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ANALYTICAL DEFINITION OF CITY URBANIZATION MODELS PROMOTING SUSTAINABLE MOBILITY

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To my mother and sister, for their constant support.

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Abstract

Sustainable urban planning policies put a strong focus in promoting walkability and public transportation. In this research, an approach is adopted through simple calculations on how urban form parameters can influence mobility flows, and their interrelation with space occupation in street cross sections. With the main objective of providing a simple rule of thumb on how to manage street space and transportation demand inside the sustainability frame, basic theoretical hypotheses will be applied to two street models with different land use distributions. These models are ideal, linear representations of a street but can be adapted to the study of different city morphologies. Results will demonstrate the important role of mixture of land uses in transport efficiency, and the potential of modelling pedestrian demand and flow as a direct function of distance and population density. In addition, a simple set of calculations will be proposed for the computation of space needs, which will show that efficient streets, in general, do not need more than two car lanes per sense of circulation. Results will be put along with perceptual considerations which, according to literature, have been for long omitted in urban planning but, however, can significantly improve walkability and sustainability. The whole set of explored conceptions wins a great importance in the panorama of the post-COVID19 city, which supposes an ideal opportunity for improved approaches in mobility and environmental sectors.

ANALYTICAL DEFINITION OF CITY URBANIZATION MODELS PROMOTING SUSTAINABLE MOBILITY

Addressing mobility and its relationship with urban form parameters

1. Introduction

1.1. Context

After the Industrial Revolution, factors such as the development of transportation systems and information media, the relocation of economic activity or the homogenization of behaviour patterns and lifestyles have made it ever more difficult to give a concrete description of what a city is. Although definitions cover a wide range, some elements have been found as common definer parameters. These include size and density; the existence of a core; the non-agricultural activity and lifestyle; as well as other social traits like heterogeneity, urban culture and the degree of social interaction (Capel, 1975).

This complexity in the definition of the city is even greater nowadays, not only because of the acute growth of population and technological breakthroughs (main features of the globalisation epoque), but rather because these two factors have brought, almost unavoidably, an alarming danger to the natural environment that surrounds and embraces cities. Nowadays, political and social agendas are obliged to place a major spotlight on climate change, which is a direct consequence of the increase of greenhouse gas emissions (GHG) derived from human activity. Transportation is the sector where this emissions grow faster (Ministerio de agricultura, 2015): it accounts for more than 13% of Greenhouse Gas (GHG) emissions, and if trends hold, it could reach 40% in 2050; while its share of global oil demand accounted 47% in 2002 and will probably reach 54% by 2030 (Cervero, 2014).

There is strong evidence that fossil fuel dependency and global warming (the most important problems of globalization) are inextricably tied to the increasing automobile-dependency of cities, which also promotes other problems such as poverty and social exclusion (Cervero, 2014). Both global performance and effects of the transportation sector are not only based, but also boosted and sustained by the underlying concept of structure. This is mainly because the way in which streets are shaped and connected, and how uses are distributed in space, are key factors in the decision making of dwellers and, thus, their mobility behaviour.

At this point, understanding the structure, organisation and impacts of the city is no longer a tool for boosting economic or political development; rather it is potentially the best -and perhaps only- instrument for fighting against the damaging effects that this same progress is causing in our natural environment; effects which, if not paid enough attention to, may ultimately cause our own extinction at least as the intellectual, technological and successfully evolving society that we consider ourselves to be. Evidently, the structure of the city varies depending on various factors. For this reason, scaling has been considered by some authors (Batty, 2012) as the first step in understanding the problems associated with efficiency, for that in each city or case of study a different density, size, or even set of needs, can be found.

Sustainable development is characterised by "*meeting the needs of current generations without compromising the ability of future generations to meet their own needs*" (World Commission on Environment and Development, 2017). In 2015, all members of the United Nations joined the adoption of 17 Sustainable Development Goals (SDG) as part of the 2030 Agenda for Sustainable Development, which aims to tackle universal problematics related to poverty, gender inequality and climate emergency by a 15-year programme, and calls all sectors of society to contribute both at local and global levels (United Nations, 2020).

The concept of Sustainable Development comprises three aspects: economic, social, and environmental, and the relationships between each of these need to be *equitable* (interaction between social-economic dimensions), *liveable* (referring to the quality of life, linked to social needs) and *viable* (economic development must respect the supportive capacity of natural ecosystems). Some author (Pozniakova, 2007; Tanguay et al., 2010) have offered a detailed scheme of the factors included in this equilibrium (see *Figure 1*).

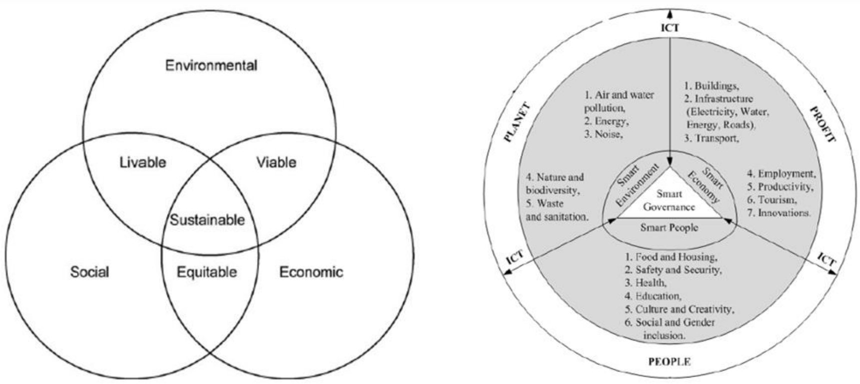

Figure 1. Classic dimensions of sustainable development[1].

The diagnosis of the situation nowadays falls far from this equilibrium: "*cities consume between 60% and 80% of natural resources; produce 50% of global waste and 75% of green-house emissions*" (Slovic et al., 2016; Williams, 2019). Air pollution affects 90% of the population worldwide and represents the number one cause of premature deaths (Slovic et al., 2016; Zeliger, 2020). These problems are ever sharpened by the increasing rates of population: whereas today more than 50% of the world population live in urban zones (O'Neill, 2019), this percentage is expected to reach 66% in the not-so-far horizon of 2050 (Williams, 2019).

In sight of this problematic, there is a great need to promote the concept of 'smart sustainable cities' to try to restore the equilibrium and palliate the negative effects that inneficient transportation trends have caused in the environment, while better practices are fomented in a society which keeps growing faster.

[1] *Source (from left to right): Tanguay et al. (2010); Pozniakova (2007).*

1.2. State of the Art

Although transportation engineering embraces a wide set of mathematical and theoretical approaches, one of its main challenges lays in the strong impact of human features and behaviours, which are difficult to model numerically. Also, individual decisions might not suppose a big change from a local perspective, but their aggrupation in what is called 'society' has the power of shaping global trends, which need to be answered through street planning and city development procedures.

Furthermore, urban mobility and structure hold strong interdependencies between many variables. It could be said that human trends produce urban shapes, which change human trends; and so on. This is the reason why understanding the main variables involved is important to avoid as much the negative externalities and implications that a certain street design, or mode prioritization, could cause in the future urban dynamics.

The following list provides the main factors that influence the decision making of travellers when it comes to choosing a transportation mode (Calastri et al., 2019; Ko et al., 2019; Levinson et al., 2017). They are not arranged in order of importance, because this can change depending on the case.

- Journey time
- Flexibility
- Effort minimisation
- Need of a reservation
- Personal space and privacy
- Cleanliness
- Perceived monetary costs
- Congestion
- Stress
- Air pollution
- Health risk
- Schedules and frequencies
- Punctuality and reliability
- Fares
- Possibility of a door-to-door service

Trip demand generation is usually studied through the Logit model (Borck, 2019; Daziano, 2019; Levinson et al., 2017; Miller & Baker, 2016), a set of formulations which assign predicted probabilities to outcomes of a set of alternative options (Nguyen & Schumann, 2019). However, this is based on human behaviour and might sometimes fail to promote more sustainable trends (by instead maintain the current ones). Sustainable approaches need to provide a scenario attractive enough (from social, economic, and environmental frames) as to change human behaviour and, ultimately, modal shares and their overall efficiency.

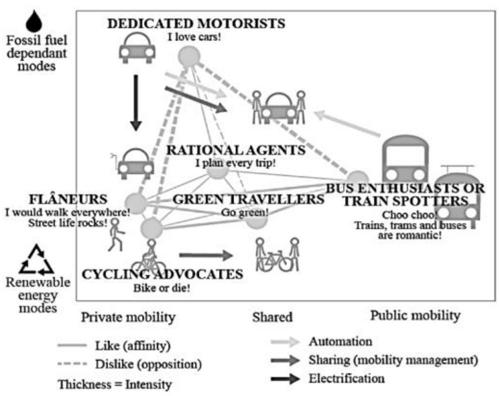

Figure 2. Mobility subcultures and their interactions. Source: Stojanovski (2019).

It has been claimed for long that urban planning is so focused on comfort that nowadays, the tendency of "*separating everything from everything else and reconnect it only with automotive infrastructure*" or "*building our landscapes to accommodate cars first*" (Speck, 2016) have become common practices. The comfort offered by car usage, along with its flexibility and speed, are main advantages promoting the demand of this mode. This, added to its prioritization in urban planning procedures, has become a major cause of global modal shares scenarios manifesting a clear devotion to private car users in detriment of pedestrian or non-motorized modes.

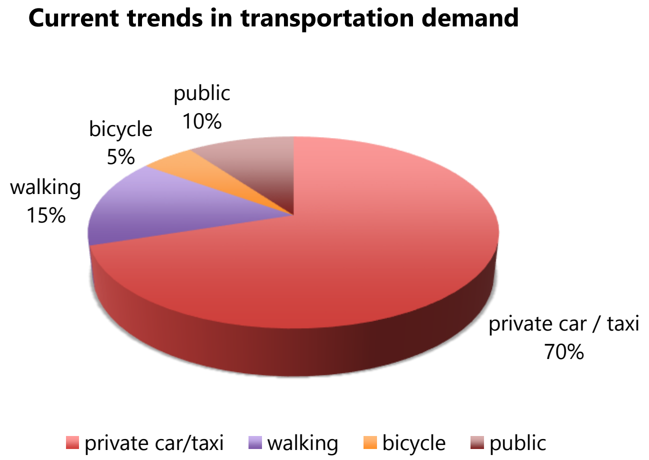

Figure 3. Global transportation modal shares[3]

The city is seen as a 'machine' and no longer as the 'organism' which encompasses and permits all our social and economic interactions (Batty, 2012). The problem has not been born today: many authors, such as Peter Calthorpe (1989), were talking about the 'narcissistic autonomy' derived from isolating the private space and dedicating the public one to automotive already thirty years ago (Carlthorpe, 1989). Even Jane Jacobs, back in 1973, already pointed out that streets "*serve for something more than to support automobile traffic*" (J. Jacobs, 1973). These ideas; along with the current alarming evidences related to climate change and GHG emissions; and the recognition of a lack of efficiency in many growing cities; demonstrate that the willingness of humans to improve commodity and wellbeing has in fact ended up in ever diminishing the quality of our life and our surroundings, while threatening our future possibilities.

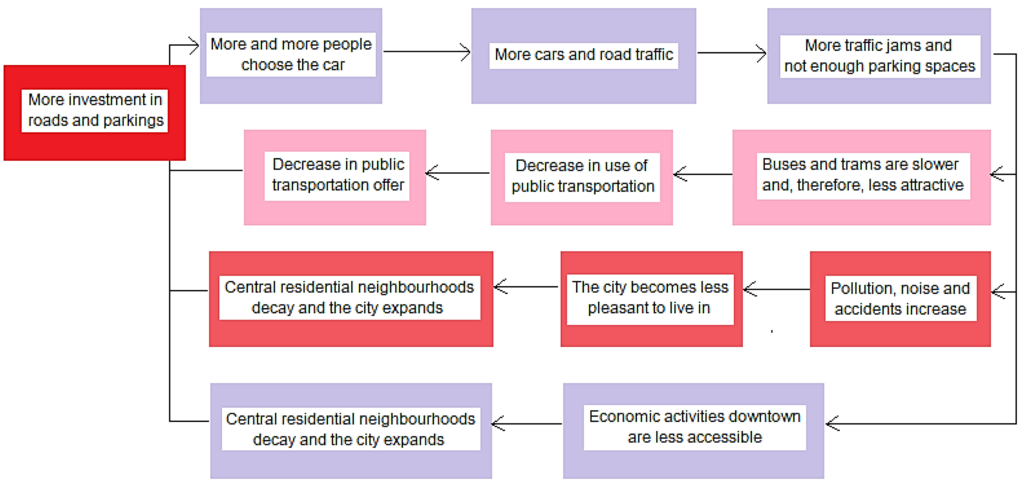

Figure 4. Loop created by car-dependency. Source: modified from Instituto Sindical del Trabajo (2009).

[3] *Source: elaboration from Daziano (2019); Dell (2017); Dixon et al. (2017); Victoriano et al. (2020).*

Fortunately, in sight of this problematic some cities have already begun to reverse this tendencies, by showing a willingness to promote public transport and non-motorized modes (walking and cycling). The main goal of such measures is to dedicate more space to land in a diverse combination of uses, thus increasing compactness of cities.

Examples of this are the introduction of Bus Rapid Transit, a transport system in which buses operate on exclusive dedicated lanes and mimic the speed advantages of metros while guaranteeing a way cheaper cost (Cervero, 2014); or the concept of carsharing, managed by apps which not only permit setting a reservation, but also show how much CO2 has not been emitted to the atmosphere thanks to a shared use.

In regards of the advantages of non-motorized modes, abundant research has developed on how to make cities 'more walkable'. Urban planner Jeff Speck has complained about new projects tending to highway-led designs instead of boulevard-inspired, suggesting that the simplest way to design efficient streets is "*to copy the ones that already work*" (Speck, 2016). According to him, walkable streets do not encourage fast turns while driving and have narrow lanes, continuous shade trees in any medians, parallel parking along every curb, and are lined by buildings that give them life.

1.3. Objectives

Considering this scenario, which would be the ideal structure of a city? How would its modal shares be distributed? How would the transport system work to reach an accurate equilibrium in terms of environmental impact?

Streets are the arteries of the body that is the city. They connect humans to every single destination involved in their day-to-day. As Jane Jacobs said (1973), "*when [the streets of a city] look sad, the whole city seems sad*". If there is evidence of illness, a closer look must be taken on blood pressure, temperature, composition, defense tools inside those arteries. In this example, arteries are mentioned as the defining unity of blood pumping while evoking the role of streets in transportation (of both goods and persons), which exists thanks to and for the city, and ultimately society. And in this case, the doctor is engineering. Which parameters should be regarded? How do the different possible land uses, the percentage of street dedicated to each mode, the nature elements, and the mixture of all these influence the efficiency -not only in terms of time or user satisfaction, but also of sustainability- of the transportation performance? The focus of this research comprises, from particular to more general:

- Reviewing previous literature and exploring the characteristics of sustainable mobility.
- Studying which variables and parameters influence traffic distribution, and particularly pedestrian demand.
- Obtaining simple analytical formulations that explain mobility flows in main streets.
- Providing a simple rule of thumb for practitioners on how to allocate and manage street space as a function of land uses, transportation means and other parameters influencing the mobility behaviour and promoting sustainability.

There exist many types of city and each one has its own size, organisation, and patterns. It has been proved that efficiency and sustainability indicators do not only depend on how big or populated a city is, but rather on a global perspective with inclusion of many variables. Taking this into account, and with the aim of providing more concrete insights and specifications, this discussion is going to focus on the characteristics of the street, understanding it as the first and functional unit, rather than in the whole package of the city.

The following sentence, from *Great Cities* (A. Jacobs, 1993), elegantly describes the importance of the street:

> *"Streets [...] are more than mere traffic conduits [...]. Streets shape the form and comfort of urban communities. Their sizes and arrangements give or deny light and shade. They may focus attention and activities on one or many centres, at the edges, along a line, or they may simply direct one's attention to nothing in particular [...] Streets are also places of social and commercial encounter and exchange. They are where people meet -which is a basic reason we have cities in any case".*

Figure 5. Avinguda Diagonal. View from Passeig de Gràcia in 1907 (left) and in 2020 (right).[4]

1.4. The post-COVID19 city

The worldwide sanitary emergency into which we have been drown during these months has changed our lives in so many aspects. From the professional perspective, many people have switched from an established dynamism of work schedules and tasks to an almost forced routine of teleworking. The same has happened with students, and even with kids or elder people, who have needed to accommodate quickly to isolation measures in one way or another.

This panorama has been translated in urban mobility through major, striking consequences. Measures as travel and work restrictions, quarantines, curfews, cancellations of events, and facility closures (Warren & Skillman, 2020), aiming to reduce the spread of the virus though interpersonal contact, have led to a situation of almost empty streets, and a rethinking of the dispensability of certain activities linked to mobility.

[4] *Source: labarcelonadeantes.com (left) and Google Earth (right).*

Figure 6. Images of popular Gran Vía in Madrid, in 2017 (left) and in 2020 during lockdown (right)[6].

Some studies have already been interested in the extent of these changes. In Europe, the continent the most affected, decreases on mobility have been found between 70 % and 90 % (Falchetta & Noussan, 2020). These diminishments started around the outbreak of the virus (late January), but were notably accentuated once official stay-at-home orders were implemented in most countries, and particularly in zones with high population density or with larger preponderance of population over age 65 (Engle et al., 2020).

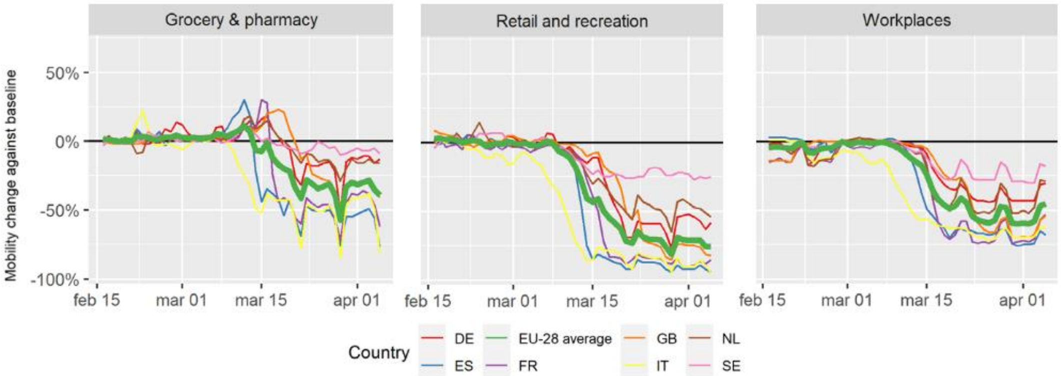

Figure 7. Change in mobility demand in some European contries. Source: Falchetta & Noussan (2020).

In Catalonia, for instance, mobility had dropped around 40 % to workplaces and transport stations and around 30 % to leisure and commercial spots in early May (Google Mobility Reports, 2020).

In reference to the environmental effects of lockdown measures, a decrease of 17 % in daily global CO2 emissions was reported by early April (compared with mean 2019 data). Particularly for surface transportation, this percentage was of 36 % (Le Quéré et al., 2020). Dramatic reductions of NO2, Particulate Matters and GHG emissions have also been as a result of car use reduction worldwide, especially in China and Europe (Zambrano-Monserrate et al., 2020).

As a consequence of mobility rationalization, along with the sight of many potentials of teleworking which had never been explored until now, the significant decrease on global emissions; and the economic crisis caused by the pandemic; it has been suggested that transportation demand will be gradually incorporating to the network again but will not be, however, the same as before (Ortigosa et al., 2020). In fact, these changes have revealed several weak and potential points in the urban environment which suppose a great opportunity for developing and promoting sustainable measures globally, and particularly in the transportation sector. Some of these proposals include:

[6] *Source: (JMCadenas, 2017; ondacero.es).*

- Blurring peak hours through flexible working schedules and online working (where possible), in order to decrease transportation demand (Ortigosa et al., 2020). The economic crisis will probably lower the investment on new and clean vehicles; at the same time, public transport and car-sharing models will probably suffer a strong impact due to the preference for social distancing (Falchetta & Noussan, 2020). For these reasons, private car transportation is likely to increase its share, and its effects should therefore be as palliated as possible.
- Increasing the offer of public transport by improving commercial velocities and space hierarchies (Ortigosa et al., 2020), as another measure to mitigate the effects exposed in the previous point. Because many people are dependent on public transport for travel, this should be in hand to the guaranty of safety, cleanness and performance effectiveness of multimodal transportation, which has been found to be a resilient practice, key for long-term sustainable development (Amekudzi-Kennedy et al., 2020).
- Promoting the so-called concept of the "15-minute city", based on radii of short distances being able to embrace the main urban functions of living, working, stocking up, etc. This concept has been proposed by Córdoba Hernández et al. (2020) and seems to be adequate for those cities with *multicentralities* and a population density between 100 and 300 $inhab/ha$.
- In more densely populated cities or zones, pedestrianization politics focused on freeing space for walkers will be a key measure guaranteeing both social distancing and the promotion of pedestrian mobility in detriment of private motorized vehicles (Córdoba Hernández et al., 2020). Actions will include the increase of sidewalk width and other pedestrian areas and the enhancement of proximity commerce and other features of mixture (as required by the "15-minute city" conception).

In summary, the mobility scenario posterior to the COVID19 pandemic turns out to be an ideal opportunity for sustainable transportation dynamics. Urban planning has to be focused now more than ever in guaranteeing the safety and promotion of pedestrian mobility, and improving public transport systems so that all population sectors are supplied and the increase of private car use is attenuated. In this respect, the literature reviewed and exposed in this work becomes crucial for understanding and physically apply the new mobility needs, which are more than ever based in the guarantee of health, both human and environmental.

2. Methodology

The procedures in transportation engineering generally focus on improving the demand-related capabilities of a given system (commercial speeds, for instance) through particular changes in physical features (for example, by increasing the width of the sidewalk, by adding or removing bus stops…). In general, due to the existence of established trends or dynamics, street cross-sections cannot be designed from scratch. However, this could provide a great advantage if used as an auxiliary tool, since a theoretical approach implies almost no restrictions and, therefore, can offer a more global and objective management of the variables. For this reason, this work will be based on the establishment of a theoretical street model, where the different parameters involved in mobility will be applied and assessed along with geometry considerations.

The first stage is to establish a coordinate system which defines the starting geometry of a general street model in a (X, Y) plane. In the y-direction, the street will have a total extension of ω ("width of the street"), formed by the lane widths ω_{lane_i} of the different modes i present (for instance car lanes, bus lanes, sidewalks…), with an additional influence zone x in each side. Regarding the x-direction, the street length L will be divided into slices of $1\,m$. This approach is coherent with urban analysis procedures found in literature (Guo et al., 2019; Shen et al., 2017).

Figure 8. Basic sketch of the street, with length L and width ω.

The research will be based on the mentioned sketch and divided into different stages:

- A numerical approach will be developed on how distances and land uses can shape pedestrian mobility. This part of the work is essential for that it represents a set of simple and objective calculations, which can later be modified by perceptual parameters.
- A set of computation steps will be proposed on how to translate transportation flow data of different modes into their physical needs, based on simple calculations and some general hypotheses. This will be followed by the consideration of non-numerical parameters which also influence mobility demand and its space occupation.
- An analysis on the results obtained will be made, engaging the particularities and limitations of the hypotheses.

Previous to the progressive addition of parameters, a starting point is needed in order to know how the structure and functionality of a street is first influenced, and how many different scenarios can be explored, as to have an accurate but compact comparison.

According to Cervero and Kockleman (1997), "*the built environment is thought to influence travel demand along three principal dimensions: density, diversity and design*" (Cervero & Kockelman, 1997). Knowing that travel demand is the main variable both influencing and being influenced in transport engineering, this theory easily draws the basis of the sketch. In the street models, 'design' can be represented by the geometrical parameters L and ω. 'Diversity' is considered of the land uses, in a variable that we will refer to as 'degree of mixture'. Finally, 'densities', of both population and workplaces, also play a key role.

Two basic models will be considered according to land use. In the "segregated land use model", sectors of households and workplaces divide the street in two differentiated halves, whereas in the "mixed land use model", uses are mixed homogeneously along the length. The different parameters treated in the study will be applied to each of these variants.

2.1. Segregated land use street model

In this scheme L is divided in two halves, the first one representing households and the second one representing the sector of workplaces. No travel is considered between pairs of points if being both located inside the same sector, as dwellers (i.e. travellers) only move from points between $x = 0$ and $x = \frac{L}{2}$ to points between $x = \frac{L}{2}$ and $x = L$ and vice-versa (only work-related trips)[8].

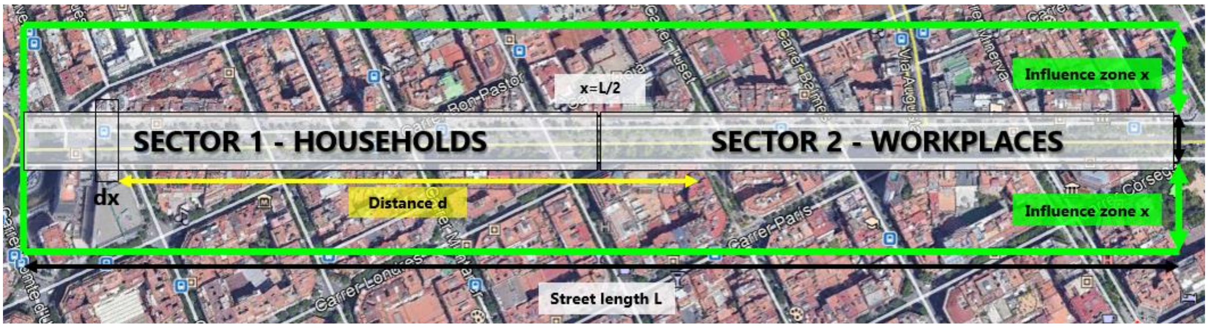

Figure 9. Distribution of households and workplaces in the segregated land use model.

A uniform probability density of workplaces location is assigned to sector 2. This means that the likelihood of the job location of any household $x = i$ to be placed at $x = q_i$ inside sector 2 is:

$$f(q_i) = \frac{1}{\frac{L}{2}} = \frac{2}{L} \qquad \textit{Equation 1}$$

<u>Distance travelled distribution</u>

The likelihood that a random individual travels a distance lower or equal to d can be addressed as the combined likelihood that (a) the individual lives in a certain slice dx at a certain coordinate x from the origin (left extreme) and (b) his job is located at a certain coordinate before $x + d$ (recalling movement is only allowed towards the right hand-side, for that the activities sector is located there).

[8] The following calculations (2.1.1., 2.1.2.) are provided complete in annexes 9.1.1. and 9.1.2.

The combined likelihood is (logical connector *and*):

$$P\ (travelling \leq d) = P\ (inhabiting) \cdot P\ (working\ before\ x + d) = \frac{1}{\frac{L}{2}} \cdot \frac{x + d - \frac{L}{2}}{\frac{L}{2}} \qquad \textit{Equation 2}$$

However, depending on the value adopted by d, the casuistry is divided into two scenarios:

1) If $d < \frac{L}{2}$

$$P(travelling \leq d)_{if\ d<\frac{L}{2}} = \frac{2 \cdot d^2}{L^2} \qquad \textit{Equation 3}$$

2) If $d > \frac{L}{2}$

$$P(travelling \leq d)_{if\ d>\frac{L}{2}} = -\frac{2 \cdot d^2}{L^2} + \frac{4 \cdot d}{L} - 1 \qquad \textit{Equation 4}$$

<u>Average distance travelled</u>

Because we assume that no displacements are performed between points belonging to the same sector, the average distance travelled corresponds to the length travelled by a dweller who would go from the midpoint of sector 1 ($x = \frac{1}{4}$) to the midpoint of sector 2 ($x = \frac{3}{4}$):

$$Av = \frac{L}{2} \qquad \textit{Equation 5}$$

2.2. Mixed land use street model

In this scheme, land uses are homogeneously distributed along the length L.

Figure 10. Mixed land use model, where households and workplaces are equally distributed along the street length.

A uniform probability density for job locations is assigned to the total length L such that its density function is attributed to each of the households. This means that the likelihood of the workplace of any household $x = i$ to be placed at $x = q_i$ ($0 \leq q_i \leq L$) is:

$$f(q_i) = \frac{1}{L} \qquad \textit{Equation 6}$$

Distance travelled distribution

As previously, the likelihood that the random individual travels a distance lower or equal to d can be addressed as the combined likelihood that (a) the individual lives at a certain coordinate x from the origin and (b) that its workplace is, at most, d metres away from x. In this case that is at a coordinate either somewhere between $x - d$ and x, or somewhere between x and $x + d$.

The combined likelihood is:

$$P(travelling \leq d) = P(inhabiting) \cdot P(work\ closer\ than\ d\ meters) = \frac{1}{L} \cdot \frac{d}{L}$$ *Equation 7*

These considerations divide the study into three scenarios, depending on the value of d:

1) If $d < \frac{L}{2}$

$$P(travelling \leq d)_{if\ d<\frac{L}{2}} = -\frac{d^2}{L^2} + \frac{2 \cdot d}{L}$$ *Equation 8*

2) If $d = \frac{L}{2}$

$$P(travelling \leq d)_{if\ d=\frac{L}{2}} = \frac{3}{4}$$ *Equation 9*

3) If $d > \frac{L}{2}$

$$P(travelling \leq d)_{if\ d>\frac{L}{2}} = -\frac{d^2}{L^2} + \frac{2 \cdot d}{L}$$ *Equation 10*

Average distance travelled

Because all the points are homogeneously distributed, to assess the average distance travelled (by any transportation choice) the following integral is introduced:

$$Av = \int_0^L \int_0^L \frac{1}{L} \cdot \frac{1}{L} \cdot g(x_1, x_2)\, dx_1\, dx_2 = \cdots = \frac{L}{3},\quad \text{where } g(x_1, x_2) = \begin{cases} x_1 - x_2\ if\ x_1 \geq x_2 \\ x_2 - x_1\ if\ x_2 \geq x_1 \end{cases}$$ *Equation 11*

This gives:

$$Av = \frac{L}{3}$$ *Equation 12*

3. Results

3.1. Distance travelled distribution

Applying the formulations obtained in 2.1. and 2.2. for a general domain $d \in [0, \dots, L]$ of a street results in a 'travel distribution curve' for each model, which shows the percentage of people who travel less than, or equal to, each distance d.

As shown in the plots below, the main characteristic of these distributions is that their shape does not depend on the value of the variables (length, population density...) but only on the grade of mixture of the models.

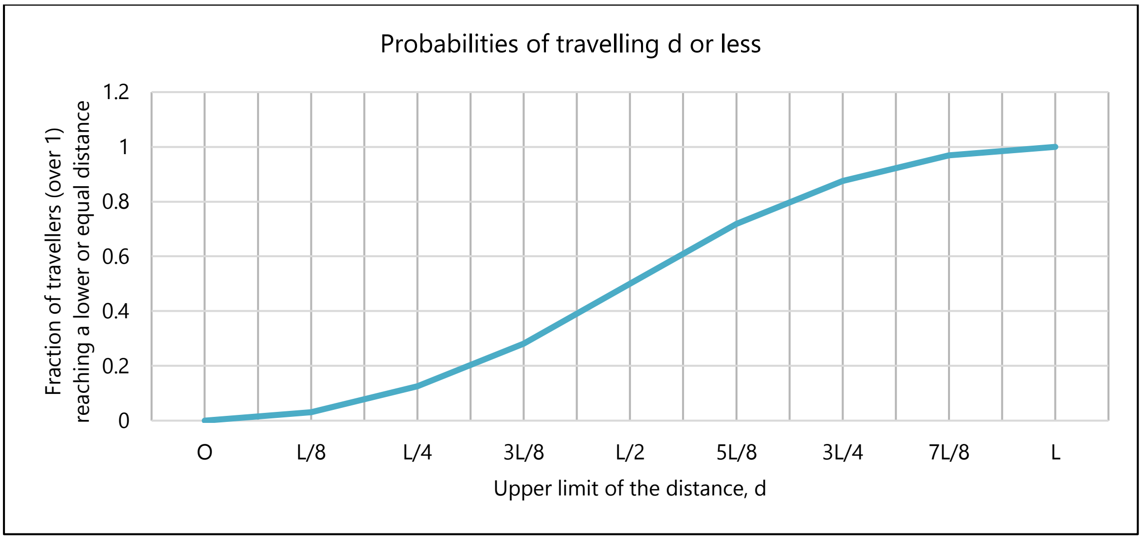

Figure 11. Distance travelled distribution in the segregated land use model.

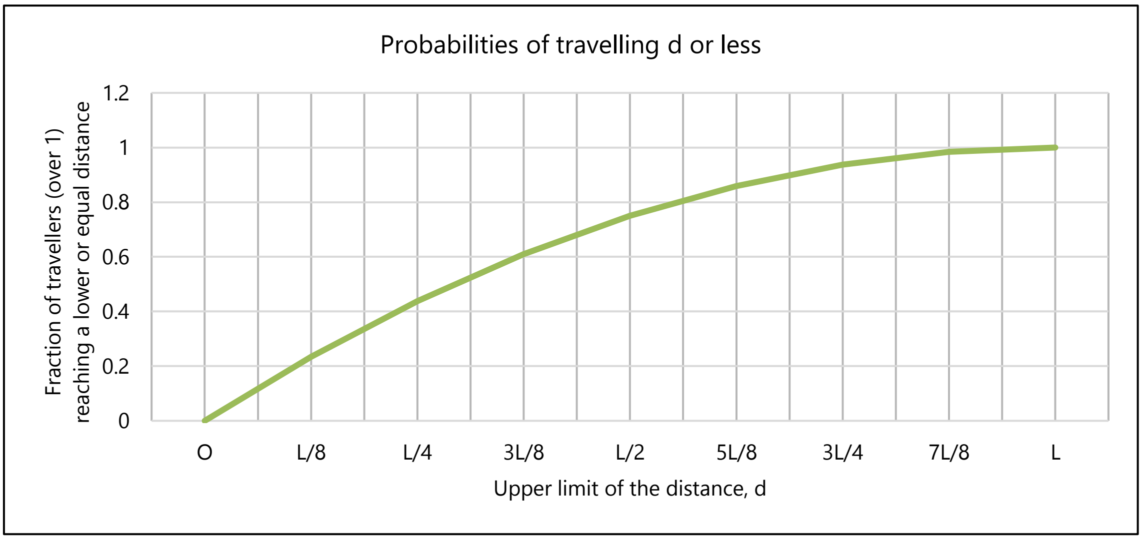

Figure 12. Distance travelled distribution in the mixed land use model.

It can be observed that the distribution in the segregated land use model shows a change from convexity to concavity at $d = \frac{L}{2}$, while the distribution in the mixed land use model has a uniform curvature (second derivative of the function is constant). This is a consequence of the fact that in the first case the location of workplaces is restricted to only on one side of the total length, whereas in the second case both households and workplaces are equally possible at any point (due to its homogeneity).

3.2. Pedestrian demand as a function of distance

In most cases, the governing variable in the election of transportation mode is time (Delso et al., 2018; Ko et al., 2019; Nguyen & Schumann, 2019; Song et al., 2017). The average individual does not want to spend too much time on displacement: he decides to go by foot, say, only if it involves less than 15 minutes. As pointed out by Cervero and Kockleman (1997) "*by bringing origins and destinations closer together, there become many more opportunities for leaving one's car at home and walking or cycling to a destination".*

In sight of this, let the variable u be defined as the 'maximum distance that a person is willing to walk'. If a range of pedestrian velocities between $v^w \in [3,6]\frac{km}{h}$, endorsed by literature (Delso et al., 2018; Polus et al., 1983), is considered, distance u would typically range between $750\ m$ and $1500\ m$ (10~20-minute walks).

At this point, and recalling the travel demand distributions obtained in the previous section, it is useful to note that if applying the change of variables $d = u$, the distributions provide the percentage of people ($\%^w$) choosing pedestrian transportation as a function of the distance u. Because u is a fraction of L (i.e. $u = \alpha \cdot L$), depending on the size of u in comparison to L, the walking mode share $\%^w$ will represent a lower or greater part of the total demand.

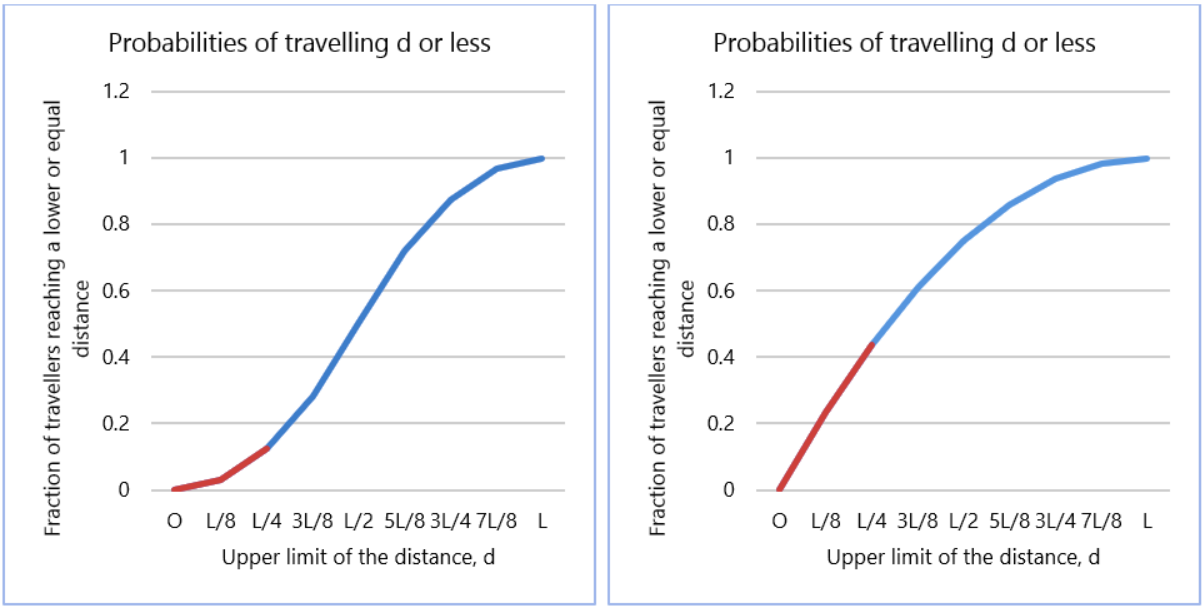

Figure 13. Span of the walking mode (red) in the distance travelled distributions for the example u = (1/4) · L.

If, for instance, $L = 4000\ m$ and $u = 1000\ m$, then $u = \frac{L}{4}$ and therefore the percentage of pedestrian demand would be $\%^w = 12.5\%$ in the segregated land use model and $\%^w = 43.75\%$ in the mixed land use model (see *figure 13*). Because in the mixed land use model there is a greater probability that the individual is closer to the workplace, the percentage of walking mode choice is also greater.

In the following figures, results on the pedestrian modal percentage $\%^w$ are shown for different (L, u) combinations in the segregated land us (above) and the mixed land use (below) models. Pairs of equal L and u translate into a pedestrian demand of 1, as any dweller would be able to walk the whole length L according to the numerical approach.

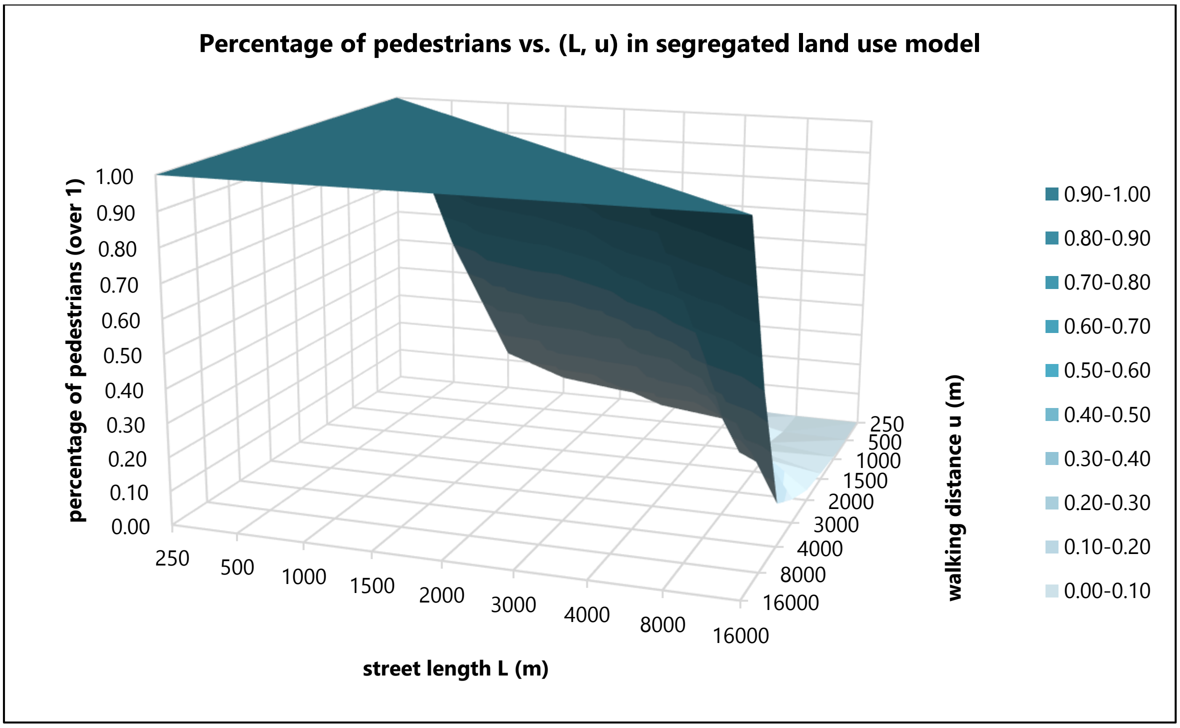

Figure 14. Pedestrian demand in segregated land use model.

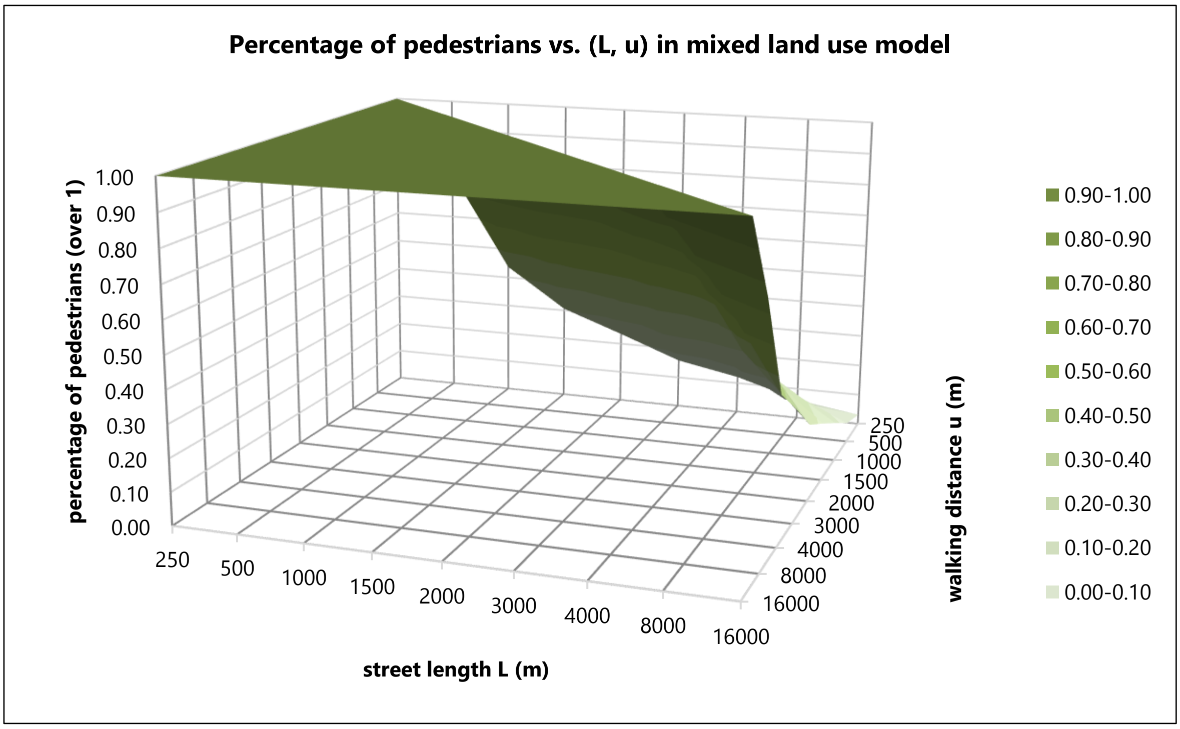

Figure 15. Pedestrian demand in mixed land use model.

A slice has been extracted from these charts to have a more detailed perspective. To do so, a value of $u = 1{,}000\ m$ has been fixed as a common or likely value for the distance willed to be walked. The following charts are obtained. Although these functions could be expressed through equations $3 - 4$ and $8 - 10$, the hypotheses made for those equations that u is greater than the length of the street, along with the fact that they are piecewise functions, suggests that a more direct formula would be desirable.. For this reason, Excel trendlines have been added which provide an approximation of the functions obtained for $u = 1{,}000\ m$.

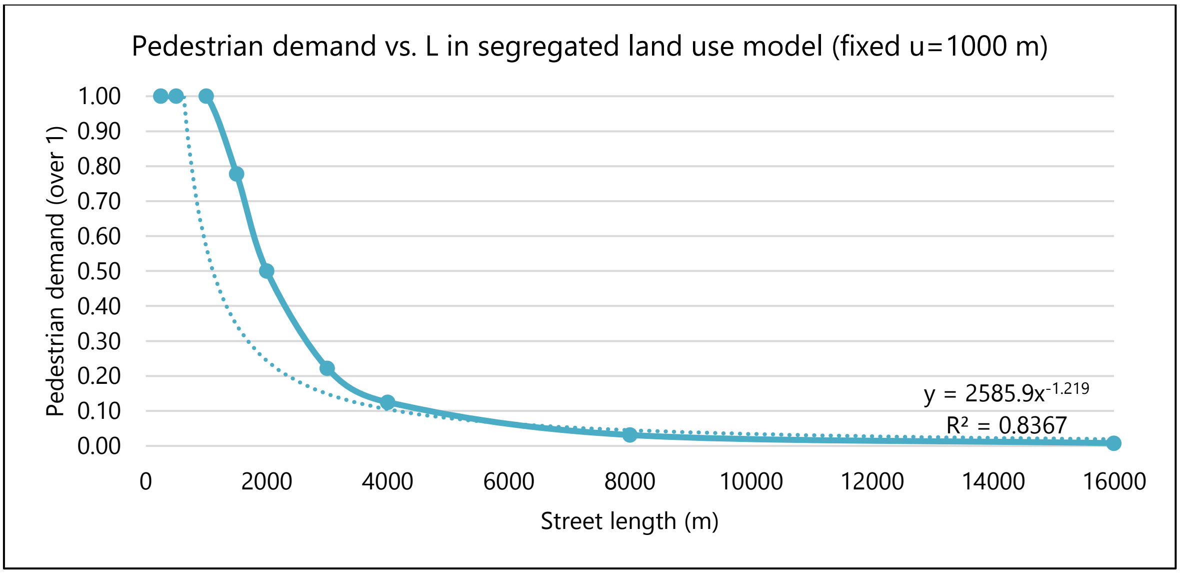

Figure 16. Pedestrian demand vs. street length in segregated land use model (for fixed u).

For the segregated land use model, the trendline chosen is of type potential. Election has been based on the preference for error on the left rather than on the right (as this latter would give demands higher than real for longer streets, which could lead to misconceptions). The obtained equation is the following and would permit to calculate pedestrian demand in the segregated land use model for a fix $u = 1000\ m$ and any given street length:

$$\%^{w}_{segregated} = 2{,}585.9 \cdot L^{-1.219} \qquad \textit{Equation 13}$$

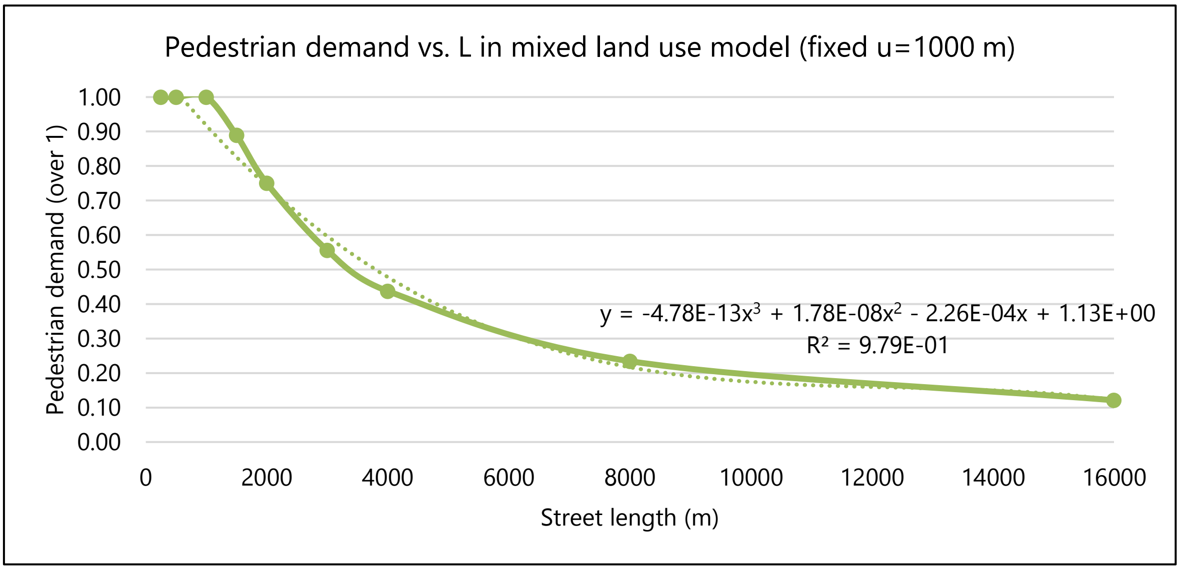

Figure 17. Pedestrian demand vs. street length in mixed land use model (for fixed u).

For the mixed land use model, the trendline chosen is of type polynomial of grade 3 and adjusts satisfactorily to the curve. The obtained equation is the following and would permit the calculation of pedestrian demand in the mixed land use model for a fix $u = 1000\ m$ and any given street length:

$$\%^{w}_{mixed} = -4.78 \cdot E^{-13} \cdot L^{3} + 1.78 \cdot E^{-08} \cdot L^{2} - 2.26 \cdot E^{-04} \cdot L + 1.13 \qquad \textit{Equation 14}$$

Comparison of both graphs indicates an acute change of demand trends between $2{,}000\ m$ and $4{,}000\ m$ in the segregated land use model. Whilst this model lowers to 0.125 for $L = 4{,}000\ m$, due to its smoother slope the mixed land use model does not reach such low demand until street lengths of around $16{,}000\ m$.

3.3. Pedestrian flow as a function of population density

Pedestrian flow is computed as a fraction of the total flow, by applying the pedestrian demand obtained:

$$q^w = \%^w \cdot q \qquad \text{Equation 15}$$

The calculation of the total flow is based on the following hypotheses, where P is The total quantity of inhabitants, $P = \rho \cdot L_{residential}$[9].

I. The whole quantity P are willing to travel for work-related purposes.
II. Each one might do it at a different moment of a time range, which is set as $12\ h$ (daylight).
III. Two total trips are assumed per person, as going 'to' and '$back\ from$' work.

The result of this is understood as the total flow q of the network:

$$q \left[\frac{pax}{hour}\right] = \frac{\rho \left[\frac{pax}{m}\right] \cdot L_{residential}\ [m] \cdot 2\ [trips]}{12\ [hours]} \qquad \text{Equation 16}$$

Combining equations 15 and 16, pedestrian flow can be generally calculated as:

$$q^w = \%^w \cdot \frac{\rho \cdot L_{residential}}{6} \qquad \text{Equation 17}$$

Density is expressed as linear for adjustment to the 1D-scheme, and depends highly on the influence zone x of the street, (which represents the sector having access to the street, through a straight line extending beyond its width on both sides). Population per square meter can be therefore expressed as:

$$\bar{\rho} \left[\frac{pax}{km^2}\right] \cdot x\ [m] \cdot \frac{1\ [km^2]}{1{,}000{,}000\ [m^2]} = \rho \left[\frac{pax}{m}\right] \qquad \text{Equation 18}$$

The following chart (*figure 18*) shows this conversion for some examples of $(\bar{\rho}, x)$ values.

[9] $(L_{residential\ (segregated)} = \frac{L}{2}$ whereas $L_{residential\ (mixed)} = L)$.

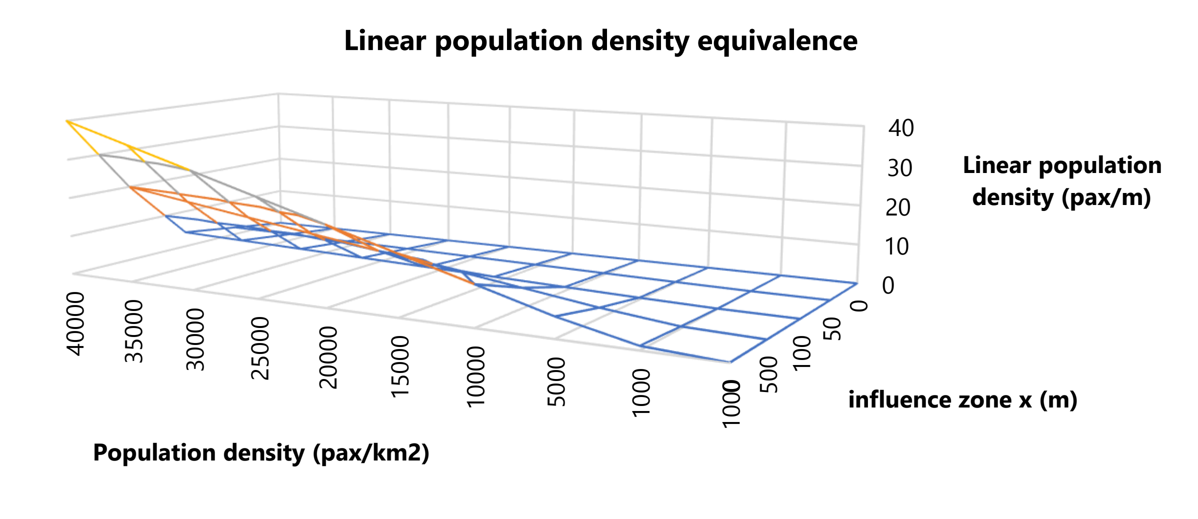

Figure 18. Linear population density vs. influence zone and population density.

Recalling the fixed $u = 1{,}000\ m$ along with equations 13 and 14, pedestrian flow can be calculated in both models directly as a function of street length.

For the segregated land use model, pedestrian flow is computed as follows, and is shown in figure 16:

$$q^{w}_{segregated} = (2{,}585.9 \cdot L^{-1.219}) \cdot \frac{\rho \cdot \frac{L}{2}}{6} \qquad \textit{Equation 19}$$

For the mixed land use model, pedestrian flow is computed as follows, and is shown in figure 17:

$$q^{w}_{mixed} = (-4.78 \cdot E^{-13} \cdot L^{3} + 1.78 \cdot E^{-08} \cdot L^{2} - 2.26 \cdot E^{-04} \cdot L + 1.13) \cdot \frac{\rho \cdot L}{6} \qquad \textit{Equation 20}$$

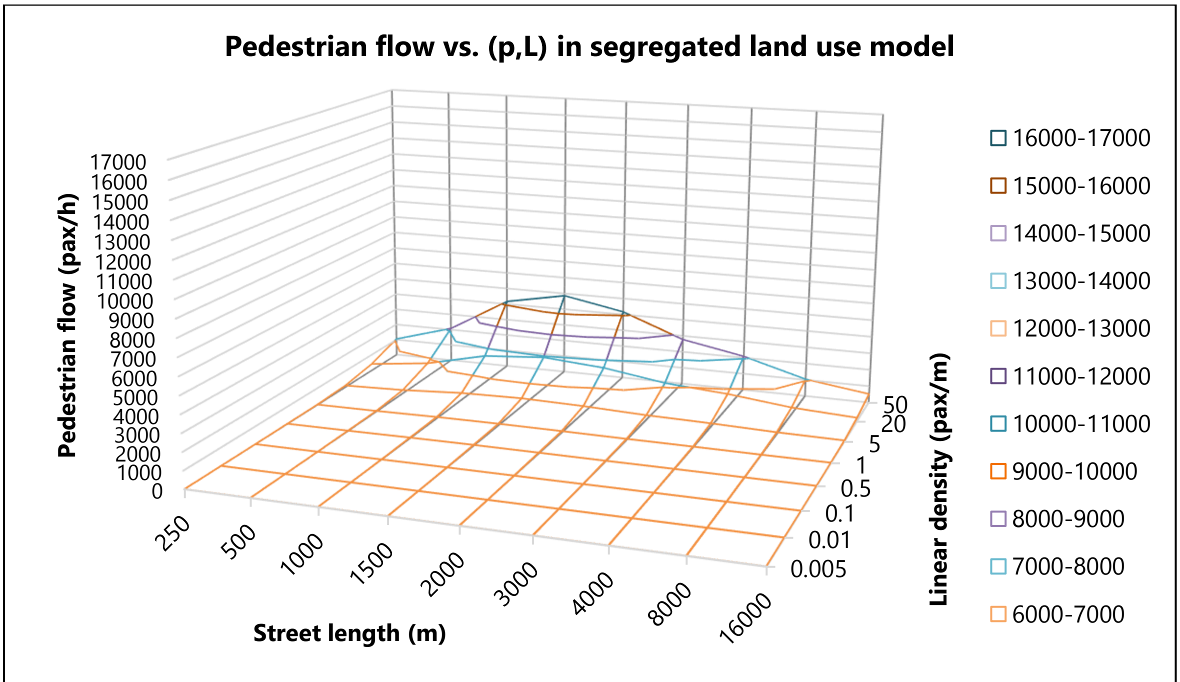

Figure 19. Pedestrian flow vs. p and L in segregated land use model (for fixed u).

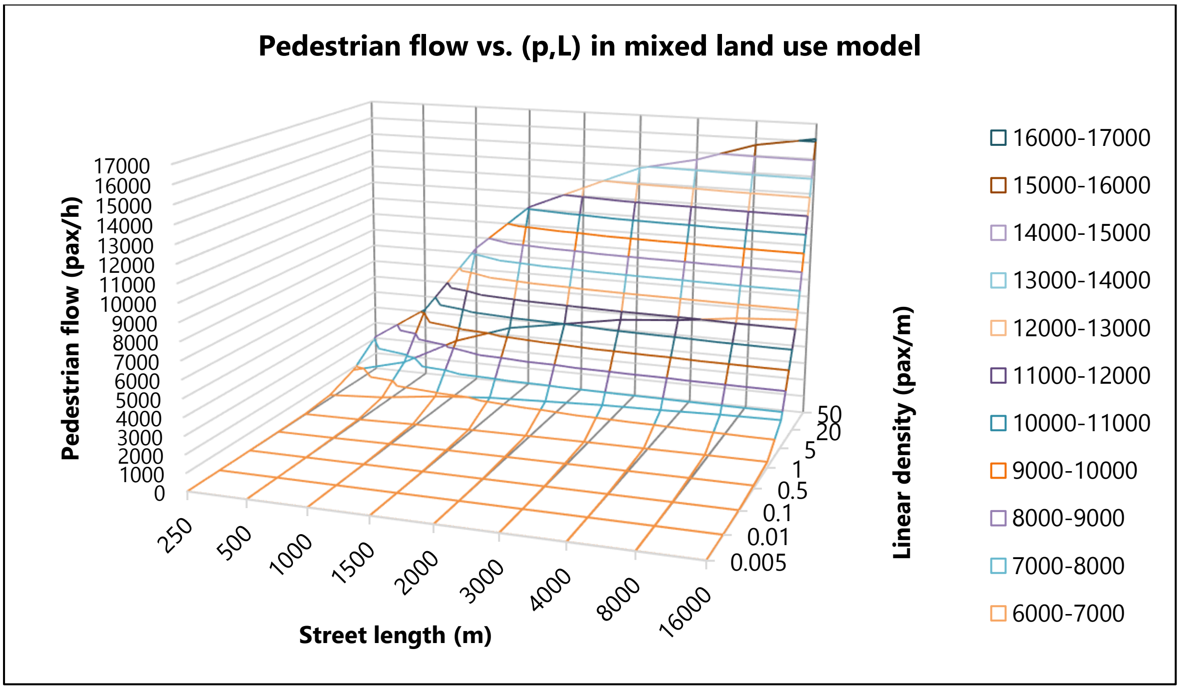

Figure 20. Pedestrian flow vs. p and L in mixed land use model (for fixed u).

In order to slice the charts for a more detailed approach, street length will be fixed to $L = 4{,}000\ m$ (along with $u = 1{,}000\ m$) for the following reasons (apart from the one suggested from figures 16 and 17):

- $L = 4{,}000\ m$ seems to represent a not-too-short, not-too-long linear representation of a street. In fact, real-life streets can be found inside a wide span of lengths possible (fact that would be addressed later). From $L = 1{,}300\ m$ in the case of the Rue de Saint-Denis (Paris), to the almost $L = 7{,}000\ m$ of the Kentish Town Road in its itinerary from Archway to Victoria Embankment (London)[10].
- Walking distance u representing a 25% of the total length of the street seems to grant a fair span for the pedestrian mode, being not so low as to set the mode shares far from sustainability conceptions (too few people walking); but neither so high as to cut down interesting distributions and combinations of other transportation modes (neither a prevalence of walking).
- In connection with the previous point, and observing the following figure, representing the competitiveness between transport modes as a function of time and distance, the zone around $L \in [3, 5]\ km$ seems to be where the paths start to have a more defined behaviour (already before $5{,}000\ m$, car is preferred over bike, for instance), but still in a local extension (suggesting street lengths rather than inter-city distances). Because $4{,}000\ m$ belongs to that range, it seems a good choice.

[10] *Source: Wikipedia, "Streets in the 1st arrondissement of Paris", "Streets in London".*

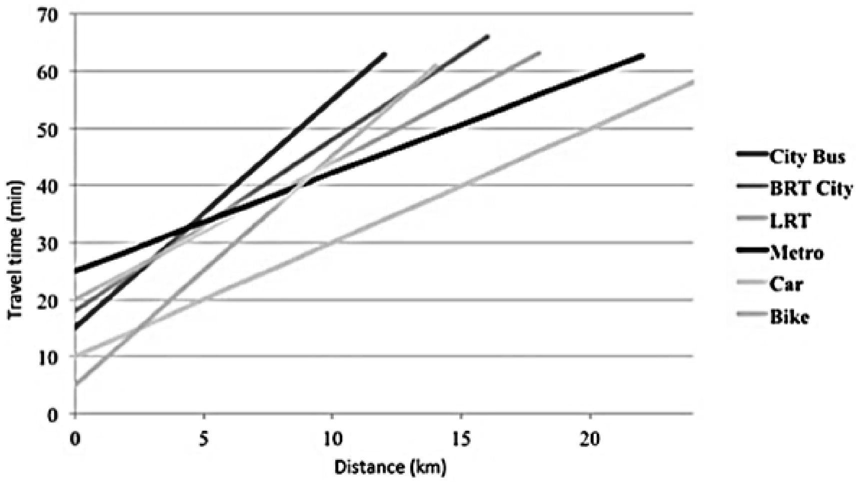

Figure 21. Local journey time competition between modes of transport, as function of distance (Roselló et al., 2016).

As shown in the following chart, if setting $L = 4{,}000\ m$ as standard street length, significant increases on pedestrian flow start occurring around $\rho = 5{\sim}20\ \frac{pax}{m}$. In that zone, the slope of the mixed land use function already represents approximately 500% that of the segregated land use, then it increases even more.

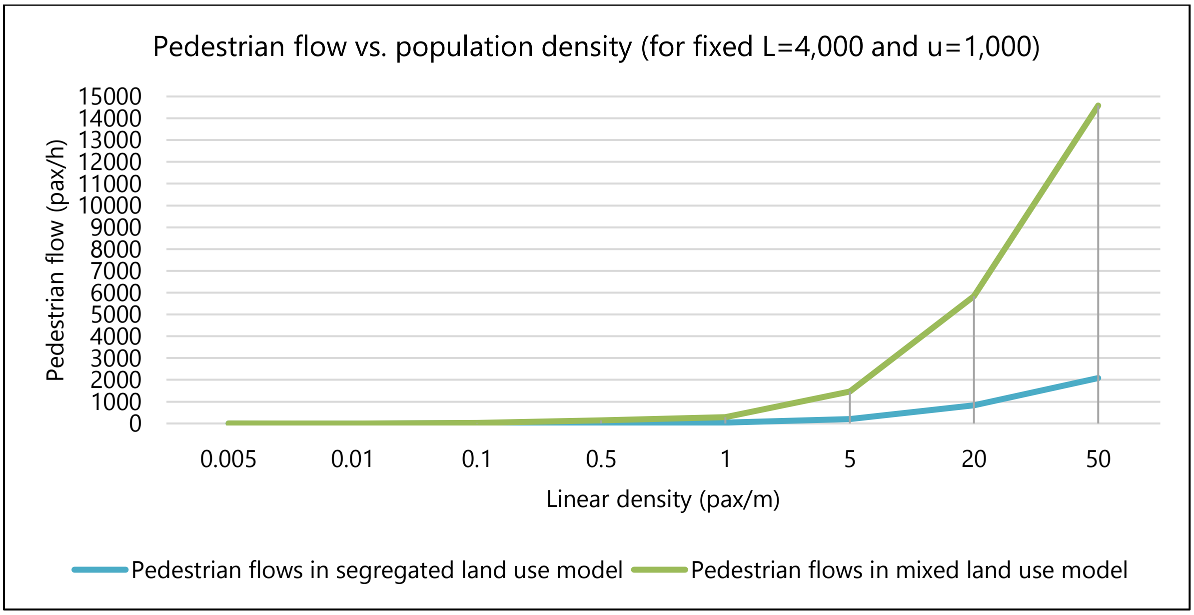

Figure 22. Pedestrian flow vs. population density (for fixed L,u).

To obtain substantial flows which lead to more interesting comparisons, in further calculations population density will be set to $\rho = 20\ \frac{pax}{m}$. According to equation 18, if stating an influence length of $x = 1{,}000\ m$, this will correspond to $\bar{\rho}\ \left[\frac{pax}{km^2}\right] = 20{,}000\frac{pax}{km^2}$. This value could be typical for very large influence zones and in cities like Hong Kong ($\bar{\rho} \approx 40{,}000\ \frac{pax}{km^2}$) rather than European cities, but however results interesting when it comes to comparing both models (for the reason explained in the previous paragraph). Nevertheless, any values could be applied depending on the case, and different results on flow could be obtained according to both the $\bar{\rho}$ and x of the city or zone. *Annex 9.5.* provides further insight on how different densities and street morphologies could shape different flows, for some examples of European cities.

The following table summarizes the set of variables selected from the approach.

description	variable	value	units
total length of the street	L	4,000	m
distance willed to be walked	u	1,000	m
population density[11]	ρ	20	$\frac{pax}{m}$

Table 1. Set of variables chosen for analysis.

The Results obtained for pedestrian transportation are shown in the following table.

	Segregated land use model	Mixed land use model
$\%^{w}$ (walking demand percentage)	12.5 %	43.75 %
q^{w} (walking flow)	833.33 pax/h	5,833.33 pax/h
$\%^{other}$ (percentage to distribute among other modes)	87.5 %	56.25 %
q (total transportation flow)	6,666.67 pax/h	13,333.33 pax/h

Table 2. Results on pedestrian demand and flow.

[11] Note: the value for population density has been established as 20 $\frac{pax}{m}$ for both models to maintain the maximum quantity of values in common. It can be understood that in the mixed land use model households are lower in number but more densely occupied (even besides having the same density, a mixture of uses is applicable in this case).

4. Methodology for space assignment

In real-life scenarios, transportation demand is usually assessed through formulations such as the Logit model, which take into account statistical data (Levinson et al., 2017). But because these procedures are based on an already existing system (defined street, defined schedules, etc), they are not valid for a model which aims to define the street from scratch and from a substantially objective perspective. As an alternative to this, a numerical approach has been proposed which has allowed to model how pedestrian demand can be obtained as function of land uses, street length, population density, and the distance u that people are willing to walk in favourable conditions. However, this approach cannot provide a direct calculation of the space needs of pedestrian mobility, i.e., sidewalk width.

On the other hand, this numerical approach is not valid for other transportation options (car, bus, etc), where an equivalent parameter "u" cannot be found so easily. However, for these cases an alternative will be suggested which will permit to calculate the proportion of street that each mode occupies. This alternative will be referred to as the "algorithm proposal" and is based on the translation of dynamic variables (velocities, flows…) into spatial needs. If combining both approaches, the geometric definition of the street cross-section can be completed satisfactorily from calculations which are based on objective variables but which, however, can also be bounded by perceptual considerations.

This section provides the basic formulations developed for the additional approach. Fist, the Flow-Density Fundamental Diagram is introduced as the main tool engaging the three main variables of transportation engineering: flow, density, and velocity. Next, the calculation steps of the algorithm proposal are described. Finally, after applying pedestrian demand as obtained in section 3, results of different cross-section designs are commented, highlighting the importance of demand percentages and lane widths as key inputs.

A first boundary of the design relies in that the categorisation of the street model as a 'metropolitan avenue'. The concept of 'metropolitan avenue' refers to streets which have a great importance as the principal axis structuring the territory, and whose connections respect historical outlines while promoting sustainable mobility. Metropolitan avenues are characterized by a strong human component, and therefore are seen as "*central and reference spaces rather than as simple traffic channels*" (Ortigosa et al., 2020). Generally, their widths are large and show prioritization for pedestrian and public transport, as well as the pleasurable inclusion of trees, urban furniture, and varied spaces.

These 'metropolitan avenues' are a key concept in the proposals of the Urban Development Plan (PDU) in the Metropolitan Area of Barcelona, which aims to tackle the diverse set of challenges related to housing, climate change, globalization, etc, through a highly integrated and transdisciplinary vision. Its streams in the mobility sector draw a clear need for improving "*the permeability of urban fabrics, establish metropolitan continuities and ensure that the territory has interconnection networks that promote sustainable mobility*" (AMB, 2020c). In this respect, "*the traditional order and priority of roads is redefined, which are classified according to the intensity of use by people and not by vehicles*" (AMB, 2020a). Along with metropolitan avenues, which represent the principal structural axis of the metropolis, four more categories are proposed (AMB, 2020a):

— Metropolitan streets, which are similar to avenues but without their structuring character. They will connect nuclei in a smaller scale.
— Metropolitan connectors, which will provide segregated high capacity roads, and also will connect urban nuclei which are separated by open spaces.
— Finally, metropolitan ways will be designed as pedestrian-only supports, mainly by fomenting access to agroforestry areas or alternative routes.

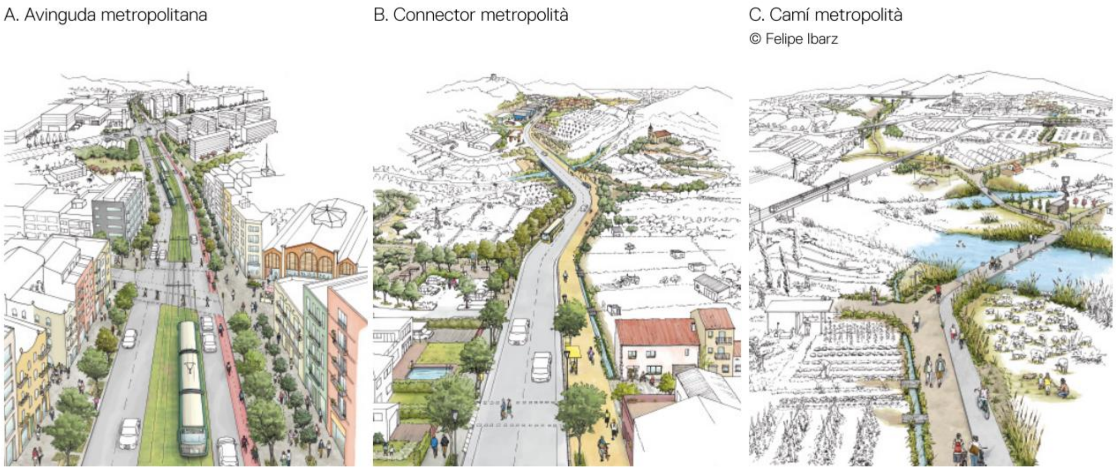

Figure 23. Example of metropolitan avenues (far left), connectors (middle), and ways (far right).[12]

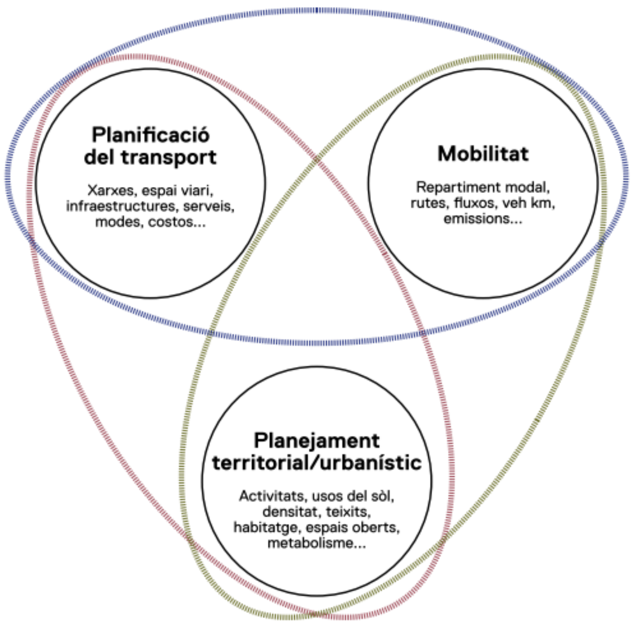

Figure 24. Connecting territorial planning, transport planning and mobility.[13]

As an additional demonstration on how sustainability-led street designs can be applied to different street hierarchies, *annex 9.6.* presents an example of a real project, for the case of a highway.

[12] *Source: (AMB, 2020a).*
[13] *Source: (AMB, 2020c).*

4.1. Introduction to the Flow-Density Fundamental Diagram

Fundamental Diagrams (FD) are a tool used in transportation engineering to assess the relationship between the main variables involved in traffic situations. There exist three main variations of FD: Flow-Density, Speed-Density, and Speed-Flow. Each one of them shows the variation of one of the variables as a function of the other, characterizing the traffic dynamics of a particular scenario (TU Delft OCW, n.d.). If this characterization englobes a network of streets, it is usually referred to as Macroscopic Fundamental Diagram.

In this section, the Flow (q)-Density (k) Fundamental Diagram is proposed as the base of an approach that would permit to translate transportation demand data into spatial needs in the cross section of the street models. Although the numerical values shown in the Fundamental Diagram depend on each case, its shape is invariable due to the existence of three main stages governing every transit context:

- Stage 1: When density k $[\frac{veh}{km \cdot lane}]$ is null, there are no vehicles circulating and thus flow q $[\frac{veh}{h \cdot lane}]$ is also null. From this point on, k and q increase as more vehicles incorporate. In this stage velocity of vehicles is not restricted because interactions between them are seldom, due to low densities (Levinson et al., 2017).

- Stage 2: It is called capacity, and it is represented by the pair (k^*, q^*). Capacity represents the peak of the curve and therefore the maximum flow $q = q^*$. Its characteristic $k = k^*$ is in the midpoint between a great amount of unoccupied space and an excessive accumulation of vehicles and differentiates between stage 1 (left hand-side) and stage 3 (right hand-side).

- Stage 3: It represents the states in which there is such quantity of vehicles circulating that, due to physical accumulation, their movement starts to get limited, thus higher k imply lower q until a point where $k = k_{max}$ and $q = 0$ again (too many vehicles per km produce a traffic jam).

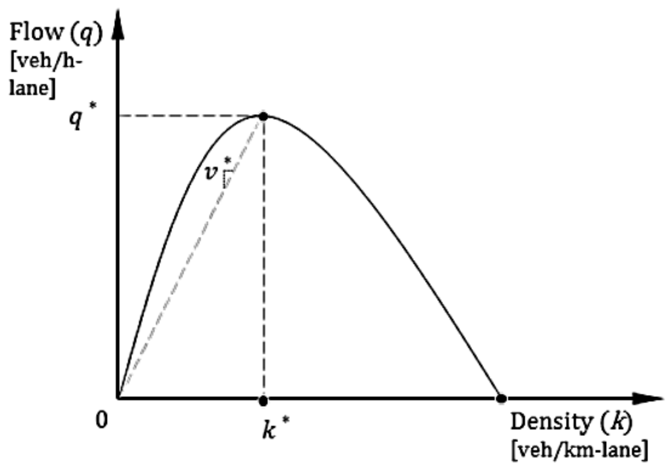

Figure 25. General MFD scheme. Source: Roca-Riu et al. (2020).

The path of the curve can also be described through six different stages called "Levels of Service", which are based on visual perception and measure the quality of the traffic states (from free circulation to traffic jams).

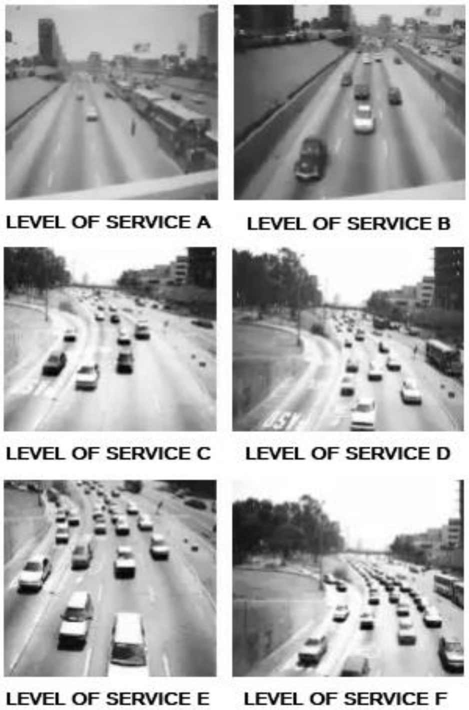

Figure 26. Visual explanation of the Levels of Service. Source: VCHI S.A. (2005).

The slope of a line linking the origin with any point on the curve represents the average velocity v $[\frac{km}{hour}]$ in that state. The combination of velocity with q and k defines how easily the set of vehicles circulates in a certain scenario: "*the speed of travel depends on the number of travellers*" (Levinson et al., 2017), and vice-versa.

Transportation planning procedures generally focus on the improvement of capacity, for that it represents the flow and density variables linked to a greater efficiency and overall performance. Following this argument, all the hypotheses and calculations in this report will be referred to the situation of capacity as an attempt to be as generic as possible.

4.2. Calculation proposal

This proposal translates modal flows to geometrical parameters (density, number of lanes...) that can ultimately describe the structure of the street cross-section. It is aimed for the consideration of bicycle, car, bus, and tram transportation[14], once pedestrian demand is known from the approach described in section 2 and 3. The algorithm needs the input of approximate demand values $\%^i$ for the different modes (for that they define flows), and therefore can be a useful tool in the determination of demand and flow boundaries and their implications on the physical environment and sustainability. If the design considered wants to fulfil particular modal shares, these can be implemented in the algorithm as a way to know, for instance, which modes would fit in a certain street model, or which is the necessary total width. Information of stipulated lane widths and other normative considerations are also needed as input. *Annex 9.3.* provides the basic data related to these requirements -for the particular case of Barcelona, but others could be studied.

The different stages of the approach are described as follows. Note that stages $1-5$ are already assessed through the approach in sections 2 and 3.

1. Definition of the total length L of the street.

2. Definition of the model (segregated land use or mixed land use).

3. Computation of the linear population density ρ $[\frac{pax}{m}]$ (as in section 3.3.).

4. Definition of u in favourable conditions (i.e., straight line, null slope, etc).

5. Input of the pedestrian demand, $\%^w$ and flow q^w as resulting from the approach in section 3.

6. Input of the demand percentages of the remaining modes ($\%^c, \%^{bi}, \%^b, \%^t$ ...).

   Because even in an eco-friendly perspective it is likely that a fraction of the population prefers private transportation, it is suggested[15] to start assigning $\%^c$.

7. The product of each percentage times the total flow results in the flow assigned to each mode.

$$q^c = \%^c \cdot q \qquad \textit{Equation 21}$$

8. Establishment of average velocity v^c and occupation o^c.

9. Definition of the total individual car distance e^c, as the sum of the average length l^c occupied by the car itself, plus the average distance s^c to the precedent vehicle (see figure 17). This distance should be considered of capacity to guarantee that design is based on efficient traffic conditions.

[14] Note: metro and train transportation are not addressed in this report due to their lower percentage of superficial land occupation in the conception of the supposed street models.

[15] In steps 7-13, superscript "c" can be substituted by "bi" (bicycle), "b" (bus), or "t" (tram) for the assessment of other transportation options.

10. Calculation of the number of lanes n^c needed.
Car density is extracted as $k^c = \frac{q^c}{v^c}\ [\frac{cars}{m}]$. Because no car could fit into a m, this will be a decimal result. Because there are k^c cars in every meter of length, and, in a single lane, there is 1 car occupying every e^c metres of length (stage 9), a simple interpolation gives us the number of lanes being needed.

$$1\ car \rightarrow occupies\ e^c\ m\ length$$
$$k^c \rightarrow occupy\ (1\ m\ length) \cdot (n^c\ lanes)$$

$$\frac{k^c\ [\frac{veh}{m}]}{n^c\ [lanes]} = \frac{1\ [veh]}{e^c\ [m]} \quad \textit{Equation 22}$$

where $\frac{k^c\ cars}{n^c\ lanes \cdot 1\ m}$ represents the average quantity of vehicles per lane per slice. Rearranging this equation, the number of lanes is finally found as:

$$n^c\ [lanes] = k^c \cdot e^c \quad \textit{Equation 23}$$

Because the number of lanes is an integer quantity and there are two directions of circulation, n^c will be rounded to the multiple of 2 immediately superior.

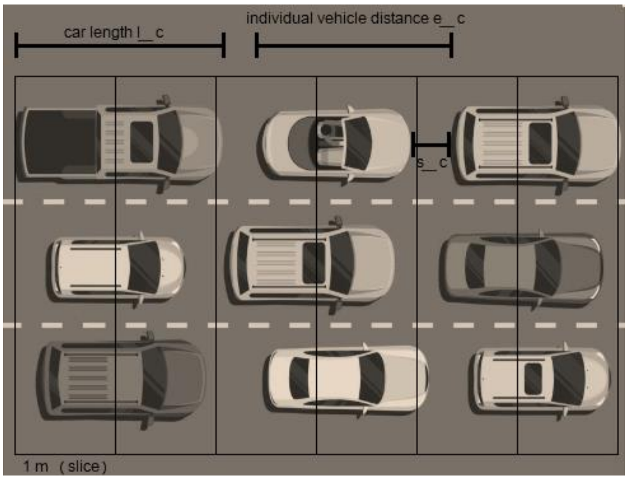

Figure 27. Representation of the distances used in the calculation of the number of lanes (3 in this example).

It is suggested to reject the solution if $n^c > 4$ (more than two lanes per direction of circulation). This is seen as an undesirable option in the design of the avenue and is considered a demonstration of an excessive private transportation share. The recommendation in such case is to return to the modal distribution step and impose a lower $\%^c$. Otherwise, if $n^c \in [2,4]$:

11. Input of lane width ω_{lane-c}

12. Calculation of the total width ω^c occupied by the transportation mode as:

$$\omega^c = \omega_{lane-c} \cdot n^c \quad \textit{Equation 24}$$

It must be taken into account that, in order to simplify, these results consider that car circulation only takes place in car lanes, and never in bus lanes, which are therefore exclusive to buses. This Right of Way implementation can, however, be different in real-life scenarios.

13. For the application of this algorithm, two scenarios are possible. Either the total width of the street is fixed, or it is not. The latter option allows a lax inclusion of additional vehicle lanes of all kind; with the last step being the determination of ω. On the contrary, a fixed value for ω restricts the possibilities and requires a wiser perspective on mode accommodation. The width that remains available (for inclusion of other modes) at this stage is therefore:

$$\omega_{av} = \omega - \omega^c \qquad \textit{Equation 25}$$

14. Different mode combinations are explored. To test each one, it is necessary to return to step 6 and provide the necessary parameters for each transportation option. Generally, for bicycle or bus transportation, $n^{bi} = n^b = 2$, but it can be checked via step 10.

15. Once the modes are allocated, the resulting space available $\omega_{av} = \omega - \omega^c - \cdots - \omega^N$) is destined to sidewalks ($\omega_{av} = \omega^w$).
If it is qualified as not sufficient, it is likely that either the number of lanes obtained, or the number of transportation options included, is inadequate for the available ω of the street. In this case, the solution is rejected, and the process restarts with an arrangement of the modal percentages.
The set of mode shares will be taken as correct only as long as ω^w is large enough.

16. When $\sum \omega^i = \omega^w + \omega^c + \omega^{bi} + \omega^b + \omega^t + \omega^{other} = \omega$, the definition of the cross section is completed. Assessment is recommended to discern pros and cons. The dynamics resulting from this final definition include many non-numerical variables which have a huge importance in feedback (mainly by affecting the final flows in the network) but which are not so easy to address through the algorithm. This will be more detailed in the next section and is also drawn in the algorithm scheme provided in *annex 9.2*.

Although *annex 9.3* provide all the required information, the following table summarizes the values chosen for the implementation of the algorithm in space assignment[16].

	walking	bicycle	car	bus	tram
Speed v ($\frac{m}{h}$)	4,000	10,000	40,000	20,000	30,000
Occupation o ($\frac{pax}{veh}$)	1	1	1.2	45	200
Lane width ω_{lane} (m) *Standard. Changes apply according to annex 9.3.*	2 *(minimum)*	1.40	3.5	1.4	3.9

Table 3. Basic mode-defining variables.

[16] Data sources are indicated in annex 9.3.

4.3. Feedback streams on street design. Walkability.

Pedestrian flow has been treated in this report from a different approach than that of cars or buses. A numerical approach permitted to find a set of formulations which link the walking demand with the length u, the length of the street, the population density, and the type of land uses. This approach is not useful for the direct computing of a sidewalk width. On the contrary, for cars and other transportation modes, an algorithm has been proposed which transforms flows into number of lanes (whose width is established by codes and recommendations) and therefore defines the occupation of space. This implies that, once the computations are finished for all the modes to be included in the street, sidewalks will be placed in the remaining space.

Pedestrian mobility is particularly important because of the positive characteristics that it involves, not only environmentally but also personally. It "*favours healthy habits, a sense of belonging to the neighbourhood, the social use of public space and the proximity commerce*"[18].

However, urban development has in many cases omitted these advantages. "*Deciding which mode of transportation is going to have a wider design value than the suggested minimum is a matter of engineer discretion, and engineers traditionally choose car user interests over the pedestrians*" (Kim et al., 2011). This usually results in street configurations destining a major fraction of the space to private car transportation and omitting the consequences that such scenario can have as reducing pedestrian demand and flows.

A broad extent of literature (Ferreira & Sanches, 2007; Kim et al., 2011, for example) has focused on the evaluation of the negative effects that a bad sidewalk design produces in the network (an example of this is shown in Figure 28).

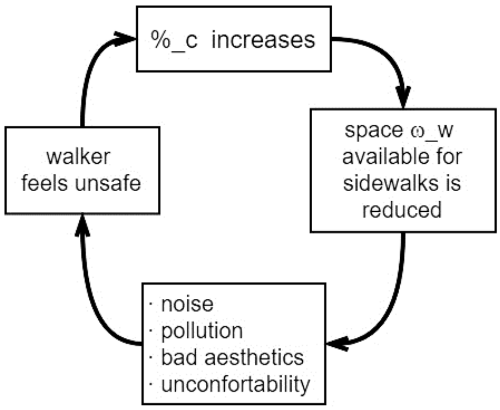

Figure 28. Loop caused by inadequate pedestrian design derived from a too-narrow sidewalk. Source: own elaboration.

With the aim of amending the unbalances present in modal distribution, and most importantly in its physical translation, the word 'walkability' was introduced as a key concept in understanding and prioritizing pedestrian mobility (Klinger et al., 2010; Serrano-López et al., 2019). Walkability reflects "*how the built environment facilitates or hinders walking*" (Delso et al., 2018) and is influenced by both objective and subjective factors. The walkable city "*is a city in which the car is an optional instrument of freedom rather than a prosthetic device*" (Jeff Speck, 2014).

[18] *(barcelona.cat).*

Some of the spatial characteristics defining walkability include urban density and sprawl, land-use mix distribution, connectivity, greenery, the presence of sidewalk and its width, safety, accessibility, lighting, and the spatial configuration of streets (Delso et al., 2018; Janssen & Rosu, 2012; Torres Martínez, 2019). In many cases, these qualities are perceptual (Ewing & Handy, 2009) and therefore difficult to quantify, which makes them frequently omitted. *Figure 29* shows the main physical features to assess in the study of walkability.

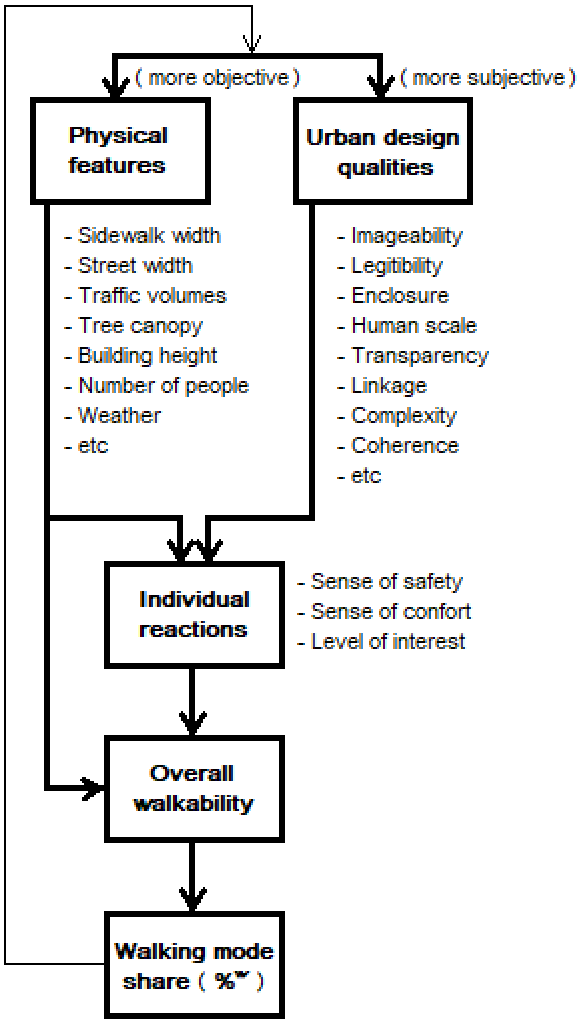

Figure 29. Aspects involved in walkability. Source: modified from Ewing and Handy (2009).

The variable u mentioned in previous sections stands for a distance "in favourable conditions" because it aims to evidence that, even if an individual agreed to spend a certain quantity of time walking, other requisites will play a role in his decision making. Would he have the same willingness if the pavement is noticeably damaged? What if there are no trees to give some charm to the trip, neither a bench to rest in case of need? What if cars are driving in such a high speed and proximity that the comfort of the walk falls in danger? Even if leaving u untouched, these events would for sure cause a decrease in the demand $\%^w$. This decrease in $\%^w$ would consequently increase one or more of the remaining transport modes ($\%^{other}$). Because private transportation offers independence and a lower travel time, among other advantages, in many cases t is $\%^c$ the mode share experiencing the main increase (as in the example of *figure 24*); and this intensifies the cycle (more cars produce more noise and pollution, thus walking results ever more unpleasant; thus $\%^w$ keeps transitioning to $\%^c$, and so on).

On the contrary, if the individual finds himself in an embracing environment with enough room to walk; protected from other kinds of circulation; and offered a visual and environmental scenario which encourages him not only to walk, but most importantly to 'enjoy' the walk, the consequences are opposite: $\%^{w}$ could probably be increased, thus reducing $\%^{c}$, and with it pollution and noise rates, among other. Figure 26 provides a schematic representation of this process, where feedback is key. For example, if $\%^{w}$ decreases, enhancing of walkability features, such as increasing sidewalk width, could be a solution. This also highlights that both time and planning criteria are important in the cycle.

Current procedures to promote walkability are led by some 'visionary transport engineers' who, contrary to isolating different modes as much as possible (which has been a trend for long in transport planning), seek to increase interactions between transportation modes by removing horizontal and vertical elements of separation. This results in an equal respect for all modes, providing a street design characterized by the presence of attributes which are highly different but, however, seem to vary gently and harmoniously along their physical allocations. "*By removing what seems to give us 'order' in the transport system, the theory of shared spaces is that we force road users to react to social cues. [...] The thinking is that this creates more awareness, and that perhaps we can achieve even greater 'order'*" (Levinson et al., 2017).

In the following table, some aspects related to walkability are explored as an indication of which features should be evaluated once the first iteration of the cross-section design is performed, and to amend possible drawbacks. While the walking demand distributions related with the parameter u represent the "objective" approach of pedestrian demand (influenced by time, land uses, etc), these qualities also have a great importance, given their high power of influencing the mentioned demand.

PERCEPTUAL FEATURES INVOLVED IN WALKABILITY *[cntd'.]*
SIDEWALK WIDTH
Most important parameter of walkability. Some studies suggest that narrow sidewalks suppose the main reason for the individual to prefer other transport means in detriment of walking (Kocklemann, 1997). Street crossings, bollards, stairs, lamp posts, trees, and even other pedestrians, usually act as barriers where pedestrians have to stop and wait, and can influence travel mode choice (Delso et al., 2018; Kim et al., 2011). This is highly interrelated with sidewalk width, for that as greater the space is, the easier it is to dodge the obstacles. Furthermore, it strongly influences the rest of parameters. Values attributed to a good pedestrian Level of Service usually range between $\omega^{w} \in [2.5\,,3]\ m$ (Kocklemann, 1997). Values over 5 m are linked to an excellent walkability (Fallahranjbar et al., 2019). In *Recomanacions de mobilitat per al disseny urbà de Catalunya*, a minimum is established of $\omega^{w} = 2\ m$ which allows room for two wheelchairs and the installation of the urban services beneath the sidewalk, but it is advised to adopt a broader perspective which considers pedestrian flows, adjoining activities (commerce, neighbours, bus stops, etc) and landscaping features (Departament de Política Territorial i Obres Públiques, 2009).
ACCESSIBILITY
It is the product of travel times and the location of activities, and has a great influence on mode choice (Levinson et al., 2017). Because every trip "*begins and ends with walking*" (Levinson et al., 2017), pedestrian transportation is the choice granting a greater accessibility. This represents a key reason why environments need to be designed pedestrian-friendly).

[cntd.'] **PERCEPTUAL FEATURES INVOLVED IN WALKABILITY**
TREES AND GREEN COVER
Presence of trees and green areas enhances walking demand and quality, while preserving the natural environment. Fortunately, it can be easier to measure than other walkability indicators. For example, (Ortigosa et al., 2020) used the Normalized Difference Vegetation Index (NDVI), extracted from satellite information, to calculate the proportion of pixels representing the green cover which intersected with the street. Visual assessments are also usual which roughly calculate the percentage of trees or grass in any street section.
POPULATION HEALTH AND LIFESTYLE
A pedestrian-friendly environment is related to a lower degree of sedentary lifestyle, especially among the population which depends the most on local neighbourhoods such as children and the elderly (Torres Martínez, 2019). This proves that by promoting walkability not only increases 'environmental health', but also the wellbeing of the population.
IMAGEABILITY
It is "*the quality of a place that makes it distinct, recognizable, and memorable"* Clemente et al. (2005), in other words, "*that shape, colour, or arrangement which facilitates the making of vividly identified, powerfully structured, highly useful mental images of the environment*" (Lynch, 1960). Picadilly Circus (London) or Plaça Catalunya (Barcelona) are examples. Defining qualities include presence of historical buildings, landmarks, bodies of water (Clemente et al., 2005).
ENCLOSURE
It represents how much "*public spaces are visually defined by buildings, walls, trees and other elements*" Clemente et al. (2005), Too wide a visual range could make the individual feel disconnected from the city around him, while a too restricted one would be overwhelming and disruptive. The mid-point is described as an "outdoor room", which instils "*a sense of position, of identity with the surroundings [...] and embodies the idea of hereness*" (Cullen, 1961). Features defining enclosure include how much far can one see, the proportion of walls in the street sides, and the proportion of sight of the sky (Clemente et al., 2005).
HUMAN SCALE
Human scale refers to "*the size, texture, and articulation of physical elements that match the size and proportions of humans and [...] correspond to the speed at which humans walk*" (Clemente et al., 2005). It includes presence of street furniture, protection from traffic, proportion of windows at street level, presence of benches and lamp posts, and speed limitations in motorized circulation.
TRANSPARENCY
It is *"the degree to which people can see or perceive human activity beyond the edge of a street or other public space*" and "makes the surrounding uses to be perceived as clear and accessible" (Clemente et al., 2005). It is classically detected by the presence of walls, doors, landscaping, openings, and display windows.
COMPLEXITY
It represents *the number noticeable differences to which a viewer is exposed per unit time. Human beings are most comfortable receiving information at usable rates. Too little information produces sensory deprivation, too much creates sensory overload*" Ewing and Handy (2009). It is highly related to human scale and variety of architecture and landscape (Clemente et al., 2005). Jacobs (1993) let intuit this quality when narrating "*perhaps it is the monuments that compel some attention, perhaps it is just the pleasantness of the drive and the not overly wide roadway- drivers seem to proceed reasonably, not speeding*".

5. Results on space assignment

The proposed algorithm was applied for the set of values obtained for analysis in section 3 (tables 1, 2). General recommendations on space assignment were also applied following the tables in annex *9.3.* (and summarized in *table 3*). Results depend on the assignation of mode percentages $\%^i$ for the computation of flows.

Figure 30 shows, for the case of obtaining two lanes ($n = 2$) in all modes, the modes that can be added in the cross section as a function of the total width ω. More lanes would imply bigger space needs and therefore restrict mode inclusion, as well as the resulting sidewalk width. Every label in the y-axis means that all modes below it are included. It is important to know that the shape of the chart could vary depending on which modes are first assessed (because the available width changes). In this case, the order has been established as: pedestrian, bicycle, car, bus, and tram, and a minimum sidewalk width is considered of $\omega^w = 2m$.

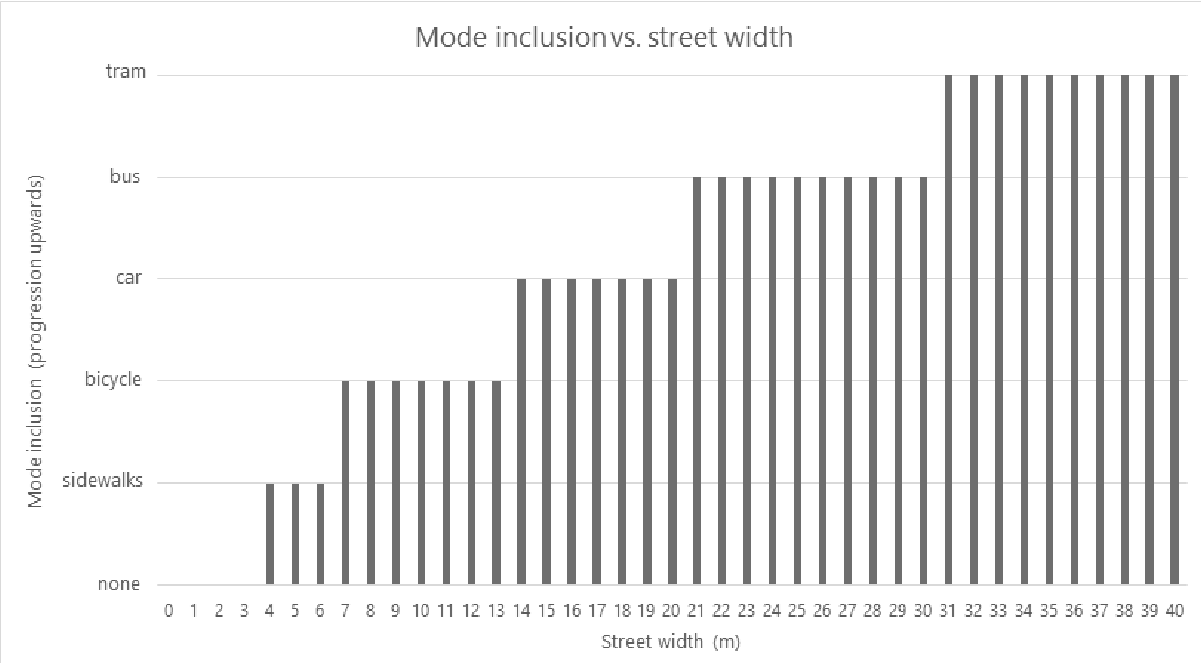

Figure 30. Example of mode inclusion for the case of two lanes per mode.

A total street width of $\omega = 24\,m$ was chosen for application, as it is inside the common range in metropolitan avenues.

The input of different modal percentages for bicycle, car, bus and tram resulted in a set of different scenarios of space configuration. Some of these are shown in *annex 9.4*.

According to the approach, car demand can cause major changes in street configuration. Due to its spatial needs, increase in its modal share have shown to be strongly tied to space unavailability for other modes, for that it can result in 2, 4 or 6 lanes. Figure shows the results on the space need as a function of car demand percentage. Note that the upper limit of the y-axis accounts for the total width of the street, so that the remaining space is the one destined to other modes (including sidewalks).

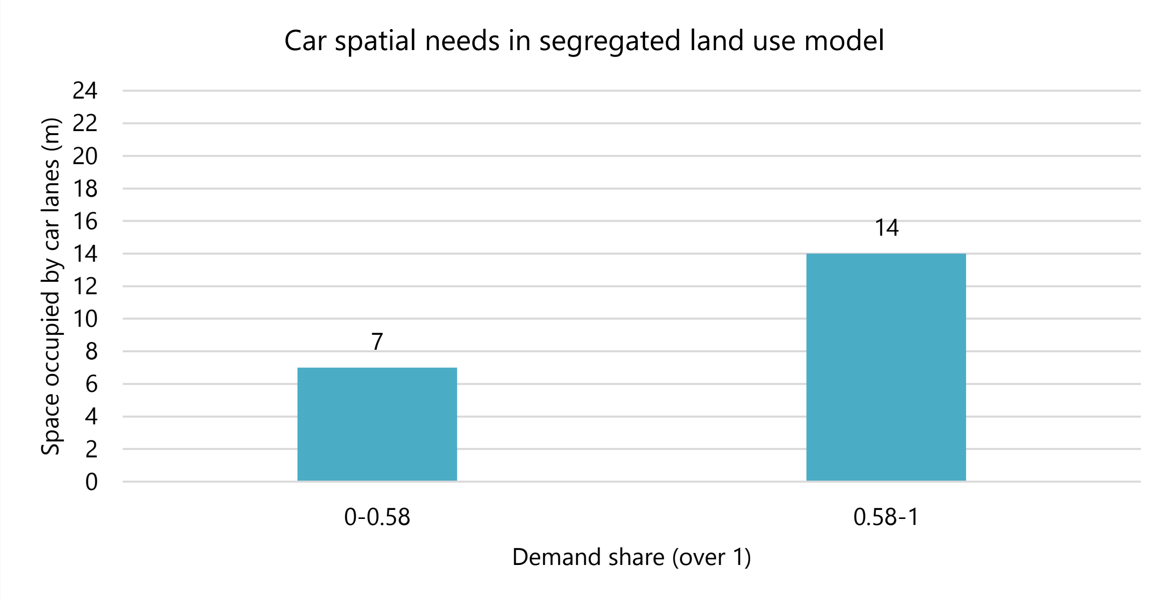

Figure 31. Car spatial needs in segregated land use model.

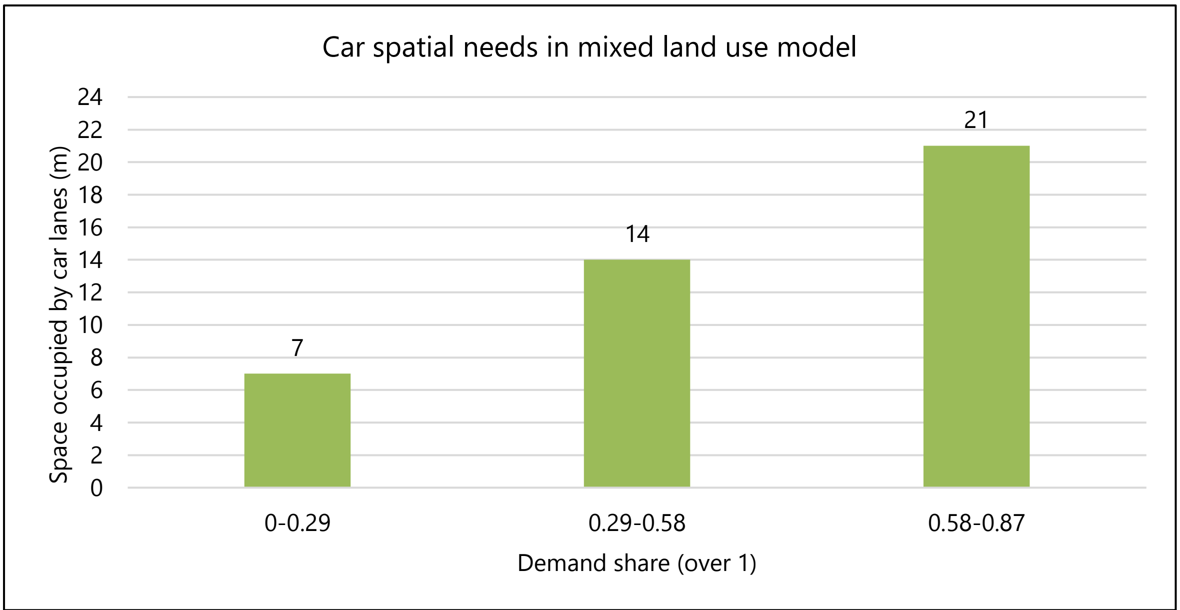

Figure 32. Car spatial needs in mixed land use model.

Below, results are shown from an exemplary implementation of the algorithm, where demand percentages $\%^{b} = 30\%$ and $\%^{bi} = 10\%$ have been input as a representation of sustainable-led mode shares. If tram is not included, car must be assigned the remaining demand percentage, as $\%^{w} + \%^{b} + \%^{bi} + \%^{c} = 100$. Variable "space %" has been computed representing the percentage of total space occupied by each mode. Sidewalks occupy 32.9% of the space, which corresponds to 7.9 m (around 3.9 m each). This is summarized in *table 4*.

Modes	notes	Segregated land use, modal %	Mixed land use, modal %	space %
walking	*Resulting from section 3*	0.125	0.435	0.329
bicycle	*Input*	0.10	0.10	0.117
car	*Remaining %*	0.475	0.165	0.292
bus	*Input*	0.30	0.30	0.263

Table 4. Example of algorithm input demand data.

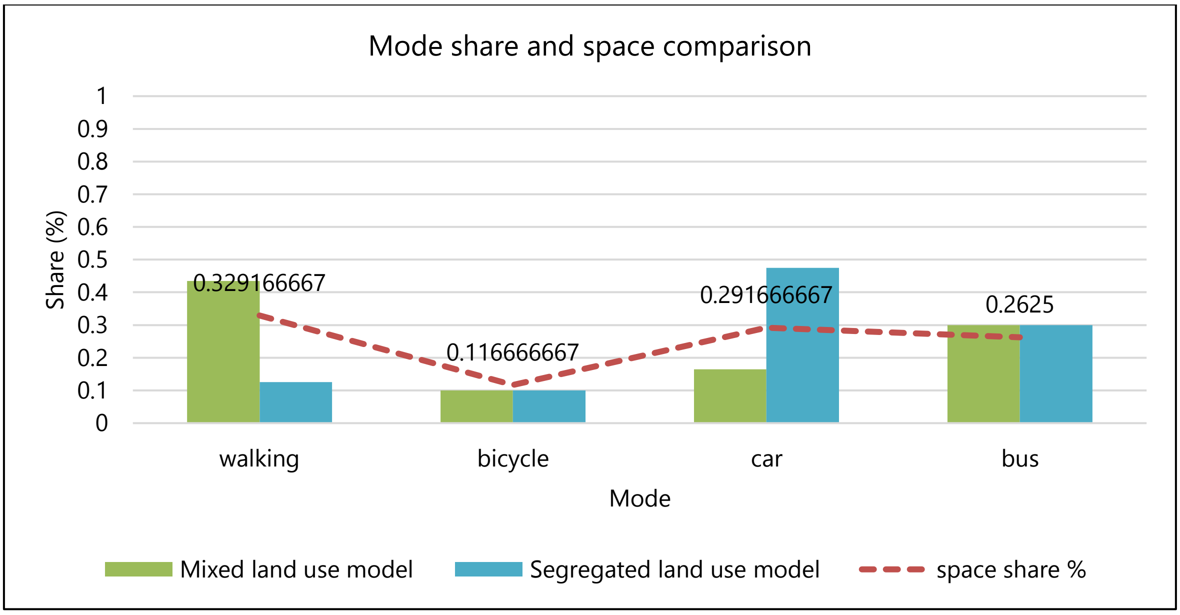

Figure 33. Mode share and space comparison.

Flows corresponding to this distribution are shown in figure 31.

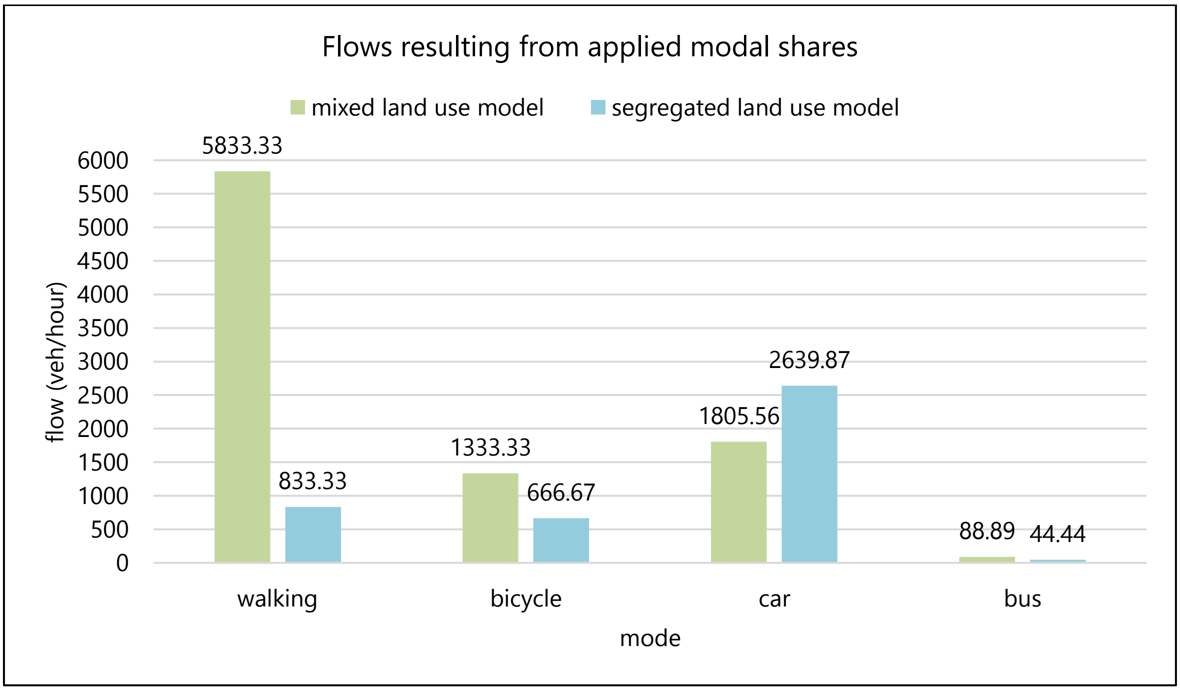

Figure 34. Flows obtained for applied modal shares.

6. Analysis

The numerical approach developed in section 2 offers an estimation of pedestrian demand as a function of street length, population density, the walkable distance u, and the type of model applicable in terms of land use. Although the pedestrian mode share is also influenced by perceptual factors apart from time or distance, the approach seems to be adequate in giving coherent results which can later be put in context, along with other objective and subjective variables.

The most striking finding is linked to the concept of mixture. Already in the comparison of the distance travelled distributions of both street models, the average distance travelled in the segregated land use model is 1.5 times that of the mixed land use one, demonstrating that, in general, people will have to travel further if residences and workplaces are in two separated sectors. This is also perceptible in the uniform curvature of the mixed land use model, whose radius is bigger than the convexity in the segregated land use model (after the change of curvature at $L/2$), meaning that the likelihood of having to travel longer distances is greater in the latter.

In reference to the maximum distance u that a person is willing to walk, the range between $750\ m$ and $1500\ m$ seems to be coherent with literature and corresponds to walks up to 20 minutes long. The likelihood of walking depends on the size of u in comparison to L and can be computed after the change of variable $d = u$ in the previous distributions.

Fixing $u = 1{,}000\ m$ as an average value permits to obtain pedestrian demand directly as a function of total street length through equations 13 and 14, extracted from the trendlines applied to the curves. Error is almost imperceptible in the mixed land use model function, whilst in the segregated one it remains on the safety side (reaching lower percentages than real) and is limited to lengths lower than $4{,}000\ m$. Pedestrian demand could be in fact obtained from the equations developed in 2.1. and 2.2., but this would be more tedious as functions are piecewise and based on the hypotheses that $u < L$. Instead, modelling through trendlines permits a faster calculus, in which error is slight, especially in the mixed land use model ($R^2 \approx 0.84$ in the segregated land use model and $R^2 \approx 0.98$ in the mixed land use model).

In reference to the research of an optimal street length (which promotes walkability but is at the same time coherent with real-life street cases), $L = 4{,}000\ m$ seems to be adequate for many reasons, apart from the one mentioned in the previous paragraph. First, an acute diminishment of pedestrian demand is perceived in that point for the segregated land use model, which suggests that in order in order to hold competitivity between both models in terms of walking, street length has to be below $4{,}000$. Second, this value seems to represent a midpoint in real cases (in which, because city structures are so varied, street length comprises a wide range of values anyway). Finally, as suggested by literature, a zone is found around $4{\sim}5\ km$ distances in which transportation modes start to have a more established behaviour, which grants a better reliability of hypotheses and assessment.

Pedestrian demand resulting from pair $(L, u) = (4{,}000, 1000)$ is 12.5% for the segregated land use model and 43.75% for the mixed land use model if assessed through the piecewise functions (2.1.1. and 2.1.2.), whereas if input to the trendlines (equations 13 and 14), values 10.5% and 45.4% are obtained, respectively. This reassures the reliability of the trendline functions, due to their small error, and is important because it suggests that any pair (L,u) could be applied in the approach while ensuring satisfactory results.

The importance of mixture of land uses is evidenced again by the fact that the percentage of people willing to walk is around 4 times greater in the mixed land use model than in the segregated one.

In section 3.3., equation 17 has been proposed to calculate pedestrian flow, q^w, as a function of street length and population density (with fixed $u = 1000\ m$). When Applying $L = 4{,}000\ m$ and $\rho = 20\frac{pax}{m}$, flow values obtained were higher than usual, realistic values. However, this is not considered as incorrect taking into account that the street model is perfectly straight and hold no interactions with other streets or elements, for what flows obtained are ideal and therefore probably higher than in real cases, even if considering the same base variables (distances, velocities, densities). Furthermore, additional inclusion of other transportation modes (through the proposed algorithm) will show that the assessment derived from such high flows obtained is in fact on the safety side, which foments the potential of the approaches as useful tools in real-life procedures. This will be analysed later.

High pedestrian flows also accentuate the need of a correct sidewalk design, especially in the case of the mixed land use model, where flows are more than 4 times greater than in the segregated one, and can therefore be translated into highly densely occupied sidewalks.

Also, it is important to point out that hypotheses I, II and III made for the calculation of the total flow of the street might vary according to general considerations, such as time range, possible inclusion of a peak hour factor, average number of trips, etc. Also, the influence zone x of the street has shown to have a big importance for that it serves to convert population densities in pax/km^2 into a one-dimensional variable $\rho\ [pax/m]$ which can be applied for the calculation of flow. *Figure 22* presents the evolution of pedestrian flows as a function of linear density for the pair (L,u) fixed previously. Steep slopes in the mixed land use model show that linear densities above $1{\sim}5\ pax/m$ can drastically increase pedestrian flow. In order to treat this question with care, both population density $\bar{\rho}\ [pax/km^2]$ and the extent $x\ [m]$ of the influence zone would need to be accurately defined. Even if $\bar{\rho}$ is low, large values of ρ can be obtained if having a long influence axis x. This might be possible in sparce street networks (for that more people will be 'users' of the same street). Finally, the assessment of population density is especially important in mixed land use models, for that the variation of slow with population density is much faster than in the segregated land use model.

In reference to the space assignment approach, the set of calculations proposed seems to be useful, as it requires basic data and provides flows higher but not so different from the ones generally found in cities (see *annex 9.5.*). Note that linear density has been applied as $\rho = 20$, because it enhances that with lower densities (appropriate for most European cities), the obtained flows would be lower, for which some results on space assignment, for example in the case of cars, would reach even lower values of lanes need (in other words, this value for linear density is on the safety side).

Results in *figure 30* show that, for street widths between $20{\sim}30\ m$, tram implementation is not possible along with walking, bicycle, car and bus modes. However, in this example the latter modes have enjoyed prioritization and also the need of only two lanes per mode has been shown , which means that other configurations can be possible depending on the size of the cross-section, the space needs resulting from the algorithm approach, and the modes aimed to be included (which will be expressed by the input of demand percentages).

For the example of a 24-m wide street, application of results selected in section 3 for pedestrian demand, along with standard mode shares for bus and bicycle, has shown major differences between the segregated land use model and the mixed one. Already in section 3, it was shown that pedestrian flows are more than four times lower in the first mode than in the latter. The input of the same $\%^{b}$ and $\%^{bi}$ in both models results in bus and bicycle flows in the segregated land use model being around half of those in the mixed one; whereas car flows represent 1.5 those of the mixed one. This highlights once more the importance of mixed land uses in sustainable mobility.

Another important finding is that the quantity of lanes needed for car transportation is $n = 2$ in both models. The percentages obtained ($\%^{c} = 0.165$ in the mixed model and $\%^{c} = 0.475$ in the segregated model) correspond to a space need of $\omega^{c} = 7\ m$ (two $3.5m$-wide lanes) according to both figure 28 and figure 29. This is important because, although demand distribution is not satisfactory in the segregated model, it still does not exceed in space requirements. This is a key result, for that it can evidence that in many cases, a big number of car lanes is unnecessarily included in street designs. Also, it should be put along with the fact that in real-life streets, circulation is also permitted in bus lanes. Furthermore, a smarter distribution of space grants a greater sidewalk width, and with it many walkability features which can further increase pedestrian demand. At the same time, decreasing car demand share ensures that the jump between the need of two lanes and the need of 4 or 6 lanes is not reached. These limits are $\%^{c} = 0.58$ in the segregated land use model and $\%^{c} = 0.29$ in the mixed land use model.

The quantity of lanes needed for bus, bicycle and tram transportation has also been obtained as $n = 2$. This is coherent with the fact that, for these transportation options, it is not likely to find or design avenues with more than one lane per sense of circulation.

Although some results on cross section configurations are shown in *annex 9.4.* for the values applied, the analysis of an example of real street in the following paragraphs could be useful to wrap up the evaluation process for the case of an already-existing space assignment.

Let us consider that Avinguda Diagonal in Barcelona follows a model of type mixed land use. The street has a total length of $L = 10{,}000\ m$ and width of $\omega = 50\ m$[19]. If considering $u = 1{,}000\ m$, the expression to calculate pedestrian flow would be the one in *equation 20*.

Population density can be rounded to $1{,}000\ pax/ha$ in Eixample of Barcelona[20], which corresponds to $0.1\ pax/m^2$. The zone of influence should not be so long, for that there are many street intersections around which take part of the transportation demand of the zone. If rounding it to $x = 100\ m$ (25 m on each side, if setting ω apart), the linear density obtained is $10\ pax/m$.

$$\%^{w}_{mixed} = -4.78 \cdot E^{-13} \cdot 10{,}000^3 + 1.78 \cdot E^{-08} \cdot 10{,}000^2 - 2.26 \cdot E^{-04} \cdot 10{,}000 + 1.13 = 0.17$$

[19] Source: https://es.wikipedia.org/wiki/Avenida_Diagonal_(Barcelona)
[20] Source: https://opendata-ajuntament.barcelona.cat

If this result[21] is put along with $\%^{bi} = 10\%, \%^{b} = 30\%$, the percentage for car is $\%^{c} = 43\%$.

Description	Variable	Units	TOTAL	CHECK "1"	Walking	Cycling	Car	Bus	Tram
Total length	L	m	10000						
Population length	Lsector	m	10000						
Population density	ρ	pax/m	10						
Working time interval	h	hours	12						
Maximum distance to be walked	u	m			1000				
Modal transportation percentage	%	unit %		1	0.17	0.1	0.43	0.3	0
Flow	q	pax/hour	16666.66667		2833.33333	1666.666667	7166.66667	5000	0
Vehicle flow	**q**	**veh/hour**			**2833.33333**	**1666.666667**	**5972.22222**	**111.1111111**	**0**
Average occupation		pax/veh			1	1	1.2	45	300
Average velocity		m/hour			4000	10000	30000	20000	70000
Average space between vehicles (capacity) (space including 1 veh+separation)									
number of lanes	n	#		round!	-		3.98148148		2
effective number of lanes	n	#			2	2	4	2	2
Stipulated lane width	ω_lane	m		codes		1.4	3.5	3.15	3.9
Total parking width (considering both sides)				choose	0	0	5	0	0
If TOTAL WIDTH is fixed	**ω**	**m**	**50**		**21.9**	**2.8**	**19**	**6.3**	**0**

Figure 35. Results of the algorithm for Avinguda Diagonal (approximate).

As shown in the screenshot (*figure 35*) of the algorithm results for Avinguda Diagonal, the percentages input give a total number of car lanes of four (two per sense), to which widths of parking can be added (a 2.5-m lane on both sides, for instance). Placing two lanes for buses and two lanes for bicycles results in $21.9\ m$ for pedestrian transportation. This distance, however, is not effective, for that a part of this width will be destined to separation elements and buffers, etc.

In fact, if comparing these results with an actual section of Avinguda Diagonal, it is noticed that the design is quite similar to the one obtained in the algorithm. Although lane widths adopted might vary, and speed of cars, for example, has been restricted as a "zone-30" conception in the algorithm, values obtained seem adequate. For instance at around nº400-500, Avinguda Diagonal has a central sector where two car lanes circulate per each sense; it also has two lanes for buses/taxis and two lanes for bicycles. Although it has two additional lanes (one per sense) for car circulation, these are useful for vehicles to access turns more easily than if circulating through the central lanes. The resulting sidewalks are wide (between 5-7 m) as to allow comfortable pedestrian circulation, which is also protected from the lateral car lanes by the parking spaces. In regards to the bicycle lanes, they are protected from the lateral car lanes by a line of rubber buffers; and from the central lanes by a wide section of pots with trees and plants. This adds greenery and pleasant shadow/light alternances while also attenuating traffic noises.

Overall, the design of the from a sustainable-led approach seems go coincide with that of the proposed algorithm. More than two car lanes per sense are added, but distribution of space plays a key role in protecting every stream of traffic, and the street width is large enough as to still result in satisfactory sidewalks. In fact, other allocation decisions could result in less efficient flows even besides the large width of the street. If, for instance, the lateral car lanes were placed along with the central ones, turns would be difficult and probably affect bicycle circulation. Or, if for instance, the big planter strips were placed between sidewalks and parking spaces, bicycle lanes would be not so protected, which could consequently decrease demand. Bus stops are placed in a space taken from the section of tree pots,

[21] If applying the piecewise functions, the result is 0.19, which is similar and therefore confirms the suitability of the trendline equations.

which has easy access from the sidewalk through short pedestrian crossings. In regards to walkability, the presence of display windows and shops, diverse building typologies, trees, benches, bar terraces, etc, is another consequence of mixture which could be enhancing pedestrian demand.

Figure 36. Avinguda Diagonal around the zone indicated. Source: Google Earth.

7. Conclusions

Literature review has shown that sustainable transportation is based in the promotion of non-motorized modes, and that this is extremely linked with the geometrical design of the street. For pedestrian and public transport demand to increase, urban planning procedures must guarantee an environment which is safe, pleasant and adequate for the necessities of all sectors in the society.

With the aim of assessing the potentialities of pedestrian transportation, an approach has been suggested composed of simple calculations, and based in the hypotheses that there is a maximum distance that people would agree to travel by foot. This distance has been established as $u = 1{,}000\ m$ for further calculations, but could vary from case to case depending on statistical data such as average population age, lifestyle, topology constraints, etc. It has been proved to be a useful tool for the numerical, objective estimation of pedestrian demand in particular street models.

The most striking finding provided by this approach is the confirmation of the important role of land use mixture as a parameter defining walkability. Results show that the percentage of people willing to walk to work can be around four times greater in a mixed land use model than in a segregated one, which is linked to the fact that mixture increases the range of possible locations of workplaces in relation to residences. If also considering a more subjective conception of mixture, an argument is added based on that people tend to enjoy walking more easily in an environment that offers more variety (houses, shops, workplaces, historical buildings, etc). "*Mixture is a positive factor, as it helps reduce mobility and promotes urban life and the social control of space*" (AMB, 2020b). This latter argument, although harder to be numerically defined, is important because it further contributes to increase the initial, length-based pedestrian demand $\%^{w}$.

Pedestrian demand has shown to vary according to the relationship between u and the total length L of the street. Formulae have been extracted which permit an estimation of walking percentage directly as a function of L (once u is appraised) depending on the degree of mixture of the street. The estimation is of better quality in the case of the mixed land use model than in the segregated one, for that it shows a lower error ($R^2 = 0.98$) due to the smoother decrease of pedestrian demand with L.

Similarly, the establishment of both u and the total length L of the street permits to study how pedestrian flows can be shaped by population density as a result of simple hypotheses related to the motive and time range of trips. The influence zone of the street can be highly important in determining the linear approximation of population density, and, therefore, the flows obtained.

These relationships are simple, but could be further explored for different city or street structures, by considering the particular variables applying in each case. This could represent a way of estimating pedestrian demand, either as a result of a given scenario (therefore permitting potential improvements or corrections), or with the aim of implementing a sustainable-led design in rather undeveloped cases or zones.

In real-life scenarios, flows would probably be lower than the ones obtained with this approach (even if the same values are applied), for that they do not only depend on population density or the pair (L, u), but also on the great quantity of interactions and stimulus present in the street. Streets are not perfectly straight and horizontal, and they hold a high variety of interrelations with other elements such as other street crossings, stops, social activities, etc; which cause flows to be significantly lower and more changing. To correctly represent the characteristics of a street or city sector, a more specific study would consider all these interactions in more detail.

A set of simple calculations has been proposed to calculate the number of lanes needed as a function of demand percentage. If flows and densities of a network are carefully considered, this might have a potential utility in real-life approaches, especially because it demonstrates that in many cases, metropolitan avenues do not need more than one car lane per sense of circulation. Automobile promotion could therefore be mitigated through a more objective perspective of which are the real space needs of transportation modes, and which is the space allowance of the street.

Allocation of all modes in the street width can in some cases be not possible. However, if mode inclusion results from a study of the transportation options which better fulfil the needs of the population, while promoting sustainable dynamics, it is likely that a coherent definition of the cross section will be obtained which grants a satisfactory sidewalk width. Sustainability-led modal shares can be used as the tool determining which of the modes has more chances of being successful if implemented. However, other factors play a role, such as the particularities of the city or the population; the different alternatives of location (central lanes; lanes on both sides, etc), which could diminish the available space by imposing the need of separation strips, medians, waiting zones, etc; as well as the specific code requirements applicable. For example, some districts or zones may opt for the promotion of bus transportation whereas others would rather rely on tram lines (an example by excellence: San Francisco). This is one of the facts highlighting the huge importance of city structure and its idiosyncrasy.

Figure 37. Are its steep slopes determinant for the promotion of tram transportation in San Francisco?[22]

[22] *Source: k2partnering.com*

It is important to bear in mind that the analysis of the most efficient configuration does depend on sidewalk width and other walkability indicators; but not exclusively. Because there are people with special mobility or accessibility needs (the disabled or the elderly, for example), inclusion of different modes, particularly the public ones, is key. Economic considerations also should be devoted to guarantee affordability for these and the whole set of population sectors.

Literature review, along with the developed approaches, have permitted to summarize the key features of an efficient, sustainability-led street design. By merging both the objective and subjective factors, a definition of an ideal metropolitan avenue is obtained which consists of:

A mixed land use model, so that pedestrian mobility is enhanced. Promotion of sustainable modes (cycling, public transport rather than cars…), as long as street width and the city dynamics permit it. A sufficiently wide sidewalk. Promotion of accessibility, both physical (to buildings, through street crossings…) and economical (accessible bus or tram fares for all population statuses).	Objective
Promotion of imageability: respect of details and the idiosyncratic elements or historic buildings that might make the street interesting and recognisable, maybe unforgettable. Enclosure: the room-like quality. A well-defined space, with a not-too-restricted but neither not-too-wide visual range. Respect of the human scale, by setting speed limits for motorized modes, and utilities and urban furniture in coherence with flow needs (clear indications, lightning, etc). Promotion of transparency: display windows, landscaping, clarity of the surrounding. Inclusion of a certain level of complexity though different modes, landscape elements, human activity; but modulation of streets and signal coordination so that stimulus are not excessive and belong to a harmonized environment. Inclusion of greenery: trees, plants, decorative natural elements, to enhance environmental health but also to palliate noise impact and offer alternatives of shadowed/sunny areas to improve the quality of the walk.	Subjective

A cycle of analysing, proposing, and analysing again, is the key to sustainability in all its senses. This cycle represents the approach of a society that aims to evolve and improve, and what attains by doing so has the most amazing consequence: that the biggest cycle, the cycle of the planet, keeps spinning on.

8. References

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9. Annexes

9.1. Calculations in 2.1. and 2.1.

9.1.1. Segregated land use model

This scheme divides L in two halves, the first one representing households and the second one representing the activity sector. No travel is considered between pairs of points inside the same sector, as dwellers (i.e. travellers) only move from points between $x = 0$ and $x = \frac{L}{2}$ to points between $x = \frac{L}{2}$ and $x = L$ and viceversa.

A uniform probability density of workplaces location is assigned to sector 2 such that its density function is attributed to each of the households in sector 2. This means that the likelihood (probability density) of the job location of any household $x = i$ to be placed at $x = q_i$ inside sector 2 is:

$$f(q_i) = \frac{1}{\frac{L}{2}} = \frac{2}{L}$$

<u>Distance travelled distribution</u>

The likelihood that any random individual travels a distance lower or equal to d can be addressed as the combined likelihood that (a) the individual lives in a certain slice dx (grey), at a certain coordinate x from the origin (left extreme) and (b) its job is located at a certain coordinate before $x + d$ (recalling movement is only allowed towards the right hand-side, for that the activities sector is located there).

The likelihood that the individual lives at a certain x is represented by the quotient of such point (which holds an actual infinitesimal length dx), and the total sector destined to households, which is $\frac{L}{2}$. Hence:

$$P^{dwelling} = \frac{1}{\frac{L}{2}}$$

The likelihood that the individual works before a distance d corresponds to the quotient between the space that such event represents, this is a sector of length $x + d - \frac{L}{2}$ and the total space where workplaces are feasible, $\frac{L}{2}$. Hence:

$$P^{working\ before\ x+d} = \frac{x + d - \frac{L}{2}}{\frac{L}{2}}$$

The combined likelihood is (according to the logical connector *and*):

$$P^{travelling \leq d} = P^{dwelling} \cdot P^{working\ before\ x+d} = \frac{1}{\frac{L}{2}} \cdot \frac{x + d - \frac{L}{2}}{\frac{L}{2}}$$

However, depending on the value adopted by d the casuistry is divided into two scenarios.

1) If $d < \frac{L}{2}$

This is the simplest case, for that the distance to travel does not exceed the length of the activity sector, and thus the computation of the likelihood is governed by the previous equation. Note that the lower bound of the integral is $x = \frac{L}{2} - d$ because travel is only understood towards the workplace, and any dweller located before such point would not "reach" the activity sector with the distance d, for what $P^{working\ before\ x+d} = 0$ its likelihood would be zero (he would only have a likelihood of travelling a distance 'greater' than d).

$$\boldsymbol{P^{travelling \leq d}}_{\boldsymbol{if\ d<\frac{L}{2}}} = \int_0^{\frac{L}{2}-d} \frac{1}{\frac{L}{2}} \cdot 0 + \int_{\frac{L}{2}-d}^{\frac{L}{2}} \frac{1}{\frac{L}{2}} \cdot \frac{x + d - \frac{L}{2}}{\frac{L}{2}}\, dx$$

$$\boldsymbol{P^{travelling \leq d}}_{\boldsymbol{if\ d<\frac{L}{2}}} = \cdots = \frac{\boldsymbol{2 \cdot d^2}}{\boldsymbol{L^2}}$$

2) If $d > \frac{L}{2}$

Because any individual living between $L - d$ and $\frac{L}{2}$ will definitely travel a distance lower or equal to d to go to work, and therefore $P^{working\ before\ x+d} = 1$, the sumand corresponding to this sector will only involve the integration of the dwelling probability. Instead, for people living before $L - d$ the probability is still depending of how much of the activity sector is wrapped into d.

$$\boldsymbol{P^{travelling \leq d}}_{\boldsymbol{if\ d>\frac{L}{2}}} = \int_0^{L-d} \frac{1}{\frac{L}{2}} \cdot \frac{x + d - \frac{L}{2}}{\frac{L}{2}}\, dx + \int_{L-d}^{\frac{L}{2}} \frac{1}{\frac{L}{2}} \cdot 1\ dx$$

$$\boldsymbol{P^{travelling \leq d}}_{\boldsymbol{if\ d>\frac{L}{2}}} = \cdots = -\frac{\boldsymbol{2 \cdot d^2}}{\boldsymbol{L^2}} + \frac{\boldsymbol{4 \cdot d}}{\boldsymbol{L}} - \boldsymbol{1}$$

■

Note: If $d = L$ then

$$\boldsymbol{P^{travelling \leq d}}_{\boldsymbol{if\ d>\frac{L}{2}}} = \int_0^{\frac{L}{2}} \frac{1}{\frac{L}{2}} \cdot 1\ dx = \frac{2}{L} \cdot \left[\frac{L}{2} - 0\right] = 1$$

(the likelihood of travelling a distance lower than or equal to d is 1).

Average distance travelled

Because we assume that no displacements are performed between points belonging to the same sector, the average distance travelled corresponds to the length travelled by a dweller who goes from the midpoint of sector 1 ($x = \frac{1}{4}$) to the midpoint of sector 2 ($x = \frac{3}{4}$):

$$Av = \frac{L}{2}$$

9.1.2. Mixed land use model

In this scheme land uses (residence and occupation areas) are homogeneously distributed along the length L.

A uniform probability density for job locations is assigned to the total length L such that its density function is attributed to each of the households. This means that the likelihood (probability density) of the job location of any household $x = i$ to be placed at $x = q_i$ ($0 \leq q_i \leq L$) is:

$$f(q_i) = \frac{1}{L}$$

Distance travelled distribution

As previously, the likelihood that the random individual travels a distance lower or equal to d can be addressed as the combined likelihood that (a) the individual lives at a certain coordinate x from the origin and (b) that its workplace is, at most, d metres away from x. In this case that is at a certain coordinate either somewhere between $x - d$ and x, or somewhere between x and $x + d$.

Analogously to the previous section, the likelihood that the individual lives at a certain x is represented by the quotient of such point and the total sector destined to households, which in this case is the whole length L. Hence:

$$P^{dwelling} = \frac{1}{L}$$

The likelihood that the individual works past a maximum distance d corresponds to the quotient between the space that such event represents, this is a sector of length d, and the total space where workplaces are feasible, also L. Hence:

$$[P^{working\ before\ x+d}\ or\ P^{working\ between\ x-d\ and\ x}] = P^{working\ less\ than\ d\ metres\ away} = \frac{d}{L}$$

The combined likelihood is:

$$P^{travelling\ \leq d} = P^{dwelling} \cdot P^{working\ less\ than\ d\ metres\ away} = \frac{1}{L} \cdot \frac{d}{L}$$

These considerations divide the study into three scenarios, depending on the value of d: (1) $d < \frac{L}{2}$, (2) $d = \frac{L}{2}$ and (3) $d > \frac{L}{2}$.

1) If $d < \frac{L}{2}$

In this case, the casuistry is divided into two possibilities:

a) The dweller at x can travel the distance d either in the backward or in the onward direction on the scheme

For this sector ($d \le x \le L - d$) the combined likelihood would be expressed like:

$$P^{travelling\ \le d}{}_{for\ d \le x \le L-d}{}_{if\ d < \frac{L}{2}} = \int_{d}^{L-d} \frac{1}{L} \cdot \left(\frac{d}{L} + \frac{d}{L}\right)\ dx$$

as the individual is allowed to travel in either of both directions. Note that the 'probability of travelling a distance d or lower to the right' is $\frac{d}{L}$, and the 'probability of travelling a distance d or lower to the left' is analogously $\frac{d}{L}$, therefore the 'probability of travelling a distance d or lower either to the left or to the right' is the sum of scenarios $\frac{d}{L} + \frac{d}{L}$ (logical connector *or*).

b) The dweller is so close to one of the extremes that, in the particular case in which he moves towards such extreme, he is <u>surely</u> travelling a distance d or lower.

This would happen for those dwellers living at $0 \le x \le d$ and those at $L - d \le x \le L$. Note that, in this case, when addressing the movement onwards (for the latter example), the concept of "probability of travelling a distance $\le d$ onwards" is surely accomplished, then turns out to be equivalent to the "probability of travelling for work somewhere onwards".

b.1) For those living at $0 \le x \le d$:

$$P^{travelling\ \le d}{}_{for\ 0 \le x \le d}{}_{if\ d < \frac{L}{2}} = \int_{0}^{d} \frac{1}{L} \cdot \left(\frac{x}{L} + \frac{d}{L}\right)\ dx$$

Where $\frac{x}{L}$ represents the probability of working anywhere on the left hand side.

b.2) For those living at $L - d \le x \le L$:

$$P^{travelling\ \le d}{}_{for\ L-d \le x \le L}{}_{if\ d < \frac{L}{2}} = \int_{L-d}^{L} \frac{1}{L} \cdot \left(\frac{d}{L} + \frac{L - x}{L}\right)\ dx$$

Where $\frac{L-x}{L}$ represents the probability of working anywhere on the right hand side.

Finally, the total probability of travelling a distance d or lower is the sum of section (a) and subsections (b.1) and (b.2):

$$P^{travelling\ \leq d}{}_{if\ d<\frac{L}{2}} = P^{travelling\ \leq d}{}_{for\ d\leq x\leq L-d}{}_{if\ d<\frac{L}{2}} +$$

$$+P^{travelling\ \leq d}{}_{for\ 0\leq x\leq d}{}_{if\ d<\frac{L}{2}} + P^{travelling\ \leq d}{}_{for\ L-d\leq x\leq L}{}_{if\ d<\frac{L}{2}}$$

$$\boldsymbol{P^{travelling\ \leq d}{}_{if\ d<\frac{L}{2}}} = \int_{d}^{L-d} \frac{1}{L}\cdot\left(\frac{d}{L}+\frac{d}{L}\right)\,dx + \int_{0}^{d} \frac{1}{L}\cdot\left(\frac{x}{L}+\frac{d}{L}\right)\,dx + \int_{L-d}^{L} \frac{1}{L}\cdot\left(\frac{d}{L}+\frac{L-x}{L}\right)\,dx$$

$$\boldsymbol{P^{travelling\ \leq d}{}_{if\ d<\frac{L}{2}} = \cdots = -\frac{d^2}{L^2}+\frac{2\cdot d}{L}}$$

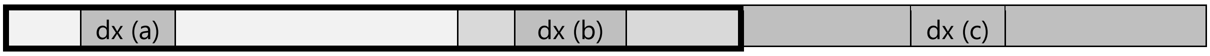
2) If $d = \frac{L}{2}$

The result will be that of (1) with the particularity that the first integral becomes 0 ($\int_{d}^{L-d}\frac{1}{L}\cdot\left(\frac{d}{L}+\frac{d}{L}\right)\,dx \equiv 0$), because $\int_{y}^{y} z = 0$ always. The expressions in (3) can be applied as well, because of continuity the result will be the same.

$$\boldsymbol{P^{travelling\ \leq d}{}_{if\ d=\frac{L}{2}}} = \int_{0}^{d} \frac{1}{L}\cdot\left(\frac{x}{L}+\frac{d}{L}\right)\,dx + \int_{L-d}^{L} \frac{1}{L}\cdot\left(\frac{d}{L}+\frac{L-x}{L}\right)\,dx$$
$$= \int_{0}^{\frac{L}{2}} \frac{1}{L}\cdot\left(\frac{x}{L}+\frac{1}{2}\right)\,dx + \int_{\frac{L}{2}}^{L} \frac{1}{L}\cdot\left(\frac{1}{2}+\frac{L-x}{L}\right)\,dx$$

$$\boldsymbol{P^{travelling\ \leq d}{}_{if\ d=\frac{L}{2}} = \cdots = \frac{3}{4}}$$

3) If $d > \frac{L}{2}$



Similarly to section (1), the casuistry here is divided into three scenarios:

a) Dwellers between $x = 0$ and $x = L - d$

People in this sector will be geometrically allowed to reach a distance d (or even greater) towards the right hand-side, but their possible displacement towards the left hand-side will not have such extension ($x < d$), for that the combined, work-related probability $\frac{d}{L}+\frac{d}{L}$ will be $\frac{x}{L}+\frac{d}{L}$ instead.

$$P^{travelling\ \leq d}{}_{for\ 0\leq x\leq L-d}{}_{if\ d>\frac{L}{2}} = \int_{0}^{L-d} \frac{1}{L}\cdot\left(\frac{x}{L}+\frac{d}{L}\right)dx = \cdots = \frac{1}{2}-\frac{d^2}{2\cdot L^2}$$

b) Dwellers between $x = L - d$ and $x = d$

There is a sector, located in the centre of the length, in which dwellers would not be able to reach a distance d towards neither of both directions. In this case, the computation of the probability of working somewhere in the left hand-side of dx is expressed as $\frac{x}{L}$, whilst the probability of working somewhere in the right hand-side of dx is expressed as $\frac{L-x}{L}$; thus the combination of both possibilities is $\frac{x}{L}+\frac{L-x}{L} = 1$, and only the household-related probability has to be integrated.

$$P^{travelling \le d}{}_{for\ L-d\le x\le d}{}_{if\ d>\frac{L}{2}} = \int_{L-d}^{d} \frac{1}{L}\cdot\left(\frac{x}{L}+\frac{L-x}{L}\right)dx = \int_{L-d}^{d}\frac{1}{L}\,dx = \cdots = \frac{2\cdot d}{L}-1$$

c) Dwellers between $x = d$ and $x = L$

This last sector has analogous characteristics to (a). Dwellers will be able to reach a distance of d metres or more to the left hand-side, but their displacement towards the right hand-side will be limited by how close dx is to the final coordinate L.

$$P^{travelling \le d}{}_{for\ d\le x\le L}{}_{if\ d>\frac{L}{2}} = \int_{d}^{L} \frac{1}{L}\cdot\left(\frac{d}{L}+\frac{L-x}{L}\right)dx = \frac{1}{2}-\frac{d^2}{2\cdot L^2}$$

Finally,

$$P^{travelling \le d}{}_{if\ d>\frac{L}{2}} = P^{travelling \le d}{}_{for\ 0\le x\le L-d}{}_{if\ d>\frac{L}{2}} + P^{travelling \le d}{}_{for\ L-d\le x\le d}{}_{if\ d>\frac{L}{2}} +$$

$$+P^{travelling \le d}{}_{for\ d\le x\le L}{}_{if\ d>\frac{L}{2}}$$

$$\boldsymbol{P^{travelling \le d}{}_{if\ d>\frac{L}{2}}} = \frac{1}{2}-\frac{d^2}{2\cdot L^2}+\frac{2\cdot d}{L}-1+\frac{1}{2}-\frac{d^2}{2\cdot L^2}$$

$$\boldsymbol{P^{travelling \le d}{}_{if\ d>\frac{L}{2}} = \cdots = -\frac{d^2}{L^2}+\frac{2\cdot d}{L}}$$

■

<u>Average distance travelled</u>

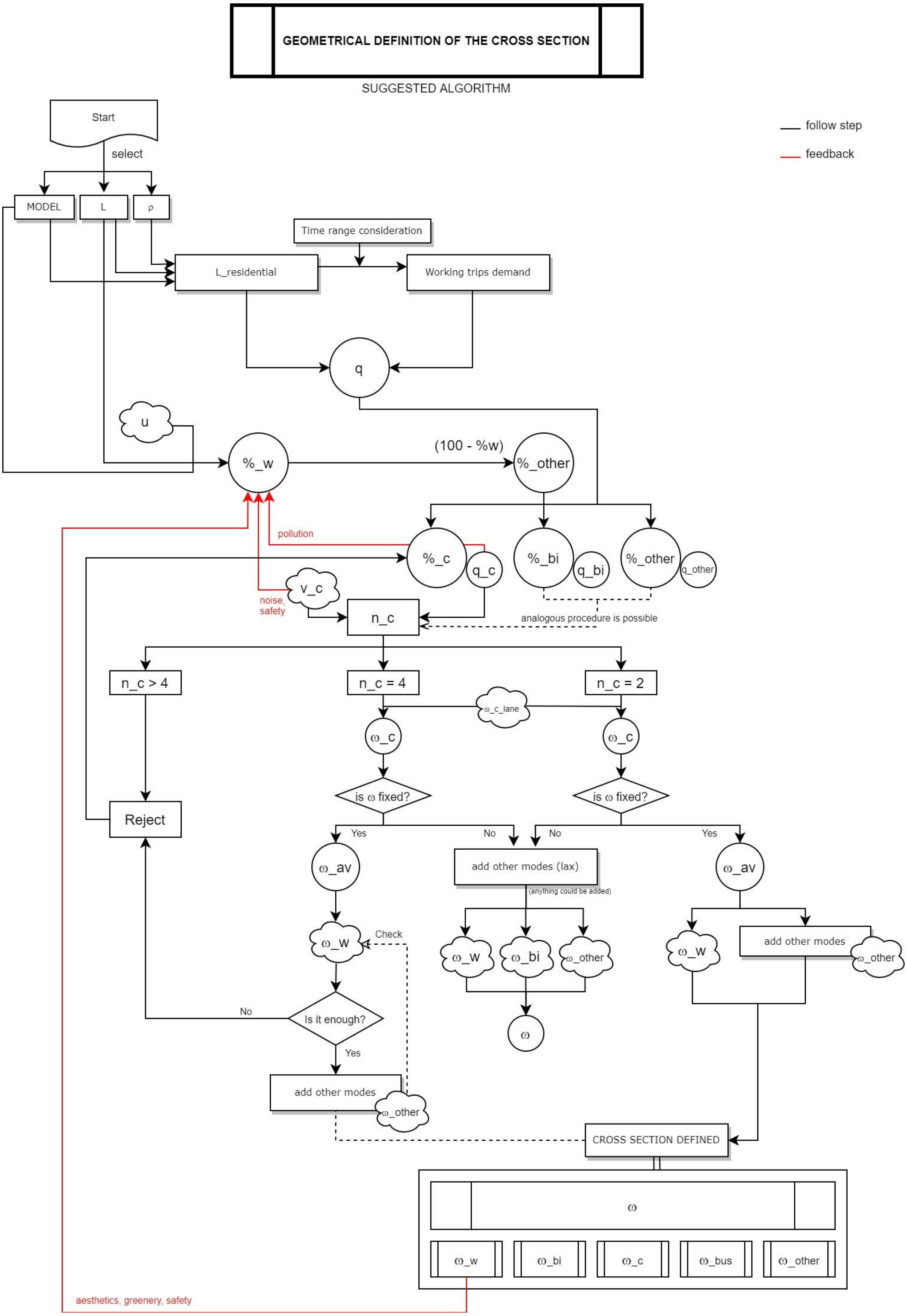
Because all the points are homogeneously distributed, to assess the average distance travelled (by any transportation choice) the following integral is introduced:

$$Av = \int_0^L\int_0^L \frac{1}{L}\cdot\frac{1}{L}\cdot g(x_1,x_2)\,dx_1\,dx_2 = \frac{1}{L^2}\cdot\int_0^L\int_0^{x_1}(x_1-x_2)\,dx_2\,dx_1 + \frac{1}{L^2}\cdot\int_0^L\int_{x_1}^{L}(x_2-x_1)\,dx_2\,dx_1 = \cdots = \frac{L}{3}$$

Where $g(x_1,x_2) = \begin{cases} x_1 - x_2\ if\ x_1 \ge x_2 \\ x_2 - x_1\ if\ x_2 \ge x_1 \end{cases}$

$$Av = \frac{L}{3}$$

9.2. Space needs calculation proposal (“algorithm”)



9.3. Lane widths and requirements of modes

	BICYCLE			CAR
Description/ characteristics	Reaches a higher velocity than the walking mode, while still being a non-motorized mode. Promotes physical activity. Velocities in urban areas range around 10~20 km/h. Produces no pollutant emissions.			Car velocities in capacity usually range between $v^c \in [40,60]$ km/h. Maximum lane flows are frequently around $q^c = 500$ $veh/(hour \cdot lane)$ and correspond to a density at capacity of $k^c = 100$ $veh/(km \cdot lane)$. In city sectors where intensity is low, the so-called " streets of zone-30" can be implemented based in the restriction of motorized speed to 30 $km/hour$ as a tool to improve the level of protection of cyclists and pedestrian.
Lane width		One-directional lanes	Bidirectional lanes	Usually around $\omega^c_{lane} \in [3,3.7]$ m. In Spain, most urban roads measure $\omega^c_{lane} = 3.5$ m.
	Minimum	1.20	1.10	
	Recommended	1.40 *(guarantees safety both in parallel circulation and overtaking)*	1.50	
Location / other spatial requirements	Bike-sidewalks (a space in the sidewalk only destined to bicycles and limited by horizontal signalization and trees or urban furniture) can be implemented in wide sidewalks and have a minimum width of 1.50 m. Central cycling lanes are not recommended due to their inconveniences on accessibility, fluency and comfort. In cases of more than one lane, it is necessary to split the directions into both sides of the street.			General recommendations of the Dirección General de Tráfico (DGT Spain) relate velocity to the safety spacing s^c $[m]$ between vehicles, so that: $s^c = 0.5 \cdot v^c/1000$ (velocity in m/hour). Parallel parking can act protecting people on the sidewalk (Speck, 2005). Usually $\omega^c_{parking\ lane} = 2.5$ m, or $\omega^c_{parking\ lane} = 3$ m if loading/unloading). If no parallel parking is designed, alternative parking spaces need to be provided (parking lots, parking inside buildings, etc).
Occupation capacity				Average $o^c = 1.2$ pax/veh. Increasing occupation can reduce vehicle flows, and therefore emissions. An example of this are carsharing systems.
References	*(Direcció de Serveis de Mobilitat, 2016); (AMB, 2014).*			*(Levinson et al., 2017); (Roca-Riu et al., 2020); (AMB, 2014); (Ministerio de Fomento, 1999).*

[cntd'.]

[cntd'.]

<table>
<tr><td></td><td colspan="2">BUS</td><td colspan="3">TRAM</td></tr>
<tr><td>Description/ characteristics</td><td colspan="2">Right of Way can be of typology A, this is, lanes are exclusive for buses.

Although aimed for the circulation of buses, in many cases bus lanes can be used by taxis and emergency vehicles; sometimes, even by bicycles.

Average speeds belong to the range $v^b \in [10,20]\ km/hour$.</td><td colspan="3">Completely independent from the rest or circulation. Reserved platforms.

In comparison to bus, lower emission costs and bigger occupation capacity. Higher space occupation.

Speed around $v^t = 20\ km/hour$.

It combines some characteristics of train systems (such as rails, specific platforms, etc) with the accessibility of urban bus transportation.</td></tr>
<tr><td rowspan="4">Lane width</td><td>If bus lane located next to parking lane, and/or</td><td rowspan="2">3.50</td><td></td><td>At stop points</td><td>Between stops</td></tr>
<tr><td>bus circulates in opposite sense to adjacent transit</td><td>Unidirectional platforms</td><td>3.1</td><td>3.7</td></tr>
<tr><td>Otherwise, and/or</td><td rowspan="2">3.15</td><td>Bidirectional plat. (central catenary)</td><td>6.6</td><td>7.8</td></tr>
<tr><td>bus and adjacent transit circulate in the same sense</td><td>Bidirectional pl. (poles on both sides)</td><td>6.2</td><td>7.4</td></tr>
<tr><td rowspan="2">Location/ other spatial requirements</td><td colspan="2">One possibility is in the right side of the street and in the opposite direction.
Common when stops are close to each other (between 250~500 m).
Central lanes are common in sections without stops.

Streets with transit problems may opt for central, reserved bus lanes the section. This enhances the Right of Way due to the lower risk of being impeded by other traffic, but it is restricted to the space available.</td><td colspan="3">Central catenary poles or catenary poles on each side.

Central platform or platforms in each side of the street.</td></tr>
<tr><td colspan="2">Minimum equipment of a bus stop is a stop stick and a support holding all the necessary information (schedules, routes, etc).

Whenever the sidewalk width is enough (above 1.6 m), installation of a glass canopy is recommended to guarantee safety and comfort of the users and protect them in cases of rain, snow, and similar.</td><td colspan="3">User platform width is 3 m if platform typology is one per sense.

If platform is central (poles on each side), platform width is 9 m.</td></tr>
<tr><td>Occupation capacity</td><td colspan="2">Depends on the typology of bus system (urban, articulated …).
Usual values range between $o^b = 20{\sim}80\ pax/veh$.</td><td colspan="3">Usual values range between $o^t = 200{\sim}400\ pax/veh$.</td></tr>
<tr><td>References</td><td colspan="2">(AMB, 2014).</td><td colspan="3">(AMB, 2014); transportpublic.org/es/argumentari-grafic/.</td></tr>
</table>

9.4. Examples of resulting cross-section scenarios

Following the procedure of the proposed algorithm and the values chosen for implementation, some configurations are shown below for a total street width of $\omega = 24\ m$. Comparison between them should consider all the aspects developed in the memory. Lane width requirements have been applied from *annex 9.3*. A brief description is made on the demand percentages and mode inclusion defining each case.

- Parking lanes provided so that parking is guaranteed all along the length and it can act as a protector barrier for the bicycle width, which is therefore set as minimum ($\omega^{bi} = 1.2\ m$). Two car lanes per sense result from the application of a demand $\%^c = 0.70\%$ in the segregated land use model. $\%^w$ adopts the value resulting from the (L, u, ρ) input in the distributions developed. Bicycle mode is included as taking the remaining demand share. No public transportation option is possible. Sidewalks are obtained of $1.1\ m$ each, which is considered unsatisfactory. Removing park lanes would widen them, but alternative parking in form of parking lots located outside the street (in plots next to or inside buildings) should therefore be provided.

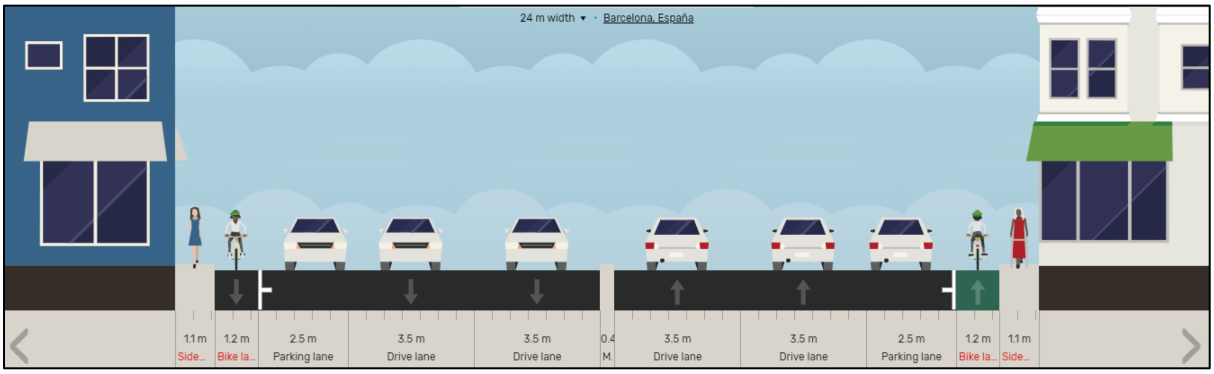


Figure 38. Configuration example a).

- Parking lanes are included and permit the bicycle lane widths to be minimum. To add greenery, plant strips can be included as a separation between lanes of opposite senses. This configuration is possible either in the segregated land use model or in the mixed land use model if car percentages are lower than 0.58 and 0.29, respectively (because such values result in a circulation lane per sense -parking is included additionally).

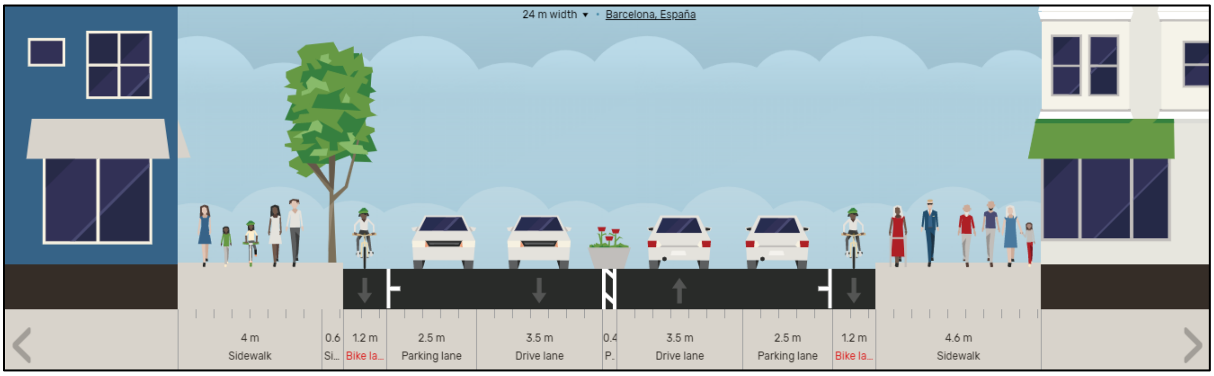


Figure 39. Configuration example b).

- Inclusion of pedestrian, bicycle, and car modes. Because the total sidewalk space reaches $4\ m$, canopies can be installed at bus stops. In the length between stops, this space is walkable as long as crossings with the bicycle lanes are correctly placed. Parking alternatives should be planned outside the street width.

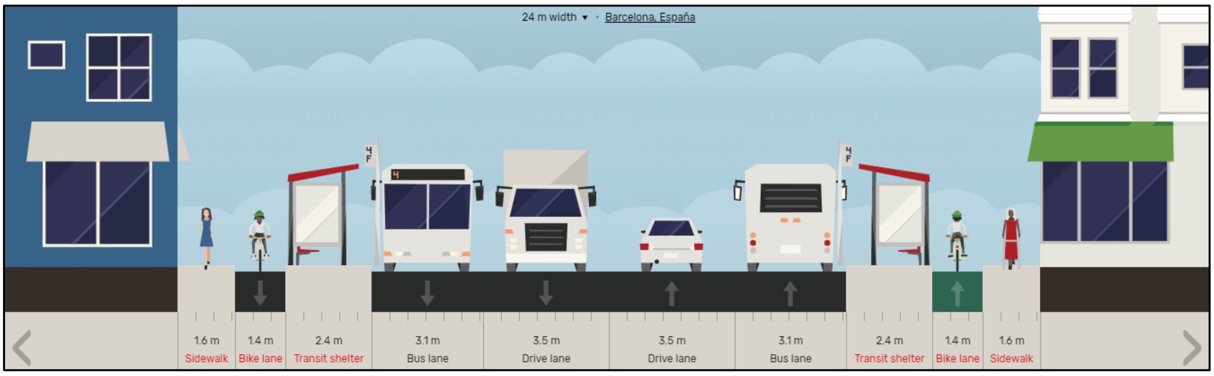


Figure 40. Configuration example c).

- Simultaneous inclusion of pedestrian, bicycle, car, and tram modes showed to create a design conflict in the 24m-wide street. Although tram waiting platforms are wide enough as to be walkable between stops, the sidewalk adjacent to buildings is insufficient, and therefore the disposition is not safe (pedestrians have no space in the transition street-buildings).

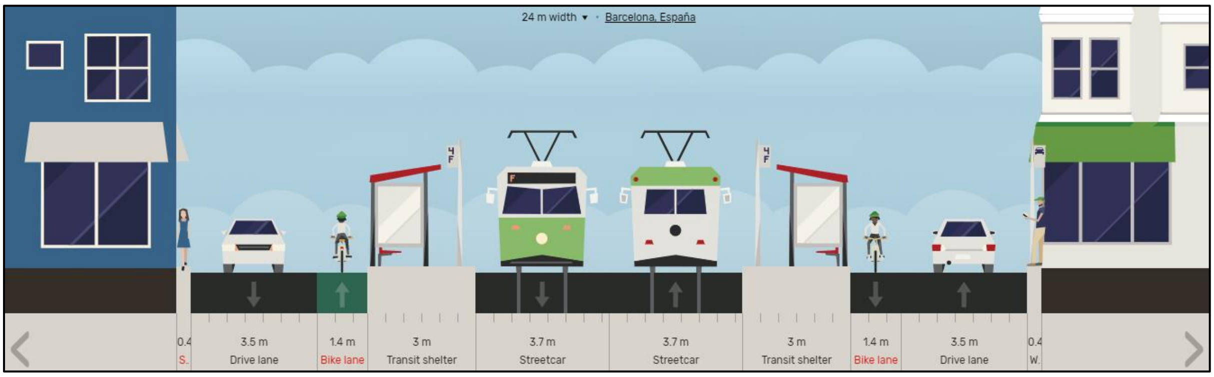


Figure 41. Configuration example d).

9.5. Real-life streets. Morphology and transport systems in the cities of today

As it has been already emphasized, the design criteria for transport systems does not follow a universal pattern. Cities differ in many aspects, from size or population to the levels of mixture, past trends, or even the extent of the organisms in charge of mobility policies.

In the attempt to exemplify how different city morphologies can shape different transportation dynamics, in this section a comparison is going to be shown between some important cities and their features in the mobility sector. The main cities to be explored are Barcelona, London, Paris, and Berlin.

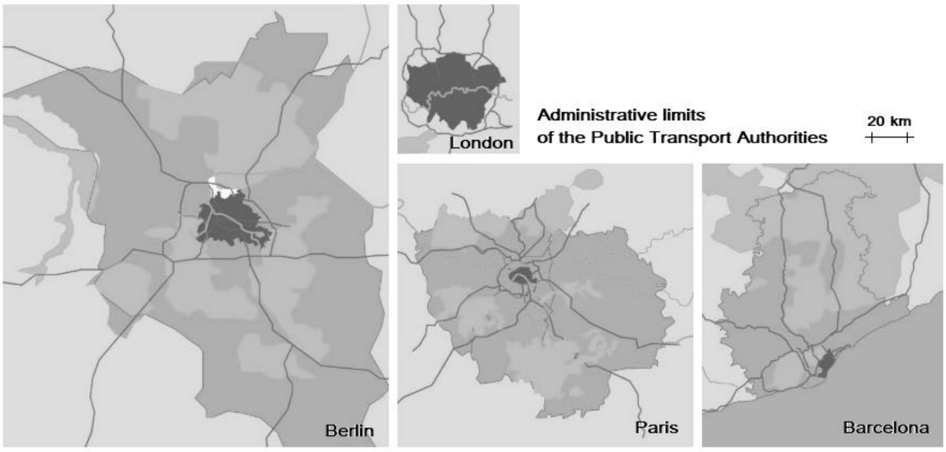


Figure 42. Administrative limits (in grey; main cities in black) of the Public Transport Authorities in the cities mentioned[24].

The previous figure aims to show the difference between the size of the city, and the whole territory where the mobility authorities have governance. For example, in the cases of Berlin, Paris and Barcelona, this latter extension represents a more or less similar percentage with respect to the size of the main city (in black), whereas in the case of London the Public Transport Authorities are restricted to the main city and not further.

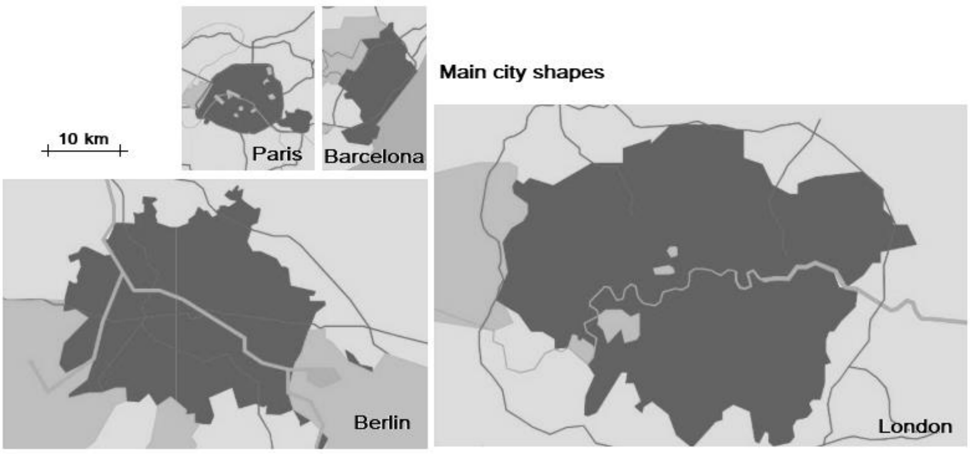


Figure 43. Main city shapes and sizes (in black). Source: EMTA (2020).

[24] *Source: EMTA (2020).*

This latter figure is provided as an introduction to the first differing parameter: size. The arrangement of the four images in the same scale highlights the differences on size, London and Berlin being the larger ones, and Paris and Barcelona being significantly lower.

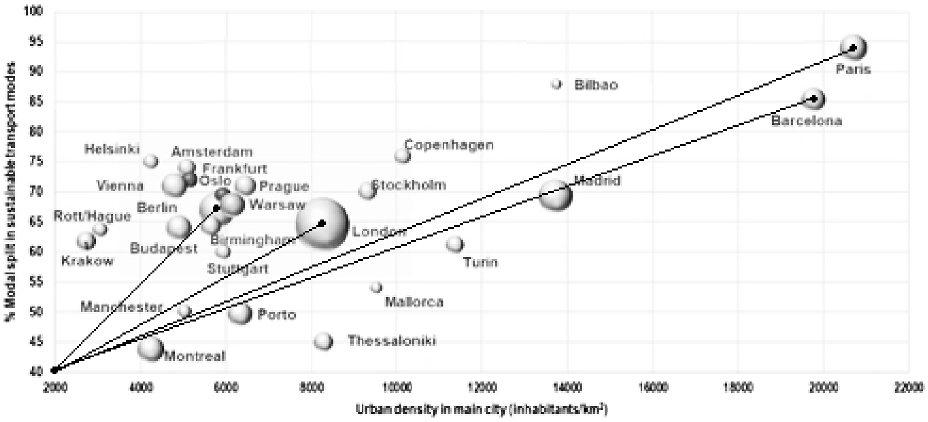


Figure 44. Urban density versus modal split in sustainable modes in main cities. Sources: EMTA (2020).

Figure 44 shows a graph comparing the urban density of the main cities regarded by the EMTA Barometer and their corresponding percentage of modal split in sustainable transportation (EMTA, 2020). Four lines have been added linking the origin coordinate to each of the four cities selected. With this approach, Berlin would be the most sustainable one, because the slope of its corresponding line (representing an average proportionality between density and sustainable mode promotion of around 0.7%) is greater. However, if considering urban density of the total public transport authorities instead, results change: the slope for Barcelona is the greatest (6%), whilst London still holds a slope of 0.5% (London is the only case where administrative limits of the public transport authorities coincide with the main city size). These results highlight the importance of relativizing and draw a rough perspective on the different degrees of urban intensity around the European nuclei chosen.

The following table is an own elaboration based on an approximation of the values provided by EMTA (2020) and other sources particular to each city.

Flow estimation $\left(\frac{veh}{h}\right)$	Bicycles	Cars	Bus	Tram
Barcelona[25]	*ND*	300~1,500	20~40	20
London[26]	50~800	400~3,000	50~200	*ND*
Paris[27]	30~50	200~2,000		*ND*
Berlin[28]	200 − 800	1,000~4,000	10~30	2~10

Table 5. Representative average modal flows in the four cities.

As has been shown in the exposition on the different parameters assessing walkability, factors such as openness or the presence of straight lines can highly affect the comfort on the user and thus modulate future travel demand choices. At the same time, the mention parameters are definers of the street morphology, and, if present in a great part of the streets, they can form a pattern representing the idiosyncrasy of the city.

[25] Source: Alcalde López (2012).
[26] Source: London Traffic Counts map (https://vis.oobrien.com/trafficcounts/).
[27] Source: (Paris Data, 2018, 2019).
[28] Source: Senate Department for Urban Development and the Environment of the State of Berlin (2017)

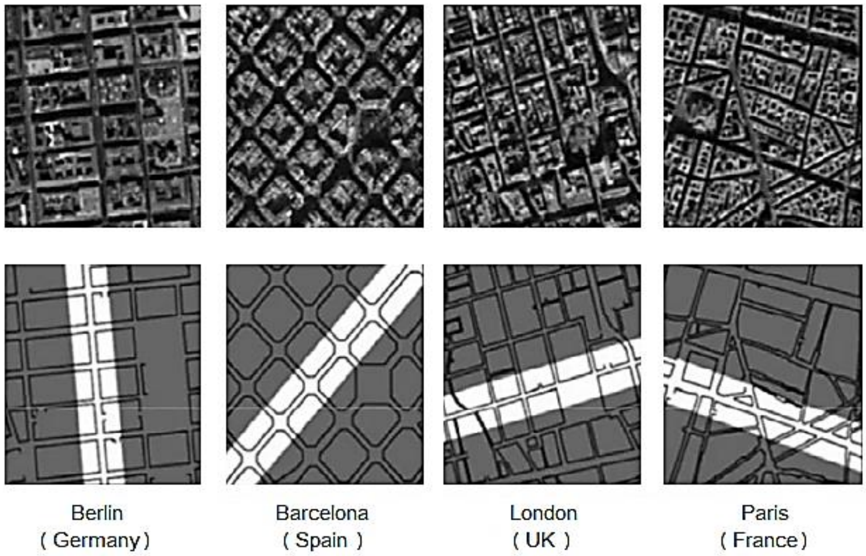


Figure 45. Representative street structures in the four cities.

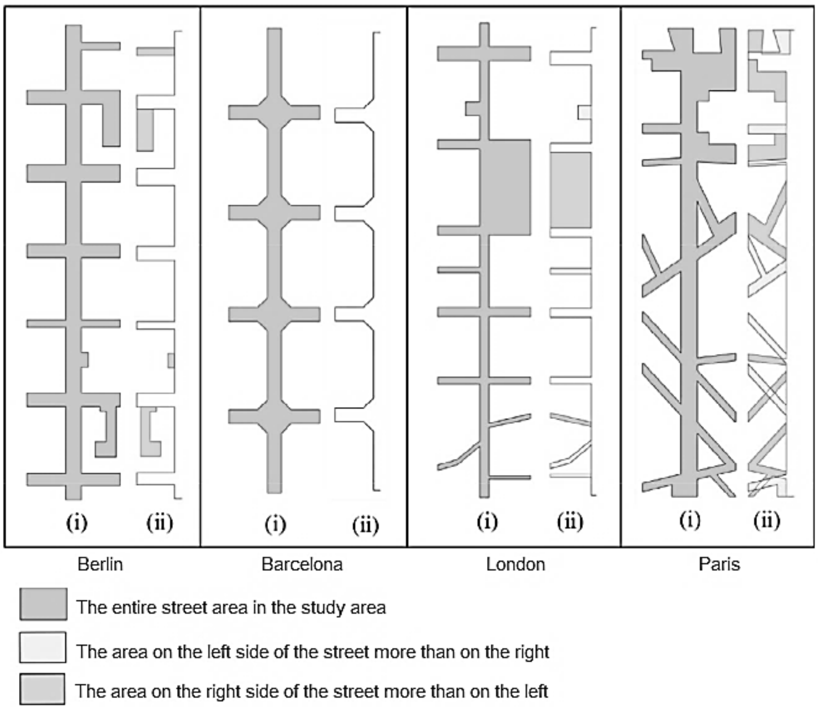


Figure 46. Street morphologies and approach for symmetry measure.

It is already known that both the physical characteristics of the terrain and the historical evolution are the main factors in charge of generating city morphology. But, what does "define" it?

In an investigation on the correlation between street morphology and thermal environment, Guo et al. (2019) developed a set of urban design indicators which can be more-or-less directly computed from satellite images; and could also be easily related to some walkability qualities. These are the Sky View Factor, the Opening ratio, the Smoothness ratio, and the level of Symmetry; and represent a tool to numerically represent some physical characteristics that could later lead to the distinction between street typologies, and ultimately the mobility trends or behaviours associated to them.

- The Sky View Factor represents the fraction of the overlying hemisphere occupied by the sky. It could be closely related to enclosure, the walkability parameter related to the feeling of an 'outdoor room'.

- The Opening ratio $R0$ expresses the proportion of street opening lengths over the total length of a street. If $L1$ and $L2$ are the sums of the total street opening distances in the respective sides of a street, the opening ratio is computed as:
  $$R0 = \frac{L1+L2}{2L}.$$
  $R0 = 1$ means the largest opening.
  This indicator could be linked to different aspects of walkability, for example transparency (the more or wider the street openings, the easier it is to see what is beyond the main way) or accessibility (if the number of street openings influences the provision of more or less route possibilities).

- The smoothness ratio Rs represents the proportion of perimeter of the study area over the total line length of street contour, and it is defined as: $Rs = \frac{C}{C1+C2}$. A higher smoothness ratio corresponds to a higher smoothness of the street. In reference to walkability features, this could be closely related to land uses or the shape and size of buildings, thus with parameters such as imageability, human scale or complexity.

- The symmetry ratio therefore reflects whether the street is symmetrical with respect to the central axis. $Ra = 2\sum Sn\,/S$, where Sn represents the difference between overlapped and non-overlapped areas if the street was folded 180º along its longitudinal axis (the greater it is, the lower the symmetry).

Morphological index	Barcelona	Berlin	London	Paris
Opening ratio (R_o)	0.12	0.22	0.20	0.21
Smoothness ratio (R_s)	0.75	0.51	0.54	0.45
Symmetry ratio (R_{sy})	1.00	0.92	0.82	0.69

Table 6. Morphological indexes of the street models[29].

[29] *Source: modified from Guo et al. (2019).*

From the cities mentioned, Barcelona shows the highest symmetry and smoothness ratios, due to the consideration of a street sector governed by the Pla Cerdà, where all the streets are parallel. Its opening ratio is the lowest, probably because of the size of the gridded *super-islands* patterns in comparison to the street widths intersecting on the sides. Interceding streets in Berlin, for example, have more variable widths and this may explain its opening ratio being the highest.

As argued by the authors, "one of the reasons of street evenness is the presence of street openings, so that a high opening ratio usually results in a low smoothness ratio". This is the case of Paris, for example. Although many of the intersecting streets are smaller in width that those of Barcelona, their variability and abundance give a greater R_o, but the smoothness ratio is the lowest. The symmetry ratio is also the lowest, which is also understandable given the number of different orientations and frequencies in which streets cross in each side.

When putting these results in context with the idiosyncrasy of the city, some conclusions can be extracted. For example, the fact that the city of Paris has a greater radial character and does not have a squared distribution, but instead the low graded streets flow to the principal ones through different angles and heaps, could explain why its bicycle, car and bus flows are apparently lower than in Barcelona (see *table 5*), which has a similar population density but a totally different street structure, based to a big extent on the Pla Cerdà. Roughly speaking, finding shorter and more intricated streets leads to globally perceiving slower performances, which could explain the lower flows. It is important to note that comparing Paris with Berlin or London, which also have a different morphology, would however be not so fair, because the main dissimilarity on population densities could result in different transportation flows even if the urban schemes followed the same patterns.

Figure 47. Barcelona street morphology. Source: Google Earth. Lines added with PowerPoint.

Figure 48. Paris street morphology. Source: Google Earth. Lines added with PowerPoint.

In the figures above, the previous explanation is demonstrated graphically, highlighting the main patterns through white lines. In the example of Paris, the zone around Boulevard de Saint Germain is focused, where the merging streets are found to intersect through different angles and extensions. Oppositely, if capturing a satellite image of Barcelona with the same scale, its characteristic, squared scheme accounts for a great percentage of the area. A more inexact structure starts to be noticed at the bottom on the image[30], and would follow further on until reaching the harbour, but still some streets keep maintaining the parallelism.

[30] In fact, although Pla Cerdà is very well known, Barcelona embraces fourteen different categories of residential fabrics (AMB, 2020b). For the sake of comparison with Paris, and also regarding its importance, only Eixample Cerdà is addressed here.

9.6. Extending beyond: from 'metropolitan avenues' to highway rethinking

In just a latest mention to the concept of 'metropolitan avenues', an interesting observation can be brought related to that all the sustainable-oriented conceptions explored in this research can not only be applied to streets, but also to the creation of 'boulevards' which derive from healing 'highways'.

Already in 2016, in *The Simplest Way to Avoid Bad Street Design: Copy the Ones That Work*, city planner Jeff Speck complained about the Lord Overpass reconstruction project (in the city of Lowell, Minnesota). Although the idea was to put the depressed highway back up at grade "to create more of a boulevard condition" (from what was initially a squared traffic circle floating above a highway, in a key area of the city which links the downtown to the train station), the resulting proposal was, according to the planner, so far from the conception of 'boulevard' that comes to mind, and based on a configuration which belonged to suburban, drive-only locations rather than to a city. The description included four lanes for straight-through motion; three lanes for turns; two dedicated bus lines; bike lanes only partly protected; a collection of treeless concrete wedges; no parallel parking; and too shallow open spaces.

In sight of these features, Professor Speck made his alternative proposal. In Speck's version (Speck, 2016), lanes were narrower (around 100 feet); shade trees where placed in a continuum in any medians; parallel parking was located in every curb, thus protecting pedestrians and bikes from moving traffic; and streets where lined by buildings giving them life (and also promoting land sales as a key measure to defray the costs of the project). All this was, according to him, really a representation of a walkable street, and in summary a definition of a complete boulevard.

With this example, I would like to recall the potential that walkability-design procedures might not only be applied in a local, central nucleus, where streets can be transformed to 'metropolitan avenues'. If a correct evaluation of the needs and utility of mobility is made, this kind of improvements can also be done in a greater scale, from city to city: thus transforming 'highways' into vivid 'boulevards'.

Figure 49. The planned reconstruction (above) versus Prof. Speck's proposal (below).

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