Decentralized management of ephemeral traffic incidents

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Abstract
Ephemeral traffic incidents, such as a fallen tree on a road, pose traffic safety hazards, and impact locally on traffic. While these incidents are neither predictable nor persistent, their existence is relevant for all vehicles planning to pass by while the impact continues. This article develops a novel communication strategy for vehicular ad hoc networks aiming to inform all the affected vehicles, while involving only the minimum number of non-affected vehicles. This strategy exploits time geography as a spatial and temporal filter, ensuring also that the information broadcasting timely terminates when the incident is over. Agent-based traffic simulations show that, when a road is temporarily blocked due to an ephemeral incident, the proposed decentralized information management model achieves significant improvement in travel efficiency and automatically updates outdated incident information in time.

1 | INTRODUCTION

Ephemeral traffic incidents, that is, non-recurring short-term events, have adverse impacts on the efficiency of traffic (Falccchio & Levinson, 2015) and travelers’ safety (Wang et al., 2019). For instance, a fallen tree branch or a flash flood may block the road for a short period of time (Li et al., 2018), which not only disrupts traffic but may also result in secondary incidents. However, due to their ephemeral nature, it is difficult to capture these ephemeral incidents and share any information about them with vehicles that are potentially affected in their travel. But only if the information can be timely transmitted to these vehicles, the negative impacts caused by ephemeral
incidents can be minimized (Kuroki et al., 2009). Effective distribution and management of traffic incident information is essential for travelers to alleviate the negative impacts of incidents (Neudorff et al., 2003).

There are many traditional methods to manage traffic incidents, such as lane control, dynamic traffic signs, and ramp metering control (Dressler et al., 2008; Neudorff et al., 2003; Sheu & Chang, 2007). These strategies are labor-intensive, inflexible, and costly. With the advancement in communication technologies for intelligent transportation systems, real-time traffic information can be obtained through centralized or decentralized channels. Radio with its traffic message channel (Dietmar & Bev, 1998) or commercial navigation platforms (e.g., Google Maps, Waze, TomTom, and HERE) are common centralized systems that help drivers keep track of incident information. However, the usage of centralized methods is limited by information heterogeneity between platforms (De Souza et al., 2017), insufficient incident coverage (Amin-Naseri et al., 2018), and time delay in releasing incident information (Neudorff et al., 2003).

Alternatively, vehicular ad hoc networks (VANETs), also called vehicle-to-vehicle (V2V) networks, that are established between connected vehicles (CVs), can distribute incident information in a decentralized manner without a centralized platform. The drawbacks of centralized methods can be solved by decentralized methods to some extent. Once a CV in V2V networks is involved in or detects an incident, it can generate some incident information by onboard sensors, such as an estimation of the incident’s gravity or duration (Levi et al., 2015; Levering et al., 2020), and then incident information is broadcast to other nearby CVs immediately. However, decentralized methods also have a challenge of timely updating incident information (Chavhan et al., 2021).

In V2V networks, since CVs detecting the incident, or hearing about the incident, continue travelling, they carry and broadcast information that might get outdated. In addition, as CVs only communicate via V2V networks within their local range, there may be vehicles affected by the incident that never receive the message—a limitation of the decentralized methods caused by the movements of broadcasters combined with the market penetration rate of CVs. This article addresses both the decentralized management of ephemeral incident information for its reach and the timely updating of this information. An event-driven model is proposed to manage information about ephemeral incidents in a decentralized manner, including broadcasting incident information, guiding the traffic, and updating the last incident information, to improve traffic efficiency. In the model, it is assumed that decentralized CVs can detect and classify an ephemeral incident with encounter, and will turn around to search for alternative routes, now carrying a message to inform other vehicles. Once informed vehicles find that the incident message is outdated, an updating strategy is triggered to suppress invalid broadcasts. This model is investigated by agent-based simulations, and the performance of the model in terms of reduction of the travel delays and of broadcast efficiency is evaluated. Our contribution can be summarized as follows:

- An event-driven model of decentralized information management for ephemeral traffic incidents is developed that effectively manages incident information and traffic.
- The model is experimentally evaluated by agent-based traffic simulations using a real-world road network.
- To improve the generalizability of the results, the proposed method is applied to three cities whose road networks differ significantly. The results demonstrate that our method can effectively alleviate the impact of ephemeral incidents on travel time for affected vehicles.

With the collected evidence, the study will provide the case for implementing decentralized incident management and even self-driving intelligent vehicles in the future, which also holds a number of important planning and management implications for transport departments.

This article is organized as follows. Section 2 provides a review of the related literature. Section 3 introduces the decentralized traffic incident management model. Section 4 presents the simulation setup and results. The practical implications of the proposed model and limitations are discussed in Section 5. The major conclusions are stated in Section 6.
This section reviews the recent literature on traffic incident management (TIM) by centralized platforms and VANETs. TIM is a systematic effort to predict the duration of an incident, to alleviate the impact of an incident and to reduce the time for detection, response to, and clearance of an incident (Neudorff et al., 2003). Here, we focus only on incident information relevant for vehicles in traffic, not for incident cleanup personnel.

TIM consists of incident detection, incident information distribution, and traffic control (Neudorff et al., 2003). For incident detection, conventional methods rely on police patrols, surveillance cameras, and other similar sensors (Ikeda et al., 1999), which lack efficiency due to the limitation of searching space and cost. With recent developments in computer vision, incidents can be detected and classified already by sensors on board vehicles. For instance, Levi et al. (2015) and Shang et al. (2014) presented methods to effectively detect road dangers caused by obstacles using 3D LiDAR and RGB cameras. Chen, Yang and Kong (2017) developed a method to detect water hazards on roads in real time. Levering et al. (2020) proposed a taxonomy of ephemeral road incidents and developed convolutional neural networks (CNNs) to effectively identify and classify unsigned physical incidents based on vehicle-borne RGB cameras. For the remainder of this article, we assume the problem of incident detection by vehicles as solved.

In terms of incident information distribution, several technologies have been used, including dynamic traffic signs and advisory radio (Dressler et al., 2008), relying on a centralized management platform. However, due to the limitations of space and market share, these methods usually cannot achieve the expected performance. The more recent commercial navigation systems, such as Google Maps, Waze, TomTom, and Here, are also centralized platforms; they collect information based on crowdsensing. These platforms enable vehicles to receive (nearly) real-time information about traffic. However, since navigation systems rely either on reports or on trajectory analysis, it takes a certain time for incidents to be detected and verified, resulting in a delay in distributing the information: by the time a vehicle receives the information about the incident, it might be already stuck in the traffic congestion or have triggered secondary accidents caused by the incident, if the (ephemeral) incident is not already over (Chavhan et al., 2021; De Souza et al., 2017; Neudorff et al., 2003). Besides, these navigation systems provide traffic information to the typically small proportion of vehicles on the road that are connected to them (Petrovska & Stevanovic, 2015), causing problems of information heterogeneity between clients of different platforms (De Souza et al., 2017) and suffering from low coverage rate (Amin-Naseri et al., 2018). With advances in VANETs, CVs are seen as promising alternative to manage traffic incidents, and will soon become widely available (Bansal & Kockelman, 2017). Once the incident is detected by a CV, incident information can be spread to nearby CVs. Suriyapaiboonwattana et al. (2009), Shah et al. (2019), Jin et al. (2015), and Schwartz et al. (2010) proposed protocols to transmit warning messages on highways (which are simpler to manage due to their linearity) or city areas, for example, airbag inflation and tire blow out. However, these studies did not consider the spatio-temporal management of the ephemeral incident information.

In principle, the distribution of incident information and traffic control during the incident can be mutually reinforcing. Currently, lane control and speed limit control are widely used in incident management, while they require human involvement to control traffic. Incident management systems based on CVs also allow informed vehicles to take proactive actions accordingly. It relies on wireless communication to enable seamless interactions and the exchange of information between vehicles, thereby breaking through some of the limitations mentioned above. Most research investigating traffic control in incidents is focusing on the lane assignment strategy. For instance, Mehr & Eskandarian (2021) proposed an onboard system for CVs to guide the lane changing during a freeway incident and showed that the proposed method can reduce travel delays. Farrag et al. (2021) proposed a smart TIM system based on CVs and evaluated the performance of traffic safety, traveler mobility and gas emissions. All studies using the lane assignment strategy are simulating a freeway incident. Unlike the freeway scenario, it is not enough to just control upstream traffic from the incident point in city areas, since then vehicles...
driving on other roads may be affected by the incident as well. In addition, if a road is completely blocked, the lane assignment strategy no longer works.

Studies show that vehicular traffic rerouting to avoid worse traffic conditions is key to improve traffic efficiency and safety (De Souza et al., 2020). A few studies consider the relevant response of vehicles to avoid the incident area after receiving incident information. For instance, Santamaria et al. (2014) developed a traffic management protocol to inform nearby vehicles about accidents, and then affected vehicles receiving the accident message reroute to avoid the accident. Zardosht et al. (2017) developed a decision-making module for accident management that can process information from vehicular communication and provide drivers with alternative routes to avoid the accident site. Qi et al. (2018) proposed a dynamic strategy to deliver information to selected vehicles and help them make detours. However, based on our thorough literature review, we argue that most of the existing approaches assume that a CV involved in the incident continuously broadcasts information to nearby vehicles at the site of the incident once it occurs. For incidents without CVs involvement, such as a fallen tree blocking a road, these methods lose their effect since the CV will by-pass or turn around and move on. Another challenge of managing incident information between CVs is about sharing false information (Eskandarian et al., 2021). While we address outdated information in this research, dealing with deliberately misleading information constitutes another field of research (Abu Talib et al., 2018).

Thus, all of these related works about decentralized management of traffic incidents suffer from two major limitations. First, all the CV-based solutions developed previously rely on a vehicle involved in the incident to broadcast incident information at the site of the incident. Second, once the incident information is broadcast, due to the lack of global knowledge between vehicles, vehicles may not know when the information is outdated. Previous research has not considered how to update incident information in decentralized communication. In this study, a decentralized model is proposed that can be applied to manage any kind of ephemeral traffic incident by effectively distributing incident information, updating the outdated information in a timely manner, and improving traffic efficiency during incidents.

3 | DECENTRALIZED INCIDENT INFORMATION MANAGEMENT MODEL

In this section, a decentralized traffic incident management model is introduced. For the formal specification, some definitions are introduced first (Section 3.1). Following this, we present the movement of vehicles and the reactions of affected vehicles that are informed about incidents (Section 3.2). Finally, the algorithm for incident information broadcast is introduced (Section 3.3), which is a kind of gossip algorithm (Jelasity, 2011).

3.1 | Definitions and notation

The parameters we used to explain the methods and algorithms in this article are defined in Table 1.

3.2 | Vehicle movement

In this article, we assume that all vehicles are equipped with maps of the road network, such as the length, speed limit, and direction of each road. Thus, each vehicle is capable of traveling the fastest route, without considering traffic conditions. There are three kinds of vehicles traveling in the network—centralized CVs (C-CVs), decentralized CVs (D-CVs), and non-CVs. C-CVs are equipped with a centralized communication channel, for example, an online navigation system, so that all C-CVs can receive incident information after the information is published by the platform. Once informed, C-CVs determine whether the incident location is on their planned route. If so, they are affected vehicles
and will reroute to the fastest alternative route (Figure 1c). Otherwise, these C-CVs will follow their planned routes. D-CVs, using the proposed decentralized model, have the ability to detect an incident, and to collect, broadcast, and receive incident messages. Once a D-CV receives an incident message, the vehicle will determine whether its route ahead contains the incident location. If the D-CV’s route ahead contains the incident location, it will first identify whether the travel time to the incident location is shorter than the remaining estimated duration of the incident. If that is the case, the vehicle is an affected vehicle and will calculate the fastest alternative route in advance (Figure 1c). If the remaining estimated duration is shorter, or the incident location is not on the route, the vehicle is considered unaffected and will continue their journey as planned. Non-CVs cannot receive any information from any sources so that they always take the planned route unless they arrive at a road closure due to an incident (Figure 1b), in which case they turn around and seek the shortest detour.

### 3.3 Broadcasting incident information

The broadcast process by the centralized communication channel is simple. Incident information is generated centrally, for example, from trajectory analysis of C-CVs, and is only then (i.e., with a delay) broadcast to all C-CVs. Similarly, road reopening information is broadcast with a delay time after the incident is over. In the proposed decentralized management model, the process of broadcasting incident information is mainly divided into three steps: (1) incident detection; (2) incident message broadcast; and (3) incident message refresh. When a D-CV detects an incident and infers further incident information, this triggers the incident broadcast. Then incident messages are broadcast between D-CVs, controlled by an algorithm. The algorithm limits broadcasting to locations and times where affected vehicles can be assumed. Finally, when the incident is over, incident information becomes outdated, thus the outdated information will be stopped from being broadcast any further. The details are as follows.

### TABLE 1 Parameters used

| Parameters | Description |
|------------|-------------|
| id         | Identification number (ID) of each vehicle |
| $T_{\text{start}}$ | The time when the incident occurs |
| $T_{\text{end}}$ | The time when the incident is resolved |
| $I_{\text{first}}$ | The time when the vehicle first receives the incident message |
| $T_{\text{start}}$ | The estimated start time of the incident |
| $T_{\text{end}}$ | The end time of the incident broadcast |
| $t$ | The present time |
| $AR$ | The maximum affected range of the incident |
| $AR_t$ | The affected range of the incident at time $t$, that is, the geofenced region of broadcasting at time $t$ (Equation 1) |
| $D_{\text{est}}$ | The incident duration as estimated by vehicles |
| $D_{\text{act}}$ | The actual incident duration |
| $D_{\text{invalid}}$ | Outdated incident message broadcasting duration, that is, the invalid duration of broadcasting |
| TTS | The average reduction of travel time (Equation 2) |
| NB | The number of broadcasts |
| $R_c$ | The radius of radio communication between vehicles |
3.3.1 | Incident detection

Once an incident occurs on a specific road, D-CVs running into this road or reaching the location will detect the incident during the incident duration ($D_{act}$). We assume that D-CVs are capable of recognizing the type of incident, and thus assume a typical duration of the incident. Thus, when a D-CV that does not carry the incident message reaches the incident location, we assume it generates an incident message, a tuple of the form $<\text{Location}, \text{TE}_{\text{start}}, \text{Dest}, \text{AR}>$. The Location is the coordinate where a D-CV detected the incident. The $\text{TE}_{\text{start}}$ is actually the time of the detection of the incident. The $\text{Dest}$ is the incident duration, estimated based on the class of the incident (Levi et al., 2015; Levering et al., 2018). Additionally, the maximum affected range of the incident (AR) is calculated by $D_{est}$ and speed limits in the road network. Once the incident is over, the incident can no longer be detected. Thus, if vehicles carrying the incident message discover that the incident has been resolved, they will label the incident message as outdated. Details of the algorithm are shown in Algorithm 1. Note that D-CVs that detect the incident may or may not be affected vehicles, since D-CVs reaching the incident location are capable of detecting the incident, but their routes may not contain the incident road.

3.3.2 | Incident message broadcast

Following the detection, D-CVs that detect the incident initiate a decentralized broadcast between vehicles. Since the information about the ephemeral incident is relevant only for affected vehicles, which are unknown to the sender while the sender knows at least the region in which these affected vehicles could be found, a single-hop periodic and geofenced broadcast strategy is applied. Those vehicles carrying the incident message and broadcasting it periodically terminate broadcasting in two circumstances. One case is that the vehicle arrives at its destination. The other case is that the vehicle is moving outside of the geofenced region (i.e., $AR_t$, the affected range at time $t$). Due to the connection of space and time expressed in time-geography, the $AR_t$ shrinks over time due to the incident’s limited duration. Thus, $AR_t$ is a function of the location of the incident, the remaining estimated incident duration, and the maximum travel speed (Miller, 2005; Raubal et al., 2009). The $AR_t$ at time $t$ is defined as follows:

$$AR_t = D_{est} \times \text{VehicleSpeed} \times (t – \text{TE}_{\text{start}}) \times \text{VehicleSpeed}$$

(1)
For any vehicle outside of the AR_t, the incident information is irrelevant since the incident is expected to have been resolved by the time when these vehicles arrive at the incident location.

In addition, an information update mechanism is applied in the algorithm of incident message broadcasting. This mechanism caters for affected D-CVs that might not have been informed about the incident in time. If D-CVs do not receive the incident message before reaching the incident location, they will detect the incident again, and independently start broadcasting the message about the same incident. The message will contain the same Dest (based on the class of the incident), but with their own observation time, that is, a different T_Estart. Thus, in the process of periodic broadcasting, these D-CVs may encounter other D-CVs carrying incident messages with earlier T_Estart for the same incident. As the first detection of an incident is closer to the actual start time of the incident, D-CVs carrying later observation times, when they hear about an earlier detection, will automatically update their conflicting information to the information at the earlier detection time (Algorithm 2).

3.3.3 Incident message refresh and discard (updating strategy)

Due to the lack of global knowledge, as well as the unknown periods between incident starts and their detection (i.e., T_Estart + Dest ≥ T_end), the outdated incident messages might still be broadcast between D-CVs after the incident is over. Therefore, an updating strategy for refreshing the outdated message is needed. The standard method of refreshing outdated messages between vehicles is by applying the broadcast schemes to actively broadcast the refreshed message. In terms of the active method, D-CVs carrying the refreshed message continually broadcast until they leave AR_t, and then discard the refreshed message. During the time, the D-CVs cannot stop broadcasting early even if there are no outdated incident messages spreading within the AR_t.

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**Algorithm 1 Incident Detection**

Input: All vehicles and a supposed incident.

1. class Vehicle
2. id : String
3. location : Double
4. isCV : boolean
5. iCarryInfo : boolean
6. TRest : Integer
7. Incident : Dictionary
8. checkOutdated : boolean
9. end class
10. if vehicle reaches the incident location then
11.   if t within Dest then
12.     if vehicle is CV and vehicle iCarryInfo then
13.       initialize an empty dictionary for this incident
14.       Incident ← {}
15.       Incident[Location] ← Location
16.       Incident[T_Estart] ← t
17.       Incident[Dest] ← Dest
18.       Incident[AR] ← Dest × Vehicle Speed
19.       vehicle iCarryInfo ← true
20.       vehicle TRest ← t
21.   end if
22.   end if
23.   if t beyond Dest then
24.     if vehicle is CV and vehicle iCarryInfo then
25.       vehicle checkOutdated ← true
26.     end if
27.   end if
28. end if
In order to improve the refreshing efficiency (i.e., informing the vehicles carrying the outdated messages with fewer broadcasts) and reduce the $D_{invalid}$, we consider a passive strategy for refreshing the outdated message. After the incident is over, a D-CV carrying the outdated incident message and reaching the incident location will detect that the incident message is out-of-date and label the message $<checkOutdated>$. The D-CV will stop broadcasting this labeled outdated incident message and keep monitoring the received messages. If this D-CV received later the outdated incident message from another vehicle, it will immediately respond by a broadcast of the refreshed message (Algorithm 2) allowing the other vehicles to label their message as outdated as well. Finally, the incident message will be discarded once either: (a) the estimated event duration has been reached; (b) the carrying vehicles leave the $AR_i$; or (c) they arrive at their destinations. Note that if the incident still exists (i.e., $TE_{start} + D_{est} < TI_{end}$), vehicles that have already discarded the incident message due to time-out might detect the incident again.
4 | SIMULATION AND RESULTS

This section describes the simulation setup and results of the experiment. A traffic simulator, Scalable Microscopic Adaptive Road Traffic Simulator (SMARTS, https://github.com/Smart  sDev/SMARTS) (Ramamohanarao et al., 2016), is employed to simulate vehicle movement and incident message broadcasting between vehicles (Section 4.1). Three sets of comparative experiments are designed. The aim of the first set of experiments (E-I and E-II) is to evaluate the improvement of travel efficiency using decentralized and centralized incident management models. The second set of experiments (E-III) explores the advantage of the updating strategy from the perspective of broadcast efficiency, where we evaluate the performance of the decentralized traffic incident management model by the $D_{\text{invalid}}$ and $NB$ (Section 4.3). The third set of experiments (E-IV and E-V) investigates the generalizability of our method under different road conditions and road networks.

4.1 | Simulation setup

Additional modules for incident information broadcasting, as well as for the response of vehicles to incidents and for updating outdated information, are developed in SMARTS. Meanwhile, SMARTS can handle large road networks and various road rules, for example, left- or right-hand driving, car following, traffic lights, and slowed movements at intersections. The main study area is located in Melbourne, Victoria, Australia. This area is about 30 km², linking the city center with suburban regions. To demonstrate the generalizability of the proposed method, we select two additional study areas, in Shanghai, China and Berlin, Germany, which have significantly different road network topologies (Thompson et al., 2020). In the simulation, the input datasets include the road network of the study area and the routes of all vehicles. The road network dataset is from OpenStreetMap, representing the roads, the speed limits of the road segments, the number of lanes on road links, the direction of road links, traffic lights, and road intersections. The vehicle routes are randomly generated by SMARTS.

To simulate the process of incident message broadcast, some parameters also need to be set up (Table 2). In the study area of Melbourne, we intentionally insert an ephemeral incident in Victoria Street from William Street and Chetwynd Street (Figure 2a). The maximum vehicle speed for calculating AR is set at 60 km/h to cater for speed limits of 30–60 km/h in the city area (https://en.wikipedia.org/wiki/Speed_limits_by_country). The actual driving speed of each vehicle is based on the car following model. The density of vehicles is set to approximately 10 vehicles per kilometer. In terms of incident durations, in E-I and E-II, three incident scenarios with various durations ($D_{\text{act}} = 5, 10$ or 15 min) are simulated. To evaluate the performance of suppressing invalid broadcasts, in the E-III, three classes of incidents are simulated: Class I ($D_{\text{act}} = 3, 5$, or 7 min), Class II ($D_{\text{act}} = 8, 10$, or 12 min), and Class III ($D_{\text{act}} = 13, 15$, or 17 min). They represent classes of incidents that the vehicles estimate to endure 5, 10,
or 15 min, respectively, although actual incidents in these classes may take longer or shorter. Thus, the following three scenarios are considered:

- **Scenario 1**: accurately estimating the duration of an incident. The estimated incident duration is exactly the same as the real incident duration ($D_{\text{est}} = D_{\text{act}}$), or 5, 10, or 15 min, respectively. After an incident occurs on a road, the incident is detected by a D-CV. The discrepancy between the time of occurrence of the incident and the time of its detection is unavoidable and remains unknown to the vehicle. The situation also appears in the following two scenarios.

- **Scenario 2**: overestimating the duration of an incident. The estimated incident duration is longer than the real incident duration ($D_{\text{est}} > D_{\text{act}}$), or $D_{\text{act}}$ is 3, 8, or 13 min, respectively. In this case, after the incident has been resolved, the vehicle carrying the incident message and reaching the incident location would discover the message is outdated and trigger the process of incident message refresh. Thus, the outdated message can be stopped broadcasting in the network early. Note that the incident message refresh will not be triggered without the updating strategy.

- **Scenario 3**: underestimating the duration of an incident. The estimated incident duration is shorter than the real incident duration ($D_{\text{est}} < D_{\text{act}}$), or $D_{\text{act}}$ is 7, 12, or 17 min, respectively. In this case, when the first wave of message broadcast is terminated, the incident is still not over, so vehicles arriving at the incident location will detect the incident again and trigger a second wave of broadcasting, still (or again) classifying the duration to 5, 10, or 15 min, respectively. Following this, if the incident has been resolved during the process of the second wave, the process of incident message refresh would be triggered by vehicles discovering that the incident message is outdated. Similarly, the incident message refresh will not be triggered without the updating strategy.

In terms of broadcast parameters, for the decentralized model, the transmission range is 250 m (Ding et al., 2018), and the time interval (TI) is 10 s; for the centralized model, the delay time of releasing incident information is 180 s. In order to evaluate the impact of delay time on the centralized method, we also set a variety of delay time from 0 to 240 s (E-II). Additionally, the effects of the market penetration of C-CVs and D-CVs among all vehicles will be investigated by setting different proportions of CVs. In the first set, there are three kinds of vehicles, involving C-CVs, D-CVs, and non-CVs. The market penetration of C-CVs and D-CVs is set as 0, 25, 50, 75, and 100%. In the second

| Name                        | Setting of E-I | Setting of E-II | Setting of E-III | Setting of E-IV | Setting of E-V |
|-----------------------------|----------------|----------------|-----------------|----------------|----------------|
| Study area                  | Melbourne      | Melbourne      | Melbourne, Berlin, Shanghai |
| Traffic volume              | 10 vehicles per km | 10, 15 vessels per km | 4, 10 and 15 vehicle per km |
| $D_{\text{act}}$            | 5, 10, 15 min  | 5, 10, 15 min  | Class I, Class II, Class III | 10 min | 10 min |
| $D_{\text{est}}$            | 5, 10, 15 min  | 10 min         |                  |                |
| Communication range of D-CVs| 250 m          | N/A            | 250 m           | N/A            | 250 m          |
| Delay time of C-CVs         | 180 s          | 0, 30, 60, 90, 180, 240 s | N/A | 180 s | N/A |
| Time interval of D-CVs      | 10 s           | 10 s           | N/A             | 10 s           |
| Market penetration rate of C-CVs| 0, 25%, 50%, 75%, 100% | 100%          | 0               | 100%           |
| Market penetration rate of D-CVs| 0, 25%, 50%, 75%, 100% | 0             | 0, 10%, 25%, 50%, 75%, 100% | 0 | 100% |
set, only two kinds of vehicles—D-CVs and non-CVs are used. Here, the market penetration of D-CVs is set as 0, 10, 25, 50, 75, and 100%. Since we employ random vehicles, the results shown below are the average of 10 simulations by various routes to avoid bias in the results. However, in each group of experiments focusing on the effect of one parameter, the vehicle routes are kept the same in order to compare the differences in performance.

Similarly, we also simulate ephemeral incidents that occurs under different road conditions in different cities (E-IV and E-V). A 10-min incident is inserted in Prenzlauer Allee from Saabrucker StraBe to Torstrabe, Berlin and Fuxing (E) Road from Zhonghua Road to Xixang (S) Road, Shanghai, respectively (Figures 3b,c). To simulate traffic conditions during peak hours and off-peak hours, we also set a variety of traffic volumes from 4 to 15 vehicles per road kilometer. The detailed parameters are shown in Table 2.

4.2 | Evaluation metrics

To evaluate the performance of the proposed approach, we estimate the TTS (Table 1) of affected vehicles and all vehicles (including affected vehicles) driving during the incident duration. By comparing the travel time of affected vehicles and all vehicles with and without the traffic incident management model, the TTS is obtained. A larger TTS shows that the traffic incident management model can save more travel time when an incident occurs on a road.

\[
TTS = \frac{\sum_{i=1}^{N} T_{T_i} - \sum_{i=1}^{N} T_{T_i}}{N}
\]

where \(N\) is the number of affected vehicles or all vehicles driving during the incident. \(T_{T_i}\) and \(T_{T_i}^\prime\) are the travel times of the \(i\)th vehicle with and without the decentralized traffic incident management model.

Second, we evaluate the ability of the proposed method to terminate the broadcast of the incident message by computing the invalid duration of broadcast (\(D_{\text{invalid}}\)).

Finally, we count the number of broadcasts (\(NB\)) to evaluate the broadcast efficiency. The lower the number of broadcasts, the better the broadcast efficiency.

4.3 | Results

4.3.1 | Centralized model versus decentralized model

One of the main purposes of the proposed decentralized incident management model is to save travel time when an ephemeral incident occurs on a road. This section analyses the TTS with various market penetration rates of D-CVs and C-CVs, looking at both affected vehicles and all vehicles on the road during the incident duration, compared with the base case scenario that includes only non-CVs (Figure 3). Figure 3 shows the TTS for affected vehicles and all vehicles in the incident scenarios of various durations. The shades of green and red represent how much travel time, in seconds, for affected vehicles (a–c) and all vehicles are saved (d–f), respectively. A darker color means more travel time is saved. Visually, the reduction of travel time is significant when affected vehicles are able to get the incident information. It is shown that centralized and proposed decentralized models can reduce the travel times for affected vehicles up to 90 and 101 s, respectively. In general, as the number of CVs increases, the reduction of travel time increases. Meanwhile, Figure 3 reveals that the improvement of affected vehicles’ travel efficiency using the proposed decentralized model is greater than that of the centralized model. Especially, for the incident with a short duration, the advantage of the decentralized model is more obvious. For instance, in the 5-min incident scenario (Figure 3a), when there is only one kind of CVs with D-CVs and its penetration rate
The incident may not only impact directly affected vehicles, but also cause traffic congestion on other roads. Therefore, we also analyzed the travel time of all vehicles driving during the incident duration. Figures 3d–f show that the proposed decentralized and centralized model can improve travel time for all vehicles to various extents. Unlike the TTS for affected vehicles, the improvement of travel time for all vehicles does not always increase with the increase of CVs market penetration rate in short-duration (5 and 10 min) incident scenarios. The TTS for all vehicles even decreases with the proportional increase of C-CVs. This observation indicates that the increasing number of C-CVs does not always result in greater TTS. This may be explained by the fact that once the incident information is distributed by the centralized model, all C-CVs will avoid the incident location. In this case, with higher percentages of C-CVs, more vehicles that are far away from the incident and will not be affected by it will unnecessarily detour even after the incident due to the delay in releasing road reopening information. Thus, traffic on the road of the incident cannot be resumed in time after the incident is over, burdening other roads. In contrast, the TTS for all vehicles show an upward trend with the increase of D-CVs market penetration, but the trend is gentle. Overall, compared with the centralized model, the proposed decentralized model achieves better travel efficiency when an ephemeral incident occurs on a certain road.

The above result shows that due to the inevitably delayed release, centralized systems are not as efficient as the decentralized ones, in terms of travel time savings. Here, in order to determine the influence of delay release, various delay times (0, 30, 60, 90, 180, and 240 s) are set up and simulated (E-II). Figure 4 shows the TTS for affected vehicles and all vehicles with 100% CVs in scenarios of various incident durations. Different colors stand for various incident durations, while different line types represent different kinds of CVs. It is expected that with the increase of delay time, the improvement of travel efficiency decreases gradually. Even though the delay time is 0, the decentralized model has a similar or even better performance than the centralized model. This is because when information about ephemeral incidents is published by a centralized system, all affected C-CVs that receive incident information reroute to avoid the incident location. As a result, with the centralized system, some vehicles unaffected by the incident would make an unnecessary detour. However, in terms of D-CVs, since incident information is broadcast in a limited area considering the estimated incident duration, only the affected vehicles will divert to avoid the incident location. These results show that the proposed decentralized traffic incident management model can significantly reduce travel time when an incident occurs on a road, and reductions are greater than that of the centralized model.
4.3.2 Advantages of the updating strategy

In the study, an updating strategy is designed to suppress broadcasting of outdated information after the incident is over (E-III). In this section, the ability of the proposed method to suppress invalid broadcasts and to improve broadcast efficiency is evaluated by comparing the method without the updating strategy.

The number of broadcasts is calculated to evaluate broadcast efficiency. Figure 5 shows the average number of broadcasts (\( NB_{\text{avg}} \)) for various market penetrations of D-CVs with and without the updating strategy, respectively, and the difference (\( \text{Diff} \)) of the \( NB \) between these two strategies in incident scenarios of various durations. The area chart shows the trend of \( \text{Diff} \) as the market penetration of CVs increases. As can be expected, as the duration of the incident increases, the number of broadcasts increases. If the incident duration can be estimated accurately (Scenario 1), the updating strategy has little effect. Besides, the gap between the updating and no-updating strategies gradually decreases as the market penetration of CVs increases. This is intuitively understandable because with a high market penetration of D-CVs the incident is likely to be detected from early on. Since \( D_{\text{est}} \) is close to \( D_{\text{act}} \) the updating strategy may not be triggered, resulting in only a small gap. However, it is unexpected to exactly estimate the incident duration, thereby leading to invalid broadcasting and reducing broadcast efficiency after the incident is over. By implementing the updating strategy, the number of broadcasts can be significantly reduced compared with results not using the updating strategy, especially in Scenario 3. Meanwhile, the result shows that the advantage of the updating strategy is greater as the market penetration of D-CVs increases.

Outdated incident message broadcast duration (\( D_{\text{invalid}} \)) is calculated to evaluate the accuracy of incident information being broadcast. Figure 6 shows the \( D_{\text{invalid}} \) with various market penetration rates of D-CVs in scenarios of various incident durations. The different colors stand for different scenarios (mentioned in Section 4.1), and the different line types stand for whether the updating strategy is used. The results show that if the incident duration can be accurately predicted (Scenario 1), \( D_{\text{invalid}} \) generally decreases with the increase of
the market penetration of D-CVs no matter if the updating strategy is used or not. When the market penetration of D-CVs is 100%, $D_{\text{invalid}}$ is nearly 0, which means that the outdated message can be quickly stopped from being broadcast. However, inaccurately estimated durations lead also to invalid broadcasts. Compared with the result of not using the updating strategy, it is obvious that the updating strategy can help vehicles timely terminate invalid broadcasts to some extent. The usage of the updating strategy makes the invalid broadcast end earlier, in our scenarios between 10 and 590 s earlier. In addition, it is worth noting that in most cases, when using the updating strategy, the $D_{\text{invalid}}$ in Scenario 2 is less than in Scenario 3, which reveals that overestimating incident duration is relatively better than underestimating. In addition, the market penetration of D-CVs influences the effectiveness of the updating strategy. In Scenario 2, the $D_{\text{invalid}}$ decreases with the increase of D-CVs market penetration rates, while the $D_{\text{invalid}}$ first increases and then decreases in Scenario 3. These results show the updating strategy can effectively terminate invalid broadcasts after the incident is resolved.

4.3.3 | Generalizability

E-IV and E-V investigate the performance of the proposed method in TTS of affected vehicles under different road conditions and in different cities whose road network topologies differ significantly (Table 2). Figure 7 shows the TTS of affected vehicles using our proposed decentralized method compared to the centralized method in three different cities with different traffic flows. The x-axis indicates the traffic density, and the y-axis indicates the TTS for affected vehicles (in seconds). Blue and orange bars represent TTS of 100% C-CVs and 100% D-CVs, respectively. First, the results show that by implementing CVs to broadcast information about the ephemeral incident, the travel time of affected vehicles can be significantly reduced under different road conditions in all study areas (shown by the increase of savings). The decentralized method has always a better performance in saving travel time than the centralized method. Second, for different cities, due to various road network topologies and road connectivity, the travel time savings are significantly varying. However, it can be seen that the denser the traffic, the more travel time affected vehicles save. It is intuitive that when the traffic flow is dense, the more likely a road closure will cause traffic congestion on the surrounding road sections. Detours in advance using the centralized method or the decentralized method can effectively alleviate traffic congestion near the blocked road, thereby saving more travel time. It is also intuitive that higher traffic density improves the connectivity of connected vehicles.

5 | DISCUSSION

This paper proposes a new event-driven model to manage ephemeral traffic incidents by a decentralized manner. Its properties have been studied by a micro-simulation approach, simulating traffic including C-CVs and D-CVs
The contributions to practice and the limitations in this study are discussed in Sections 5.1 and 5.2.

5.1 | Practical implications

For travelers, by implementing the proposed decentralized model, affected vehicles can find alternative routes to avoid the incident location in advance. Since these affected vehicles receiving incident information will not reach the incident location, they can avoid the risks of local congestion and of secondary incidents (Fullerton et al., 2010). Meanwhile, the decentralized model can improve travel efficiency for all vehicles by changing the routes of the few affected vehicles with foresight.

Findings from this study can help developers and policymakers determine better practices for the design and implementation of protocols for connected vehicles to reduce negative effects caused by ephemeral incidents. Our results show that with the increase of CVs on the roads the benefits of decentralized management of ephemeral incidents increase as well, confirming general expectations (Bansal et al., 2016). In addition to implementing the proposed model to improve traffic efficiency, the model can also be used to evaluate the impact of ephemeral incidents on traffic with different market penetration rates of CVs. Relevant departments can respond accordingly to manage traffic for non-CVs. Although the era of autonomous driving is not yet here, the proposed decentralized model is of practical significance to manage incident information. Vehicles equipped with relevant sensors and wireless communication hardware can employ the decentralized model. The decentralized model can also be a complementary tool of centralized methods. For instance, it can be used for incidents that are not covered in centralized systems. In addition, the decentralized approach is relatively secure as it does not spread incident information over a large area. Even if there is false information communicated between vehicles, the information will not be widely spread. Thus, in addition to the application to ephemeral incidents, the proposed decentralized model can be a supplement tool of centralized methods that is used from the beginning of the incident before the incident is confirmed, and even before the related personnel have arrived at the incident site to manage traffic.

5.2 | Limitation

The results of our study need to be interpreted in consideration of several limitations. In this study, as the model proposed is viewed as an application-level protocol instead of MAC layer protocol, we ignored some technical limitations of the network level, such as signal interference or signal collision. This, to some extent, reduces the success rate of information transmission between vehicles. In this study, the affected CVs can hear incident information from different informed vehicles to improve the success rate of receiving incident information. Another limitation is that the traffic generated in the simulation is not based on real trajectory data due to the lack of

FIGURE 7  TTS for affected vehicles in different cities
observation data. The travel routes are generated randomly and calculated based on the fastest travel time. Travel time is not the only evaluation metric of routes while driving. It could also include travel distance, easiness of driving, and travel cost. Further research should explore the role of other travel characteristics on the model. Besides, in this study, we mainly focus on ephemeral incidents occurring in urban areas. However, in remote areas with sparse road networks and fewer vehicles, incident information may not be effectively discovered, not to mention broadcast between vehicles. Future works can explore the performance of vehicle-to-infrastructure communication in effectively broadcasting incident information in rural areas. Finally, for simplicity, we only focused on simulating a single incident in the article, but the model leaves room for managing multiple incidents concurrently in the road network.

6 | CONCLUSIONS

In this article, we proposed a decentralized model to manage ephemeral traffic incident information by CVs. In this model, once an incident is detected by D-CVs, a process of broadcasting incident messages integrating a time-geography framework is triggered to inform other vehicles. When affected vehicles receive the information, they can plan an alternative route to avoid the incident. After the incident is over, vehicles carrying the incident message and encountering no incident any longer will trigger a refresh message being broadcast, which suppresses the further broadcasting of outdated messages. In conclusion, the model manages the decentralized distribution of ephemeral incident information, guides traffic on roads, and timely updates the incident information.

By agent-based traffic simulation, in three case studies, we have shown that the decentralized traffic incident management model is more effective than the centralized model of navigation platforms. We have shown the strong performance of the decentralized model for different market penetration rates of CVs in traffic, and for various degrees of uncertainty in the prediction of the incident duration. So, in addition to a conceptual model, we also contribute an empirical model to investigate the efficiency of the decentralized management of ephemeral traffic incidents that can be applied to different road networks, different traffic scenarios, and different market shares of communication technologies.

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CONFLICT OF INTEREST
No potential conflicts of interest are reported by the authors.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are generated by SMARTS, a traffic simulator, that can be obtained in GitHub repository (https://github.com/SmartsDev/SMARTS). The relevant paper is published (DOI: https://doi.org/10.1145/2898363). Data are also available upon request to the authors.

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