Public transport accessibility through co-modality: Are interconnectivity indicators good enough?

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1. Introduction

The role of transport networks and services is to allow people and goods to move between different points in space, i.e. to provide accessibility. When new infrastructures or modifications of transport supply are planned their performance is assessed in terms of the impact on accessibility. Road transport (i.e. better roads, new motorways) has played a big role in improving accessibility in the last half century. The undesired consequences of private transport such as congestion and pollution, but also fossil fuels consumption and greenhouse gases emissions, have however prompted authorities to promote the use of public transport.

Unfortunately, public transport modes often supply a lower accessibility level than car. This is one major reason why inducing mode shift from private cars to public services is difficult. One possible strategy to improve accessibility by public transport is to extend the possibility to use public modes in various combinations (or even in combination with car). The basic idea is that even if one public transport network (e.g. rail) alone cannot provide high accessibility, an integrated use of different networks (e.g. rail plus bus) can.

When a combination of transport modes is involved, interconnection represents a key part of the trip and the quality of interconnectivity is then a major requirement. A smooth transfer from one network to another is a matter of physical connections but also of functional and organisational aspects like e.g. integrated services and ticketing. A consequence is that measuring accessibility through modal combinations is challenging. Usually accessibility indicators do not distinguish between uni-modal and multi-modal trips, but just consider a measure of overall “distance” between zone pairs or nodes. This measure generally overlooks the functioning of interconnections, especially with reference to qualitative aspects. Ex-post, when an integrated transport service is implemented and the quality of its interconnections is implicitly embedded in total travel times between zone pairs and in the amount of the demand between zone pairs, common accessibility or interconnectivity indicators can provide useful indications. For ex-ante analysis, using indicators to forecast the effectiveness of new transport services can be more problematic.

This paper tries to address this issue building on results of the European project INTERCONNECT, aimed at investigating interconnection between short distance and long distance transport networks. After a definition of the research questions and of the methodology, the paper presents a theoretical background on accessibility and interconnectivity indicators. The concept of co-modality is introduced with special emphasis on its qualitative aspects. Then an application of interconnectivity indicators computed ex-ante on modelling output is presented and results are discussed in the light of co-modality. The implications of the analysis for managerial procedure and for future research end the paper.

2. Research questions and method

Accessibility indicators are used to analyse the relative position of regions in location terms but also to analyse the quality of transport networks. The latter purpose does not include only ex-post assessment of existing transport supply, but also ex-ante studies to identify
the expected outcome of new infrastructures or services and maybe to discriminate between alternative solutions. For ex-ante analyses, accessibility indicators are basically summaries of modelling output in terms of e.g. travel times between zone pairs of nodes.

In most cases, accessibility indicators consider some synthetic measures of the “distance” between zones, therefore direct connections between zones give rise to better accessibility measures. Where a transfer between networks is needed the relative accessibility is lower: in order to improve it the most intuitive strategy is to provide a direct connection. This strategy makes implicit reference to private car as the best solution (at least at the urban scale). In these terms public transport services are improved only if they reduce the need of interchanges or reduce the time required for the interchanges.

Assuming the point of view of co-modality, where the use of different networks is not a suboptimal solution but the best strategy, do measures of accessibility based on distance and minimised transfer provide a representative picture of the transport network? Can traditional simulation models provide enough elements to estimate ex-ante the improvements of interconnectivity and their impact on demand? These are the questions addressed in this paper.

The objective of the paper is not to provide conclusive responses to these questions, but rather to present the need for further reflections on the matter. We address the research starting from the theoretical definition of accessibility indicators and then to the translation of this definition for the analysis of interconnectivity. Then we discuss in some detail the concept of co-modality and the various elements of interconnectivity that have to be considered to design networks to promote co-modality. In the light of this theoretical analysis we introduce an example of calculation of interconnectivity indicators based on a modelling application designed to analyse interconnection and discuss the significance of the results.

2.1. The concept of co-modality

There are no official definitions of the terms used for describing the mobility of passengers or the transport of goods using more than one transport mode. In literature one can often come across the words “multi-modality” and “inter-modality” to define a characteristic of a transport system that allows at least two different modes to be used in an integrated manner in a door-to-door transport chain. The major distinction between the two terms is that multi-modality is generally applied to passenger mobility while inter-modality usually refers to freight transport.

Multi-modal or inter-modal transport usually implies that one transport mode is used as main mode for making the trip, while the other(s) is (are) used as access or egress mode(s). Consequently, the transport modes, and thus also the related transport networks, operate together in a hierarchical structure. It is easy to distinguish such hierarchical structures in existing networks, for instance, regional roads and freeways, or short-distance and long-distance public transport services.

Interconnectivity is a characteristic of a transport network that allows multi-modal or inter-modal transport. Interconnections are the connections between the infrastructures of the various transport networks. However, interconnectivity goes beyond multi-modality and inter-modality. The SORT-IT Project defined interconnections as “connections between international, national, regional and local networks, both within and between transport modes” (Institute for Transport Studies (ITS) et al., 1999). It might be noted that according to this definition a trip composed a short urban segment made by bus followed by an inter-urban long segment still made by (a different) bus is considered an interconnected trip. Also, an urban trip started on an underground line and ended on a different underground line is also an interconnected trip.

These examples highlight that the core concept of interconnection is not only the use of different transport modes but especially the need to make a transfer during the trip. The difference between using different transport modes for one trip or travelling on interconnected networks can be subtle. If this difference exists its essence should be found in the functioning of interconnections between different networks considered as a sort of single super-mode of transport. Traditionally it is assumed that a multi-modal or inter-modal trip is made because a uni-modal connection is not available between origin and destination. However multi-modality and inter-modality can allow for combining the strengths of the different transport modes (and to avoid their weaknesses) in order to optimise the travel time and costs. For instance, even if one might use only road or direct rail services to reach one destination, it might well be that a multi-modal trip road + air + rail can significantly reduce travel time without a significant increase of travel cost. On this respect a new definition has taken place in recent years: co-modality.

Co-modality refers to the use of different modes on their own and in combination in order to obtain an optimal mobility outcome in terms of travel effort as well as transport sustainability and supply efficiency. Co-modality recalls the principle that “public transport operates most successfully when it is planned as a unified network to support seamless multi-destination travel rather than as individual lines catering to single trips” (Dodson, Mees, Stone, & Burke, 2011). This principle is based on the concept of public transport network planning, i.e. “serving the maximum number of possible journeys with the minimum of operational resources” (Mees, Stone, Imran, & Nielsen, 2010). In other words, the way the various means of transport are utilised should always result in the best possible combination, in ecological, economic and social terms. Co-modality therefore widens the analysis of interconnections from a pure “shortest-path” approach to a more comprehensive definition where the user perspective is enriched with considerations about the quality of interconnections and is complemented with elements concerning supply.

The supply-side is related to the efficiency of the service. According to a co-modality perspective, the optimal connection between two zones is not the best conceivable service that any mode can provide (e.g. a direct underground connection, a very frequent bus service, etc.) but the best service that could be provided with an optimal use of resources in the whole transport system. In other words, improving accessibility by providing direct, fast and frequent services by means of a single mode can be less preferable than improving accessibility by providing working interconnections to build a co-modal path. At least if the latter solution costs a fraction of the former one and its burden on travellers (both as user and taxpayers) is significantly lower.

Following the approach proposed by Keller (2001) physical and functional dimensions of interconnectivity can be distinguished. In the narrow physical sense, interconnections are structural transitions between the infrastructures of the various transport networks. They consist of structural and technical installations providing access to the networks (platform, transhipment installations, etc.). From this point of view, improving interconnectivity means provide better transfer facilities, which is the kind of intervention closer to the traditional concept of good interconnection.

Functional dimensions of interconnectivity are those more linked to the principle of co-modality. Acting on functional dimensions improvements should be reflected in better accessibility, but “better” does not necessarily mean “faster”. Even when zone pairs become closer in terms of travel effort, this can be the effect of qualitative aspects. For public transport network planning a significant literature exists (see e.g. the aforementioned contribution by Dodson et al., 2011). The interconnection between long distance and short distance networks presents specific questions to be addressed. For instance, unlike urban cases, different operators are almost always involved. Also, while urban networks are often used by regular users (e.g.
commuters) the interconnections between long distance and short distance networks serve a large share of occasional travellers that have limited or no experience of transfer points.

A review of relevant aspects can be enumerated building on the intermediate results of the INTERCONNECT project (http://www.interconnect-project.eu/). INTERCONNECT started in 2009 within the 7th Research Framework Programme of the European Commission and aims to investigate interconnection between short distance and long distance transport networks. Within the project examples of good practice from Europe and elsewhere have been analysed to show how passenger interconnectivity could benefit from a co-modality approach (Ulied et al., 2010b). INTERCONNECT has identified the functional dimensions of interconnectivity include aspects like the followings.

2.1.1. Co-ordination and co-operation

Effective interconnection requires the provision of both integrated networks and services. The achievement of this integration usually requires a strong co-operation between a range of authorities and providers in the public and private sectors. The creation of effective interconnection may sometimes conflict with the priorities of authorities and providers who have hitherto be concerned solely with serving a local constituency.

In general, the various transport networks (infrastructure and services) are owned and/or operated by different independent public or private organisations, which in many cases compete against each other for a share of the transport market (e.g. road, rail, air). Therefore, each transport company endeavours to optimise the building and operation of its own network and transport services. Thus mono-modal operational and economic interests take precedence over customers’ co-modal interests. Passengers appear only of interest as long as they stay on a given network. Particularly in passenger transport none of the various actors is responsible for the whole intermodal route from house to house or for intermodal network connection. No transport company is generally responsible for building and operating interchange points either. Transfer processes in passenger transport are generally accompanied by loss of time, costs, safety and reliability problems and loss of comfort. There is therefore room for significant improvements of co-modality through co-ordination of different actors.

2.1.2. Information

In the case of interconnected multimodal transport chains it is necessary that users can obtain information quickly and easily. Often, many sources of information deal only with a subset of the modes and services required to complete the journey and generally information on offered intermodal services is still definitely rare. For example, many travel agents will have no knowledge of local bus services linking an airport to the local city and are unlikely to be able to sell tickets for such services in conjunction with an air ticket. Similarly, most internet-based journey planners deal only with a single mode. This may be because they cannot earn any commission from sale of the “local” tickets, or because of institutional and technical barriers involved in accessing such information.

Barriers to consistent information and marketing can be found even within a single mode. A good example is the UK rail system where services are operated by more than 20 different companies who are allowed to, and to some extent are encouraged to, develop their own brand and marketing strategy. Operators will, quite naturally, give more priority to publicising their own services than interconnected services for which they will receive only a share of the revenue. Also, they may not wish to compromise their own brand image by allowing it to be diluted by association with a joint venture with another provider. As a result passengers are exposed to inconsistent or incomplete information and marketing messages as each operator strives to differentiate its service and promote a distinctive brand. Since inter-modal traffic typically represents only a small proportion of each individual operator’s demand their marketing will be tailored to their core market, their particular priorities and operating practices.

Making access to full information for easy and fast planning a co-modal trip is one of the key aspects to improve interconnectivity between networks.

2.1.3. Pricing and ticketing

Especially for long distance trips, travel tickets are mostly valid only for parts of the overall route (e.g. long distance only). Each passenger buys individual transport services on specific networks. The requirement to purchase separate tickets for each journey can be particularly onerous for travellers who do not know the location of the places where tickets can be bought and may be unsure of the type(s) of ticket that can or should be purchased.

Integrated pricing and ticketing schemes (e.g. allowing travellers to make a journey involving both long distance rail and local transport modes with a single ticket) would facilitate passengers’ multi-modality especially for long distance trips and encourage travellers to use a combination of the long distance and local public transport services. Of course in this case the basis assumption is that the integrated ticket price should be not higher than the combined cost of separate tickets for any trip of the different modes within the integrated network.

2.1.4. Timetabling

The successful operation of connected transport services cannot be separated from harmonised schedules of all modes available at a certain interchange point, providing both short transfer and waiting times. Improvements in this sense could be directly achieved by optimising services’ timetabling. As an example, when a non frequent long distance service is fed by a regional service, the schedule of such a service to and from the interchange point should be designed such as safety margins exist in order to reduce the likelihood that any delays will have cumulative effects. Schedules with built-in safety margins are termed “robust”.

Creating robust schedules for co-modal trips is challenging but it can greatly improve interconnectivity even without reducing travel time. For instance, if the schedule of a regional train is changed to reach the interchange station 15 min in advance with respect to the departure time of high-speed services (instead of 5 min), travel time increase, but in fact the connection is made more robust and the interconnection is improved.

2.2. Co-modality and indicators

2.2.1. Accessibility and interconnectivity indicators

Accessibility determines the location position of an area relative to all areas (including itself). In general terms, accessibility is the outcome of two functions, one representing the attractiveness of the areas that can be reached and one representing the “effort” needed to reach them (European Spatial Planning Observation Network (ESPON), 2010):

$$A_i = \sum_j g(W_j) f(c_{ij})$$  \hspace{1cm} (1)

Where:

- \(A\) accessibility of area \(i\),
- \(W_j\) attractiveness to be reached in area \(j\),
- \(c_{ij}\) the “effort” for reaching area \(j\) from area \(i\).

The functions \(g(W_j)\) and \(f(c_{ij})\) are called “activity function” and “impedance function”, respectively. According to the form of these
two functions, different types of accessibility indicators are calculated. Widely used indicators include e.g.:

Travel cost where \( g(W_j) \) has value “1” or “0” depending on the destination zone (e.g. it is “1” for zones where attractiveness exceeds a given threshold) and the impedance function is travel time or travel cost itself.

Daily accessibility where \( f(C_i) \) is expressed in terms of travel time and only destinations within 24 h (or another threshold) are considered.

Potential accessibility Where the impedance function is generally nonlinear, (e.g. exponential) and also the activity function may take account of agglomeration effects or economies of scale and therefore can be nonlinear (e.g. a power function).

Indicators can be estimated for alternative modes to show, for instance, that road accessibility and rail accessibility of regions may vary depending on existing infrastructures. When trips require to use more than one mode, also intermodal accessibility can be estimated. In such cases the impedance function should implicitly or explicitly include also the effort to transfer between modes. Examples of accessibility indicators computed according to [1] can be found in Lutter, Pütz, and Spangenberg (1993) for passengers and in Chatelus and Ulled (1995) for freight.

From a different perspective and with specific reference to multimodal trips, the Interconnectivity Ratio indicator has been proposed by Krygsman, Dijst, and Arentze (2004) as the proportion of access and egress time to the network to total trip travel time:

\[
IR_i = \frac{\sum (AT_{ij} + ET_{ij})}{\sum \tau_{ij} \text{TotT}_{ij}} \tag{2}
\]

Where:

\( IR_i \) Interconnectivity Ratio of area \( i \),
\( AT_{ij} \) access time to the network for reaching area \( j \) from area \( i \),
\( ET_{ij} \) egress time from the network for reaching area \( j \) from area \( i \),
\( \text{TotT}_{ij} \) total travel time for reaching area \( j \) from area \( i \).

This indicator stems from the consideration that access and egress stages are the weakest part of a multimodal chain and their contribution to the total travel disutility is often substantial.

A third group of accessibility indicators that are applied to multimodal transport are interconnectivity indicators, derived from the graph theory and network analysis. Such indicators provide alternative measures of nodes “centrality” within a graph, i.e. its relative importance. Different measures of centrality have been applied to the analysis of public transport networks (Scheurer & Curtis, 2008; Scheurer, Curtis, & Porta, 2007).

One of such measures is the Degree Centrality of a node, which denotes the number of connections and local opportunities associated to that node. A possible application of this concept to a transport network is computing the degree centrality as follows:

\[
DC_i = \frac{\sum MT_{ij}}{N} \tag{3}
\]

where:

\( DC_i \) Degree Centrality of node \( i \),
\( MT_{ij} \) 1 if area \( j \) can be reached by underground from area \( i \) without interchanges, 0 otherwise (\( ij \in N \) and \( i \neq j \))
\( N \) all nodes in the network.

With this formulation the indicator depicts the average minimum number of transfers required to travel between any pair of nodes in the network. Reducing the transfer-dependency of a network, offering more direct links between different nodes and routes, gives rise to a lower degree centrality index.

A second measure taken from graph theory is Closeness Centrality defined by the inverse of the impedance between the node in question and all other nodes in the network:

\[
CC_i = \frac{(N-1)}{\sum \text{Dist}_{ij}} \tag{4}
\]

where:

\( CC_i \) Closeness Centrality of node \( i \),
\( \text{Dist}_{ij} \) impedance between nodes \( i \) and \( j \) \((ij \in N \) and \( i \neq j)\)
\( N \) all nodes in the network.

Closeness Centrality is similar to a traditional accessibility indicator. It increases when the impedance between zones is reduced, but does not provide any specific information on how the existing interconnections work. This aspect can be considered in the definition of the impedance, which can be measured in several alternative ways: distance, travel time, travel cost, etc. (Scheurer et al. (2007)) used travel time divided by frequency. Other measures of impedance where e.g. a penalty for transfer time is applied could be used to emphasise the role of interconnectivity.

2.2.2. Measuring co-modality with indicators

Co-modality assumes that mode transfer is an inherent feature of trips taking place onto networks planned and managed to be used for multi-modal trips. In making interconnectivity between networks work, qualitative (functional) aspects can play a major role. In this context, indicators like those examined above are much less informative to measure the level of interconnectivity.

In general, despite multi-modal accessibility being explicitly considered, the goal of accessibility indicators remains to provide a representative measure of the overall impedance in physical terms rather than investigating how the interconnectivity between modes work. In other words, the focus is on overall travel “distance” than on interconnections conditions. If one of the interconnected modes becomes faster (e.g. a high speed train replaces a conventional rail connection available from the airport) this is reflected in some improvement of the accessibility indicator. However, this effect has nothing to do with an enhancement of the interconnection. If the “interface” between the two modes remain the same (e.g. no facilities to reach the rail station from the terminal, no possibility to purchase a single ticket for the whole trip or, at least, to buy the rail ticket during the flight, etc.) the level of co-modality is not changed. The higher accessibility is due to higher speed of one of the modes, not to some change planned to make the combination of more modes work better.

Also interconnectivity indicators are unable to capture the manifold dimensions of co-modality. The Interconnectivity Ratio as proposed for public transport networks is mostly a “network” index and it is a reflection of the “relative time catchment. […] It represents that part of trip time that the user is physically occupied or willing to “sacrifice”, to reach the public transport system and their final destination. (Krygsman et al., 2004). In this form the Interconnectivity Ratio does not provide a reliable measure of the quality of a multi-modal trip for long distance journeys where long access and egress stages do not necessary mean a bad quality of interconnection. For instance, if an Interconnectivity Ratio of 0.3–0.4 is high in case of local transport, it can be a normal value when an air trip over 700–1000 km is considered. Furthermore, in the proposed index access and egress times do not include waiting and transfer times while aspects like the service frequency or the optimisation of timetable at the interchanges are important elements in passenger
interconnections. Including average waiting and transfer times in the index could provide a more representative index that inform, at least partially, also on the quality of interconnection.

Closeness Centrality is similar to traditional accessibility indexes, being focused on total travel impedance, and so it is “blind” with respect to the quality of interconnections.

In the definition of Degree Centrality, transfers are by definition negative circumstances that should be minimised. So, Degree Centrality is basically incompatible with the concept of co-modality. Even if one may agree that in principle direct connections are preferable, in some cases there might be strong organisational reasons to design a network according to a hierarchical, hub-and spokes type system. For instance, buses acting as feeders to rail at dedicated interchanges or using one major airport as hub can provide a more efficient service (thus impacting also on user costs) than many direct connections. In such cases a lower degree centrality network would arise. Also, if an underground network is opened to replace a bus system on some routes, it can happen that two zones are connected through an interchange rather than with a direct service. If the interchange is well designed total travel time can be significantly reduced despite the need for the interchange. However, the Degree Centrality index would decrease since a higher number of transfers are required.

In literature one may find other indicators of interconnectivity (e.g. Gonçalves, da Silva Portugal, & Nassi, 2009; Kazerani & Winter, 2009; Scheurer et al., 2007), but they also do not inform on the quality of interconnectivity, but on the relative position of nodes within the network. This is the case for instance of Betweenness Centrality (defined for each node as the average proportion of paths between any two nodes within the network that traverse the node in question); Straightness Centrality (defined as the ratio of the actual inverse average shortest path length within the node in question and all other directly connected nodes, to the theoretical average shortest path length within that sample) and Information Centrality (defined as the relative drop in network straightness in case the node in question is removed from the network).

Using the concept of co-modality, measuring the level of interconnectivity does not correspond to measuring total travel time or cost nor the number of direct connections. Even the time spent at interchanges or its weight on total travel time is not a representative measure of co-modality since other key aspects like information, ticketing, interoperability is not reflected in the indicators.

The problem can be considered of minor importance for ex-post analyses. Once interconnections between different networks are established, also qualitative aspects contribute to define the overall travel “effort”. Thus, travel costs, total travel time, waiting time at transfer points partially reflect the level of “co-modality”. Furthermore, if the functionality of interchanges is good, the amount of demand between region pairs can increase, i.e. the activity function of regions is higher. Assessing whether the integration of different networks has arisen. Also, if an underground network is opened to replace a bus system on some routes, it can happen that two zones are connected through an interchange rather than with a direct service. If the interchange is well designed total travel time can be significantly reduced despite the need for the interchange. However, the Degree Centrality index would decrease since a higher number of transfers are required.

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underground. The Interconnectivity Ratio has been computed partially different than in [2], using the formula:

\[ IR_i = \frac{\sum (AT_{ij} + ET_{ij} + TT_{ij})D_{ij}}{\sum TOT_{ij}D_{ij}} \]

Where:
- \( IR_i \): modified Interconnectivity Ratio of area \( i \).
- \( AT_{ij} \): access time to the underground network for reaching area \( j \) from area \( i \).
- \( ET_{ij} \): egress time from the underground network for reaching area \( j \) from area \( i \).
- \( TT_{ij} \): transfer time (including boarding and alighting times and waiting time at stops) for reaching area \( j \) from area \( i \) by underground.
- \( TOT_{ij} \): total travel time for reaching area \( j \) from area \( i \) by underground.
- \( D_{ij} \): demand (modelled number of trips in peak time) between area \( i \) and area \( j \).

The reason for using a modified formula is twofold. First, in the context under analysis interchange is quite relevant. Adding transfer time to the numerator allows for better measuring the share of 'interconnectivity-related' transport time. Second, introducing the demand between the zones allows for weighting the relative importance of each destination (i.e. the role of activity function in accessibility indicators).

The Interconnectivity Ratio decreases for most of the zones where new underground lines are built or existing underground lines are extended. These zones benefit from a larger number of direct connections and their access, egress and interchange time is reduced. However, in several zones the ratio increases. It is quite clear that such
increase does not reflect a worsening of the services, with lower frequencies or more distant stations. Instead, the higher ratio is due to the larger number of indirectly (i.e. by means of some feeder mode) connected zones after the extension of the network.

In fact, the indicator has been computed considering in each scenario all origin-destination pairs that are directly or indirectly (i.e. by means of some feeder mode) connected by underground. In the alternative scenarios the number of connections increases, thus the indicator is computed on a larger group of pairs. Computing the indicator on the same set of pairs would significantly underestimate the impact of the new infrastructures. This applies to the other indicators presented below.

Thus the Interconnectivity Ratio provides a biased picture of the accessibility level in the network (by underground) by considering only physical aspects. Looking at Fig. 2, one should incorrectly conclude that for most of the zones the new infrastructure give rise to poorer interconnectivity.

Fig. 3 shows the variation of a Degree Centrality-type index between reference and alternative scenarios. In this case, Degree Centrality has been computed as:

\[
\text{DC}_i = \frac{\sum_j (MT_{ij} + DT_{ij})}{N \sum_j DT_{ij}}
\]

where:
- \(\text{DC}_i\) modified Degree Centrality of node \(i\)
- \(MT_{ij}\) 1 if area \(j\) can be reached by underground from area \(i\) without interchanges, 0 otherwise
- \(N\) number of destinations that can be reached by underground from area \(i\).
- \(DT_{ij}\) demand between area \(i\) and area \(j\).

A modified formula instead of [3] is used to take into account the relevance of destinations, under the assumption that a direct connection to poorly attractive zones is not the same as direct connections to most attractive areas.

It is important to note that according to this definition, the numerator of the index increases when the number of interchanges is reduced (whilst in the Eq. (3) the numerator decreases). It should also be noted that for computing the index, interchanges are not only those between two different underground lines, but also between underground and bus or urban rail services.

As for Interconnectivity Ratio, there are improvements for zones with more direct connections. However, in most of the area the index is lower because the number of total connections (weighted by their relevance in terms of demand) increases more than the number of direct connections. From a co-modal point of view the possibility of reaching more destinations through the interconnection with other networks is a positive effect, but the Degree Centrality indicators seems rather suggesting that the North-East of the study area worsens its connectivity.

Finally, in Fig. 4, the variation of Closeness Centrality between the two scenarios is shown. Closeness Centrality has been computed as:

\[
\text{CC}_C = \frac{N^* \sum_j DT_{ij}}{\text{Av} \left[ \frac{\sum_j DT_{ij}}{\text{TotT}_{ij}} \right]}
\]

where:
- \(\text{CC}_i\) modified Closeness Centrality of node \(i\)
- \(\text{TotT}_{ij}\) total travel time for reaching area \(j\) from area \(i\).
- \(DT_{ij}\) demand between area \(i\) and area \(j\).
- \(N\) number of destinations that can be reached by underground from area \(i\).
- \(\text{Av}\) average function

Apart the weighting of destinations with demand, the main change with respect to [4] is that denominator is made of the average (weighted) travel time rather than total distance. The reason for this change is that using total distance would invariably lead to increase denominator more than numerator, thus reducing the value of the Closeness Centrality. Using the average time, in regions for which faster (direct) connections become available the denominator can decrease or at least not increase too much as effect of the new (indirect) connections. Another change is that \(N\) represents the number of destinations rather than the number of nodes in the network. In the network used for the modelling simulation, only nodes representing the zones (i.e. the centroids) are relevant. Therefore the indicator is computed with reference to those nodes.

![Fig. 3. Variation of Degree Centrality (DC) for underground service.](image-url)
Indeed, looking at Fig. 3, the largest part of the zones shows a positive change of the index. This index, under this specific form seems more able to capture the improvement of accessibility given by the new infrastructures.

4. Implications for managerial practice

From the concepts developed above the following main considerations emerge for the managerial practice.

First of all, if transport should provide accessibility, this goal can sometimes be more efficiently met by exploiting the relative strengths of different modes than trying to supply direct services. Assuming this perspective, interconnections and transfers between networks should not be regarded as something to eliminate as much as possible, but as one part of the trip that should be made as smooth as possible.

Second, implementing co-modality successfully is challenging as the various transport networks should be considered as a single entity and managed as such. This condition is very far from the current experience. Let us consider a trip between two different countries using air as the main mode, but relying on an intercity rail service at the origin and a local bus service at the destination. In this example, the passenger starts by using a rail service provided by a national operator, possibly regulated by the Ministry for Transport. The traveller will then need to navigate through a rail station, operated by the rail infrastructure manager, and an airport, operated by the airport authority and regulated by a separate national agency. He will then board a plane run by an airline regulated by an international agency and repeat the reverse process upon arrival at the destination airport, except that each station and service will again be run by a different operator regulated by a different national agency. At the local level, in particular, it is likely that bus services will be regulated by local transport authorities with a narrowly defined remit not extending much beyond their municipal boundaries.

This example clarifies that the major difficulties to create co-modal connections may be not only on the infrastructural side. Physical separation exists and may be difficult to eliminate especially when existing transport networks to be connected were planned independently and built in different times in the past and in different locations like e.g. rail networks and airports. However, putting together several different subjects to manage functional aspects of interconnectivity can be even more complicated. To remain on air and rail transport, examples of agreements between air and train operators exist in Europe to enhance procedures for check-in and luggage transfer. For instance, Lufthansa and Deutsche Bahn for check-in or Vienna airport and Vienna central train for full luggage check-in or “Fly rail” service that transports luggage from many airports in the world via Geneva and Zürich airport to most Swiss train stations.

However, all these examples involve bi-lateral agreements. When more networks and more subjects are involved, interests may be much more diverging, especially if sensitive aspects like ticketing and pricing are involved. One of the most critical elements for co-modality is probably arranging robust timetables. In principle the introduction of robust schedules could be applied anywhere — particularly where delays can result from incidental effects. Nevertheless it is often difficult to achieve the balance between sufficient safety margins on the one hand and efficient usage of the system on the other. Ideally the margins would be created by optimising the schedules to create even gaps in the schedule, but more often this can only be achieved by reducing either average speed on route or increasing the times at stations, and this in turn may — where the schedules are very dense and tight — only be possible through reducing the number of services that are run. This is of course not desirable from the point of view of the single operators.

This suggests that a more open-minded approach is needed. An effort to promote a common strategy and to combine resources should emerge as an opportunity for achieving a higher market share. An open-mind would be probably helped by a strong regulatory environment. While in a local transport context it could be expected that dominant operators take the lead, some form of higher level regulation is likely to be critical for intermodal long distance travel.

The main message that this paper adds to such considerations is that measuring interconnectivity, assuming a co-modality perspective is complex, especially for ex-ante analyses. Co-modality is today still in a very embryonic stage. Current infrastructures and services should be re-organised in order to build interconnected services where different networks work like a single mode. In many cases, new services and also new infrastructures should be put into practice. In the planning phase, promoters and investors would like to estimate the impact of the interconnected services and the demand for new infrastructures. Public authorities would like to forecast the improvement of accessibility that
clever interconnectivity would bring about. Both private and public subjects would like to compare alternative solutions to choose the best alternative. Most likely, modelling simulations of alternative scenarios would be requested.

The discussion presented in this paper suggests that summary indicators used to measure accessibility and interconnectivity are structurally insufficient to capture the essence of co-modality. Many interventions that could improve accessibility from a co-modal point of view are poorly reflected, not reflected at all or give rise to misinterpretation. While the indicators available in literature to measure interconnectivity can provide useful information to policy makers and planners for designing networks and assessing nodes accessibility, their usefulness to analyse the quality of interconnections in the light of co-modality is not fully satisfying.

All in all, it could be said that co-modality begs for a change of perspective in transport networks management as well as in transport network performance measurement.

5. Conclusions

This paper deals with existing accessibility and interconnectivity indicators seen from the perspective of co-modality, which is still quite a theoretical concept. Two main steps ahead are suggested by this work. First of all, the ways that co-modality could be put into practice should be studied in detail. There are organisational, infrastructural as well as legal issues to be overcome and contributions to research in this field would be one natural consequence of this work. Secondly, if current indicators seem not fit to measure interconnectivity from a co-modal point of view, new indicators could be developed. In order to be useful such indicators should be based on elements available not only ex-post, but also ex-ante. Suggestions for modelling applications capable to provide the needed elements could be also developed to help the planning phase of interconnected services.

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References


