would be resulted in. Later, Ref. [14] applied and tested the strategy in a car-following model proposed by Ref. [15].

One of the foundations of the work in Ref. [13] is the assumption that the jam region kept expanding based on the “frustration effect” of drivers [16]. However, more recent works and various detailed trajectory datasets showed a constant jam region [2], [17]–[19]. These empirical observations are more consistent with Newell’s car-following theory. In addition, the theoretical framework proposed by Ref. [13] has not been ready to be practically applied. Neither a realistic simulation scenario or a field test scenario is provided. Even in their following work given by Ref. [14], where the strategy was applied and tested in a car-following simulation scenario, the results may be not practical. For example, to absorb a jam, a vehicle has to begin slowly moving in advance of about 10000 m (see Figure 7 in Ref. [14]).

To demonstrate the JAD in a more practical manner, the paper aims at mitigating the frequently-occurred traffic oscillations on freeways, and proposes a JAD strategy in the framework of Newell’s car-following theory. The JAD strategy is applied and tested in more realistic traffic-oscillation scenarios generated by using a recently proposed nonparametric car-following model driven by field data. The remainder of the paper is organized as follows: The following section...
first introduces some background of this research, including Newell’s car-following theory and the nonparametric car-following model; Then, Section III proposes the details of the JAD strategy based on Newell’s car-following theory; Section IV demonstrates the effectiveness of the JAD strategy in two traffic-oscillation scenarios; A conclusion and discussion are made at last.

II. BACKGROUND

A. Newell’s car-following theory

This paper intends to propose the JAD strategy in the framework of Newell’s car-following theory [8]. This well-known Newell’s theory gives an exact solution of kinematic wave theory [20], [21] with a triangular fundamental diagram, which only requires three parameters, namely, free-flow speed $v_f$, wave speed $-w$, and jam density $\kappa$. It is the only fundamental diagram that is able to produce acceleration and deceleration waves propagating upstream at a constant speed and without rarefaction fans [9], [22]. Thus, when the traffic is congested and lane changes are few, a wave propagates with a constant length of the jam region instead of an expanding length, which has been empirically observed from world-wide traffic data [2], [17]–[19], [23].

More specifically, this theory defines a linear spacing function for the congested traffic conditions, i.e.,

$$s(v) = \delta + \tau v$$

(1)

where $\tau = 1/(w\kappa)$ is the wave trip time between two consecutive trajectories and $\delta = 1/\kappa$ is the jam spacing. According to the theory, a following vehicle can be simply determined by shifting its leading vehicle along the wave direction, and $\tau$ and $\delta$ are the horizontal and vertical displacements, respectively. The model reads

$$t_i = t_{i-1} + \tau$$

(2a)

$$x_i = x_{i-1} - \delta$$

(2b)

where time $t_i$ and position $x_i$ indicate the trajectory of vehicle $i$, and vehicle $(i-1)$ is the leading vehicle of vehicle $i$.

B. A nonparametric car-following model driven by field data

To test this JAD strategy, this paper constructs two traffic-oscillation scenarios by using a recently proposed simple nonparametric car-following model [24]. The car-following model is based on a prevailing nonparametric approach, called $k$-nearest neighbor, which is very simple to understand but works incredibly well in practice. Based on the truth that drivers usually repeat their driving behavior in similar circumstances, the model takes the average of the most similar historical cases as an output estimation. Four inputs are selected to determine the similarity, which are the moving distance of the leading vehicle in the latest two time steps, and the space headways of the following vehicle in the latest two time steps. The output is the moving distance of the following vehicle at this time step. $k$ is the only parameter, which indicates the number of historical cases considered as the most similar cases. Neither fundamental diagrams nor driver’s behavior parameters is assumed. It has been shown that the simple model is able to realistically reproduce traffic characteristics contained by field data, such as all stages of stop-and-go oscillations, fundamental diagrams, periods, and amplitudes of oscillations.

As it has been done in Ref. [24], the underlying database of the model is built by using the US-101 trajectory dataset released by NGSIM. The trajectory dataset was collected on a 6-lane segment in the vicinity of Lankershim Avenue on southbound US-101 freeway in Los Angeles, California. The time period of data collection ranges from 7:35 a.m. to 8:35 a.m. on June 15, 2005. The trajectory dataset collected on Lane 1, 2, and 3 are adopted, and the original dataset provides a data sample every 0.1 sec. This paper simply averages these data sample every 1 sec (arithmetic mean) to smooth out the detection errors. It is also consistent with the selected simulation time step in the upcoming simulation scenarios.

III. THE JAM-ABSORPTION DRIVING STRATEGY

A. Basic idea of the jam-absorption driving strategy

The basic idea of the JAD strategy is to guide the absorbing vehicle (i.e., the vehicle implementing the JAD strategy) slowly move with an absorbing speed before it reaches an oscillation, and terminate the slow movement when the absorbing vehicle would begin to leave the jam region if no such a JAD strategy was implemented. See Figure 1 as an example: when an oscillation is detected, we activate the vehicle at point $A$ to implement the JAD strategy and guide the vehicle slowly move towards point $B$ with an absorbing speed as follows

$$v^* \approx V(A, B) = \frac{x_B - x_A}{t_B - t_A}.$$  

(3)

where $V(\cdot)$ is the function of the slope between two points in the time-space plane. When the absorbing vehicle arrives at point $B$, we terminate the JAD strategy.

If the traffic evolves strictly following Newell’s car-following theory, no second wave will form, and the following vehicles will slowly move as the absorbing vehicle does (see the green lines in Figure 1). However, the driving behavior in reality is non-equilibrium, and a traffic oscillation could be triggered by inhomogeneous driving behavior [7], [9], [10], or
even by a small perturbation [24], [25]. Therefore, it is possible that the second wave forms due to the resulted high density and occasional driving behavior. To the best of the authors’ knowledge, there is still no empirical finding that unveils the relationship between the magnitude of the non-equilibrium behavior and traffic conditions. Therefore, this paper doesn’t focus on avoidance of the formation of the second wave.

### B. A two-step estimation of the ending point

The two-step method ensures activating an absorbing vehicle as soon as a vehicle is observed to begin stopping or a wave is predicted to form (i.e., Step-1), and we further modify the absorbing speed when a jam is confirmed to be stable (i.e., Step-2). Referring to Figure 2, a vehicle begins slowly moving at point $C$. According to the formation process of empirical traffic oscillations, a stable wave usually forms starting from traffic deceleration [2]. Thus, the vehicle may have not completely stopped, but a wave could begin growing. This step allows us to activate an absorbing vehicle as soon as a wave is just triggered. Behind this vehicle, we define point $D$ (see Figure 2), where a vehicle is accelerating to leave the jam. Point $C$ and $D$ indicate the trigger and the formation of the oscillation, respectively. Thus, the two-step method is given as follows:

**Step-1:** When point $C$ is observed, we estimate the ending point $B'$ of the JAD strategy based on Newell’s car-following theory:

$$t_{B'} = t_C + n\tau + T$$  \hspace{1cm} (4a)$$

$$x_{B'} = x_C - n\delta$$ \hspace{1cm} (4b)

where $n$ is the vehicle number between point $C$ and the absorbing vehicle (if we count the vehicles behind point $C$, $n$ is the number of the absorbing vehicle), and $T$ is a predefined estimation of the jam length in time. An accurate value of $T$ is not crucial, because Step-2 will make a revision independent of $T$. Accordingly, the absorbing speed is determined as

$$v_1^* \approx V(A, B').$$ \hspace{1cm} (5)

**Step-2:** When point $D$ is observed (the absorbing vehicle is now located at point $E$), the estimated ending point is updated from $B'$ to $B$ as follows:

$$t_B = t_D + n'\tau$$ \hspace{1cm} (6a)$$

$$x_B = x_D - n'\delta$$ \hspace{1cm} (6b)

where $n'$ is the vehicle number between point $D$ and the absorbing vehicle. The estimation of the ending point is more accurate in this step, because when point $D$ is observed, the jam has surely formed and we can make an estimation without taking $T$ into account. Accordingly, the absorbing speed is updated to be

$$v_2^* \approx V(E, B).$$ \hspace{1cm} (7)

Because the speeds $v^*, v_1^*$, and $v_2^*$ are all determined based on the estimations of the ending point, it should satisfy

$$v^* \approx v_1^* \approx v_2^*$$ \hspace{1cm} (8)

In case the observation of point $C$ doesn’t finally trigger a stable wave, we should cancel the absorbing behavior. Thus, after a few seconds when point $C$ is observed, we check if the vehicles behind actually stop. If no vehicle in a standstill is observed, which implies that a stable wave doesn’t form, we terminate the strategy immediately.

### C. Specifying a proper absorbing vehicle

Given an expected absorbing speed $v^*$ and based on the above method of estimating the ending point, we can now determine which vehicle is proper to be an absorbing vehicle, and then obtain point $A$. A practical consideration for specifying an absorbing vehicle is that the absorbing vehicle should not be too far away from the trigger (i.e., point $C$), and meanwhile should result in an absorbing speed as close to $v^*$ as possible. Being not far away from the trigger means that the absorbing vehicle begins to absorb the jam soon after the jam forms, and it can absorb more wave propagation. The absorbing speed close to $v^*$, not too smaller than $v^*$, usually brings better absorbing effect.

Before proposing a method, we analyze the relationship between the following vehicle $n$ and its possible absorbing speed. Suppose a homogeneous traffic condition in the upstream of point $C$, and thus the initial speeds of all following vehicle $n$ at time $t_A$ are the same; denoted by $v_A$. Substituting Equation 1 and 4 into Equation 5, the possible absorbing speed for the following vehicle $n$ can be calculated as

$$v_1^*(n) = \frac{[x_C - n\delta] - [x_C - n(\delta - \tau v_A)]}{[t_C + n\tau + T] - t_C} = \frac{n\tau v_A}{n\tau + T},$$ \hspace{1cm} (9)

where replacing $v_1^*$ with $v_1^*(n)$ is to indicate that the possible absorbing speed pertains to the following vehicle $n$. It can be seen that the greater the initial speed $v_A$ is, the greater the absorbing speed $v_1^*(n)$ will be achieved. Treating $v_A, \tau$, and $T$ as constants, take the first-order and second-order derivatives of $n$, respectively, and the results are shown as follows:

$$\frac{dv_1^*(n)}{dn} = \frac{2Tv_A}{(n\tau + T)^2} > 0$$ \hspace{1cm} (10)$$

and

$$\frac{d^2v_1^*(n)}{dn^2} = \frac{-2\tau^2Tv_A}{(n\tau + T)^3} < 0$$ \hspace{1cm} (11)$$

$$v^* = v_1^* = v_2^*$$ \hspace{1cm} (8)
It turns out a basic relationship that $v_1^*(n)$ is positively correlated to $n$, while the larger $n$ is (i.e., the further the absorbing vehicle is away from point $C$), the slower the increase of $v_1^*(n)$ is.

However, the traffic conditions in the upstream of a trigger may be not homogeneous in practice, and local fluctuations may exist in the relationship. To relax the assumption of homogeneous upstream traffic, we propose a more practical method to determine the absorbing speed. We first define the furthest following vehicle $n_{\text{max}}$ being potential to implement the JAD strategy, and calculate the possible absorbing speeds for all following vehicles starting from the furthest one, i.e., $v_1^*(n), n = n_{\text{max}}, \ldots, 1$. After sequentially discarding all vehicles with a possible absorbing speed larger than $v^*$, we calculate the difference between the possible absorbing speeds of two successive following vehicles, i.e., $\Delta v^*(n) = v_1^*(n) - v_1^*(n-1)$, where $v_1^*(n) \leq v^*$ and $v_1^*(n-1) \leq v^*$. Once two successive differences are larger than a given value $\Delta v^*$, i.e., $\Delta v^*(n) > \Delta v^*, \Delta v^*(n-1) > \Delta v^*$, we take the following vehicle $n$ as the absorbing vehicle.

We launch the searching from $n = n_{\text{max}}$, and terminate it when two successive differences are successively larger than a given value, which means the current absorbing speed is surely accelerating to leave a slowly-decreasing part of the changes of the absorbing speeds. Searching starting from $n = n_{\text{max}}$ usually corresponds to searching starting from the large absorbing speed. Then, even if the searching is trapped in a local fluctuation, the resulted absorbing speed is usually relatively large. In contrast, if we search starting from $n = 1$, which corresponds to searching starting from the small absorbing speed, the absorbing speed is usually relatively small if the searching is trapped in a local fluctuation. Apparently, the larger absorbing speed is better than the smaller one. In the following simulation test section, the process will be illustrated along with detailed instances.

**IV. VALIDATION OF THE JAM-ABSORPTION DRIVING STRATEGY**

**A. Implementing the absorbing speed**

The JAD strategy assigns a slowly-moving speed for an absorbing vehicle. Obviously, the artificial intervention changes the natural car-following behavior. In detail, if we assign an absorbing speed $v^*$ at the starting point, it is unrealistic that the vehicle moves with $v^*$ immediately, and a deceleration process must be taken into account. Thus, when an absorbing speed has been determined, let the absorbing vehicle move as follows:

$$v(t + \Delta t) = \max \left\{ \frac{x_B - x(t)}{t_B - t}, (1 - \theta)v(t) \right\}$$ (12)

where $\Delta t$ is the time interval of updating speed, $x(t)$ is the position of the vehicle at time $t$, $\theta \in (0, 1)$ is a given deceleration rate. The first term in the brace guarantees that the absorbing vehicle is able to accurately arrive at the end point $B$, and the second term integrates the deceleration constraint.

This deceleration model simply ensures the movement with a speed close to $v^*$ and the accurate arrival of the ending point. In the following two simulation scenarios we set $\theta$ to be 0.2. See Figure 3 for the result of a numerical experiment.

**B. A scenario with a single oscillation**

This scenario simulates a platoon following an empirical leading vehicle, and tests the basic idea of the JAD strategy in the framework of Newell’s car-following theory. To this end, we select a typical vehicle who traverses an oscillation on Lane 1 of the US-101 dataset (Vehicle No.1989). A new vehicle is sent on the roadway with a speed of 15 m/sec after its leading vehicle has left the entry 35 m away. It is known that the length of the US-101 segment is only about 640 m, and to exhibit more wave propagations we extend backward the roadway and the empirical leading vehicle in the simulation scenario. Figure 4(a) presents the time-space diagram of the trajectories without implementing the JAD strategy. It can be seen that a stable oscillation forms behind the empirical leading vehicle.

To absorb the oscillation, we guide the 11th vehicle to implement the JAD strategy. Since the purpose is to test the basic idea, we predetermine the ending point exactly following Newell’s car-following theory, i.e., the time-space point where the 11th vehicle would recover from the oscillation if the JAD strategy was not implemented. In Figure 4 the point is labeled as $B$. We now implement the JAD strategy with different absorbing speeds. See Table I for the details of the settings, and see Figure 4(b)-(d) for the time-space diagrams of the resulted trajectories. To clearly show the effect, the last vehicle in the case without implementing JAD strategy (i.e., Figure 4(a)) is plotted into the other subfigures as a benchmark. It can be seen that even though the absorbing vehicle can exactly arrive at the ideal ending point, the results are strongly influenced by the absorbing speed. The larger the speed is, the better the effect may be. In Figure 4(b), the relatively high absorbing speed absorbs the jam, and no following vehicle completely stops. However, it is noticed that the JAD strategy decentralizes the oscillation into wider high-density traffic. In Figure 4(c), although there is no jam closely behind the absorbing vehicle, the second wave forms after a while due to the sensitivity of the high-density traffic. In contrast, the absorbing effect is quite limited in Figure 4(d), which demonstrates that low
absorbing speed doesn’t bring us benefits. It also implies that personal behaviors, i.e., a driver temporarily slowly moves in order to avoid being captured by a jam, may not help to improve the traffic efficiency.$^1$

### Table I

<table>
<thead>
<tr>
<th>Case</th>
<th>Starting point</th>
<th>Ending point</th>
<th>Absorbing speed (m/sec)</th>
<th>Duration (sec)</th>
<th>Displacement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$A_1$</td>
<td>$B$</td>
<td>7.4</td>
<td>36</td>
<td>267</td>
</tr>
<tr>
<td>2</td>
<td>$A_2$</td>
<td>$B$</td>
<td>5.7</td>
<td>26</td>
<td>149</td>
</tr>
<tr>
<td>3</td>
<td>$A_3$</td>
<td>$B$</td>
<td>3</td>
<td>16</td>
<td>48</td>
</tr>
</tbody>
</table>

Figure 5 presents the changes of the flow behind the absorbing vehicle in Figure 4(a) and (b), which is measured based on Edie’s generalized definitions [26] (For more details about the way to measure, one can also refer to Ref. [27]). It can be seen that capacity drop occurs accompanying the oscillation, which demonstrates the side effects of an oscillation. In contrast, sending an absorbing vehicle is able to prevent capacity drop, and the traffic efficiency is thus improved due to the higher queue discharge rate and congestion speed [3].

### C. A scenario with a series of traffic oscillations

In this scenario, we test the complete JAD strategy in a scenario containing a series of traffic oscillations. To construct the scenario, we simulate drivers’ rubbernecking behaviors as it has been done in Ref. [10] and [24]. Specifically in this paper, a 2.25 km one-lane roadway is simulated for 1 hour. For the entry boundary conditions, a new vehicle is sent on the roadway with an initial speed of 15 m/sec, when its leading vehicle has left the entrance 35 m away. The rubbernecking zone is located at section [2, 2.05] km. When vehicles enter the zone, they have a probability $r$ to rubberneck and then slow down by 20%. If rubbernecking occurs, it will occur at most once. The influence of the rubbernecking lasts for 5 simulation steps, i.e., 5 sec. We compare two cases with different $r$-values, i.e., $r = 0.05$ and $r = 0.07$, respectively. See Figure 6(a) and 6(c) for the natural oscillations triggered by the rubbernecking behavior. It is obvious that when $r = 0.07$, more oscillations form and the period of oscillations is smaller.

Now we implement the JAD strategy to mitigate the oscillations. According to the simulated traffic, we regard that an oscillation will be triggered (i.e., the determination of point $C$ in Figure 2) when the speed at this time is smaller than the speed at last time (i.e., decelerating), and meanwhile the speed at this time is smaller than 0.5 m/sec. Regard a vehicle being recovering from a jam (i.e., the determination of point $D$ in Figure 2) when the speed at this time is larger than 1 m/sec, while 4 sec ago the speed is smaller than 0.1

$^1$When we discuss with drivers about the strategy, some of them are interested in sharing their personal experience, i.e., when they realize that the traffic begins to stop, they may not follow the leading vehicles; instead, they drive slowly in order to avoid being captured by the jam and to accelerate with speed later. However, this result indicates that this personal behavior doesn’t benefit the traffic, because they usually start to decelerate too late and the resulted absorbing speed is too low to absorb the jam.

![Fig. 4. A simulation test for the basic idea of the JAD strategy with different absorbing speeds.](image-url)
Fig. 5. Comparison of the flow-density relationship behind the absorbing vehicle. The colors in subfigure (c) correspond to the regions with the same colors in subfigure (a) and (b), respectively. The flow and density are calculated by using a tool called “Trajectory Explorer” [28].

Fig. 6. Trajectory comparisons between the scenario with natural oscillations (no strategy) and the one implementing the JAD strategy.

In specifying the absorbing vehicle, we set the expected absorbing speed $v^* = 6$ m/sec, as well as $v_{\text{max}} = 40$, $\Delta v^* = 0.05$. Other settings include $w = 4.16$ m/sec (i.e. 15 km/h), $\kappa = 0.13$ veh/m (i.e., 130 veh/km), and $T = 20$ sec. These settings are given based on basic traffic flow knowledge, although some of them are somewhat arbitrary.

Figure 6(b) and 6(d) present the effect brought by the JAD strategy. It can be seen that oscillations are indeed absorbed, in particular when the period of the oscillations is relatively large in Figure 6(a) and (b), where $r = 0.05$.

Compare Region 1 in Figure 6(b) with Region 2 in Figure 6(d). Before being captured by the oscillations, the vehicles freely moves in Region 1. It is easy to obtain an absorbing vehicle moving with a speed approximate to the expected absorbing speed $v^*$. In contrast, the traffic has been congested in Region 2, and we may not find a proper absorbing vehicle moving with a speed of about $v^*$. Instead, an absorbing speed smaller than $v^*$ is specified. Thus, the resulted traffic behind the absorbing vehicle is more dense, and it is easier for the growth of a second wave. Fortunately, when a second wave forms, another absorbing vehicle will be accordingly activated.

Figure 7 and 8 exhibit more statistical results, which further confirm the effect of the JAD strategy. Figure 7 combines the total stopping time of a vehicle with the vehicle number, where the total stopping time of a vehicle is the total time that the speed of a vehicle is lower than 1 m/sec. For example, point
oscillations during the period of data collection [10]. It may be 4.6% [9]. Rubbernecking was also reported as the trigger of uphill segment with percentage grades ranging from 2 to nonparametric car-following model was collected from an the sensitivity. More specifically, the database underlying the fact that the strategy decentralizes the oscillation into more (d) (where \( r \)) respectively; The numbers are 10 and 17 in Figure 6(c) and 8 and 14 oscillations in Figure 6(a) and (b) (where \( r \)) located at about 1500 m in Figure 6. It turns out that there are more oscillations. In Figure 8, the frequency of different decelerations are presented. It is clear that the JAD strategy reduces the total stopping time for an individual vehicle as well as the number of vehicles in a standstill. In particular, it is more obvious for Figure 7(b) where \( r = 0.07 \) and there are more oscillations. In Figure 8, the frequency of different decelerations are presented. It is clear that the JAD strategy particularly reduces the number of declarations in the region from about \(-2.6 \) m/sec\(^2\) to \(-1 \) m/sec\(^2\). The reduction in the number of vehicle stops and the intensity of deceleration benefits emission reduction.

It is also noticed that the JAD strategy may result in more oscillations, even though the rubbernecking probability is the same. Roughly count the oscillations along the horizontal line located at about 1500 m in Figure 6. It turns out that there are 8 and 14 oscillations in Figure 6(a) and (b) (where \( r = 0.05 \)), respectively; The numbers are 10 and 17 in Figure 6(c) and (d) (where \( r = 0.07 \)), respectively. It could be attributed to the fact that the strategy decentralizes the oscillation into more sensitive high-density traffic. Although it is known that the high-density traffic is usually sensitive, we may still argue that the employed car-following model contributes a part of the sensitivity. More specifically, the database underlying the nonparametric car-following model was collected from an uphill segment with percentage grades ranging from 2 to 4.6% [9]. Rubbernecking was also reported as the trigger of oscillations during the period of data collection [10]. It may be reasonable to conjecture that such a database is more sensitive than regular driving behavior. Thus, more oscillations may be resulted in spontaneously or non-spontaneously by the car-following model.

At last, we exhibit the process of specifying an absorbing vehicle, which was proposed in Section III-C; See Figure 9. Each line in the figure corresponds to a process of specifying an absorbing vehicle starting from \( n_{max} \). The x-axis shows the number of the following vehicles, and the corresponding values in the y-axis are its possible absorbing speeds. The searching direction is from right to left. The spot indicates the finally specified absorbing vehicle and its absorbing speed. See those thicker lines in Figure 9, for example. These lines empirically validate the relationship derived from the theoretical analysis, i.e., the possible absorbing speed is positively correlated to the number of the followers, while the larger the number is, the slower the increase of the speed is. In addition, the parts of the lines at the left of the spots are steeper, while the parts at the right are flatter. It means that the locations of the spots roughly satisfy the consideration that the number of the following vehicles is as small as possible (i.e., close to the trigger), and the absorbing speed is as large as possible.

V. CONCLUSION AND DISCUSSION

To mitigate frequently-occurred traffic oscillations, this paper proposes a JAD strategy in the framework of Newell’s car-following theory. The JAD strategy determines the ending point in two steps, and selects the proper absorbing vehicle.
extract the required information by exploiting certain traffic estimation approaches based on current technical conditions. When applying the JAD strategy, we may encourage drivers to join in the JAD project by offering rewards. Also as stated in [13], overtaking an absorbing vehicle may reduce the effect of the JAD strategy, and it could be prevented by educating drivers.

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Fig. 9. Determination of the absorbing vehicle.

Based on the given absorbing speed and the upstream traffic conditions. Two traffic-oscillation scenarios respectively with an oscillation and a series of oscillations are simulated by using a realistic nonparametric car-following model. The proposed JAD strategy is implemented to mitigate the traffic oscillations in the two scenarios. The results show that the proposed JAD strategy is able to effectively prevent the propagation of traffic oscillations, which benefits us in the aspects such as (i) increasing the traffic efficiency by decreasing the magnitude of capacity drop, (ii) reducing the total stopping time and the intensity of deceleration, and thus improving the driving safety.

Nevertheless, it is also noticed that second waves or more oscillations may be triggered due to the instability of high-density traffic. On one hand, it indeed unveils a drawback of the JAD idea originally introduced by [11], [12] and [13]. On the other hand, we may argue that the employed database underlying the nonparametric car-following model increases the sensitivity of the simulated traffic, and more oscillations and second waves may be generated in the scenarios based on the model. Fortunately, the proposed JAD strategy is capable of activating another absorbing vehicle to mitigate the new oscillation.

The present JAD strategy needs to know the motion of on-road vehicles as inputs. It may be difficult for current technical conditions, but in the near future, with the development of advanced communication technology, such as an environment of connected vehicles, it would be a practical and feasible means to prevent the propagation of traffic oscillations. Or, we may
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