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EVALUATING ACCESSIBILITY OF SMALL COMMUNITIES VIA PUBLIC TRANSIT

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Abstract:

Accessibility to and from urban centres allows small communities' dwellers to participate in primary activities and use essential services that are not available on-site, such as educational, work and medical services. Public transport networks are supposed to enhance accessibility and pursue equity principles, overcoming socio-economical differences among people that can exacerbate during crisis. In this paper a methodology is proposed and implemented to assess small communities' accessibility via public transit. A metric is defined based on the calculation of total travel time, taken as a proxy of travel impedance, with consideration of in-vehicle time, schedule delay and users' arrival and departure preference curves (i.e. time-of-day functions). A "rooftops" model is specified and implemented under the assumption that travellers cannot accept (scheduled) late arrival or early departure time penalties before and after the participation in their activities in the main urban centre, as many activities rarely admit time-flexibility. Also, a public transport specific impedance factor (PTSIF) is proposed, in order to account for travel impedance determinants, which are a consequence of service scheduling and routing decisions and not due to inherent geographical and infrastructural disadvantages affecting car users too.

An application of the methodology for the city of Cesena, Italy, and 90 surrounding small communities is presented. The city is served by train and bus services. Assessment of small communities' accessibility based on both total travel time and PTSIF is presented and discussed.

This practice-ready quantitative method can help transport professionals to evaluate impacts on small communities' accessibility in light of public transport service changes or reduction. Quantitative approach to support strategic decisions is needed, for example, both to assess public transport strengthening politics against depopulation of rural and marginal mountainous areas and to mitigate the effects of possible increasing concentration of services towards high-demand lines, which may follow as a consequence of budget cuts or contingencies, such as vehicle capacity reductions required by sanitary emergencies.

Keywords: *public transit accessibility, travel impedance, schedule delay, rooftops model, time-of-day preference curves.*

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1. Introduction

Accessibility refers to the potential to overcome travel impedance in order to reach different locations, where people can participate in their spatially-differentiated daily activities, such as employment, shopping, recreation and study (Dalvi and Martin, 1976; Paez et al., 2012; Kim and Lee, 2019). Indeed, travellers accept to face various forms of friction (Dalvi and Martin, 1976; Kim and Lee, 2019), namely travel impedance, and thus pay a generalised travel cost (Cascetta, 2009), which depends on transport system, land use and travellers themselves (Boisjoly and El Geneidy, 2016), in exchange of a series of benefits they presume to gain at their point of destination.

Accessibility can be measured from the perspective either of the location of origin or the destination of potential trips. Typically, accessibility measures involve the analysis of a multifaceted perceived travel impedance (i.e. generalised travel cost), as well as the number, type and spatio-temporal distribution of socio-economic activities with reference to users' places of residence and preferences (Paez et al., 2012; Nassir et al., 2016; Kim and Lee, 2019; Cheng et al., 2018). In other words, accessibility measures focus on the estimation of two different components: on the benefit side, the number, distribution and attractiveness of activities and, on the cost side, travel impedance from residential areas in the network (Cascetta et al., 2016; Nassir et al., 2016).

As far as public transit accessibility is concerned, the problem is quite complex. First of all, the analysis of real-scale public transit networks usually requires to deal with extensive, non-standardised sources of data. Secondly, public transit networks are time-dependent and provide services with inherent limitations and constraints in both spatial and temporal dimensions (Nassir et al., 2016).

Public transit accessibility problems regard both the evaluation of the accessibility to public transit services and the accessibility via public transit services from/to a series of locations (Mavoa et al., 2012). Therefore, on one hand, studies regarding the proximity of transit stops are needed, which take into account the presence of transit services in an area (e.g. in terms of transit stops available within a specified walking distance) as well as the estimation of walking times as a critical component of generalised travel cost (Mavoa et al., 2012). On the other hand, a number of other factors, which are specific to the structure and functioning of public transit networks, impede users in their travel, well beyond simple on-board travel times (Kim and Lee, 2019). Among the latter factors, service frequency is paramount.

Public transit accessibility analyses are crucial to identify areas in need of transit service improvements and to prioritise investments, so that inefficiencies due to poor coverage determined by planning and scheduling processes can be distinguished by purely geographical disadvantages (Fayyaz et al., 2017). Indeed, the importance of public transit accessibility strongly relates to equity issues: vulnerable segments of population, such as youth, elderly, poor, disabled and marginalised people, do not have access to private car and rely on public transport for their mobility needs (Mavoa et al., 2012).

In general, evaluating and improving the level of public transport accessibility is essential to the sustainability, liveability and welfare of modern human society (Nassir et al., 2016). Accessibility is a major determinant of transit level-of-service and it can directly and heavily affect the degree of social inclusion of large sectors of the population. Moreover, an increase in public transit accessibility level can lead to relevant modal shifts, with possibility to reduce the need for travellers to implement car-based mobility choices and the related social and environmental impacts.

This paper presents a methodological and procedural framework to evaluate travel impedance by public transit in the case of low-frequency bus and rail services linking small communities, i.e. rural and peripheral urban areas, to larger urban centres. Such kind of intercity and suburban transit services are particularly important for small communities, so that all segments of the population can reach educational, medical and other services that are not available on-site.

In this framework, travel time is chosen as a proxy of travel impedance and it is calculated by taking into account both on-board scheduled travel times and the so-called schedule delay. The estimation of schedule delay as a component of travel impedance can capture the impact of service frequency and timetable quality on public transit accessibility. The final aim is to identify small communities' public transit gaps and inequalities, which are not due to inherent geographical and infrastructural disadvantages and can be improved by transit agencies under appropriate interventions and investments.

The present analysis is implemented for the case study of the intercity public transport network serving the suburban and rural areas located in the surroundings of Cesena, a city including nearly 100'000 inhabitants in Northern Italy, where bus services and trains are scheduled for daily travellers, mainly students, commuting from their place of residence in a maximum range of roughly 40 km and 1 hour of on-board journey time. Taking advantage of recent state-of-the-art approaches discussed in the scientific literature, this study aims to offer a practice-ready framework to be implemented in real-scale networks with limited effort, for public transit accessibility assessments, by transport professionals, planners and policy makers.
This paper is organised as follows. The proposed methodology is described, in Par. 2, for modelling total travel times by public transit, with consideration of schedule delay, on the basis of time-of-day users' preference functions, and application of a modified rooftops model. In addition, the definition a public transit specific impedance factor (PTSIF) is presented. Par. 3 illustrates the case study of the accessibility assessment performed for the bus and rail transport network linking the city of Cesena, to the small communities in its surroundings. Par. 4 presents a brief discussion of the results and conclusive remarks.

2. Modelling travel impedance for low-frequency public transit services

2.1. Total travel time as a proxy for travel impedance

In this study, total travel time is chosen as the metric for travel impedance and, thus, for accessibility problems of public transit services. The total travel time spent by a generic user can be estimated as the weighted sum of a list of sub-components (Teodorovich and Janic, 2017), which usually depend on user's perceptions and change between actual and programmed values. Moreover, they vary for the cases of low frequency and higher frequency services (Fosgerau, 2009). In particular, it can be written:

$$t_{tot} = w_1 \cdot t_{acc} + w_2 \cdot t_{in} + w_3 \cdot t_{transf} + w_4 \cdot t_{egr} + w_5 \cdot t^* \quad (1)$$

where t_{tot} is either the programmed or actual total perceived travel time spent by a generic user of public transit for a trip between origin *O* and destination *D*, t_{acc} is user's access time from point *O* to the initial boarding stop, t_{in} the total in-vehicle time, which the user spend on-board of public transit vehicles in the whole trip, t_{transf} the transfer time required to the user for possible vehicle interchanges, t_{egr} the egress time from the final unboarding stop to destination *D*, t^* a term depending on service frequency, which takes different forms for low-frequency and higher frequency services and w_i, with $i = 1, 2, \ldots, 5$, the travel time component weights accounting for different user disutilities associated to different time components.

In frequent transit services, e.g. with more than 2-3 services per hour, users do not plan to use a specific service and they just arrive at their favourite transit stop in order to catch the next vehicle departure and they arrive at any time between two departures (Fosgerau, 2009). Thus, in the case of frequent services, it holds: $t^* = t_W$, being t_W the waiting time at the departure station, that may range from zero to the (actual or programmed) service headway, i.e. the value of the time interval between two consecutive departures.
In less frequent transit services, such as many intercity bus and rail services, travellers choose a specific service to use, provided that they are informed about service schedule, so that the waiting time cost t_W is not relevant compared to the so-called schedule delay t_{SD}, also named rescheduling time. Therefore, it holds, in this case: $t^* = t_{SD}$.
From a single passenger's perspective, schedule delay can be defined as the difference between passenger's preferred and scheduled departure (or arrival) times (Small, 1982; Kroes and Daly, 2018; Fosgerau, 2009; Rietveld and Brons, 2001; Koppelman et al. 2008; Mueller and Aravazhi, 2020).
In this research, total travel time t_{tot} of intercity and suburban public transport services is taken into account, as a proxy of travel impedance, for the purpose of evaluating the accessibility of small communities to larger communities, by means of an appropriate but also transparent and straightforward methodology, which does not necessarily require the implementation of expensive and time-consuming demand surveys. In this framework, given that the simulation of passengers' travel choices is out of the scope of the analysis, the following set of simplifying assumptions can be written:

1) total travel time t_{tot} refers to scheduled and not to actual travel times, so that impacts on travel impedance due to transit service reliability factors are not taken into consideration in the present analysis;
2) travellers are not differentiated by categories and show uniform preferences and equal deterministic behaviour;
3) all travellers perceive all components of total travel time as they contribute to the same extent to their travel impedance, i.e. $w_i = 1$, with i = 1, …, 5;
4) travellers are provided with low-frequency transit services, are perfectly informed about service schedule and rationally choose their services without incurring into unnecessary waiting times, i.e. $t^* = t_{SD}$;
5) possible transfer times occur only occasionally, so that any transfer time, when required to users for vehicle interchange, can be implicitly incorporated into the value of t_{in} and t_{transf} can be set to a null value[1];
6) access and egress times to/from public transit stops do not show paramount criticalities, do not differ significantly between travellers and are negligible compared to t_{in} and t_{SD}, so that $t_{acc} = t_{egr} = 0$, being the present analysis focused on accessibility via public transit more than on accessibility to public transit.

Under the previous assumptions, total travel time t_{tot} is modelled as a deterministic and "non-subjective" variable, in line with the approach adopted by Mavoa et al. (2012), and equation (1) can be rewritten as:

$$t_{tot} = t_{in} + t_{SD} \tag{2}$$

with all terms that result to be dependent on time and change minute by minute in a day, week, season.

It can be noted that, on one hand, total in-vehicle time t_{in} (Teodorovich and Janic, 2017) is mainly affected by the following factors:

- distance covered by transit vehicles, which can show even significant de-routing amplifications compared to the shortest path that may be chosen by car users;
- type, characteristics and level of congestion of transport infrastructure;
- dynamic vehicle performances in all phase of the motion;
- number of intermediate stops for boarding and unboarding passengers;
- dwell times at intermediate stops, which depend on vehicle type and lay-out as well as number and category of travellers to embark and disembark at transit stops.

On the other hand, schedule delay t_{SD} reflects the quality of public transit schedule, especially for what concerns (Kroes and Daly, 2018):

- service frequency;
- proper alignment between scheduled departure and arrival times and travellers' preference curves;
- number of daily (and weekly) route operating hours and first and last times of departures in both upward and downward directions (Cheng et al., 2018).

2.2. How to estimate total travel time accounting for schedule delay

Low-frequency public transit passengers cannot choose their departure and arrival times freely but they are constrained by service schedules (Fosgerau, 2009). Indeed, passenger transport demand is a derived demand that reflects users' desire to participate in activities at their travel destination. While the scheduling of these activities determines passengers' preferred departure and/or arrival times, on the other hand, with schedule-based transport services, passengers can hardly depart or arrive at their preferred time, so that schedule delay has to be taken into account at the point of origin and/or destination (Kroes and Daly, 2018; Rietveld and Brons, 2001; Danesi, 2010; Munoz et al. 2020).

In this paper, a method for estimating total travel time, with consideration of schedule delay, is presented, in order to capture the effect of timetable structure on travel impedance, for the specific case of small communities linked to larger urban centres by low-frequency public transit services. This method is based on a modified version of the so-called "Rooftops model", which is well known in the rail transport planning sector and whose name is due to the shape of the total travel time graph plotted along the time axis when schedule delay cost is taken into account and expressed in equivalent travel time (Douglas et al. 2011; Langdon and McPherson,

[1] t_{tot} can be incorporated in t_{in} based on the preliminary assumption of equalities of weights, $w_i = 1$, with $i = 1, \ldots, 5$.

2011; Prior et al. 2011; Kroes and Daly, 2018; Mueller and Aravazhi, 2020).

Indeed, in addition to the basic assumptions listed in Par. 2.1, in this research passengers are supposed to travel from a small community to a larger centre in a week day, by low frequency rail or bus services, in order to perform an activity that has a fixed time, so that (1) user's desired time of arrival from home at the final stop of destination cannot admit any late schedule delay but only early schedule delay and (2) user's desired time of departure in the downward direction, from the urban centre to home, cannot admit any early schedule delay but only late schedule delay. Such assumptions appear to be more appropriate than the assumption made by the classical version of rooftops model, which weights both early and schedule delay equally. In fact, public transit users, who live in small communities, tend to belong to low-income and fragile categories and show limited elasticity with respect to the timing of activities they perform in the urban centres, such as school attendance, medical examinations, etc.

In this framework, a total travel time measure able to capture schedule delay effects, can be calculated by means of the modified rooftops model, minute by minute, in a week day, for each small community being represented by one (undifferentiated) user, for both the upward and downward directions. The calculations take as a reference the actual public transit schedules of arrivals to the urban centre, in the upward direction (from small communities), and the actual public transit schedules of departures from the urban centre, in the downward direction (to small communities). Furthermore, an average total travel time for each small community, as a proxy of travel impedance by public transit, can be computed as the arithmetic mean of the two values obtained for each travel direction separately. Average upward total travel times for every small community under study can be computed as a minute-by-minute weighted average, i.e. by weighting each minute-by-minute value obtained of total travel time in a week day, on the basis of the (normalised) preference values assigned by the time-of-day users' arrival preference curves to each time instant (each time instant is thus considered as a desired arrival time to the urban destination). The same can be done in order to obtain average downward total travel times for every small community. In the latter case, the (normalised) weight assigned to each time instant in the weighted average operation corresponds to the value assigned by the time-of-day users' departure preference curves, which consider time instants as possible departure times from the urban centre to the small community, where users are supposed to be resident. In mathematical terms, under the assumptions presented in Par. 2.1 and Par. 2.2, it can be written, for a traveller of the i-th small community:

$$t_{tot}(i) = \frac{t_{tot,u}(i) + t_{tot,d}(i)}{2} \tag{3}$$

where $t_{tot}(i)$ is the total travel time, as a proxy of travel impedance by low frequency public transit, with reference to a week day, for the i-th small community, $t_{tot,u}(i)$ the total travel time in the upward direction and $t_{tot,d}(i)$ the total travel time in the downward direction, being $i = 1, \ldots, N$, and N the number of small communities under study.

Let now $t_{tot,u}(i,t)$ be the total travel time, including schedule delay contribution, required in the upward direction to travel from the i-th small community to the urban centre so that the user is present at the transit stop of final destination at instant t, with $t = 1, \ldots, 1440$[2]. Furthermore, let $f_{arr}(t)$ be the value of the selected normalised users' time-of-day preference curve calculated for each $t = 1, \ldots, 1440$, provided that t is considered as the arrival time to the urban centre of a theoretical transit service available in the upward direction. Then, $t_{tot,u}(i)$ can be computed as:

$$t_{tot,u}(i) = \sum_{t=1}^{1440} f_{arr}(t) \cdot t_{tot,u}(i,t) \tag{4}$$

Similarly, $t_{tot,d}(i)$ can be computed as:

$$t_{tot,d}(i) = \sum_{t=1}^{1440} f_{dep}(t) \cdot t_{tot,d}(i,t) \tag{5}$$

In expression (5), $t_{tot,d}(i,t)$ is the total travel time, including schedule delay contribution, required in the downward direction to travel to the i-th small community from the urban centre, when the user is

[2] Note that 1440 corresponds to the number of minutes in a 24-h day.

present at the transit stop of departure at instant t, with $t = 1, \ldots, 1440$; $f_{dep}(t)$ is the value of the selected normalised users' time-of-day preference curve calculated for each $t = 1, \ldots, 1440$, if t is considered as the departure time of a theoretical service available in the downward direction, from the urban centre[3]. Now $t_{tot,u}(i,t)$ and also $t_{tot,d}(i,t)$ can be computed by means of the rooftop model, under the aforementioned modifications. More in detail, it holds:

$$t_{tot,u}(i,t) = \begin{cases} \min\left\{ \begin{array}{l} t_{in,j}(i) + t - t_{arr,j}(i), \\ \forall j = 1,\ldots,A \,\middle|\, t \geq t_{arr,j}(i) \end{array} \right\}, & if \;\; t_{arr,1}(i) \leq t \leq 1440 \\ t_{in,0}(i) + t + t_{arr,0}(i) - 1440, & if \;\; 0 < t < t_{arr,1}(i) \end{cases} \quad (6)$$

$t_{in,j}(i)$ is the total in-vehicle time required by the j-th public transit trip arriving, in the week day taken as a reference, from the i-th small community to the urban centre at time $t_{arr,j}(i)$, among a total number of A daily arrivals. $t_{in,0}(i)$ is the total in-vehicle time required by the last service arriving at time $t_{arr,0}(i)$ the day before, from the same community. On the other hand, it can be written:

$$t_{tot,d}(i,t) = \begin{cases} \min\left\{ \begin{array}{l} t_{in,h}(i) + t_{dep,h}(i) - t, \\ \forall h = 1,\ldots,D \,\middle|\, t \leq t_{dep,h}(i) \end{array} \right\}, & if \;\; 0 < t_{dep,D}(i) \\ t_{in,(D+1)}(i) + t_{dep,(D+1)}(i) + 1440 - t, & if \;\; t_{dep,D}(i) < t \leq 1440 \end{cases} \quad (7)$$

where $t_{in,h}(i)$ is the total in-vehicle time required by the h-th public transit trip departing, in the week day taken as a reference, from the urban centre to the i-th small community at time $t_{dep,h}(i)$, among a total number of D daily departures, and $t_{in,(D+1)}(i)$ is the total in-vehicle time required by the first service departing at time $t_{dep,(D+1)}(i)$ the day after, to connect the same community.

Fig. 1 and Fig. 2 illustrate an exemplification of $t_{tot,u}(i,t)$ and $t_{tot,d}(i,t)$ functions calculated for public transport services departing from (arriving to) the urban centre at minute 600, 680, 720, 800 of the day and with an alternating 60'-80' in-vehicle journey time. They can be compared to the functions obtained by Kroes and Daly (2018) through the implementation of a classical instead of modified rooftops model.

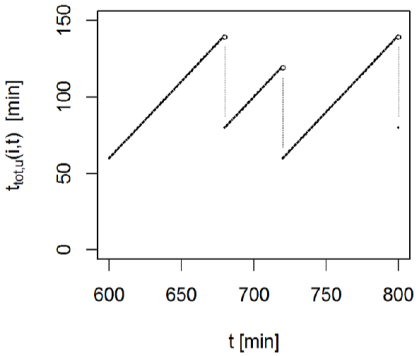

Fig. 1. Total travel times (in minutes, zero being midnight) by public transit calculated, in the same case described by Kroes and Daly (2018), for different preferred arrival times (in minutes), according to the modified rooftops model that does not admit late schedule delay for commuters travelling to the main urban centre as a destination

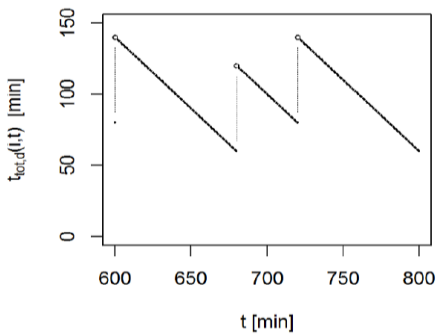

Fig. 2. Total travel times (in minutes, zero being midnight) by public transit calculated for different preferred departure times (in minutes) at the main urban centre, according to the modified rooftops model that does not admit early schedule delay for commuters travelling in the downward direction

[3] $f_{arr}(t)$ and $f_{dep}(t)$ can be assumed not to differ between the various small communities as they mainly depend on the activities to be performed at the urban centre, which has been chosen as common destination of all transit trips by all users living in the small communities under study.

2.3. Time-of-day users' preference functions

Departing and returning passengers travelling between a small community and a larger urban centre typically assign different preferences to different times of the day to be chosen as an arrival time to the urban centre and a departure time from the urban centre respectively. For example, students are expected to perceive a connection departing from their place of residence to the urban centre in the early morning to be much more attractive, at least for school attendance than a connection leaving in the late afternoon (Babu et. al., 2018; Alex et al., 2019). Furthermore, for many users, downward transit services scheduled in the early morning from the urban centre to any small community are likely to be perceived as less attractive than a service whose time of departure is scheduled in the late afternoon.

In this paragraph, two possible options are proposed, in absence of validated travellers' time preference curves, in order to specify the normalised functions $f_{arr}(t)$ and $f_{dep}(t)$ as required in formulas (4) and (5), so that total travel times as a proxy of public transit impedance can be estimated for the set of communities under analysis.

The first and simplest suggested method is to divide the time axis of a 24-h week day in a series of time intervals and to assign them different levels of expected demand for public transit services. For instance, let us consider upward trips from a small communities and classify time instants as belonging to one and only one of three categories (sets of time instants in a 24-h day), e.g. peak hours (PH), non-peak hours (NPH) and night hours (NH). If T_p is the total duration of peak hours, T_n the total duration of night hours and T_{np} the total duration of the remaining non-peak hours in the 24-h day, measured in minutes, coefficients can be assigned to take into account the different level of demand characterising the different time intervals, namely, just for example: $c_p \geq c_{np} \geq c_n$, e.g. $c_p = 100$, $c_{np} = 60$ and $c_n = 5$. Then, it can be written:

$$f_{arr}(t) = \begin{cases} \frac{c_p}{C}, & if \quad t \in PH \\ \frac{c_{np}}{C}, & if \quad t \in NPH \\ \frac{c_n}{C}, & if \quad t \in NH \end{cases} \tag{8}$$

being

$$C = c_p \cdot T_p + c_{np} \cdot T_{np} + c_n \cdot T_n \tag{9}$$

so that $f_{arr}(t)$ is a normalised function corresponding to the probability density function for any user having to choose an instant of time of day as an arrival time for a transit service connecting the place of residence to the urban centre. Similarly, $f_{dep}(t)$ can be specified by the analysts as the probability density function for any user having to choose an instant of time of day as departure time for a transit service connecting the urban centre to the place of residence.

A second possibility that looks appropriate to build users' time-of-day preference curves, at least under the objectives and limitations of this study, is to graph public transport scheduled arrival times to the urban centre as well as scheduled departure times from the urban centres to small communities. Provided that transit schedules for commuters tend to be quite constant even over many years and are usually built with careful consideration of the passengers' basic needs, at least for what concern the participation to the main activities located in the urban centre and not directly available in smaller communities, it can be roughly assumed that the provision of transit services perfectly fits travellers needs. Under the aforementioned hypothesis[4], histograms can be built accounting for:

- the number (n_{arr}) of public transit service arrivals to the urban centre, from small communities, registered in every time interval ΔT of the 24-h day, as well as
- the number (n_{dep}) of public transit service departures from the urban centre, to small communities, registered in every time interval ΔT of the 24-h day.

Possible values of ΔT can be, for instance: 15', 20', 30'. Then, $f_{arr}(t)$ and $f_{dep}(t)$ can be obtained as (normalised) step functions, being:

$$f_{arr}(t) = \frac{n_{arr}(\Delta T_i)}{\Delta T_i \cdot N_{arr}}, \quad 0 < t \in \Delta T_i, \quad i = 1,..., \frac{1440}{\Delta T} \tag{10}$$

[4] In this research, all travellers are assumed to belong to the same category, thus being represented in their preferences by the same time-of-day arrival and departure curves; nevertheless, following the first option (but not the second one) suggested in this paragraph for the specification of time-of-day curves, it is possible to associate different time-of-day preference curves to different users' categories, if the case.

and

$$f_{dep}(t) = \frac{n_{dep}(\Delta T_i)}{\Delta T_i \cdot N_{dep}}, \quad 0 < t \in \Delta T_i, \quad i = 1,...,\frac{1440}{\Delta T} \quad (11)$$

In formulas (10) and (11) N_{arr} and N_{dep} correspond to the total daily number of public transit service arrivals and departures to/from the urban centre from/to the small communities considered within the process of building the time-of-day curves; indeed N_{arr} and N_{dep} may or may not correspond to A and D values previously defined in formulas (6) and (7), depending on the particular set of transit services chosen by the analysts for interpreting users' time preferences.

2.4.Public transit specific impedance factor (PTSIF)
An index can be now introduced, in order to catch the specific contribution of public transit routing and scheduling decisions to the determination of travel impedance levels affecting passengers commuting between a small community and a larger urban centre. Indeed the "public transit specific impedance factor" can be defined, for the *i*-th small community, being $i = 1, \ldots, N$, and N the number of small communities under study, as:

$$PTSIF(i) = \frac{t_{tot}(i)}{t_{car}(i)} \quad (12)$$

where $t_{tot}(i)$ is the total travel time defined, in formula (3), as a proxy of travel impedance by low frequency public transit, with reference to a week day, and $t_{car}(i)$ is the travel time required by car users to travel between the same origin and destination, under the hypothesis of null parking problems and related time penalties.

$PTSIF(i)$ accounts for the time penalty associated to all extra in-vehicle travel times as well as schedule delay affecting a *i*-th small community's user travelling by public transit compared to the case of a passenger of a private car travelling between the same points. $PTSIF(i)$ accounts for transit specific gaps and disadvantages, while it does not depend on geographic, infrastructural and flow-related conditions that characterise the road network itself.
The higher is $PTSIF(i)$ value for the *i*-th small community, the higher is the transit specific impedance and thus the poorer is the connection provided to the users of the public transit network compared to the connection available through the private car network. PTSIF(i) is very likely to take values that are greater than 1, but, theoretically, it can also take values between 0 and 1, in the case of enough frequent rail connections, or even bus connections travelling along reserved paths, which are more direct than the shortest (in time) itinerary available to private car users.

3. Application of the methodology to a real-scale public transit network

The study area is included in the province of Forlì-Cesena, in Northern Italy. It comprises the territory of the municipality of Cesena and a dozen of other smaller municipalities in the surroundings, for a total surface of roughly 800 km^2 and a total resident population of about 200'000 inhabitants. More than the half of the population settled within the study area are inhabitants of smaller either urban or rural communities. Indeed, small communities are linked to the main urban centre, namely the city of Cesena, by rail and bus services that are essential for all people who need to participate in activities, e.g. workplaces, secondary schools, hospitals, etc., that are not directly available at their place of residence. In this framework, 90 small communities, totalling more than 100'000 inhabitants, are taken into account, within a range of 35 km driving distance (Fig. 3). They are linked to the city of Cesena through 31 bus lines and 1 railway line, whose extension is 1320 km long and provide users with 425 return trips in a week day under winter seasonal schedule. In Fig. 4 the distribution of public transit service frequencies by rail and bus between the small communities under study is presented.

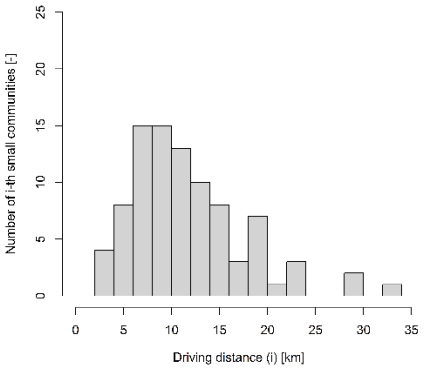

Fig. 3. Distribution of driving distance values between the 90 small communities belonging to the study area

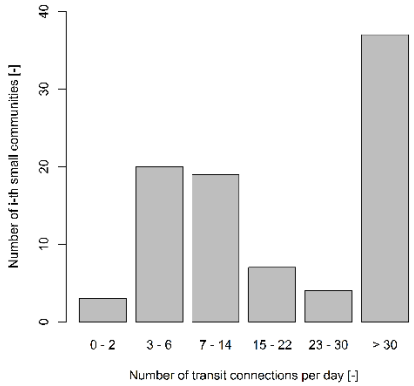

Fig. 4. Distribution of public transit connections, according to 6 classes, between the 90 small communities belonging to the study area

The graph of public transit network has been built by considering each small community as concentrated into a single centroid. The main urban centre of Cesena has been represented itself by a single centroid located at the train station, where also the main bus station of the city is situated. Data regarding bus service routes and schedules have been collected through General Transit Feed Specification (GTFS) data that are made available by START-Romagna, i.e. the main operator providing public transit services in the study area. Rail service data have been collected through Trenitalia website. Data refer to public transit service schedules of Wednesday 20th November, 2019.

All main calculations and elaborations have been performed, under the assumptions listed in Par. 2, by means of R software environment for statistical computing and graphics, in order to assess, for each small community, the total travel time by public transit, with consideration of schedule delay, as well as the value of PTSIF index, which can provide information regarding the specific impedance contributions due to reasons other than those affecting car users too.

First, the modified rooftops model has been applied in order to estimate, for each small community and each instant in a week day, subject to the winter service schedule, the total travel time by public transit, as the sum of in-vehicle travel time and schedule delay, both in the upward direction, i.e. from the main urban centre to the small community, and in the downward direction, i.e. in the opposite direction. Fig. 5 shows, as an example, the travel time functions obtained for the small community n. 6: in this figure, it can be noted that the values $t_{tot,u}(i,t)$ and $t_{tot,d}(i,t)$ functions are dependent not only on in-vehicle travel times but mainly on service frequency and number of daily operating hours as well as first and last vehicle departure/arrival times. On the other hand, peaks in $t_{tot,u}(i,t)$ and $t_{tot,d}(i,t)$ functions, which tend to appear during late evening, night and very early morning times, are likely to be smoothed as far as the modified rooftops functions have to be combined with the coefficients emerging from the estimation of the time-of-day users' preference curves. In the present application, time-of-day preference curves are estimated by means of the approach leading to formulas (10) and (11). Fig. 6 and 7 suggest that users' preferences derived by the actual scheduling of intercity transit services to/from the city of Cesena are tailored mainly on the needs of students and workers, who need to travel to the main urban centre in the early morning and be back to the place of residence in a small community at lunch time more than in the late afternoon or evening.

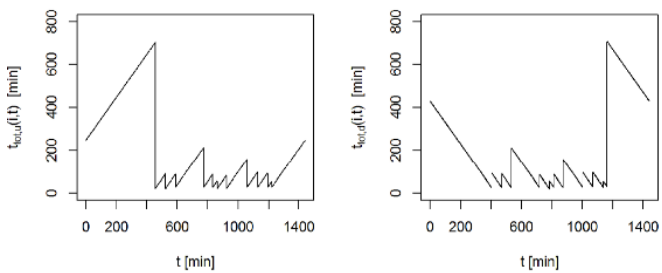

Fig. 5. Total travel times (in minutes) by public transit calculated, for small community with identity code n. 6, both in the upward direction (on the left) and in the downward direction (on the right) for each time of the day as a preferred arrival and departure time, respectively (in minutes)

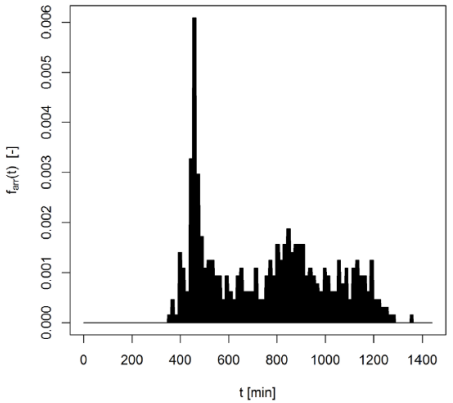

Fig. 6. Normalised time-of-day $f_{arr}(t)$ function, which associates to each minute in a day the fraction of users selecting that minute as preferred arrival time, when travelling by public transit from their small community to the city of Cesena

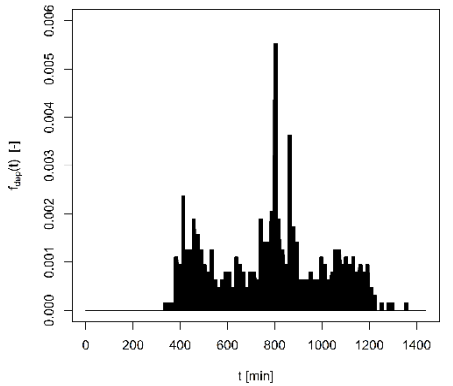

Fig. 7. Normalised time-of-day $f_{dep}(t)$ function, which associates to each minute in a day the fraction of users selecting that minute as preferred departure time, when travelling by public transit from the city of Cesena to their small community

As a result of the implementation of the methodology defined in this research, values of total travel times $t_{tot}(i)$ for the small communities under study have been calculated, whose distribution is shown in Fig. 8. Values of total travel times vary widely between less than 1 hour to more than 10 hours in a few cases of very low frequency connections.
Then, driving times and distances of the fastest route have been calculated in R (Fig. 9), using the "osrm" package (Giraud et al. 2020) based on the Open Source Routing Machine and OpenStreetMap project, between each small community and the centroid located at Cesena train station, in order to evaluate public transit specific impedance, by means of the new PTSIF index (Fig. 10). For a given origin-destination pair, random checks along the network, during off-peak and on-peak periods, have pointed out that driving times do not vary considerably, so that the network is assumed to work in uncongested mode.

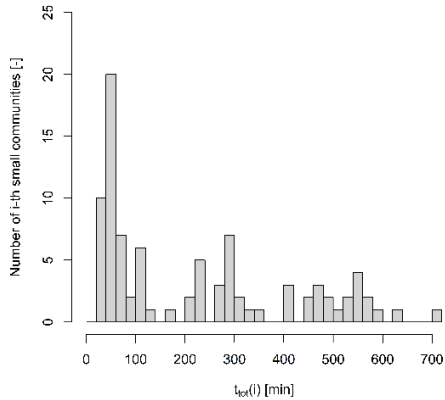

Fig. 8. Distribution of total travel time values between the 90 small communities belonging to the area under study

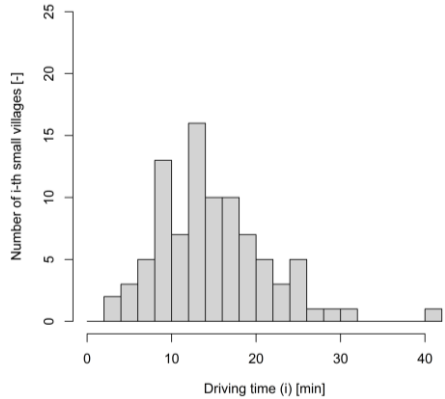

Fig. 9. Distribution of driving time values between the 90 small communities belonging to the area under study

Under the previous hypothesis, values of PTSIF have been obtained that vary between 1.6 and 51.0 in the worst cases. Wide ranges of PTSIF indicate

that public transit services provided in the area under study to the various small communities lead to very relevant differences for what concerns the level of service offered and the resulting transit specific impedance.

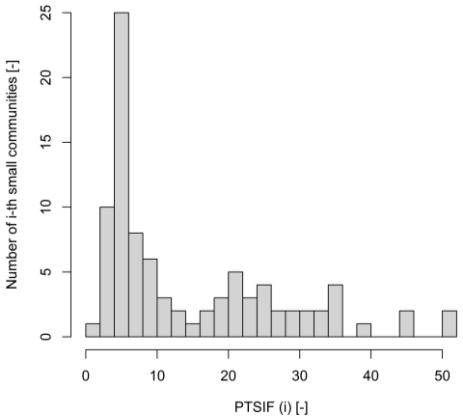

Fig. 10. Distribution of PTSIF values between the 90 small communities belonging to the area under study

The map represented in Fig. 11 summarises the main results obtained . It illustrates all 90 small communities considered in the analysis, with numbers used as identifiers. Geographically, small communities are represented by their main public transport access/egress point. Histograms adjacent to each small community show PTSIF (light grey bar) and t_{tot} (dark grey bar) values, calculated for each small community according to the methodology proposed in Par. 2. It can be seen that, generally speaking, as distance increases from the main urban centre of Cesena, t_{tot} does not increase accordingly. Certain small communities show relatively low values of both PTSIF and t_{tot}, along well served transit corridors.

For example, in the south-western area, small community 65 and 84 are roughly equally distanced from Cesena, but public transport accessibility is higher for the former than the latter small community. This can be due, for example, to service frequency differences (number of services and their time distribution), scheduling (service at low-preference times), presence of direct services (non-stop instead of connections with significant de-routing penalties), operating time window (first and last service in a day).

Moreover, comparing small community 65 and 8 (south of Cesena), it can be seen that PTSIF have similar values despite experiencing high differences in distance from Cesena and in $t_{tot.}$ This means that both mountainous small communities and suburban ones can enjoy relatively good public transport accessibility, if compared with private automobile. On the other hand, in the north-western area, small community 96 and 78 are very close to each other (about 3 km) and located roughly at the same distance from Cesena, but small community 96 is characterised by higher t_{tot} and PTSIF than small community 78, which is located along a major transit corridor.

4. Conclusions

This paper illustrates and implements a practice-ready methodology to evaluate public transit impedance in the case of low-frequency bus and rail services linking small communities to larger urban centres. The ultimate goal is to assess possible gaps and inequalities in the provision of public transit services and to help experts and decision makers to define appropriate routing and scheduling solutions to criticalities that are not merely inherent to general geographical and infrastructural issues.

In this framework, total travel time is chosen as a proxy of travel impedance and it is calculated by taking into account both in-vehicle scheduled travel times and schedule delay. Indeed, schedule delay is the variable that can catch the impact of service frequency and timetable quality on accessibility levels of small communities via public transit.

The proposed methodology estimates total travel time, with consideration of schedule delay, based on a modified rooftop model, accounting for the hypothesis that travellers are not in the position to accept any scheduled late arrival or early departure time penalties before and after the activities representing the reason of their trip.

Building on such total travel time metric, which provides an absolute evaluation of users' travel impedance for each small community under study, a new index is proposed (PTSIF). It introduces a relative metric to assess the contribution of public transit impedance that is related to the specific timetable structure correcting for determinants, which are common to those faced by car users as well. PTSIF can be considered as the actual public transport travel time with schedule delay normalised over driving time, as an estimate for an "ideal" public transport service (i.e. infinite frequency, no schedule delay, fastest route).

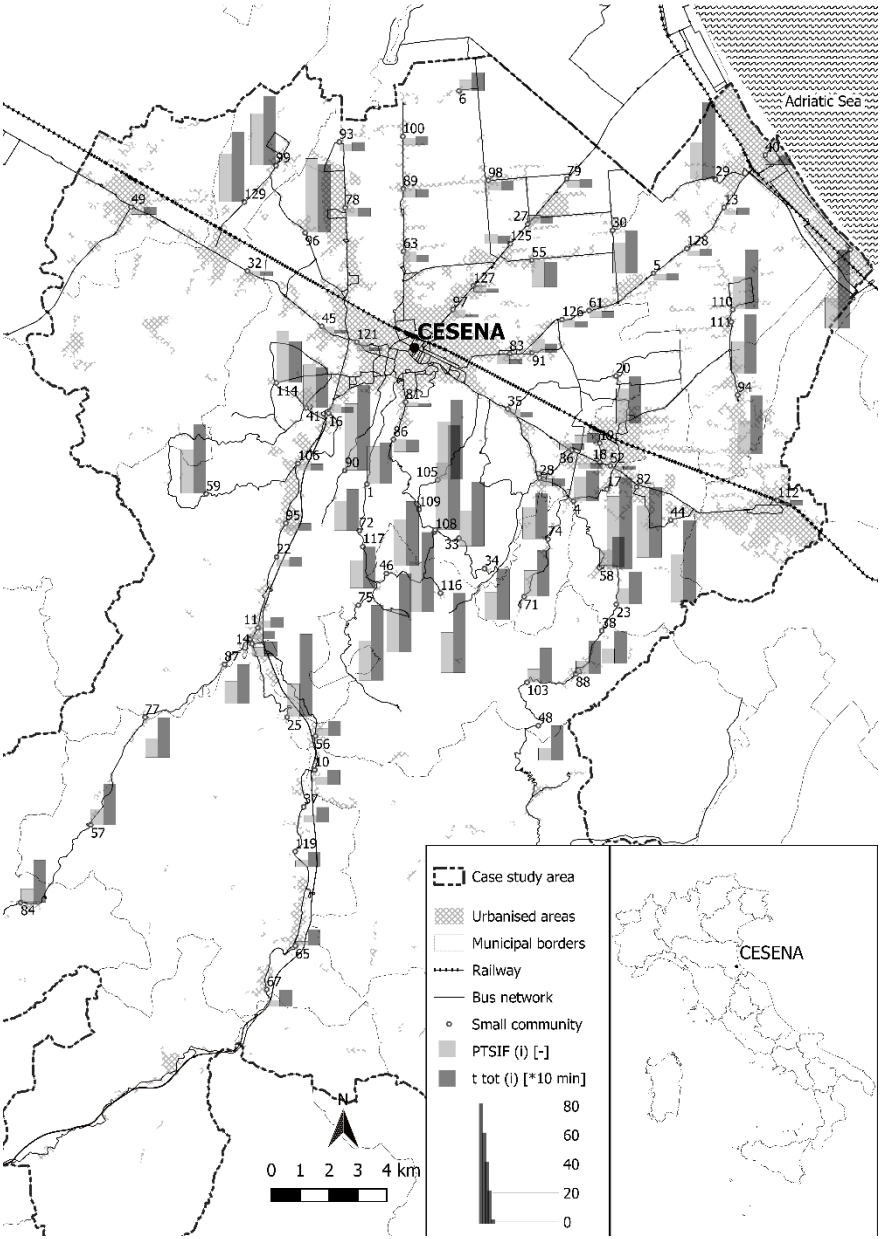

Fig. 11. Graphical representation of total travel time and PTSIF values for the small communities belonging to the study area; for all small communities under consideration, light grey histograms indicate the values of PTSIF index (dimensionless), while dark grey histograms indicate the total travel times (in minutes) spent for one-way trips by public transit, with consideration of schedule delay, calculated on the basis of the proposed methodology

This framework implementation for the case study of Cesena shows its feasibility and reproducibility to real-scale networks, using open-source tools and data (e.g. GTFS files, R software). The results obtained through the implementation of the proposed methodology highlight differences among small communities. Similarly-distanced small communities from the main urban centre widely differ in terms of absolute (e.g. total travel time) and relative (e.g. PTSIF) impedance metric, showing that inequalities do exist and tend to assign heavier penalties to rural communities that are out of the main rail and bus line paths.

In fact, the particular area under study is characterised by quite different types of small communities: small villages located in rural and hilly areas, medium-small towns with about 5-10 thousands inhabitants, settlements originally representing separated rural villages and now incorporated as suburbs of the main urban centre, as a consequence of urban sprawl. In general, it can be observed that the travel impedance measured in the case study is quite high, both in absolute terms and compared to car users' travel time values, with the only exceptions of (1) small communities of the urban peripheral areas (closer to Cesena), who are served by the terminal segments of suburban transit (higher frequencies); and (2) further small communities that are served by direct, limited-stop services. In such cases, PTSIF shows the lowest values in the sample and indicates that public transport can be an appealing alternative, if compared to driving, even in far and mountainous small communities. Also, small communities that are close to each other can experience relatively high differences in impedance/accessibility level.

Overall, in the Cesena case study, it can be observed that distance from the major urban centre is not the most important determinant of inequalities related to the public transit travel impedance and accessibility. In addition, it can be argued that, because of suboptimal level of accessibility, at least as far as public transport network is concerned, there is a risk for further marginalisation of small communities with subsequent acceleration of urban sprawl and depopulation of rural and mountainous areas. Indeed, in the current period, cuts in public service investments and expenses may follow prolonged sanitary emergency and downturn of the economic cycle.

In general, ranking small communities according to the proposed metrics can help transport professionals to prioritise interventions for improving and homogenising public transport accessibility, leveraging transport frequency (number and time distribution of services), speed (direct services, bus-only lanes), as well as evaluating route detours, extension of operating time, on demand services, etc.

Future prosecution of the present research may look into the application of the proposed metrics to compare different case studies in European countries. Surveys could be conducted to assess satisfaction of public transport service in small communities and rank it against the PTSIF index. Also, research efforts may be focused into improving the PTSIF index. For example, passengers can be classified in different categories and sensitivity analyses may be conducted in order to evaluate potential advantages in the usage of perceived and weighted impedance time-related factors instead of purely chronological measures. Finally, driving times may account for different flow conditions in congested networks, or, where cycling is an appealing alternative (distance and comfort-wise), cycling time may be considered.

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