

CRITICAL INFRASTRUCTURE: A CASE STUDY OF URBAN MOBILITY IN MEDELLÍN (COLOMBIA)

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ABSTRACT

Critical infrastructure refers to the type of facilities, services, and installations (e.g., transportation, communication, energy systems) that are essential for the functioning of a community, city or country. This paper describes the findings of the research conducted to identify the transportation network critical facilities (road links) and its impacts on urban mobility for the city of Medellín, the second largest city in Colombia. The paper analyses the negative effects on travel time when a

facility is disrupted or the capacity is suddenly reduced (e.g., accident, natural or manmade disaster, dedicated bike-route, maintenance, construction). Criticality is identified following two methodologies: 1) comparing the travel time of the network users solving the User Equilibrium (UE) Traffic Assignment problem between the base case and the disrupted network; and 2) assessing the impact of the disrupted facility on the path travel times between affected origin-destination zones.

1. INTRODUCTION

Medellín, with 2,200,000 inhabitants, is the second largest city in Colombia. The city is part the Metropolitan Area of the Aburrá Valley (which includes Medellín and nine other municipalities) with 3,300,000 inhabitants (Departamento Administrativo Nacional de Estadística, 2005). The public transportation system of the city is comprised of buses, a new Bus Rapid Transit (BRT) system, taxis and a Metro. According to the Valle de Aburrá's 2005 Origin-Destination (O-D) Survey (Área Metropolitana del Valle de Aburrá, 2006), 4.8 million journeys take place in a typical day (34% buses, 10% Metro, 13% automobile, and 43% others). Moreover, the vehicle fleet is increasing year after year, reaching more than 850.000 vehicles by August 2010 (Alcaldía de Medellín, 2011). As a consequence, the transportation infrastructure has been struggling to deal with this burden, making mobility one of the biggest challenges the city will need to face in the coming years.

In 2004, traffic studies on strategic corridors showed that the average speed was about 22.1km/h in the morning peak period and 17km/h in the evening peak period. The average travel time in public transport was 35 minutes over an average distance of 8.75km. Speeds on the public transport network ranged between 5 and 26km/h (Vélez, 2005). The lower speeds were observed in the downtown area (Central Business District) with values between 5 and 13km/h; these low speeds are the result of traffic congestion and transit routing converging in the area (Gonzalez-Calderon and Ospina, 2004). Overall, there are high levels of congestion throughout the city, resulting from a saturated transportation network. This is even worst when disruptions (e.g., due to weather conditions, accidents) affect the network.

In this context, and given that one of the economic engines of a society is the transportation system as it implies the movement of individuals and cargo, it is vital to analyze the importance or criticality of the pieces of infrastructure (e.g., bridges, roads) that carry these flows. Critical infrastructure refers to the type of facilities, services, and installations (e.g., transportation, communication, energy systems) that are essential for the functioning of a community, city or country. Therefore, an assessment of the critical infrastructure is important to evaluate the responsiveness of the network to a disruption in strategic facilities. This is normally referred to as the Most Valuable Node/Most Vital Edge (MVN/MVE) problem in Graph Theory, where the idea is to find the node or edge that when removed produces the maximum deterioration of the network performance.

The paper identifies the criticality of a transportation facility using an economic quantitative measure, specifically, the impact on “travel time” following the work by Ukkusuri and Yushimito (2009). Since travel time depends on route choice, and route choice depends on the road network conditions, this paper assesses the importance of a facility by examining the negative effect on travel time if the facility is disrupted or the capacity is suddenly reduced for a prolonged period of time. This is done by estimating the travel time of the network users solving the User Equilibrium (UE) Traffic Assignment problem in the updated network. The UE solution is reached only when no traveler can improve his travel time by unilaterally changing routes (Sheffi, 1984).

The paper describes the findings from assessing and identifying the critical facilities of the Metropolitan Area of the Valle de Aburrá road network (2530 links, 1516 nodes) using the Production and Attraction patterns obtained from the Valle de Aburrá’s 2005 Origin-Destination Survey (Área Metropolitana del Valle de Aburrá, 2006).

The paper is organized as follows. Section 2 presents some methodologies used to assess critical infrastructure. Section 3 describes the study area in terms of zoning system, network, and vehicular traffic. Section 4 shows the results from the analyses for the study area. Finally, Section 5 discusses the mayor findings and research recommendations.

2. CRITICAL INFRASTRUCTURE

The criticality of infrastructure facilities has been evaluated from multiple domains. For instance, from the Graph Theory perspective, it has been addressed as the effect of a disruption in a link or node from a network graph resulting in the most valuable node (MVN) problem and most vital edge (MVE) problem. These two problems seek to find the node and link whose removal deteriorates one network performance—usually measured in terms of distance (Latora and Marchiori, 2005) or in terms of throughput (Ratliff et al., 1975). However, these theoretical approaches have limitations when applied to transportation networks. One limitation is the treatment of travel times which is not usually assumed as flow dependent and therefore does not consider congestion. Omer et al. (2011) tried to address this issue by considering a BPR congestion function to assess resiliency and criticality in a transportation network, though their treatment is still limited as they include a change in travel times for traversing a particular infrastructure without consideration of the equilibrium condition in the user travel time (Wardrop’s first principle, Wardrop (1952)).

Additional studies, based on qualitative factors, have developed guidelines to measure and assess the importance of infrastructure facilities (Ham and Lockwood, 2002; National Cooperative Freight Research Program, 2002; National Cooperative Freight Research Program, 2006). More elaborate models and applications include Murray-Tuite (2003); Grubestic and Murray (2006); Scott et al. (2006) and Chen et al. (2007). For a more complete review of the different methodologies the reader is referred to Ukkusuri and Yushimito (2009) and Nagurney and Qiang (2007); (2008). Furthermore, Ukkusuri and Yushimito (2009) and Nagurney and Qiang (2007); (2008) propose methodologies that include equilibrium travel times in their assessment. These methodologies

have important different considerations in terms of the disruptions effects. Nagurney and Qiang (2007); (2008) define a criticality measure as an average network efficiency matrix. In their analyses, they do not consider O-D pairs that have no associated demand, that is, if a node is completely disconnected, due to network disruption, the demand associated is not accounted for the efficiency measure. On the other hand, in Ukkusuri and Yushimito (2009)'s measure this is not the case as the demand is never removed from the analyses because a disruption is evaluated in terms of the impacts on the links capacity—reduced to a minimum value—and not in terms of demand. Their procedure ranks facilities based on how the total system travel time, measured as the sum of all equilibrium travel time in all arcs of the network, is affected. They also show the advantages of using this type of measure over other more traditional measures such as the Volume/Capacity ratio which do not consider user behavior (route-choice).

2.1. Criticality Measure

As previously discussed, Ukkusuri and Yushimito (2009) introduce a methodology to assess the criticality of links of the transportation network by examining the negative effects on travel time when a facility is disrupted or the capacity is suddenly reduced (e.g., accident, natural or manmade disaster, dedicated bike-route, maintenance, construction) for a prolonged period of time. The methodology is based on the estimation of the travel time of the network users solving the User Equilibrium (UE) Traffic Assignment problem in the updated network. Specifically, a criticality ranking is estimated by iteratively choosing a link from the network and eliminating or reducing its capacity, computing the UE solution and then comparing with the UE solution of the original (base case) network. The process is repeated for all links, l , (or specified links) in the study network. The criticality index $D(l)$ is then estimated by the following expression:

$$D(l) = \frac{\phi_l - \phi}{\phi}, \forall l \quad (1)$$

Where ϕ is the total travel time in the network without disruption, and ϕ_l is the total travel time in the network after link l is disrupted.

2.2. Proposed methodology

In this paper, we propose a different approach for assessing criticality in an urban network. Our assumption is similar to the one in Ip and D. (2011) where the authors evaluated resilience as the number of reliable paths between any pair of nodes after a disruption. However, in this research we do not consider the number but how the path travel times between origin-destinations nodes are affected. In that sense the approach followed has similarities with the “Path Travel Time Reliability Index” (Lam et al., 2007). Nevertheless, instead of using the free-flow travel time as the benchmark for assessing the level of service (LOS) on alternative paths, we use the equilibrium travel time without disruptions as the benchmark. In other words, if a link l is disrupted, the index to assess the criticality of a path j is:

$$D^{rs}(l) = \frac{\pi_{j,-l}^{rs}}{\pi_j^{rs}}, \forall r, s, j, l \quad (2)$$

Where π_j^{rs} is the path j travel time (computed using the equilibrium travel times) for an r - s O-D pair, and $\pi_{j,-l}^{rs}$ is the path j travel time (computed using the equilibrium travel times) after the disruption of link l for an r - s O-D pair.

The procedure is performed in three stages. The first stage computes the equilibrium travel times for the network without disruption. The minimum path is then obtained using a multiple origin-destination shortest path using the equilibrium travel times in the links as the link costs. In the second stage the equilibrium travel times with a disruption in one selected link is obtained. The multiple origin-destination shortest paths are then computed to obtain the path travel times. This stage is repeated for each facility evaluated. The third stage ranks the facilities. Figure 1 shows the pseudo-code for these three procedures.

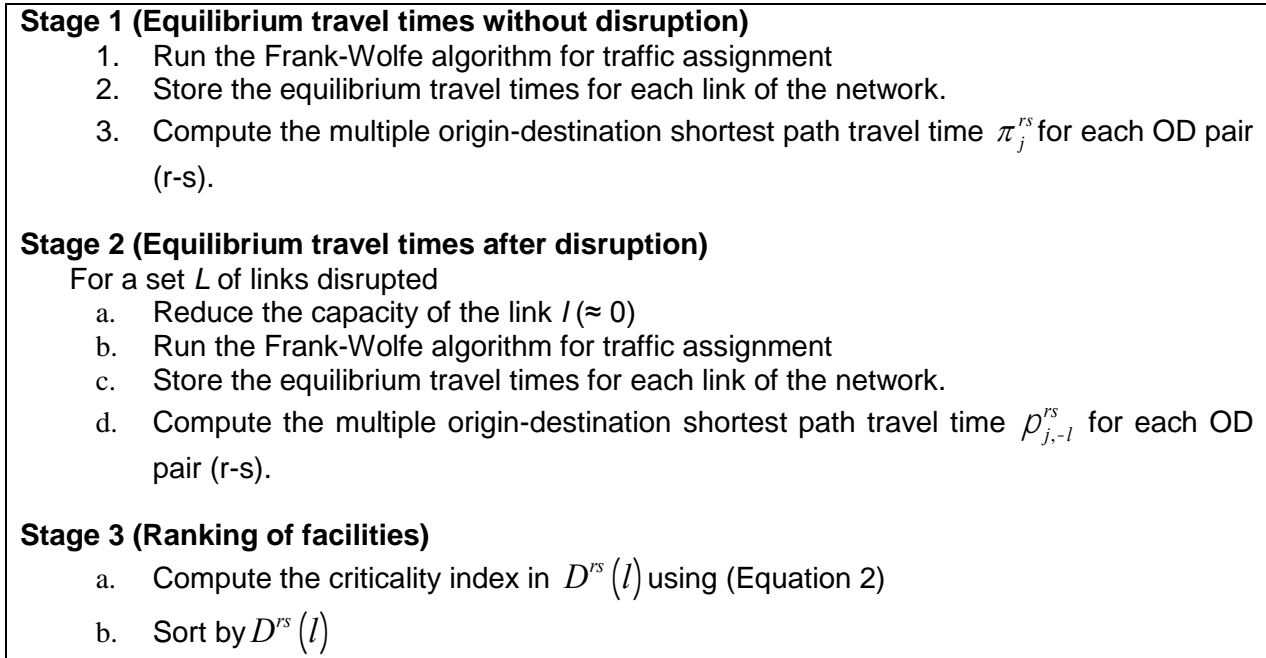


Figure 1: Pseudo-code of the procedure to rank facilities

The following sections describe the characteristics of the study area, its network and discuss the empirical results.

3. STUDY AREA

This study focuses on the Metropolitan Area of the Aburrá Valley in Colombia, which includes the city of Medellín and nine other municipalities. Traffic flow data was obtained from previous

transportation studies conducted in the region such as the 2005 Origin-Destination Survey and the Mobility Master Plan.

3.1. Zoning system

Two geographic areas were analyzed: the entire Metropolitan Area and the city of Medellín. Figure 2 shows the 419 Transportation Analysis Zones (TAZ) that are part of the Metropolitan Area (Área Metropolitana del Valle de Aburrá, 2006). Figure 2 also shows the TAZ for the city of Medellín. These TAZ were defined as the 16 Comunas of the city, which are the political divisions that facilitate aggregate data analysis.

Considering auto-ownership, traffic congestion and economic activity, the most important Comunas in Medellín are El Poblado, Laureles-Estadio, Belén and La Candelaria. The first three Comunas represent about 53% of the total vehicles in the city (Área Metropolitana del Valle de Aburrá, 2006). There are important socio-economic differences among the various Comunas. For instance, El Poblado is the home to the population with the highest average income, though it is the Comuna with the lowest population and road densities. This mix of high auto-ownership and low road density results in high congestion levels in this Comuna. La Candelaria contains the city's Central Business District where many bus routes converge, producing congestion.

In addition to the definition of the TAZ, origin-destination flows for the AM peak for the two areas were used for the analyses. For the Metropolitan area, the AM peak corresponds to about 990,000 trips, from a total of 4.8 million trips in a day in 2005. The AM peak inside the city corresponds to about 710,000 trips.

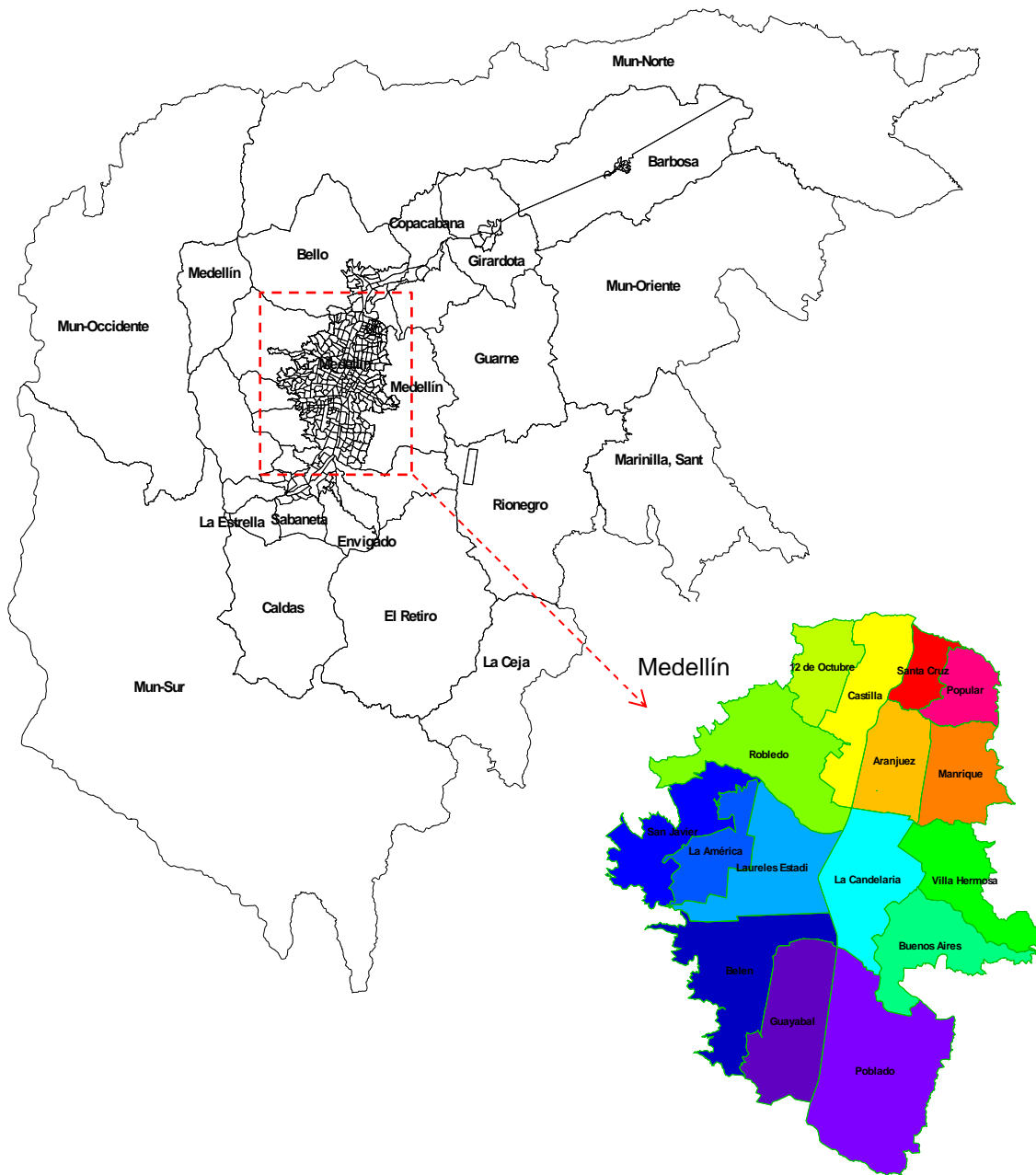


Figure 2: Zoning system of the study areas

3.2. The Network

The other important data for the analyses correspond to the transportation network. Medellín's network is comprised of 1516 nodes and 4502 links connecting all nodes (see Figure 3). The most important roads in the city are labeled in the figure below: Avenida Colombia, Autopista Sur,

4. EMPIRICAL RESULTS

This section discusses a set of numerical results using the AM peak O-D flows. First, these O-D flows were assigned to the network (Metropolitan area and Medellín) using the Deterministic User Equilibrium (UE) method. Based on Wardrop's first principle, UE states that the travel time on all used paths for any O-D pair equals the minimum travel time between the O-D; this is achieved when no traveler can improve his/her travel time by unilaterally changing routes. To assess the impacts of the flows on the networks' capacity and travel time, the cost function used for the links in the network, developed by the Bureau of Public Roads (BPR function), is given by:

$$t(x_a) = t_o \left[1 + \alpha \left(\frac{x_a}{c} \right)^\beta \right] \quad (3)$$

Where, $t(x_a)$ is the cost of using link a (given by time); t_o is the free flow time; x_a the flow assigned to link a ; c is the capacity of the link; and α, β are given parameters of the cost function, assumed at $\alpha = 0.15$ and $\beta = 4$.

Figure 4 shows the traffic assignment for the Metropolitan Area. As expected, the largest volumes of traffic use the main roads discussed in Section 3.2. Specifically Autopista Sur, Avenida Regional, Avenida El Poblado, Avenida Las Vegas, and Autopista Medellín-Bogotá.

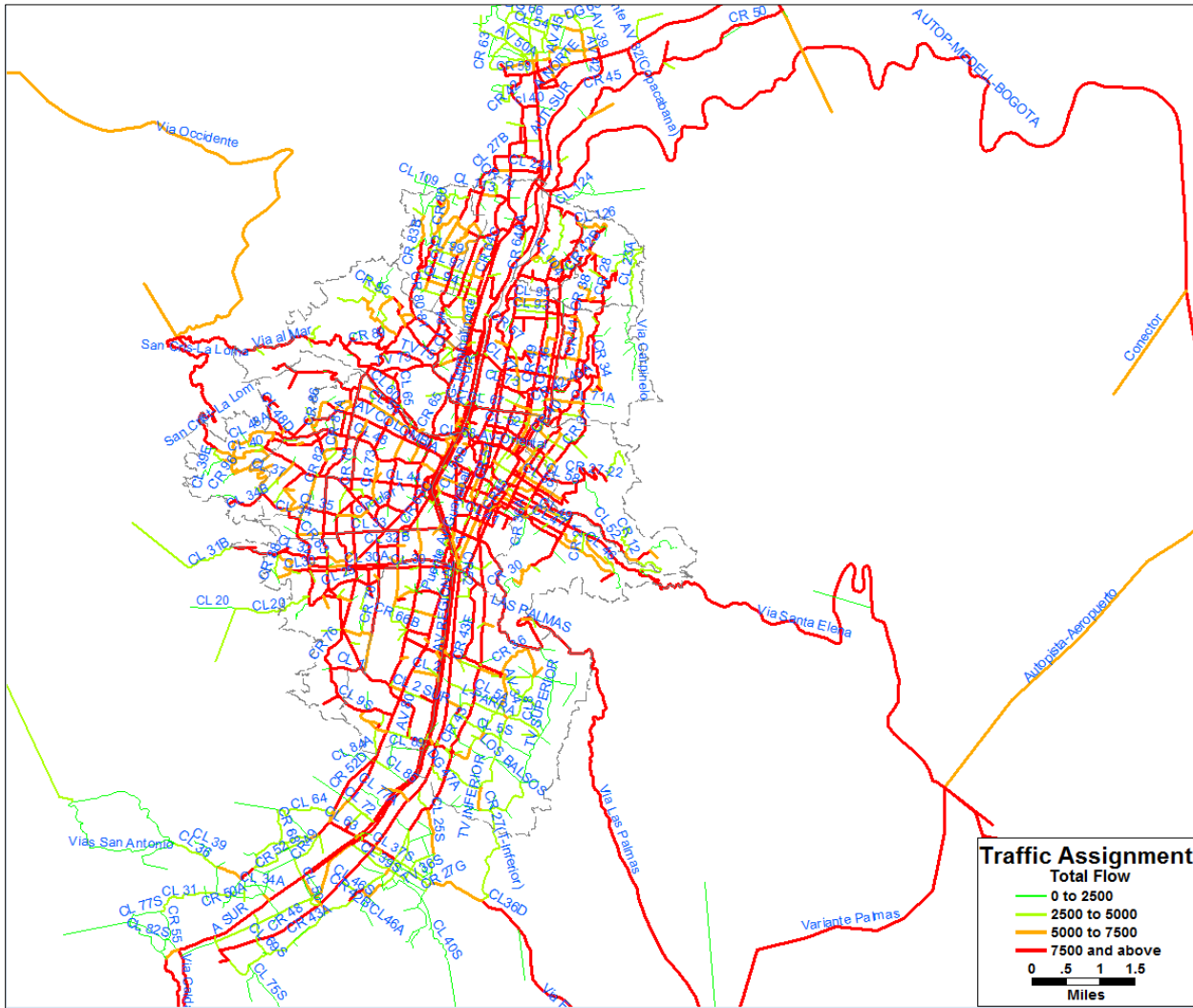


Figure 4: Traffic Assignment (Metropolitan Area)

Similarly, Figure 5 shows the traffic assignment for the O-D flows for the 16 Comunas. Here again, concentrations of the largest flows are located along the same corridors. Figure 5 also shows a higher concentration on the West side of the city resulting from the incoming traffic flow from the Vía Occidente. In addition, during peak hour, El Poblado Comuna and downtown Medellín (Comuna La Candelaria) are heavily congested due to bus and taxi traffic.

Name	Name
Autopista Norte	CR 37
Via Girardota	CL 31B
Vía Barbosa	CL 48D
Via Occidente	CL 34B
CR 34	Via la Ceja
Acceso Retiro	Avenida Regional
Autopista Medellín-Bogotá	Autopista Sur
CL 54	CL 52
CR 27-22	CR 28
CR 28	Vias San Antonio

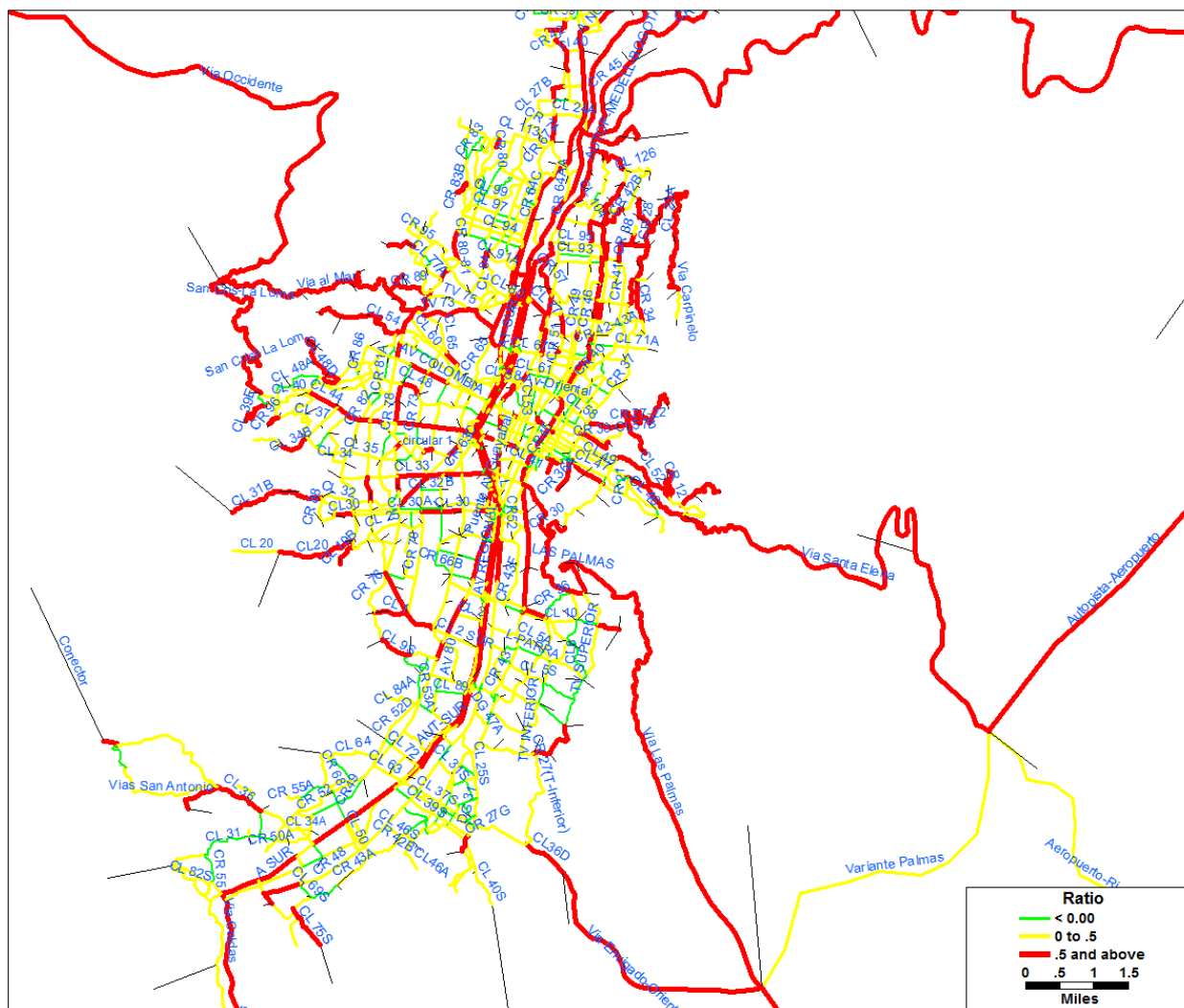


Figure 6: Critical Links in the Metropolitan Area

The same process was implemented for the City's network. Table 2 shows the 20 most critical links for the 16 Comunas. Considering that the flows inside Medellín represent about 70% of the total flows in the Metropolitan area, the similarity between the location of the critical links between shown in Figure 6 and Figure 7 comes as no surprise.

Table 2: Most Critical Links in Medellín

Name	Name
Avenida Regional	Puente CL 58(Minorista)
Autopista Sur	L
Puente CL 44(S.Juan)	CL 71
CL 33	CR 52
Avenida Guayabal	Las Palmas
Avenida Vegas	CR 65D
Avenida Poblado	DG 74B
CR 65	CR 46
CR 64C	PuenteCI 125(Soya)
Puente Ter.Norte(Mico)	Via al Mar

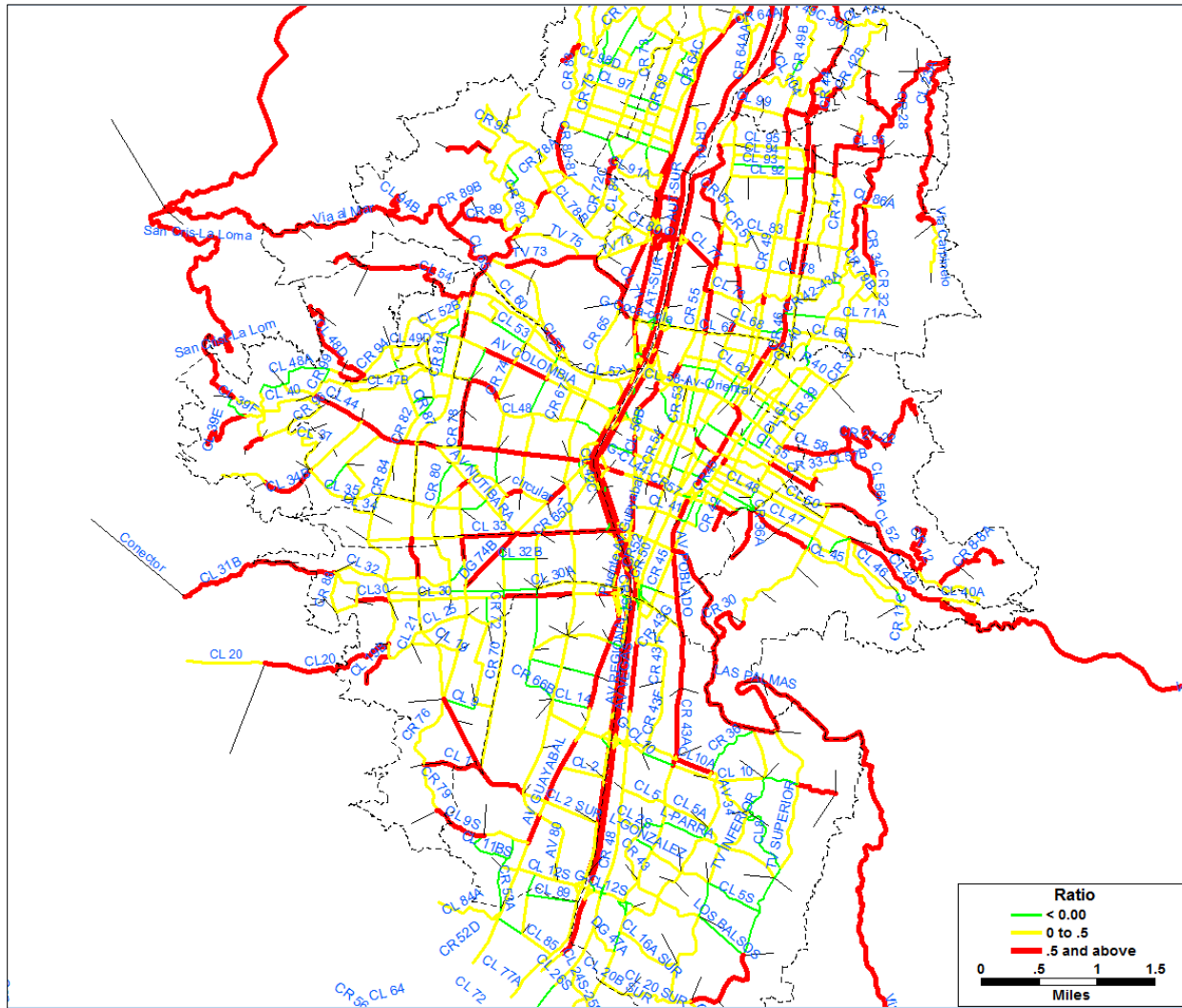


Figure 7: Critical Links in Medellín

Another objective of this paper was to identify the critical links in terms their impact in the connectivity between origin-destination pairs, measured by a comparison of travel times before and after the disruption.

5. CONCLUSIONS AND RECOMMENDATIONS

This paper discusses the implementation of a methodology to assess the critical infrastructure of the transportation network. Criticality is defined as the impact of a disrupted network in total travel times, based on the User Equilibrium traffic assignment. The assessment can be done for the entire network which provides a ranking of the most critical links for the overall system. In addition, a procedure methodology is proposed to assess the criticality of a link in the connectivity between origin-destination pairs, measured by a comparison of travel times before and after the disruption.

With an application to the transportation network of the Metropolitan Area of the Aburrá Valley which includes the city of Medellín and nine other municipalities in Colombia, the results provide insights about the critical and strategic road network facilities for the area (e.g., links, corridors). The analyses suggest that the corridors along Medellín river (NB and SB), 80th Avenue, 33rd Avenue, and Las Vegas Avenue are the most susceptible (critical) roads in the city. In essence, if the capacity of these corridors is affected (disrupted), the traffic in the city will collapse. Furthermore, comparing the critical links identified between the Metropolitan Area and the City alone, showed a high correspondence within the findings, which could be explained by the large share (almost 70%) of city's traffic over the Metropolitan area. The results also showed the level of criticality of different links when comparing the impact in the total travel times and the connectivity of specific links.

These results can be used, among other things, in the decision making process for future investments (e.g., increase capacity; building new infrastructure); for the design of sustainable transportation policies; for the operational and strategic planning (e.g., scheduling road work, maintenance); for the design of emergency routes in case of evacuation or to distribute supplies; and, for the implementation of future mobility plans in the city. It is expected that these methodologies can provide benefits to transportation planners and agencies of different geographic areas.

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