Quantifying the Impacts of Right-Turn-on-Red, Exclusive Turn Lanes and Pedestrian Movements on the Efficiency of Urban Transportation Networks

Hao Liu
Postdoctoral Scholar
Department of Civil and Environmental Engineering
The Pennsylvania State University
College Park, PA, 168082
Email: hfl5376@psu.edu

Zecheng Xiong
Department of Civil and Environmental Engineering
The Pennsylvania State University
College Park, PA, 168082
Email: zqx5116@psu.edu

Vikash V. Gayah*
Associate Professor
Department of Civil and Environmental Engineering
The Pennsylvania State University
College Park, PA, 168082
Email: gayah@engr.psu.edu

* Corresponding author

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ABSTRACT
Right-turn-on-red (RTOR) is commonly applied at signalized intersections to improve intersection capacity. The benefits associated with RTOR depend on the presence of exclusive right-turn lanes and the presence of pedestrians in adjacent crosswalks. This paper examines the influence of these three factors on the operational performance of grid networks. Three different grid network configurations are tested: a network made up of alternating one-way streets (OW), a network consisting of two-way streets that accommodates left turns at intersection in a protected manner (TW), and a network consisting two-way streets for which left turns are prohibited at intersections (TWL). The results reveal that the TWL network has the highest efficiency while the TW network has the lowest under all tested scenarios. When there are no pedestrians, RTOR can improve the operational performance regardless of the existence of exclusive lanes, but the presence of exclusive turn lanes increases the benefits obtained by allowing RTOR. The results also suggest that allow RTOR is more important than if exclusive lanes are provided (but RTOR is not allowed) when the traffic load is light; however, under heavier traffic exclusive turn lanes become more important. The presence of pedestrians reduces overall network performance and the benefits provided by RTOR, as expected. This decrease in performance is larger for TW and TWL networks than for a OW network. Exclusive lanes are also found to be critical for for the TW network to maintain the network efficiency.

Keywords: Right-Turn-On-Red, Macroscopic Fundamental Diagram, Network Exit Function, Pedestrians, Microscopic Simulation

INTRODUCTION

The provision of Right-Turn-On-Red (RTOR) allows vehicles at a signalized intersection to turn right during the signal red period after yielding to conflicting traffic streams and pedestrians with the right-of-way. RTOR was first introduced as an energy savings measure as it reduces the waiting time for right-turn (RT) vehicles (*1*, *2*). In most urban networks, RTOR is assumed to be allowed unless explicitly stated otherwise. However, the network-wide impacts of allowing RTOR is not well understood.

Previous studies mainly focus on the impact of RTOR applied at individual intersections. Two aspects are considered: operating performance (*2–7*) and safety (*8–13*). It has been shown that RTOR can help improve intersection capacity and reduce control delay at individual intersections by serving RT vehicles during the red periods. Lin (*3*) showed that RTOR can significantly reduce the traffic delay for RT vehicles if the delay without RTOR is higher than 15 sec, even if the fraction of RT vehicles is as low as 10 percent. As suggested by the Highway Capacity Manual (HCM94) (*14*), the improvement in the traffic operations from RTOR is highly dependent on the RTOR volume at an individual intersection and should be assessed using field-measured volumes. Since the RTOR volume is not always available, Abu-Lebdeh et al. (*4*) proposed a regression model to forecast the RTOR volume from a single exclusive RT lane using predictors that can be easily observed; the study found the most important factors are RT volume and the proportion of red time for the subject approach. Creasey et al. (*5*) proposed a deterministic model to forecast RTOR volume for shared lanes; the study showed the HCM model results in an underestimation of capacity and an overestimation of delay if the RTOR occurs. More recently, Massaad and Massaad (*2*) proposed a multiple linear regression model for RTOR volume prediction that works for both shared lanes and exclusive lanes and assessed the improvements in the mobility performance at critical intersections, which are characterized by high traffic and pedestrian demands.

In addition to the RT volume, another critical factor influencing the traffic operations with RTOR at isolated intersections is whether the exclusive RT lanes exist. An exclusive lane can help maximize the operational benefits from RTOR since it reduces the chance that RT vehicles would get blocked by through-moving vehicles when the signal is red. Lin (*3*) found that an exclusive lane can reduce the delay of the right-turn vehicles, especially when the through and right-turn mixed vehicle flow is higher than 144 vph. The study also discussed the influence of the length of the exclusive lane. Tian and Wu (*6*) proposed a probabilistic model which confirmed the length of exclusive lane will affect the capacity of the intersection and found that the capacity is positively related to the length of the exclusive lane. Kikuchi and Kronprasert (*7*) proposed a method to determine the length of the RT lane that limits the propobability of RT vehicles and straight-through vehicles blocking each other. In addition to the impact on operation, a well-designed exclusive lane can also improve the safety at the intersections, see (*9*, *11–13*).

Although RTOR is an effective solution to enhance the efficiency of traffic operations at isolated signalized intersections, it may present an adverse impact on safety measurement since it generates conflicting traffic streams, especially when pedestrians and bicycles are considered. Therefore, pedestrian interaction is another subject that has been discussed widely with the deployment of RTOR at signalized intersections. Preusser et al. (*9*) concluded that allowing RTOR increased the number of pedestrian and bicycle crashes significantly because drivers only pay attention to their left for a gap in traffic and do not see pedestrians and bicycles from their right. Retting et al. (*1*) stated one primary reason for RTOR increasing crashes is many drivers do not come to a stop before turning right on red and proposed two methods to enhance the safety by reducing the number of RTOR vehicles: prohibiting RTOR at specified times and prohibiting RTOR when pedestrians are present. However, some studies claim the safety impacts are minimal; e.g. (*10*) finds that RTOR is not a dangerous maneuver for either vehicles or pedestrians in most circumstances since the proportion of RTOR crashes is usually very low. Apart from the safety concerns, pedestrians also impact the efficiency improvement from RTOR because they increase the number of conflicting movements and decrease the available gap that can be used by the RT vehicles during the red period. However, most studies focus on the safety, and only a few studies (*2*) investigate the impact of pedestrians on traffic operations.

Above all, the RTOR, exclusive lanes and pedestrians have a coupling influence on the efficiency of traffic operations at signalized intersections. However, to the best of our knowledge, all previous studies only consider the impact at an intersection-level, and the influence of these factors at a network-level is still missing in the literature. To partially bridge this gap, this paper investigates the influence of these three factors on the mobility of a network consisting of signalized intersections by microscopic simulations. (Note the safety issue is explicitly not covered in this paper and it is assumed only safe RTOR movements are made.) Newtork-wide traffic models, specifically the network Macroscopic Fundamental Diagram (MFD) and Network Exit Funciton (NEF) that characterize a well-defined relationship between the average network producitivty and use, are used to measure operational performance under a range of congestion levels. Such relationships have been demonstrated by both theoretical (*15*) and empirical studies (*16*).

The MFD and NEF have been used in previous studies to examine the network-wide implementation of other urban traffic management strategies. This includes left-turn prohibitions (*17*) and one-way to two-way street conversions (*18*, *19*). Both one-way streets and left-turn prohibitions at two-way streets could improve intersection capacity by eliminating conflicting vehicule movements. Even when considering the additional travel distance imposed, the studies found that the overall impact would be an increase in the rate vehicles could reach their destination and exit the network. However, both strategies would increase the number of non-conflicting movements (i.e., RTs) at the intersection. Thus, it is of interest to examine how the presence of RTOR, exclusive turn lanes and pedestrian activity impact the performance of these strategies. This paper combines the aforementioned factors and these traffic management strategies and tests the impact of the combination on the productivity of a network.

The rest of this paper is organized as follows. The next section provides a thought experiment to forecast the impact of the studied factors on the operational performance of a network. The subsequent section introduces the simulation settings for three types of networks. The following section shows the simulation results and depicts the influence of RTOR, exclusive lanes and pedestrians for all network types. The final section provides concluding remarks.

THOUGHT EXPERIMENT

The goal of this section is to provide a thought experiment to forecast the impact of RTOT, exclusive turn lanes, and pedestrians. This information will provide insight into the micro-simulation results, which have known to be noisy and difficult to obtain insightful trends(*20*). This section uses the Macroscopic Fundamental Diagram (MFD), which is the relationship between the average traffic flow and the average denstity in a network, to assess the impacts of these features. Note that the simulation results instead use the Network Exit Function (NEF), which relates average trip completion rate with vehicle accumulation. However, the two are related by a constant and are identical if the average trip length in a network is invariant.

Macroscopic fundamental diagram

The general form of MFD can be expressed as:

$$q = Q(k), \tag{1}$$

where q (veh/hr/lane) is the average flow rate across the whole network and k (veh/km/lane) is the average density of the network. To analyze the influence of the three factors (RTOR, exclusive lanes and pedestrians) on the MFD, we assume:

- Vehicles have relatively fixed routes with a network. More specifically, if vehicles do change routes, that this will not sufficiently change their average trip length. Such an assumption is reasonable in redundant grid networks with multiple paths between origins and destinations.
- RTOR vehicles will always yield to the conflicting traffic streams that have the right-of-way. This includes the straight-through vehicles from the perpendicular approach of which the signal light is green and pedestrians in the downstream crosswalk.

- The saturation flow of RT movement is lower than the straight-through movement. This is reasonable since right-turn vehicles must slow to move through the intersection. The HCM suggests that the saturation flow of RT movements is typically 84.7% of through movements (*21*).

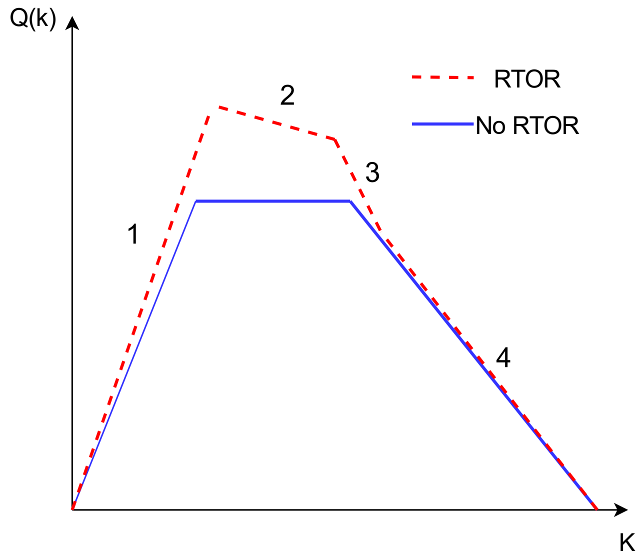


Figure 1 Influence of RTOR on MFD

Under the assumptions above, a general comparison of the expected functional form of a network's MFD with and without RTOR is shown in Figure 1. The blue curve represents a typical unimodal MFD for urban traffic networks. It consists of three parts: free flow domain with low average densities for which the average flow increases with the average density; capacity domain where the average flow reaches its maximum and stays (relatively) constant for a certain range of average densities; and the congested domain in which average flow decreases with the density. In general, RTOR can improve the average flow since it can not only serve RT vehicles during the red time, but this also leads to a higher proportion of straight-through vehicles during the green time, which are served at a higher rater. However, the improvement suffers from competiting effects: more RT vehicles could potentially use the RTOR, but more through-moving vehicles on the cross-street would reduce the available gaps for RT vehicles to use. To explain the influence of RTOR for the full range of densities, the MFD is divided into four parts, as shown in Figure 1:

- **Part 1:** When the density is low, the average time gap from the conflicting approach is relatively large, so RT vehicles have a higher chance to proceed during the red time. As a result, the average flow during the red time for this approach can be increased when RTOR is provided. In addition, the green time can be utilized by a higher portion of straight-through vehicles. Because the straight-through movements have a higher saturation flow than the RT movements, the average flow during the green time can be increased as well if there are enough vehicles. Note, however, that this increase is small at lower densities due to the fewer vehicles (including RT vehicles) in the traffic stream. Still, when the average density is low, the average flow with RTOR can be expected to be higher than the case without RTOR. Since the average density is low in this part, the increase in RT vehicles outweigh the decrease in the available gaps, and the improvement is enlarged with the increase in the average density.
- **Part 2**: For the same reason as part 1, the capacity, which is the maximum of the average flow in the network, is increased when RTOR is permitted. However, the increase suffers from the competiting effects mentioned above. Therefore, with the increase in average density, we expect

the average flow to decrease. This part starts with the capacity point, where the network reaches its highest productivity; however, the decreasing rate is expected to be not large.

- **Part 3**:When the average density exceeds a certain value, the decrease in the available gap provided by the conflicting traffic streams starts to dominate. Thus, the improvement from RTOR dimishes faster than part 2, as illustrated in part 3 of Figure 1.
- **Part 4**: When the number of vehicles exceeds a certain value, the gap is so small that no vehicle can turn right on red. Consequently, there is no impact from RTOR for this section, as shown by the part 4 in Figure 1.

Note Figure 1 and the above analysis only serve as a thought experiment showing the general effect of RTOR; the actual shape depends on various factors, such as network road configuration, existence of exclusive lanes, pedestrians, number/proportion of RT vehicles. For instance, for networks in which the RT movements share lanes with the straight-through movement, only the RT vehicles ahead of the first straight-through vehicle in the queue can turn right on red, and all vehicles behind are blocked by the straight-through vehicle. Therefore, the improvement in the average flow highly depends on the turning ratios. On the other hand, this dependence is weakened for networks with exclusive RT lanes because RT vehicles use a separate lane so they will not be blocked by the straight-through vehicles if the straight-through queue does not block the entrance of the exclusive right lane. Additionally, since the presence of pedestrians add extra conflicting movements and reduce the available gap that can be used by RT vehicles during the red period, the improvement is expected to decline with the increase in the demand of pedestrians.

Network exit function

Before proceeding to the microscopic simulation tests, we next describe the relationship between the average flow rate and the network exit rate to demonstrate the conclusions above also apply to the NEF. If the average trip length is stable over time, the NEFcan be expressed as:

$$f(k) = \frac{q \times L}{l} = \frac{Q(k)L}{l} \qquad (2)$$

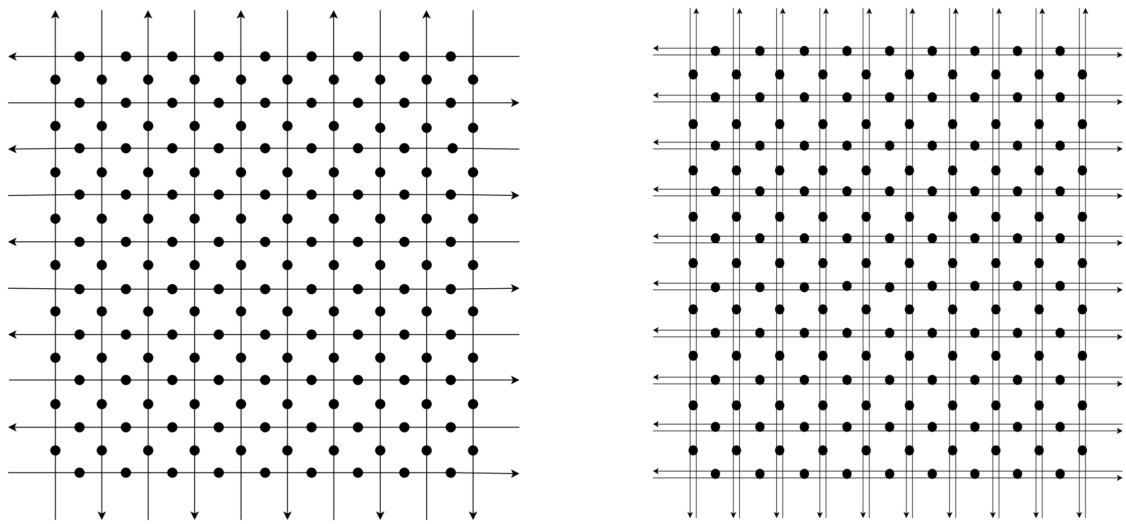
where l and L indicate the average trip length and the total length of streets in the network, respectively; f (vph) is the network exit rate which represents the rate at which trips are completed across the network (*22*). Equation (2) indicates that given a fixed average trip length, the network exit rate in a network linearly increases with the average flow. Since we assume the trip routes/lengths will not be changed by RTOR, the influence of RTOR on NEF is thus similar to MFD for a given network.

SIMULATION SETTINGS

The previous section provides insights on the influence of RTOR on the NEF via thought experiments; however, there are a variety of realistic factors (such as the signal settings and driving behaviors) that would influence its impact on network operations. To investigate the influence of RTOR, exclusive lanes and pedestrians on the NEF in a more practical environment, microscopic simulations were performed using the AIMSUN simulation software. Recent studies have proved that left-turn prohibitions (*17*) and one-way to two-way street conversions (*18*, *19*) can improve the mobility of signalized traffic network. To combine the target factors and these traffic management strategies, microscopic simulations for three types of networks are conducted in this section. The remainder of this section describes the network layout, demand description and output processing method used in this study.

Network layout

Since grid networks are common across the world, for simplicity and generality, we consider two ideal 10×10 grid networks consisting of alternating one-way streets (OW) and two-way streets, respectively, as shown in Figure 2. In both networks, links were assumed to be 125 m long with a speed limit is 50 km/h.

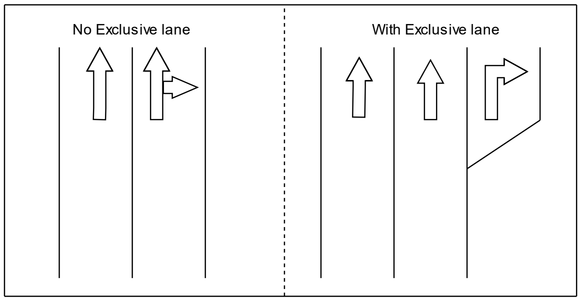


(a). One-way network (b) Two-way network

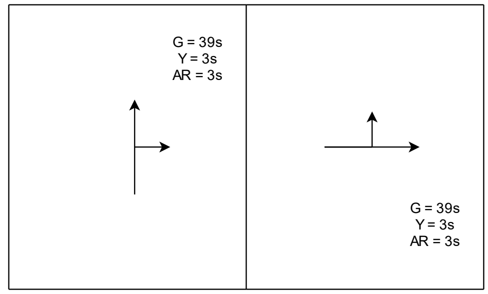
Figure 2 **Network layout**

The simulation time is set to 3 hours and vehicle positions were updated at regular 1-second intervals. The stochastic c-logit route choice model was used in Aimsun to emulate user-equilibrium routing conditions in which vehicles make routing decisions to minimize their own personal travel times.

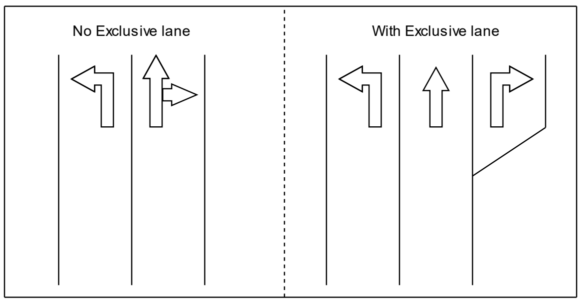
DePrator et al. (*17*) showed that for a two-way network, left turn prohibiting has the potential to improve the NEF since it reduces the lost time and increases the capacity at signalized intersection. The only exception is when the average trip distance is very short in which the increase in the trip distance outweighs the increase in the capacity. It is of interest to combine this strategy with the factors that this paper aims to investigate. Therefore, we created two types of two-way network: one with left turns allowed (TW) and one with left turns prohibited (TWL). If left turns are permitted, there is a protected left turn phase; otherwise, the phase is removed. Figure 3 shows the lane configuration and signal timing plans for these networks. In addition, for each network type, we created one network with RT exclusive lanes and one network without to study the influence of exclusive lanes. The length of the shared lanes is 30 m. After adding the exclusive lanes, the shared lanes become dedicated lanes for straight-through movements while the signal timings stay the same. For OW networks, Figure 3(a) and Figure 3(b) show the lane configuration of a northbound link that intersects an eastbound link and the corresponding signal timing at that intersection, respectively. As shown in Figure 2(a), the one-way streets are alternating so the streets at other intersections can differ. Therefore, some streets allow left turns than right turns. However, for OW networks, left turns and right turns are considered as the same maneuver since they do not cross opposing through vehicles; therefore, we do not distinguish them in this paper and call them collectively as right turns.



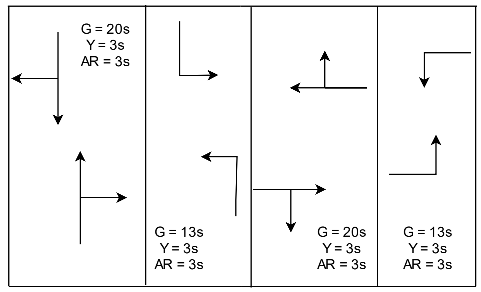
(a). Lane configuration for the OW network



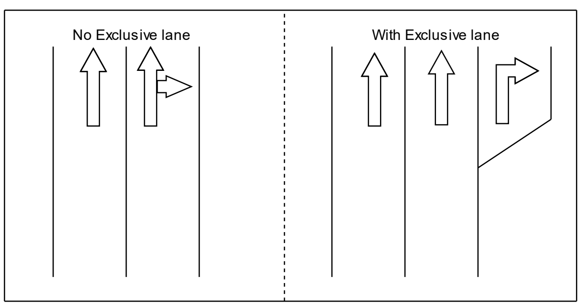
(b). Signal timing for the OW network



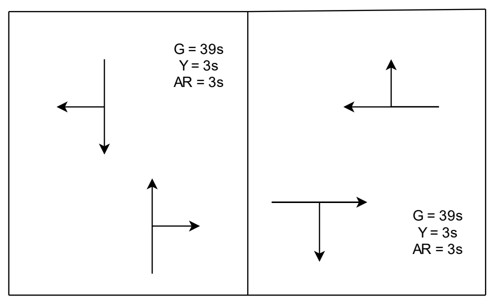
(c). Lane configuration for the TW network



(d). Signal timing for the TW network



(e). Lane configuration for the TWL network



(f). Signal timing for the TWL network

Figure 3 Lane configurations and signal timing plans

Demand

Centroids – which serve as both an origin and destination for trips – were placed at the midpoint of all links; see Figure 2. In total, 180 centroids were used, resulting in 32,220 unique OD pairs. We use uniform demand pattern in all networks, which means the demand between all OD pairs is identical. To have a complete NEF, we increase the demand over time to make the network gradually evolves from an extremely light-traffic condition to a totally jam condition. The time interval for the demand increment is 20 mins except for the last interval. Figure 4 shows the demand pattern between an arbitrary OD pair. There are a total of 105,037 trips during the whole simulation.

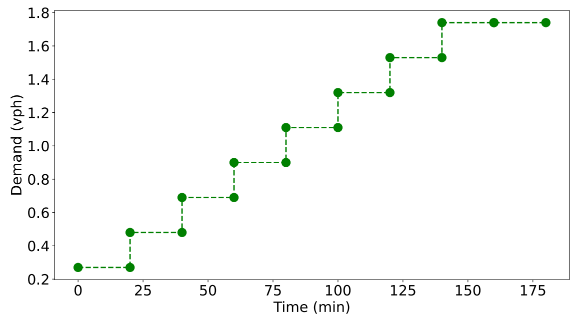


Figure 4 Demand pattern

The introduction demonstrates that pedestrian movements are an important factor to be considered for the implementation of RTOR; the appearance of pedestrians may significantly reduce the chance that a RTOR movement may occur. This paper investigates the NEF for all three networks with and without pedestrians. For the simulations with pedestrians, we created a rectangular pedestrian area (pa), within which pedestrian movemets are allowed, around each intersection. There are one entrance centroid and one exit centroid at each corner of the pedestrian area. Figure 5 shows an example for the TW network. It is the same deployment for OW and TWL networks. For pedestrian demand modeling, we use a time-invariant and uniform OD matrix. Two values for the pedestrian demand are considered: 6 ped/min/pa and 12 ped/min/pa.

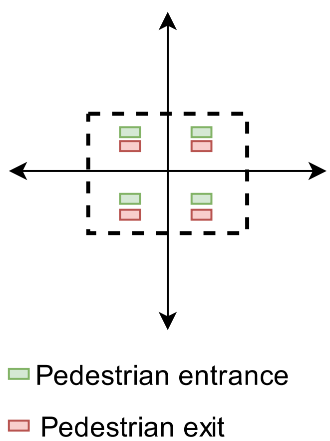


Figure 5 Pedestrian deployment for the TW network

Output processing

For each scenario, we conducted 10 simulation replications with different starting random seeds. The random seeds are the same across the scenarios. In each simulation, we retrieve the number of vehicles in the network and the number of completed trips every second. Then, the density is computed as the number of vehicles divided by the network length, and the network exit rate is computed as the number of completed trips scaled up to an hourly rate. Both the density and trip completion rate are averaged every 5 minutes. Note for the comparison purposes, when we compute the density for the networks with exclusive lanes, we ignore the length of the exclusive lanes to make the range of density identical. In this way, the average densities are equivalent to the network accumulations.

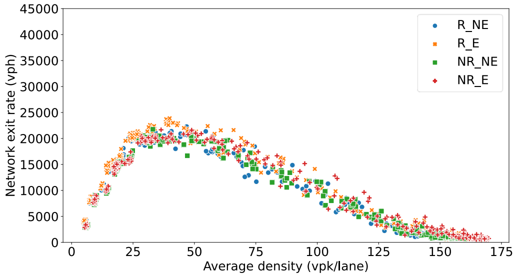
RESULTS

This section shows the NEF comparison for OW, TW and TWL networks. For each network type, we studied the effect of RTOR, exclusive lanes and pedestrians on NEF. The results without pedestrians and with pedestrians are discussed separately. NR_NE, NR_E, R_NE and R_E indicate the scenarios without RTOR (NR) and exclusive lanes (NE), without RTOR (NR) but with exclusive lanes (E), with RTOR (R) but without exclusive lanes (NE), and with both RTOR (R) and exclusive lanes (E), respectively.

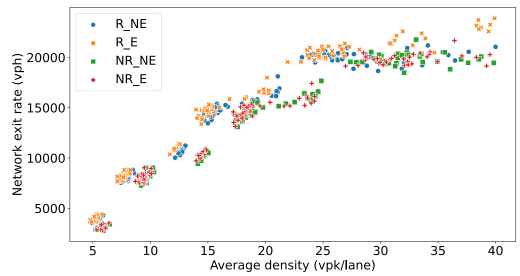
Without pedestrians

Figure 6 shows the NEFs obtained from the simulations when pedestrians were not present. First, we analyze the overall difference across the three networks. Second, we discuss the influence of RTOR and exclusive lanes for individual networks.

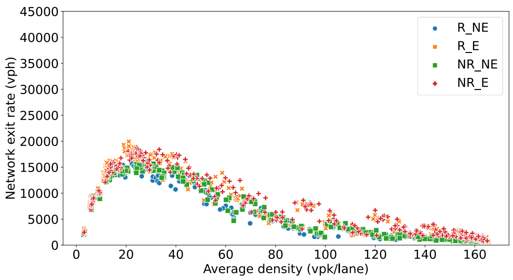
The NEF for the TWL network is much higher than the TW network, which agrees with the findings in (*17*). This implies that although prohibiting left turns increases the average trip length, according to Equation (2), its negative impact on the NEF is outweighed by the improvement in the average flow. This finding suggests that prohibiting left turns is beneficial for improving the overall mobility of an urban traffic network. Similarly, although the network length for OW is only half of TW, and the average trip length from the OW network is longer due to detours incurred, the maximum NEF is even higher than TW networks thanks to the larger average flow provided. Another finding is that although the TWL network has the maximum network exit rate, its resilience is the lowest, i.e., it falls into the congested domain once the average density exceeds the critical value while the TW and OW networks can maintain the maximum network exit rate for a range of densities. This phenomenon is also in line with the findings in (*23*, *24*). The reason is that there is only one unique shortest-distance route for any OD pair in a TWL network while there are multiple for both OW and TW networks. Hence, if a link becomes congested in a TWL network, all vehicles using that link for their shortest-distance routes would be blocked, which provides uneven traffic patterns and reduce the mobility of the network. However, since the vehicles in OW and TW networks have multiple shortest-distance routes, they can switch to an alternate route if one is congested, which makes the traffic patterns more even and the systems more resilient. Next, we evaluate the impact of RTOR and exclusive lanes on the NEF of the three networks.



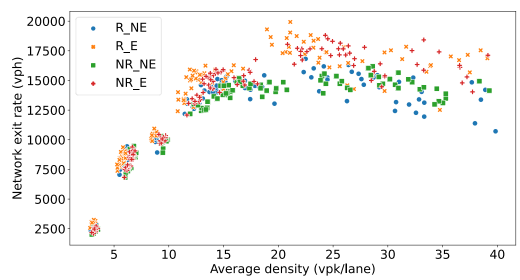
(a). OW network



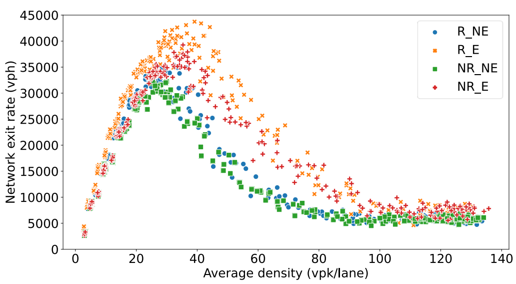
(b). Free-flow branch of OW network



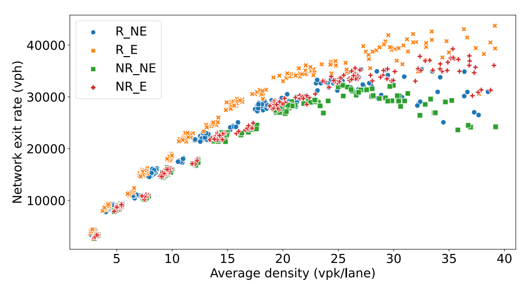
(c). TW network



(d). Free-flow branch of TW network



(e). TWL network



(f). Free-flow branch of TWL network

Figure 6 Simulation-based comparison of NEF without pedestrian

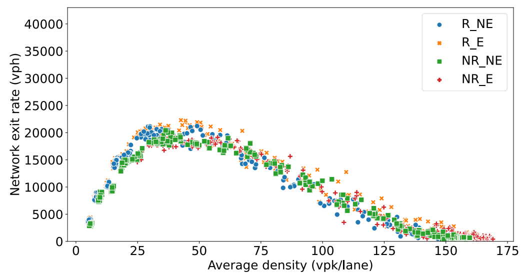
First, the RTOR increases the network exit rate at the free-flow domain for all networks, regardless of the existence of exclusive lanes; this agrees with part 1 in Figure 1. Due to the figure scale, this impact is difficult to observe in the complete NEFs. Therefore, we created the zoomed-in version for the free flow domain of the NEFs to make the comparison clear, as shown in Figure 6, right side. In addition, the improvement for the TW network is smaller than the other two networks, as shown in Figure 6 (d). The reason is that the number of RT vehicles in the TW network is lower than the other network types; TWL and OW newtorks only have one turning type so all turning vehicles only make a RT. Thus, the improvement due to RTOR for these networks is higher.

Second, the average network exit rate in the R_NE scenarios is higher than the NR_E scenarios when in the free-flow domain. For example, the network exit rate of R_NE (blue points) is higher than NR_E (red points) for the TWL network. This occurs for all networks but is particularly true for the OW and TWL networks. This additional benefit in the OW and TWL networks is because the number of RT vehicles for both TWL and OW networks is relatively high; thus, the number of RT vehicles ahead of the first straight-through movement in a queue on average is relatively large, and these vehicles can be served during red when RTOR is allowed, even if there is no exclusive lane. On the other hand, an exclusive lane can only accommodate very few vehicles so that the contribution of the exclusive lanes to the flow is relatively small. For example, the length of the exclusive lanes is 30 m in this simulation which can only accommodate 5 vehicles, so compared to the scenario in which no RTOR or exclusive lane exists, it can serve at most 5 extra vehicles for a cycle. This is the reason why RTOR outperforms exclusive lanes when the number of vehicles in the network reaches a certain value. When the number of vehicles is extremely low, this difference is diminished, and both strategies have small impact on the NEF.

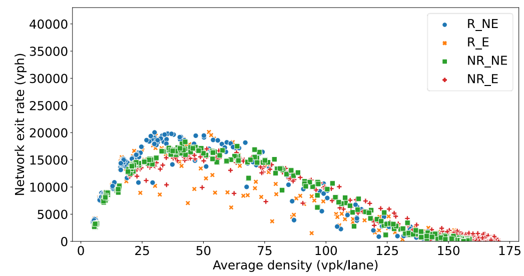
Third, when the network falls into the congested region, exclusive lanes play a more important role than the RTOR, while the R_E scenario still performs the best. For both OW and TW networks, the strategy of the NR_E scenario has a very similar performance as the R_E scenario. This is because when the traffic is high, very few vehicles can perform RTOR maneuvers due to the lack of enough gap from the conflicting traffic streams. Therefore, the influence of RTOR on the NEF is negligible when the traffic volume is very high. With exclusive lanes, the flow during the green time is enlarged. Consequently, the overall NEF is improved as well.

With pedestrians

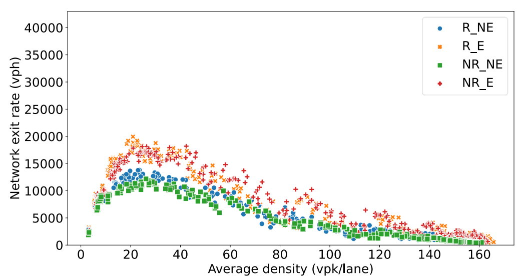
The results considering the pedestrians with two demands are shown in Figure 7. As expected, the NEFs for all networks and all strategies are reduced compared to the no-pedestrian situation, due to turning vehicles needing to yield to pedestrians in addition to the conflicting vehicle streams, which reduces the capacities of the intersections. The reduction in the NEF is more significant with the increase in the number of pedestrians. Across the different network types, the same general pattern remains: the TWL network provides the best performance, while the TW network provides the worst mobility. To quantify the impact of pedestrians, we use the average value of the first 10 largest network exit rate values for each scenario to represent the network mobility. The results are shown in Table 1. For the results with pedestrians, the numbers in the parenthesis are the percentage reduction of network exit rate compared to the results without pedestrians. The color scheme is used to visualize the reduction percentage.



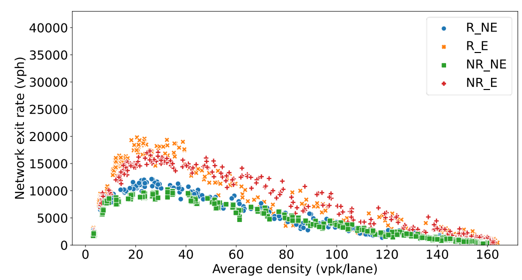
(a). OW network. Ped demand: 6 ped/min/pa



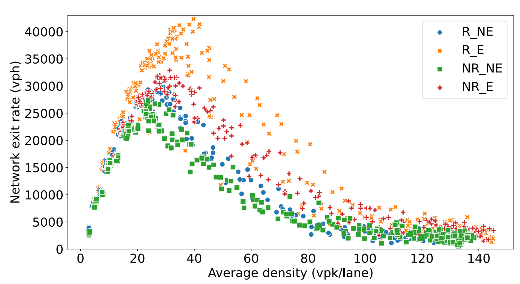
(b). OW network. Ped demand: 12 ped/min/pa



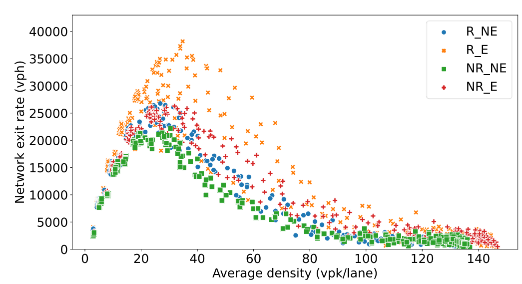
(c). TW network. Ped demand: 6 ped/min/pa



(d). TW network. Ped demand: 12 ped/min/pa



(e). TWL network. Ped demand: 6 ped/min/pa



(f). TWL network. Ped demand: 12 ped/min/pa

Figure 7 Simulation-based comparison of NEF with pedestrians

First, Table 1 shows that the reduction in NEF for the TW and TWL networks is larger than the OW network for both pedestrian demand levels, especially for the NR_NE and the R_NE scenarios. Figure 8 depicts the impact of pedestrians for all three networks without exclusive lanes on turning vehicles having green time. The lane designation in Figure 8 is consistent with Figure 3. For simplicity, the currently served movements are shown by green arrows while all idle phases are omitted from the figure. Pedestrians only impact the turning vehicles, and all turning vehicles potentially need to yield to pedestrians. Figure 8(a) shows that for the OW network, only about half of the pedestrians will impact the turning movements under the homogeneous pedestrian demand since vehicles from one approach are only allowed to turn to another one direction. However, all pedestrians can influence the turning flows for both TW and TWL networks, as shown in Figure 8(b) and Figure 8(c). Therefore, pedestrians impose higher restrictions on the mobility of TW and TWL networks than OW networks. For the networks without exclusive lanes, the turning vehicles can further block the straight-through vehicles, as shown in Figure 8. This explains why TW and TWL networks have a more significant reduction in NEF than OW networks when exclusive lanes do not exist. When the networks have exclusive lanes, the probability that turning vehicles would be blocked by straight-through vehicles is reduced. Therefore, the reduction percentage of the NEFs in the TW and TWL networks is smaller in scenarios with exclusive lanes than the scenarios without exclusive lanes. In addition, the number of turning movements from TW networks is less than OW and TWL networks. Hence, the impact of pedestrians on the TW networks is less significant than the other two network types, and the reduction percentages for the NR_E and R_E scenarios are the smallest for TW networks. This suggests that exclusive lanes are very important for TW and TWL networks to maintain network efficiency when there are pedestrians.

Table 1 Influence of pedestrians on the maximum NEF ($\times 10^3$ vph)

	NR_NE	NR_E	R_NE	R_E
	No Pedestrians			
OW	20.58	21.23	21.27	23.13
TW	15.53	18.13	15.87	18.82
TWL	31.73	37.61	34.73	42.32
	With Pedestrians: 6 ped/min/pa			
OW	19.46 (5.44)	19.05 (10.27)	20.81 (2.16)	21.68 (6.27)
TW	11.58 (25.43)	17.71 (2.32)	13.42 (15.44)	18.9 (-0.43)
TWL	26.22 (17.37)	31.78 (15.50)	29.35 (15.49)	40.89 (3.38)
	With Pedestrians: 12 ped/min/pa			
OW	17.42 (15.35)	16.6 (21.81)	19.62 (7.76)	19.20 (16.99)
TW	9.76 (37.15)	16.50 (8.99)	11.76 (25.90)	19.19 (-1.97)
TWL	21.20 (33.19)	25.86 (31.24)	26.11 (24.82)	35.82 (15.36)

Values in parentheses represent the percentage reduction compared with the equivalent case with no pedestrians.

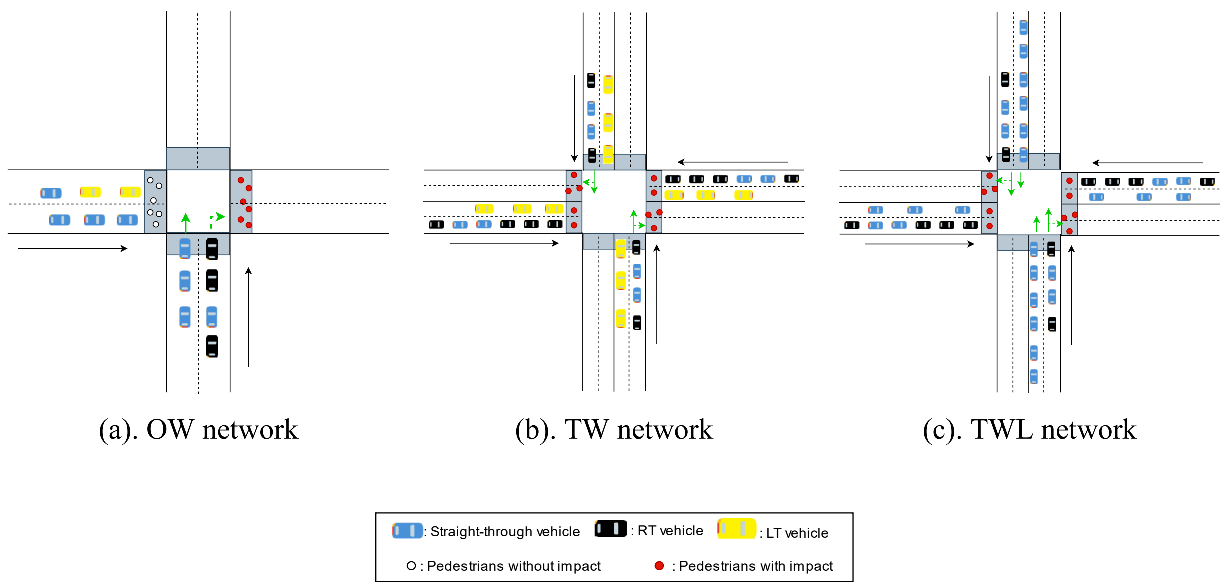


Figure 8 Impact of pedestrians

Second, as shown in Figure 6 and Figure 7, the gap between the cases with and without exclusive lanes considering pedestrians is significantly larger than the case without pedestrians for the TW network.

This is because, even during the green time, the pedestrians can block vehicles. For the TW network without exclusive lanes, as shown in Figure 3 (c) and Figure 8 (b), one lane is left-turn only and the other is shared by RT vehicles and straight-through vehicles. Therefore, the turning vehicles stopped by pedestrians can further block the straight-through vehicles behind them. Consequently, the NEF drops significantly with pedestrians. Note, even if we make the left lane shared by left-turning vehicles and straight-through vehicles, this phenomenon is also expected for the same reason. On the other hand, for both OW and TWL networks without exclusive lanes, one of the two lanes are dedicated for straight-through movement, so this influence is less significant. This suggests that dedicated lanes for straight-through vehicles are critical to maintain the efficiency of the network, which again implies that the exclusive lanes are necessary for a TW network with two-center-lane streets.

Third, another interesting finding is that the pedestrians increase scatter observed in the congested domain of the NEFs, which is the most obvious for R_T scenario of the TWL network. This phenomenon can be explained by the low resilience of the TWL networks mentioned before. Figure 6 shows the congested domain of TWL networks is more scattered than the other two types of networks. Pedestrians lead to higher probability of congested streets, so this scatter, which is the result of uneven vehicle distribution (*25*), is enlarged.

CONCLUSIONS

This paper examines the influence of RTOR, exclusive lanes and pedestrians on the network-level operational performance of three types of networks: OW, TW and TWL. The performance is measured via macrosocpic or network-wide traffic models, including the MFD and NEF. The major findings include:

1. Both RTOR and exclusive lanes are beneficial for traffic operations for all studied network types. The improvement in OW and TWL networks is stronger than TW networks due to the difference in the number of turning movements.
2. The comparison of efficiency improvement from RTOR and exclusive lanes differs between the free-flow region and congested region. In the free-flow region, RTOR is more beneficial since it can increase the intersection capacity by both serving RT vehicles in red and increasing the proportion of straight-through vehicles in green time. In the congested region, the effect of RTOR is diminished due to the lack of time gap from the conflicting traffic streams, but the exclusive lanes are still able improve the capacities. Therefore, exclusive lanes are more beneficial for this region.
3. Pedestrians reduce the NEF for all scenarios. The negative impact from pedestrians is the least for the OW network because only approximately one-half pedestrians interact with turning vehicles.
4. When pedestrians exist, it is very critical to have at least one dedicated lane for the straight-through movements to maintain the network mobility.
5. The TWL network with both RTOR and exclusive lanes has the highest efficiency. However, it has a poor resilience, so the NEF is much more scattered than other scenarios in the congested region.

It should be noted that this paper investigates the influence of three factors on certain networks with given lane configuration and signal timing plans. Different lane configuration and phase timing plans are of interest to be investigated in the fugure. For example, does the conclusion for the TW network still hold if we change the phase for left turns to permitted? Moreover, the length of the exclusive lane is the primary parameter affecting its efficiency. Therefore, the design of exclusive lanes under various network configurations and traffic patterns is another promising topic to investigate. Nevertheless, the findings are based on generic observations on how RTOR, exclusive lanes, and pedestrians impact these network types. Thus, the findings should be general and hold for more realistic network structures. Further simulation and empirical evidence in these more realistic situations should verify this conclusion.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: H. Liu, Z. Xiong and V. Gayah; analysis and interpretation of results: H. Liu, Z. Xiong and V. Gayah; draft manuscript preparation: H. Liu, Z. Xiong and V. Gayah. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Retting, R. A., M. S. Nitzburg, C. M. Farmer, and R. L. Knoblauch. Field Evaluation of Two Methods for Restricting Right Turn on Red to Promote Pedestrian Safety. *ITE journal*, Vol. 72, No. 1, 2002, pp. 32–36.
2. Massaad, A., and Z. Massaad. Right-Turn-on-Red Impact Assessment and Volume Estimation Model for Critical Intersections. *International journal of transportation science and technology*, Vol. 9, No. 3, 2020, pp. 229–238.
3. Lin, F.-B. Right-Turn-on-Red Characteristics and Use of Auxiliary Right-Turn Lanes. *Transportation Research Record*, Vol. 1010, 1985, pp. 9–15.
4. Abu-Lebdeh, G., R. F. Benekohal, and B. Al-Omari. Models for Right-Turn-on-Red and Their Effects on Intersection Delay. *Transportation Research Record*, Vol. 1572, No. 1, 1997, pp. 131–139.
5. Creasey, F. T., N. Stamatiadis, and K. Viele. Right-Turn-on-Red Volume Estimation and Incremental Capacity Models for Shared Lanes at Signalized Intersections. *Transportation research record*, Vol. 2257, No. 1, 2011, pp. 31–39.
6. Tian, Z. Z., and N. Wu. Probabilistic Model for Signalized Intersection Capacity with a Short Right-Turn Lane. *Journal of Transportation Engineering*, Vol. 132, No. 3, 2006, pp. 205–212.
7. Kikuchi, S., and N. Kronprasert. Determining the Length of the Right-Turn Lane at a Signalized Intersection. *Transportation Research Record*, Vol. 2060, No. 1, 2008, pp. 19–28.
8. Dussault, C. Safety Effects of Right Turn on Red: A Meta-Analysis. 1993.
9. Preusser, D. F., W. A. Leaf, K. B. DeBartolo, R. D. Blomberg, and M. M. Levy. The Effect of Right-Turn-on-Red on Pedestrian and Bicyclist Accidents. *Journal of safety research*, Vol. 13, No. 2, 1982, pp. 45–55.
10. Fleck, J. L., and B. M. Yee. Safety Evaluation of Right Turn on Red. *ITE journal*, Vol. 72, No. 6, 2002, pp. 46–48.
11. Jiang, C., R. Qiu, T. Fu, L. Fu, B. Xiong, and Z. Lu. Impact of Right-Turn Channelization on Pedestrian Safety at Signalized Intersections. *Accident Analysis \& Prevention*, Vol. 136, 2020, p. 105399.
12. Al-Kaisy, A., and S. A. Roefaro. Channelized Right-Turn Lanes at Signalized Intersections: The US Experience. *Advances in transportation studies*, Vol. 26, 2012, pp. 57–68.
13. Guo, Y., P. Liu, Y. Wu, and J. Chen. Evaluating How Right-Turn Treatments Affect Right-Turn-on-Red Conflicts at Signalized Intersections. *Journal of Transportation Safety \& Security*, Vol. 12, No. 3, 2020, pp. 419–440.
14. TRB. Highway Capacity Manual. 1994.

15. Godfrey, J. W. The Mechanism of a Road Network. *Traffic Engineering \& Control*, Vol. 8, No. 8, 1969.
16. Geroliminis, N., and C. F. Daganzo. Existence of Urban-Scale Macroscopic Fundamental Diagrams: Some Experimental Findings. *Transportation Research Part B: Methodological*, Vol. 42, No. 9, 2008, pp. 759–770.
17. DePrator, A. J., O. Hitchcock, and V. V Gayah. Improving Urban Street Network Efficiency by Prohibiting Conflicting Left Turns at Signalized Intersections. *Transportation Research Record*, Vol. 2622, No. 1, 2017, pp. 58–69.
18. Ortigosa, J., V. V Gayah, and M. Menendez. Analysis of One-Way and Two-Way Street Configurations on Urban Grid Networks. *Transportmetrica B: transport dynamics*, 2017.
19. Gayah, V. V, and C. F. Daganzo. Analytical Capacity Comparison of One-Way and Two-Way Signalized Street Networks. *Transportation Research Record*, Vol. 2301, No. 1, 2012, pp. 76–85.
20. Daganzo, C. F., V. V Gayah, and E. J. Gonzales. The Potential of Parsimonious Models for Understanding Large Scale Transportation Systems and Answering Big Picture Questions. *EURO Journal on Transportation and Logistics*, Vol. 1, No. 1–2, 2012, pp. 47–65.
21. Manual, H. Highway Capacity Manual. *Washington, DC*, 2000.
22. Daganzo, C. F. Urban Gridlock: Macroscopic Modeling and Mitigation Approaches. *Transportation Research Part B: Methodological*, Vol. 41, No. 1, 2007, pp. 49–62.
23. Yu, Z., and V. V Gayah. Resilience of Urban Street Network Configurations under Low Demands. *Transportation Research Record*, Vol. 2674, No. 9, 2020, pp. 982–994.
24. Yu, Z., and V. V Gayah. Simulation Analysis of Urban Network Performance under Link Disruptions: Impacts of Information Provisions in Different Street Configurations. *Journal of Intelligent Transportation Systems*, 2022, pp. 1–17.
25. Daganzo, C. F., V. V Gayah, and E. J. Gonzales. Macroscopic Relations of Urban Traffic Variables: Bifurcations, Multivaluedness and Instability. *Transportation Research Part B: Methodological*, Vol. 45, No. 1, 2011, pp. 278–288.