Impact of pedestrianization on traffic in a circular city

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ABSTRACT
This paper presents an evaluation of the impacts of pedestrianization from a traffic management point of view. Based on a user equilibrium traffic assignment in an idealized ring-radial city, the model characterizes the flow distribution patterns in a neighborhood with a central pedestrian area that cars are not allowed to enter. With uniformly distributed demand, the analysis shows that there are not significant benefits of introduicing such a zone in terms of travel time of the users who have to walk long distances. However, as soon as they can increase their moving speed within a car-free central area, by using bicyles for example, the implementation of a pedestrian center become beneficial. The model gives quantitative indications regarding the optimal size of a pedestrian center in view of providing theoretical traffic related guidelines for urban planners.

Keywords: Pedestrianization, traffic management, flow distribution

INTRODUCTION

Pedestrianization is a more and more implemented measure in several cities around the world as a way to face various crucial issues. According to N. Soni and N. Soni (2016) the benefits are not only environmental or congestion related but also economic, social and health related. However, only a few empirical studies (Cairns et al, 2002; Keseru et al 2016) were made to analyze the impact of the creation of a pedestrian zone on the traffic nearby and even less was done from a more theoretical point of view. Although several papers developed assignment models to determine optimal pricing and cordon toll location to reduce congestion in city centers (Mun et al, 2005; H.W. Ho et al, 2005), the search for the appropriate characteristics of a pedestrian zone is a problem barely treated in the literature.

Thus, we tried in this paper to draw some general principles on the traffic distribution around a pedestrian zone in view of giving out guidelines for urban planners. The adopted approach lies within a series of models based on idealized circular cities. Smeed (1963) and Haight (1964) first established the features of trips in such areas according to different network patterns only with travel distances considerations. Lam and Newell (1967) then tried to find analytically a flow-based equilibrium in a ring-radial network in wich all travelers want to exit the CBD. Polar routeings were also used to design optimal transit networks (Vaughan, 1984; Badia, Estrada and Robusté, 2014) but these analyses were not directly based on the distribution of vehicle flows over the network.

These models often allow a clearer overview on the influence of different parameters but remain a very simplified representation of existing cities. A way to take into account a part of the complexity of real networks is to make use of the Macroscopic Fundamental Diagram (MFD) which relates density to flow in a network while characterizing traffic speed and network capacity (Daganzo and Geroliminis, 2008; Geroliminis and Daganzo, 2008). Although the concept of MFD can be the starting point to design parking policies (Liu and Geroliminis, 2016) or perimeter control (Haddad and Shraiber, 2014), only an experimental example was used in this study.

METHODS

Network structure and demand distribution

Consider a circular neighborhood only composed of circular and radial roads as the one represented in Figure 1. The street network surrounds a central circular-shaped pedestrian zone. It is characterized by the number of circular roads n_c, the number of radial roads n_r, the distance between adjacent circular roads d, the radius of the neighborhood R, and the radius of the pedestrian zone γ. The demand is divided into two kinds of distributions: a uniform demand associated to a density λ_b trips/dist^2 and a monocentric demand λ_c trips/dist^2. Centroids are located at every intersection and each of them generates a number of trips proportional to its area. For a centroid associated to an area of surface S, $\lambda_b S$ trips are uniformly shared out of all over the network and $\lambda_c S$ trips head to the center of the neighborhood.

Only two modes are considered: travel by personal car over the road network and walking inside the pedestrian zone. The case where all travelers use bicycles instead of walking when moving inside the pedestrian zone will be developed further. The hypotheses made on traveler route choices are: 1) If the destination is located inside the pedestrian zone and the origin outside, the closest point from the destination on the road of radius γ is reached by car and the rest is covered by foot; and 2) If both origin and destination are inside the pedestrian zone, only walking mode is used. The objective is to observe general patterns on the influence of the pedestrian area on the distribution of traffic flow so that the network can be managed to avoid congestion.

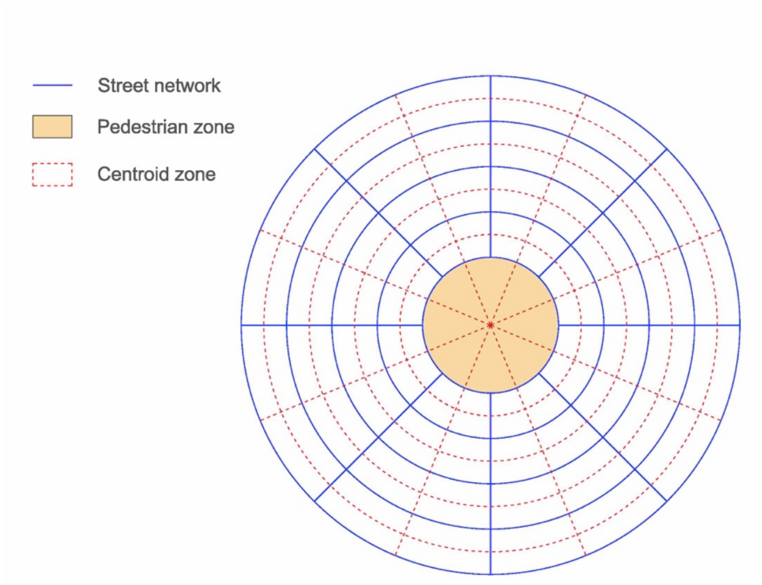


Figure 1: Idealized polar network for $n_c = 5$ and $n_c = 8$

Traffic assignment

In spite of the simplicity of the network structure, the flow distribution is very difficult to established analytically. Instead a numerical examples can be studied to get an outline of the influence of different parameters. To draw a spatial traffic distribution, the exhaustive description of the network is combined with a more aggregated approach based on an MFD. The Frank-Wolfe assignment algorithm was applied to a graph of $n_c \times n_r$ nodes representing the polar network. The baseline flow between two centroids of surface S_{origin} and $S_{destination}$ is $\lambda_b S_{origin} \frac{S_{destination}}{\pi R^2}$. The central flow originating from a centroid is $\lambda_c S_{origin}$.

Each link has the same cost function, which was defined from the Yokohama's MFD established by Geroliminis and Daganzo, (2008). Yokohama's street pattern has no particular similarities with the idealized polar network considered in this model, but the use of its MFD can be a way to account for the complexity of traffic flow in a dense city. Since we are interested in managing a street network to avoide congested conditions, we choose to focuse on a travel time function that represents the uncongested branch of the MFD and avoids the inefficient backward bending curve. This cost function only depends on travel time t, which is related to the flow q as follow:

$$t(q) = l\,\frac{k(q)}{q} \qquad \text{for } q < \mu \qquad (1)$$

$$t(q) = t_c \times \left(\frac{q}{\mu}\right)^{20} \qquad \text{for } q > \mu$$

where μ is the capacity of the link, assumed to be the same for every link, l is the length of the link and $k(q), veh/km$ the concentration given by the uncongested branch of Yokohama's MFD. The exponent of q in the expression of t_k when $q > \mu$ is was chosen high to limit the case where a flow which overtake the capacity is assigned to a link in a user equilibrium situation.

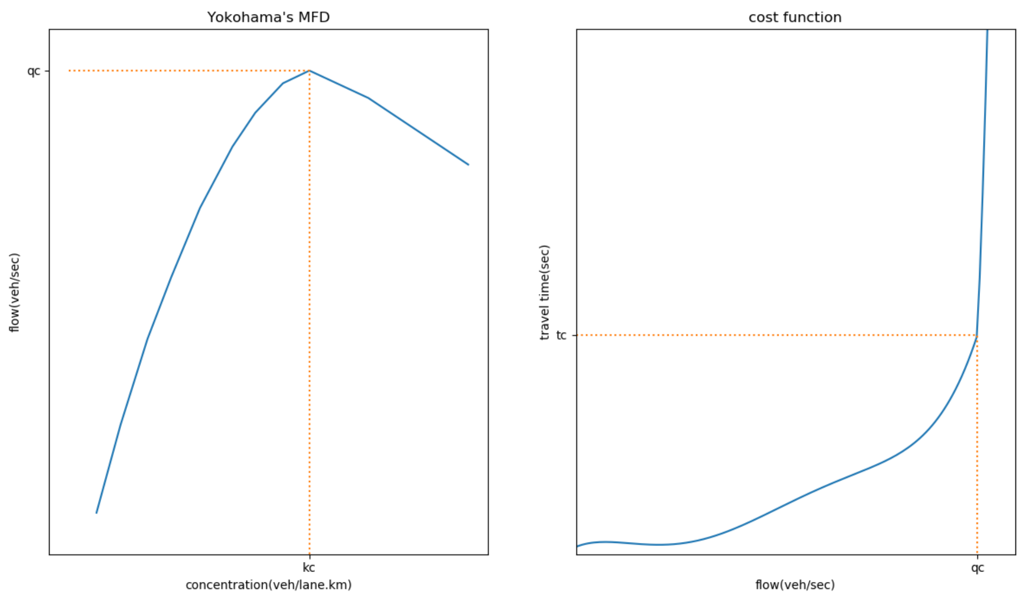


Figure 2: Yokohama's MFD (Geroliminis and Daganzo, 2008) and shape of the cost function

Pedestrian moves

The hypothesis made on travelers' route choices lead to three types of trips:

- Type 1: Unimodal walking trips between two points of the pedestrian zone
- Type 2: Bimodal trips when the origin or the destination is located inside the pedestrian zone
- Type 3: Unimodal car trips between two points located outside the pedestrian zone

Also, while moving in the pedestrian area a traveller can only move toward the center or around it by following a circle arc.

A distinction must also be made according to weather a trip is generated by the baseline demand (b) or by the central demand (c). Let D_{ij} be the demand amount and l_{ij} the average walking distance covered in each case ij where i=1 or 2 and j=c or d. The total distance covered by foot L is then:

$$L = D_{1b}l_{1b} + D_{1c}l_{1c} + D_{2b}l_{2b} + D_{2c}l_{2c} \tag{2}$$

Each of these distance components is defined as follows:

- D_{1b} is the product of the number of trips from the baseline demand originating from the pedestrian zone by the proportion of these trips which ending inside the pedestrian zone: $D_{1b} = \lambda_b \pi \gamma^2 \times \frac{\pi\gamma^2}{\pi R^2}$
- D_{2b} is the sum of the trips originating from the pedestrian zone which end outside and the ones which start outside and end inside. Both of these terms are equal to $\lambda_b \pi (R^2 - \gamma^2)\frac{\gamma^2}{R^2}$, so $D_{2b} = 2\lambda_b \pi (R^2 - \gamma^2)\frac{\gamma^2}{R^2}$.

- D_{1c} and D_{2c} are the total number of trips from the central demand originating inside the pedestrian zone and outside, respectively. $D_{1c} = \lambda_c \pi \gamma^2$ and $D_{2c} = \lambda_c \pi (R^2 - \gamma^2)$
- Haight (1964) showed that the average distance travelled by an individual going from the edge of a disk of radius r to a random point inside the disk with only ring-radial moves is $\frac{5\pi-4}{3\pi} r$. Given that the density probability function f of the random variable which gives the distance to the center of a point taken randomly in the disk of radius γ is $f(x) = \frac{2x}{\gamma^2}$, the average distance l_{ped} travelled by a pedestrian in the pedestrian zone is given by:

$$l_{1b} = \int_0^\gamma \frac{5\pi - 4}{3\pi} r\, f(r) dr = \frac{2(5\pi - 4)}{9\pi} \gamma$$

- Every trip from central demand is supposed to end at the center of the city. Thus l_{1c} is the average distance between a point taken randomly in the disk of radius γ and the center, that is $\frac{2}{3}\gamma$.
- $2b$ trips have destinations that are uniformly distributed over a disk portion of angle $\frac{2\pi}{n_c}$. l_{2b} is the distance between a centroid located on the road of radius γ and this final destination. This distance is composed of a radial part and a circular part. The expected radial part is $\frac{1}{3}\gamma$. The expected circular part is the product of the expected radial part by the expected angle between the centroid and the destination, which is $\frac{1}{4} \times \frac{2\pi}{n_c}$. Finally, $l_{2b} = \frac{1}{3}\gamma + \frac{1}{3}\gamma\left(\frac{1}{4} \cdot \frac{2\pi}{n_c}\right) = \frac{\gamma}{3}\left(1 + \frac{4\pi}{n_c}\right)$.
- l_{2c} is the distance between a centroid of the road of radius γ and the center of the city, that is γ.

Replacing all D_{ij} and l_{ij} in (2), it comes:

$$L = A\gamma^5 + B\gamma^3 + C\gamma \qquad \text{with} \quad \begin{cases} A = \frac{2}{3R^2}\lambda_b\left(\frac{2\pi-4}{3} - \frac{4\pi}{n_c}\right) \\ B = \frac{\pi}{3}\left(2\lambda_b\left(1 + \frac{4\pi}{n_c}\right) - \lambda_c\right) \\ C = \lambda_c \pi R^2 \end{cases} \tag{3}$$

This total walking distance is of course a monotically increasing function of γ in the interval $[0; R]$.

Dimensionless Parameters

To have a more general idea of the influence of the different parameters, the car flow distribution was analysed through the variation of three unitless parameters. Due to the fundamentally physical relationship between the size of the city, the size of the network, the demand, and the capacity of streets, there must be a physical relationship between these parameters. The 7 following variables: $q, r, \gamma, R, d, \mu, \lambda_b$ involve only 2 fundamental dimensions: time and distance. According to the Buckingam-Pi theorem, any physical relationship that exists between these values can be rewritten in terms of a set of $7 - 2 = 5$ dimensionless parameters. The five parameters selected for the analysis are: $\frac{q}{\mu}$, $\frac{r}{R}$, $\frac{\gamma}{R}$, $\frac{d}{R}$, $\frac{\lambda_b R}{\mu\delta}$, where δ is the density of road infrastructure equal to $\frac{Total\ road\ lenght\ in\ the\ network}{Network\ surface} = \pi\left(\frac{1}{d} + \frac{1}{R-\gamma}\right)$. It was verified that for different values of the 7 original variables letting $\frac{\gamma}{R}$, $\frac{d}{R}$ and $\frac{\lambda_b R}{\mu\delta}$ constant the curve defined by $\frac{q}{\mu} = f\left(\frac{r}{R}\right)$ remains unchanged.

RESULTS

To determine the relevance of a pedestrian zone in a neighborhood from a traffic management perspective, the influence of two main parameters was studied: the size of the pedestrian zone and the demand distribution. We will first present how they impact the flow distribution across the network before analizing the evolution of a global performance indicator. In all the following simulations, consider a city with a radius $R = 2km$, a distance $d = 0.1$km between two circular streets, $n_c = 16$ radial streets and a constant lane capacity defined by Yokohama's MFD $\mu = 486veh/h$.

Traffic distribution

Uniform demand

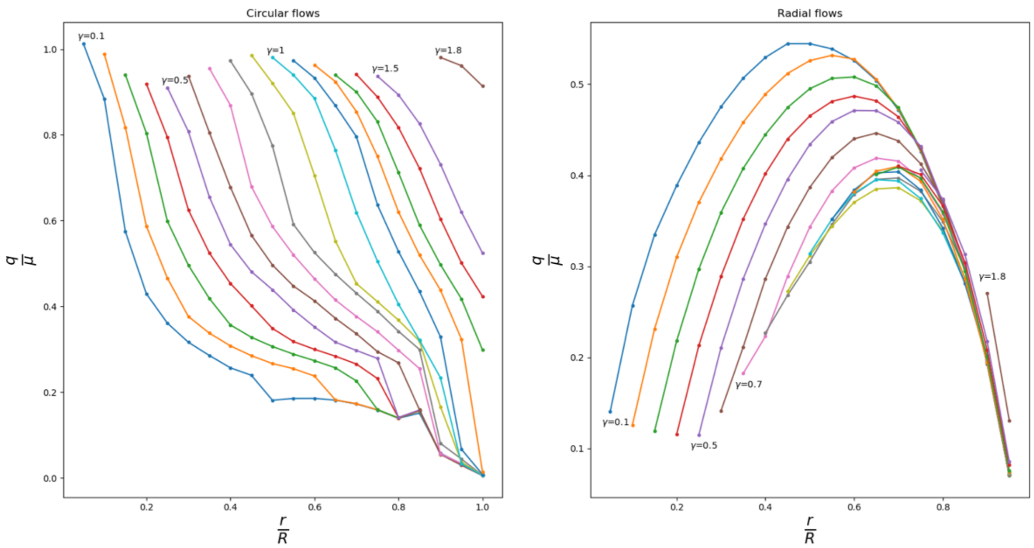
Let us first consider only a uniform demand distribution ($\lambda_c = 0$). Figure 3a shows the evolution of the ratio $\frac{q}{\mu}$ at a distance r from the center on circular roads (a) and radial roads (b) according to differents values of $\frac{\gamma}{R}$. The parameters used for the simulation are summarized in Table 1.

In this uniform demand scenario, the geometry of the network makes the central rings more congested regardless of the size of the pedestrian zone: for any value of γ, the flow on the central ring is aproximetly equal to the road capacity and is then monotically decreasing with the distance to the center. While $\frac{\gamma}{R} < \frac{1}{4}$, the radial flows reach a maximum around $r = \frac{\gamma+R}{2}$, then the curve shifts to this parabolic shape to a monotically decreasing function for $\frac{\gamma}{R} > \frac{3}{4}$.

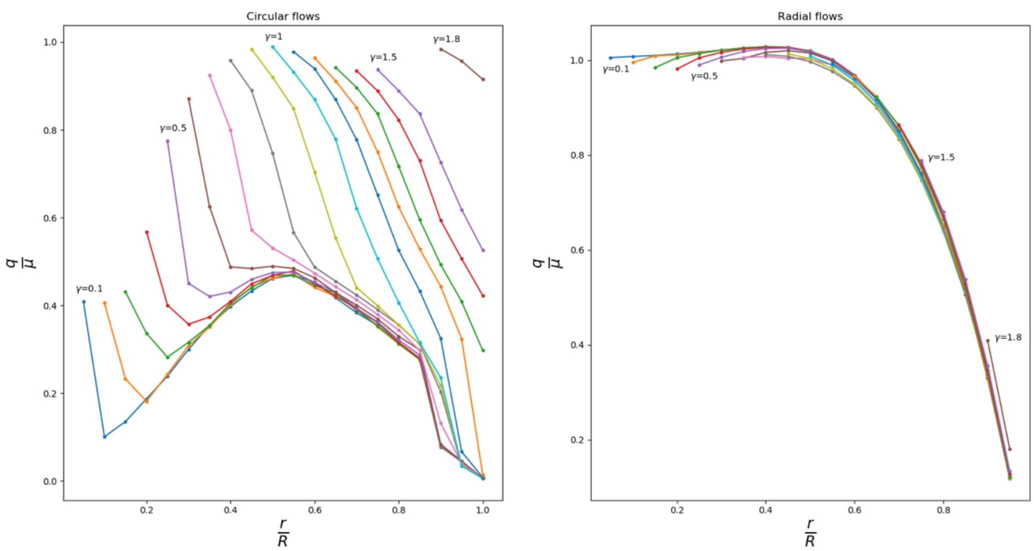
We also notice that as the pedestrian center grows, a part of the traffic shifts from radial to circular. An increase of γ involves an increase of the circular flow at a distance r from the center: the bigger the pedestrian area, the longer the distances travelled on circular roads to bypass it. This leads to the increase of the use of circular roads. On the contrary, when γ gets bigger, the radial flow at r decreases.

Monocentric demand

Figure 3b represents the traffic distribution on with a monocentric demand in addition to the baseline demand ($\lambda_c = 0.165\ veh.km^{-2}s^{-1}$). As the central demand makes radial roads more congested, it became less worth it for drivers to use central rings because they are more difficult to reach. This explains the difference of the shape of circular flow curves for low value of $\frac{\gamma}{R}$. However, for higher values of γ, these curves are similar to the ones obversed in the uniform case. This can be explained by the decrease of radial flow as more and more trips are completed inside the pedestrian zone.



(a) Uniform demand



(b) Uniform demand and central demand

Figure 3: Flow distribution with uniform demand (a), and with additional centralized demand (b).

Table 1: Simulated flow distributions with varying size of pedestrian zone

Simulation	$\boldsymbol{\gamma(km)}$	$\boldsymbol{R(km)}$	$\boldsymbol{d(km)}$	$\boldsymbol{\lambda(veh.km^{-2}.s^{1})}$	$\boldsymbol{\frac{\lambda R}{\mu\delta}}$
1	0.1	2	0.1	0.25	0.112
2	0.2	2	0.1	0.25	0.112
3	0.3	2	0.1	0.251	0.112
4	0.4	2	0.1	0.252	0.112
5	0.5	2	0.1	0.253	0.112
6	0.6	2	0.1	0.254	0.112
7	0.7	2	0.1	0.256	0.112
8	0.8	2	0.1	0.257	0.112
9	0.9	2	0.1	0.259	0.112
10	0.10	2	0.1	0.261	0.112
11	0.11	2	0.1	0.264	0.112
12	0.12	2	0.1	0.267	0.112
13	0.13	2	0.1	0.271	0.112
14	0.14	2	0.1	0.277	0.112
15	0.15	2	0.1	0.285	0.112
16	0.18	2	0.1	0.356	0.112

Global benefits

The assessment of a situation characterized by a demand distribution and a value of γ can be made through the total travel time (time.veh) and distance travelled (dist.veh) by all users including the car and walking parts. The distances traveled by car and their associated travel time follow from the traffic assignement and the duration of walking trips were obtained simply by multiplying the distance travelled within the central zone by a constant walking speed set at 4km/h. To justifie the implementation of a pedestrian area from a traffic management point of view, the benefits of deleting congestioned links must balance the increase of walking trips. According to the simulations made, in a situation where all users move inside the pedestrian zone by foot, an increase of its area will never make the total travel time smaller.

However, Figure 5 shows that, if bicycling is used, that is, if the moving speed shifts from 4 to 16km/h within the central area, with the previously selected parameters, a threshold central demand above which a closed center can reduce total travel time is observed. We can see that the curve relating the sum of travel times of all users in the network to the radius of the central zone admit a minimum for λ_c superior or equal to 0.15 $veh.km^{-2}.s^{-1}$. Not surprisingly, the minimum value of $\frac{\gamma}{R}$ tends to increase when central demand intensifies. It goes from 0.3 for $\lambda_c = 0.15veh.km^{-2}.s^{-1}$ to 0.7 for $\lambda_c = 0.2veh.km^{-2}.s^{-1}$.

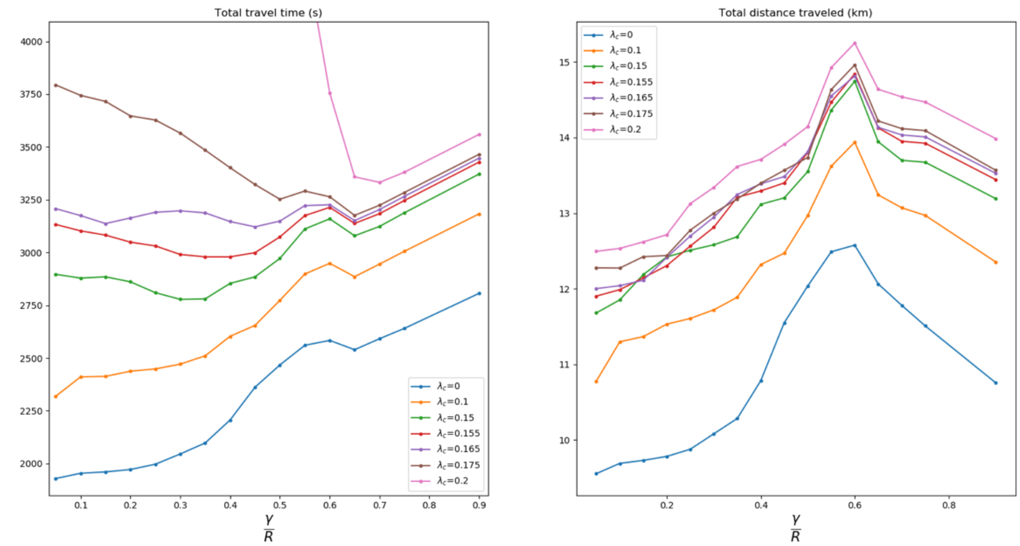


Figure 5 : Total travel times and distances for various values of $\lambda_c(trips.km^{-2}.s^{-1})$

Finally, Figure 6 shows the contribution of both modes to total distance and travel time for $\lambda_c = 0.165$. We can see that both the distance travelled by car and the proportion of the car travel time are decreasing. This intuitive consequence of reducing the space allowed to cars must be associated with faster moves than the one usally completed by a pedestrian.

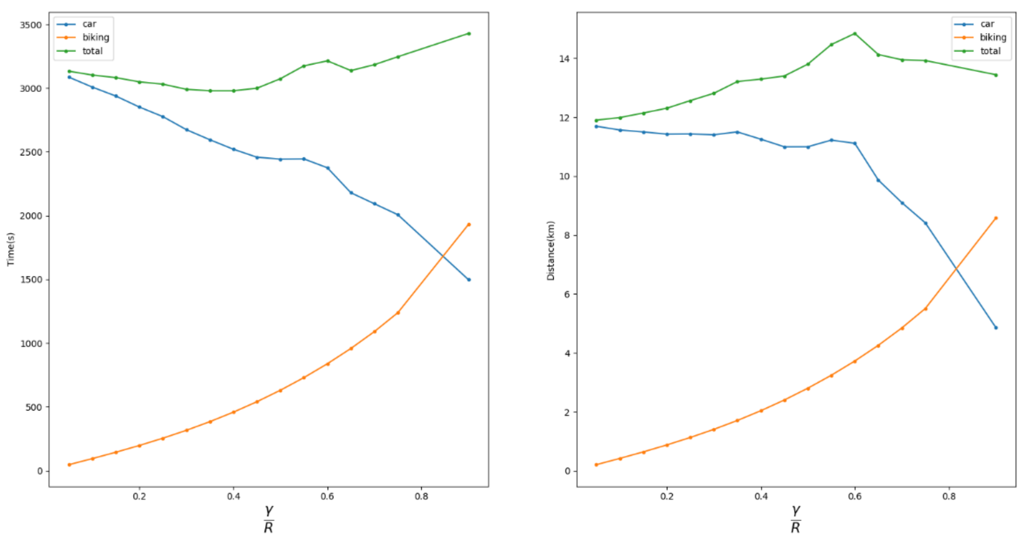


Figure 6: Decomposition of total travel time between the two transportation modes

CONCLUSIONS

In this paper, an analysis based on simple considerations on travel route choices across a city with a radiocentric street pattern was proposed to model traffic flows around a pedestrian area. Several numerical examples have permitted to set up two kinds of results: some expected features of the traffic distributions and some conditions under which the pedestrianization of a crowded area can lower the total user cost.

On the one hand the observations made regarding the transfert of a part of radial flows to circular roads could turn out to be useful to improve traffic management in the context of the implementation of a new pedestrian area. On the other hand, this type of model can also be helpful from a decision-making point a view as a tool to evaluate a priori the benefits of cutting out car traffic on a city center. The simulations did not show benefits in a uniform demand situation, but the existence of an optimal size for a central pedestrian zone was observed in a monocentric demand scenario where people are moving at bike speed within this central zone. In other words, our results suggest that pedestrianization can have an effective lowering impact on users'cost when demand is concentrated around a limited area where city-dwellers are moving faster than a simple pedestrian. These two conditions could easily be met as bike share services and personal transportation devices are overrunning already very dense cities across the world. The model allows to evaluate this impact quantitatively according to the severals parameters of the network: size of the neighborhood, density of streets and level of demand.

However, because of the idealized network used in the model, the accuracy of the conclusions exposed here should definetly evolves according to the actual street pattern of real cities. This studied has not considered changing the MFD characterizing the traffic assignement or the street pattern but this could be a way to improve the model. We could for instance expect a greater impact of pedestrianisation in a neighborhood with an MFD admitting a lower aggregated capacity as congestion would appears more easily.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: L. Valverde, E. Gonzales; analysis and interpretation of results: L. Valverde; draft manuscript preparation: L. Valverede, E. Gonzales. All authors reviewed the results and approved the final version of the manuscript.

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