Feeder-trunk and direct-link schemes for public transit: a model to evaluate the produced accessibility

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Abstract

In a public transport network, a more intense integration between lines generally involves, on one hand, the reduction in the number of direct links, which forces users to perform more transfers, and on the other hand, the possibility of achieving a greater number of rides with the same whole mileage. Thus, the move towards feeder-trunk schemes produces both negative and positive effects on accessibility and on the quality of service perceived by users. That implies the need to evaluate accessibility realized on a territory by transit service patterns characterized by different levels of line integration.

This research was focused on the development of an accessibility model able to estimate an equivalent travel time and to consider the discomfort resulting from possible transfers between vehicles and the benefits arising from available transit rides. As reported in this paper, the proposed model, that measures accessibility through an equivalent travel time, determines the latter as a function, in addition to the time spent inside the vehicle, also of the time and discomfort consequent to the transfers as well as of the number of supplied rides. With reference to the regional public transport, the values obtained by the calibration of the constants show how the waiting time has a weight for the user twice as much compared to the time spent on the vehicle, whilst the time required for the transfer has about a once and half weight. Finally, the discomfort caused by each transfer is evaluated by the user as an increase to the overall travel time of about 3 and a half minutes. The calibrated model has been applied to a real case, in order to validate it and highlight benefits and limitations resulting from feeder-trunk supply patterns.

The developed tool is useful in the design of a public transport service, especially in areas with weak demand, allowing to compare, in terms of produced accessibility, supply schemes with different levels of line integration, variable from direct-link type (also called point to point) to that feeder-trunk.

1. Introduction

In recent years, the rationalization of local public transport services has been an important tool in Italy and in other European countries for the public spending efficiency in this sector. In geographical areas with a diffused transport demand, the rationalization often involves reduction in total produced mileage. It is usually achieved not by reducing the number of links, but by replacing a certain number of direct links with

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integrated ones, because links involving two or more lines in connection usually allow saving of mileage with the same number of daily rides or increasing the number of supplied rides while keeping the total mileage unchanged.

A comparison between the two schemes in figures 1 and 2 intuitively proves the above-mentioned relationship between mileage and the number of rides in direct and integrated services. The comb pattern that can be found in many public intercity transport networks serving inner areas is characterized by the presence of a valley railway or main road with high standards, directly connecting two or more major centres (points 1 and 2, in figures 1 and 2) and some roads, usually with lower standards, connecting the main infrastructure to the smaller centres at high altitudes (points 3, 4, and 5). Obviously, the same infrastructural scheme can be found in many different situations that are even more articulated than the one, for simplicity of exposure, referred here.

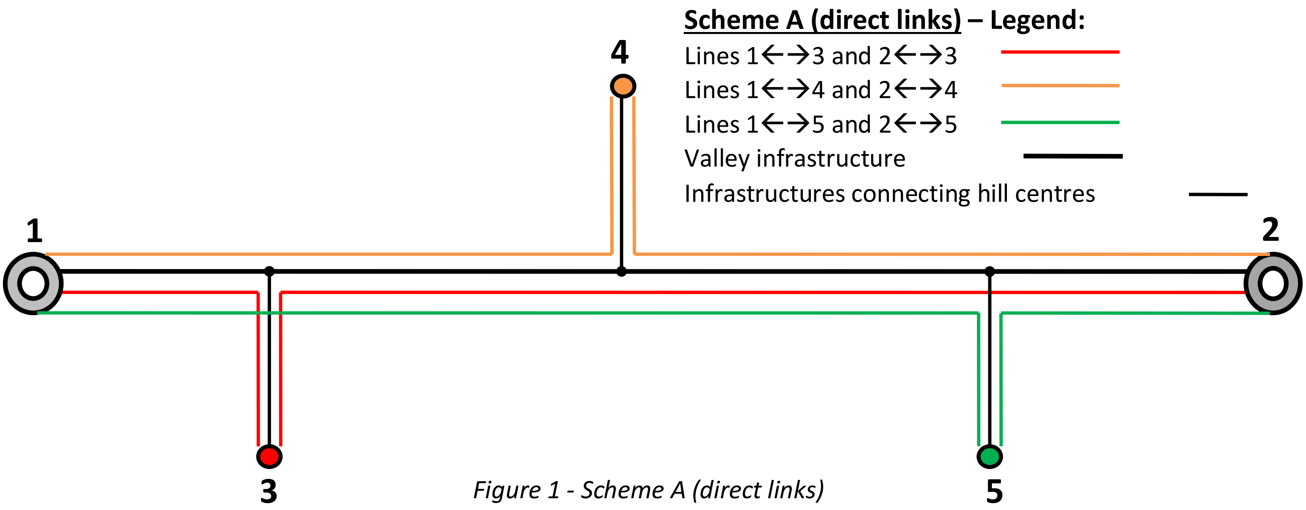

Figure 1 - Scheme A (direct links)

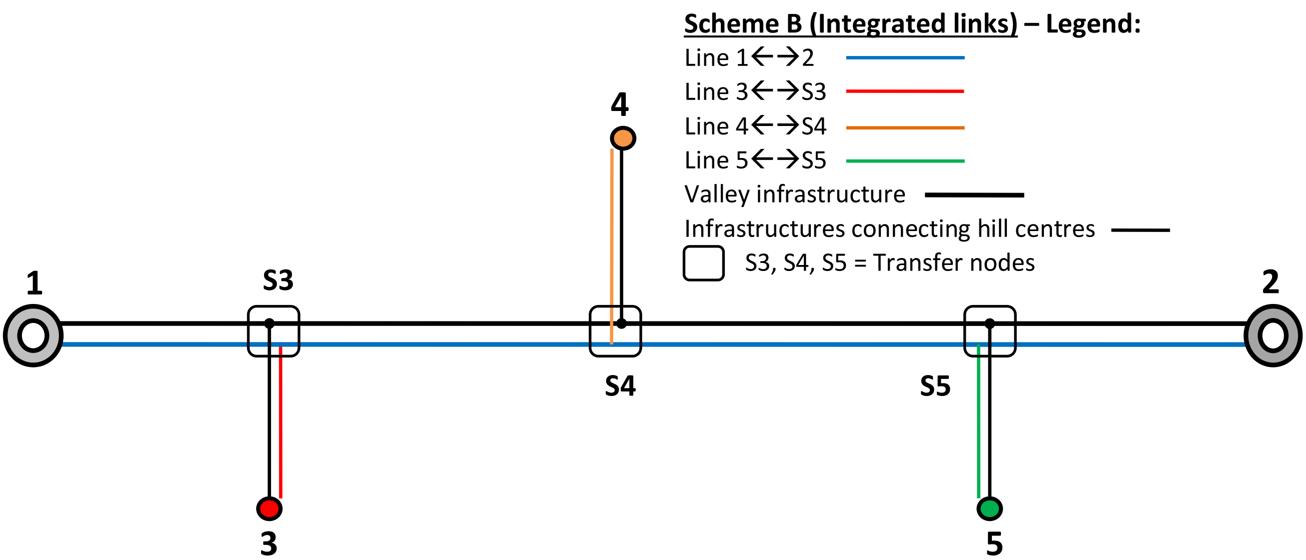

Figure 2 - Scheme B (integrated links)

Scheme A, which is characterized by direct lines, in contrast to scheme B with integrated lines, requires, in principle, a major mileage for the same number of supplied links. This is a consequence of the rides overlapping along the route sections common to several lines, which are necessary in direct lines and conversely, avoided in integrated ones. In particular, we travel the valley infrastructure two more times and one more the infrastructures connecting the smaller centres 3, 4, and 5 in scheme A compared to that of scheme B. Moreover, scheme B ensures linking all centres, while scheme A only links the smaller centres to the main ones. However, it is worth noting that scheme B, notwithstanding the advantages, requires all travellers, except those who move between the major centres 1 and 2, to change vehicle at least once in going from a secondary centre (3, 4, 5) to a main one (1 or 2) or vice versa, and even two times in moving from a secondary centre to another. Clearly, the possibility of adopting scheme B depends on the capacity available along the valley line, which should be verified, but it is usually existing at least in the off-peak hour and in the not high-density settlements areas.

A particular case of operation of the feeder-trunk scheme is represented by rides (of trains or buses), running on the main line in the opposite direction, which meet at the same time in each station or stop. This type of service organization, which occurs very rarely because it requires cadenced rides and equidistant stops, has further advantages in terms of mileage travelled because it makes it possible with a single feeder ride to guarantee, in each exchange node, the coincidence with two rides of the main line, which are running in the opposite direction. The standard schemes compared above are of general value and, therefore, also include this particular one.

Thus, the change in service from type A (direct links or point to point) to type B (integrated links or feeder-trunk), which obliges most users to have at least one transfer, is accompanied, at the same overall mileage, by the increase in the number of rides owing to the re-use of the saved mileages (as moreover confirmed by some studies e.g. Gschwender et al., 2016, Sivakumaran et al. 2012). The higher number of rides compensates for the sacrifice imposed on the users by the transfers; the integrated scheme provides a further appreciable advantage, that is, as can be observed from the example above, the strengthening of the links between the smaller centres. This fact, although important for territorial implications, unfortunately has no great transport value, either because it requires a double transfer which is scarcely accepted by users, and because of the minimum transport demand existing between these centres.

Different schemes for public transport service, with the same total mileages and thus, in principle, with the same cost of production, could differ according to the number of direct and integrated links between the points of the territory to be served. The fewer the direct links (and the more the integrated ones), the more the transfers required for users; however, in this case, there may be some major supplied rides. Therefore, high integration schemes, on one hand, require the users to make transfers but on the other hand, offers the possibility of making the trip at different times owing to the higher number of rides achievable with equal overall service mileages.

As better discussed in the next section, the measure of accessibility of a territory, simpler and more often used, is an inverse function of the travel time necessary to reach it and move between the main poles of internal demand. This measure, very effective in representing the accessibility produced by one or more infrastructures, is not the same for transport services. In fact, in relation to the latter it is essential to take into account the monetary cost, comfort and especially how much the time when the service is offered approaches the demand time thus allowing the user to reduce the time lost to the destination after the arrival and before departure for the return ride. Evidently, the greater the number of offered rides, the less time is lost. So the accessibility produced by a public transport service can be measured with a function that takes into account, with an appropriate weight, each of the service attributes that affect the generalized cost suffered by the user as well as the time lost by the latter at destination as a consequence of the non-perfect correspondence of the time of the ride used, to the purposes of the journey. These weights or coefficients represent the trade-off between the attributes, that is the user's willingness to exchange a quantity of an attribute with a different quantity of another.

The number of transfers imposed on travellers and the number of offered rides have an opposite effect on the generalized cost of transport. In fact, the load breakage resulting from the transfer from one vehicle to another affects the generalized cost of transport by raising it due to an increase in travel time and a decrease in comfort. The addition in the number of rides also influences the generalized cost but, on the contrary, decreases it, thanks to a reduction in the total travel time resulting in an abatement in waiting times, in particular those for the return ride. Accessibility, as an inverse function of the generalized cost, varies accordingly. Therefore, the level of integration of the lines, through which the supplied links are made, conditions the accessibility given to the served territory.

Enhancing accessibility is the main objective to be achieved through public transport supply, especially in areas with low settlement density; therefore, the effectiveness of the service can be assessed through a measure of accessibility produced by it.

The diagram in Figure 3 clarifies the contrasting effect on accessibility resulting from the transition from a direct link scheme to a feeder-trunk one.

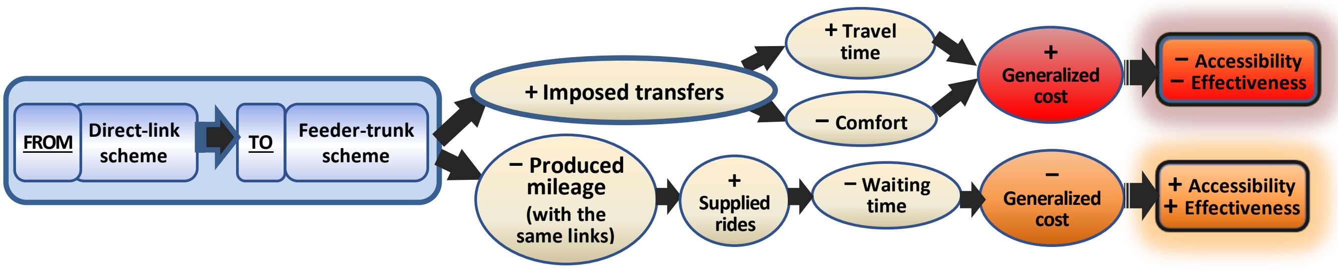

Figure 3 - Outcomes on accessibility (and therefore on the effectiveness related to the accessibility objective) of the transition from a direct-link supply scheme to a feeder-trunk one.

Naturally, if we do not take into account the possibility of compensating by a greater number of supplied rides the inconvenience imposed by the transfer, the validity of the feeder-trunk schemes for the user is limited to scenarios where the demand is such as to keep the number of users forced to transfer low (Jara-Díaz et al., 2012). Conversely, the service feeder-trunk shows great potential if, when passing from a direct-link scheme to a feeder trunk one, the economized mileage is returned to the services in terms of new rides in order to compensate for the deterioration in service quality and accessibility produced by transfers.

2. Formulation of the problem

Accessibility, measured as an inverse function of the generalized cost incurred to move between the demand generators and attractors identified in the territory served by the public transport system in question, can be expressed as

$$A = K / Cg \tag{1}$$

Being:
A = measure of accessibility
K = constant ≠ 0
Cg = generalized cost perceived by the user of the transport system

The generalized cost of transport or cost perceived by the user is expressed by

$$Cg = M + w_T \cdot T + w_R \cdot R + w_S \cdot S \tag{2}$$

Where:
M = monetary cost associated with the trip;
T, R, S = (respectively) the total travel time, the risk and the stress borne to move;
w_T, w_R, w_S = the monetary value of a unit quantity of time, risk and stress, respectively.

In turn, the total travel time T in (2) can disappear through the relationship

$$T = T_V + T_A + T_T + T_I \tag{3}$$

With T_V, T_A, T_T, T_I the total travel time components, which can be identified, respectively, in travel time, waiting time, any transfer time from one vehicle to another and time necessary to reach the departure stop from the origin of the journey and to reach the destination from the arrival stop.

We built a tool to measure accessibility produced by different road transit supplies. This tool evaluates an equivalent travel time representative of the generalized cost that is an inverse function of the accessibility according to (1). By this tool, we can compare different transit supplies that are realized with the same transport system on the same routes and stops but differ from each other only for getting closer a direct-link scheme or a feeder-trunk one. Therefore, the only two terms that can vary from a supply to another, in the formulation of the generalized cost (2), are the total travel time T and the stress S. Moreover, the possible variation of the latter in the different schemes compared is, however, attributable only to the different number of imposed transfers and the difficulty with which they occur. Therefore S, as it varies from each scheme to another only due to transfers, can be neglected within the generalized cost (2) if an appropriate weight is attributed to the "transfer time" component contained in the total travel time (3). On the other hand, since the components of the total time expressed by (3) have different importance for the user, it is appropriate to attribute to each of them a weight representative of how much each is considered more burdensome by the user compared to the on-vehicle time T_V. Thus, from (3) it is possible to deduce the equivalent total travel time, i.e. the total time as perceived by the user

$$T_E = T_V + K_A \cdot T_A + K_T \cdot T_T + K_I \cdot T_I \tag{4}$$

For what has been said, the weight K_T associated to the transfer time is representative of the stress or discomfort caused by the transfer. The greater number of offered rides can reduce waiting times at departure stops, especially for the return journey. In fact, in transport services performed with rides at scheduled times, as generally in the regional one considered here, the user exhibits a different behavior in accessing the departure stop, depending on whether he has to make the outward journey or that of return. In particular, in the first case, he moves from home to reach the departure stop only a few minutes before the time of the chosen ride, thus being able to spend most of the waiting time in other activities and then minimizing the unproductive part of this time. Otherwise, on the return journey, the user spends time waiting for the departure of the chosen ride, at the stop or anyway away from home, without being able to make this time productive.

Anyhow, the greater number of rides offered results in a reduction in waiting time (T_A) and therefore in total travel time. Furthermore, because the supply schemes to compare have the same stops, the time T_I necessary to reach the departure stop from the origin of the journey and to reach the destination from the arrival stop is the same in every scheme compared. Therefore, the term T_I in (4) can be omitted. On the other hand, the weighted time of transfer is better represented by a straight line with an intercept ≠ 0, like ($T_D + K_T \cdot T_T$) with $T_D \neq 0$, since the transfer is, however, perceived by users as an additional time even if it could be realized in no or negligible time. Therefore, (4) turns in the following expression

$$T_E = T_V + K_A \cdot T_A + (T_D + K_T \cdot T_T) \quad (5)$$

Eq. (5) allows to evaluate an equivalent time to move from each origin to each destination. By this time, we measure the travel generalized cost only in terms of time spent. As the generalized cost is an inverse function of accessibility, the equivalent time evaluated by (5) is a measure of the accessibility and it is suitable to compare supply schemes that do not differ for monetary cost, comfort of the vehicle or the road and risk, i.e. schemes of road transit that have the same type of vehicles, the same routes and stops but differ for the number of transfers imposed and the number of rides supplied to users.

Therefore, since $A = K / Cg$ for (1) and having set $Cg = Cg\ (T_E)$, it follows that it is also

$$A = A\ (T_E) \quad (6)$$

where T_E is the equivalent time expressed by (5). In explicit terms

$$A = K / T_E \quad (7)$$

with K = constant ≠ 0.

The replacement of direct links with integrated ones, without having negative repercussions on accessibility, requires knowing how burdensome the vehicle exchange in terms of not only lengthening the travel time but also of the inconvenience and loss of comfort is for the user. Also it requires knowing how advantageous it is to have a greater number of rides in the day that bring the transport supply closer to the travel time requirements of trips without precise features.

Basically, the question is: how many rides should be added, in the face of an imposed transfer, so that the accessibility remains unchanged? In other words, the change in accessibility resulting from the transition from direct to feeder-trunk service is measurable if we know, at all other conditions that generally exist within the same transport mode, the trade-off between the number of transfers with well-defined characteristics (exchange knot equipment and average transfer time) and the number of additional rides.

The question mainly concerns, even if not exclusively, the areas and traffic routes with weak and widespread demand where direct links (which, however, remain valid in the presence of a high demand characterized by common and well-defined path and time requirements) achieve low load factors and then need to be converted into feeder-trunk links.

In this work, the problem of the choice among different public transit supply schemes, evaluated under the aspect of accessibility that they are able to give to the served area, has been addressed. The inputs of the problem are the overall mileage to be produced, generally assigned on the basis of the available resources to the practitioner who have to plan and schedule the service, and the points of the area to be connected (and therefore the connection matrix), as well as the number and location of the origin and destination stops (a review about planning and scheduling transit network is provided by Guihaire and Hao, 2008). The feasible supply schemes, which represent alternatives of the same project, are characterized by a certain number of direct links and links by integrated lines, corresponding to a certain number of imposed transfers and supplied rides depending on how much each scheme approaches to the opposite direct-link or feeder-trunk types. Among the feasible supply schemes, it is necessary to select the one that ensures maximum accessibility. To this end, we developed a tool to compare, in terms of generalized cost and then of produced accessibility, different public transit schemes (also with the same overall mileage). This tool takes into account only the discomfort and the time-delay resulting from transfers, as well as the number of supplied rides affecting the waiting time. The calibration of the model has been made by values taken from the literature related to situations similar in some respects.

The issue dealt with in this work, concerning the evaluation of the overall accessibility produced by different public transport schemes, is not explicitly covered in any research published in the international literature. Nor it is possible to find scientific works that deal with the effects on the produced accessibility, of the number of transfers imposed and the number of rides supplied to users. The topic is of great importance in the context of improving the efficiency of public transport services which often, in technical practice, is pursued precisely by modifying the direct link schemes in favor of the feeder-trunk ones, without taking into account the consequent effects, often negative, on accessibility of the served area.

The following is a bibliographic analysis (section 3) regarding the evaluation of accessibility as a variation of some features of the network scheme and the impact that a transfer and waiting time at a destination have on the accessibility produced by the transport system. The proposed model is built and calibrated as described in section 4. In section 5, we present its application to a real case in which a transport supply organized according to scheme A (direct links) is redesigned according to scheme B (integrated links) without the user perceiving a decrease in its potential for travel and that is without a reduction of accessibility. The final considerations on the validity and usefulness of the model are presented in section 6.

3. Literature review

The design of a public transport service is a complex issue, usually divided into several phases, each oriented to define specific features of the project, which are combined to build a suitable supply (see for example Guihaire and Hao, 2008). The present work does not address the topic of the design of the overall transit service but aims to provide a tool to evaluate the effects on accessibility resulting from the operation of different supply schemes with particular reference to the direct connection scheme (point to point) and the integrated connection one (feeder-trunk). Therefore, we had first of all to identify a measure of accessibility that is sensitive to some characteristics of the public transport.

Even at present, a single and precise definition of accessibility does not exist because this feature has many aspects, each closely related to the requested use and to the context in which we operate. However, aspects common to all the accessibility definitions could be summarized in terms of the ease of reaching each activity on the territory from a separate location, using a given transport system (Dalvi and Martin, 1976). The research produced many indicators enabling the concept of accessibility and measuring its main aspects. This variety is essentially due to the different ways by which the key principles included in the notion of accessibility are evaluated, and according to the different weights attributed to these principles in relation to the specific application. Among the accessibility indicators, it is possible to distinguish those based only on physical measures from those that also refer to the settlement characteristics of the territory.

Accessibility in terms of physical distance is expressed by a distance indicator, which measures it in terms of travel space or time from origin to destination. More often, we use as indicator, the generalized cost that is more representative of the travel charges. Accessibility as a direct function of the average distance, time, or generalized cost, unlike the majority of the other parameters, expresses a value as lower as the greater the ease to reach the site. The indicator is often used in the theory of graphs with other topological measurements such as the number of network nodes or links (Cattan, 1992), as well as in geographic research and network analysis.

The accessibility as a physical measure, expressed as a function of the generalized cost of travel, is the most suitable way of evaluating and comparing the quality of connection realized by different public transport schemes serving the same territory. Indeed, this type of accessibility shows the advantage of being free from the territorial settlement features that, in the short term, are independent from the transit supply.

On accessibility related to public transport, the attention of scholars has been directed to aspects different from those discussed in the present work. For example, Murray and Wu (2003) tried to establish the optimum between increased stops and consequent decrease in commercial speed. Indeed, an increase in the former reduces the time of access to the service but decreases the commercial speed negatively affecting the travel time. The aforementioned study proposes a function for measuring the accessibility of the served area, which takes into account the number of stops and the commercial speed. Vasconcelos and Farias (2012) instead studied the influence, on accessibility, of the overall distance to be overcome which represents an impedance to possible trip.

Complying with the formalization of the problem developed in section 2, the accessibility model proposed in the following is based on a measure of the generalized cost of travel, limited only to the travel time, but considering its main parts and associating to them suitable weights that are calibrated on their importance, which is ascribed by the transport users. The importance of the different parts of travel time is obtained from some studies mentioned below, which developed modal choice or perceived quality models.

An integrated transport system has great potential as it makes possible a considerable number of links avoiding overlaps of services. There are five main requirements for an integrated system (Chowdhury and Ceder, 2013) and all must be satisfied in order to consider a transport system as properly planned (Figure 4).

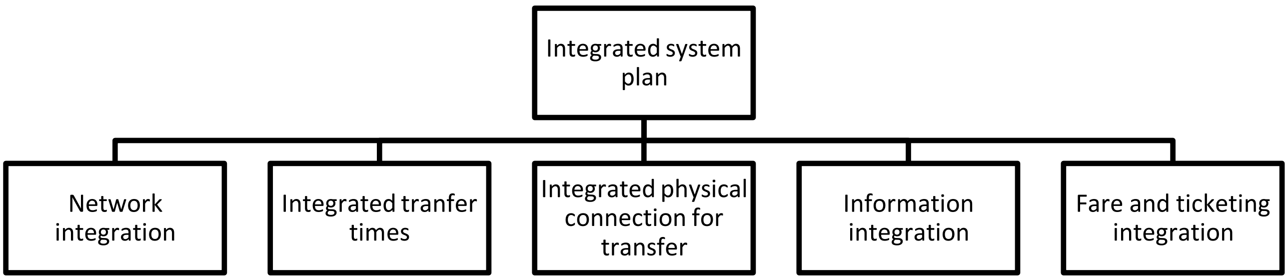

Figure 4 – Main features of an integrated transport system

In our work, due to the specific problem dealt with, the last three attributes are satisfied, as they are the conditions to realize the integration. Network integration consists of designing public transport routes connected to each other in precise points of transfer, taking for granted the ease of accessibility to transport services. The integration of transfer time consists of minimizing the same to achieve by an excellent synchronization of the times of the rides.

A contribution to the estimate of the generalized cost for the users of public transport has been given by some scholars who, although with purposes other than the present research, have dealt with the evaluation of the discomfort endured by users during the waiting or in the transfer.

The transfer from one vehicle to another influences the perceived quality and usefulness of the service to varying degrees depending on the type of user. Chowdhury et al. (2018) found that for occasional users who are forced to transfer, the most important attribute is 'fare and ticketing integration' while for habitual ones, all attributes have a considerable weight, particularly 'integrated time transfers' or transfer time.

It is known that public transport users, both frequent and occasional ones albeit with a slightly different sensitivity, are very sensitive to the time spent outside the vehicle and, in particular, to the time spent waiting at stops. In general, the scientific community has always considered that the waiting time and the time spent walking are more expensive as the one spent on board. There are many studies that try to establish, with precision, what is actually the relationship between waiting time and time on board. In the US, a value ranging from 2.0 to 4.5 was found; in particular, it is 2.58 in Houston, 3.41 in Chicago (Parsons Brinckerhoff Quade and Douglas Inc., 1998, 1999), and 2.13 in Cleveland (Barton-Ashman Associates, 1993). These values do not differ significantly from those found in Europe (Wardman, 2013).

Fan et al. (2016), in a research on the perception of time at stops and at stations, provided, moreover, the most frequently proposed values for the ratio between perceived waiting time and in-vehicle time (IVT), showing a concentration around 2.5.

The change of vehicle imposes an additional cost to the passengers as well as an increase in the time required to make the move. Generally, the models translate this mathematically with a penalty owing to the transfer. Douglas and Jones (2013) interviewed, through stated preference (SP) questionnaires, 900 passengers of all transport modes thus obtaining, for 50% of the observations, a transfer penalty (in IVT minutes) between 5 and 9. Douglas and Jones also reported, for bus users, transfer penalty values determined in Australia in a range from 5 to 8.5 min, although the value of 5 min is more reliable because it was obtained from a greater number of observations.

Iseki and Taylor (2009), highlighting in literature the general lack of a clear conceptual framework about the effect of waiting and transfers on the users of public transport, tried to place the penalties resulting from these operations, inside of the generalized travel cost. To this end, they developed an analysis of the values attributed in literature to the waiting and the transfer time, with the ultimate goal of supporting the evaluation of improvements to be made at the transfer stops / stations.

In addition, the work of Wardman (2001) is aimed at analysing transfer operations. He carried out a specific study, based on SP questionnaires, concerning the transfer penalty and the time spent waiting or walking. The study established that for users of road transit, the transfer penalty ranges from 3.6 min to 4.5 min if the connection is guaranteed. Moreover, it also determined that the waiting and walking time are, respectively, 1.2 and 1.6 times the travel time.

A strong variability of the weight attributed by the user to the time spent outside the vehicle (walking or waiting) compared to the one spent on the vehicle emerges from the literature. This weight is affected by many factors attributable to the characteristics of transport service, user and the context in which this time is spent. The main influencing factors are:

- Characteristics of the transport service
  - Transport mode
  - Interval between rides
  - Uncertainty about arrival time
  - Predictability of waiting (scheduled or unscheduled waiting)
  - Length of the walking path (nonlinear variation with the path length)

- User and travel characteristics
  - Purpose of the trip (greater sensitivity of business-related trips)
  - Need to arrive on time (penalties for any delay)
  - Knowledge and experience of the user about the transport system (walking and waiting are more burdensome for users that are unfamiliar with a transit system)
  - Choice or imposition of waiting or walking to the user (less weight of walking or waiting time if it is chosen by the user as a cheaper travel alternative)
  - Possibility of using the waiting time in pleasant activities
  - User's gender
  - Transport of objects with him/herself

- Environmental aspects
  - Context in which the waiting or walking take place (safety, security, climate, comfort)
  - Urban dimension (time weight decreases as the size of the city increases)
  - Variation over the years (time weight decreases back in time).

It is also noted that, if the studies on the weight attributed by the user at the time outside the vehicle are numerous with reference to the urban context, they are very scarce in the extra-urban context.

In summary it can be stated that a precise estimate of the weight of the time spent outside the vehicle for the user would require field investigations, carried out on very large samples, able to detect the value attributed in a specific combination of the characteristics of the service, of the user and context. However, the values thus derived would have a decidedly limited scope to the specific context to which they refer, with very little possibility of generalization. On the contrary, an estimate based on values taken from the literature, while being less precise, guarantees values applicable to broader areas on the condition of selecting bibliographic sources based on the similarity between the contexts considered therein and the one studied. This approach was followed in this study.

4. Model and calibration

Since the accessibility has been defined in section 2 by (7) as an inverse function of the equivalent travel time expressed by (5), it is possible to directly use the relation (5) as an inverse measure of the accessibility produced by a transit service. To this end we must express T_E, and therefore its different parts, as function of the only characteristics that vary between the type A supply scheme (direct links) and the type B one (integrated links), that are:

• total travel time (T),
• discomfort resulting from any transfer (D), and
• number of rides available in the considered range of time (C).

We decided to neglect the largest number of connections between minor centres, generally made possible by the type B integrated scheme (as defined above) compared to the type A characterized by direct connections without transfers. The choice is supported by the fact that these connections have little importance, precisely because smaller centres play the same territorial role; moreover, they often require two transfers with a total travel time that most often does not exceed an hour.

Therefore, the equivalent travel time must be

$$T_E = T_E\,(T, D, C) \qquad (8)$$

But, since $T_E = T_V + K_A \cdot T_A + T_D + K_T \cdot T_T$ (for 5), we have to express the variables T_A and T_T as a function of D and C and then calibrate the constants.

The equivalent travel time T_E used here measures the impedance connected to the trip and takes into account, in addition to the time spent running on the vehicle, also that necessary for any transfer as well as that lost at destination due to the arrival time of the outward ride and the departure time of the return ride which differ from those necessary to meet the purposes for which the journey is made. The time lost at destination is inversely proportional to the number of rides available in the considered time frame.

It is worth noting that we refer here to generic users, whose time needs are neither known nor similar. Otherwise, as already known, with habitual users for work and study characterized by common and sufficiently defined time requirements, direct links with time schedules calibrated to such needs respond well to the transport demand and they usually also produce high load factors. Hence, the problem of replacing direct links with integrated ones generally does not arise. We did not take into account the waiting time at departure because the intercity public transport service considered here is generally on time and not on frequency. In this case, the user reaches the bus stop, for the outward journey, only a few minutes before the time of the ride, and therefore, this waiting time is independent from the number of supplied rides. These limitations may be eliminated, with proper attention, without imposing any restrictions on the applicability of the proposed method.

Referring to intercity transport, in order to relate the number of rides to idle or waiting time at destination (T_A) in correspondence of the arrival or restart, we assumed a range in which the departure and return should be included (for example from 6:00 to 18:00) and it was divided into two equal parts (hence, two successive intervals from 6:00 to 12:00 and 12:00 to 18:00). As a result, the number of forward rides in the first semi-interval was considered in the hypothesis, generally valid, that the returning rides in the second range are the same and take place in the opposite direction.

The possible presence of a single ride in the semi-interval divides it into two parts and forces the user to wait on average, half of one of the two parts of the semi-interval. In the range from 6:00 to 12:00 (6 h), the presence of just one ride implies a mean waiting time (in hours) of $0.5 \cdot 6/2$, with two rides of $0.5 \cdot 6/3$, with three rides of 0.5 · 6/4, and so on. Thus, in general, denoting N_C as the number of forward rides in the semi-interval I_N, the theoretical waiting time T_A that should be added to the travel time T_V is

$$T_A = 0.5 \cdot \frac{I_N}{(N_C+1)} \tag{9}$$

with I_N = 6 h (or 360 min, one-way interval, equal to half of the total daily range, assumed to be approximately 12 h considering the type of mobility) and N_C = number of one-way rides in the I_N range.

The equivalent travel time T_E defined by (6) can be expressed as:

$$T_E = T_V + K_A \cdot 0.5 \cdot \frac{I_N}{(N_C+1)} + N_T \cdot (T_D + K_T \cdot T_T) \tag{10}$$

where T_V = real travel time from the origin to destination, (that is the time spent inside a vehicle) net of the transfer time;

T_D = time penalty representative of the discomfort associated with the transfer operation;

N_T = number of transfers necessary for the journey;

T_T = overall average time to make a transfer;

K_A and K_T = calibration coefficients representative of the weight (compared to the travel time on the vehicle T_V = 1.0) of the T_A and T_T times, i.e. the user's willingness to exchange a certain amount of these times with a T_V unit.

It should be noted that by maintaining the number of routes at the denominator in (10), T_A leads to a decreasing function with the number of rides having a nonlinear trend and upward concavity. This is consistent with what can be observed in reality in which the contribution, in terms of accessibility, provided by each additional ride with the same travel time, decreases as the number of available rides increases.

In Eq. (10), the term related to transfer is composed of two addenda: the first concerns the penalty representing the discomfort resulting from the transfer while the second takes into account the time, appropriately weighted, used in this operation. The trend of the representative function is linear with the intercept different from zero and equal to T_D.

The application of (10) requires the calibration of the coefficients K_A and K_T and the discomfort time T_D and also the set of an I_N interval consistent with the analysed context. For this last parameter, it is necessary to consider the characteristics of the trips that should be served, which influence the maximum time available to depart, carry out activities at a destination, and return. The first difference should be made according to the periodicity of the considered journeys: for a daily trip, the amplitude of the interval I_N is approximately 12 h, and it is extended to 18 h in occasional regional travels. The consideration that supports this choice is based on the assumption that we considered regional and intercity trips requesting a return in the day. With this assumption, an occasional trip allows a longer total time spent off the home than a daily travel.

The calibration of the K_A and K_T coefficients and of the transfer penalty T_D should be performed by surveys through submitting questionnaires, with revealed and stated preferences, to users. However, in the first instance, values drawn from literature, calibrated on equivalent fields and services, may be taken as bases. Indeed, the searched K_A and K_T values are the importance attributed by users to T_A and T_T accessory time with respect to the time spent on board T_V. Thus, we used international studies drawing these values mainly in the building of quality and utility models for public transit.

As already known, the waiting time at the bus stop and that spent during a possible transfer have a different value for the user than the time on the vehicle. Therefore, the K_A and K_T coefficients assume values that are certainly more than one unit. The K_A coefficient is the equivalent or the trade-off value ascribed by users between a unit of waiting time T_A and a unit of travel time spent on board T_V. The K_T coefficient represents the equivalent or the trade-off value on a unit of time spent in transfer T_T and a unit of time on board T_V. Therefore, K_A and K_T are multipliers that are proportional to the weight associated by the user, respectively to the waiting and transfer time, compared to the time spent on board.

Table 1 refers the values determined in some studies concerning the analysis of the assessment of the time perception by users of public transport:

Reference	Wait time/Travel time
Parsons Brinckerhoff Quade and Douglas Inc. (1998)	2.58
Barton-Ashman Associates (1993)	2.13
Parsons Brinckerhoff Quade and Douglas Inc. (1999)	3.41
Wardman (2001a, 2001b)	1.47
Average value	**2.40**

Table 1 - Values of waiting time multiplicative coefficient, considering 1.0 as the time on board, taken from Iseki and Taylor (2009)

The values set in the main studies analysed by Fan et al. (2016), which can be used for our purpose, are summarized in table 2:

Reference	Ratio
Wardman (1998a)	1.2 ÷ 1.7
Wallis et al. (2013)	1.3
Wardman (2013)	1.5 ÷ 1.9
Abrantes and Wardman (2011)	1.4 ÷ 2.3
Horowitz (1981)	1.9 ÷ 2.3
Wardman (2004)	2.5
Average value	**1.82**

Table 2 - Ratio between waiting time and IVT summarized by Fan et al. (2016)

Finally, considering all the results of the analysed studies, we decided to assume a value of the waiting time coefficient K_A equal to 2.11 (slightly above 2.0, which is generally accepted in the modelling of the modal choice).

To evaluate T_T and K_T (in table 3) we refer to the work of Wardman et al. (2001).

	Minutes	Ratio
Penalty at transfer between buses (Transfer discomfort as time)	4.5	-
Penalty at transfer between buses (Transfer discomfort as time) at guaranteed connection	3.6	-
Time at transfer between buses; walk time to travel time ratio	-	1.6
Time at transfer between buses; wait time to travel time ratio	-	1.2

Table 3 – Transfer discomfort as time (transfer penalty) in minutes and weight of waiting and walking time at vehicle interchange, compared to travel time (Wardman et al., 2001)

Therefore, the values of 3.6 min and 1.4 will be used in the model (mean between walking and waiting time values) for T_D and K_T , respectively.

The transfer operation takes for granted a minimum time necessary to be able to get off one bus and get on the other. We assumed this time as 5 min as we took for granted a good synchronization of coinciding rides and in any case a guaranteed connection.

In summary, the calibration values for the model constants (11) are

$K_A = 2.11 \qquad K_T = 1.4 \qquad T_D = 3.6$ min

Therefore, the calibrated model is

$$T_E = T_V + 2.11 \cdot 0.5 \cdot \frac{I_N}{(N_C+1)} + N_T \cdot (3.6 + 1.4 \cdot T_T)] \quad (11)$$

$$T_E = T_V + 1.055 \cdot \frac{I_N}{(N_C+1)} + N_T \cdot (3.6 + 1.4 \cdot T_T)] \quad (12)$$

with the meaning as previously described and with all times (T_E, T_V, T_T) in minutes.

5. Application to a case study

The present accessibility model has been applied to a portion of the intercity local public transport service network of the Matera Province, in Southern Italy (Figure 5). The current transport supply consists of all direct links between the served municipalities, which are carried out without transfers, and it has a configuration similar to the previously discussed scheme A. The service has currently reached a very low average load factor and therefore, it requires a rationalization, while still ensuring the existing connections.

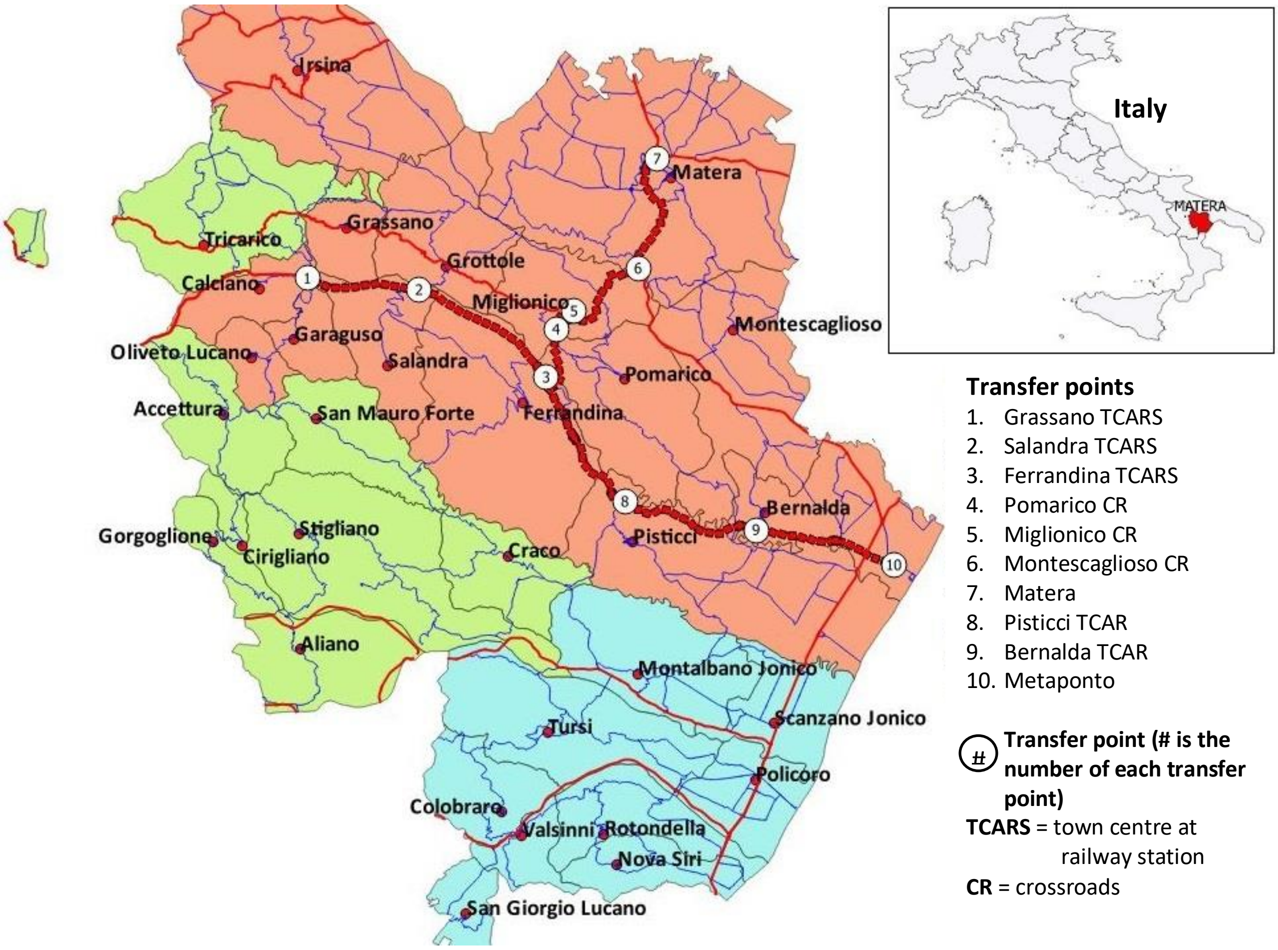

Figure 5 - Area of study: province of Matera (Italy) with transfer points of the projected network[3]

In this context, we decided to redesign a part of the current network of transport services by replacing most of the direct links with integrated ones. This is realized by using connection lines at certain transfer points from departure to arrival. Therefore, the new service network is ascribable to the previously discussed scheme B.

Then, through the accessibility model, the current supply pattern and that of the project have been compared. They, while carrying out roughly the same overall mileage, differ by type because the first has all direct links and less number of rides, whereas the second has mostly integrated links and a greater number of rides. In particular, we calculated the average equivalent time T_E for the current scheme, and then, repeatedly for the project, increasing the number of supplied rides each time from the number of the rides

[3] *The transfer points numbered in Figure 4 are*

- ***Line Matera – scalo Grassano (along S.S. 7 and S.S. 407)**: Matera – Montescaglioso CR – Miglionico CR – Pomarico CR – Ferrandina TCARS – Salandra TCARS – Grassano TCARS;*
- ***Line Matera – Metaponto (along S.S. 7 and S.S. 407)**: Matera – Montescaglioso CR – Miglionico CR – Pomarico CR – Ferrandina TCARS – Pisticci TCARS – Bernalda TCARS – Metaponto*

on present scheme, and consequently detect a decrease in T_E, until it reached a value close to that of the current scheme. Thus, we obtained an integrated link supply network, which, owing to an additional number of routes compared to the current network, compensates for the discomfort resulting from the transfers and ensures the same accessibility evaluated through the average equivalent time T_E. The result showed that the number of additional required rides restores the accessibility produced by the integrated scheme (penalized by transfers) to a value equal or very close to that of the direct link pattern.

The present intercity local public transport supply has divided the territory of the province of Matera into three traffic sub-basins (Matera, Policoro, and Stigliano), each one is an area within which most of commuter trips to work and study have both origin and destination. It should be noted that the examined supply network is only that of the traffic sub-basin of Matera and that the redesign did not cover the dedicated services, which, being programmed for the specific needs of time and route common to special categories of users (students and workers), have a satisfactory load factor and do not require changes. Generic services, which are not dedicated, are developed within 87 lines. In the supply reconfiguration, the municipality of Irsina was skipped because, despite being part of the Matera sub-basin area, it cannot be inserted effectively within a type B scheme and therefore, will be connected by the present services. Table 4 reports some summary data of transit service in question.

	Dedicated local public transport services (LPT)	**Generic (non-dedicated) LPT services (to be redesigned)**	**Total LPT services**
ML Bus km/year	1,506,151	**2,089,291**	3,595,442
Rides/day	141	**166**	307

NB: the number of lines including generic (non-dedicated) rides object of the design is globally 87; many of them also include dedicated rides.

Table 4 - Intercity local public transport service operating in the Matera sub-basin

The redesigned supply is structured with two valley lines having adequate capacity suitable for the low demand. These run along S.S. 407 (part of the European Route E 847) and S.S. 7, from Ferrandina rail station (TCARS) to Matera and vice versa, and along S.S. 7 and S.S. 407 from Matera to Metaponto and vice versa, respectively. On these routes, transfer points were located (highlighted in Figure 5). The transfer between the valley lines and that of the connections to the hill centres will take place at these points. It is worth noting that to expand the analysis to non-dedicated services of the entire traffic basin of Matera rather than limiting it to a part (as already done in the present study), the identified valley lines should be extended, first to the regional capital Potenza and second to Nova Siri TCARS (MT), by also considering S.S. 106 along the European Route E 90.

In line with the schematization adopted in the construction of the model, we divided the interval in which the transport services are supplied (6:00–18:00) in two semi-intervals (6:00–12:00 and 12:00–18:00), during which all outward and return rides, respectively, are carried out. Therefore, the redesign of services concerned only the first half interval, because in the second, the same rides in the opposite direction take place.

By processing the timetables, the mileages and travel times of each line have been calculated and then, according to the method mentioned previously, the proposed model has been applied.

Obviously, the number of transfers is always zero in the existing services, because the current supply is scheme A (direct links). Concerning the project supply ascribable to scheme B (integrated links), the time required for one transfer has been set as 5 min. Actually, it is a precaution because the transfer of a few passengers, mostly devoid of baggage, from one bus to another arriving almost simultaneously requires less time.

The number of valley line rides and of those connecting the hilly centres with the transfer points have been calculated based on the rides added in order to overcome the disutility owing to the transfer requested by most of the links. We emphasize that to ensure a complete connection, the link of each centre to a close transfer point must provide a forward and return ride (to and from the centre); consequently, the number of rides is doubled in the mileage evaluation. The valley lines are set in such a way that a ride starts from each of the opposite terminal, and the number of rides in these lines has been doubled for the proper mileage counting, albeit for a different reason.

It should be noted that the equivalent time T_E resulting from the application of the model to both the project scheme and the current one is expected to achieve the same value as the target. Indeed, the application proposed is finalized to quantify the number of rides that should be added in the integrated link pattern to compensate for the time that has been wasted and the discomfort imposed on users by the transfer. Therefore, the application method, as already mentioned, implies consecutive elaborations using as input the number of rides starting from that of the current supply scheme as input in order to reduce the equivalent time T_E in the project supply pattern until it reaches the value of the current scheme. Unfortunately, the necessary approximation (in this case, for excess) of the number of rides to the unit on each line, does not allow the T_E of the projected scheme to achieve exactly the same value of the current pattern (specifically, 16 min less, equivalent to −9.3%).

The results reported in Table 5 show that, for the examined situation, the equivalent time T_E of the projected scheme (integrated links) almost equal the value reached in the current scheme (direct links), thus the number of rides in the 6:00–12:00 time slot needs to increase by 39.0% , from the current 82 (the only non-dedicated rides considered in the redesign) to the provided 114. Furthermore, the increase in the number of rides from the current situation allows a reduction of 28 min (−23%) on the weighted waiting time at the destination ($K_A \cdot T_A$).

	Current [1]	Design [2]	Δ [2-1]	Δ% [2-1]
N_C : Number of rides in the interval 6:00–12:00	82	114	32	39%
N_T : Number of transfers (1 connection/route)	0	32	32	---
($K_A \cdot T_A$) [min]: Average of weighted waiting time	119	91	−28	−23%
($TD + K_T \cdot T_T$) [min.]: Average of weighted transfer time	0	8	8	---
T_E [min]: Average equivalent time	185	169	−16	−9%

Legend:
[1] Current transport supply (scheme A)
[2] Transport supply redesigned according to scheme B, with number of rides greater than the current and suitable to approximately match the current average equivalent time T_E

Table 5 – Public transit alternatives compared by the built model

The higher number of rides in the integrated supply scheme does not necessarily imply a greater overall mileage than the existing one with direct links, as the first type of scheme, being more efficient, is generally able to guarantee a greater number of rides with the same mileages. Indeed, in the examined case, despite the increase in the number of rides from 82 to 114, a slight mileage saving of only over 4% resulted from the project scheme.

As mentioned before, the scheme B with integrated links has also the advantage of making possible, for the same total mileage of supply services, a number of connections (although with transfers) greater than that of scheme A with direct links. Even if this feature is not very important because it mainly concerns trips between the minor centres characterized by minimum demand, we wanted to estimate it even in a real analysed situation. To this aim, the two schemes were compared through a network connectivity index, as follows:

$$C = \frac{A}{\left[N \cdot \left(\frac{N-1}{2}\right)\right]} \tag{13}$$

where N is the number of centroid nodes (origin and destination of the trip) and A the number of non-oriented links, being the transport service realized by bidirectional links. This parameter is equal to 0 if there is no connection between the centroids, or 1 if the graph connects each node to each other, because in the last case $A = N \cdot \left(\frac{N-1}{2}\right)$. We selected this simple index because it is particularly effective in measuring the number of origin / destination poles that can be connected by a transport network. However, the literature provides many indexes to measure the connectivity of a graph (see for example Mishraa et al., 2012 or Kindlmann & Burel, 2008).

Even if in this application the project supply allows us to connect each centre with each other accepting the furthest three transfers, we considered possible fair links with a number of transfers not greater than 2. This is because a greater number of them are hardly acceptable to the user for the type of travels considered. Therefore, as there are 13 municipalities for which the public transport supply has been redesigned and thus 13 centroid nodes, we have these results:

- Scheme A (direct routes): C = 0.295
- Scheme B (integrated routes): C = 0.846

Thus, an increase in connectivity between the served centres of 186% with a slightly lower total mileage of service (−4%) is evident.

6. Conclusions

The present work proposes a model for evaluating, by the equivalent travel time, the accessibility produced by a public transit service.

The developed assessment tool fills an important gap in the scientific literature of the sector. Indeed, the latter rarely dealt with accessibility given by public transport to the served area and in any case lacks a model suitable to evaluate, in this respect, supply schemes that differ mainly in the level of integration of the lines between them and the number of offered rides. This tool is particularly useful in the design of the public transport service to compare different supply schemes in terms of accessibility.

The model built was finally applied to a real case to test its functioning and highlight the advantages and limitations deriving from the supply schemes with a high level of line integration.

The number of transfers from one vehicle to another while travelling and the number of rides supplied over a defined period play an important role in the accessibility produced by a public transit service. In fact, transfers cause a reduction in comfort and an increase in travel time, and consequently, an increase in the generalized cost for users. The increase in the number of supplied rides brings the time of service closer to the needs of the users and, therefore, reduces the time lost at a destination and the time interval between departure from the origin and return to the same point (total travel time in round trip).

It is also evident that the number of transfers needed and the number of rides supplied are related service parameters. In fact, the integrated public transport supply scheme, i.e. the one that makes possible each link by forcing users to move from one line to another allows, with respect to the direct link scheme, to realize the same connections with a total mileage saving that can be redeployed to increase the number of supplied rides. Thus, it can be concluded that there is a need to compare, in the design stage, the effectiveness in terms of accessibility given by different transit supply schemes that offer the same mileage but differ on the number of required transfers and of supplied rides. Therefore, the accessibility model presented here has been formulated to take into account the inconvenience caused by possible transfers from one vehicle to another and the advantage produced by the greater number of available rides.

The equivalent time T_E provided by the model is an inverse measurement of the accessibility between different origins and destinations of transport service on the territory. It is possible to calculate T_E for each of the pairs of linked centres and to add all the obtained values or to average them (possibly weighted on the demand) to obtain an inverse measure of accessibility produced by the transport supply in the served area. This allows us to compare the accessibility offered by more network schemes having the same or different mileages, differing on the level of integration among the lines and thus, in the number of required transfers, as well as by the number of rides supplied on the realized connections. This model is a useful support tool to design and/or optimize local public transport services. Indeed, when we pass from a low integration scheme to an higher integration one, it also allows us to evaluate the minimum number of rides that should be added to the original supply scheme, to compensate, in terms of the equivalent time T_E, the time wasted and discomfort for users coming from a greater number of transfers which are a consequence of the replacement of a number of direct links with integrated ones. Realizing this compensation between the number of additional transfers and additional rides, the user will perceive the service supplied with integrated connections (concerning the accessibility measured through equivalent time T_E) as equivalent to that of direct links. A possible increase in the number of rides higher than strictly necessary to compensate for the larger number of transfers will result in a greater accessibility perception by users and, therefore, a better quality and utility of the service. On the other hand, a number of additional rides lower than the minimum necessary for the compensation will make the new transport service more undesirable than the previous.

The proposed model is generally valid, but the calibration carried out under the precise assumptions limits the range of applicability. Its employment in different areas requires a new calibration of the constants. Therefore, the developed model is applicable for evaluating the accessibility (expressed through the equivalent travel time T_E herein defined) produced by public transport services by road or rail or in combination, which realize intercity connections in regional or sub-regional areas with travel times of the order of 20÷120 min. It is worth noting that, in this travel time considered, the maximum number of accepted transfers is 2 but the majority of links should have no more than 1 to ensure a more attractive service.

The time required for transfers should be minimized and this operation should be easier by equipping the transfer points in a more suitable manner. Finally, it is evident that the supply patterns with a predominance of integrated links (and therefore tending to feeder-trunk scheme) are easily applicable to widespread demand areas, if we have free capacity available on the main lines, which receive users from more connecting lines. With a more concentrated demand, such capacity availability should be properly verified. On the other hand, feeder-trunk supply schemes are less suitable to serve a concentrated demand in terms of time and origin/destination, such as that generated by a commuting mobility for work or study towards well-defined destinations.

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