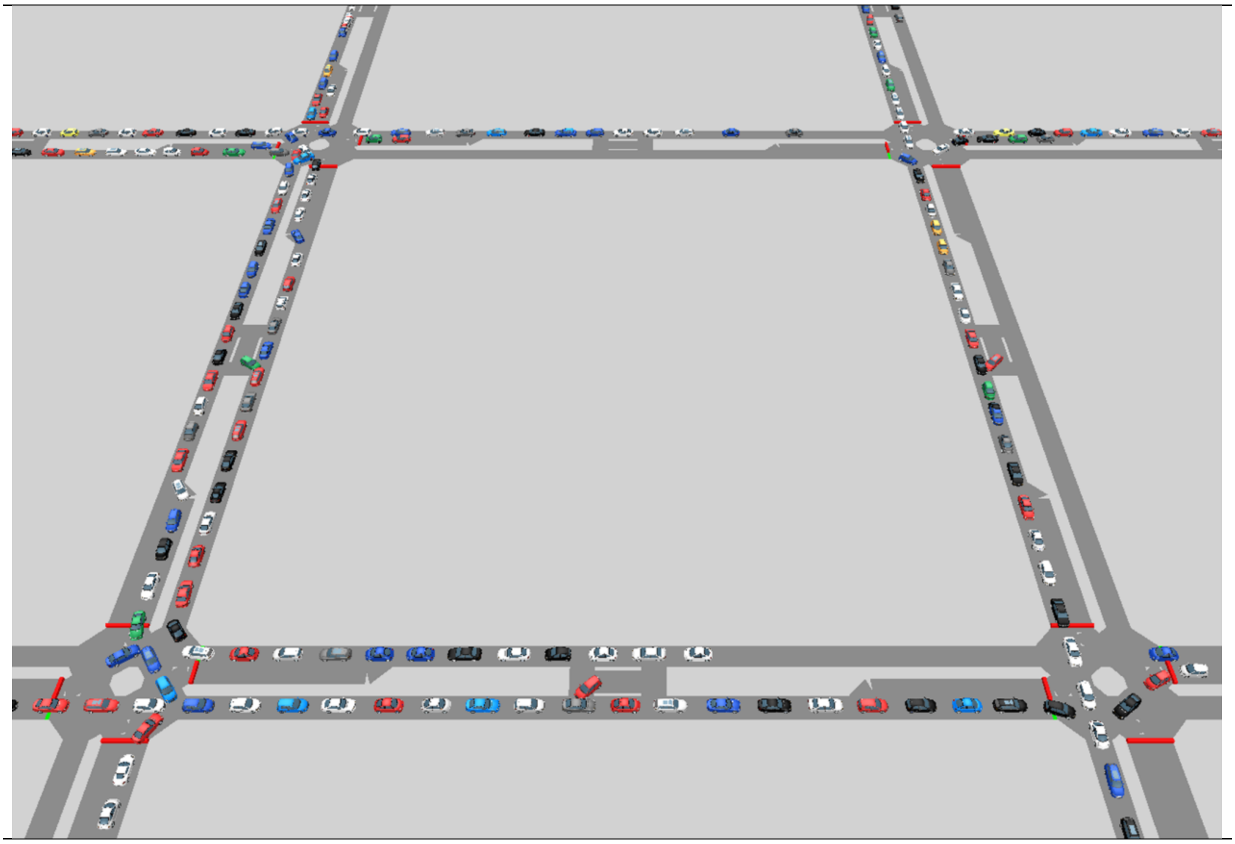

Dynamic properties of grid urban networks

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Abstract

Urban grid networks might present different ways to structure streets and consequently, traffic, might be accommodated differently. In the present paper, we analyze three grid configurations: two-way streets, two-way streets with prohibited left turns, and one-way streets. We simulate traffic in them with the micro simulation software VISSIM and we distribute trips employing the dynamic traffic assignment integrated in it. In this way, we are able to analyze the dynamic behavior of traffic. Typically, in static simulations, oversaturated links or intersections have really large delays but these delays, contrary to what happens in reality, do not affect other links. We are interested in understanding which configuration is more resilient to the propagation of congestion, and this cannot be seen when employing static models. In addition, the static simulations provide macroscopic indicators such as the total travel time or the total travel distance. However, the dynamic perspective provides a new set of indicators to evaluate our networks, and we are especially interested in using the Macroscopic Fundamental Diagram (MFD) as one of them. The MFD is a traffic monitoring scheme that determines the upper bound of network traffic states relating trip production rate and density of trips. Our goal is to generate MFDs in the different networks and to employ it as indicators of the network performance. Depending on the MFD shape, networks might have different properties when dealing with traffic. In this paper, we discuss this issue by comparing the three different urban grid configurations.

Keywords

Traffic operations – MFD – network modeling – DTA – grid – urban planning.

1. Introduction

Urban grid networks might present different ways to structure streets and consequently, traffic, might be accommodated differently. Defining the optimal street network layout is a controversial among traffic engineers and urban planners. Even for basic cases, e.g. one-way or two-way streets in grid urban networks, there are many authors advocating for one or another configuration (Hocherman et al., 1990; Stemley, 1998; Walker et al. 2000, Lyles et al. 2000, Tindale and Hsu, 2005) because there are many other factors besides traffic that can be decisive (e.g. safety, land use). But even, in strictly traffic analysis cases, there is also some discrepancy (e.g. Walker et al. 2000; Meng and Thu, 2004; Gayah and Daganzo, 2012; Boyles et al. 2014).

In a recent study, Ortigosa et al. (2014) analyze in detail the pros and cons of 3 different street network layouts: two-way streets (TW), two-way streets with prohibited left turns (TWL), and one-way streets (OW); in urban grids. They employ analytical formulations for non-congested scenarios, and a static traffic assignment for congested scenarios. Their conclusion is that TWL networks offer the best trade-off between distance travelled and capacity in intersections for most of the cases (see routing in Figure 1). However, the low redundancy of routing that TWL networks have (they only provide one shortest distance path between two nodes) makes them very susceptible to congestion. Ortigosa et al. (2014) did not account for the spill-overs and dynamics of traffic because the assignment method was static.

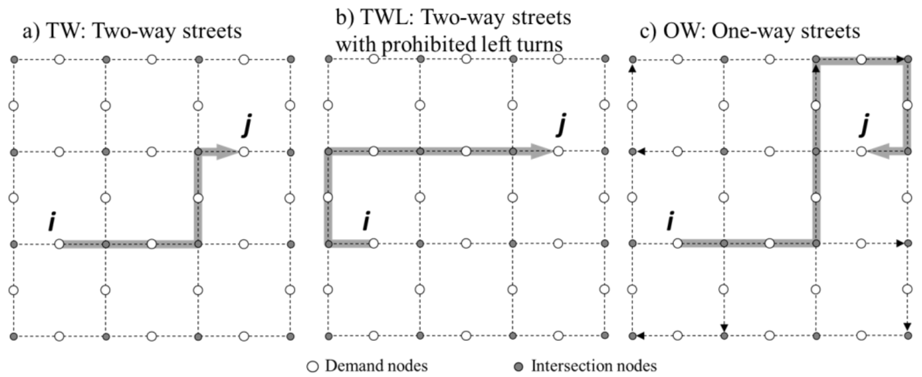

Figure 1. The three networks and their routing options (Ortigosa et al., 2014)

In this paper, we aim at following this previous study by analyzing the effects of the dynamics of traffic in these networks employing a dynamic microscopic simulation software. Our goal is to compare the 3 different networks employing a unique indicator that is able to depict the congestions effects. For this purpose, we use the Macroscopic Fundamental Diagram (MFD). In addition, we also employ other indicators to support our conclusions.

The MFD (or Network Fundamental Diagram, NFD), has been widely used in traffic research (Geroliminis and Daganzo, 2008; Daganzo and Geroliminis, 2008). It is an aggregate relationship between the number of trips ending in a network and the accumulation of vehicles that the network has. Many of the research proofs that this relationship exists have been done by using microscopic simulations, e.g.: San Francisco, CORSIM (Geroliminis and Daganzo, 2008); Athens, AIMSUM (Keyvan-Ekbatani et al., 2013); Zürich, VISSIM (Ortigosa et al. 2013). In this paper, we are generating the MFDs of abstract grid networks with uniform demand (every demand node exchanges the same amount of trips with the other demand nodes) and assigning traffic using the dynamic traffic assignment (DTA) module included in VISSIM.

The MFD was conceived as a macroscopic traffic control scheme, if it is possible to know an overall state of congestion of a network for a certain time interval at real time, it is also possible to adjust, for example, traffic lights to control the number of cars in that area and hence reduce congestion. However, the MFD provides also information on how this network deals with traffic, and it could be used for classifying networks, for example, for urban planning purposes. There are not many studies that deal with that topic. The most similar one was carried out by Knoop et al (2014). In that paper, they generate different MFDs with different networks. These networks, although keeping the same demand, are not necessarily grid like structures and might have different street characteristics.

2. Methodology

The present paper employs the micro simulator VISSIM 6.0.15 to generate the grid networks and simulate traffic on them. We generate the structure of the three following networks: Two-way streets (TW), Two-way streets with prohibited left turns (TWL), and one-way streets (OW). Demand nodes, i.e. where trips are generated and attracted, are located in the middle point of each link. As Figure 2 shows, we employ an extra link on TW networks as a pocket for cars that want to turn left.

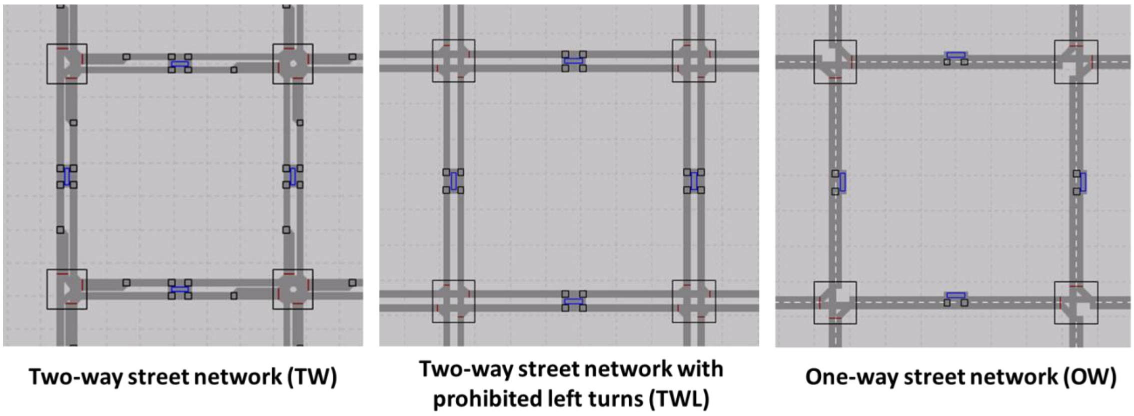

Figure 2. The three networks analyzed modeled with VISSIM.

We employ an uniform demand pattern, i.e. every demand node exchanges the same amount of trips to the others. Within this demand pattern we run a 3 hours simulation with different demand levels to cover both normal and peak conditions: 0.8 trips between demand nodes in the first hour, 1.6 trips between demand nodes in the second hour, and 2.4 trips between demand nodes in the last hour. We analyze square grid networks with 36 intersection nodes. All intersections are signalized with the same phase. Table 1 presents the characteristics of the networks.

Table 1. Characteristics of the networks.

	TW	TWL	OW
Network size:	6 x 6 intersection nodes	6 x 6 intersection nodes	6 x 6 intersection nodes
Link length:	120 m	120 m	120 m
Left pocket:	20 m	-	-
Signalized intersections:			
Green time for through and right movements	19 s	26 s	26 s
Green time for left movements	5 s		
Lost time	12 s	8 s	8 s

VISSIM is a microscopic simulation software which loads a network dynamically representing the interactions between cars. At a network level, especially in an urban environment, where most of the time overtaking is not allowed, we are not that interested in seeing microscopic traffic phenomena. However, we are very interested in seeing the evolution of the queues and how the dynamics of traffic lights affect congestion. In the version employed, there is also a dynamic traffic assignment routine which we use to approach to the user's equilibrium. The details of this method can be seen at the manual (PTV AG, 2014). In short, VISSIM, in every iteration (3 hours simulation) searches for the most efficient routes (a combination between time and distance) between every origin and destination, and distributes the trips according to a Logit discrete choice model. Also, in every interval (in hour simulation we consider intervals of 1 hour, being the total simulation time 3 hours), the program searches for new shortest routes and distributes vehicles accordingly. When defining the generalized travel time in each route for the discrete choice model, the travel times are smoothed with the 10 previous iterations according to the Method of Successive Averages (MSA). The convergence criteria, in our case, are: 1) there is a travel time difference lower than 5% among the different routes vehicles can take from each origin to each destination; and 2) the volume of vehicles in each link does not change more than 5 vehicles from one iteration to another. We use a resolution in our simulations of 5 time steps for each simulation second.

The indicators that we employ for analyzing the different networks are included in the Network Performance indicators of VISSIM. The program calculates these indicators every 200 seconds (3.3 min) periods of the 3 hours simulation (10.800 s), obtaining 54 values for each iteration. We use the following ones:

- vehicles that have reached their destinations during the each period,
- vehicles that are still in the network in each period,
- total travel time and delay per vehicle in each period,
- total travelled distance in the simulation in each period,
- average speed of vehicles in each period, and
- average number of stops for each vehicle and trip in each period.

To create the Macroscopic Fundamental Diagrams we use the number of vehicles that have reached their destination in each interval, and the excess accumulation (or the vehicles that are still on the network); we average them (as Figure 3 shows) and we obtain the trip production rate and the accumulation of the network in each interval. This simplification, allow us to compute the MFDs much more efficiently.

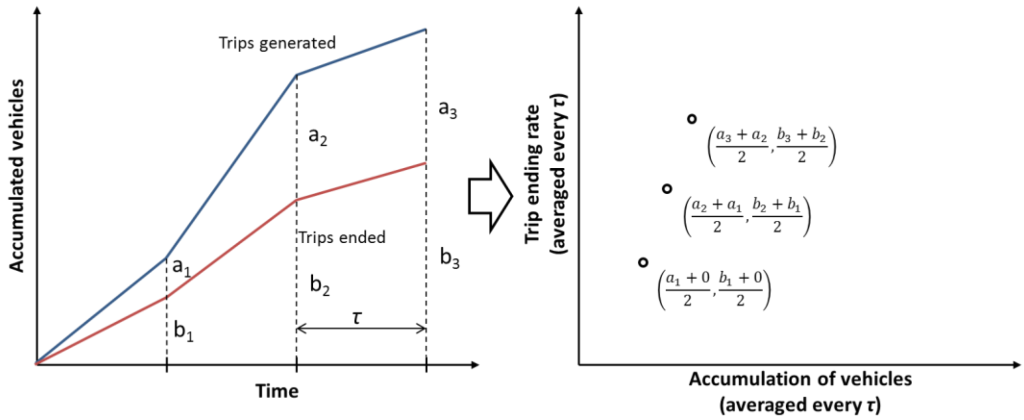

Figure 3. Example of how we obtain the MFD from the accumulation vehicle curves.

3. Analysis of results

As we described in the previous section, the DTA was run for the three networks considering a total simulation time (for each iteration) of 3 hours with three levels of uniform demand in every hour (0.8, 1.6, and 2.4 trips between each OD pair). Routes were updated every hour of each 3 hours simulation. The convergence criteria were that for each OD pair, if there are several possible routes, the travel times are not more than 5% different; and also that the difference in volumes of the links was not more than 10 vehicles between iterations.

Unfortunately we could only achieve these convergence criteria for the case of OW networks which happened after 112 iterations. In the other two cases, after 350 iterations the convergence criteria were not fulfilled. To the author’s knowledge, this is the first work of this kind done with the DTA algorithm of VISSIM 6. Most of the studies that employ micro simulation in networks have a fixed routing defined beforehand with a static traffic assignment where convergence is much faster because the travel time calculation is done in a static way (e.g. with the BPR function). In this case we are not only carrying a microscopic simulation of every iteration to calculate travel times, but we are trying to make converge a 3 hour simulation period where, in every hour, the demand level changes and we give the opportunity of rerouting trips. Luckily, as we see in this section, the MFD shape, after some iterations is fairly stable, and therefore, we are carrying out our analysis despite convergence is not achieved.

Figure 4 depicts the MFDs generated for the 3 networks for iterations: 1, 50, 100, and the final iteration calculated. The behavior is similar for the three networks, we see how, at the beginning, the MFDs are lower and cover both uncongested and congested cases. As soon as the demand rearranges in the system, the congested part tends to shrink until there is only uncongested branch. That phenomenon is explained by Gayah et al. (2011). The MFD is the upper bound of aggregated flow and density relationships because it considers that traffic is homogeneous across the network. In the first iterations, traffic is highly inhomogeneous because the system is routing vehicles among fewer routes making the system gridlock easily. As soon as the DTA has more information about the routes, the traffic is distributed more homogeneously and hence, the curves are closer to the real MFD. The TW network, depicted in Figure 4a, needs more iterations to achieve a fully uncongested curve. Instead the OW network seems to be the most robust in that sense, achieving really fast convergence, but also not presenting a congested MFD. However, this is not necessarily true because we have observed that even if the first iteration the MFD is completely uncongested, the second iteration is congested (represented in Figure 4c), and that phenomenon is repeated in several iterations. That fact denotes that also OW might be quite sensitive to the route chosen. Finally, the TWL network, also tends to achieve uncongested curves quite fast but, as in the case of OW networks, every certain iterations another congested curve appears due to a change on the routing.

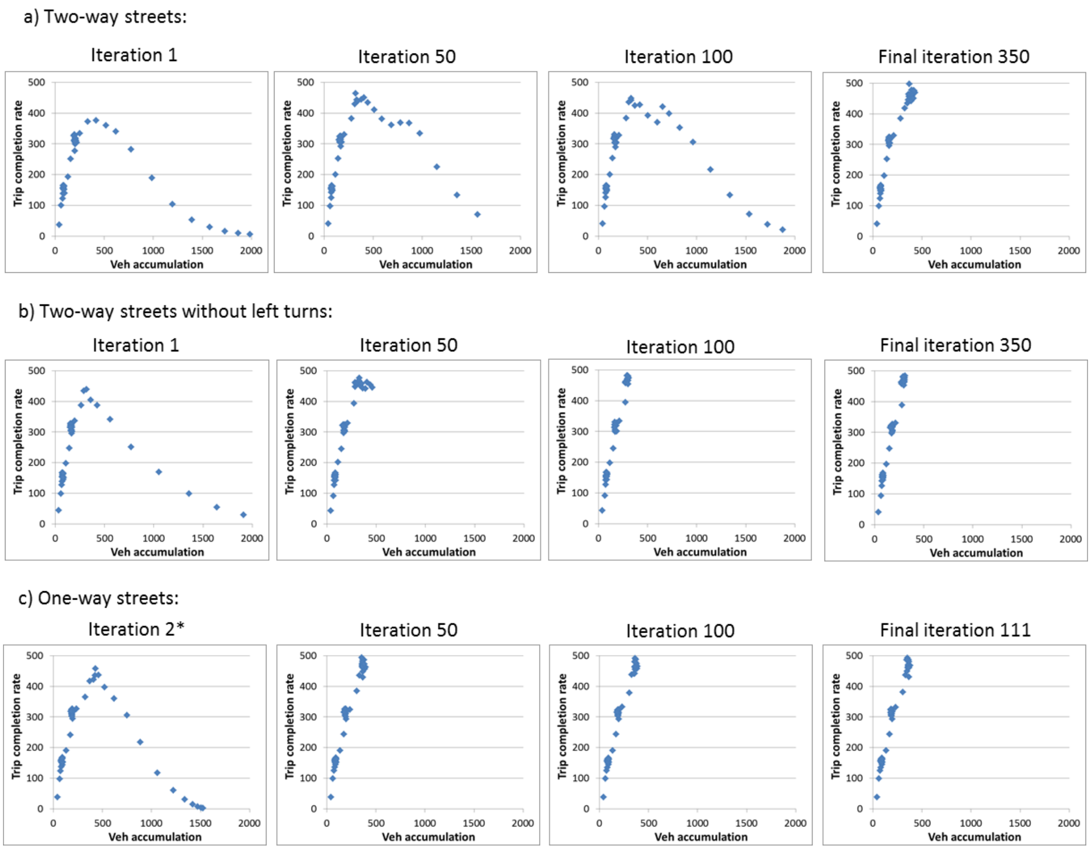

Figure 4. MFDs generated for a) TW, b) TWL, and c) OW networks, and at different iterations of the convergence process.

Let us now compare in Figure 5, the 3 resulting MFDs after all the iterations represented in Figure 4. The difference is not that great because the networks have the same characteristics and the demand is also the same. But it is possible to identify a slightly difference between them. Basically, the MFD of the TWL network would be the curve with higher slope (if we approached the curve to a line) , followed by OW and finally, TW. Having then a higher slope involves that for a smaller accumulation of vehicles, the trip completion rate is faster.

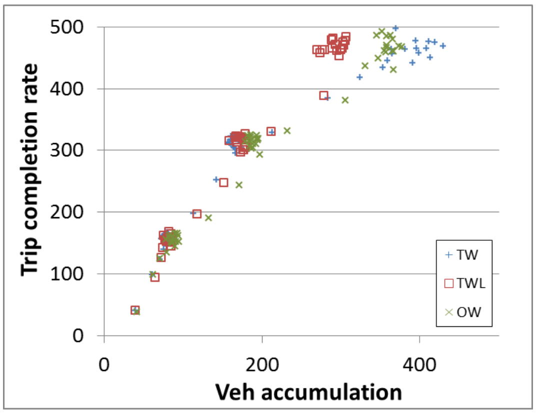

Figure 5. MFDs for TW, TWL, and OW networks in the final iteration, 350, 350, and 112 respectively.

Following this analysis, other network performance indicators were also measured during the 200 seconds interval in the last iteration carried out for each network. We have chosen: the average delay of trips, the average speed, the total distance travelled, and the number of stops. From an efficiency on the trip making perspective, the TWL network is better than the other two because systematically achieves lower delay and higher speed than the rest (Figures 6a and 6b); i.e. trips can go faster from each origin to each destination. This is perfectly consistent with studies in the literature (Gayah and Daganzo, 2012; Ortigosa et al., 2014) that show how the TWL networks present the best trade-off between distance travelled and delay at intersections.

If we looked the efficiency of the network from a sustainability perspective, e.g. emissions or energy consumption, the results might differ. Typically, the factors more related to emissions are: distance, stops made, and speed. In this case we see how the TW network provides lower speed and more stops than the TWL network, which might be bad for emissions, but on the other side TW provide significantly lower distance travelled when networks are near the capacity, which might be a great advantage for emissions and energy consumption (Frey et al., 2001). Nevertheless, these issues are not the focus of this paper and should be properly assessed.

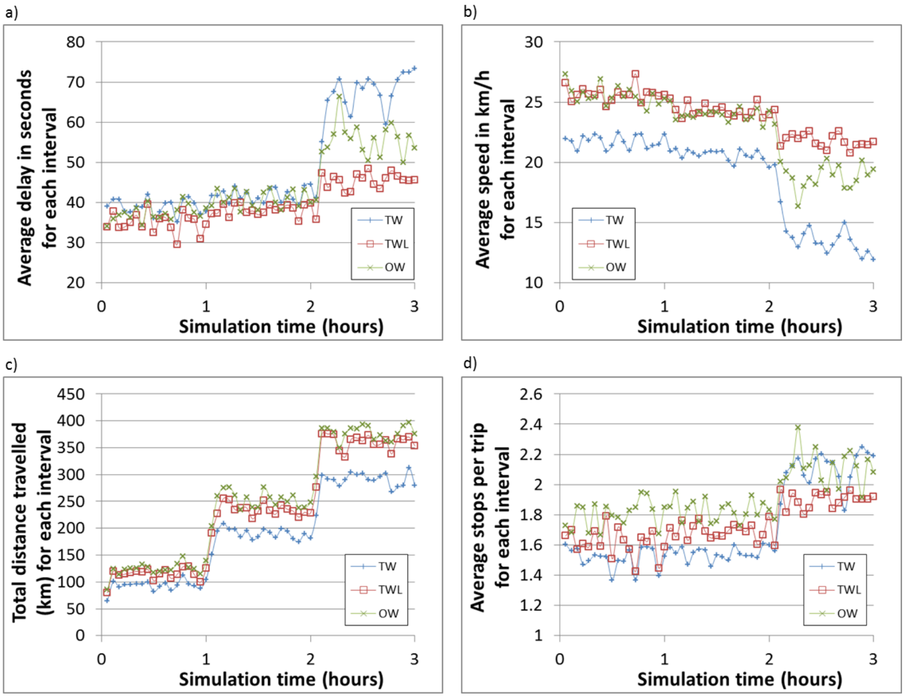

Figure 6. Other network performance indicators for TW, TWL, and OW networks in the final iteration, 350, 350, and 112 respectively.

In Figure 5, MFDs reach capacity but not congestion. To get a better idea of how the different networks deal with congestion we have carried out one more iteration -taking advantage of the routing patterns achieved for the previous case after many iterations- with the same demand patterns but with higher levels of demand: 1.2 in the first hour, 2 in the second hour, and 2.8 in the third. Figure 7 shows the resulting MFDs. It can be seen how the TW and OW networks gridlock later, especially TW. After the simulation, also TW is the network where less cars have not been able to enter the network because of the gridlock (this indicator called latent demand is provided also by the program in each period of measurement).

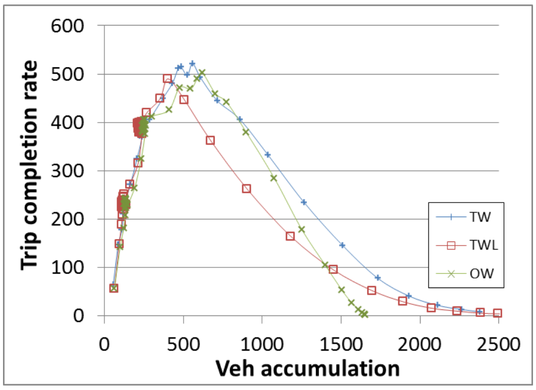

Figure 7. MFDs for TW, TWL, and OW networks considering a higher demand profile (levels of 1.2 – 2 – 2.8).

Looking at the network performance indicators now for the saturated case (Figure 8), the pattern is repeated. TW is the network that is able to cope better with very congested cases and provides lesser delay and higher speed. Looking at distance travelled and number of stops, there is a drop in the gridlock case because vehicles are not able to move, still TW suffers the drop after the other two. The

TWL network is the worst network under congestion. A possible explanation for this behavior is the rigidity in the routing that TWL networks present. According to Ortigosa et al. (2014), since TWL networks only have one minimum distance route between two points, that makes them more vulnerable to spill-overs of certain links.

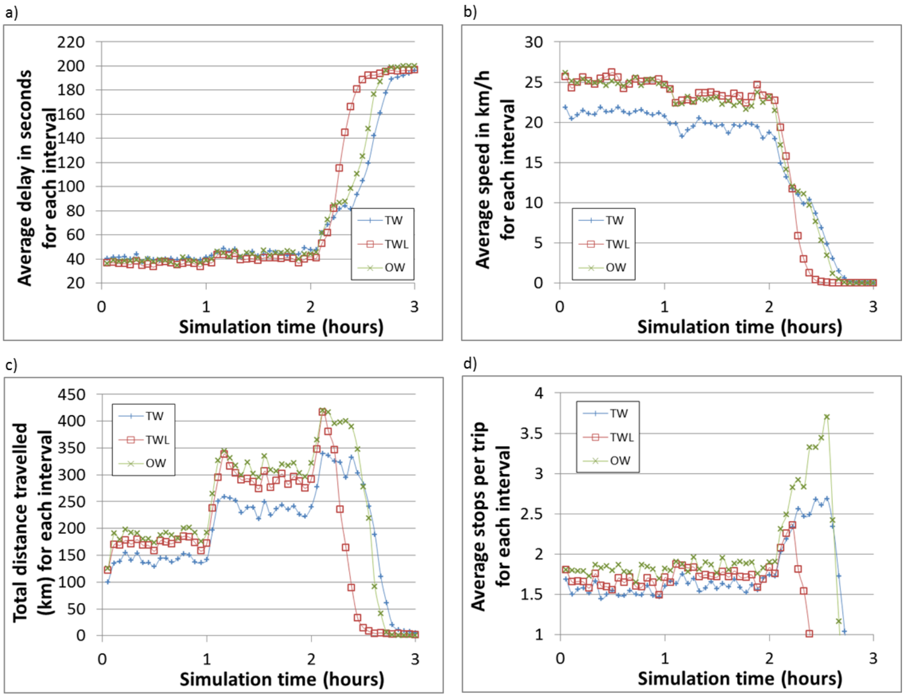

Figure 8. Network performance indicators for TW, TWL, and OW networks considering a higher demand profile (levels of 1.2 – 2 – 2.8).

We need to consider that these MFDs have been created with the routing from the previous demand, so it will be necessary to run again the DTA in this context. Unfortunately that might be unfeasible because in such saturated case the convergence can be even harder to achieve than the normal case.

4 Conclusions

In this paper we have analyzed three configurations urban grid networks of 36 intersection nodes (6x6): two-way streets, two-way streets with prohibited left turns, and one-way streets. This analysis has been done employing a microscopic simulation to see the dynamics of these networks in uncongested and congested states. Previous analysis of these networks (e.g. Gayah and Daganzo, 2012; Ortigosa et al., 2014) had not studied the dynamic perspective.

A novelty in this paper is that we have employed the dynamic traffic assignment module of VISSIM 6.0.15 to achieve the network equilibrium of traffic flows starting from an uniform trip demand. That process has resulted very costly, computationally, and we have only achieved the convergence of the case of one-way networks. Nevertheless, we believe that this direction is very useful if we want to consider the driver's adaptation to traffic conditions. We need to bear in mind that many micro simulation research studies have a fixed routing coming from a static traffic assignment. It is needed, then, as future work, to further investigate on the efficiency and accuracy of VISSIM dynamic traffic assignment.

The analysis of the three networks has given the expected results. TWL networks are the most efficient when the system is not congested because they offer the best trade-off between distance travelled and capacity at intersections. However, when networks are congested, TWL networks seem to gridlock faster than the other two because the routing is more rigid. These results are consistent with the assumptions made by Ortigosa et al. (2014) on the rigidity of TWL networks. However, further analysis must be done carrying out a full convergence assignment, and analyzing different network sizes and link lengths. In addition, in the future, it would be interesting to see how the different networks are affected by the removal of certain links in the network.

The main indicator to compare networks was the Macroscopic Fundamental Diagram. We believe that it can be very useful not only as a traffic control scheme but as an indicator of the efficiency of the network to support urban planning decisions. What is the desirable shape of the MFD when we compare two networks with the same demand? Dividing the MFD into the uncongested and congested part, a network with a higher slope on the uncongested branch and a higher capacity will be able to make that more trips are able to go from their origins to their destinations; and they are able to do that faster. On the congested branch, a desirable network is that one with a flatter slope towards the gridlock, i.e. even it is congested the network can foster many vehicles without totally gridlock. However, if we include other measures of efficiency such as the distance travelled, it can be harder to see that reflected on an MFD. Further research on the shape of the MFD should focus on how to obtain other network measures.

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