Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 52 (2021) 3–10

Transportation Research Procedia

www.elsevier.com/locate/procedia

23rd EURO Working Group on Transportation Meeting, EWGT 2020, 16-18 September 2020, Paphos, Cyprus

Accessibility analysis for Urban Freight Transport with Electric Vehicles

Filippo Carrese*, Chiara Colombaroni, Gaetano Fusco

Sapienza Università di Roma - Piazzale Aldo Moro 5, 00185 Roma, Italia

Abstract

Urban Freight Transport is a continuously growing market mainly based on the use of vehicles with combustion engines, whose environmental impact has become unsustainable. Because of the technological improvement of electric vehicles and their growing economic feasibility, the introduction of electric fleets for urban freight distribution is now a considerable opportunity. Cities are rapidly adapting, in need of tools to properly guide and manage these changes, as the rise of electric vehicles must be encouraged by an appropriate infrastructural system, from charging stations to dedicated areas. What is proposed in this work is an aggregate approach to the freight system, transport demand and supply, to support the design of a distribution system based on electric vehicles by means of an accessibility indicator that takes into account the supply of facilities, vehicle performances, and freight demand patterns. A study case regarding the Metropolitan City of Rome is also presented to interpret and understand the potentialities of this approach.

Keywords: Accessibility analysis; Freight transport; Electric Vehicles; E-mobility.

1. Introduction

Accessibility is a very broad research topic and can effectively be used to analyze and support the design of freight distribution. The benefits and uses of accessibility for policy makers and urban and regional planning make the subject extremely interesting also for researches. Accessibility is nowadays currently used for i) understanding and modelling transportation/land-use interactions, ii) understanding and modelling travel demand (e.g. activity participation and travel levels), iii) assessing the effectiveness of transportation plans and projects with respect to the planning

* Corresponding author. Tel.: +39 329 329 3422.
E-mail address: filippo.carrese@uniroma1.it

10.1016/j.trpro.2021.01.002

objectives (e.g. equity and territorial development), and iv) solving optimal location problems for Public Utilities and Services (Cascetta et al., 2013). Along with passenger mobility, the concept of accessibility is widely used also in logistic studies. However, few practical applications to derive accessibility indicators for freight systems can be found. A noteworthy attempt has been carried out by Cartenì (2014), proposing a methodology to estimate transport terminal influence area based on an accessibility analysis.

With the increase of use of electric vehicles, cities have started building charging stations to favour the transition towards greener modes of transport. Also distribution systems have been led to a greater of use of echo-friendly vehicles, that give them the possibility to access restricted traffic zones but poses new challenges and problems (Fusco et al., 2013). Driving range of vehicles becomes an issue that previously was not considered, due to its decrease and since refuelling operations with combustion vehicles are not as significantly time consuming. These limitations, along with the need of developing and managing adequate infrastructures for charging and loading/unloading operations, increase the levels of complexity of freight systems, already burdened with their own problematics, such as the need of optimizing tours and the interaction between the many stakeholders (customers, decision makers, drivers). Therefore, new methods and practices to evaluate logistic operations are needed, and a deeper investigation on accessibility potentialities may bring to higher performances and efficiency. In addition, new data sources are becoming always more influential in transportation modelling, and especially in aggregate models, whose strength lies in their simplicity and versatility. Combining new and heterogeneous data sources with traditional modeling allows to achieve a cost-effective trade-off between the amount of data required and yet preserving realistic results (Carrese et al., 2019), (Cantelmo et al., 2020).

Therefore, the objective of this work is to propose an aggregate formulation of accessibility for freight distribution systems with electric vehicles, that permits to analyse the current state of city logistics expressing the potentials or weaknesses for e-mobility freight companies of positioning deposits in certain zones, for different types of distributions. Accessibility is analysed for different areas and different periods, focusing on the particular characteristics of freight transport, such as the distribution of customers and the creation of tours, and of electric vehicles and recharging processes. Specifically, three research questions are addressed:

RQ1 - How does the location of the deposit and the dispersion of customers (density of activity system) influence the size of the tours?

RQ2 - How do we consider the constraints due to the limited range of electric vehicles in an aggregate formulation?

RQ3 - Can the presence of charging stations around the city increase the autonomy of vehicles and increase accessibility?

2. Literature review

2.1. Accessibility

Accessibility has been present in literature for over 50 years and under different study areas (urban planning, transportation, geography). Transport planning has seen a shift from a focus on mobility to a focus on accessibility, representing a measure of the potential to interact, while mobility is the realisation of this potential in terms of actual travel (Miller, 2018). A unique definition of accessibility, accepted by the whole scientific community, still hasn't been found, mainly due to its extensive use in numerous fields. In transportation, one of the most influential contributions was given by Hansen in 1959, who defined accessibility as "potential of opportunities for interactions", shifting the attention from measuring the "ease of interaction" to the "intensity of the possibility of interaction". In the following years, a more specific definition was given by Dalvi (1978), according to which accessibility denotes the ease with which any land-use activity can be reached from a location, using a particular transport system. This notion introduces two basic aspects of the satisfaction derived from undertaking a trip: achievement of desired opportunities, balanced with the service provided by available transport (Koenig, 1980).

Different formulations of accessibility measures have been proposed throughout the years, Handy and Niemeier (1997) organized these traditional measures accessibility in three categories:

- Isochrone-based measures, or cumulative-opportunity measures, are the simplest and most used in practice, based on the number of opportunities that can be reached within a maximum threshold.

- In Gravity-based measures, the opportunities are weighed according to an impedance function, resembling the gravitational law. It was first derived by Hansen in (Hansen, 1959), defining accessibility as “the potential of opportunities for interaction”.
- Utility-based measures derive from the need of introducing a differentiation among the users. The use of Random Utility Models was a necessary step to represent the heterogeneous availability of transportation of individuals.

A new frontier is constituted by the Activity-based measures, in which the presence of various diaries of activity is essential to indicate the possible options to carry out all the movements of the day. The major contribution of the activity-based accessibility measure is that it incorporates the impact of trip chaining, the full set of activities pursued in a day, and the scheduling of activities (Dong et al., 2006).

To conclude, different situations and purposes demand different approaches (Reggiani and Martín, 2011), and different methods bring different results, depending on the research goal (van Wee, 2016). Accessibility formulations are usually not applied to freight traffic, but even for passenger mobility a unified theory considering all aspects and all research dimensions of accessibility is still not developed. A more general framework able to include all approaches propose in literature is strongly recommended and endorsed by the scientific community, emphasising the need of comparative studies.

2.2. Electric Freight systems

By extending the concept of trip chaining, an investigation on urban freight transport with electric vehicles accrues of interest since the central problem that logistic operators must overcome is that autonomy of electric vehicles (EV) might not cover the whole length of the desired trips. To overcome the freight distribution problems with limited driving range, in literature, many works are addressing the Electric Vehicle Routing Problem (E-VRP), each considering different constraints and approximations. An important aspect of fleet routing is the possibility for EVs to recharge, totally or partially, at a Charging Station (CS). Many formulations keep this element in consideration, and various solutions can be found based on different assumptions (Erdelic et al., 2019).

Due to the currently low market share of EVs, the number of CSs installed in the road infrastructure is still relatively small. Cities and communities are starting to discover the benefits of e-mobility and are willing to boost their use of improving recharging infrastructures (Liberto et al., 2018). Therefore, also the decision of optimal placement for new CSs is an issue for smart cities, and researchers have begun to study and develop the Charging Station Location Problem (CSLP) (Xiong et al., 2015). The need for battery recharging may significantly affect the accessibility of a zone to be served by electric vehicles for freight delivery or distribution. Thus, a specific formulation of the accessibility has to be introduced that expresses the dependency on the battery vehicles’ autonomy, the spatial distribution of electric charging stations, and the length of distribution tours, which depend –on their turn– on the spatial distribution of customers to visit.

3. Formulation

In this work, an aggregate approach to estimate accessibility for freight distribution systems with electric vehicles is presented, representing a first step in answering the research questions. It is based on Hansen’s gravity-based measure, since it the earliest and still one of the most used in literature, which explicitly expresses spatial relationships. The new contribution to the traditional formulation is the introduction of a term that considers delivery tour strategy, the autonomy of electric vehicles, and intermediate recharges at the available charging stations.

$$A_i = \sum_{j=1}^{n} X_j \cdot f(c_{ij}) \cdot g(M_{ij}, d_j, CS_j) \tag{1}$$

In addition to Hansen’s formulation, where accessibility A_i of zone i is obtained by summing over all $\boldsymbol{n}$ zones the number of opportunities X_j present in zone j weighed by an impedance function of the generalised cost for a trip from i to j, a new term $g(M_{ij}, d_j, CS_j)$ is introduced, that is influenced by different factors:

- The autonomy of electric vehicles: M_{ij} is the available range (in km) of an electric vehicle that starts the tour in zone i and must deliver in zone j;
- The density d_j of potential shops where to deliver in zone j: the lower the density of certain types of shops, the larger the tour of a vehicle must be to include other shops in the same tour;
- The density CS_j of charging stations in zone j plays an important role when considering autonomy limitations.

Specifically, the new term $g\left(M_{ij}, d_j^s, CS_j\right)$ accounts for how the factors listed above interact with each other: how a low density of potential customers increases the length of tours, that cannot exceed the autonomy of electric vehicles, and how charging stations can improve driving range. This term can be explained through the following steps.

The first and most complex task is to determine how the density of customers influences the length of a tour, or more specifically how long a vehicle must travel to find other customers to deliver to. A decreasing function that links the customer density to the tour length is introduced to synthetically represent the complex delivery process. On this regard, it is not mandatory to have complete information about the total number of customers, but only a representative measure of how they are spatially distributed across the study area. Of course, the average length of a tour is not uniquely related to the absolute value of activity density because depends on the daily demand for deliveries and is typically given by the solution of a vehicle routing problem. The parameter of the function between tour length and customer density depends on the number of activities and their density as well as on the features of the delivery system; that is, the fleet size, the vehicles' capacity and autonomy.

Once chosen the more appropriate function with its the relative parameter, and determined the resulting length of the tour, the second step consists in comparing the tour length resulting from the first step with the remaining autonomy of the electric vehicle. After having calculated the distance matrix between pairs of customers to visit, the remaining autonomy is calculated for each O-D pair by subtracting the distance from zone i to zone j and from zone j to zone i from the autonomy of the electric vehicles: $M_{ij} = AU - c_{ij} - c_{ji}$.

Having defined for each O-D pair how many kilometers a vehicle must travel in order to complete a tour, taking into account the autonomy constraints, a metric that transforms this number of kilometers into a measure to be included in the formulation must be defined. This term represents an impedance, as it describes how much critical is battery autonomy in deliveries. It would be equal to 1 if the customers are very close and the area to serve has a high density of charge stations, so that autonomy is absolutely not critical; and is equal to 0 when the low density of activities requires as long trips as long is the vehicle autonomy. Different functions can be chosen, considering that, if we exclude the extreme case of a zone as far as vehicle's autonomy from the nearest charging station, the final accessibility value is not significant as an absolute value but only as a relative measure of the ease of delivering in each zone of the study area compared to the other zones.

The last step to specify this term is related to the availability of charging stations. Recharging infrastructures can increase driving autonomy of electric vehicles, and since their distribution is not homogeneous, some zones will benefit more than others. In particular, this element contributes by decreasing the impedance due to autonomy limitations: for the O-D pairs where the remaining distance is not enough to complete a tour, the density of charging station around zone j mitigates the negative effects that this term would have on the accessibility calculation.

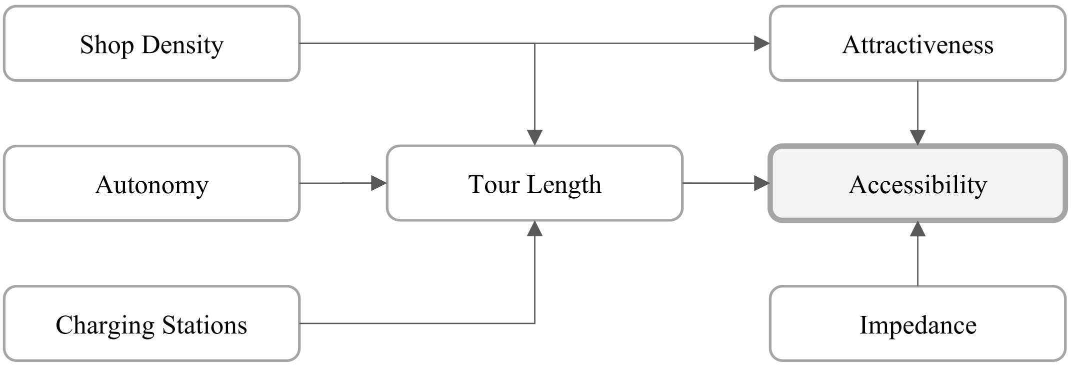

Figure 1: Block Diagram representing relations between the variables

4. Case study

Here, we apply the proposed formulation on the metropolitan area of Rome, including a wide part of the region around the city, identified as "Agro Romano", containing tracings on flows entering and exiting from inside the city. In the innermost neighbourhoods, traffic congestion represents an issue for freight operations, that can benefit from an identification of recurring patterns. On the other hand, deliveries and unloading manoeuvres deeply affect local traffic, since loading/unloading areas are not sufficient and freight vehicles are often obliged to an inappropriate parking (Carrese et al., 2014). Furthermore, at the moment, in 2020, Rome's urban centre presents at least three different limited traffic zones, and the most restrictive one (*Tridente* area) limits access to only electric vehicles.

Zoning is defined aggregating census zones in 60 traffic zones.

4.1. Data and Tools

QGIS software has been used to download and show the spatial distribution of the POIs available on OSM. Figure 2 shows two types of venues: 82 charging stations (in green/yellow) and 5313 shops (blue), while figures are coloured according to the respective density of each zone.

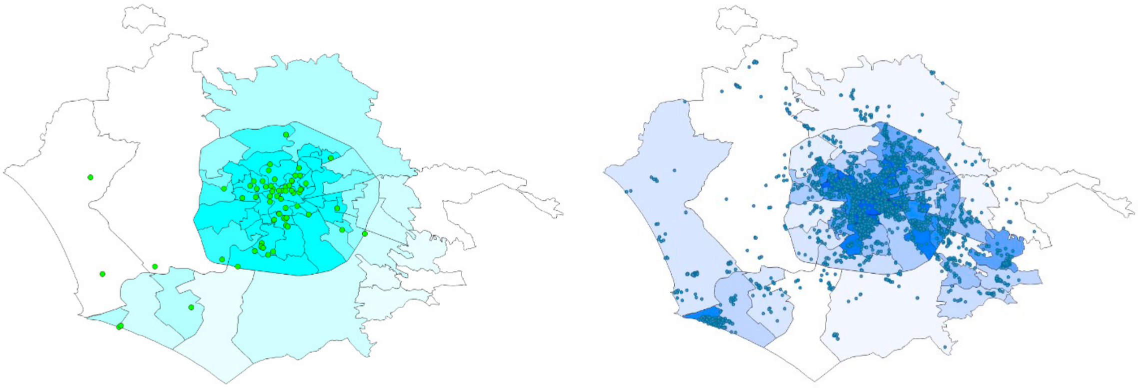

Figure 2. (a) Charging stations (turquoise) and (b) Shops (Blue)

Travel times are determined by using a dataset of two months of tracking of Floating Car Data, originated from insurances' black boxes. More than 30 million geo-localized points with a temporal frequency of 30 seconds were processed with MATLAB software and included information about users, instant speed and direction and start/stop of the engine. How travel times are temporally and spatially distributed is illustrated below: figure 3a shows the average travel time of a trip per hour of day (congestions at morning and afternoon peak hours) while figure 3b shows which zones have lower average travel time to reach them.

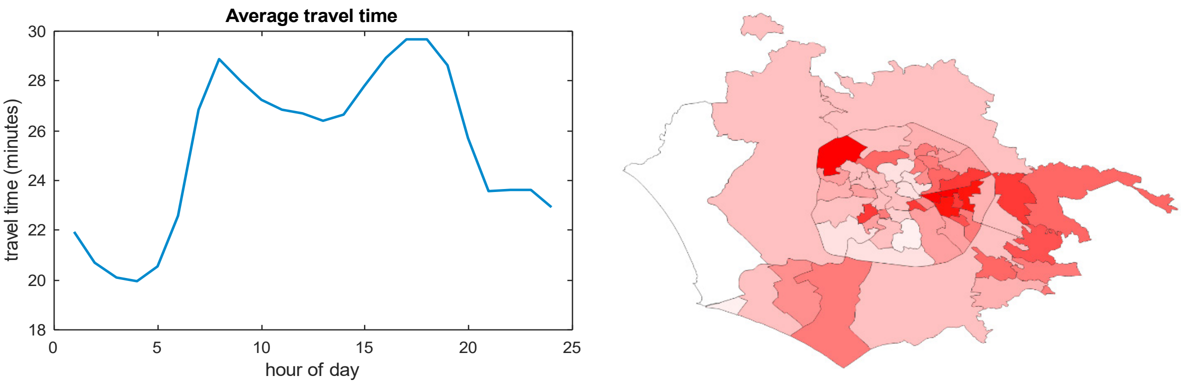

Figure 3. (a) Average travel time per hour of day – (b) Inverse of average cost to reach each zone, at 8AM (the darker the red the lower the impedance).

4.2. Application

This section explains which variables and functions have been chosen to be inserted as elements of equation (1).

- Attractiveness: X_j is represented by the total number of shops in zone j available from OSM (Figure 1(b)). All categories of goods have been used, considering that the distribution of any sector will approximately follow the total of shops. Also, since OSM has only a small percentage of all the real POIs, concentrating on a specific goods' sector would have lost data significance.
- Cost of transport: c_{ij} is the average travel time from zone i to zone j, derived from FCD trips. Travel time can be calculated for each hour of day and for working days or weekends, reflecting different congestion patterns. This application uses travel times measured during morning peak hour period, from 7AM to 9AM.
- Cost Function: $f(c_{ij}) = 1/c_{ij}$ an inverse function has been chosen to best fit the relationship between travel time and accessibility.
- Autonomy: The value of autonomy that appears in the term M_{ij} noticeably changes according to the mechanical characteristics of a fleet of electric vehicles. The results exposed in the next section assume two values of autonomy, 80 and 150 km, showing the contribution of this component in the formulation.
- Density of activities: d_j^s is the number of shops in a zone divided by the area of that zone.
- Density of charging stations: CS_j has been calculated by counting all charging station within a 10km radius from each zone centroid. The simple count of infrastructures per zone can bring to a bias, since charging stations in the zone nearby would obviously be considered by drivers.
- Tour function: $g(M_{ij}, d_j^s, CS_j)$ this function is formalized as follows: a hyperbolic function is chosen to represent the interaction between density of activities and length of the tour:

$$L(d_j) = \alpha(n, \overline{d_j})/d_j \tag{2}$$

The choice of a hyperbolic function is justified by being one of the simplest inverse function and requiring just one parameter to determine. The parameter α is determined by simulating a test case: simulating to serve n randomly extracted customers throughout the study area, determining the average number of kilometers necessary to serve them. This number of kilometers is therefore linked to the average density of shops over the entire study area ($\overline{d_j} = 3.373\ shops/km^2$), thus arriving to define a point of the function ($L;\ \overline{d_j}$) and determine the parameter α. Two test cases have been analyzed, evaluating the need to serve a different number n of customers per tour. For $n = 3$, the length of the resulting tour equals to 20km with an $\alpha = 67{,}46$, and assuming $n = 10$ resulted in a tour of 100km and a parameter $\alpha = 337{,}3$.

The following step is to define how and in which cases autonomy becomes an issue. This is done by comparing the length of tour $L(d_j)$ previously derived with every element M_{ij}, determining for which OD pairs autonomy of vehicles is not sufficient to travel from zone i to zone j, complete the tour and travel back to zone i. When autonomy problems overcome, this term acts as an impedance and, as in equation, the contribution to accessibility of that specific OD pair decreases. The impact of charging stations is also considered in this process mitigating the impedance due to autonomy: the higher the distribution of charging densities, the lower the effect of this impedance.

$$for: L(d_j) > M_{ij} \qquad g(M_{ij}, d_j^s, CS_j) = 1 - \frac{L(d_j) - M_{ij}}{max\{L(d_j) - M_{ij}\}} * \left(1 - \frac{CS_j}{max\{CS_j\}}\right) \tag{3}$$

4.3. Results

The influence of the first two terms of the formulation on the final accessibility measure are already shown in section 4.2: the attractiveness of different zones is represented by the density of spatially distributed activities (Figure 2b), while Figure 3b illustrates an average measure of the impedance due to cost of transport to reach each zone.

In this section we will show the contribution of the new term $g(M_{ij}, d_j^s, CS_j)$ and the spatial distribution of the accessibility measure for two different scenarios. The first one considers delivering on average to 10 different customers per tours where the autonomy of electric vehicles is limited to 80km, the second one involves an average of only 3 customers per tour with an autonomy of 150km. These two scenarios represent limit cases to better illustrate the effects of autonomy: in the first case we expect a lower accessibility because of the risk of incurring in complications due to autonomy; in the second case autonomy should rarely be a criticality and accessibility shouldn't vary too much from Hansen's gravity based measure of accessibility.

Figure 4 shows the comparison between accessibility calculated without the tour impedance function, as it would be for internal combustion engine vehicles, and accessibility calculated considering 80 km of autonomy (Figure 4a) and 150 km (Figure 4b). Blue and red markers indicate accessibility for all zones at morning peak hour and afternoon peak hour. In both time periods, the results were constant with expectations. If freight delivery were carried out only through electric vehicles the accessibility would decrease on average of 5% for the lower value of autonomy, with a maximum decrease of 9.9%. However, with the greater driving range of 150 km, accessibility would decrease on average of 2.5% with a maximum reduction of 4.6% compared to the reference scenario with traditional internal combustion engine vehicles.

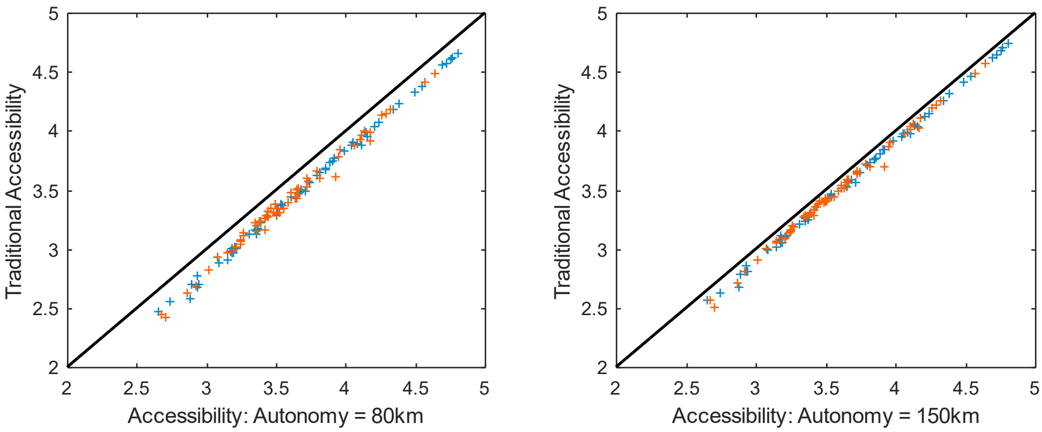

Figure 4. Comparison between Accessibility with no autonomy problems and the two scenarios: (a) Autonomy=80km and (b) Autonomy=150km

To conclude, figures 5a and 5b show how the spatial distribution of accessibility, as formulated in paragraph 3, during the morning peak period and for the two different scenarios, does not change significantly from zone to zone. However, it can be noted that zones characterized by the lower values of accessibility are the ones who are mostly affected and register the highest decrease: the 5 zones with the lowest accessibility values register a decrease of 7.6% and 4.1% for a vehicle autonomy of 80 km and 150 km, respectively; that is, in both cases, over 50% higher than the average of all other zones.

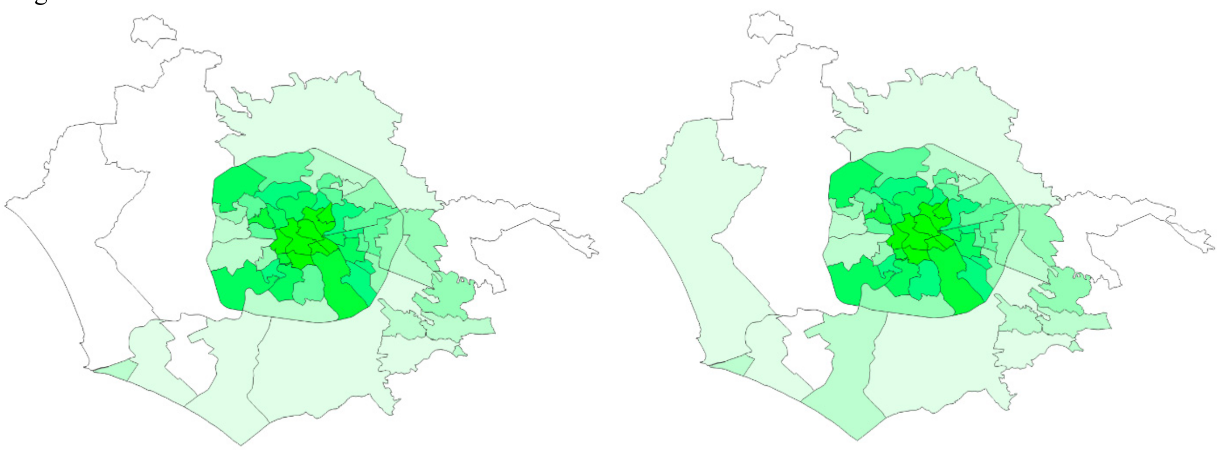

Figure 5: Spatial distribution of Accessibility for the two scenarios: (a) Autonomy=80km and (b) Autonomy=150km

Conclusions and future work

In this paper, an ambitious goal has been targeted: to represent very complex interactions between components of freight distribution systems through an accessibility analysis based on an aggregate approach, avoiding cumbersome simulations of all possible tours, customers and deliveries. The proposed formulation aims at answering the research questions stated in the introduction and yields an accessibility measure useful to evaluate the potentialities of different zones of an urban or regional area in delivering to the surrounding customers with electric vehicles. This methodology is completely versatile and can be adapted to many different situations: the final measure will strongly depend on which variables are introduced and which customers are considered. Even though accessibility is rarely directly addressed for freight distribution systems, the theory that is behind this concept may lead to the discovery of new frontiers, considering the ease of use of aggregate models and the large amount of research concerning them.

The formulation proposed is complete but there still is wide room for improvement: the functions describing the relations between variables in the application phase are experimental, and even though results are consistent, further research will be carried out aimed at including vehicle routing problem implicitly. Future analysis will be directed towards a validation of the relation between length of tour and density of customers, using real test cases and trying to obtain a more accurate function. Another aspect of the future research may focus on the temporal dimension, adding dynamicity to the application. By specifying temporal information to the opportunity parameter (for example opening hours of POI if available), it is possible to see how accessibility of different zones varies throughout the day.

References

Cantelmo, G., Vitello, P., Toader, B., Antoniou, Viti, F., 2020. Inferring Urban Mobility and Habits from User Location History, in: Transportation Research Procedia. https://doi.org/10.1016/j.trpro.2020.03.100

Carrese, F., Cantelmo, G., Fusco, G., Viti, F., 2019. Leveraging gis data and topological information to infer trip chaining behaviour at macroscopic level, in: MT-ITS 2019 - 6th International Conference on Models and Technologies for Intelligent Transportation Systems. https://doi.org/10.1109/MTITS.2019.8883329

Carrese, S., Mantovani, S., Nigro, M., 2014. A security plan procedure for Heavy Goods Vehicles parking areas: An application to the Lazio Region (Italy). Transp. Res. Part E Logist. Transp. Rev. https://doi.org/10.1016/j.tre.2013.12.011

Cartenì, A., 2014. Accessibility Indicators for Freight Transport Terminals. Arab. J. Sci. Eng. https://doi.org/10.1007/s13369-014-1333-y

Cascetta, E., Cartenì, A., Montanino, M., 2013. A New Measure of Accessibility based on Perceived Opportunities. Procedia - Soc. Behav. Sci. 87, 117–132. https://doi.org/10.1016/j.sbspro.2013.10.598

Dong, X., Ben-Akiva, M.E., Bowman, J.L., Walker, J.L., 2006. Moving from trip-based to activity-based measures of accessibility. Transp. Res. Part A Policy Pract. https://doi.org/10.1016/j.tra.2005.05.002

Erdelic, T., Carić, T., Lalla-Ruiz, E., 2019. A Survey on the Electric Vehicle Routing Problem: Variants and Solution Approaches. J. Adv. Transp. https://doi.org/10.1155/2019/5075671

Fusco, G., Alessandrini, A., Colombaroni, C., Valentini, M.P., 2013. A Model for Transit Design with Choice of Electric Charging System. Procedia - Soc. Behav. Sci. https://doi.org/10.1016/j.sbspro.2013.10.607

Handy, S.L., Niemeier, D.A., 1997. Measuring accessibility: An exploration of issues and alternatives. Environ. Plan. A.

Hansen, W.G., 1959. How Accessibility Shapes Land Use. J. Am. Plan. Assoc. https://doi.org/10.1080/01944365908978307

Koenig, J.G., 1980. Indicators of urban accessibility: Theory and application. Transportation (Amst). 9, 145–172. https://doi.org/10.1007/BF00167128

Liberto, C., Valenti, G., Orchi, S., Lelli, M., Nigro, M., Ferrara, M., 2018. The impact of electric mobility scenarios in large urban areas: The Rome case study. IEEE Trans. Intell. Transp. Syst. https://doi.org/10.1109/TITS.2018.2832004

Miller, E.J., 2018. Accessibility: measurement and application in transportation planning. Transp. Rev. https://doi.org/10.1080/01441647.2018.1492778

Reggiani, A., Martín, J.C., 2011. Guest Editorial: New Frontiers in Accessibility Modelling: An Introduction. Networks Spat. Econ. https://doi.org/10.1007/s11067-011-9155-x

van Wee, B., 2016. Accessible accessibility research challenges. J. Transp. Geogr. https://doi.org/10.1016/j.jtrangeo.2015.10.018

Xiong, Y., Gan, J., An, B., Miao, C., Bazzan, A.L.C., 2015. Optimal electric vehicle charging station placement, in: IJCAI International Joint Conference on Artificial Intelligence.