Simulation analysis of urban network performance under link disruptions: Impacts of information provisions in different street configurations

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Acknowledgements

This research was supported by NSF Grant CMMI-1749200

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This study uses aggregated network-level operation metrics to examine the performance of three street network configurations, namely two-way (TW), two-way without left turns (TWL), and one-way networks (OW), under disruptive events in the network. Overall, a TWL network is found to be the most efficient both with and without disruptions. When there is no disruption, a TWL network show a comparable trip completion rate as a TW network with turn pockets at intersection. Although the mean travel distance in the TWL network is about 30% higher than the TW network, its mean trip time is only 16% higher due to lower intersection delays. When disruptions take place, only TWL network is found to accommodate the most challenging ones in the central area due to its higher intersection efficiency and more evenly distributed traffic inside. The study also examined the impacts of various ITS-related strategies to provide drivers with advanced information on the disruption to mitigate its negative effects. The results revealed that providing information on disruptions that occur outside the most congested areas when vehicles start their trip might actually reduce overall network performance, since doing so may cause vehicles to reroute through heavily congested areas. For disruptions in the central region of the network, alerting drivers just one or two blocks upstream of the disruption can achieve similar delay reductions to broadcasting the disruption to 75% of road users.

Keywords: Urban traffic; grid networks; one-way streets; two-way streets; left turns; network resilience

Introduction

Motivated by the recent trend of converting historically one-way street networks back to two-way operation to revitalize urban centers (Dorroh & Kochevar, 1996; R. W. Lyles et al., 2000; Sisiopiku & Chemmannur, 2008; Walker et al., 2000), many recent studies have examined how street network configurations (specifically, the use of one-way or two-way streets) influence operational performance (DePrator et al., 2017; Gayah & Daganzo, 2012; Javier; Ortigosa et al., 2019; Javier Ortigosa et al., 2015). Under this context, planners begin to re-evaluate the negative impacts of one-way streets, such as neighborhood concerns regarding noise and safety issues from high-speed and high-capacity one-way streets (R. Lyles et al., 2000). It is also believed a conversion from one-way streets to two-way streets helps calm traffic, facilitates pedestrian and bicycle movements, and promotes economic activity in the area (Baco, 2009; Riggs & Appleyard, 2018; Speck, 2012; Walker et al., 2000). On the other hand, such conversions are believed to reduce traffic operational performance, as many studies concluded that one-way streets were more efficient than two-way streets since the former provides higher travel speeds and greater vehicle-moving capacities (Edwards, 1998; N Enustun, 1969; Meng & Thu, 2004; Murphy, 1950; Pline, 1992).

However, these early studies did not quantify how the higher travel speed and vehicle-moving capacity of one-way streets would be offset by the additional travel distance incurred. Several more recent studies have reconciled this discrepancy by leveraging the existence of well-defined relationships between traffic metrics aggregated across spatially compacted regions of networks (Geroliminis & Daganzo, 2007, 2008). These studies measured the efficiency of a network using the maximum rate that trips could be completed in a network, termed the trip-serving capacity, which combined both flow capacity and travel distance (DePrator et al., 2017;

Gayah & Daganzo, 2012; Javier; Ortigosa et al., 2019; Javier Ortigosa et al., 2015). The results revealed that one-way street networks only had higher trip-serving capacities than two-way street networks when trips were relatively long; when trips were short, the additional flow capacity was negated by the trip circuity one-way street networks imparted. Furthermore, these studies showed that two-way street networks could always be more efficient than one-way street networks if left-turns were restricted at intersections, which effectively reduced conflicts at intersections similar to that in one-way street networks while requiring less additional travel distance.

So far, relatively little attention has been paid to 1) comparison of different street network configurations during day-to-day disruptive events and 2) how technology can help mitigate the negative impacts of disruptive events in urban networks. There has been a large amount of work focusing on urban infrastructure resilience (Liu & Song, 2020), but almost all of them focus on wide-spread and long-lasting disruptions caused by nature disasters or other rare events, which fundamentally differ from the scope of this work. A recent study that involved both topics (Amini et al., 2018) tested the impacts of temporary disruptions in a two-way street network, but it did not compare among different street network configurations and only studied for a specific urban area (a 1km × 1km network in Sioux Falls). Others (Javier Ortigosa & Menendez, 2014, 2016) studied the impacts of link and lane removals inside grid networks. However, these works focus on permanent removals of road space and assumed users have good knowledge about the travel times on each link, which do not quite represent traffic behaviors when unexpected disruptions take place. More recently, one study examined the impact of both unexpected and expected disruptions on grid networks but only considered low demand scenarios and did not examine strategies to mitigate the negative impacts of the disruptions (Yu & Gayah, 2019).

[Table 1 here]

In light of this, this paper further compares the operational performance among different network configurations, namely two-way (TW), two-way without left turns (TWL), and one-way (OW), when disruptions take place. The networks are modeled in a microscopic traffic simulation environment where road users choose their routes based on their perceived link travel times. Aggregated traffic models are used as a tool to evaluate the operation of these network configurations and metrics such as network accumulation, trip completion rates, travel distances, and trip times are derived and compared. Some advanced travel management strategies that provide disruption information to a subset of users locally or globally are then tested and compared, since it has been shown that providing travelers with additional information can significantly improve their behavior (Chorus et al., 2010). The results of this paper provide insight into how street networks could be organized to provide better resilience to link disruptions and how information could be provided to travelers using ITS to mitigate the negative impacts of link disruptions.

The remainder of this paper is organized as follows. First, the simulation methodology and metrics used to evaluate network performance are described. Then, the experimental setup is presented, including network geometry, signal control settings and vehicle routing strategies. Next, the results of the simulation experiments are provided, which illustrate how disruptions impact the various street network types differently and how information can be used to mitigate some of the negative effects. Finally, some concluding remarks are provided.

Methodology

This section describes the experimental setup used in this paper to assess the operational performance of traffic networks under link disruptions, as well as the traffic performance metrics that were used to quantify overall network operation.

Simulation setup

The microscopic traffic simulation environment Aimsun was used to model network operations in both undisrupted and disrupted networks for this paper. Aimsun models each individual vehicle inside the network and can accurately describe traffic dynamics in urban areas, including intersection congestion and queue spillbacks, as well as vehicle routing decisions. The latter is critical since the performance of a network under disruptions would be impacted by how users detour themselves. The network was further validated to ensure that traffic dynamics – such as queue growth and dissipation – were reflective of realistic driving behavior. The remainder of this section provides details on the network geometry, traffic signal settings, and vehicle routing logic implemented in the microscopic traffic simulation environment.

Network geometry

All the experiments are performed using 10 by 10 grid street networks with 0.2-mile-long blocks. This structure was chosen since many actual urban street networks are grid-like in fashion. While perfect grid networks do not exist in reality, an idealized grid can reveal insights that are generalizable to a range of network structures and would serve as a “starting point” to understand more realistic networks that are less idealized in nature. Such a method has been employed in several studies related to street network design in the literature (Daganzo et al., 2011; DePrator et al., 2017; Gayah et al., 2014; Gayah & Daganzo, 2012).

In this idealized grid, each block is assumed to have two travel lanes. In the TW and TWL networks, one lane for each direction; in the OW networks, the two lanes are in the same direction. Additionally, parallel streets alternate directionality in the OW network so that the network maintains homogeneity; e.g., streets in the north-south direction alternate northbound and southbound travel moving west to east across the network, and vice versa. It is assumed that each lane shares the same traffic properties: a free-flow speed of 24 mph, capacity of 1200 veh/hr/lane, and jam density of 200 veh/mi/lane; see Figure 1a for the flow-density relationship assumed in this paper.

[Figure 1 here]

Origins and destinations in the networks were placed at mid-block locations to better represent how vehicles can enter and exit the network from internal driveways or garages. To ensure that all vehicles can reach their destination in each of the three network configurations, links on the outside-most ring of the network operate without any movement restrictions (i.e., are assumed to have two-way streets without any left-turn restrictions). Figure 1a provides an illustration the 10 by 10 network used in the simulation. Squares in the figure represent mid-block locations where entering and exiting links are connected to the street network. The shaded area in the center of the network represents the inner part where movement restrictions (i.e., one-way streets or left-turn restrictions) are applied. Although origins and destinations are only located in the inner part of the networks, external demands can be easily accommodated as well. Simulation tests reveal that the existence of external demands does not change the overall trends and results presented in this study and so are excluded without loss of generality. Note also that vehicles are assumed to be able to exit the network on the periphery as they arrive to the periphery boundary. This assumes that no congestion exists outside of the network boundary. This is a reasonable assumption when focusing on the performance of a dense urban center surrounded by a less dense suburban area, as is the case here. However, vehicles still suffer from internal congestion near the boundaries.

As will be revealed later, the TW network exhibits a much lower ability to serve vehicle trips (i.e., has a lower trip-serving capacity) than the TWL and OW networks and thus gets congested and even gridlocks at much lower demands. This is mainly attributed to the interruptions caused by the left-turning vehicles queuing at intersections. In order to provide a more meaningful comparison between the network types, a fourth configuration in which left-turn pockets are added to the two-way street network (designated TW-TP) is considered. The addition of left-turn pockets can effectively mitigate the queueing interference by physically separating left-turning vehicles so that they do not block other vehicles while waiting to traverse the intersection. However, since the intersections still operate with a two-phase signal timing plan, the turn pockets only provide extra storage space for the left-turn vehicles. Such treatments can be accommodated in urban areas through channelization at intersections. Figure 1b illustrates the layouts for the intersections in these network configurations.

Traffic signal settings

All intersections in the networks are assumed to be signalized and operate using a fixed two-phase signal plan with zero offset between adjacent intersections. Each of the two phasing groups, north-south and east-west movements, receives 27 seconds of green time and a 3-second yellow and all-red time is implemented between phases. Although coordination has been proven to improve traffic operation along a corridor, a recent study shows that it brings limited benefits when applied to a two-dimensional grid as operation improvement to one favorable direction brought by coordination can be offset by the operation degradation in conflicting directions (Girault et al., 2016). This is especially true when the traffic demand is homogeneous and there is no preferable coordination direction. In this work, homogeneous traffic demands are chosen to test the general performance of different network configurations, and therefore, such a zero-offset traffic signal setting is used.

Vehicle routing

Vehicles in the simulation experiments are assumed to route themselves to minimize their own perceived costs. The perceived link costs are updated every three minutes based on the experienced travel times on the links in the past six minutes. In the route choice process of each vehicle, the C-logit model (Cascetta et al., 1996) is used and a maximum of three alternative paths are allowed. When disruptions take place, the information is provided to vehicles by modifying their perceived cost of using the impacted links. Specifically, the disrupted link receives an arbitrarily large cost that effectively makes it unusable. Drivers aware of the disruptions will avoid the disruption at the beginning of their trip, while unaware drivers can only reroute when they arrive at the disrupted link or the congestion area caused by the disruption.

In Aimsun, all vehicles are tracked and their travel times on a specific link are grouped by their turning movements at the downstream intersection. In such a way, travel times for various turning movements can be more accurately captured in path cost evaluation. At the beginning of the simulation, an initial cost function evaluates the free-flow travel times on each link and generates an initial traffic assignment. After that, historical path costs on each link are evaluated at constant time intervals through a dynamic cost function to update the traffic assignments. For all the experiments in this paper, the cost functions are defined to accommodate vehicles of different knowledge levels about disruptions. When a disruption takes place on link l at time t, an arbitrarily large value M is assigned to its user-defined cost $C_{l,t}$ while the user-defined costs for the other links are zero. This extra cost is only included in the cost for vehicles with knowledge of the disruptions, so that they seek to avoid the link in advance. At a route level, the perceived cost of route r at time interval t for vehicle group g can be expressed as

$$cost_{l,t,g} = \sum_{l \in r} TT_{l,t-1} + C_{l,t-1} \times w_g \quad (1)$$

where g = vehicle group; 0 for no-prior-knowledge vehicles and 1 for prior-knowledge vehicles; $TT_{l,t-1}$ = experienced travel time on link l during time interval $t-1$; and, w_g = user-defined cost weight for group g; $w_0 = 0$ and $w_1 = 1$.

The C-logit model is chosen as the discrete route choice model in the experiments to avoid common problems in urban networks such as route oscillation and instability. In a C-logit model, the probability that path k is chosen among the paths between a certain OD pair, K_i, can be expressed as:

$$P_k = \frac{e^{\theta(V_k - CF_k)}}{\sum_{i \in K_i} e^{\theta(V_i - CF_i)}} \quad (2)$$

where θ is the scale factor in route choice, which is set to 5 in the experiments; V_i is the perceived utility for alternative path i, which is related to the perceived cost; and, CF_k is the commonality factor for path k, which is defined as:

$$CF_k = \beta \times ln \sum_{l \in K_i} \left(\frac{L_{lk}}{\sqrt{L_l \times L_k}} \right)^{\gamma} \quad (3)$$

Here, L_{lk} is the cost of common links in paths l and k, and L_l and L_k are the costs for paths l and k. Therefore, the commonality factor is a representation of the level of overlap for path k and the other alternative paths. β and γ are two parameters that determine the commonality factor value – with a larger β and a smaller γ, CF_k takes a larger weight in the path selection, which makes paths with lower overlapped proportions more likely to be used. In the experiments, β and γ are set to 0.15 and 1, respectively. Readers interested in the selection of the scale factor θ and commonality factor parameters β and γ are referred to (Yu, 2019) for more details.

Metrics to evaluate network operation

A disruption to a single link in a network can impact traffic operations in a large spatial area. Thus, two network-wide traffic performance measures, vehicle accumulation and trip completion rate, are used as a tool to quantify the operational performance of traffic networks both under complete and disrupted networks. Vehicle accumulation represents the total number of vehicles traveling inside the network at any given point in time. This metric is directly proportional to the average density of vehicles traveling along the links within the network and serves to quantify the level of congestion within the network. Larger values in vehicle accumulation represent more congested networks. Trip completion rate measures the rate that vehicles are able to reach their destination and exit the network. This measure quantifies the overall efficiency of a network and larger values represent increased efficiency.

In addition to these aggregated metrics used to quantify the network performance, two metrics are used to quantify the performance of a network from the road users' perspective: mean travel distance and mean trip time. The former represents the average distance vehicles travel to reach their destination, while the latter represents the average time required to complete the trips. Smaller values of both metrics represent improved operation from a vehicle perspective. For this paper, these metrics are normalized using the average block length (travel distance) and free-flow travel time of a single block length (travel time) for ease of comparison and understanding. When the network begins to get slightly congested, the mean trip time increases as the vehicles stay on their original paths but experience longer travel times. However, when the network gets more severely congested, vehicles begin to take routes with longer travel distances to help mitigate this increased travel time, and this results in increases to both mean trip time and mean travel distance. Please note that these two metrics are directly tied to more aggregate metrics of network performance – such as vehicle miles traveled (VMT) and vehicle hours traveled (VHT) – since the total demand in the network is kept constant. Thus, relative changes in mean travel distance and mean trip time would reflect the relative changes in VMT and VHT, respectively.

Network operation with and without disruptions

This section first provides a brief comparison among TW, TW-TP, TWL, and OW networks when they operate without link disruptions. The operational metrics measured from these experiments are later used as baselines to evaluate the impacts of link disruptions on each network configuration.

Each experiment in this work lasts 180 minutes. The first 120 minutes represent a loading period in which vehicles enter the network with increasing traffic demands over time. This is follows by a 60-minute period with no demand (unloading), which allows most vehicles to reach their destination if the network is not gridlocked. In all experiments, the same homogeneous traffic demands are loaded onto the networks at an increasing rate: in the first 30 minutes, trips are generated at 15,000 veh/hr; from 30 to 60 minutes, the traffic demand is increased to 20,000 veh/hr; and finally, the traffic demand is further increases to 25,000 veh/hr from 60 to 120 minutes. After that point, no new trips are generated in the network. To achieve more reliable results, five replications are run for each tested scenario and their results are averaged and presented in this paper.

Operation of non-disrupted networks

First, the networks are compared under regular operation without any disruption inside. Figure 2 presents the accumulation/trip completion rate over time and the relationship between accumulations and trip completion rates. This relationship is referred often as the Network Exit Functions (NEFs. Much like the fundamental diagram of a link, the NEF describes the productivity of a network (trip completion rate) as a function of its congestion level (accumulation).

[Figure 2 here]

The NEF reveals that the TW network has a significantly lower trip-serving capacity than the other network configurations and cannot accommodate even the lowest traffic demand. From the beginning of the experiments, the trip completion rate in the TW network is constantly lower than the traffic demand (15,000 veh/hr), which causes accumulation to slowly increase within the network. When the demand increases to 20,000 veh/h at 30 minutes, the trip completion rate in the TW network did not increase and therefore the accumulation begins to increase more rapidly. Eventually, the network begins to fail after its accumulation exceeds about 5,000 vehicles, as the trip completion rate gradually drops to just 5,000 veh/hr at the 120-minute mark. This failure in the TW network is attributed to the inefficient intersections. Compared to the TWL and OW networks, the TW network has many more potential conflicts at intersections. Left-turning vehicles waiting for a gap in the opposing traffic stream to traverse the intersection can queue, blocking the intersection and keeping through-moving or right-turning vehicles from discharging during the green. Note that this can be somewhat mitigated by implementing dedicated left-turning phases. However, doing so increases the lost time at the intersection during which no vehicle can discharge, which also reduces intersection capacity.

The other three networks perform much better than the TW network. The OW network exhibits a lower capacity than the TW-TP and TWL networks. During the unloading process, the OW network also takes longer to empty, since vehicles must travel longer distances in the OW network due to the circuity caused by its movement restrictions. The TWL network performs well. Even at the highest demand level, it stabilizes in accumulation at about 110 minutes. In comparison, accumulation in the TW-TP network slowly increases at the highest demand level until the unloading process begins, indicating the highest demand level slightly exceeds the capacity of the TW-TP network. Since the TW network exhibits a significantly lower capacity than the TW-TP, TWL and OW networks, the TW network is eliminated in the following experiments.

Table 2 provides the four operational metrics inside the networks derived at three specific points in time corresponding to the demand rate changes, which can be used as a baseline for comparison when disruptions take place inside the networks. At the 30-minute and 60-minute time marks, the TW-TP network outperforms the other two networks with lower accumulation, mean travel distance, and mean trip time, since it is the most flexible network and vehicles can reach their destinations in the most efficient manner. The performance of the TWL and OW networks are similar. Vehicles in these two networks require extra travel distance on average because of the respective movement restrictions. It should be noted that the TWL network is different from the other two networks as there is generally only one shortest path between any OD pair in this network configuration (Yu & Gayah, 2019). The OW network, on the other hand, offers several alternatives for most OD pairs despite its long travel distances. At the 120-minute time mark, the TW-TP network exhibits the highest increases in mean travel distance and mean trip time, but these values are still lower than the ones from the TWL and OW network. It should be noted that the mean travel distance in the TW-TWP network is 23% lower than in the TWL network while the gap in mean trip time is only 16%, indicating a higher travel speed inside the TWL network.

[Table 2 here]

Operation of disrupted networks (without any treatment)

Results in the previous subsection provide baselines of operation in the networks, and their performance under link disruptions are now examined. In this work, disruptions are assumed to obstruct through movement on half of one block. To better understand how the location of a disruption might influence overall network operations, effects of disruptions are tested iteratively on each individual block. Disruptions are assumed to be unexpected events that road users are unaware of ahead of time. Therefore, road users do not intentionally avoid the impacted links in their route choice and will only detour after they reach the disruption or in response to the congestion that is causes. Traffic conditions under this assumption is referred to as the no-treatment scenario later. As expected, the detour traffic brings severe challenges to the operation of links near the disruption and quickly results in local congestion. If not addressed properly, the congestion can quickly spread across the network.

Figure 3 illustrates the impacts of the disruptions on the various operational metrics as a function of the disrupted link using heat maps. The shading of each link in these heat maps indicates the outcome when a disruption takes place on that specific link. A darker shade means a more severe degradation with higher accumulation, lower trip completion rate, and longer travel distances and trip times, while a lighter shade represents a less severe impact. The numbers presented in the figures provide the absolute and relative change (in parentheses) in each metric when compared to the base case for that network configuration without a disruption present. As a summary, Table 3 provides the mean and standard deviation (in parentheses) values for the metrics aggregated over disruptions on each link.

[Figure 3 here]

[Table 3 here]

In the TW-TP network, disruptions near the network center result in the most severe impacts with up to about 20% increase in mean travel distance and about 62% increase in mean trip time at the 120-minute mark compared to the no disruption case. This indicates that these central disruptions cause severe congestion inside the network. It appears that with the heavy detour traffic in the busy area, the inefficient intersection operation in the TW network can no longer be offset by the additional storage space offered by the left turn pockets. Spillover of the turn pocket soon blocks the travel lane and causes spreading congestion in the network.

In the TWL network, the impacts of disruptions are less sensitive to their locations. Unlike the TW-TP network, disruptions on some links near the boarders of the TWL network result in relatively severe network operation degradation. After examination of the traffic patterns, most sections in the TWL network carry a similar amount of traffic when the two travel lanes are combined, but those sections near the boarders have more unbalanced directional traffic demands due to the left-turn restrictions at intersections. As a result, disruptions on these links can cause relatively severe impacts as well. Although the network center is still the most vulnerable area in the TWL network, the operation degradation after disruptions in the area is relatively small.

The OW network appears to operate somewhere between the performances of the TW-TP and TWL networks. The movement restrictions inside the network help better distribute the traffic in the network so the impacts of disruptions are more even across links, but the network center is still the most vulnerable area since it carriers the highest traffic demands. Compared to the TW-TP network, intersections in the OW network operates more efficiently, and therefore, the OW network is less impacted when disruptions take place.

In all network configurations, particularly in the TW-TP and OW networks, cases exist in which disruptions near the network boundaries actually reduce network accumulations and mean trip times compared to the baseline cases without disruptions. This is because both the TW-TP and OW networks offer some level of redundancy in routing; thus, some of the vehicles encountering the disruption are able to detour easily without having to travel a longer distance. Additionally, links near the borders of the TW-TP and OW networks generally carry less traffic, so disruptions on these border links do not generally contribute to congestion. Disruptions in this case actually provides a chance for more frequent re-assignment based on more recent traffic information, which can lead to improvement in overall network operations in these more flexible networks. By contrast, the TWL networks offers little to no redundancy in routing. Only one shortest path exists between any OD pair, so link disruptions always cause a subset of vehicles to travel longer distances, and this contributes to increased congestion when disruptions occur. Thus, disruptions in the TWL network almost always cause degradation in network operation, no matter where they occur.

Impacts of information provision

As indicated by the previous results, disruptions can bring severe impacts to network operation if the road users are unaware of these unexpected events ahead of time. Especially, the TW-TP and OW networks suffer greatly when disruptions occur in the central portion of the network. Since central links generally carry heavy traffic volumes, the detours caused by vehicles arriving to a disrupted link can create congestion on detour links and this congestion can propagate to nearby links as well. This section quantifies how various information provision strategies can help mitigate the impacts of disruptions inside the different networks. First, an ideal scenario where all road users know about the disruptions is tested as a baseline. Then two sets of information provision strategies targeting a subset of road users are tested and compared.

Information provided to all vehicles

First, an ideal case is tested where the disruption information is available to all road users inside the networks. In this scenario, all road users are made aware of the disruption at the start of their trip so they can incorporate its presence in their route choice. When disruptions take place in the central portions of the networks, this information should prevent vehicles from unnecessarily entering the busy network centers and avoid concentrated detours near the disruption. Figure 4 illustrates the changes in the operational metrics when disruption information is sent to all road users in the network. The shades indicate the absolute and relative differences (in parentheses) of the operational metrics compared to the no-treatment case when that specific link is disrupted. A lighter shade indicates operation improvement with lower accumulation, travel distance, and mean trip time and higher trip completion rate.

The TW-TP network by far benefits the most when information is available for link disruptions near the network center, as indicated by significant reductions accumulation, mean travel distance, and mean trip time. The observation is attributed to the flexibility in the network configuration that offers multiple shortest-distance routes available between most OD pairs. Although a high number of vehicles use the central area in the TW network, many of them can detour to other alternatives without increasing the distance that they must travel. Provision of information does not improve the operation in the TWL and OW networks as significantly as in the TW-TP network, but still benefits the networks the most for disruptions in the centers.

It should be noted that in the TW-TP and OW networks, there are a significant proportion of links outside the network centers where prior information about the disruptions leads to a degraded operation performance. This suggests that information of the disruption might reduce the overall network efficiency. A comparison of the experiment outputs in these cases reveals the reason for this counterintuitive behavior. When road users are unaware of these border disruptions ahead of time, they only take local reroute near the disruption and therefore the negative impacts associated with the disruption remain outside congested network centers. When information on the disruption is available, the road users are more likely to detour early and travel through the busy central areas of the network, which harms overall network operations. Thus, it might be better to keep the information about disruptions from road users in these network configurations when the disruptions take place outside the network centers.

[Figure 4 here]

Information provided to a subset of users

As information provision is proven helpful in mitigating impacts from disruptions, some more realistic disruption notification strategies targeting a subset of road users are further tested. The strategies are categorized two groups according to their coverage: local and global notifications.

Local notifications refer to those set up near the disruption so that the road users can be made aware of the disruption as they get close to the disruption. The most common application in real world would be the use of variable message sign (VMS) near the disruption. Figure 5 uses a small area to illustrate the placement of VMS when disruption takes place. Without any mitigation strategy in place, unaware vehicles learn of the disruption information when they arrive to the disrupted link (i.e., reach the orange hexagons) and only then start to detour. VMS placed further away from the disruption (green stars for one intersection away, purple squares for two intersections away) can help vehicles learn of the disruptions earlier and potentially avoid the most heavily impacted area.

[Figure 5 here]

Global notifications refer to those strategies with a potential to inform the road users everywhere in the network. An extreme case of such a strategy was tested in the previous subsection in which all road users are aware of the disruptions ahead of time. Here, the global strategies assume that some fractions of vehicles are made aware of the disruptions ahead of time. In the real-world, this global notification strategy might represent the case in which some portion of vehicles have in-vehicle navigation systems with real-time disruption information.

Five sets of disruption mitigation strategies are tested in the networks: two VMS experiments where they are placed one intersection and two intersections away from the disruption and three broadcasting experiments with 25%, 50%, and 75% penetration rates. From the previous experiments, provision of information is the most beneficial for disruptions inside the 4×4 area near the network centers. In the TW-TP and OW networks, sometimes information provision reduces network efficiency when disruptions take place outside the area. Therefore, these disruption notification strategies are tested for disruptions in the 4×4 area near the network centers and the resulting mean trip times derived at the 120-minute mark are averaged and presented in Figure 6. For each of the networks, the no-treatment case and the perfect information case with 100% broadcasted road users are labeled as lower and upper bounds. The results from the VMS strategies are labeled with blue diamonds while the ones from the broadcasting strategies are labeled with orange squares.

[Figure 6 here]

It is interesting that the efficiency of the mitigation strategies varies in different network configurations. In the TW-TP network, placing VMS only at local locations (one intersection away) turns out to achieve a similar effect as broadcasting the information to 50% of road users. This can be explained by the flexibility in the TW-TP network. Knowing about the disruption just one intersection in advance allows road users to make the appropriate detours due to this network's routing flexibility. While the OW network provides routing redundancy as well, it is much less flexible than the TW-TP network. Thus, the OW network only marginally benefits from VMS placed one intersection away. However, placing VMS two intersections away from the disruption in the OW network is much more effective and even outperforms the 75% broadcasting case. This is reasonable since periodicity of the movements allowed in the OW network repeats every two blocks. Road users only have the ability to travel in multiple directions and make appropriate detours when information of the disruption is provided at least two intersections in advance. In the TWL network, placing VMS two intersections away from the disruption achieves similar operational improvements as 50% broadcasting, which appears to be less effective than in the other two networks. This is because the TWL network lacks redundancy and detouring is also difficult because of the turn restrictions. Since there is only one shortest path between each OD pair in the TWL network, any detour en-route, even if notified a few intersections early, leads to extra travel distances and travel times.

Concluding remarks

This paper uses a microscopic traffic simulation environment to study the traffic operation in different street network configurations with and without the existence of link disruptions. Different information environments are tested when link disruptions take place inside the network to seek mitigation of the negative impacts. Among the network configurations tested in this work, the TW network is the most flexible and redundant, but is naturally inefficient because of the conflicts at intersections. Even at the lowest demand level, the accumulation in the TW network continues to grow and the network soon gets congested. To ensure more meaningful experiments, a modified TW network with extra storage space for the left-turning vehicles, TW-TP, is introduced and compared with the TWL and OW networks. When the networks operate without disruptions, the TW-TP network outperforms the other two networks with the lowest travel distances and trip times. It should be pointed out, though, that the TW-TP network might require extra land allocation and therefore this is not a very fair comparison. However, even with the extra turn pocket, the TW-TP network only slightly overperformance the other two networks.

When disruptions take place, both the TW-TP and OW networks undergo severe operation degradation when disruptions take place in the central areas of the network. The turn pockets in the TW-TP network do not appear to slow down the spread of congestion under disruptions. However, TWL network is able to accommodate these disruptions due to its higher efficiency, which is attributed to its efficient intersection operation while lower travel distances than the OW network. Although the TWL network is the least redundant in terms of routing (only one shortest distance route is available between any OD pair), the central area of the TWL network does not assume as much traffic as the other two networks. Thus, it has more spare capacity to accommodate detour traffic when disruptions do occur, even though they cause vehicles to travel extra distance.

To minimize the impacts of disruptions, ITS strategies are tested that provide disruption notifications to road users. It is observed that providing information on disruptions outside the central area of the network generally causes traffic to detour through the already-congested central areas, and thus harming overall network operations. Therefore, perhaps counterintuitively, it is not beneficial to notify all users of these disruptions ahead of time. For disruptions in the central region of the network, placing VMS one intersection away from the disruption in a TW network is proven effective as it allows vehicles to make proper detours in the flexible and redundant network. In the OW network, VMS needs to be placed two intersections away to allow efficient detours of the traffic because of the periodicity of the movement restrictions. In the TWL network, however, VMSs are not ideal due to its lack of redundancy and difficulty in re-routing after selecting a route at the origin. Instead, information should be provided to road users at their origin to help mitigate the negative impacts of the disruptions.

These results contribute to the growing body of the knowledge on the operational performance of different street network configurations by considering how they perform under disruptions. The study of link disruptions is critical as disruptions occur for a myriad of reasons, including both those planned (e.g., work zones) and unplanned (e.g., traffic incidents). The analysis here can also help city planners and engineers understand the impacts of street network conversion in downtown areas by illustrating how performance of one- and two-way street networks change under disruptions scenarios (i.e., its resilience).

All the experiments in this paper are conducted in uniform grid networks with relatively simple signal control strategies. Grid networks are fairly general and often serve as the basis for many urban traffic networks in the United States and around the world. Previous studies (Daganzo et al., 2011; DePrator et al., 2017; Gayah et al., 2014) have shown that results obtained from grid networks provide generalizable insights that can be used for more realistic street networks. Thus, while magnitude of specific impacts might vary in more realistic networks, the general findings and conclusions are robust. Nevertheless, future work should confirm that the trends found in this work hold in less idealized network structures or in networks that have a combination of one- and two-way streets. In addition, it is worthwhile to experiment with more complicated signal timing strategies for the TW networks. In this work, turning pockets are added to the TW networks as otherwise they would have far lower network capacities compared to the other two networks. However, the turning pockets might not be fully utilized due to the lack of dedicated left turn phases.

Another interesting direction for future study is to create a comprehensive network evaluation framework where various aspects of transportation operation, such as efficiency, resilience, safety, and emission, etc., can be considered together. These impacts have been assessed to various degrees. For example, the safety impacts of one-way streets are not clear in the literature. One early study (Nejad Enustun, 1969) found an increase in various crash type frequencies after a two-way to one-way street conversion. Later studies indicated that the fewer conflicts at one-way streets reduce crash frequencies (Hocherman et al., 1985; Stemley, 1998), while others found that one-way streets may pose a threat to vulnerable road users due to higher speeds and conflicts coming from unexpected directions (Swift et al., 1998; Tindale & Hsu, 2005; Wazana et al., 2000).

Acknowledgements

This research was supported by NSF Grant CMMI-1749200

Declaration of interest statement

The authors have no relevant interest(s) to disclose.

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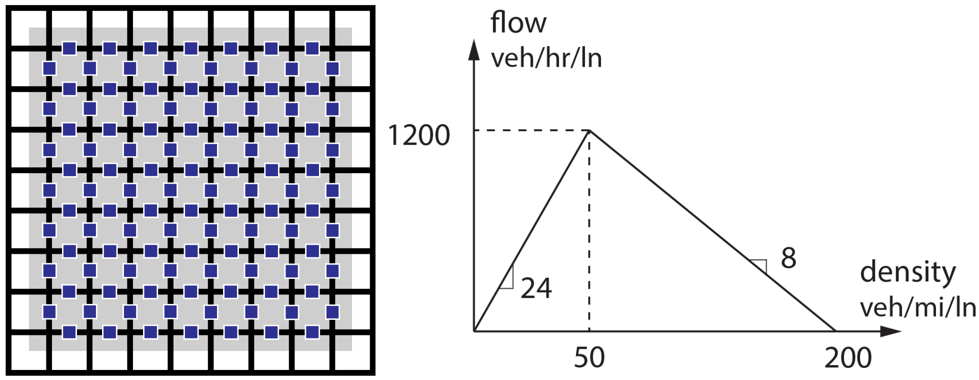
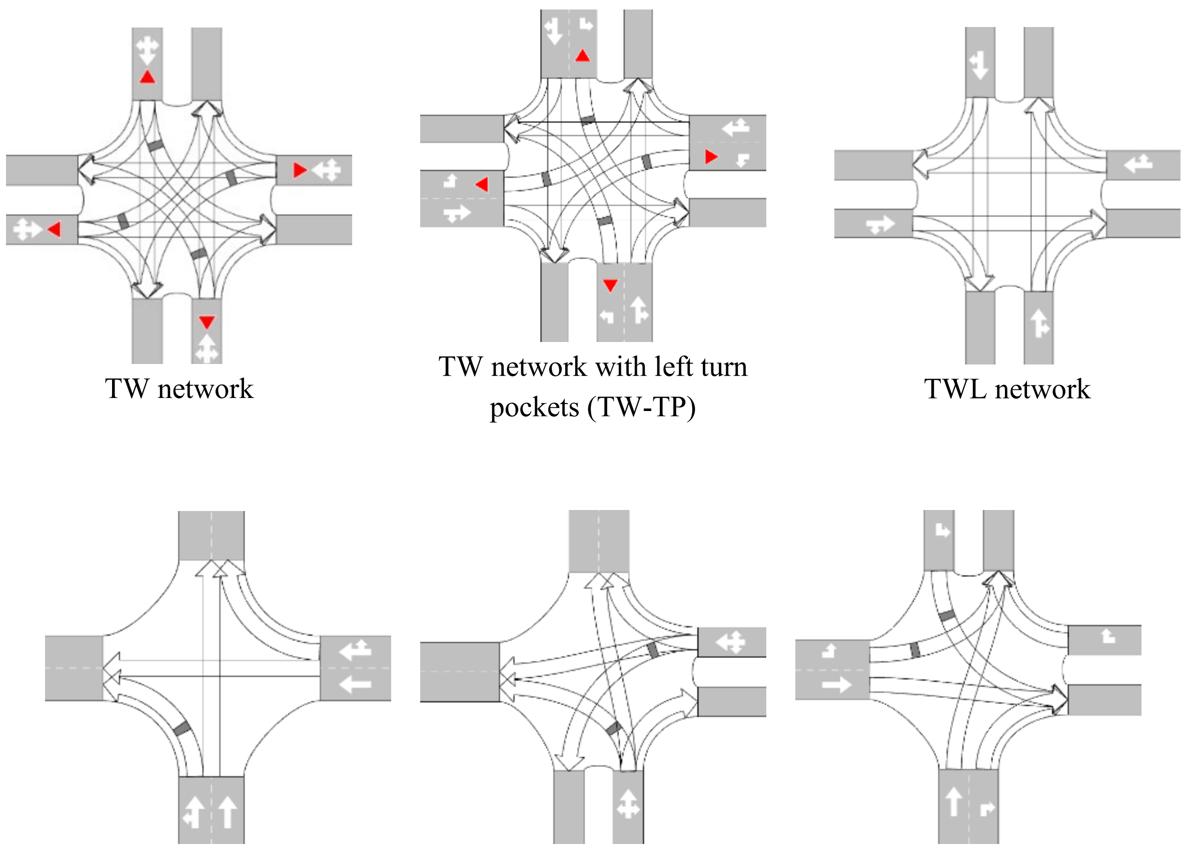
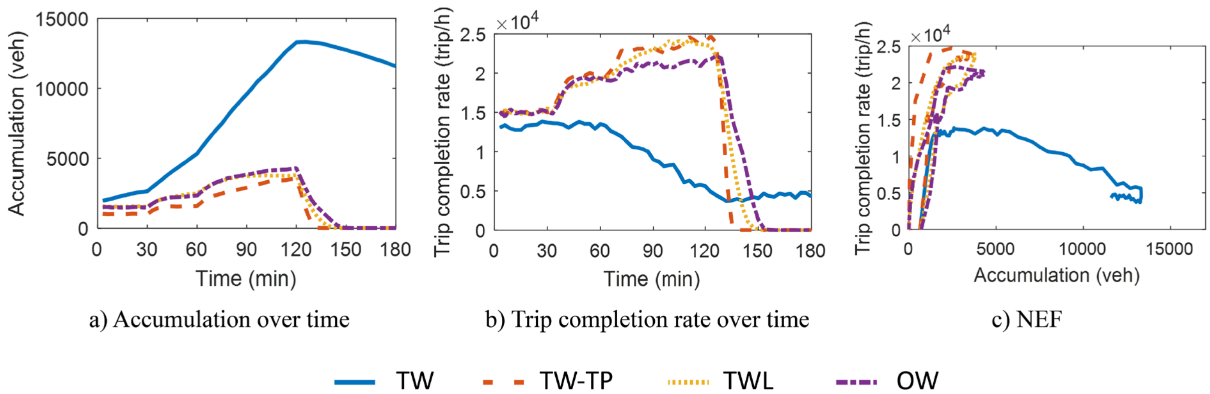


a) network setup and fundamental diagram of a lane



b) intersection layout in microscopic simulation

Figure 1 Basic network information



a) Accumulation over time b) Trip completion rate over time c) NEF

Figure 2 Network operation without disruptions

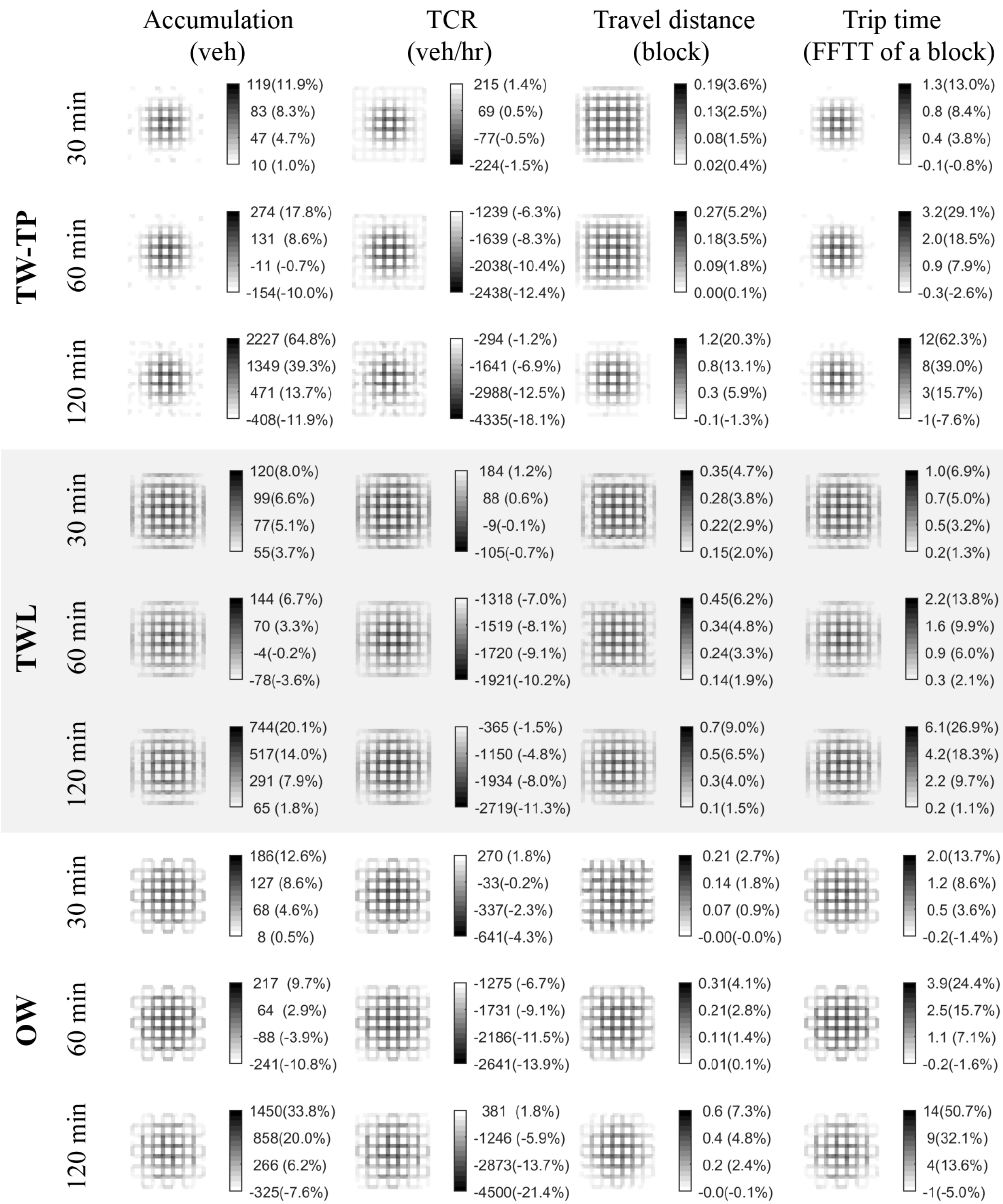


Figure 3 Network operation after link disruptions

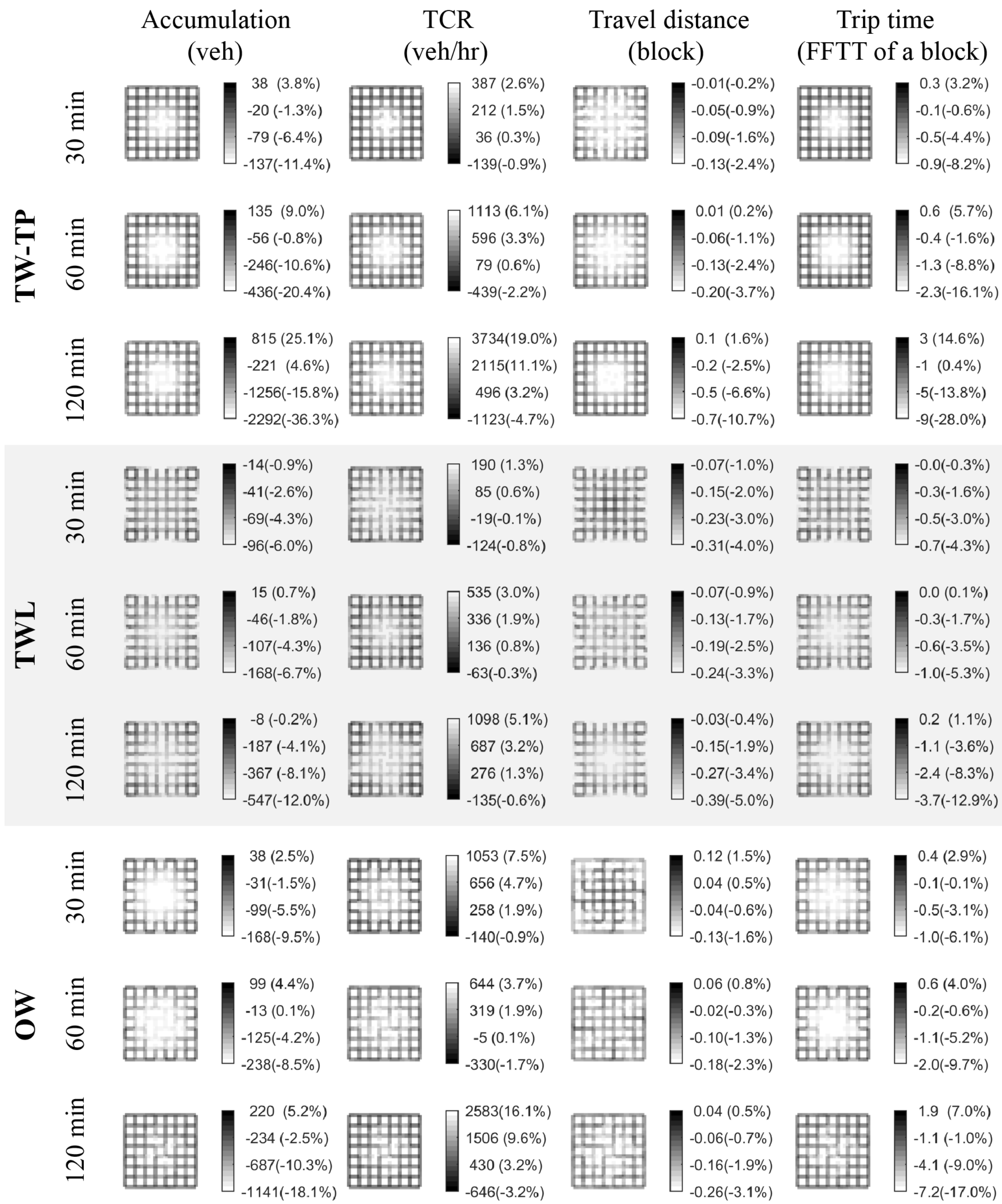


Figure 4 Network operation change after disruption is broadcasted to road users

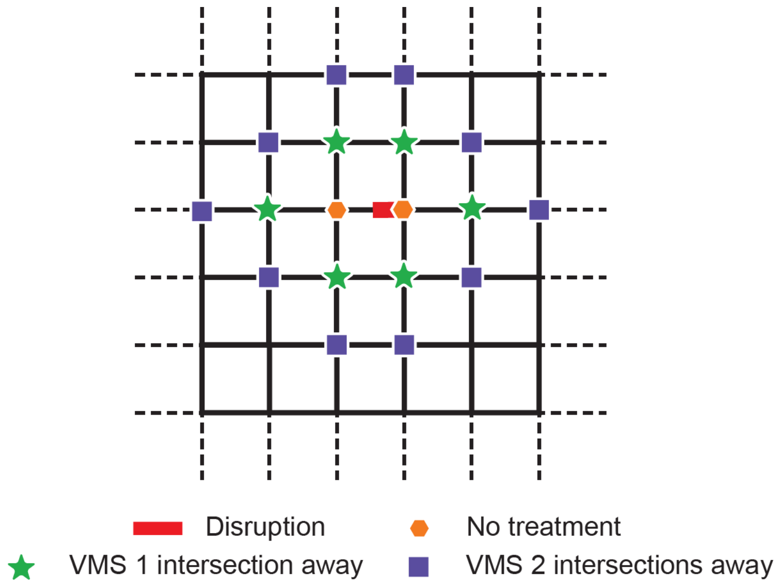
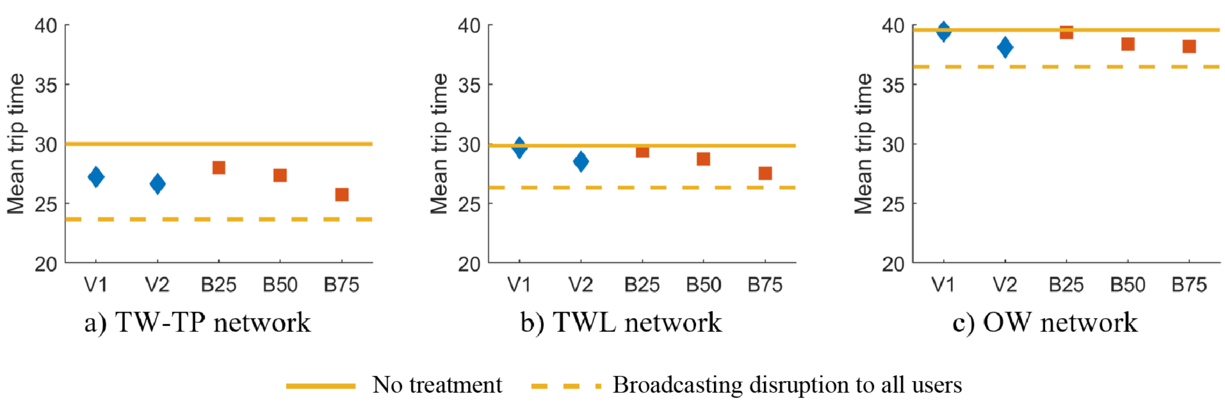


Figure 5 Placement of VMS for early notification



V1(2): VMS placed 1(2) intersection(s) away from the disruption;
B25(50/75): broadcasting disruption to 25% (50% / 75%) of road users

Figure 6 Mean travel times under different information environments

Table 1 Recent studies on network configuration comparisons using aggregated performance metrics

Work	Method and case study	Major findings	limitations
Gayah & Daganzo, 2012	Analytical; idealized grid networks	OW networks are not necessarily more efficient than TW networks when average trip lengths are short. Especially, TW networks without left turns always have higher trip-serving capacities than OW networks.	This work is based on purely analytical results and disruptions are not considered.
Ortigosa & Menendez, 2014	Micro simulation; idealized grid networks	Grid networks are resistant to link removals to some extent because of its excellent route redundancy and interconnectivity; overall, link removals in network center cause the most significant traffic impacts.	These two papers study permanent link/lane removals so that the road spaces are returned for other usage. Therefore, road users are expected to know the changes and the route choice is different from disruption scenarios.
Ortigosa & Menendez, 2016	Micro simulation; idealized one-way grid networks	Lane removals in network centers cause much more severe capacity drops than in network perimeters; however, after the initial capacity drops, further lane removals cause limited impacts in the network.	
Ortigosa et al., 2015	Micro simulation; idealized grid networks	TW network generally shows lower NEF functions compared to OW and TW networks without left turns; the performance of the latter two networks is highly dependent on traffic assignment logics (i.e., how traffic is spread out).	These two papers compare the operational performance of different street network configurations. However, disruptions are not considered.
Ortigosa et al., 2019	Analytical and micro simulation; idealized grid networks	TW network has shortest travel distance; OW network has highest intersection capacity; TW without left turns provide an ideal compromise but lacks route redundancy.	
DePrator et al., 2017	Analytical and micro simulation; idealized grid networks	Prohibiting left turns at intersections improves trip completion rates when the network is operating near capacity, but not when the traffic is light or heavy. Dynamic signal timings that only ban left turns when network is near critical accumulation helps address the downside.	Only TW networks with and without left turns are tested in this work. Disruptions are not considered.

Amini et al., 2018	Micro simulation; small network in Sioux Falls	Impacts of link closures can be significantly mitigated when a small proportion of vehicles (15%) get updates about road closures and re-route based on real-time link travel times.	This work uses a small real-world network and only tests a single mitigation strategy.
Yu & Gayah, 2019	Kinematic-Wave Theory-based model; idealized grid networks	OW networks show the highest capacity during disruptions due to its high link capacities and efficient intersection operation; TW network without left turns suffer the most from disruptions that road users are not aware of in advance, due to the difficulties in rerouting.	Model used in this work has limited options for routing and intersection control. Only two information scenarios (prior-knowledge vs no-prior-knowledge) are tested.

Table 2 Operational metrics without disruptions

		Accumulation (veh)	TCR (veh/hr)	Mean travel distance (block)	Mean trip time (FFTT of a block)
TW-TP	30 min	1004	14899	5.24	9.81
	60 min	1533	19642	5.18	10.93
	120 min	3435	23932	5.78	19.45
TWL	30 min	1498	14960	7.49	14.68
	60 min	2257	18844	7.23	15.73
	120 min	3698	24059	7.49	22.70
OW	30 min	1476	14934	7.75	14.38
	60 min	2237	19015	7.57	15.86
	120 min	4294	21029	7.68	27.46

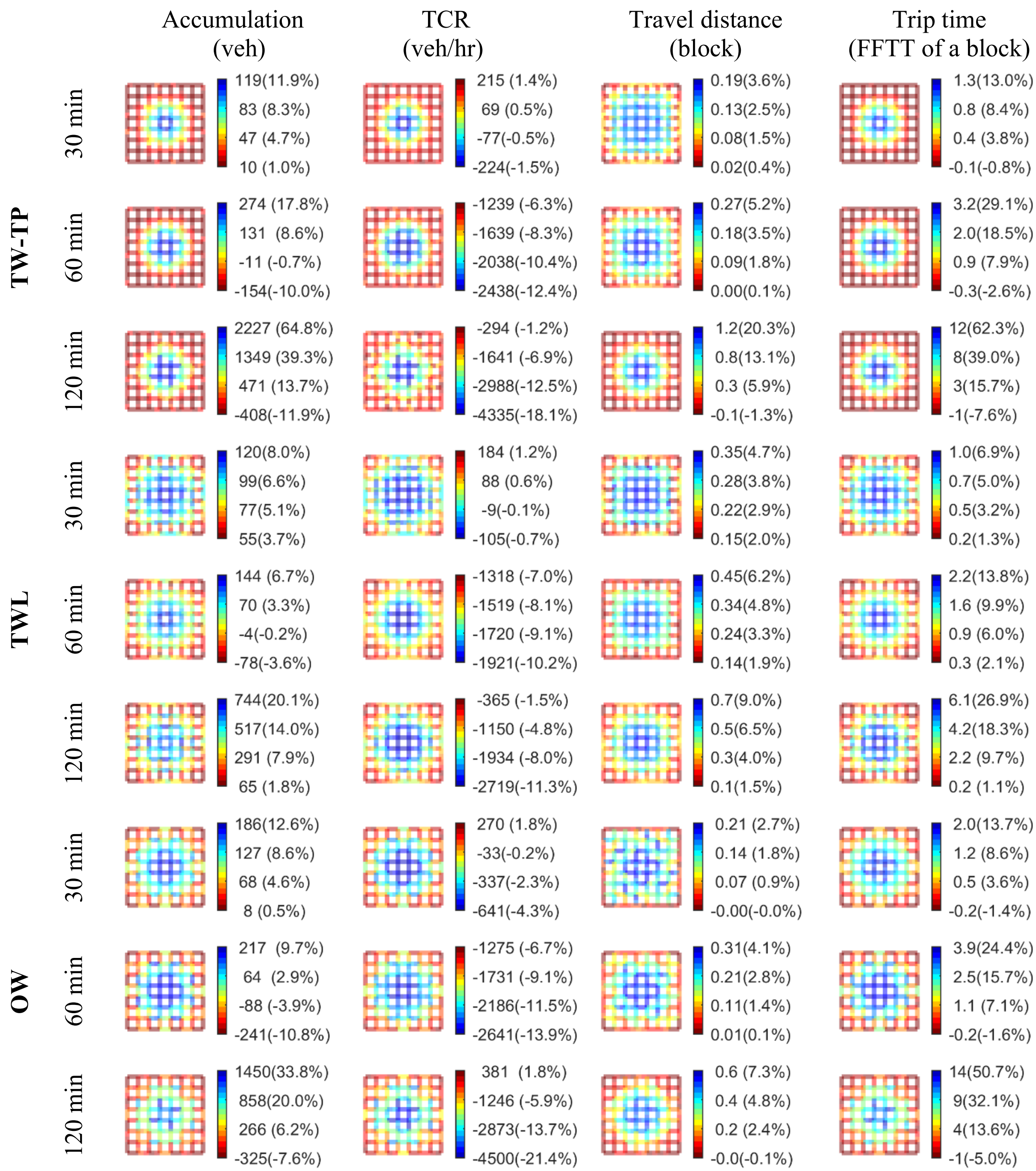
Table 3 Operational metrics after link disruptions

		Accumulation (veh)	TCR (veh/hr)	Mean travel distance (block)	Mean trip time (FFTT of a block)
TW-TP	30 min	1044 (49)	15000 (114)	5.35 (0.05)	10.05 (0.38)
	60 min	1658 (194)	19441 (421)	5.33 (0.08)	11.69 (1.10)
	120 min	4133 (925)	22555 (1233)	6.11 (0.35)	21.77 (3.83)
TWL	30 min	1596 (31)	14989 (87)	7.76 (0.06)	15.34 (0.25)
	60 min	2467 (77)	18555 (211)	7.55 (0.09)	17.10 (0.50)

	120 min	4111 (216)	22877 (731)	7.86 (0.15)	25.57 (1.78)
OW →	30 min	1603 (96)	14780 (325)	7.86 (0.07)	15.20 (0.69)
	60 min	2494 (183)	18515 (541)	7.75 (0.09)	17.85 (1.38)
	120 min	4880 (567)	19466 (1525)	7.89 (0.16)	31.92 (4.19)

Appendix

Color-scaled version of Figure 3



Color-scaled version of Figure 4