Simulation and analysis of non-recurrent traffic congestion triggered by crashes in road networks using a grid-based approach

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Abstract
The non-recurrent traffic congestion triggered by crashes is one of the most important factors that undermine the traffic efficiency of urban road networks. In this article, an improved cellular automaton model was proposed to simulate the non-recurrent congestion triggered by crashes in grid networks with signalized intersections. Four rules were adopted to represent vehicle movements on road sections and intersections. The network speed is adopted to capture the propagation and dissipation of the non-recurrent congestion. The effect of main influencing factors of crashes on the road network was evaluated through the simulation. Simulation results showed the incident duration and areas affected by the distance between the crash point and the upstream intersection, the number of closed lanes, and the crash duration. In addition, the stop-start wave was observed in the simulation. The realistic findings from the simulations validated the model to have the potential for practical applications in the analysis of the non-recurrent congestion triggered by crashes.

Keywords
Crash, road network, propagation and dissipation, non-recurrent congestion, cellular automaton model

Introduction
Nowadays, the congestion problem has become a major and costly problem in many countries due to the rapid increase in the automobile ownership. Crashes are a major cause of the non-recurrent congestion that may diminish the available capacity of the road during a certain period of time.¹ Existing research has studied non-recurrent traffic congestion detection,²,³ evolution,⁴,⁵ and control.⁶,⁷ Developing a dynamic traffic simulation model of urban road networks to reveal the evolution mechanism of a non-recurrent congestion can promote the development of effective traffic control strategies, such as the ramp metering of freeways,⁸ vehicle movement ban, and diversion for road networks.⁹,¹⁰ For the one-dimensional system such as freeways, the fundamental diagram (FD) is utilized to identify the congestion with the mean speed, flow, and density. For a road network, the macroscopic fundamental...
diagram (MFD) can describe the relationship between the network-aggregated demand and performance. MFDs have been extensively studied for being calibrated based on real world data, characterizing the network traffic behavior, evaluating the effect of adaptive traffic signal systems, and implementing traffic control strategies. MFDs can determine relationships between macroscopic network metrics and microscopic characteristics such as the flow, density, speed, and travel time. The existence of MFDs has been observed under a variety of conditions. Some crash analysis have been researched using realistic data. However, for the non-recurrent congestion, the speed change over time in the network is a more useful indicator of the traffic state. Thus, there is a need of the method that can model the detailed vehicles’ movements so as to capture the speed change triggered by the crash.

A stochastic cellular automaton (CA) model is the one that has often been utilized to simulate the evolution of traffic flows in road networks. The CA model is an effective tool to simulate the non-recurrent congestion due to its strengths in terms of simplicity, flexibility, and immediacy. The initial one-dimensional CA traffic model (Nagel-Schreckenberg) and the two-dimensional CA traffic model (Biham-Middleton-Levine) were proposed in 1992. Various factors have been incorporated into CA models to enhance their ability to simulate the detailed traffic moving phenomena. Jiang et al. utilized the Nagel-Schreckenberg CA model to simulate the traffic flow in a Manhattan-like urban network to depict the traffic breakdown. Zhang et al. studied and compared MFDs on the arterial road network governed by different types of adaptive traffic signal systems using the CA model.

In this article, the CA model is improved to simulate the effect of the network traffic density, the crash’s position on the road section, and the crash duration, on the network traffic mobility.

Improved model

The effect of a crash on the non-recurrent congestion is studied in a hypothetical urban road network in which all intersections use stop sign controls where vehicles approaching the intersection from all directions are required to stop before proceeding through the intersection. As shown in Figure 1, the network consists of $S \times S$ roads. Each road is divided into two road sections, each road section includes three lanes, which are divided into $L$ cells, and one vehicle occupies one cell on the road and two cells at the intersection. Vehicles drive on the right-hand side of the road and can go through and turn left or right, but cannot make a U-turn at the intersection. The intersection is controlled by four-phase signals, and all-red intervals are set between each phase to ensure that the vehicles in the intersection are cleared and collisions are avoided.

In the beginning, each car is randomly assigned an origin and a destination in the network and travel along the shortest path in terms of distance to their destinations. When a vehicle arrives at its destination, it will randomly select a new destination to continue its travel.

During the unit time $r$, at time step $t$, let $N_t$ be the number of vehicles in the road network, and $N_{t,i}$ and $v_{t,i,n}$ be the number of vehicles and speed of the $n$th vehicle in the road section $R_i$, respectively, and $i = 1, 2, \ldots, 4 \times S \times (S - 1)$. The road section speed $\bar{v}_i(r)$ is defined as the average instantaneous speed of vehicles on the road section $R_i$.

$$\bar{v}_i(r) = \frac{\sum_{t} \sum_{n} v_{t,i,n}}{\sum_{t} N_{t,i}}$$  \hspace{1cm} (1)

The movement behavior of a vehicle traveling through an intersection is quite different from that on a road. Hence, update rules of vehicles on roads and in intersection areas are proposed below.

As shown in Figure 2, let $x_n$ and $v_n$ be the position and speed of the $n$th vehicle on a given road section. Each vehicle has a maximum speed $v_{\text{max}}$ and $v_n = 0, 1, \ldots, v_{\text{max}}$. In particular, turning vehicles at intersections should slow down and travel at speeds of 0 or 1. Then, $d_n = x_{n+1} - x_n - 1$ is the distance between the $n$th vehicle and its leading vehicle, and if the $n$th vehicle

![Figure 1](image-url)
is the first vehicle, then $d_n = L - x_n$. $S_n = L - x_n$ is the distance between the $n$th vehicle and its downstream intersection. Let $d_{back}$ and $d_{other}$ be the distance between the $n$th vehicle and its following vehicle and leading vehicle in the adjacent lane. Let $d_{avoid}$ be the length of the prohibitive lane changing line. Let $K_n$ be the $n$th vehicle’s lane present number, where $K_n = 1$ means the innermost lane, $K_n = 2$ means the middle lane, and $K_n = 3$ means the outermost lane. Let $K_{other}$ be the number of adjacent lanes. Let $F_n$ represent the direction of the $n$th vehicle on the next intersection, and $F_n = 1$, $F_n = 2$, and $F_n = 3$ represent the left turning, through, and right turning. At each time step $\Delta t$, the speed and position of each vehicle is updated in parallel according to the following four rules:

**Lane changing according to its turn in the downstream intersection**

1. When $x_n \leq L - d_{avoid}$, the $n$th vehicle is in the front of the prohibitive lane changing line;
2. When $K_n \neq F_n$, the $n$th vehicle is not in the right lane, and it needs to change the lane;
3. When $|K_{other} - F_n| \leq |K_n - F_n|$, the $n$th vehicle will arrive or is close to the right lane after the lane changing;
4. When $d_{back} > v_{\text{max}} \times \Delta t$, the lane changing of the $n$th vehicle will not affect the following vehicle in the adjacent lane.

If the above four conditions are met, the $n$th vehicle will change its lane to the adjacent lane.

**Update rules for turning vehicles in the intersection**

If the front cell is empty, then the vehicle moves to the front cell at the end of the step; otherwise, the vehicle will hold still. This rule will be adopted for all turning vehicles in cells 1–36.

**Update rules for through vehicles in the intersection and vehicles in the lane**

**Step 1.** Acceleration: $v_n \rightarrow \min (v_n + 1, v_{\text{max}})$.

**Step 2.** Deceleration: when green light $v_n \rightarrow \min (v_n, d_n)$ for through vehicle and $v_n \rightarrow \min (v_n, d_n, s_n + 1)$ for turning vehicle; when red light $v_n \rightarrow \min (v_n, d_n, s_n)$.
The crash is assumed to happen in the middle of road section 31 from 300th time step to 600th time step under the number of vehicles $N_t = 250$ and $N_t = 750$, which results in the closure of all lanes of the crash section.

Figure 3(a) and (b) shows the effect of the number of vehicles $N_t$ on the road section speed $\tilde{v}_i(r)$. One can see that

1. When $N_t = 250$, $\tilde{v}_{31}(r)$ returns to normal at 600th time step and the incident duration is 300 time steps. When $N_t = 750$, $\tilde{v}_{31}(r)$ returns to normal at 2000th time step and the incident duration is 1700 time steps. This means that with the increase of vehicles, the incident duration increases.

2. When $N_t = 750$, $\tilde{v}_{31}(r)$ decreases to 0, and the affected area is 1 road section. When $N_t = 750$, the road sections’ speed $\tilde{v}_{31}(r)$, $\tilde{v}_{22}(r)$, $\tilde{v}_{32}(r)$, $\tilde{v}_{13}(r)$, and $\tilde{v}_{23}(r)$ decrease to below 15 km/h, and the affected area covers five road sections. This means that with the increase of vehicles, areas affected by the crash increases.

During morning and evening rush hours, there are more vehicles in the urban road network. Therefore, the crash happening during morning and evening rush hours has a greater effect than the one that happens during other times on traffic flows.

**Effect of the crash’s position on the road section $L_n$**

We assume that the crash happens in the cell away from the upstream intersection $L_n = 6\sim 20$, on road section 31 from the 300th time step to 600th time step under the number of vehicles $N_t = 500$, where two lanes of the crash section are closed.

Figure 4 shows the effect of the distance between the crash point and the upstream intersection on the road section speed $\tilde{v}_i(r)$. One can see that when the distance is 20 cells, as shown in Figure 4(a), $\tilde{v}_{31}(r)$ and $\tilde{v}_{22}(r)$ decrease to 15 km/h and below. When the distance is six cells, as shown in Figure 4(b), in addition to the above two road sections, $\tilde{v}_{13}(r)$, $\tilde{v}_{23}(r)$, and $\tilde{v}_{32}(r)$ also decrease significantly. This means that the decrease in distance between the crash point and the upstream intersection leads to a higher impact of the crash. It is easy to understand that if the crash is close to the upstream intersection, the time required to propagate the stop wave

$\tilde{v}_i(r)$ returns to normal at $750 \text{ cells}$, and the lane changing probability $p_{\text{change}} = 0.2$. The maximum velocity $v_{\text{max}} = 3 \text{ cell/s}$, then, the maximum velocity corresponds to $81 \text{ km/h}$ ($22.5 \text{ m/s}$). If the average instantaneous velocity $\tilde{v}_i(r)$ is less than $15 \text{ km/h}$, then it is considered that the road section is affected by the crash and is in a state of traffic congestion. The signal period of each intersection is consistent in the grid network. And the signal period is assumed 40 s.

**Effect of the number of vehicles $N_t$**

The crash is assumed to happen in the middle of road section 31 from 300th time step to 600th time step under the number of vehicles $N_t = 250$ and $N_t = 750$, which results in the closure of all lanes of the crash section.

Figure 3(a) and (b) shows the effect of the number of vehicles $N_t$ on the road section speed $\tilde{v}_i(r)$. One can see that

1. When $N_t = 250$, $\tilde{v}_{31}(r)$ returns to normal at 600th time step and the incident duration is 300 time steps. When $N_t = 750$, $\tilde{v}_{31}(r)$ returns to normal at 2000th time step and the incident duration is 1700 time steps. This means that with the increase of vehicles, the incident duration increases.

2. When $N_t = 750$, $\tilde{v}_{31}(r)$ decreases to 0, and the affected area is 1 road section. When $N_t = 750$, the road sections’ speed $\tilde{v}_{31}(r)$, $\tilde{v}_{22}(r)$, $\tilde{v}_{32}(r)$, $\tilde{v}_{13}(r)$, and $\tilde{v}_{23}(r)$ decrease to below 15 km/h, and the affected area covers five road sections. This means that with the increase of vehicles, areas affected by the crash increases.

During morning and evening rush hours, there are more vehicles in the urban road network. Therefore, the crash happening during morning and evening rush hours has a greater effect than the one that happens during other times on traffic flows.
upstream and the cross intersection will be shortened, and the congestion will spread to upstream roads more easily.

In addition, the congestion always occurs in the crash section and then spreads to other roads, and after the removal of the crash, the road section speed affected by the crash may continue to decline for some time. For example, as shown in Figure 4(b), when the crash happens in road section 31, $v_{31}(r)$ drops to 0 first, and after a while, $v_{13}(r)$, $v_{23}(r)$, and $v_{32}(r)$ decrease, then return to normal slowly.

Moreover, there is a speed rebound on the crash section after the removal of the crash. It is because the crash makes all lanes of the crash section closed to form an empty space in front of the crash point. Once the crash is removed, vehicles move on quickly to form a starting wave; therefore, the speed rebounds quickly first, then declines, and finally increases slowly to return to normal. When the distance is 20 cells, the maximal rebound of the crash section speed $v_{31}(r)$ after the removal of the crash is 18 km/h, and when the distance is six cells, the maximal rebound is 25 km/h. This means that the longer the distance between the crash point and the downstream intersection is, the more apparent the rebound is.

**Effect of the crash duration** $t_{duration}$

We assume that the crash happens in the middle of road section 31 from 300th time step to 600th time step ($t_{duration} = 300$) and 900th time step ($t_{duration} = 600$), under the number of vehicles $N_r = 500$, and all lanes of the crash section are closed.

Figure 5(a) shows the effect of the traffic duration on the speed of road sections 31, 22, 32, 13, and 23 when the traffic duration is 300 time steps. One can see that $v_{22}(r)$ and $v_{32}(r)$ seriously. However, when the traffic duration is 600 time steps, as shown in Figure 5(b), $v_{13}(r)$ and $v_{32}(r)$

![Figure 4. The effect of distance $L_n$ on the road section speed $v_i(r)$: (a) $L_n = 20$ and (b) $L_n = 6$.](image)

![Figure 5. The effect of traffic duration on the speed: (a) $t_{duration} = 300$ and (b) $t_{duration} = 600$.](image)
decrease to 15 km/h or below and the affected area includes five road sections plus road sections 13 and 32. These mean that the increase of the traffic duration leads to the expansion of the influence scope, which is because with the increase of the traffic duration, the congestion will propagate much longer and affect more roads.

Conclusion
This article established an improved CA model for the simulation of the non-recurrent congestion triggered by crashes in road networks with signalized intersections. The proposed model can be used to investigate the effects of the number of vehicles, the distance between the crash point and the upstream intersection, the severity of the crash, and the traffic duration on the non-recurrent congestion.

Simulation results showed that the incident duration and affected area increased with the increase of vehicles, the decrease of the distance between the crash point and the upstream intersection, the increase of closed lanes, and the increase of the crash duration. In addition, the stop-start wave was observed in the simulation. The findings drawn from the simulations validated that the proposed model could represent the real traffic flow phenomenon and thus had the potential for practical applications.

Although the model is rather simple, it has captured the most important parameters in non-recurrent traffic congestions in road networks, that is, the formation, propagation, and dissipation of the traffic congestion affected by crashes and effects of the crash on the network traffic. In the future, more realistic road networks including various types of roads and intersections need to be considered, and more realistic origin-destination data need to be applied with a consideration of time-varying traffic demands. In addition, studies should be conducted to model the real route choice behavior of drivers with a consideration of the heterogeneity of travelers, the dynamic control methods, and strategies for managing traffic congestions, such as the dynamic route guidance, temporary vehicle ban, and adaptive traffic lights.

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References
1. Emmerink RHM, Axhausen KW, Nijkamp P, et al. The potential of information provision in a simulated road transport network with non-recurrent congestion. Transport Res C-Emer 1995; 3: 293–309.
2. Anbaroglu B, Cheng T and Heydecker B. Non-recurrent traffic congestion detection on heterogeneous urban road networks. Transportmetrica A 2015; 11: 754–771.
3. Ahmed F and Hawas YE. An integrated real-time traffic signal system for transit signal priority, incident detection and congestion management. Transport Res C-Emer 2015; 60: 52–76.
4. Chung KH, Hui PM and Gu GQ. Two-dimensional traffic flow problems with faulty traffic lights. Phys Rev E 1995; 51: 772.
5. Long JC, Gao ZY, Zhao XM, et al. Urban traffic jam simulation based on the cell transmission model. Netw Spat Econ 2011; 11: 43–64.
6. Gayah VV, Gao X and Nagle AS. On the impacts of locally adaptive signal control on urban network stability and the macroscopic fundamental diagram. Transport Res B-Meth 2014; 70: 255–268.
7. Ortigosa J, Menendez M and Gayah V. Analysis of the network exit functions for different urban grid network configurations. Transport Res Rec 2015; 2491: 12–21.
8. Spiliopoulou A, Papageorgiou M, Herrera JC, et al. Real-time merging traffic control at congested freeway off-ramp areas. Transport Res Rec 2016; 2554: 101–110.
9. Shi JQ, Hu YJ, Li SL, et al. Simulation and analysis of road construction traffic flow in urban road networks. Adv Mech Eng 2015; 7: 1–6.
10. Long JC, Gao ZY, Orenstein P, et al. Control strategies for dispersing incident-based traffic jams in two-way grid networks. IEEE T Intell Transp 2012; 13: 469–481.
11. Geroliminis N and Daganzo CF. Macroscopic modeling of traffic in cities. In: Proceedings of the 86th annual meeting of the Transportation Research Board, Washington, DC, 21–25 January 2007. Washington, DC: Transportation Research Board.
12. Geroliminis N and Daganzo CF. Existence of urban-scale macroscopic fundamental diagrams: some experimental findings. Transport Res B-Meth 2008; 42: 759–770.
13. Gayah VV and Daganzo CF. Clockwise hysteresis loops in the macroscopic fundamental diagram: an effect of network instability. Transport Res B-Meth 2011; 45: 643–655.
14. Geroliminis N and Sun J. Properties of a well-defined macroscopic fundamental diagram for urban traffic. Transport Res B-Meth 2011; 45: 605–617.
15. Haddad J and Mirkin B. Adaptive perimeter traffic control of urban road networks based on MFD model with...
time delays. *International Journal of Robust and Nonlinear Control* 2016; 26: 1267–1285.
16. Geroliminis N, Haddad J and Ramezani M. Optimal perimeter control for two urban regions with macroscopic fundamental diagrams: a model predictive approach. *IEEE T Intell Transp* 2013; 14: 348–359.
17. Aboudolas K and Geroliminis N. Perimeter and boundary flow control in multi-reservoir heterogeneous networks. *Transport Res B-Meth* 2013; 55: 265–281.
18. Shi JQ, Cheng L, Long JC, et al. A new cellular automaton model for urban two-way road networks. *Comput Intel Neurosc* 2014; 2014: 685047.
19. Keyvan-Ekbatani M, Kouvelas A, Papamichail I, et al. Exploiting the fundamental diagram of urban networks for feedback-based gating. *Transport Res B-Meth* 2012; 46: 1393–1403.
20. Gayah V and Daganzo C. Effects of turning maneuvers and route choice on a simple network. *Transport Res Rec* 2011; 2249: 15–19.
21. Wu J and Xu H. Driver behavior analysis on rural 2-lane, 2-way highways using SHRP 2 NDS data. *Traffic Inj Prev* 2018; 19: 838–843.
22. Wu J and Xu H. Driver behavior analysis for right-turn drivers at signalized intersections using SHRP 2 naturalistic driving study data. *J Safety Res* 2017; 63: 177–185.
23. Nagel K and Schreckenberg M. A cellular automaton model for freeway traffic. *J Phys I* 1992; 2: 2221–2229.
24. Biham O, Middleton AA and Levine D. Self organization and a dynamical transition in traffic flow models. *Phys Rev A* 1992; 46: R6124–R6127.
25. Jiang R, Chen JY, Ding ZJ, et al. Network operation reliability in a Manhattan-like urban system with adaptive traffic lights. *Transport Res C-Emer* 2016; 69: 527–547.
26. Zhang LL, Garoni TM and de Gier J. A comparative study of macroscopic fundamental diagrams of arterial road networks governed by adaptive traffic signal systems. *Transport Res B-Meth* 2013; 49: 1–23.