Optimizing Superblock Placement in Barcelona

Clarice Mottet, Amber Walker, Mox Ballo

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Abstract

With the goal of creating a healthier city environment through the increase in public use space and reduction in air pollution while minimizing impact to commuters, we seek to identify an optimal location to incorporate a Superblock within the city of Barcelona. By determining the Nash equilibrium and social optimum of traffic flow on Barcelona as a result of incorporating one Superblock at a time, we analyze best placement options tied to overall travel time, travel cost and Price of Anarchy.

1 Introduction

Urban cities, including Barcelona, face challenges such as air pollution with traffic congestion as the main contributor of pollution levels [Benavides et al., 2021]. In response, urban planning strategies such as implementing Superblocks - large urban areas redesigned to minimize traffic and expand public spaces - within Barcelona have been explored and found to reduce major pollutants, improve traffic conditions and maintain stable travel demand [Sánchez-Vaquerizo and Helbing, 2023].

In line with current urban planning trends to reduce space allocated for cars, our study aims to analyze the effects of incorporating Superblock structures within Barcelona's street networks detailed in Section 1.1. Specifically we look at the the Nash equilibrium of traffic flow on Barcelona to analyze best placement options tied to overall travel time, travel cost and Price of Anarchy discussed in Section 1.2. With this approach, the ultimate goal is to repurpose these new spaces exclusively for public use and green areas thereby reducing air pollution and enhancing urban quality of life in Barcelona.

1.1 Research Background

Since the EU established annual NO_2 emission limits in 2000, Barcelona has exceeded these standards with a majority of emissions due to vehicles [Benavides et al., 2021]. In 2017, the local Public Health Agency reported that about 70% of its 1.6 million residents were exposed to NO_2 concentration levels exceeding the annual air quality threshold. These levels of NO_2 exposure were associated with approximately 929 premature deaths [ASPB, 2018]. As such there has been increasing motivation to reduce air pollution and increase car-alternative modes of transportation as urban living is projected to rise [Glazener and Khreis, 2019]. While cities with residential green spaces have been linked to reduced mortality rates [Gascon et al., 2016], simulations of converting roads into public use space have increased in recent years ([Bagloee et al., 2019], [Eggimann, 2022], [Sánchez-Vaquerizo and Helbing, 2023]).

Analysis of a Superblock structure, consisting of nine 3×3 urban city blocks with both exterior and interior streets, as seen in Figure 1, has shown promising results in cities of varying densities. Implementing such a structure has contributed to reduced air pollution, increased motivation for alternative transportation methods, green space expansion and minimal vehicle commuter disruption [Eggimann, 2022]. With regard to Barcelona in particular, a series of simulations were performed to compare the impacts of various planning strategies. The simulations focused on the incorporation of Superblocks; "Green axes" (restricted groups of blocks following a grid structure), "No diagonals" (restricted groups of blocks that do not follow a grid structure), and a hybrid approach combining "Green axes" and "No diagonals". The results were able to achieve reductions in air pollution while also being able to minimize disruption to commuters [Sánchez-Vaquerizo and Helbing, 2023].

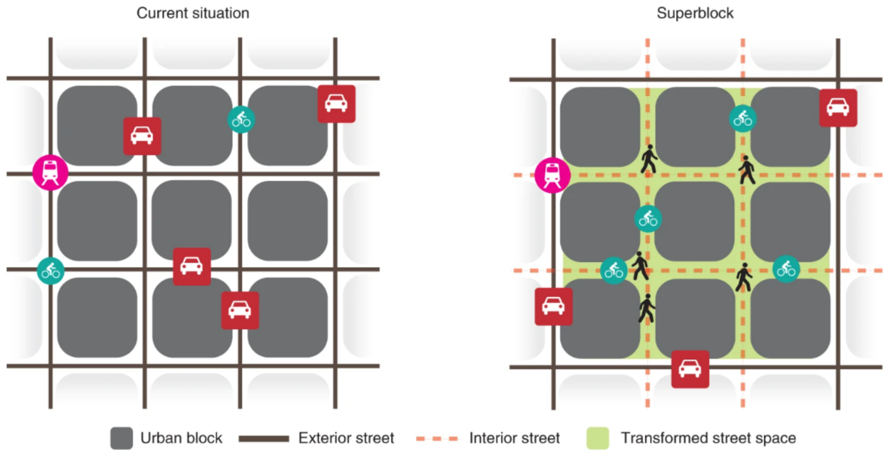

Figure 1: Definition of a Superblock [Eggimann, 2022]

1.2 Research Objective

While the cutting edge simulations of converting various road structures to public space yielded compelling results, only road structures proposed by the city of Barcelona were considered [Sánchez-Vaquerizo and Helbing, 2023] and thus, simulations were performed for only two Superblock options. We hope to further add to the discussion by conducting a simulation of traffic impact considering all identified Superblocks within the city of Barcelona individually. Annother notable difference in our analysis is our plan to convert the roads in our Superblock solely for the purpose of public use, prohibiting any local traffic or vehicles whatsoever, a divergence from the paper we aim to build upon.

Simulations of traffic impact relied on the use of a digital twin of Barcelona traffic and proposed an agent-based model where an agent may be represented by a person walking, cyclist, car, or traffic light, and utilizes "Simulation of Urban Mobility" software to assess impact on the city with the incorporation of public use space conversion structure [Sánchez-Vaquerizo and Helbing, 2023]. For the purposes of our analysis, and lack of data availability, we follow a process of assessing traffic impact on the incorporation of a Superblock by comparison of a socially optimal total travel time and cost, Nash equilibrium total travel time and cost, and the resulting Price of Anarchy [Youn et al., 2008].

2 Data

We utilized Barcelona road network data available for transportation research [Transportation Networks for Research Core Team, 2016]. While the paper we are building upon utilized Barcelona data from OpenStreetMap, the data had to be converted into a directed graph network format and manually checked and corrected based on satellite data [Sánchez-Vaquerizo and Helbing, 2023], a process that we did not replicate.

The Transportation Networks data available to us is comprised in two files. The first being `Barcelona_net.tntp`. This details the starting and ending node for every directed edge, forming the basis of the directed graph that will represent the Barcelona road network. This file also gives us associated characteristics of the road such as the capacity of the road the edge represents, the length, and the free flow time.

The second file, `Barcelona_trips.tntp`, is an example trip file to be used when we search for the optimal flow when a Superblock is removed. Detailed is origin node, destination node and the origin-destination flow or the amount of traffic that must leave the origin node and reach the destination node.

Overall, the Barcelona road network is comprised of 930 nodes and 2,522 edges while our simulated demand, or trip file, starts with 97 origin nodes and ends at 108 nodes. Unfortunately our data does not include coordinate information and are therefore unable to construct a visualization in line with a map like representation of the city as seen in Figure 2.

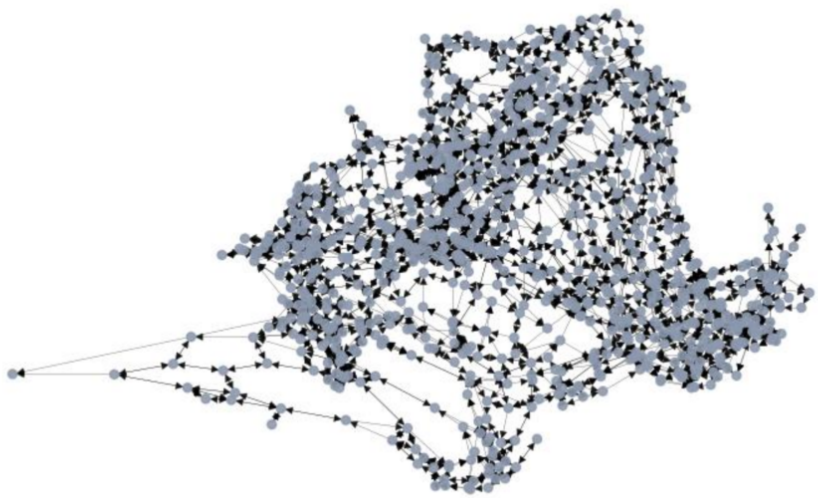

Figure 2: A directed graph representation of Barcelona road network.

3 Methods

In section 3.1, we review the algorithm created to identify all Superblocks in a network. Then in section 3.2, we discuss models and algorithms used to simulation traffic impact due to road closure. Lastly, in section 3.3 we detail how we utilized the methods to conduct on our analysis.

3.1 Superblock Identification

We first start by developing logic to identify a Superblock within a road network that can later be used in an algorithm to find all distinct Superblocks within a road network. Let us begin with a toy example as displayed below and define a Superblock to be the nodes on it's outer perimeter (in purple) and nodes within its center (in green) seen in Figure 3.

As we plan to define a Superblock by nodes and not edges, we convert our directed graph to a graph. Starting from a single node in the graph, we traverse to its neighbors, ensuring particular conditions are met relating to whether nodes have common neighbors or not, until at the end of our logic we have found the outside nodes and all of the center nodes of a potential Superblock. To ensure that we do not close roads that would overlap with another busy road, we ensure that all the center nodes are exclusively degree 4. To ensure that the removal of a road does not cause a bottleneck, we apply a condition that all nodes on the perimeter of the Superblock must have at least one in-degree and one out-degree after the removal of the edges to the center nodes.

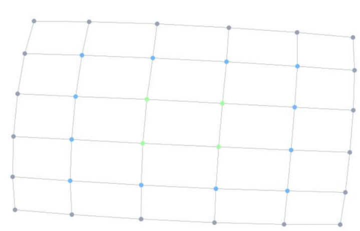

Figure 3: A simple example of a node representation of a Superblock.

From our algorithm, we identified 87 Superblocks in Barcelona seen in Figure 4. Because a Superblock is a three-by-three grid, there is overlap between many of these Superblocks as if one were to move a

Superblock over by one block. As such all nodes that appear as centers are presented in green below and all nodes that appear only as perimeter nodes are presented in purple. Because we plan to remove all edges connected to center nodes, thereby removing roads available to cars, we performed a preliminary check to see if any of the center nodes present in any of the Superblocks were origin or destination nodes in our trip file. We found that none of the center nodes were origin or destination nodes, yet a few of the perimeter nodes on Superblocks were origin or destinations nodes, and therefore we are able to use the same trip file for all traffic simulations.

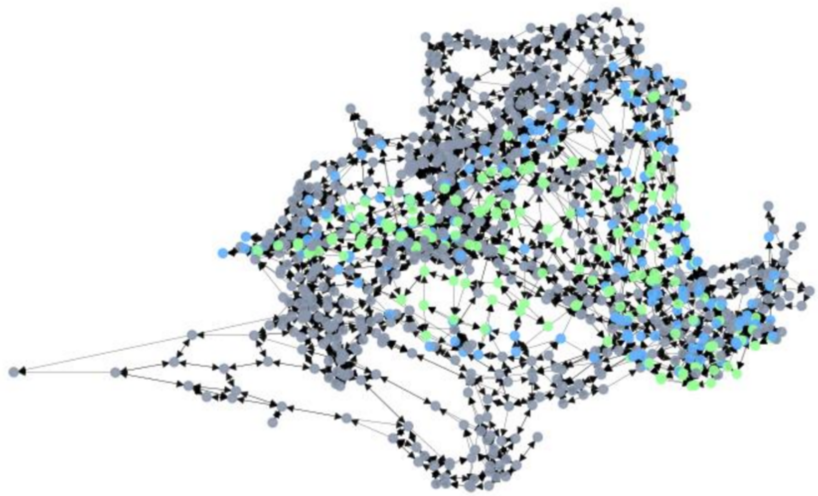

Figure 4: Barcelona with all Superblocks Identified.

3.2 Model

As stated previously, we follow a process of assessing traffic impact after the incorporation of a Superblock by calculating the total travel time and travel cost related to a socially optimal solution, the total travel time and travel cost related to the Nash equilibrium of flow and the resulting Price of Anarchy.

Drivers may choose roads that benefit themselves individually yet do not benefit society as a whole. To capture this behavior in our simulation we calculate the Nash equilibrium of flow, defined as the flow on a network when all individuals choose the route that minimizes their time spent in transit. The unintended consequence of this driver behavior is an increase in total travel time and travel cost on the network as a whole and can be thought of as a "worst-case" traffic scenario.

It may also be the case where drivers stay put on their path regardless of other options resulting in a socially optimal solution on the road network as a whole, what we consider a "best-case" traffic scenario for the purposes of our analysis.

To find the Nash equilibrium of flow on our road network, we utilize the Bureau of Public Roads (currently known as the U.S. Federal Highway Administration (FHWA)), (BPR) as our edge cost function which models the travel time T on edge e as a function of f_e on the edge:

$$T_e(f_e) = T_{e0}\left(1 + \alpha\left(\frac{f_e}{C_e}\right)^{\beta}\right) \tag{1}$$

Here $T_e(f_e)$ is the travel time on edge e as a function of flow f_e, where T_{e0} is the free-flow travel time on edge e, C_e is the capacity of edge e, and α and β are calibration parameters that determine the shape of the function.

Shown by [Beckmann et al., 1956], the Nash equilibrium of flow can be solved for by the following optimization problem where f* is an equilibrium if and only if it is a solution to:

$$\min \sum_{e \in E} \int_0^{f_e} T_e(z)\, dz \tag{2}$$

$$\sum_{\substack{p \in P \\ e \in p}} f_p = f_e, \quad \forall e \in E \tag{3}$$

$$\sum_{p \in P_{od}} f_p = D_{od}, \quad \forall (o,d) \in OD \tag{4}$$

$$f_p \geq 0, \quad \forall p \in P \tag{5}$$

These equations define the solution to Nash equilibrium of flow as the minimum of the sum over all edges in our network of the edge cost function (BPR) (2) subject to the amount of flow entering a node has to equal the amount of flow exiting a node (3). For all demand D_od on our network, defined in the trip file, the sum of the flow along the path must meet the demand, not exceed or under report demand (4). The flows along each edge used in a path must be greater than or equal to zero.

To solve for the Nash equilibrium of flow, we utilize the Frank-Wolfe algorithm:

1. We start with an initial feasible flow distribution, typically distributing traffic evenly across the network.
2. Using the current flow distribution, the travel time on each edge is calculated using the BPR function. Then, the algorithm seeks to the shortest path from every origin to every destination. The goal of this step is to identify the direction in which to move to improve the solution.
3. Afterwards, the flow distribution is adjusted towards the shortest paths identified previously. This involves solving a line search problem to find the optimal step size (can otherwise be thought of as how much of the traffic to shift) with the objective being to minimize the total travel time across the network.
4. If the difference in step size from the previous step to the current is less than .001, the algorithm has converged to a solution. Otherwise, we look to determine a new shortest path and repeat the process until we converge to an optimal flow distribution (Nash equilibrium of flow) or until 3000 iterations of the algorithm have taken place.

To determine a social optimum flow solution, we adapt the Frank-Wolfe algorithm to use a marginal social cost function as a basis to find the shortest path from origin to destination instead of BPR (or individual travel times). This encourages paths chosen that may be longer for individual drivers but result in a lower overall network travel time. In line with the use of the Frank-Wolfe algorithm, we our calibration parameters $\alpha = .15$ and $\beta = 4$.

We utilize preprogrammed source code to implement the Frank-Wolfe algorithm and solve for Nash equilibrium of flow and social optimum flow solutions. The $PyTrans$ source code, developed by the same team that maintains the database we retrieved our data from [Transportation Networks for Research Core Team, 2016].

Using the flow solutions, we calculate total travel time on the network given by:

$$T_{\text{total}} = \sum_{e \in E} T_e(f_e) = \sum_{e \in E} \left(T_{e0} \left(1 + \alpha \left(\frac{f_e}{C_e} \right)^{\beta} \right) \right) \tag{6}$$

where f_e is either the Nash equilibrium of flow or the social optimum of flow.

Total travel cost, C_{total}, on the road network is given by:

$$C_{\text{total}} = \sum_{e \in E} f_e \cdot T_e(f_e) = \sum_{e \in E} f_e \cdot \left(T_{e0} \left(1 + \alpha \left(\frac{f_e}{C_e} \right)^{\beta} \right) \right) \tag{7}$$

To capture the lack of coordination among self-interested drivers and socially conscious drivers, we calculate the Price of Anarchy, PoA, of our road network with and without the incorporation of a Superblock. The PoA is defined as the ratio between the "worst-case" scenario of traffic (the total cost Equation 7 of Nash equilibrium of flow) and the optimal performance of traffic as a whole (the total cost of social optimum flow in Equation 7). When the PoA is 1, it indicates that the Nash equilibrium of flow is equal to the the socially optimal flow and there is no loss in efficiency due to individualistic driving decisions. A PoA greater than 1 indicates inefficiency due to individualistic driving decisions that cause an increase traffic cost to the road network as a whole.

$$\text{PoA} = \frac{C_{\text{total,NE}}}{C_{\text{total,SO}}} \tag{8}$$

Lastly, we calculate a total time differential between the Nash equilibrium flow total time and the social optimum flow total time for the baseline network and each simulation, T_{diff}, as a reference point to the impact on PoA.

$$T_{\text{diff}} = \frac{T_{\text{total,NE}} - T_{\text{total,SO}}}{T_{\text{total,SO}}} \tag{9}$$

3.3 Procedure

We begin by determining the Nash equilibrium of flow and social optimum flow on our Barcelona road network without the incorporation of any Superblocks, to have a benchmark against which we can compare to. Using these two flow solutions, we calculate overall travel travel time on the network with Equation 6 and a baseline PoA, given by Equation 8.

Our Superblock simulation procedure is as follows:

1. Import the Barcelona road network and trip file (or origin and destination demand data) into the programming environment and create a directed graph.
2. For one Superblock, remove the edges connected to the center nodes of the Superblock from the directed graph.
3. Use the Frank-Wolfe algorithm to find the Nash equilibrium of flow. Using this flow solution, calculate total travel time and total travel cost using BPR.
4. Use the Frank-Wolfe algorithm again to find the social optimum of flow. Calculate total travel time and total travel cost using BPR.
5. Calculate the PoA and T_{diff} using the previous two flow solutions.
6. Continue for every Superblock identified, one at a time.

Once the total travel time and travel cost given by the Nash equilibrium of flow solution, the social optimum of flow solution and the PoA and T_{diff} is calculated, we then compare these metrics describing the impact on traffic due to the incorporation of the Superblock with the total travel time of the baseline Barcelona road network.

4 Results

Starting with presenting an assessment on the impact of total cost of the network, C_{total}, for the Nash equilibrium flow solution on the left and social optimum flow solution on the right in Figure 5, with the incorporation of a Superblock on the network, we see there are seven cases where the incorporation of a Superblock produces a Nash equilibrium flow solution that results in a lower total cost on the network. We do not see this behavior to the same extent yet there is one Superblock that does yield a lower social total cost on the network compared to baseline.

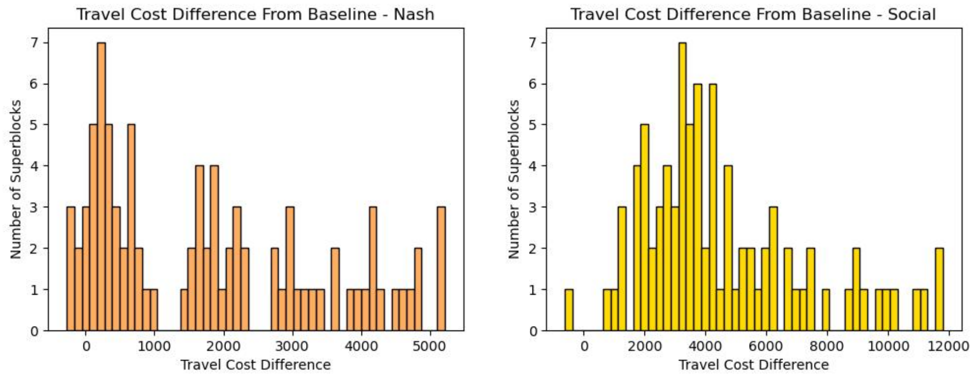

Figure 5: Nash Total Cost and Social Total Cost Difference from Baseline with Superblock Incorporation.

Next we compare the total travel time, T_{total}, for the Nash equilibrium flow solution on the left and social optimum flow solution on the right in Figure 6, with the incorporation of a Superblock on the network. We found that for every simulation, we yielded a lower total travel time compared to baseline.

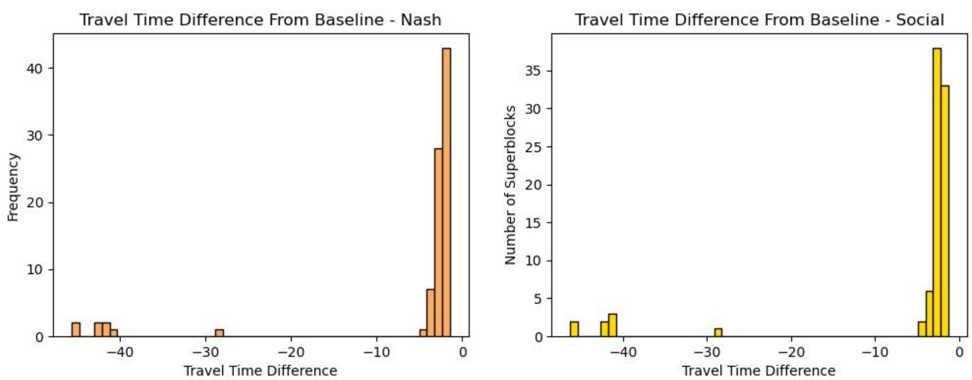

Figure 6: Nash Total Travel Time and Social Total Travel Time Difference from Baseline with Superblock.

In Figure 7, on the left we compare the change in the PoA between the Superblock simulations from baseline. Previously in Figure 5, we saw different total cost behavior between Nash and social flow solutions where Nash typically had a closer total cost to the baseline, yet the social total cost had a higher cost compared to the baseline. We see this translate into PoA values less than one in Figure 7 on the left. Typically we would never expect to see a PoA value less than one.

On the right in Figure 7, we create a scatter plot to assess how the PoA relates to the travel time differential between the Nash and social flow solutions. At baseline, we see that the Nash flow solution yields a total travel time 3% greater than the social optimum. For total time on a network, we almost always see that the Nash flow solution produces a higher travel time than the social optimum, the opposite case we see as it relates to total cost. While the majority of simulations yielded a lower PoA, or disruption to traffic than the baseline model, we see that not all simulations (those in the upper left quadrant) closed the gap between travel time related to the "worst-case" Nash solution and "best-case" social optimum solution.

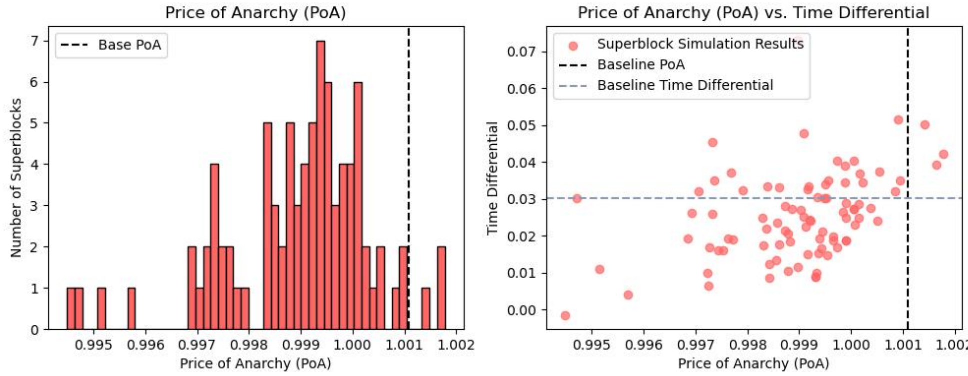

Figure 7: Impact on Price of Anarchy and Total Time Differential with Superblock Incorporation.

5 Discussion

A surprising find in these simulations is that the Braess Paradox appears to be more the rule than a paradox. While the Braess Paradox describes a reduction in total travel time and total cost with the removal of one road, with the incorporation of a Superblock on a road network we remove twelve edges leading for us to expect the total travel times and total travel costs to increase. We found the opposite occur for both total travel and total cost related to Nash equilibrium flow solutions and social optimum flow solutions quite frequently.

Another surprising twist to this simulation procedure was the frequency in which we saw Nash equilibrium flow solutions (our projected "worst-case" traffic scenarios) yield one total time and seventy total cost metrics lower than their corresponding social optimum (our projected "best-case" traffic scenario) flow solutions. Typically we would expect to see the social optimum flow solution always yield a lower total travel time and lower total cost on the network than an individualistic minded Nash equilibrium flow solution based on how we have set up our Frank-Wolfe algorithm.

Turning our attention to the Price of Anarchy, the main metric we use to assess the impact on traffic with the incorporation of a Superblock, we find almost every Superblock produces a reduced PoA than the baseline network. To further understand our PoA metric, we compare to the time differential of the total time given by the Nash flow solution as a percent change from the total time given by the social optimum flow solution. We find that almost half of the simulations that produce a lower PoA do not in fact produce a lower Nash equilibrium travel time when compared to their corresponding socially optimal total travel time.

While we saw that the majority of simulations yielded a reduced PoA, we took the top 5 Superblocks with the lowest PoA and plotted them simultaneously in Figure 8. What we hoped to gain through this is if the Superblocks with the lowest PoA are concentrated in the same region within Barcelona. We find they are not extremely concentrated in the same area.

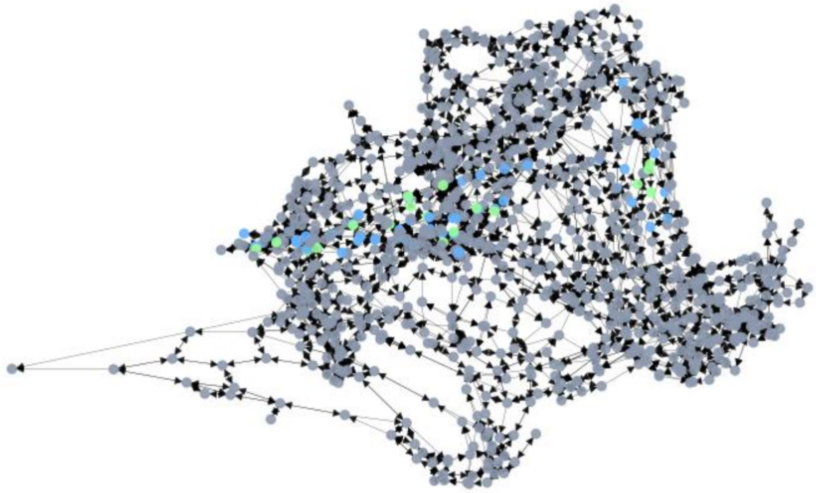

Figure 8: A directed graph representation of Barcelona road network with the top 5 Superblock placements.

Similarly, we took the top 5 Superblocks with the highest PoA and plotted them simultaneously in Figure 9. Again, we hoped to infer if the Superblocks with the highest PoA, causing the most distruption, are concentrated in the same region within Barcelona and see they are not.

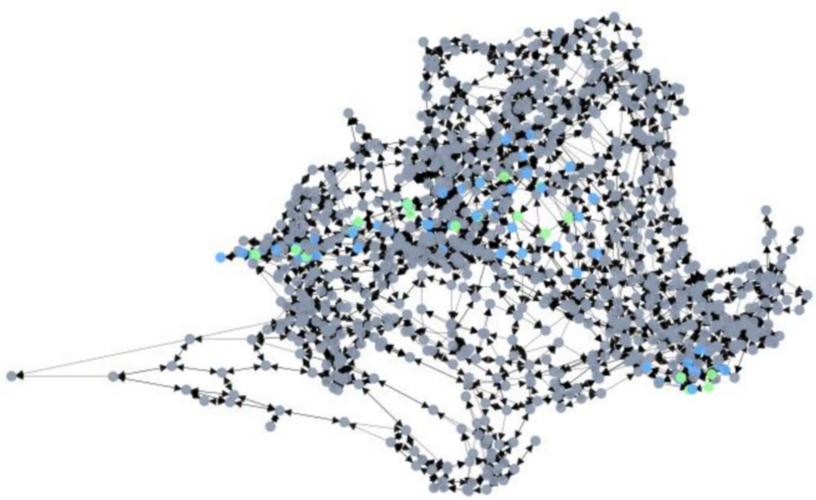

Figure 9: A directed graph representation of Barcelona road network with the worst 5 Superblock placements.

6 Conclusion

For each simulation, we only calculated one Nash equilibrium flow solution and one socially optimal flow solution. In further analysis we would prefer to conduct a analysis of an average of multiple flow solutions as making such a stark change of removing twelve edges on a network and determining flow could produce varying results. We look at our results with general skepticism as intuitively we would expect disruption, PoA, to increase in our road network with the removal of twelve road options. We would also run the simulations with multiple different trip files, instead of just one, to gain a more robust understanding of Superblock incorporation on impact of traffic.

Another aspect we would adjust in a further analysis would be to gather data containing coordinate information to aid in the identification and efficacy of the incorporation of a Superblock.

With our goal of extending the research on the impact of traffic when converting roads for public use space [Sánchez-Vaquerizo and Helbing, 2023], we find that our results require further investigation and analysis.

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