Controlling Congestion in a Neighborhood Center for Ring-Radial and Grid Networks

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***Abstract*— Whether by intentional design or organic development, cities often exhibit travel patterns converging towards a central location. Even polycentric cities experience converging traffic flows to a degree, albeit towards multiple centers. This concentration of travel eventuates in congested city centers when the maximum throughput of the road network is exceeded, resulting in inefficient networks affecting the economic productivity and overall quality of city life. To address this issue, policies can be developed to encourage more spatially efficient travel, such as walking, cycling, or transit, by charging for parking or creating a dedicated bicycle/pedestrian zone. This paper presents a continuous approximation model using the Macroscopic Fundamental Diagram (MFD) of network traffic flow to provide insights into the placement and pricing of parking, as well as the required perimeter roadway capacity for the pedestrianization of the city center. This model is then empirically applied to the case study of Melbourne, Australia; a highly monocentric rectilinear grid city with a partially pedestrianized city center.**

I. 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 can be used to represent a network in which some part of the travel demand is concentrated on a central location, such as a transit station or town.

There is a mature body of literature modeling the relationship between city structure to traffic congestion. Previous studies of city structure have largely focused on monocentric demand collapsed to a single corridor [1–3]. On a macroscopic city network, traffic flow can be modeled using a macroscopic fundamental diagram (MFD), which relates traffic density to flow in a network, which also characterizes traffic speeds and network capacity [4–6]. Other studies have linked the MFD with parking policies [7, 8] and perimeter control [9, 10], seeking to control traffic within a larger central network area. For transit networks, analytical approaches making use of smooth continuous approximations have employed ring-radial or rectilinear grids to model transit network operation and reveal optimal design parameters [11–14]. This study makes use of continuous approximation models of demand in ring-radial and rectilinear grid networks to characterize the distribution of vehicular flow across the network. The purpose is to provide a simple model to provide general insights about the effective placement of congestion reducing policy zones (e.g., no parking or parking pricing zones), and also the perimeter road capacity required for a more severe policy of creating a dedicated central pedestrianized zone.

II. Methodology

Consider a street network in a neighborhood or city 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 1. 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).

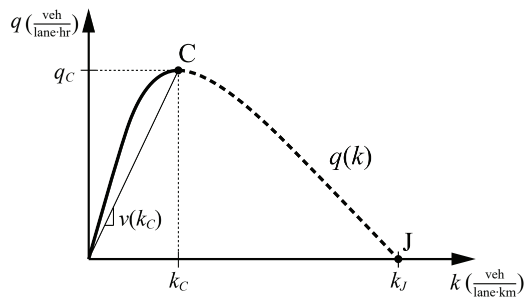

Fig. 1: Macroscopic Fundamental Diagram

Consider two types of travel demand patterns in a neighborhood or city; a monocentric demand of λ_m trips/dist^2·time for travel to or from the center (e.g., commuters), and 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 (e.g., ambient "cross-town" traffic). The average trip length l for baseline traffic flows across the network in a rectilinear grid may be represented as half the

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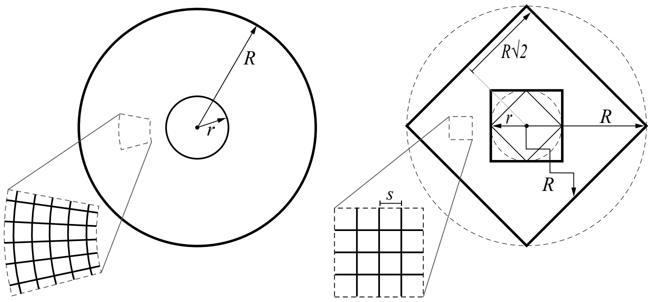
possible travel distance $l = R$, and for a circular ring-radial city, it may be calculated as $l = \frac{128R}{45\pi}$.

Carrying this demand is a street network with either a ring-radial structure as illustrated in Figure 2a, or alternatively a uniform rectilinear grid structure as illustrated in Figure 2b. Both cities possess the dimension R as the actual travel distance, but in the rectilinear grid the equivalent "Manhattan" travel distance at non-orthogonal angles results in the square diamond shape of dimension D, which can be calculated as $D = R\cos(\pi/4) = R\sqrt{2}/2$. The density of street infrastructure is δ lane·dist/dist^2, which is either constant dependent upon street spacing s (e.g., as in the case of a uniform rectilinear grid), or can vary with radius distance r from the center in $\delta(r)$.



(a) Ring-radial Network (b) Rectilinear Network

Fig. 2: Aggregate Traffic Model for Circular and Rectilinear Networks

Efficient traffic management strategies should keep traffic states on the left side of the MFD in Figure 1 by incentivizing drivers to use the network efficiently [6]. 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 Figures 2a and 2b, 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 or square of infinitesimal width dr at radius r from the center. The total demand for trips crossing this ring is $\lambda_m\left(\pi R^2 - \pi r^2\right)$ in a ring-radial city, or $\lambda_m\left(2R^2 - 2r^2\right)$ crossing the square in a rectilinear grid city. Each of these vehicles travels a distance dr within the ring or square, and the amount of road infrastructure is $2\pi r\delta(r)$ in the ring, and in the square is $8r\delta$ as "Manhattan distance" (or $4\sqrt{2}r\delta$ as 45° straight line square perimeter). As a result, the combined network flow from baseline and monocentric traffic at a distance r from the center in a ring-radial city is given by:

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

and in the rectilinear grid city by:

$$q(r) = \frac{\lambda_b l}{\delta} + \frac{\lambda_m}{4r\delta}\left(\frac{R^2}{r} - r\right) \tag{1b}$$

For simplicity in the ring-radial city, we may consider the density of infrastructure to be constant $\delta(r) = \delta$ across the neighborhood, as is the case in the rectilinear grid city. 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.

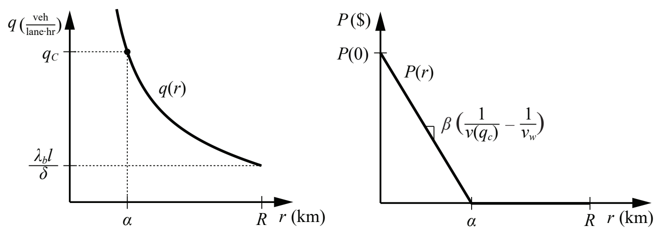
A. Parking Management

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 3a). 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 $\lambda_b l/\delta < q_c$ for ring-radial and rectilinear grid networks, respectively. In this case, the minimum distance for placement of central parking facilities from the neighborhood center in a ring-radial city is given by solving for α:

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

and for a grid city by:

$$\alpha = -\frac{2}{\lambda_m}(q_c\delta - \lambda_b l) + \sqrt{\frac{4}{\lambda_m^2}(q_c\delta - \lambda_b l)^2 + R^2} \tag{2b}$$



(a) Distribution of Network Flow (b) Parking Price

Fig. 3: Parking Policy for Radial Trips

A related policy is to determine the 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 not 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 results in a location-specific parking price of

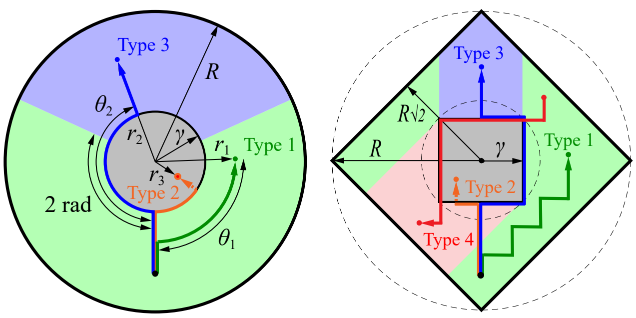
$$p(r) = p(0) + \beta r \left(\frac{1}{v(q_c)} - \frac{1}{v_w} \right) \quad \forall r \leq \alpha \tag{3}$$

where v_w is the speed of walking. The parking price beyond radius α may be normalized to zero as shown in Figure 3b, 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

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

B. *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 network are also affected, because some routes must be diverted to travel around the pedestrianized center (see Figures 4a and 4b).



(a) Ring-radial Routes (b) Rectilinear Routes

Fig. 4: Effects of Pedestrianization Policy on Distributed Network Routes

In a ring-radial network, there are three route types with trips of type 2 and 3 contributing to circumferential travel around the pedestrianized zone. The affected routes depend on the angle θ exceeding 2 radians from the origin to destination, relative to the center [13, 15]:

1) $r > \gamma$, $\theta \leq 2$ radians: route is unaffected by the pedestrianized zone
2) $r \leq \gamma$: 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
3) $r > \gamma$, $\theta > 2$ radians: route that would have passed through the center travels a distance $\theta \cdot \gamma$ around the perimeter of the pedestrianized zone

In order to make a policy to eliminate (or even dissuade) drivers from traveling through the center, sufficient capacity must be provided on the perimeter road 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, provides the flows of vehicles/time on the perimeter road at distance γ from the center for each type of trip. The traffic flow components on the perimeter road in a ring-radial network is:

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

$$q_2(\gamma) = \left[\lambda_b \pi (R^2 - \gamma^2) \times \frac{\gamma^2}{R^2} \times \frac{\pi}{2} \cdot \gamma \right] \frac{1}{2\pi\gamma} \tag{5b}$$

$$q_3(\gamma) = \left[\lambda_b \pi (R^2 - \gamma^2) \times \frac{\pi - 2}{\pi} \cdot \frac{R^2 - \gamma^2}{R^2} \times \frac{\pi + 2}{2} \cdot \gamma \right] \frac{1}{2\pi\gamma} \tag{5c}$$

The case is similar in a rectilinear network, but only routes located immediately opposite the pedestrianized zone are affected, and do not depend upon θ. This creates an additional fourth trip type to account for the probability of diagonal trips. However, unlike the ring-radial network which concentrates traffic along the perimeter road, a rectilinear grid provides multiple equivalent shortest routes around the pedestrianized center. This means that the quantity of perimeter infrastructure is multiplied by the average number of equivalent routes $\frac{R-2}{4s}$. The perimeter traffic in a rectilinear grid network is:

$$q_1(\gamma) = 0 \tag{6a}$$

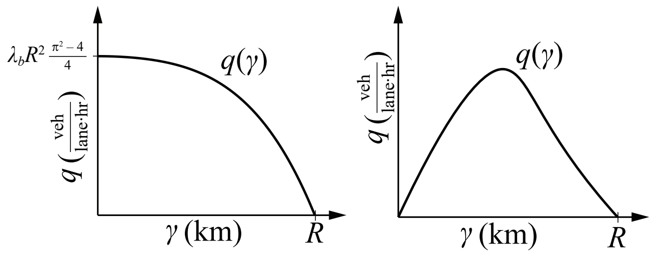
$$q_2(\gamma) = \left[2\lambda_b (R^2 - \gamma^2) \times \frac{\gamma^2}{R^2} \times \frac{\gamma}{2} \right] \frac{4s}{8\gamma(R-2)} \tag{6b}$$

$$q_3(\gamma) = \left[2\lambda_b (R^2 - \gamma^2) \times \frac{\gamma(2R - 3\gamma)}{2R^2} \times 3\gamma \right] \frac{4s}{8\gamma(R-2)} \tag{6c}$$

$$q_4(\gamma) = \left[2\lambda_b (R^2 - \gamma^2) \times \frac{\gamma(\sqrt{2}R - \gamma)}{R^2} \times 3\gamma \right] \frac{4s}{8\gamma(R-2)} \tag{6d}$$

The resulting bidirectional traffic flow on the perimeter road, at radius γ, is the sum of these in $q_p(\gamma) = \sum_{i=1}^{3} q_i(\gamma)$ vehicles/time. In the ring-radial network, the average perimeter flow decreases slowly with γ (see Figure 5a), 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.

Alternatively in the rectilinear grid network, the required perimeter traffic capacity follows a concave shape (see Figure 5b), because vehicles can more easily bypass the zone to reach their destination. This provides potential to implement pedestrianization policies in cities with rectilinear grid structures.



(a) Ring-radial Perimeter Flow (b) Rectilinear Perimeter Flow

Fig. 5: Traffic Flow Along Perimeter of Pedestrianized Zones

TABLE I: Input Parameters for Melbourne model

Parameter	Value	Units
R	15	km
l	15	km
s	0.95	km
δ	2.71	$^{lane\,\cdot\,dist}/_{dist^2}$
β	20	$^{\$}/_{hr}$
λ_b	150	$^{trips}/_{km^2\,\cdot\,hr}$
λ_m	90	$^{trips}/_{km^2\,\cdot\,hr}$
q_c	2000	$^{trips}/_{lane\,\cdot\,hr}$
v_f	40	$^{km}/_{hr}$
v_w	5	$^{km}/_{hr}$
$v(g_c)$	20	$^{km}/_{hr}$

III. Application: Melbourne, Australia

Melbourne, Australia is a highly monocentric city with a sprawling rectilinear grid network (see Figure 6). Perhaps a more serendipitous feature is that the Central Business District (CBD) is already partially pedestrianized and oriented 62° off from overall city grid (the overall city and CBD grids are respectively rotated 8° and 70° clockwise). The city provides an excellent empirical application for the model, potentially revealing policy insight for parking and pedestrianization.

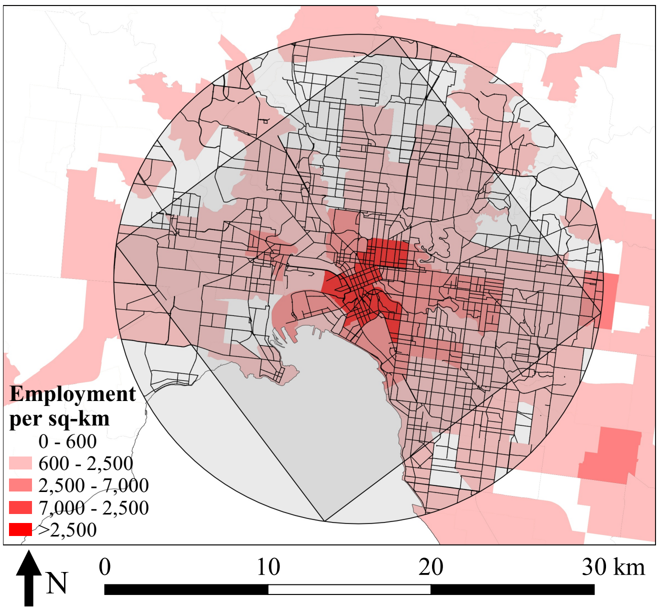
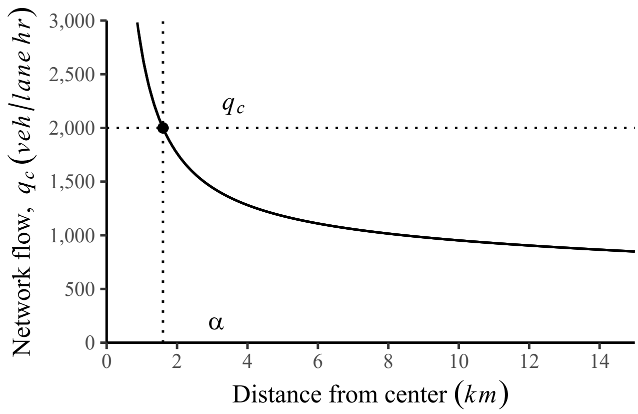


Fig. 6: Street Network and Employment Density in Melbourne, Australia

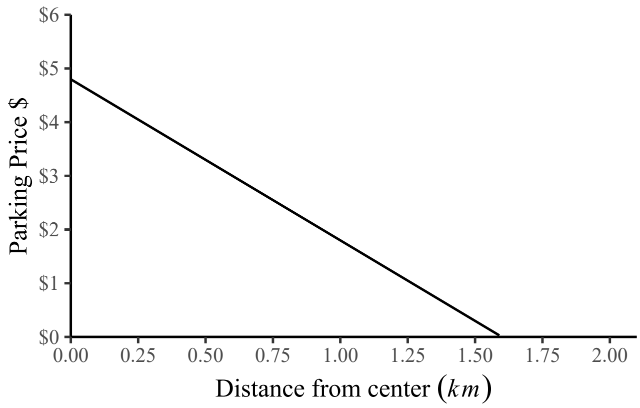
The input parameters used for the model are summarized in Table I. The average network density δ was calculated by dividing total road length L by the total area in the shaded region shown in Figure 6, resulting in $\frac{1917.19\ km}{706.54\ km^2} = 2.71\ ^{lane\,\cdot\,dist}/_{dist^2}$. The average street spacing is then calculated as $s = \frac{8R^2}{L-2R}$.

A. Parking Management

Assuming a critical network throughput threshold (q_c) is determined (or decided) as 2000 $^{veh}/_{lane\,\cdot\,hr}$, the resulting parking policy zone begins at a radius of 1.6-km from the center, as shown in Figure 7a. Then, assuming a value of time of 20$^{\$}/_{hr}$, the parking pricing within this zone is a maximum of \$4.80 at the center, as shown in Figure 7b.



(a) Network Flow at Distance α



(b) Parking pricing

Fig. 7: Parking Placement and Pricing

It is interesting to note, the calculated zone corresponds closely with the historic inner-core and current "Free Tram Zone" in the CBD (see Figure 8).

B. Pedestrianized Neighborhood Center

The parking pricing zone could be pedestrianized instead by placing parking facilities along the perimeter and closing the roads. Exploring this possibility by using the value of α

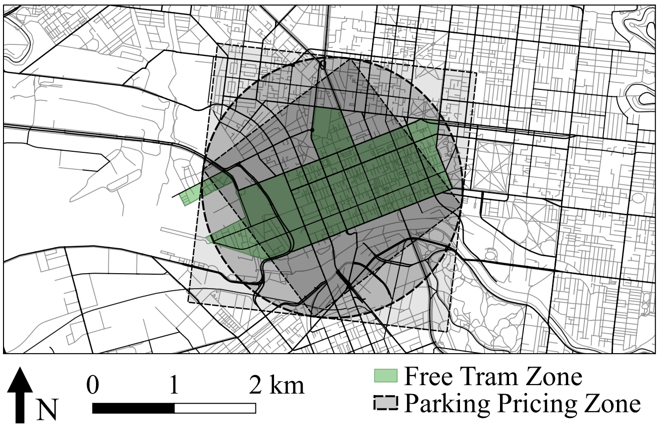


Fig. 8: Parking Pricing Zone and CBD

as the perimeter radius γ, the resulting traffic demand along the perimeter becomes $2410\ {}^{veh}/_{lane\,\cdot\,hr}$.

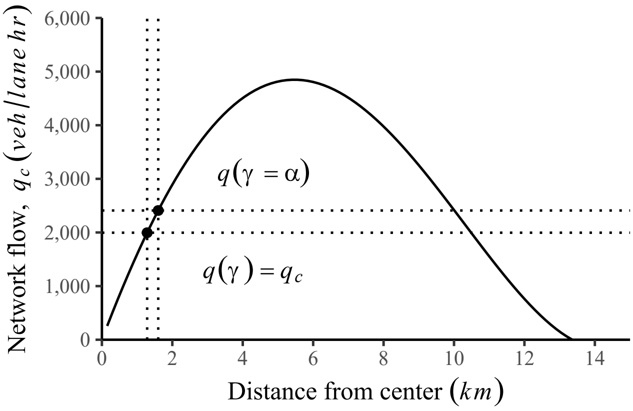


Fig. 9: Traffic flow on Perimeter at Radius γ

In this case, using the parking perimeter distance as the pedestrianized zone distance (i.e., $\alpha = \gamma$), results in traffic flow around the center exceeding the specified limit of q_c=2000 ${}^{veh}/_{lane\,\cdot\,hr}$ (see Figure 9). Alternatively, complementary policies may be used where the parking zone at 1.6-km extends beyond the boundary of the pedestrianized zone at $\gamma = 1.28$-km, keeping perimeter traffic below capacity q_c while still pedestrianizing the center.

IV. Discussion

The presented model provides a continuous approximation model to reveal general insight into the design of congestion reducing policy zones overlaid upon a city ring-radial or rectilinear grid network. The results provide an interesting case study application which roughly correspond to the real-world pedestrianization policies in Melbourne's CBD. However, the results are not quantitatively validated and any conclusions are purely speculative at this point. The model is also limited in several ways. First, it does directly model human behavior in the way that a more disaggregate behavioral model can, but instead relies on aggregated behavior (i.e., observed MFD). Second, the model lacks general multi-modality by fundamentally focusing on modeling automobile travel and ignoring transit. However, despite those limitations, the model provides a parsimonious method for approximating optimal policy outcomes that would otherwise be difficult to achieve with a more sophisticated approach.

V. Conclusion

The model presents a framework to support analytical analysis of distributions of traffic flows on centralized ring-radial and rectilinear 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 or biking.

Although the model provided interesting insights, it is a highly assumptive and simplified approximation with inherent limitations. The model is not intended to be a universal transport model that accounts for complex human behavior, it is simply intended to provide general insight for the placement and design of congestion reduction policy zones. The model's results could perhaps be validated against, or even fed into, more sophisticated models to provide more refined results. Moreover, future work on the model could be to expand it to include the impact on, and coordination of, multi-modal systems. For example, complementary transit priority policies in the congestion reduction zones in order to provide a more effective equilibrium outlet for travel demand, rather than simply discouraging travel.

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