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Framework for the Analysis and Enhancement of the Accessibility of Large-Scale Urban Transit Networks: A Data-Driven Study for the City of Lyon, France

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and Jérémie Simon³ 

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Abstract

Accessibility to a fixed point of interest is a powerful indicator for quantifying the strengths and weaknesses of a multimodal pedestrian and transit network. However, it is difficult to predict the impact on accessibility deriving from the insertion of a new infrastructure and its contribution to the urban landscape. This paper uses graph science and multisource open data to implement a tool for studying accessibility in combination with several network performance indicators. The tool allows determination of whether a transit infrastructure project can be beneficial for its potential users. In this paper, we propose to compute gravity-based accessibility, temporally bounded by an isochrone T . We assume that the user always favors the shortest route, her rationality conditioned by real-time applications provided by network operators. By the proposed approach, the impacts on accessibility deriving from the construction of a new infrastructure, such as a new transit line, can be effectively quantified and the actors of urban planning can visually evaluate the consequences of their projects to make more informed decisions.

Keywords

accessibility, multi-modal transport planning and analysis, public transportation, equity in transportation, sustainability and resilience, transportation and society

The acceleration of urban sprawl since the 1970s and into the 2000s has generated an increasing number of trips by individuals in private motor vehicles within the urban area. Combined with the increase in the number of motorized households (1), users have shifted their mobility habits toward an increase in travel time and distance covered each day, in particular to their place of work or to services. These different forms of travel have generated many negative effects, such as the time and productivity costs of congestion (2). It should also be remembered that private vehicle transport remains the primary way through which individuals travel, despite its high climate impact and the development of public transport (3).

Thus, it seems natural that access to essential services, such as medical centers or shops, should be maximized

by public means of mobility. The notion of accessibility was first formalized by Hansen in 1959 (4). According to Hansen, accessibility is the number of potential interactions that the individual can have with points of interest within a fixed perimeter.

Unfortunately, accessibility is too often a very unequally distributed resource, on the one hand because of strong economic attraction of urban districts, or, on the other hand, because of an inefficient service in the

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most disadvantaged districts (5–7). This inequality is often accentuated by political choices of local elected officials, but can also be the result of poor planning of the urban network, leading to an asymmetry of demand and supply. This can often be explained by the massive need for funding for exclusive right-of-way public transport, for example. Another factor is also the time required to carry out such projects. All these reasons, jointly with a reduced availability of tools to quantify this metric, make decisions about accessibility hard and often suboptimal. Mapping the accessibility of a territory has thus become a major challenge for companies with expertise in urban or rural development (8, 9). It allows them to ensure that the offer is well adapted to the demand, or to readjust the vision of a project to reach the objectives described by the specifications.

This paper proposes a methodology for a general analysis of the efficiency of an urban public transport (PT) network and its possible improvements by public decision-makers and transport stakeholders. The methodology has been implemented in a computer tool, and evaluated in real-world scenarios related to the Lyon agglomeration, France. This efficiency is quantified through economic performance indicators based on the accessibility to the different points of interest reachable by the user. In parallel, a simple visual approach has been developed to facilitate the understanding of the different computed metrics by the multiple stakeholders involved in the urban planning process.

State of the Art

Accessibility is a way of quantifying an individual's environment, based on a metric that describes the opportunity for people to interact with specific points of interest (4). Following Hansen's general and partial definition, several other scientists have worked to complete the definition of accessibility. Bhat et al. (10) explain that: Accessibility is a measure of how easy it is for an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time. Bhat introduces the notion of "ease of access" to the activity that the user wishes to access. In addition, the notion of choice is also strongly present, suggesting a focus on the metric of access to the desired point of interest and not on the number of opportunities in a given area.

Finally, a third definition contrasts with Bhat's: the extent to which the land use and transportation system enables (groups of) people or goods to reach activities or destinations by means of a (combination of) transportation mode(s), proposed by Geurs and Van Eck (11). Closer to Hansen's definition, Geurs and Van Eck add that accessibility measures the possibility of reaching

points of interest by a succession of modes of transport, motorized or not. This definition therefore does not take into account the measure of ease introduced by Bhat et al. (10). That the definition of accessibility is not a subject of consensus among scientists explains the plurality of definitions and calculations associated with it. Thus, it appears that there is a significant diversity of models, all of which are relevant depending on the use and the variable or hypothesis that one wishes to highlight. One of the most important conditions of this work will be the usability of the output data, because when the studies are presented, the decision-makers must understand the indicators presented to them very quickly.

The econometric approach (12–14) proposes a probabilistic and rational vision of the individual's choices that will be at the basis of our work. Such vision is based on the maximization of a user's utility function. In the economic domain, utility is a quality of an object by which it is possible to obtain a relative measure of well-being or current satisfaction through consumption, or the findable benefit of a good or several services (15). It is related to but distinct from the need of a consumer (16).

According to Nassir et al. (13), Log accessibility is an efficient technique to estimate the maximum expected utility that users of a system would perceive, given the set of choices available to them. It would thus seem that the user is rational, and that he favors the most efficient succession of mobilities, according to his choice criteria. The hypothesis of a rational individual does not seem to be erroneous, since real-time information systems, such as (transit) travel planners, provide almost complete knowledge of the urban transport network of the city of Lyon. We will therefore assume that the individual is quasi-rational and maximizes her utility by minimizing the travel time with few conditions (17, 18). However, the use of a utility function did not seem relevant in the context of creating a tool to facilitate the understanding of urban planners. This study will thus only report on the theoretical or "possible" accessibility and will not further develop the aspects related to accessibility as perceived by the user. To measure the level of accessibility of a point of interest, we have chosen gravity accessibility to impose an easily identifiable isochrone T (19). This choice is motivated by a desire to make the indicator quick and easy to interpret by decision-makers. For example, an accessibility of 4 corresponds to four points of interest that can be reached from our point of origin in a given temporal window. We have chosen to limit ourselves to travel time only, because taking into account a generalized cost would introduce other variables such as the value of time, which we have deemed irrelevant for the same reasons mentioned above and the difficulty of accurately calculating the value of time for individuals (20).

This assumption excludes individuals' preferences for a minimum number of connections and their tendency to minimize their walking time in favor of motorized transport (18).

Methodology

This section describes the proposed methodology to quantify and optimize the accessibility of an urban transit network according to a fully data-driven automatic approach. The general framework is summarized in the diagram of Figure 1, while the following subsections detail the main methodological steps. To theoretically model an urban transportation network, we adopt a graph science approach. The latter is used to compute the travel time between a given origin and a given destination in a suitable way. In our case, origins correspond to the centroid of each building present in the studied

area. We will call Ω the spatial region where the different networks and buildings modeled are taken into account.

General Analysis and Opportunities for Network Improvements

To properly model the overall urban fabric, which includes the transit network, the urban buildings as well as the different points of interest (POIs) for accessibility computation, we use diverse sources of open data. First, it is possible to use the generic GTFS (General Transit Feed Specification) data (17, 21, 22) to model the transit network. GTFS data provide theoretical schedules of a PT network according to a standardized format. Geospatial data such as stop locations are also included. In addition, in the context of this paper, only GTFS data between peak hours are considered. The accessibility is thus averaged over this time interval. Pedestrian mobility is modeled by a pedestrian-only network, which does not consider the road network or any other form approaching it, using OpenStreetMap data.

After having modeled the graph representing the urban pedestrian/PT network, we implement the buildings layer by retrieving their geo-referenced polygon shape, computing their centroids, and assimilating them as origin nodes of the graph. This manipulation allows a simple yet effective computation of the travel time in the network, by formally defining the origin points of the transit network. Building nodes are connected via an edge to the nearest existing node of the pedestrian network. The final network will thus include all the buildings of the metropolis (assimilated to origin nodes), the pedestrian network taken from OpenStreetMap, and the PT network used by GTFS (22, 23). In a similar way, POIs from specific categories, such as health services or leisure activities, are added in a second stage for the Ω region from OpenStreetMap data and used as destinations.

Each building is associated with n attributes and an accessibility value related to the selected category of POIs. In the rest of the paper, we denote as the *accessibility matrix* (illustrated in Table 1) the data structure associating the buildings with these attributes:

- *ID*: The unique building number.
- *Geometry*: The geometry of the building (in POLYGON format).
- *Net type*: The type of structure that the object takes in the network.
- *Accessibility*: The accessibility value associated with each building.

With the support of other indicators that will be detailed in the rest of the paper, the user has the possibility of proposing and evaluating an alternative configuration of the transit network, by modifying, deleting, or adding a

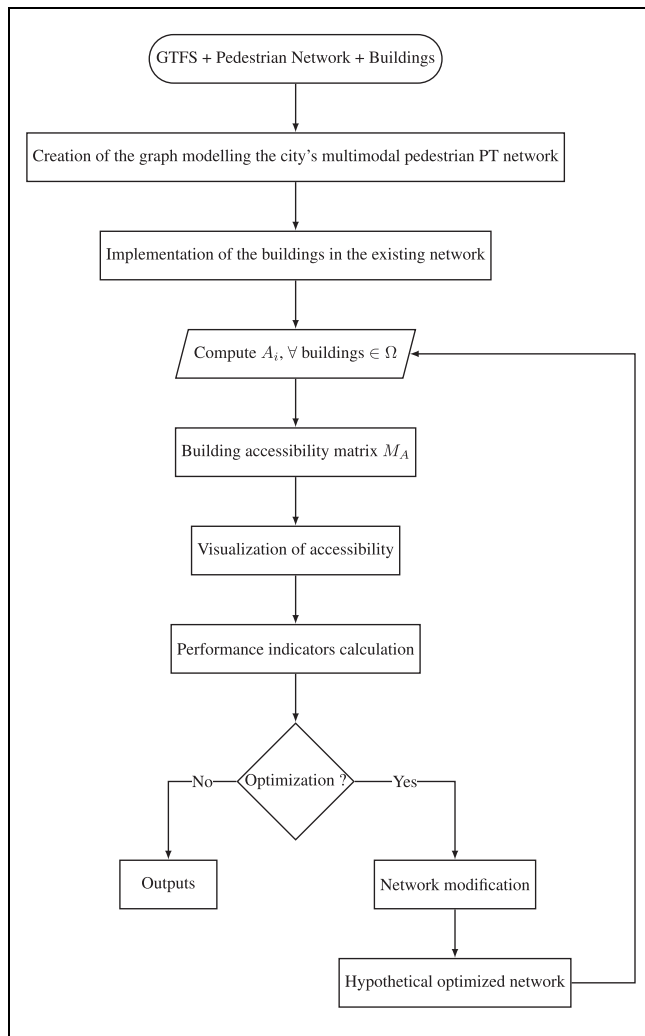


Figure 1. Diagram of the generic methodology for analysis and improvement of an urban public transport network.

Table 1. Extract of the Accessibility Matrix at the Output of the Algorithm

ID	...	Geometry	Net type	Accessibility
e	...	POLYGON Z	building	0.0
e	...	POLYGON Z	building	0.0
e	...	POLYGON Z	building	0.0
e	...	POLYGON Z	building	0.0
e	...	POLYGON Z	building	0.0
...
e	...	POLYGON Z	building	0.0
e	...	POLYGON Z	building	3.0
e	...	POLYGON Z	building	4.0
e	...	POLYGON Z	building	4.0

new infrastructure to the reference initial configuration. Thus, the algorithm modifies the network and recalculates the accessibility matrix. As depicted in Figure 1, the tool could be adopted as in an iterative approach, that is, for comparing the accessibility matrix produced at the i th with the previous one from the $(i - 1)$ th iteration, to maximize the expected results. Nevertheless, it is worth highlighting that, despite accessibility being an important criterion, it is not the only way to quantify the overall utility of an urban transport infrastructure project. Other criteria, such as environmental impact, are important and must be taken into account to reach a rational decision, but are considered outside the scope of this paper.

Accessibility Computation

Given the bounded spatial region of interest Ω , a set of building centroids $\{i|i \in \Omega\}$, and a set of POIs $\{j|j \in \Omega\}$ (i.e., destinations), the accessibility of the origin points i is defined as the sum of the number of destination POIs j reachable within a travel time $\tau_{ij} < T$ (i.e., isochrone T centered on the origin i). Based on these definitions, we can thus formally write the accessibility of i as

$$A_i = \sum_j H(\tau_{ij}) \quad (1)$$

where

- A_{ij} = the accessibility of the origin point i ;
- τ_{ij} = the different generalized costs of transport (distance, time, price), between arrival j and origin i ; and
- H = the impedance function of the selected measure, defined according to the gravity-based approach (19) as

$$H : \mathbb{R} \rightarrow [[0, 1]]$$

$$x \mapsto \begin{cases} 1 & \text{if } x \leq T \\ 0 & \text{otherwise.} \end{cases}$$

The H function acts as an indicator function: it is equal to 1 if the point of interest is included in the computed isochrone, and 0 otherwise. Thus, by summing all the values of the function over the values of all the paths from a building to a point of interest, we have a global value for the resulting accessibility. Sometimes the weighting created by the cumulative approach does not allow a good understanding of the territory, because of the low number of POIs present in the selected spatial zone. In these cases, the impedance function can be transformed to a weight function of the travel time, instead of a simple threshold (22).

Graph Construction

The modeled graph is a directed graph of the form $G = (V, E, W)$, where

- V is the set of all nodes composing the graph, these being in our case the buildings, the PT stops, and the pedestrian nodes;
- E is the set of oriented edges, such that for an element $e \in E$, e has two attributes such as start and end nodes, respectively $(u, v) \in V^2 | u \neq v$; and
- W is the set of weights w such that for any element $e \in E$, $w = \phi(e)$, with ϕ the function expressing the weight of the corresponding edge of the network.

The weight of each edge depends exclusively on the nature of the nodes it connects, and will correspond to a travel time in our context. In the following, we consider all cases that one could encounter in building a PT–pedestrian graph for the definition of the edge weights.

First of all, the travel time between two PT stops corresponds to the time it takes, in nominal conditions, to travel from u to v .

Let (u, v) be two PT stops:

$$w_{(u,v)} = t_{\text{arrival}}^v - t_{\text{start}}^u = t_{\text{PT}}^{(u,v)} \quad (2)$$

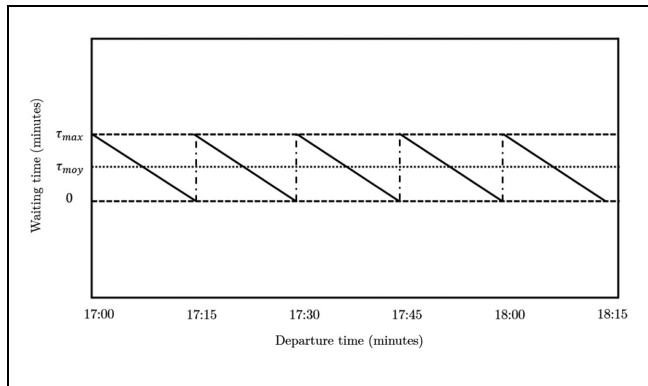


Figure 2. Graph of the individual's waiting function at any given stop.

The values $t_{arrival}^v$ and t_{start}^u can be retrieved from the GTFS. Thus, one can compute the weight of the “PT–PT” edge quite trivially. At the same time, to model the travel time corresponding to an edge connecting two pedestrian nodes, we consider the time it would take to traverse it according to a typical walking speed of $v_{walk} = 3.6\text{km/h}$ (24) to traverse it as in a straight line. Let (u, v) be two pedestrian nodes, then

$$w_{(u,v)} = \frac{d_{(u,v)}}{v_{walk}} = t_{walk}^{(u,v)}. \quad (3)$$

This formula is also valid for edges connecting a building to a pedestrian node, as well as an edge from a PT stop to a pedestrian node.

The approximation of the uniform rectilinear trajectory in Equation 3 is not aberrant in view of the average value of the distances between each pedestrian node (20 m).

Finally, to adequately model the transfer from pedestrian to PT mode, we propose to consider the waiting time of an individual at a PT stop.

Waiting times at a stop can be modeled by a continuous piecewise function such as the one reported in Figure 2 originally proposed by Kujala and al. (18).

It is moreover worth remarking that the accessibility to a POI varies significantly from one individual to another. An individual who plans her trip in advance will usually minimize her waiting time, but in the worst case, the traveler has to wait for the full duration of the line frequency, that is τ_{max} , the maximum waiting value (Figure 2).

Subsequently, we will make the simplifying assumption that individuals wait an average of $\max/2$ at the stop before starting their motorized journey. To take this assumption into account in our modeling, we add $\frac{\tau_{max}}{2} = t_{wait}^{(u,v)}$ to the weight of each edge including a public transit stop.

Let u be a pedestrian node and v a PT node, then

$$w(u, v) = t_{walk}^{(u,v)} + t_{wait}^{(u,v)} \quad (4)$$

where $t_{walk}^{(u,v)}$ is the walking time from u to v .

We could take a waiting time equal to 0 because we consider the user to be rational, but this approximation would move our results away from the real travel times of individuals.

Shortest Route Calculation

As introduced in the “State of the Art” section, we will consider users to be rational, maximizing their utility by always preferring the shortest path. Therefore, the metric used to model accessibility will be the shortest travel time between a starting node u and an ending node v .

We can consider the following minimization problem: Let $P_{(u,v)}$ be a path between nodes u and v (in our case u is a building, and v a point of interest), then, our algorithm proceeds to minimizing P such that

$$\text{Minimize } P \Leftrightarrow \text{Minimize } \sum_{(u,v) \in G} w_{(u,v)}$$

with $w_{(u,v)}$ any weight of the edge (u, v) .

In other words, the minimum of P is the shortest path from the origin to the destination among all existing alternatives (9). Shortest paths are determined by using the contraction hierarchies algorithm, which makes computation faster than using simple Dijkstra's algorithm because of the successive steps of simplification of the graph (identification of lower-importance vertices and edges of the road network and compression of the graph) performed during a pre-processing phase. The latter is performed before the actual computation of the shortest paths, which can still rely on Dijkstra's algorithm but on a contracted graph. Computation time is thus reduced because of the lower number of nodes/edges (22, 25).

Network Modification: Accessibility Estimate

While calculating the accessibility of an existing network provides a comprehensive view of the ability of a network to transport people to their chosen POIs, the choice of a new infrastructure or the introduction of a new line is often difficult to quantify. In particular, we propose to modify the existing network, by adding to, deleting from, or modifying the modeled graph. Then, it is possible to predict the accessibility behavior in the vicinity of the new structure and quantify its contribution to the community by different indicators.

Absolute Accessibility

To visualize the contributions of a new transit infrastructure, we propose as an indicator the absolute change in accessibility between the original and the modified network (26). Let us denote Δ_j the absolute accessibility of a building origin j , then

$$\Delta_j = A_j^f - A_j^i \quad (5)$$

where A_j^f is the final accessibility of the origin point, and A_j^i is the initial accessibility of the origin point.

This accessibility gap can be thus interpreted as the increase in the number of POIs that the user can now reach in a time $\tau < T$, T being the chosen isochrone.

Absolute Inequality Gap of Individuals to Accessibility

As we have seen, spatial inequality in accessibility is often a collateral effect of the polarization of economic and residential centers. The policy choices associated with the creation of a specific PT system were primarily motivated by prospects for economic productivity, which had the effect of putting equality of access on the back burner.

The notion of equity discussed in this paper comes primarily from the definition of horizontal equity (27). Horizontal equity assumes that each individual bears all travel costs unless subsidies are explicitly justified. Indeed, each individual bears the full temporal costs of the trip he or she is making, that is, the waiting time in addition to the different travel times. It is difficult to imagine temporal subsidies such as a reduction of the trip, since the infrastructure itself does not allow this. This definition implies that for a given population of individuals bearing the same costs, the most desirable distribution of the expected wealth, in this case accessibility, would be pure and simple equality between all. One of the best ways to account for the described equity situation seems to be the main economic inequality indicators. However, these indicators do not capture the spatial inequality of the service in a given area. Therefore, it appears appropriate to adopt a graphical representation of accessibility (i.e., maps with the help of GIS tools) (28). This is the approach that will be taken throughout this paper. By highlighting these inequalities, a transport stakeholder such as Egis Rail could strengthen its argument to prefer one route over another when building, for example, a new transport line. Indeed, a new tramway line route with the argument of an increase in accessibility to health services combined with a decrease in spatial inequalities is assumed to be appreciable by the community.

The usual indicator to model inequalities in transportation (5, 26, 29) is the Gini coefficient (30). The Gini

coefficient, denoted as G in the following, makes it possible to model the distribution of wealth among a group of individuals. G is bounded between 0 and 1, and it is higher when the inequalities are stronger. The situation where $G = 1$ would model a situation where one user would own the entire accessibility of the urban area. On the other hand, the situation where $G = 0$ would illustrate a perfect equality, that is, a perfect distribution of accessibility among all economic agents.

Let $(a_i)_{1 \leq i \leq n}$ be the accessibility of n individuals, then

$$G = \frac{E}{2M} \quad (6)$$

where

$$E = \frac{1}{n^2} \sum_{i=1}^n \sum_{j=1}^n |a_i - a_j|, \quad (7)$$

$$M = \frac{1}{n} \sum_{k=1}^n a_k. \quad (8)$$

The Gini coefficient can also be equal to twice the area between the equality curve and the Lorenz curve. We will combine these indicators with a graphical representation such as the Lorenz curve, generally used to represent the distribution of a wealth x , here accessibility, between the potential holders, here buildings. The Lorenz curve is defined as the inverse of the distribution function of a discrete variable X (31), such that

$$\begin{aligned} f : [0, 1] &\rightarrow [0, 1] \\ p &\mapsto \frac{\int_0^p Q_\mu(u) dl(u)}{\int_0^1 Q_\mu(u) dl(u)} \end{aligned}$$

where Q represents the quantile function, defined as the inverse of the distribution function, $Q(u) = \inf\{x : F(x) \geq u\}$; and μ is the probability law of X .

To compare several tramway lines, we will study the number of buildings whose accessibility is affected by the new line, to quantify the catchment area of each tramway option. It is also important to look at the Gini gap between the initial situation and the situation with the new infrastructure. The Gini gap reflects the variation in inequality in the accessibility of individuals. A positive Gini gap means an improvement in the inequality situation for the concerned area. In contrast, a negative Gini gap means a deterioration in the equality of access to transport of individuals in the study area. Finally, the magnitude of the value of this gap illustrates the significance of the change, which allows us to rank the network changes. For example, a line addition producing a positive Gini gap of 0.05 will be less efficient in the "horizontal equality" sense than a line addition with a Gini gap of 0.06. It should be noted that this gap may be very

Table 2. Main Input Parameters of the Model

Parameters	Inputs
City	Lyon
Average day	Monday
Time range	5–9 p.m.
Isochrone T	15 min

small, because of the small importance of the infrastructure in the overall cumulative share of accessibility of the Lyon metropolis. Finally, we will carefully study the statistics around the overall accessibility gain generated by each of the lines.

Results

Data and Software

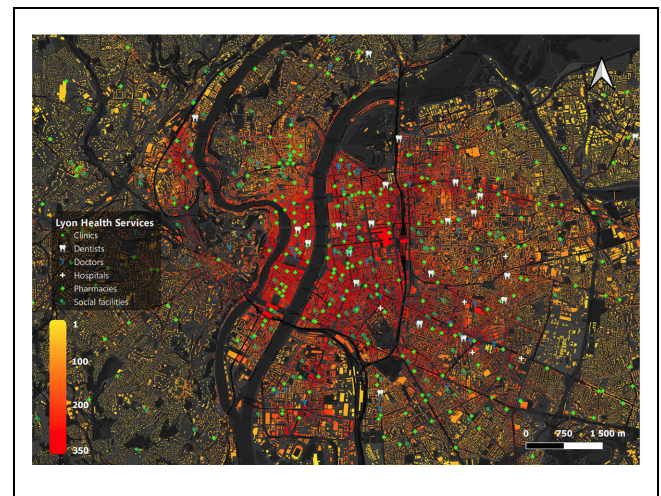
We implemented the framework described in the “Methodology” and “Network Modification: Accessibility Estimate” sections in Python 3.9, using as main libraries Pandana and UrbanAccess (22, 23). Pandana allows parallelizing of the shortest path computations because some functions are coded in C++, which very greatly decreases the computation time of the algorithm. Our case study is based on the GTFS data from the Sytral transport operator in March 2022 for the Lyon agglomeration. The pedestrian network was modeled using OpenStreetMap information (17, 32). Finally, the buildings were taken from the French governmental database BD Topo (33). Moreover, for the computation of accessibility, we considered the POIs related to health services (always retrieved from OpenStreetMap). It should be noted that such POIs may be incomplete, but are mostly usable. For our case study, we examined the situation of the city of Lyon, in respect of its access to different health buildings, with detailed parameters reported in Table 2. The time range of 5 to 9 p.m. was chosen to study the accessibility during periods of high demand. Monday was also studied for the same reasons as above. Finally, the 15 min isochrone was preferred because of the popular doxa of the quarter-hour city, an urban utopia where everyone can access any activity offered by the metropolis within 15 min.

Modification of the Network: Improvements

Let us now analyze the current accessibility of Lyon’s network with respect to health services. Figure 3 shows a heatmap of the accessibility values for each building. Hotter colors are indicative of higher accessibility. Obviously, the accessibility will be centralized around exclusive right-of-way PT in Figure 3, because it offers the shortest travel time combined with a significant

Table 3. Statistics Associated with the Accessibility of Buildings in the City of Lyon

Statistics indicators	Values
Count	170,460
Mean	57.64
Median	31
Standard error (pop)	67.3064
Minimum	0
Maximum	374
Q1	8
Q3	82

**Figure 3.** Map of accessibility to health services in Lyon within 15 min.

frequency. We can observe that the core transport mode for accessibility to health services remains the Lyon metro, with more than 300 establishments reachable from the center of the city (Figure 4b). The centralization of accessibility in the center of the metropolis could be explained by a phenomenon of inertia caused by the choice of establishments to be located around the major PT axes to increasingly serve the major economic centers. Moreover, we can observe that out of 170,460 buildings, the average of health buildings reachable in less than 15 min is 57.64, as given in Table 3. This result shows that, on average, individuals in the city of Lyon have access to a high number of health services very quickly, thus indicating an efficient network. However, a closer inspection of the results from Table 3 highlights a different outlook: the median value of accessibility is much lower than the average, showing that 50% of the individuals have an access in less than 15 min to only 31 health buildings. Interestingly, 25 % of the buildings (Q1) have access to fewer than eight health buildings, a

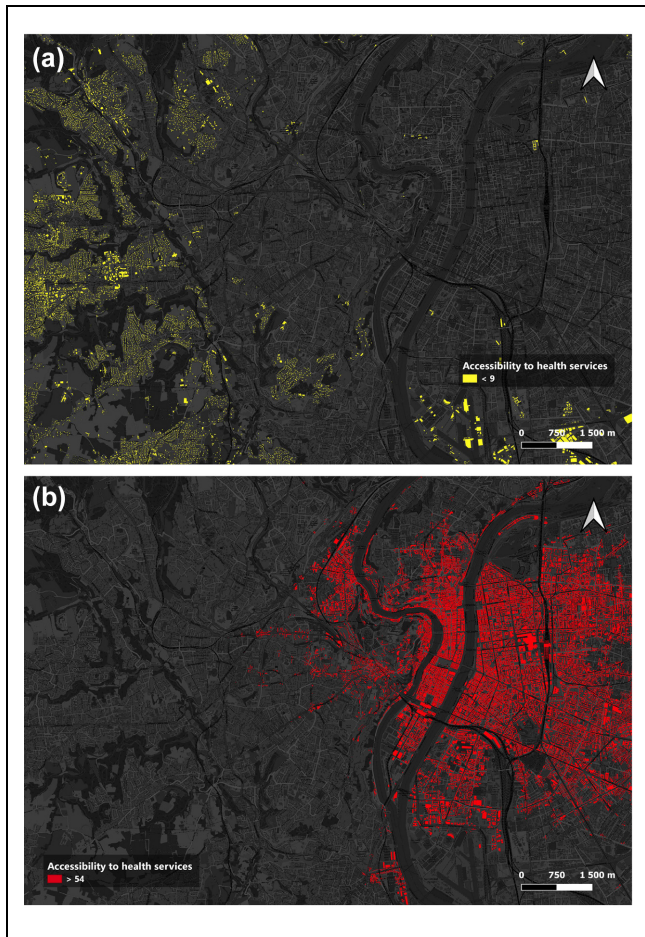


Figure 4. Maps illustrating the polarization of access to health services to the detriment of the west: (a) buildings with accessibility under the 1st quartile, and (b) buildings with accessibility above the 3rd quartile.

situation that characterizes mainly the west side of Lyon (Figure 4a). Finally, the standard deviation of 67.6034 suggests a large dispersion around the mean, which would imply very large inequalities between individuals.

The spatial distribution reported in Figure 4a, related to the buildings with accessibility inferior to the first quartile, confirms that the western part of the Lyon metropolis does not provide easy access to health-care services, which are mainly located in the city center around main transit axes. It also appears quite strikingly that the bus lines of the current system, although numerous, have a minor effect on the total accessibility of a building. This can be explained by the very high frequency of passage of the metro and its speed, compared with the other transport modes analyzed in this study. It should be noted that the definition of gravity-based accessibility does not allow for distinctions between POIs and their importance: Access to a social service is as important as access to a hospital. We can therefore only speak of overall accessibility to health services.

Table 4. Comparative Statistics of the Three Tramway Lines

Line	N_f	\bar{X}_f	M_f	ΔG
Line 1 (Sytral)	1,386	1.9	1	0.0057
Line 2	951	1.46	1	0.0072
Line 3	777	1.85	1	0.004

Several methods can be used to improve the transportation network in a city. Increasing frequency or speed can significantly augment the accessibility of users to a center of interest, because waiting and travel times are reduced.

Nevertheless, the spatial distribution of accessibility will hardly change, or will be only slightly affected. To decrease the inequalities between residents, the public decision-maker might be tempted to modify an existing PT mode route, or to create another route altogether.

Concerning these aspects, we have analyzed the impact as accessibility gain deriving from the introduction of a new tramway line (whose stops are reported with green symbols in Figure 5). When considering the introduction of a new line, we have analyzed the impact of the tramway passage frequency by considering multiple values: it appears that decreasing the frequency of transport by 1 min produces a decrease in the building accessibility gain of 25 % on average in Figure 5, with a decrease in the total number of buildings affected. This result can also be explained by the threshold effects involved in defining our accessibility. It is obvious that the argument of the quarter-hour city, in which all amenities would be accessible in a 15 min walk, remains very theoretical, and cannot be completely achieved. In the rest of the paper, we will take 6 min as the frequency of the new tramway line, approaching the average frequency of a tramway line in Lyon. Sytral, the operator of the city of Lyon's transport network, recently unveiled plans for a new tramway line to serve western Lyon. We propose this line as well as two other alternative routes detailed in Figure 6 to compare them, according to the methodology explained above. In addition, we consider POIs including doctor offices, hospitals, and clinics, to refocus our study on facilities that provide health-care services.

In Table 4 we have given the different indicators allowing a better understanding of the benefits of the different infrastructures studied. We have computed four important indicators that can potentially help in the decision of urban planning, namely:

- N_f : the number of buildings with accessibility gains.
- \bar{X}_f : average accessibility gains across all affected buildings.

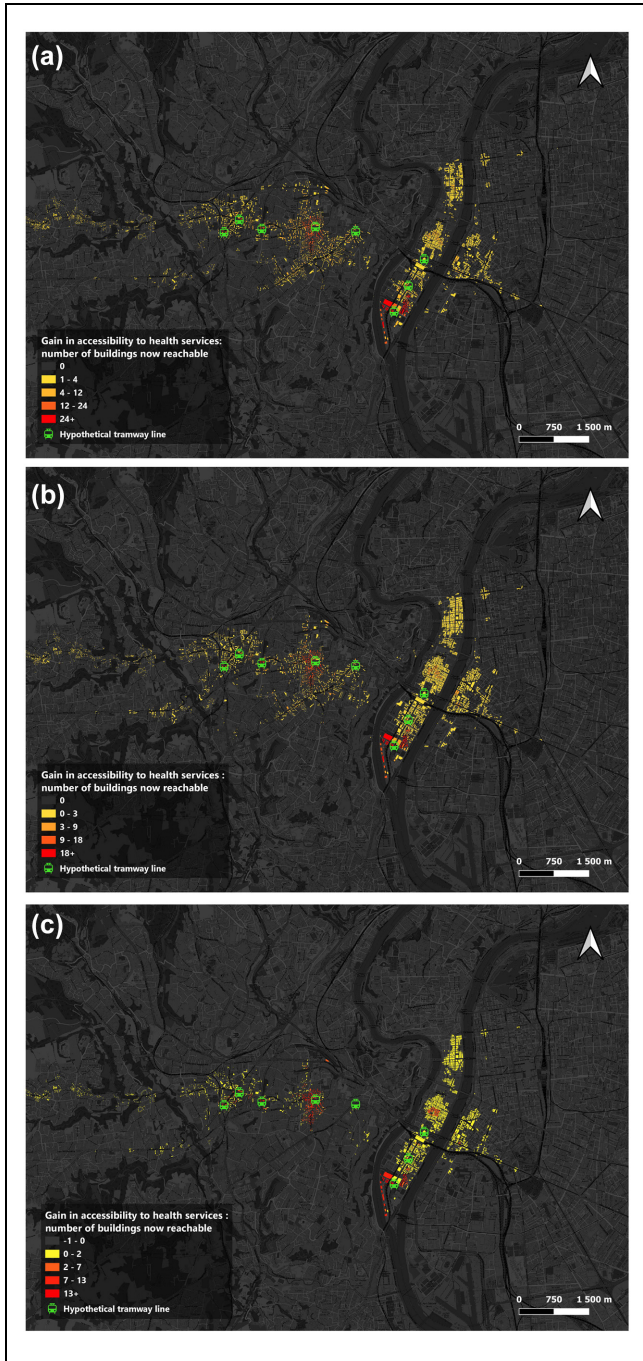


Figure 5. Accessibility gain between the initial network and the network with the added tramway line: study of different frequencies: (a) tramway line with a frequency of 6 min, (b) tramway line with a frequency of 7 min, and (c) tramway line with a frequency of 8 min.

- M_f : the median of the accessibility gains across all affected buildings.
- ΔG : the relative Gini gap between the initial situation without infrastructure and the final situation with infrastructure.



Figure 6. Illustration of the three tramway lines submitted to the study.

In relation to the last indicator, it should, however, be noted that the Lorenz curves (in Figure 7) are plotted by only including the buildings within a 200 m zone around each building with an accessibility gain. This allows the better studying inequalities at a local level. The calculation of the Lorenz curve on the whole metropolis would

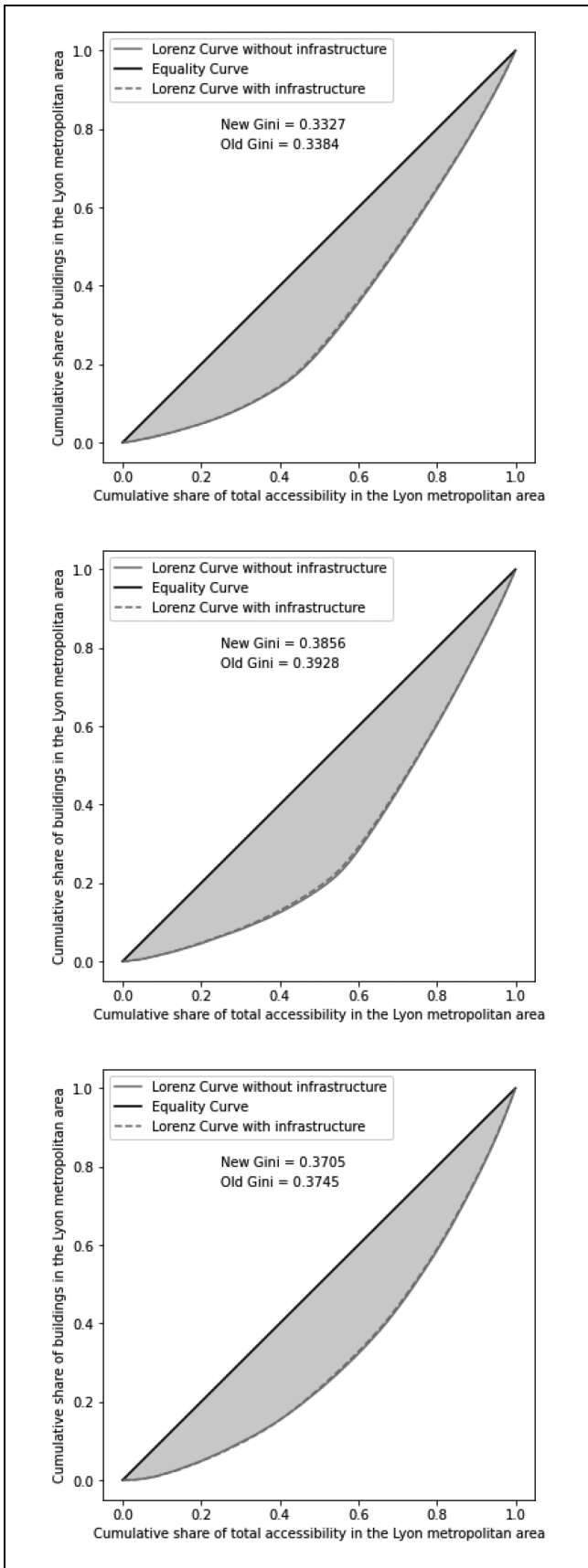


Figure 7. Lorenz curves conjugated to the different plots above.

in fact not have been relevant in view of the infrastructure change, which is very minimal compared with the global accessibility offer.

By comparing the different values of the N_f coefficient from Table 4, it appears that the line designed by the local transport authority increases the catchment area of the tramway line by 45 % compared with line 2 and 78 % compared with line 3. This can be explained by higher proximity to other transport lines with higher passage frequency in the first route than in the other two. Line 2 would also result in a much lower average accessibility \bar{X}_f gain than the other alternatives, with a difference of about 0.40 in Table 4. It is possible to correlate this result with the service stopping in the south of the Lyon peninsula, producing a geographical narrowing of the line as it does not offer an entry point to the network after the Rhone river. Finally, the relative Gini deviations ΔG are very small as the result of the low relative gain in accessibility to health services. In parallel, the number of buildings affected is small, compared with the neighborhood without accessibility gain. The difference seems to be very small but remains significant and can be studied.

We can thus observe that all three lines improve equity between individuals, to a greater or lesser extent, because all values are positive in Table 4. Subsequently, it seems that the least efficient line for equitable distribution of wealth is line 3. This can be explained by an extended service to the east, already very well served, as illustrated by Figure 4b. Line 2 seems the one that maximizes equity between individuals (higher ΔG). It would appear that maximizing service to the heart of the metropolis offers a more equitable distribution of accessibility. Users living in the east would significantly increase their access to the peninsula, while the gain in accessibility within the center would be minimal in comparison, as illustrated in Figure 5. The reported scenario illustrates well that a final choice of an infrastructure project has to be taken with respect to additional criteria, as accessibility indicators alone might provide sometimes contradictory indication. In our example, a greater average gain in accessibility and a larger catchment area point toward the choice of line 1 proposed by Sytral, but with a less equitable distribution of accessibility than line 2. The choice would thus be left to the land-use planning actor to make a decision on the chosen route. For instance, this accessibility analysis can be performed together with an environmental and financial study to fully define the public decision.

Conclusion and Future Work

In this paper, we proposed a methodology and a tool for the analysis and optimization of accessibility of a multi-modal urban pedestrian/transit network, which can be useful for data-driven urban design planning. To

quantify the accessibility of each building, we created a multimodal pedestrian/transit graph, including as additional nodes the buildings of the metropolis. In addition, we set up several performance indicators to analyze the characteristics of the network accessibility, and with the objective of optimizing it by implementing new infrastructures, or modifying existing ones. Although estimating the accessibility gain by modeling a new infrastructure can be effective with the support of decision-makers, it does not fully describe the future effects of this change. In large cities, we can propose that the Gini deviation be performed on all POIs (amenities, shops, and so on) and not on specific points like health-care buildings. We assume that the value of this gap would be more significant, because we would no longer increase the accessibility to a type of building but increase the global accessibility. In addition, several limitations must be considered in our graph science approach. Transfer times when the user does not move from a transit node (i.e., the user stops at a stop with an A bus, and picks up a B bus a few minutes later at the same stop) are not taken into account. It should also be noted that there are some threshold effects around the spatial study area: external POIs are not taken into account, which leads to edge effects and may distort the accessibility of buildings at the edge of the study area. Furthermore, the gravity accessibility described in this article does not include directly the notion of user demand. Building attractiveness is essential to define which areas are priorities for maximizing accessibility. One could refer to the notion of spatial attractiveness, which can be defined as the sum of incoming flows directed to a geographical unit. It is obvious that the calculation or retrieval of inflows information is a very complex task and would normally require availability of large-scale data on building frequentation. However, using mobile phone passive data appears a valid solution to estimate incoming flows or dynamic user presence of the studied infrastructure for each area or building (34–36) and will be a matter for future work.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: SS, AF, PP, JS; data collection: SS, PP; analysis and interpretation of results: SS, AF, PP; draft

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