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Research Paper

Quantifying the impacts of right-turn-on-red, exclusive turn lanes and pedestrian movements on the efficiency of urban transportation networks

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A B S T R A C T

Previous studies demonstrated that restricting left turning movements can enhance transportation network efficiency. However, this strategy can lead to significant increases in the volume of right-turn movements. While these right-turn movements do not conflict with opposing through traffic, they still must interact with pedestrians in adjacent crosswalks. Further, their movement is influenced by the presence of right-turn-on-red, which is commonly applied at signalized intersections to improve intersection capacity, and the presence of exclusive right-turn lanes. This paper examines the influence of these three factors (pedestrian activity, right-turn-on-red, and exclusive right-turn lanes) on vehicular operational performance at a network-wide level. Simple grid network structures are considered due to their generalizability and the performance of three network types are tested: two-way streets that accommodate left turns, two-way streets that prohibit left turns, and one-way streets. The results reveal that when there are no pedestrians, right-turn-on-red can improve the operational performance regardless of the existence of exclusive lanes, especially for the networks restricting left-turn movements, and the presence of exclusive turn lanes increases the benefits obtained by allowing right-turn-on-red. The results also suggest that allowing right-turn-on-red is more important than providing exclusive lanes 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 right-turn-on-red for most scenarios, as expected. This decrease in performance is larger for networks made up of two-way streets compared to those made up of one-way streets. Exclusive lanes are also found to be critical for two-way streets with left turns protected to maintain network efficiency. Overall, prohibiting left turns on two-way streets still provides the largest operational performance of all networks with these features considered.

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1. Introduction

Intersections of urban streets are particularly dangerous locations where conflicting traffic streams are forced to interact. Even when only vehicles are considered, traffic control measures are needed to ensure both safe and efficient movement at these locations. In addition, due to the interruption of traffic flows, conflicting traffic streams impose difficulties for evacuation planning and management (Xie et al., 2010). Conflicting through movements can be mitigated rather simply using either static or dynamic traffic control to assign right-of-way to one of the conflicting directions; e.g., stop signs can be used to force one movement to always give priority to another, while traffic signals can dynamically assign right-of-way. However, the existence of left-turning movements adds additional complexity. At signalized intersections, conflicting left-turning can be served in either protected or permitted fashion (Cottrell and Virginia Highway & Transportation Research Council, 1985). The former completely stops opposing through movements and results in safer movement for left-turning vehicles; however, these protected phases reduce the overall capacity of the intersection by adding additional lost time (Messer and Fambro, 1977; Newell, 1959). The latter eliminates the need for additional phases; however, they require drivers to identify and navigate appropriate gaps between opposing through vehicles and thus are less safe. Additionally, left-turning vehicles may still queue at intersections and block other movements on their approach (Fambro et al., 1977; Haddad and Geroliminis, 2013).

A variety of alternative intersection designs have been proposed to reduce or eliminate left-turn conflicts at signalized intersections. Examples include restricted crossing U-turn (RCUT) intersections, also known as super street intersections, median U-turn intersections, continuous flow intersections, bowties, jughandle intersections, split intersections, and quadrant intersections (Berkowitz et al., 1996; Chowdhury, 2012; Hughes et al., 2010; Hummer, 1998; Reid and Hummer, 2001). While these have been shown to offer some operational and safety benefits, their impacts have generally only been quantified when applied at individual intersections or arterials and never when implemented network-wide. Further, they are generally not applicable in urban environments since they require much more space than traditional intersection designs.

In addition to the types mentioned above, there exist other street network designs that can be used to reduce conflicts resulting from left turns while do not require large space for intersections. For example, the use of one-way streets in urban areas eliminates conflicting turning movements at intersections (Gayah and Daganzo, 2012). This significantly simplifies signal timing at intersections, which can improve overall intersection capacity. However, vehicles cannot take the most direct paths between their origins and destinations and thus have to travel longer distances on one-way streets. Similarly, two-way streets can be used in which left turns are banned/restricted at all intersections (DePrator et al., 2017). Doing so offers the same intersection-level capacity as one-way streets but requires shorter detours. Recent studies have used macroscopic traffic models to examine the network-wide performance of such strategies, while considering the competing effects of improved intersection capacity and longer travel distances (DePrator et al., 2017; Gayah and Daganzo, 2012; Ortigosa et al., 2019, 2015). Specifically, the Macroscopic Fundamental Diagram (MFD) and Network Exit Function (NEF) that characterize a well-defined relationship between the average network productivity and use, are used to measure the operational performance under a range of congestion levels. Such relationships have been demonstrated by both theoretical (Godfrey, 1969) and empirical studies (Geroliminis and Daganzo, 2008) and have been recognized as well-suited tools to understand the network-wide impact of such intersection-level strategies. As many theoretical works have demonstrated how local intersection control relates to network-level performance (Daganzo and Geroliminis, 2008; Laval and Castrillón, 2015; Leclercq and Geroliminis, 2013), the studies find that two-way streets without left turns are generally more operationally efficient than networks of one-way streets and provide higher maximum service rates than networks of two-way streets with left turns when applied in grid network structures. Other studies have examined left-turn restrictions from temporal (when to implement) and spatial (where to implement) perspective (Bayrak et al., 2022; Bayrak and Gayah, 2021; DePrator et al., 2017; Long et al., 2010; Zhao et al., 2016), as well as consider their resilience to network disruptions (Yu and Gayah, 2022, 2020). In addition to the design strategies mentioned above, a simulation model that incorporates driving behaviors into a discrete event framework was proposed recently (Zhao et al., 2023) to unveil the effect of road geometry and prevailing traffic conditions on left-turn volumes.

While the existing literature provides some insight into the potential operational benefits of left-turn restrictions applied to urban grid networks, several factors were not considered that might significantly influence these outcomes. Specifically, the elimination of left turns would necessarily increase the flow of right-turning (RT) vehicles at intersections, which could impose significant impact on the network efficiency. For one, RT vehicles generally may be served during the red period under right-turn-on-red (RTOR) rules, unless explicitly stated otherwise. Doing so allows RT vehicles to use the red period to discharge through the intersection after yielding to conflicting traffic streams and has shown to improve the intersection capacity and reduce control delay at individual intersections (Lin, 1985; Luh and Lu, 1990; Massaad and Massaad, 2020). However, this creates conflicts with the through movement from the cross streets. The impact of the increase in this type of conflict from the prohibition of left turns was not considered in the previous studies. Second, RT vehicles may have significant conflicts with pedestrians in the adjacent crosswalks. Although the adverse impact of RTOR on pedestrian's safety has been studied sufficiently (Fleck and Yee, 2002; Preusser et al., 1982; Retting et al., 2002), only a few studies (Massaad and Massaad, 2020) investigate the impact of pedestrians on traffic operations considering the deployment of RTOR. Finally, the availability of right-turn lanes may help serve the additional right-turning vehicle flow created from the prohibition of left turns, especially for the locations where RTOR is allowed (Kikuchi and Kronprasert, 2008; Lin, 1985; Tian and Wu, 2006).

Thus, the purpose of this paper is to apply similar macroscopic traffic models as in (DePrator et al., 2017) to examine how the implementation of RTOR, presence of pedestrians and right-turn lanes might influence network-wide traffic performance under different management scenarios. The scenarios considered include one-way streets and two-way streets with and without left-turn restrictions. The results are obtained using micro-simulation, and some simple thought experiments grounded in MFD-theory are used to obtain insights into expected patterns to confirm the simulation findings.

The rest of this paper is organized as follows. Section 2 provides a thought experiment to forecast the impact of the studied factors on the operational performance of a network. Section 3 introduces the simulation settings for three types of networks. Section 4 shows the simulation results and depicts the influence of RTOR, exclusive lanes and pedestrians for all network types. Section 5 provides concluding remarks.

2. Thought experiment

This section provides a thought experiment to better understand the potential impacts of RTOR, exclusive right-turn lanes, and interactions between right-turning vehicles and pedestrians. This information will provide insight that is helpful to examine and understand the microscopic simulation results in the next section. This section uses the Macroscopic Fundamental Diagram (MFD), which is the relationship between the average traffic flow and the average density in a network, to assess the impacts of these features.

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.

2.1. Impact of RTOR

To analyze the influence of RTOR on MFD, we assume:

- Lane configuration including whether exclusive lanes exist, presence of pedestrians, and signal timings except for whether RTOR is allowed are fixed.
- Vehicles have relatively fixed routes with a network. More specifically, if vehicles do change routes, this will not sufficiently change their average trip length. Such an assumption is reasonable in redundant grid networks with multiple shortest 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 cross streets 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 turning vehicles must slow down to move through the intersection. The HCM suggests that the saturation flow of RT movements is typically 84.7 % of through movements (Manual, 2000).

Under the assumptions above, a general comparison of the expected functional form of a network's MFD with and without RTOR is shown in Fig. 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;

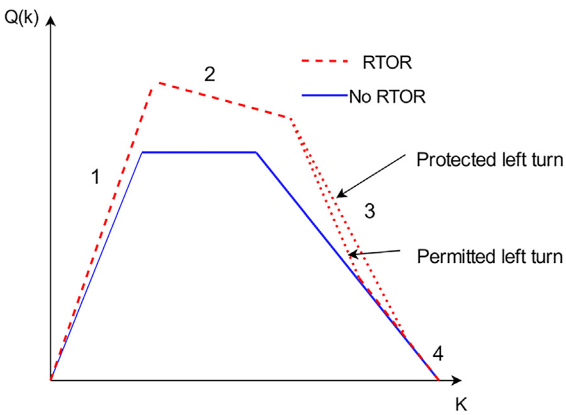


Fig. 1. Influence of RTOR on MFD.

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 rate. However, the improvement suffers from competing effects: more RT vehicles are served when RTOR is allowed, but the presence of RTOR would increase the through-moving vehicles on the cross street, thereby reducing 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 Fig. 1:

- **Part 1:** When 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 should 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 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 outweighs 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 competing effects mentioned above. Therefore, we expect the average flow to decrease with further increases in average density. 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 diminishes faster than part 2, as illustrated in part 3 of Fig. 1.
- **Part 4**: When the number of vehicles exceeds a certain value, few vehicles can turn right on red due to the short gap provided by the conflicting vehicle movement and/or the occurrence of queue spillover. Consequently, the impact from RTOR under this condition is neglectable, as shown by the part 4 in Fig. 1. Note that the network density associated with this phenomenon can be influenced by traffic signal timings. For example, it is reasonable to anticipate that this value at an intersection with protected left-turn phases is larger than that with only permitted left-turn phase since the protected left-turn phase does not generate confliction with vehicles that desire to turn right on red while the permitted left-turn phase does, as shown in Fig. 1.

2.2. Impact of exclusive lanes and pedestrians

To analyze the impact of exclusive lanes for right turns on MFD, the same assumptions for the analysis of RTOR are made except for:

- Whether RTOR is allowed is fixed.
- The existence of exclusives lanes for right turns is the only difference in lane configuration.

Under the assumptions above, the general impact of exclusive lanes on a network's MFD is shown in Fig. 2. Note, for the purpose of comparison, we assume the network lengths for both networks in Fig. 2 are identical. This treatment is equivalent to the presentation in which we replace the horizontal axis with the number of vehicles in the network. Overall, we expect that the existence of exclusive lanes can enhance the average network flow since it increases the capacity of intersections. Specifically, the MFD with exclusive lanes can be divided into three parts:

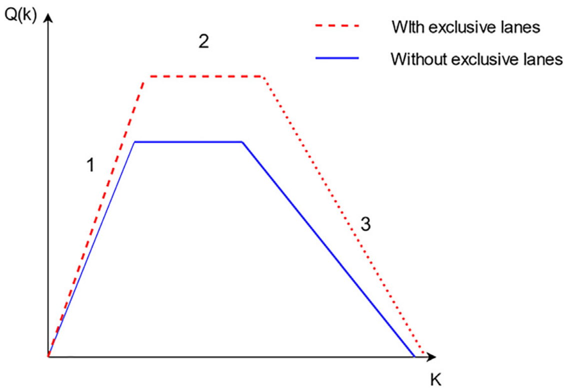


Fig. 2. Influence of exclusive lanes on MFD.

- **Part 1:** In the free-flow region, the increase in the average flow resulting from exclusive lanes is enhanced by network density. Like RTOR, when density is very low, the network without exclusive lanes can serve the demand at a high service level, so the benefit from exclusive lanes is relatively small. This benefit is expected to increase with the increase in the average density.
- **Part 2:** Unlike RTOR, the benefit from exclusive lanes does not suffer from the competing effects resulting from the increase in demand. Therefore, we expect the capacity for the network with exclusive lanes to be relatively stable for a certain range of average densities.
- **Part 3:** When the network reaches its congested domain, the average flow starts decreasing. For the same reason for Part 2, we expect that jam density of the network with exclusive lanes to be larger than that of the network without exclusive lanes.

On the contrary to exclusive lanes, it is straightforward to imagine that the existence of pedestrians generates a negative impact on the average network flow. The pattern of the influence is expected to be opposite to the pattern shown in Fig. 2.

Note the above analysis only serve as a thought experiment showing the general effect of the three factors; the actual shape depends on various factors, such as network road configuration, number/proportion of RT vehicles, and the interaction between the three factors. 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 from RTOR 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 adds extra conflicting movements and reduces 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.

2.3. Network exit function

While MFD provides a relationship between average flow and density in a network, it is often more valuable to examine the relationship between trip completion rate (i.e., the rate that vehicles reach their destination and exit a network) and density; this latter relationship is known as the Network Exit Function (NEF). If the average trip length is stable over time, the NEF can be expressed as:

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

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 (Daganzo, 2007). Eq. (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/presence of RT lanes/pedestrian interactions, the influence of RTOR on NEF is thus similar to MFD for a given network structure.

3. Simulation settings

The previous section provides insights on the influence of the implementation of RTOR, presence of pedestrians and presence of exclusive RT lanes on NEF via thought experiments; however, there are a variety of realistic factors (such as signal settings and driving behaviors) that would influence its impact on network operations. To investigate the influence in a more practical environment, microscopic simulations were performed using the AIMSUN simulation software. Recall that this study aims to investigate the impact of the interaction between these three factors and the potential increase in RT movements resulting from the prohibition of left turns, which has been shown to improve the NEF (12), on the operational performance at a network level. Therefore, in addition to these three factors, the effect of the prohibition of left turns is incorporated in the simulation by employing three network configurations: a network consisting of two-way streets allowing left turns (TW), a network consisting of alternative one-way streets (OW), which is treated as one strategy for banning left turns, a network consisting of two-way streets that do not allow left turns (TWL). The remainder of this section describes the network layouts considered in more detail, demand description, and output processing methods used in this study.

3.1. 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 Fig. 3. In both networks, links were assumed to be 125 m long with a speed limit is 50 km/h.

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 allowed, there is a protected left turn phase; otherwise, the phase is removed. Fig. 4 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 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, Fig. 4(a) and Fig. 4(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 Fig. 3(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.

3.2. Demand

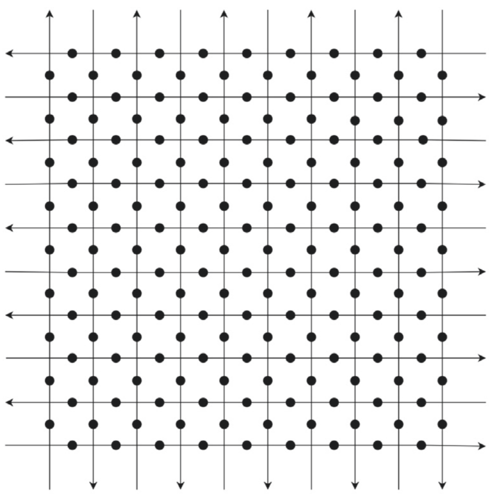
The simulation time is set to 3 hours and vehicle positions were updated at regular 1-second intervals. Centroids – which serve as both an origin and destination for trips – were placed at the midpoint of all links; see Fig. 3. In total, 180 centroids were used, resulting in 32,220 unique OD pairs. We use uniform demand pattern in all networks, which means the demand between all OD pairs is identical. Note that the turning ratio at individual intersections is determined by the stochastic c-logit route choice model, which was used to emulate user-equilibrium routing conditions in which vehicles make routing decisions to minimize their own personal travel times. To have a complete NEF, we increase the demand over time to make the network gradually evolve 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. Fig. 5 shows the demand pattern between an arbitrary OD pair. There are a total of 105,037 trips during the whole simulation.

This paper investigates the NEF with and without pedestrians for all three network types. For the simulations with pedestrians, we created a rectangular pedestrian area (pa) around each intersection, within which pedestrian movements are allowed. There is one entrance centroid and one exit centroid at each corner of the pedestrian area, and pedestrians can only use the marked pedestrian crossings to cross the intersection. Fig. 6 shows an example for the TW network, and the same deployment is used for the OW and TWL networks. For pedestrian demand modeling, we use a time-invariant and uniform OD matrix with two demand rates: 6 ped/min/pa and 12 ped/min/pa.

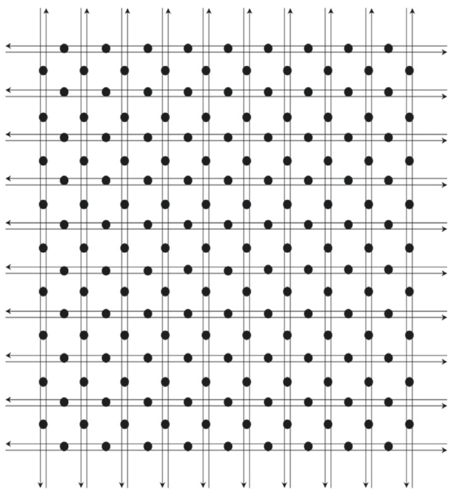
Note that although the idealized network structures and demand patterns employed in the simulation do not precisely mirror real-world conditions, such settings were employed as they have the potential to reveal generic trends and insights that are transferrable to more typical conditions. On the contrary, restricting the simulation to a limited number of more realistic situations may result in findings that are not transferrable to other conditions (Daganzo et al., 2012). Moreover, grid-like networks of two-way streets are common in urban areas around the world, and similar settings have been widely used in previous research (DePrator et al., 2017; Knoop et al., 2015; Ortigosa et al., 2015; Ortigosa and Menendez, 2014).

3.3. Output processing

For each scenario, 10 simulation replications are conducted using different starting random seeds, and the number of vehicles in the network and the number of completed trips are retrieved every second. Then, the average density is com-

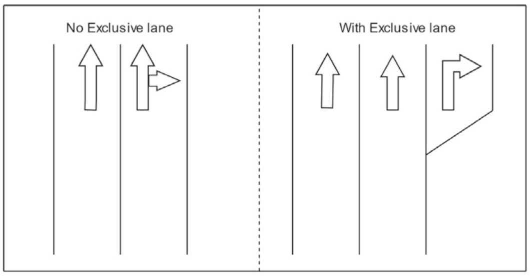


(a). One-way network

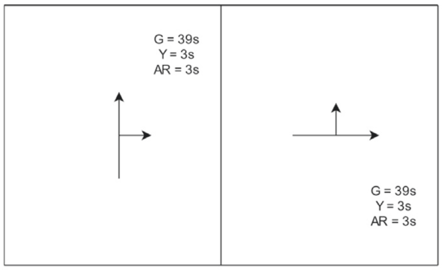


(b) Two-way network

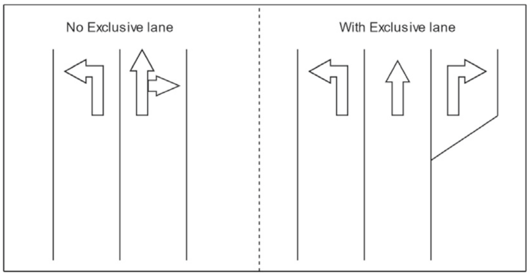
Fig. 3. Network layout.



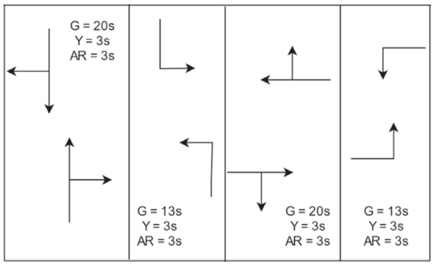
(a). Lane configuration for the OW network



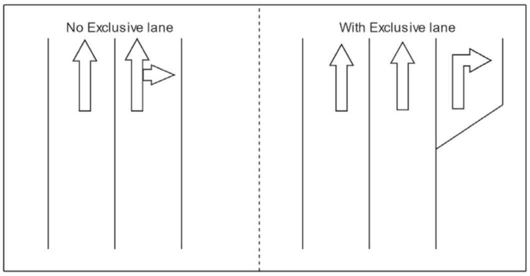
(b). Signal timing for the OW network



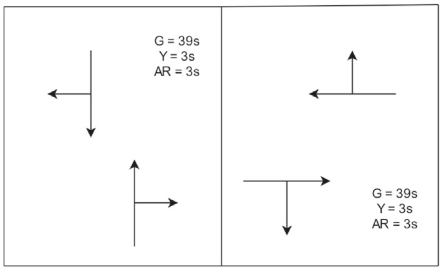
(c). Lane configuration for the TW network



(d). Signal timing for the TW network



(e). Lane configuration for the TWL network



(f). Signal timing for the TWL network

Fig. 4. Lane configurations and signal timing plans.

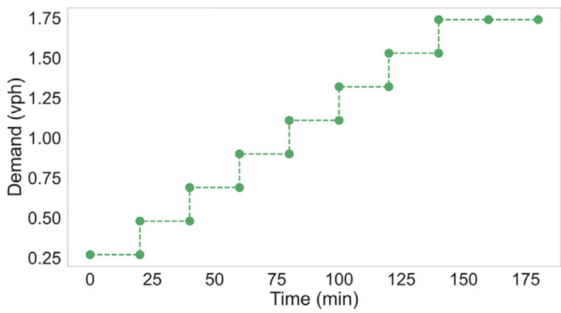


Fig. 5. Demand pattern.

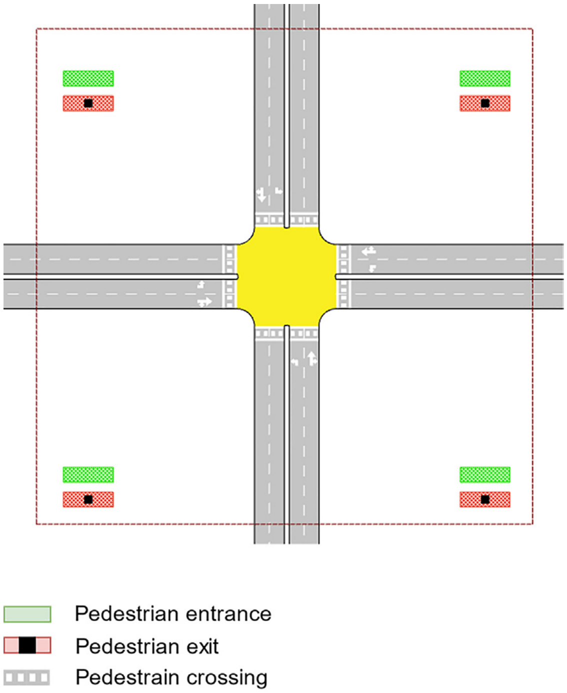


Fig. 6. Pedestrian deployment for the TW network.

puted 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 at regular 5-minute intervals. Note, the length of exclusive RT lanes is ignored for density calculations to make the density ranges identical and provide a fairer comparison.

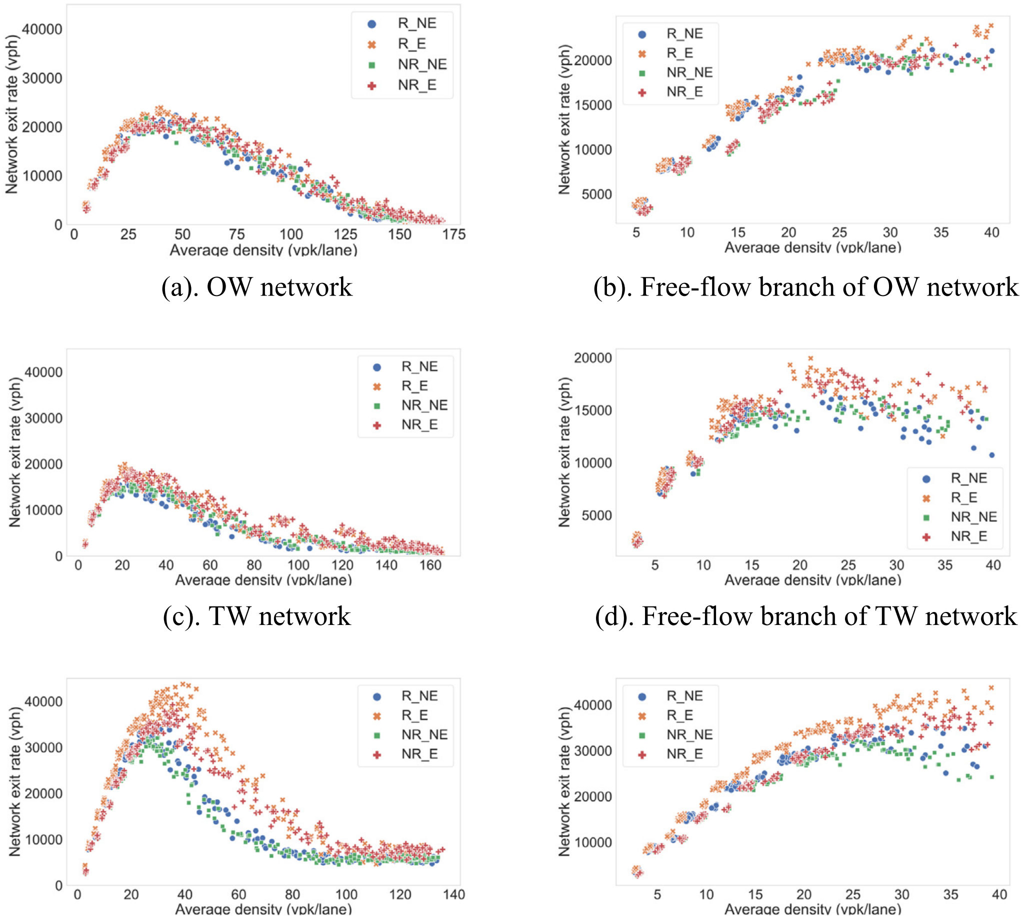
4. Results

This section shows the NEFs obtained using simulation for the 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. Then, a three-way analysis of variance (three-way ANOVA) was performed to investigate whether the effect of the three factors and their interactions on the network capacity is significant.

4.1. Without pedestrians

Fig. 7 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 RT lanes for individual networks.

Under base conditions (without RTOR or exclusive RT lanes, green points in Fig. 7), the NEF for the TWL network is much higher than the TW network, which agrees with the findings in (DePrator et al., 2017). This implies that although prohibiting left turns increases the average trip length, according to Eq. (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 (Yu and Gayah, 2022, 2020). 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 reduces the mobility of the network. However, since the vehicles in OW and TW networks have multiple



(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

Fig. 7. Simulation-based comparison of NEF without pedestrian.

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.

First, for all networks, the presence of RTOR increases the trip completion rate for all densities within the free-flow domain, regardless of the existence of exclusive lanes; this is in line with the thought experiment shown in Fig. 1. Due to the figure scale, this impact is difficult to observe in the complete NEFs. Therefore, zoomed-in versions of the free flow portion of the NEFs are provided on the right side of Fig. 7 to better observe this phenomenon. In addition, the improvement from RTOR is smaller for the TW network than the other two networks, as shown in Fig. 7(d). The reason is that the number of RT vehicles in the TW network is lower than the other network types; TWL and OW networks only have one turning type so all turning vehicles make a RT. Thus, the improvement due to RTOR for these networks is higher.

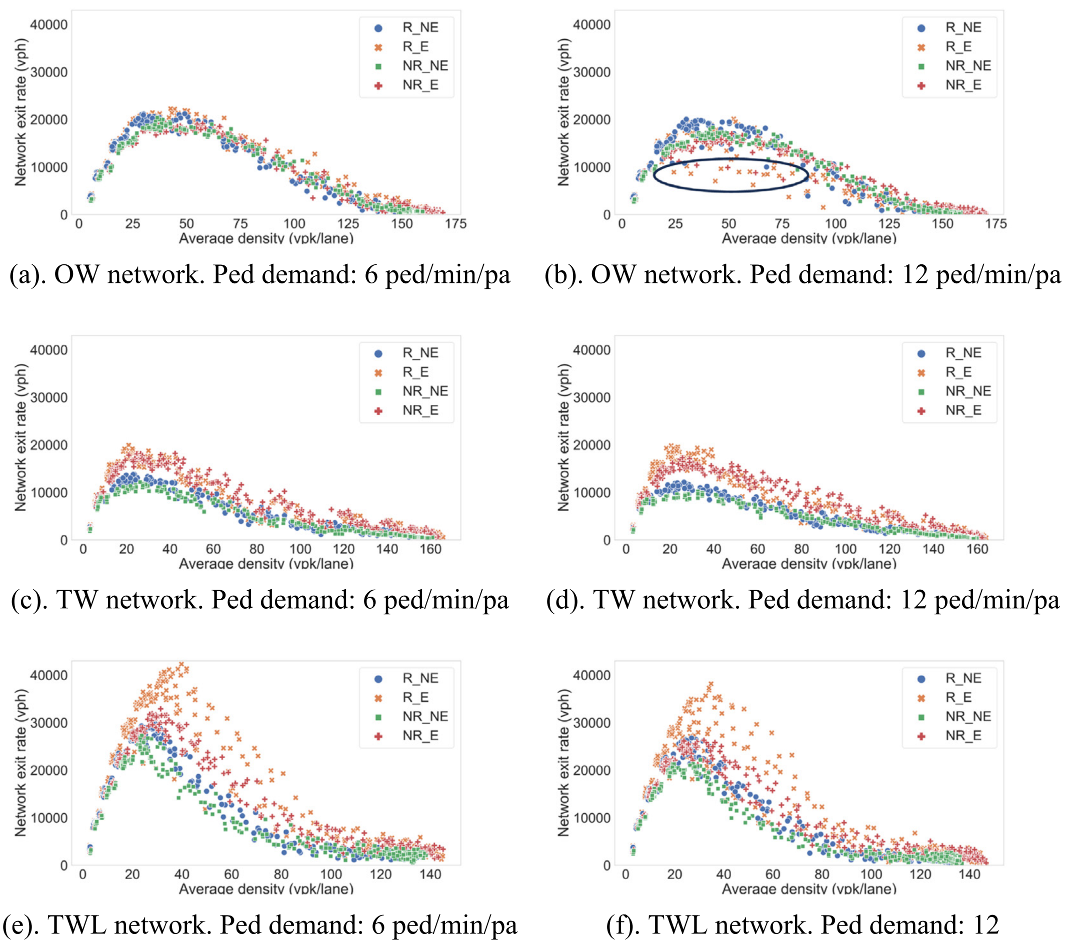
Second, the average network exit rate in the R_NE scenarios (blue points) is higher than the NR_E scenarios (red points) when in the free-flow domain, which implies the implementation of RTOR is more beneficial than the exclusive lanes when traffic load is relatively low. This occurs for all networks but is particularly true for the OW and TWL networks, in which the left turns are banned. 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. Compared to the scenario in which no RTOR or exclusive lane exists, an exclusive RT lane can serve at most 5 extra vehicles for a cycle. This is the reason why RTOR outperforms exclusive RT 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 a small impact on the NEF.

Third, when the network falls into the congested region, exclusive lanes play a more important role than RTOR, while the combination of the two strategies (R_E scenario) still performs the best. For both OW and TW networks, 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 improved. Consequently, the overall NEF is improved as well.

4.2. With pedestrians

The results considering pedestrians with two demands are shown in Fig. 8. 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 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 on the overall operational efficiency, we use the average exit rate of the two points (two 5-minute intervals) with the highest exit rate from each random seed as an estimate for capacity. Note that gridlock occurs very early for the R_E scenario of OW network under two random seeds, and this also happens for the NR_E scenario of OW network under one of those two random seeds. As a result, the capacities from those random seeds are very low and treated as outliers, as shown by the points in the oval in Fig. 8 (b). Therefore, the results from these two random seeds were removed from the following studies. Then, we performed a paired t-test across the 8 random seeds to check if the impact of the presence of pedestrians on vehicle exit rate is significant at the 95 % confidence level. The results are shown in Table 1.



(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

Fig. 8. Simulation-based comparison of NEF with pedestrians.

For the results with pedestrians, the numbers in the parenthesis are the percentage reduction of network capacity compared to the results without pedestrians. The color scheme is used to visualize the reduction percentage.

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, for the NR_NE and the R_NE scenarios. Fig. 9 depicts the impact of pedestrians for all three networks without exclusive lanes on turning vehicles having green time. The lane configuration in Fig. 9 is consistent with Fig. 4. 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. Fig. 9(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 are only allowed to make right turn or move straight, which leads to confliction with pedestrian movement on only one side of the intersection. However, all pedestrians can influence the turning flows for both TW and TWL networks, as shown in Fig. 9(b) and Fig. 9(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 Fig. 9. 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 capacities in the TW network 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.

Second, while the reduction in the network capacity resulting from the presence of pedestrians is significant for all other networks, there is no significant impact imposed on the TW R_E network. The reason is that protected left-turn phases exist for this network type, and pedestrians are not allowed to cross the intersection during these phases. Therefore, the right turning vehicles from the cross streets do not incur any conflicts in these phases. Therefore, the served right turning vehicles during protected left turn phases can compensate for the reduction in the vehicle flow during green time resulting from the interference with pedestrians. In addition, as mentioned previously, TW has the lowest number of right turning vehicles among the three tested network types. Therefore, the presence of pedestrians does not have significant impact on this net-

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

	NR_NE	NR_E	R_NE	R_E
	No Pedestrians			
OW	20.16	20.63	20.79	22.59
TW	15.08	17.76	15.36	18.16
TWL	30.61	36.11	32.76	39.98
	With Pedestrians: 6 ped/min/pa			
OW	18.95 (6.00) *	18.75 (9.11) *	20.11 (3.27)	21.05 (6.82) *
TW	11.32 (24.93) *	17.26 (2.82) *	13.04 (15.10) *	18.57 (-2.26)
TWL	24.73 (19.21) *	30.89 (14.46) *	28.36 (13.43) *	35.76 (10.56) *
	With Pedestrians: 12 ped/min/pa			
OW	17.15 (14.93) *	16.04 (22.25) *	18.89 (9.14) *	18.01 (20.27) *
TW	9.57 (36.54) *	16.13 (9.18) *	11.21 (27.02) *	18.74 (-3.19)
TWL	20.53 (32.93) *	24.95 (30.91) *	24.78 (24.36) *	30.13 (24.64) *

Values in parentheses represent the percentage reduction compared with the equivalent case with no pedestrians.
*indicates if the impact is significant at the 95% level.

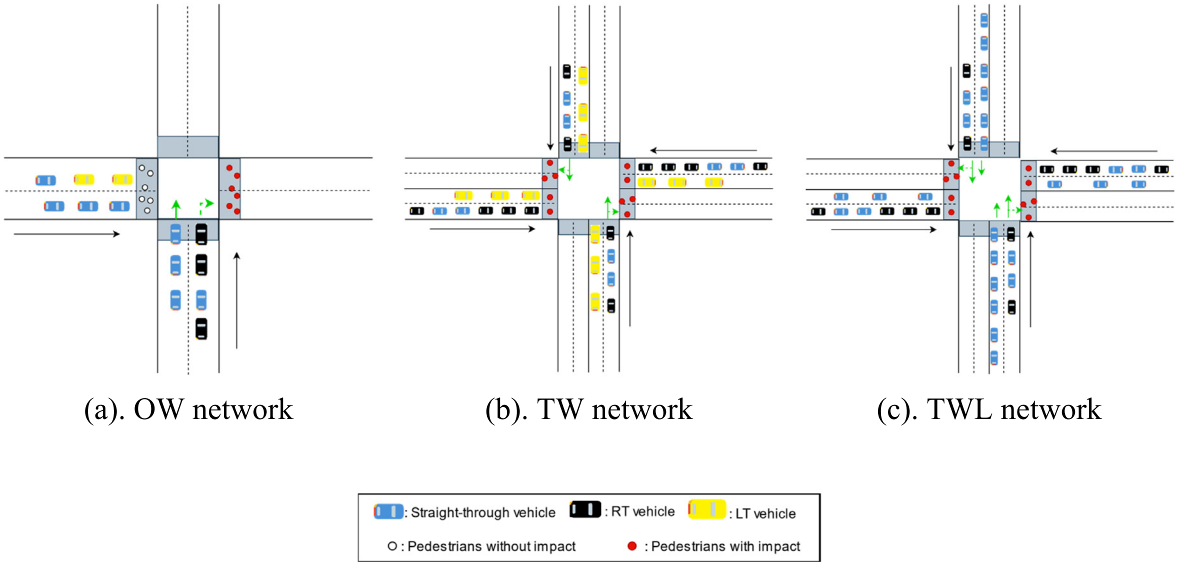


Fig. 9. Impact of pedestrians.

work type. Both exclusive turning lanes and RTOR are necessary to maintain the vehicle operational efficiency under the presence of pedestrians: without RTOR, the reduction of traffic flow during green time cannot be compensated during red time; without exclusive lanes, right turning vehicles can be blocked by through vehicles during red time. This is the reason why this phenomenon is not observed in the other three TW network types.

Third, as shown in Fig. 7 and Fig. 8, the gap between 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, pedestrians can block vehicles. For the TW network without exclusive lanes, as shown in Fig. 4 (c) and Fig. 9 (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.

Lastly, another interesting finding is that pedestrians increase scatter observed in the congested domain of the NEFs, which is the most obvious for R_E scenario of the TWL network. This phenomenon can be explained by the low resilience of the TWL networks mentioned before. Fig. 7 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 (Daganzo et al., 2011), is enlarged.

4.3. ANOVA results

A three-way ANOVA model using the same data from Table 1 was performed to test if each of RTOR (R), exclusive lanes (E), and presence of pedestrians (P) and the interaction between them generate statistically significant impact on network capacity. The results are shown in Table 2. Most effects are significant except for:

1. The effect of exclusive lanes for OW network. As mentioned before, since the proportion of RT vehicles for OW is large, the impact of exclusive lanes is less significant than RTOR for the free-flow region of MFD. Another reason might be that for OW network, there are only two incoming approaches at each intersection while for the other two network types, there are four incoming approaches. As a result, the increase in the intersection capacity from adding exclusive lanes for OW is less significant for the other two types.
2. The effect of interaction between RTOR and pedestrians for OW network. As mentioned before, on average, only half of the pedestrians will impact right turning vehicles. Therefore, the pedestrian has a less significant impact on the effect of RTOR for OW network than the other two networks.

Table 2
Three-way ANOVA results.

	df	OW		TW		TWL	
		Sum of squares	F value	Sum of squares	F value	Sum of squares	F value
C(R)	1	1.27e + 08	212.92*	1.10e + 08	308.50*	1.06e + 09	181.26*
C(E)	1	1.38e + 06	2.32	1.55e + 09	4339.07*	2.26e + 09	386.38*
C(P)	2	4.04e + 08	339.22*	3.04e + 08	425.77*	3.89e + 09	332.98*
C(R):C(E)	1	9.66e + 06	16.21*	8.76e + 04	0.25	4.86e + 07	8.31*
C(R):C(P)	2	2.83e + 06	2.38	3.23e + 07	45.20*	1.91e + 07	3.26*
C(E):C(P)	2	3.70e + 07	31.08*	1.91e + 08	267.63*	2.25e + 07	3.85*

* indicates if the effect is significant at the 95% level.

3. The effect of interaction between RTOR and exclusive lanes for TW network. The reason might be that the proportion of through vehicles for TW is the largest. Therefore, it is the most difficult network type for RT vehicles to find a safe gap during red time. Consequently, although RTOR has significant effect on network capacity, its effect cannot be enhanced by adding exclusive lanes. On the contrary, it is easier for RT vehicles in OW and TWL networks to turn on red due to the relatively small proportion of through traffic volumes. As a result, adding exclusive lanes can enhance the effect of RTOR, so this interaction for OW and TWL is significant. This is consistent with Fig. 7 and Fig. 8. It is shown more clearly in Fig. 7: for TW network, the increase in network capacity from NR_NE to R_NE is similar to the increase in network capacity from NR_E to R_E; however, for OW and TWL, the latter increase is larger than the former increase.

5. Conclusions

While restricting/banning left turns has been demonstrated to be an effective strategy to improve network mobility, the impact of the interaction between the increase in RT movements and related factors such as RTOR, exclusive lanes and presence of pedestrians on the network efficiency was not well understood. To fill this gap, 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 macroscopic or network-wide traffic models, including MFD and NEF. The result of a three-way ANOVA unveils that the effects of RTOR, exclusive lanes, and pedestrians and their interaction on MFD are significant for most scenarios. Although the specific influence of these factors on a given network is a function of the network's unique structure, we believe that the findings provide generic insights that should hold on more realistic networks. The major findings include:

1. Both RTOR and exclusive lanes are beneficial for traffic operations for all studied network types. However, the improvement in OW and TWL networks, in which left turns are prohibited, 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 except for the TW network with both exclusive lanes and RTOR. The impact for the TW network with exclusive lanes and RTOR is mitigated by the increase in the number of served right turning vehicles during the protected left turn phases. 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 future. 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. In addition, although the default AIMSUN simulation settings including the car-following model and stochastic route choice model for dynamic traffic assignment have been widely used in the literature (DePrator et al., 2017; Girault et al., 2016; Mühlich et al., 2015; Taglieri et al., 2023), the quantified impact of the three factors on the network efficiency can be influenced by such models and parameters, and it is meaningful to investigate the influence in the future. The findings are based on observations on three network types. Although they should be general and hold for more realistic network structures, further simulation and empirical evidence in more realistic situations should verify the findings.

CRediT authorship contribution statement

Hao Liu: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis. **Zecheng Xiong:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Vikash V. Gayah:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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