Controlling Congestion in a Neighborhood Center through Parking and Pedestrianization Policies

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Introduction

Traffic congestion affects many neighborhood or town centers and transit hubs as drivers converge from outlying areas to concentrated destinations at the center of the street network. This study addresses the congestion patterns on neighborhood networks that serve two types of demand: uniformly distributed origins and destinations, and trips to and from a central point. In such a neighborhood, demand is not uniformly distributed throughout the whole network. This structure of network can be used to represent a transit center, in which a substantial number of people seek to walk or drive to a transit station, or a town center, in which some part of the travel demand is concentrated on a central location.

The network or macroscopic fundamental diagram (MFD) relates density to flow in a network, which also characterizes traffic speeds and network capacity (Daganzo and Geroliminis, 2008; Geroliminis and Daganzo, 2008). Previous studies of city structure have focused exclusively on monocentric demand collapsed to a single corridor Anas et al. (1998); Rossi-Hansberg (2004); Solow and Vickrey (1971). Other studies have linked the MFD with parking policies (Liu and Geroliminis, 2016) and perimeter control (Haddad and Shraiber, 2014), seeking to control traffic within a larger central network area. This study makes use of continuous approximation models of demand in ring-radial networks to characterize the distribution of vehicular flow across the network. Although a similar approach has been use to model transit networks (Badia et al., 2014), this study provides general insights about the effective placement of parking, pricing of parking, and the required circumferential road capacity required for creating dedicated central bicycle/pedestrian zone.

Methodology

Consider the street network in a circular neighborhood that is characterized by a MFD, $q(k)$, in which average flow, q veh/lane·time, is a concave function of the density, k veh/lane·dist, as shown in Figure 1a. Each traffic state on the fundamental diagram is associated with an average traffic speed represented by the slope from the origin to the traffic state, $v(k)$. The maximum flow, q_c, is associated with a vehicle density of k_c. Traffic states to the left of this point are uncongested because increased density is associated with increased flow (solid curve), and the points to right are associated with wasteful congestion because increased vehicle density reduces flow (dashed curve).

In a neighborhood or city of radius R, consider a monocentric demand to and from the center as well as a baseline demand for monocentric radial demand of λ_r trips/dist^2·time for travel to or from the center. Over the same area there is a baseline demand density of λ_b trips/dist^2·time of average length l between origins and destinations distributed uniformly throughout the neighborhood. Figure 1b shows that this circular neighborhood with a ring-radial street network, can be locally approximated as a grid. The density

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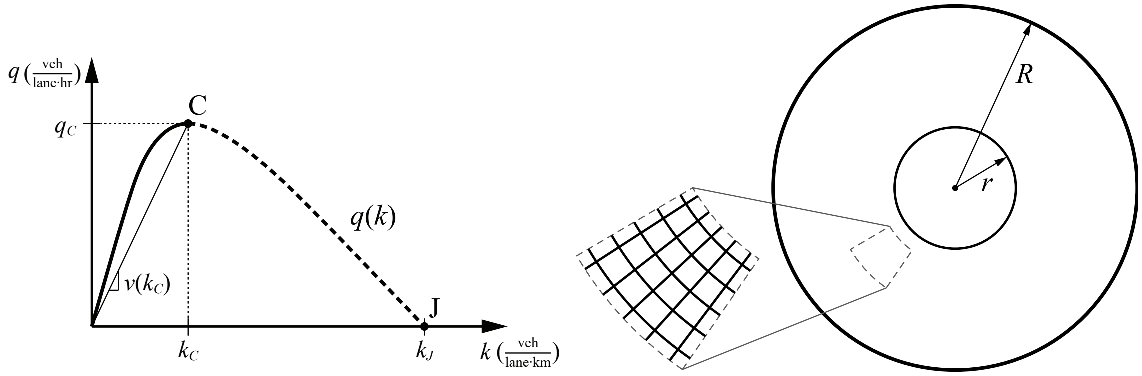


(a) Macroscopic Fundamental Diagram

(b) Ring-radial Network of Radius R

Figure 1: Aggregate traffic model for circular neighborhood

of street infrastructure in this network at radius r from the center is $\delta(r)$ lane·dist/dist^2. Efficient traffic management strategies should keep traffic states on the left side of the MFD by incentivizing drivers to use the network efficiently (Gonzales, 2015). Herein lies a challenge for cities and neighborhoods with at least some monocentric demand, because trips to and from the center lead to greater traffic demands at the center of the network than at the periphery.

In a neighborhood such as the one illustrated in Figure 1b, baseline traffic flows associated with average trip length l generate $q_b = \lambda_b l/\delta(r)$ flow across the network. The additional traffic flow associated with trips to and from the center varies with the distance from the center. Consider a narrow ring of width dr at radius r from the center. The total demand for trips crossing this ring is $\lambda_r\left(\pi R^2 - \pi r^2\right)$. Each of these vehicles travels a distance dr within the ring, and the amount of road infrastructure in the ring is $2\pi r\delta(r)$. As a result, the combined network flow from baseline and monocentric traffic at a distance r from the center is given by:

$$q(r) = \frac{\lambda_b l}{\delta(r)} + \frac{\lambda_r}{2\delta(r)}\left(\frac{R^2}{r} - r\right) \tag{1}$$

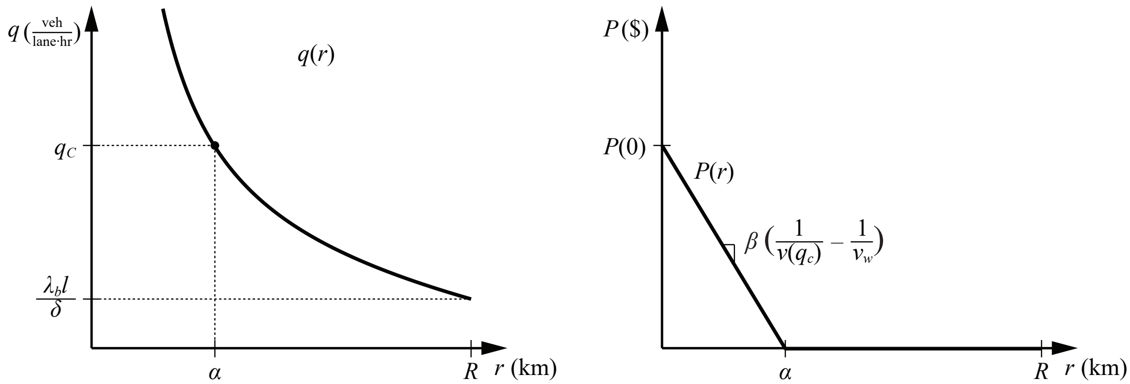
For simplicity, we may consider the density of infrastructure to be constant $\delta(r) = \delta$ across the neighborhood. Clearly, $q(r)$ increases toward infinity as $r \to 0$, so traffic must be prevented from concentrating in the very center of the network in order to maintain uncongested conditions. This is a role for traffic management policies associated with the provision of central parking or the closing of streets to create a pedestrian-only center.

Parking Management

The placement of central parking facilities can be used to manage congestion by forcing drivers to park at a distance α from the center and completing the trip on foot. From equation (1), $q(r)$ is a monotonically decreasing function of r when δ is constant (see Figure 2a). The goal is to identify radius α at which $q(\alpha) = q_c$, the capacity of the network. A feasible value of $\alpha \in (0, R)$ exists whenever the baseline demand is low enough that $\lambda_b l/\delta < q_c$. In this case, the minimum distance for placement of central parking facilities from the neighborhood center is given by solving for α:

$$\alpha = -\frac{1}{\lambda_r}\left(q_c\delta - \lambda_b l\right) + \sqrt{\frac{1}{\lambda_r^2}\left(q_c\delta - \lambda_b l\right)^2 + R^2} \tag{2}$$

A related policy is to determine price of parking at radius r from the center at which drivers are incentivized to park and walk rather than overcrowd the center of the network with cars. To maintain uncongested conditions, the price at radius r, $p(r)$, should be set at least high enough that the cost of parking and walking is no greater than the the cost of continuing to drive at speed $v(k_c)$, which is associated with the network capacity, q_c, and parking at the center for price $p(0)$. For a population with value of time, β \$/time, this



(a) Distribution of Network Flow

(b) Parking Price

Figure 2: Parking policy for radial trips

results in a location-specific parking price of

$$p(r) = p(0) + \beta r \left(\frac{1}{v(q_c)} - \frac{1}{v_w} \right) \quad \forall r \leq \alpha \tag{3}$$

where v_w is the speed of walking. The parking price beyond radius α may be normalized to zero as shown in Figure 2b, because parking prices are not needed to manage traffic congestion in outlying areas. In this case, the price of parking at the center will be

$$p(0) = \beta \alpha \left(\frac{1}{v_w} - \frac{1}{v(q_c)} \right) \tag{4}$$

Pedestrianized Neighborhood Center

Another approach to manage traffic in centralized locations is to close a central part of the network with radius γ to all vehicular traffic. In addition to forcing radial demand to park some distance from the center and walk, traffic patterns for distributed origin-destination pairs in the ring-radial network are also affected, because some routes must be diverted to travel around the pedestrianized center. Figure 3a shows the shortest path routing for three types of trips with an origin or destination outside the pedestrianized center and the other trip end at radius r and angle θ from the origin relative to center:

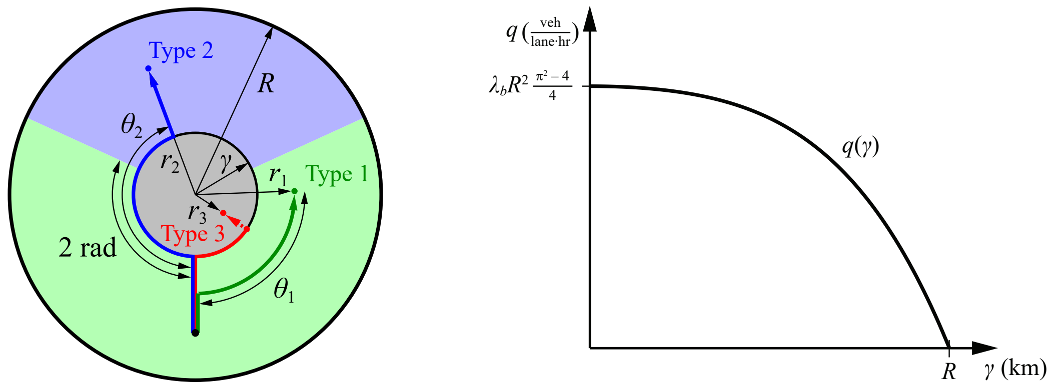
1. $r > \gamma$, $\theta \leq 2$ radians: route is unaffected by the pedestrianized zone

2. $r > \gamma$, $\theta > 2$ radians: route that would have passed through the center travels a distance $\theta \cdot \gamma$ around the perimeter of the pedestrianized zone

3. $r \leq \gamma$: route takes vehicle a distance $\theta \cdot \gamma$ around the perimeter of the pedestrianized zone to park nearest the destination, and the remaining radial distance is traveled on foot

Trips of type 2 and 3 contribute to circumferential travel around the pedestrianized zone. In order to make a policy to eliminate (or even dissuade) drivers from traveling through the center, sufficient capacity must be provided on the ring road at the perimeter of the controlled zone in order to carry this perimeter traffic.

For a uniformly distributed set of origins and destinations with density λ_b trips/dist^2·time, the expected traffic flow on the perimeter road at distance γ from the center is calculated using geometric probability. For each type of trip, the expected traffic (vehicle-distance/time) on the perimeter road is the product of three values: the number of trips originating in city between radius γ and R, the probability that a trip destination falls within a trip category, and the expected distance per trip on the perimeter road for the category. Dividing the total vehicle-distance/time by the length of the perimeter, $2\pi\gamma$, provides the flows of



(a) Effect on Routes of Distributed Trips (b) Traffic Flow on Perimeter Road at Radius γ

Figure 3: Pedestrianization policy for center of circular network

vehicles/time on the perimeter road at distance γ from the center for each type of trip:

$$q_1(\gamma) = 0 \tag{5}$$

$$q_2(\gamma) = \left[\lambda_b \pi \left(R^2 - \gamma^2\right) \times \frac{\pi - 2}{\pi} \cdot \frac{R^2 - \gamma^2}{R^2} \times \frac{\pi + 2}{2} \cdot \gamma\right] \frac{1}{2\pi\gamma} \tag{6}$$

$$q_3(\gamma) = \left[\lambda_b \pi \left(R^2 - \gamma^2\right) \times \frac{\gamma^2}{R^2} \times \frac{\pi}{2} \cdot \gamma\right] \frac{1}{2\pi\gamma} \tag{7}$$

The resulting bidirectional traffic flow on the perimeter road, at radius γ, is $q_p(\gamma) = \sum_{i=1}^{3} q_i(\gamma)$ vehicles/time. The average perimeter flow decreases slowly with γ (see Figure 3b), because a larger pedestrian zone requires vehicles to travel longer distances on the perimeter road. The required perimeter capacity only drops as γ approaches R, because the number of vehicle trips drops as more origin-destination pairs are captured within the pedestrianized center.

Conclusion

The proposed model presents a framework to support analytical analysis of distributions of traffic flows on centralized ring-radial networks. This allows aggregate traffic flow models to be applied to multimodal networks in which people seek to reach a crowded central location. The initial insights from these models show how policies like managing centralized parking or establishing central pedestrian-only zones can prevent concentrations of vehicles in the center of a network from tipping into congested conditions. The models also provide a basis to quantify the relationship between the network's vehicle-carrying capacity and the resulting travel times for users who are affected by vehicular traffic congestion or must switch to alternative modes of travel, such as walking.

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