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Accessibility and Transit-Oriented Development in European metropolitan areas

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ABSTRACT

This study investigates how urban form is related to accessibility. In particular, it explores the relationship between Transit-Oriented Development (TOD) and rail-based accessibility in a metropolitan area. The following overarching questions are addressed: Does a TOD-informed urban spatial structure correlate with high rail based accessibility? Which features of TOD are correlated to rail-based accessibility? These questions are answered through a comparative analysis of six metropolitan areas in Europe. The “TOD degree”, operationalized as the extent to which urban development is concentrated along rail corridors and stations, is correlated with a cumulative opportunity measure of rail-based accessibility to jobs and inhabitants.

The comparison demonstrates that rail-based accessibility is higher in urban areas where inhabitants and jobs are more concentrated around the railway network and in lesser measure in urban areas with higher values of network connectivity. No correlation is found between rail-based accessibility and average densities of inhabitants and jobs.

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1. Introduction

The urban and transport planning strategy of Transit-Oriented Development (TOD) has been generating considerable interest in academic and professional circles recently (Bertolini et al., 2012; Cervero, 2004; Curtis et al., 2009). TOD's approach of concentrating urban developments around railway networks builds upon strategies applied since the late 19th and early 20th centuries in the United States and Europe, when the construction of streetcar and metro lines was integrated with urban developments. After the Second World War planners in parts of Europe, most notably in Stockholm (Cervero, 1995) and Copenhagen (Knowles, 2012), were able to channel suburban development into satellite suburbs along transit corridors. In recent years a third generation of TOD approaches has emerged. In the United States, since the 1990s, following experiences pioneered in the 1970s in cities such as Portland, TOD has become the dominant urban growth planning paradigm. It is focused on combating unbridled urban sprawl and closely connected with Smart Growth (SG) and New Urbanism (NU) approaches (Dittmar and Ohland, 2004). Also in Europe many metropolitan areas (Bertolini et al., 2012; Givoni and Banister,

2010) are promoting urban development along rail corridors as a tool and, at the same time, a target for achieving more cohesive territories and sustainable urban development.

Under favourable conditions, TOD is seen as delivering multiple benefits, such as helping shape polycentric cities and regions, mitigate urban sprawl, boost public transport ridership, increase biking and walking, while accommodating economic growth and creating attractive places. Indeed, there is a substantial body of literature on the comprehensive assessment of TOD strategies (Arrington and Cervero, 2008; Renne, 2007); and on specific TOD impacts, such as on property values (Bowes and Ihlanfeldt, 2001; Duncan, 2011; Mathur and Ferrell, 2013) or on relocation of jobs and dwellings (Cervero and Landis, 1997; Pagliara and Papa, 2011) but much of the interest is related to analysing TOD impacts on travel behaviour (Cervero et al., 2002). However, none of these studies give direct insight into the relationship between TOD and accessibility, that is, the degree to which the urban and transit network structures enable individuals to participate in activities and obtain spatially distributed resources (Geurs and van Wee, 2004; Handy, 1992; Handy and Niemeier, 1997). This can be seen as a worthwhile objective in itself and as an influencing factor of travel behaviour change.

In this paper, we aim to address this gap by studying how the degree of TOD of a metropolitan area is related to the rail-based accessibility to jobs and inhabitants. The following research

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questions are addressed: Does a TOD-informed urban spatial structure correlate with high rail-based accessibility? Which features of TOD are correlated to rail-based accessibility? The latter include such characteristics as density distribution of inhabitants and jobs, and network connectivity. By exploring these issues, we aim to provide empirical insights into the understudied relationship between TOD (a transport and urban development strategy embraced by increasing numbers of cities and regions across the world) and accessibility (a key policy aim and feature of the urban system). In so doing, we also provide a comparison of TOD degree and accessibility values in six different metropolitan contexts.

Our interpretation of TOD is different from other, more localized approaches (Bernick and Cervero, 1997; Cervero et al., 2002); for us, TOD is the measure in which the whole urban area, not just a single neighbourhood, is oriented towards transit. Accordingly, we define the “TOD degree” as the degree of correlation between the railway network connectivity and the distribution of densities in the whole urban area, and “accessibility” as the number of jobs and inhabitants that can be reached by rail as a percentage of the total jobs and inhabitants in the study area. While recognising that accessibility is affected by a much wider range of factors, including subjective ones, in this study rail-based accessibility is measured as an aggregate objective indicator, and it is defined as a condition for rail use and as an enabler (or disabler) of travel choices and behaviours.

This research employs several innovative approaches. The first is the use of accessibility in analysing the TOD degree of an urban area. As previously stated, while there are multiple empirical studies on the linkages between TOD and travel behaviour, its relationships with accessibility have attracted much less attention. By definition, accessibility by rail is dependent on the spatial distribution of jobs and residents with regards to the vicinity to rail stations. However, the two measures are still conceptually distinct (the former is a condition, or quality from a system user's point of view, the second a characteristic of urban form). Accordingly, this paper innovatively contributes (1) a transparent link between the two and (2) a systematic way of assessing to what extent and because of which transport and land use features, the spatial distribution of jobs and population matches the rail network. In this sense, we offer novel, or at least more structured, insights into how certain distribution of inhabitants and job densities and rail transport characteristics, and their interrelationships, are related to rail-based accessibility. While general TOD characteristics and benefits of TOD are extensively addressed in the literature, this research focuses on the yet understudied relationship between TOD and accessibility. Furthermore, the existing literature rarely employs accessibility metrics to compare metropolitan areas, and most empirical research measuring accessibility focuses on case studies of single regions (Benenson et al., 2011; Cheng et al., 2007, 2013; for a recent exception comparing two cities see Silva et al., 2014). In this study, we instead make a systematic comparison of accessibility measures in six different urban areas, which is seen as a valuable procedure for understanding the determinants of accessibility (Levine et al., 2012). A final innovation is the focus on Europe. TOD empirical studies focus overwhelmingly on the North American context, and few studies (Keller et al., 2011; Knowles, 2012; Singh et al., 2014) propose quantitative analysis of TOD urban structures in the European context, where the urbanisation patterns and histories differ radically from those in the US.

The paper is organised in five sections. Following this introduction, in Section 2 we position our research within the relevant literature on the relationships between TOD degree of the urban structure, accessibility and travel behaviour. In Section 3, we present the research design, subsequently turning to the presentation and discussion of the results in Section 4. On the basis of the analysis provided, we formulate several conclusions in Section 5.

2. Literature review: TOD degree of the urban structure, travel behaviour and accessibility

The interaction between the TOD degree of the urban structure, accessibility and travel behaviour has attracted considerable attention in the scientific literature worldwide. Four main groups of studies can be identified (see Fig. 1) and categorized according to the main relationships studied:

1. interrelation between rail transport network and land use, and the resulting TOD degree of the urban structure,
2. TOD degree of the urban structure as a factor affecting travel behaviour,
3. impacts of accessibility on travel behaviour, and
4. impacts of TOD degree of the urban structure on accessibility.

With regard to the first relation (arrow 1), the problem of the co-development of rail infrastructures and land use has been much discussed (Levinson, 2008; Xie and Levinson, 2011) and has been treated quantitatively in a number of examples (Anas et al., 1998; King, 2011; Mogridge and Parr, 1997). The key aim of these studies is to explore the two-way dynamics whereby transport infrastructure development drives land use change and vice versa. Within the TOD literature, an increasing number of studies focus specifically on how transit development impacts land use changes (Cervero and Landis, 1997; Ratner and Goetz, 2013). The much sparser studies that examine the two-way interaction between land use and transit network are often based on the node-place model approach introduced by Bertolini (1999) and further elaborated in more recent applications (Chorus and Bertolini, 2011; Kamruzzaman et al., 2014; Reusser et al., 2008; Zemp et al., 2011a, 2011b; Vale, 2015). In our knowledge, no TOD studies specifically focus on how land use changes impact transit development.

With regard to the group of studies that are represented with arrow 2, and as already discussed in the introduction, they chiefly aim to examine the potential of the TOD degree of the urban structure to curb car travel demand and shift it towards transit and non-motorized modes. A significant body of research has been produced on the impact of the urban form on travel behaviour, in terms of travel distance, journey frequency, modal split, travel time and transport energy consumption (Boarnet, 2011; Cervero and Kockelman, 1997; Echenique et al., 2012; Ewing and Cervero, 2010; Naess, 2012; Schwanen et al., 2001; Shatu and Kamruzzaman, 2014; Stead and Marshall, 2001). Within this cluster a specific group of studies analyses the impact of TOD urban structure on travel behaviour, including studies considering TOD a systemic (urban area wide) rather than local characteristic (neighbourhood-focused). Some authors assert that a TOD structure is able to increase rates of transit use, particularly rail ridership (Cervero et al., 2002); to reduce car use and travel distances, and to reduce commuting distances and times (Arrington and Cervero, 2008; Cervero et al., 2002; Houston et al., 2015; Lund et al., 2004, 2006) and to stimulate non-motorized travel (Curtis and Olaru, 2010). On the other hand, studies also highlight that other factors (e.g. housing type and tenure, local and sub-regional density, bus service level, and especially parking availability) can play a much more important role than proximity to transit (Chatman, 2013). Yet others argue that TOD impacts on travel behaviour are also – or even principally – dependent on personal characteristics such as travel-related attitudes and residential self-selection, influenced by certain factors as income, or household composition. For instance, De Vos et al. (2014) and Kitamura et al. (1997) found that attitudes are more strongly associated with travel behaviour than are land use characteristics. They suggested that land use policies that promote higher densities and

Fig. 1. Grouping of studies on interrelations between TOD degree of the urban structure, accessibility and travel behaviour.

mixed land use may not reduce travel unless residents' attitudes also change. The answers to this broad issue remain thus ambivalent, and it is not yet clear whether land use strategies alone can have a significant effect on travel behaviour (Ewing and Cervero, 2010). However, as more recent studies have recognised (Bertolini et al., 2005; Levine et al., 2012; van Wee, 2011; van Wee and Handy, 2014), a single focus on travel behaviour impacts might be too narrow. The argument in these studies is that even if land use strategies appear to have no significant, independent effect on travel behaviour, they can still be worth pursuing if they bring sufficient benefits in the form of accessibility improvements.

Studies that focus on the direct impacts of accessibility on travel behaviour (arrow 3) or the impact of urban form on accessibility (arrow 4) are less numerous, even though accessibility is recognised as one of the key concepts that connect transportation and land use and explain regional form and distribution of population and employment opportunities (Scott and Horner, 2008). With reference to arrow 3, studies of the impact of accessibility on travel behaviour analyse how accessibility may affect individual travel behaviours (Handy, 1992; Kockelman, 1997). Over time, accessibility has been defined and measured in numerous ways (Geurs and van Wee, 2004), but in general, two main categories can be found in the literature: objective measures and subjective understandings of accessibility (Curl et al., 2015). Location-based measures, contour (or cumulative) measures and potential (or gravity) measures belong to the first group and are designed to represent the accessibility provided by the transport and land use system as an objective condition. The second group of accessibility measures relate to individuals' experiences of accessibility, taking into account the subjective dimension of mobility. Using different methods and measures of subjective or objective accessibility, many studies compare the accessibility by different modes, predominantly comparing public transport and car use (Benenson et al., 2011; Keller et al., 2011). A negative correlation is usually found between vehicle miles travelled and destination accessibility. Also, observed trip length is generally shorter at locations that are more accessible (Ewing and Cervero, 2010).

Regarding the group of studies represented by arrow 4, focusing on the impact of TOD on accessibility, it is important to underline that TOD by definition is urban development integrated with high capacity public transport and one of its main objectives is to offer city-wide and local accessibility (Cervero, 1995; Curtis et al., 2009). However, few studies measure the impact of TOD degree of the urban structure on accessibility. The few existing studies measure such things as accessibility impacts at the neighbourhood scale (Cervero and Radisch, 1996), or walkable accessibility to transit stations (Schlossberg and Brown, 2004), but studies of impacts in terms of citywide accessibility are rare (Bertolini et al., 2005;

Silva et al., 2014) and – importantly – do not distil how particular transport and land use features are related to particular accessibility levels.

3. Research design

The research methodology was set up to provide insights into the relationships between TOD degree of the urban structure and citywide accessibility. It is based on comparison of the urban structure and accessibility qualities of six European metropolitan areas and entailed the following steps:

- Design of a methodology for data-based inspection of the relationships between TOD degree of the urban structure and accessibility: grid-based data from each case is organised in a systematic spatial database and an integrated data structure for subsequent analysis, at a detailed spatial scale.
- Analysis of the correlation between TOD degree of the urban structure and accessibility for selected study cases: a correlation analysis was performed, using as variables the cumulative rail-based accessibility to inhabitants and jobs and the TOD degree of the urban structure of a study area, defined as the extent to which the distribution of urban densities is or not developed along rail infrastructures (tram, metro and regional rail).
- Comparison between the various case studies and interpretation of the results: through geographical information systems (GIS), which provides spatial analysis and comparison as well as the visualisation of results.

3.1. Case studies

We selected six Western European metropolitan areas as case studies, as this allowed heterogeneity of key land use and transport characteristics (directly related to our variables), a key criterion for our selection of case studies: the characteristics chosen were the number of inhabitants, jobs and relative densities as regards the land use characteristics (Table 1), and the rail network extension as regards the transport characteristics (Table 2). However, we excluded case studies with very large differences in size (only cities between one and four million inhabitants were considered), as this might confuse our focus on the relationships between the morphology of the railway network, the distribution of land uses, and accessibility. We did not include TOD best practices in Europe (as exemplified by Copenhagen and Stockholm) as our aim was indeed not to identify best examples, or their defining characteristics, but rather urban form determinants of accessibility by rail.

Table 1

Structural land use variables of the study cases. Source: [Statistical Office of the European Communities \(2011\)](#).

	Study area (km ²)	Inhabitants and jobs (inh. + jobs)	Average population and jobs density ((inh. + jobs)/km ²)
Amsterdam	1973	4,207,435	1714
Helsinki	2147	1,596,723	744
Munich	2219	3,528,261	1590
Naples	1906	4,627,604	2,428
Rome	2321	4,500,970	1939
Zurich	2647	2,337,367	883

With this aim in mind, we selected case studies that showed sufficient variation on possible determinants, not that were potential best (or worst) practices. The decision was made to limit the number of case studies to six: more cities would have meant that fewer types of analyses could have been performed and triangulation between them and comparisons between different cities would have been more difficult and less transparent. Fewer than six cities would have meant not enough variation in potential determinants of accessibility. Data availability was also a factor behind the choice. The choice of comparing cities in different European countries means including cases with different regional institutional systems, regulatory regimes and mobility cultures. These differences should be kept in mind when inferring policy recommendations from our empirical results, as they constitute specific implementation possibilities and constraints. A final point is that information on car ownership, the modal share and travel time of the journey to work is provided in [Table 2](#) as reference and background information. It provides additional evidence of the heterogeneity of the case studies in question even though these characteristics are not the focus of our analysis.

3.2. Data sets, study areas and spatial units

The GEOSTAT 1A project population grid ([Statistical Office of the European Communities, 2012](#)), which provides a homogeneous grid population dataset, was integrated with datasets from national census data and used for the land use analysis. Furthermore, the rail, metro and tram networks were derived from OpenStreetMap (OSM) geographical databases. Travel time datasets were constructed by taking the travel times between transit stops, accessible at the public transport agencies' websites, and adding them to the walking times along the street network from the centroid of each Accessibility Zone (AZ) to the nearest rail stop, assuming an average walking speed of 1.4 m/s (based on [Chandra and Bharti, 2013](#)).

The boundaries of the study areas were set as the circumference of 30 km radius, which approximately corresponds to the average commuting distance, centred in the main rail station, which we took as the node in the network with the highest connectivity value. Study areas in the different cases thus have similar total surface areas with only small differences because water and other non-urbanised natural areas are not computed in the boundaries of the study area, allowing a comparison between cases, as represented in [Fig. 2](#). The study areas were divided into AZs, corresponding to the 1 km by 1 km grid cell. The choice of this spatial unit has impact on the analysis results, according to the modifiable areal unit problem (MAUP) ([Dark and Bram, 2007](#)), with reference to the number of areal units used (scale effect) and depending on how smaller areal units are grouped at the local scale (zonation effect). Taking into account these two aspects, our choice was made according to three main criteria: (i) threshold of the total number of areal units for computational reasons, (ii) dimension of the spatial unit threshold based on walking accessibility to the station and (iii) comparable data availability for the six case studies. While the chosen spatial analysis unit of 1 km² is quite fine-grained, there are still issues that a finer definition would better address. Some disadvantages are in fact related to the choice of using a 1 km × 1 km grid: in few cases is the station centrally located in the grid and some units include more than one station.

3.3. Correlation variables

The first variable is the TOD degree of the urban structure defined as the extent to which the job and inhabitant densities are developed along rail transit (tram, metro and regional rail) corridors. In other words, the TOD level is the degree of spatial concentration of economic activities and population along the rail transit networks. We measured this value with a method inspired by, but distinct from the node-place model ([Bertolini, 1999](#)): for each AZ we measured a “node index” and a “place index”, and we analysed the bivariate scatterplot distribution in a xy graph of node and place index values for each AZ of the study area. The TOD degree of the urban structure was then determined by the strength of the correlation between the two variables.

The method proposed here is different from [Bertolini \(1999\)](#) in several aspects as detailed below. Differently from [Bertolini \(1999\)](#) and following adaptations and applications ([Chorus and Bertolini, 2011](#); [Kamruzzaman et al., 2014](#); [Reusser et al., 2008](#); [Zemp et al., 2011a, 2011b](#); [Vale, 2015](#)), we did not limit our analysis to the immediate surroundings of the station areas but to all areas in the city. Our reasoning is that areas further away also play a role in the TOD degree of a metropolitan area. In this perspective, not only the immediate surroundings of stations have a role, but all areas, albeit in proportion to their distance to stations. We believe

Table 2

Structural transport system variables of the case studies. Source: [Statistical Office of the European Communities](#): (a) 2004; (b) 2011; (c) 2001.

	Transport supply			Modal share journey to work					
	Number of registered cars per 1000 inhabitants (n)	Rail network		Car %	Public transport %	Motorcycle %	Walking %	Bicycle %	Average home–work journey time (min)
		(Km/mln inh.)	(n. stations/mln inh.)						
	2009	2013	2013						2009
Amsterdam	257	18	13	41 ^(a)	30 ^(a)	3 ^(a)	4 ^(a)	22 ^(a)	31
Helsinki	408	15	16	51.4 ^(b)	30.8 ^(b)	0.3 ^(b)	9.8 ^(b)	7.7 ^(b)	27
Munich	354	28	16	41 ^(a)	41.3 ^(a)	0.4 ^(a)	9.1 ^(a)	8.2 ^(a)	26
Naples	575	15	6	53.9 ^(c)	26.1 ^(c)	6.9 ^(c)	13 ^(c)	0.1 ^(c)	31
Rome	698	14	8	57.4 ^(c)	23.3 ^(c)	11.7 ^(c)	7.4 ^(c)	0.2 ^(c)	37
Zurich	361	26	26	23.7 ^(c)	62.6 ^(c)	1.3 ^(c)	7.5 ^(c)	4.9 ^(c)	26

Fig. 2. Node and place indices (Amsterdam, Helsinki and Munich study areas).

that our interpretation comes closer to actual behaviour, where stations and transit are not only used by those living in the immediate surroundings.

The proposed method has both advantages and disadvantages with respect to the node-place model. In particular, the application to every AZ is an improvement of the node-place model, which

does not account for the possibility that areas *not* in the immediate surroundings of stations contribute to rail-based accessibility. On the other hand, our characterization of node and place values is less refined, as we consider fewer variables.

Further, in our method, as regards the TOD “equilibrium” of the node and place value distribution in the Cartesian diagram, we sep-

arated two aspects that are integrated in the Bertolini (1999) model:

- the degree in which the densities and connectivity of the AZ match (measured by the coefficient of correlation and the R^2 coefficient), which demonstrates the strength of the relationship between the distribution of densities and the distribution of rail connectivity within a case;
- the degree in which the variation of densities and the variation of connectivity match (measured by the difference in inclination of the correlation line slope from a 45° line slope – which would entail a perfect match).

A high value of correlation demonstrates the existence of a strong match between densities and connectivity, or a high TOD degree of the urban structure; the inclination of the correlation slope measures to what extent the variation in connectivity values is matched by the variation in density values, or the structure of the relationship. The advantage with respect to the node-place model is that we are able to distinguish the relationships between these two distinct aspects of the notion of “equilibrium”. The disadvantage is that we have made a simple, direct comparison of TOD degree of the urban structure between different contexts more complex, as the slope of the correlation line varies between contexts, and is not fixed at 45°, as in Bertolini (1999).

The node index of an AZ (Eq. (1)) corresponds to the closeness centrality index (Sabidussi, 1966). It is calculated as the inverse of the average cumulative distance from an AZ to all the AZs in the study area, measured from their centroids, along the shortest path on the multimodal rail-based (regional rail, metro and tram) and walking network. The node index for each AZ is thus measured as:

$$\text{node index}_{AZ_i} = \frac{N - 1}{\sum_{j=1}^N d[AZ_i, AZ_j]} \quad (1)$$

where N is the total number of nodes in the multimodal graph, and $d[AZ_i, AZ_j]$ is the shortest path distance between AZ_i and AZ_j as defined in Eq. (2). It consists of three terms: the access walking distances from AZ_i to the nearest origin stations, the shortest path distance between station of origin and station of destination on the rail-based network, and the egress walking distances from the nearest destination station to AZ_j . Walking distances from stations to AZ were computed considering a multiplier of 2, which corresponds to the average available accepted multiplier for access and egress walking distance in the case studies (OECD/ITF, 2014).

$$d[AZ_i, AZ_j] = \beta d[AZ_i, \text{station}_i] + d[\text{station}_i, \text{station}_j] + \beta d[\text{station}_j, AZ_j] \quad (2)$$

The place index of an AZ is the average density of inhabitants and jobs of each AZ (3), where inh_{AZ} is the number of inhabitants of the AZ, job_{AZ} is the number of jobs in the AZ and A_{AZ} is its total surface area:

$$\text{place index}_{AZ} = \frac{\text{inh}_{AZ} + \text{job}_{AZ}}{A_{AZ}} \quad (3)$$

The use of the AZ average density as an indicator is a limitation of the proposed method. Indeed average density is not measuring if and how densities are strategically distributed and articulated in a zone, and this constitutes a problem in analysing the degree of transit and land-use integration. In order to considering “articulated densities” (Suzuki et al., 2013) instead of average densities, a spatially highly disaggregated scale should be used; on the other hand, this would arise computational difficulties or limited data

availability, as described in Section 3.2. In future work it is important to downscale the spatial unit, maintaining consistency with the original dataset, or to exclude non-urbanised land for density calculation.

In order to compare the different case studies, standardized node and place indices were calculated using a min–max normalization across the case studies.

For each case study, the resulting scatterplot was analysed in order to assess the correlation of the two indices. In particular, the correlation coefficient, the coefficient R^2 , the correlation line slope, the difference from the 45-degree slope, and the maximum and mean values of the normalized node and place indices were measured (Table 3). The mean value of the normalized node and place indices correspond respectively to the average connectivity and the average density at the scale of the study area. These values have been compared to the accessibility values, in order to understand which relationship they have with cumulative accessibility.

The second variable is cumulative rail-based accessibility. The literature documents many ways to operationalize accessibility, depending on the problem and context of its application (Geurs and van Wee, 2004; Handy and Niemeier, 1997). According to the two main categories of accessibility measures as place-based and people-based (Neutens et al., 2010) as also defined in Section 2, in our analysis we use a cumulative opportunities measure of accessibility, belonging to the first group. This choice is not without its limitations: this type of measure does not acknowledge the gradually, rather than abruptly diminishing attractiveness of opportunities located further away, it does not acknowledge competition effects (e.g. for jobs, workers), and it does not take into account person-specific space–time opportunities and constraints. It is nevertheless well established in accessibility analysis and consistent with our research question, focused on highlighting systemic, supply-side characteristics of urban form rather than on analysing effects on individual travel behaviour. Furthermore, it is a relatively transparent and easily communicable measure, which makes it more suitable for use in planning contexts that often include participants from different disciplines and non-experts (Bertolini et al., 2005).

The cumulative accessibility measure is calculated as the number of inhabitants and jobs reachable in 30 min travel time by rail (regional rail, metro and tram) and expressed as a percentage of the total number of inhabitants and jobs in the study area. The 30 min travel time threshold was defined according to the approximate average time of journeys to work in the selected study areas (see Table 2). The assumption of a constant commuting travel time in contrast with much individual variation in reality might impair the validity of our accessibility analysis (Paez et al., 2012). Furthermore, a number of important methodological issues arise with changing the scale for analysis (Horner and Murray, 2002; Kwan and Weber, 2008). In order to assess this, we performed a sensitivity analysis to determine how commuting times affected variation in estimated cumulative accessibility and seven thresholds ranging between 20 and 50 min (with an increment of 5 min) were tested using the same threshold already tested elsewhere (Luo and Wang, 2003). The results showed that the choice of a 30-min travel time has no significant impact on the average accessibility value of the study area, which is the focus of our cross-sectional comparison.

Another disadvantage of this method is not considering the competition of rail accessibility with other transport subsystems in the different case studies. As shown elsewhere (Benenson et al., 2011; Keller et al., 2011), the impact of the quality of the rail network on rail modal share or travel behaviour is always relative to the quality of other competing infrastructure systems. However, our aim is not to assess the impact of accessibility by rail on rail

Table 3

Comparison of TOD degree of the urban structure in the study cases, and other indices describing the scatterplots.

	R	R2	Line slope	45-degree slope difference (degrees)	Max value of node index norm	Mean value of node index norm	Max value of place index norm	Mean value of place index norm
Amsterdam	0.74	0.55	0.31	15.20	1	0.23	0.65	0.03
Helsinki	0.62	0.39	0.21	16.94	0.73	0.12	0.41	0.01
Munich	0.74	0.54	0.30	16.09	0.95	0.29	0.49	0.03
Naples	0.54	0.29	0.83	−25.61	0.31	0.12	1	0.05
Rome	0.70	0.49	0.40	6.07	0.84	0.18	0.97	0.04
Zurich	0.62	0.38	0.17	20.91	0.82	0.30	0.33	0.02

modal share, but to provide insights into the urban form determinants of rail accessibility.

In detail the accessibility variable, for each AZ, is the number of jobs and inhabitants that can be reached by rail as a percentage of the total in the study area, and it is measured according to the following Eq. (4):

$$Acc_{AZ_i}^{30} = \sum_{AZ \in G, t[AZ_i, AZ_j] < 30 \text{ min}} (\text{inh}_{AZ_i} + \text{jobs}_{AZ_j}) \quad (4)$$

where $t[AZ_i, AZ_j]$ is the shortest time between AZ_i and AZ_j (Eq. (5)). It consists of three terms: the access walking time from AZ_i to the nearest origin station, the shortest time between station of origin and station of destination on the rail-based network and the egress walking time from the nearest destination station to AZ_j . As for the distances, also access and egress walking times to and from the stations were computed considering a multiplier of 2, using as reference accepted multiplier values for access/egress walking time in the case studies where available (OECD/ITF, 2014).

$$t[AZ_i, AZ_j] = \beta t[\text{station}_i, AZ_i] + t[\text{station}_i, \text{station}_j] + \beta t[\text{station}_j, AZ_j] \quad (5)$$

At the citywide scale, accessibility was measured as the average value of the AZs:

$$Acc^{30} = \frac{\sum_{i=1}^N Acc_{AZ_i}^{30}}{N} \quad (6)$$

4. Outputs of study cases cross-sectional comparison

The cross-sectional analysis was completed in two steps. First, the two variables for the different case studies were calculated and analysed independently. The second step focused on the correlations between the two.

4.1. Outputs of cross-sectional analysis of TOD degree of the urban structure and accessibility in the study cases

The measurement of the TOD degree of the urban structure yielded twelve maps (Figs. 2 and 3) and six scatterplots (Fig. 4). Similarities and differences of the densities and the connectivity values and distribution in the six cases already constitute an interesting output of the analysis, as shown in Figs. 2 and 3, which allow visualisation of the different spatial distribution of node and place indices of the AZs. Different density patterns are exhibited both in terms of average values, bandwidth and geographical dispersion. In all cases analysed, population and job densities increase with proximity to the centre, but with a different bandwidth (more or less steep density gradient) and distribution (more or less dominant core). Also the node index has a different distribution in space and a different bandwidth: in the case of the Zurich study area, for example, the connectivity levels are higher than in the other cases and also more uniformly distributed throughout the study

area, while the opposite happens in the Naples study area, where the network is not well developed and well interconnected. From comparison of the distribution of the node and place indices in the different study areas, as shown by the maps, it is apparent that the combined patterns of the railway network and land use differ significantly across the six urban systems, ranging from what could be termed a 'strong core structure' (i.e. Munich and Rome), to a 'networked city-region' (i.e. Amsterdam, Zurich and Naples), to a 'corridor structure' (Helsinki).

Diagrams in Fig. 4 allow a more systematic comparison of the different interrelations and scatter distributions of the place and node indices in the six study cases. It is important to underline that the correlation coefficient and the R2 do not aim at demonstrating causality between the node and the place index, but only describe the scatterplot shape. The scatterplots show further differences between the cities, with a prevalence of unbalanced AZs, as in the case of Naples, where the AZs have relative high values of density but low connectivity of the railway network, or a prevalence of unbalanced AZs in Zurich, where the opposite applies. The other cities lie in between these two extremes.

Table 3 documents the differences of the overall TOD degree, expressed as the correlation coefficient R, the R2 coefficient, the slope of the correlation line, and the distance from the equilibrium 45-degree line and the maximum and mean values of node and place indices. As regards the values of the TOD degree, reflecting how densities and connectivity match (measured by the correlation coefficient and the R2), the six study cases show a broad range. The cities with the highest correlation between the node and the places indices, that is, the cities that are more developed around the rail network, are Amsterdam and Munich (both have $R = 0.74$). The higher correlation values for Amsterdam and Munich mean that in these cities there is a higher match between the distribution of residential and employment densities and the connectivity offered by the railway network. The opposite holds for Naples ($R = 0.54$), where areas with high density of inhabitants and jobs are not well served by rail transport services.

As regards the match between variation in densities and connectivity (measured by the correlation line slope and the difference of its inclination from the 45-degree line slope), the least balanced cases are Naples and Zurich. In the case of Naples, variation in place index values prevails over variation in connectivity values in the AZs of the metropolitan area, while the opposite holds for Zurich, where the variation in the node index prevails over the other. More balanced TOD study cases are Amsterdam, Rome or Munich where the node index bandwidth and the place index bandwidth are more comparable.

The rail-based cumulative accessibility is summarized in Table 4, as the average value of cumulative accessibility (Eq. (6)), and reported as maps showing the accessibility of each AZ in the study areas in Fig. 5. The average values of accessibility in the six cases summarized in Table 4 show that Amsterdam is the city with the highest average accessibility (on average 32.48% of all jobs and inhabitants in the metropolitan area are accessible by 30 min rail

Fig. 3. Node and place indices (Naples, Rome and Helsinki study areas).

travel) while Naples has the lowest (5.32%). The maps in Fig. 5 show different degrees of spatial concentration of accessibility (more focused on the city centre – like in Naples, Helsinki and Zurich – or more distributed across the urban area – like in Amsterdam, Rome and Munich).

4.2. Outputs of correlation analysis

The outcome of the correlation analysis between the TOD degree and the cumulative rail-based accessibility is reported in Table 5 and Fig. 6, and can be summarized as follows:

Fig. 4. Scatterplots of node and place indices for each study case (place index on x axis and node index on y axis).

Table 4

Cumulative accessibility (average value at the citywide scale).

	Cumulative accessibility (average value at the citywide scale) (%)
Amsterdam	32.48
Helsinki	7.86
Munich	22.41
Naples	5.32
Rome	21.04
Zurich	11.89

- a strong positive relationship was found between the indices measuring TOD degree (in terms of correlation coefficient R and R^2 linear) and rail-based accessibility, in line with the general expectations expressed in the literature (Ewing and Cervero, 2010);
- a positive (albeit weaker) relationship also exists between the variables representing the mean and the maximal node index and rail-based accessibility, indicating that the accessibility is higher when the network connectivity is higher, which supports the current findings in the literature (Mees, 2010);

Fig. 5. The distribution of cumulative rail-based accessibility to inhabitants and jobs in the study areas.

– on the other hand, maximum and average density (maximal and mean place value) have no correlation with rail-based accessibility values; this is a more controversial point, but one that has recently also been advanced in the literature (Mees, 2009; Morton and Mees, 2010).

Thus, three interesting results emerge. First, cumulative rail-based accessibility is strongly correlated to the TOD degree of an urban area. Indeed, cumulative rail-based accessibility almost increases in direct proportion, when urban development becomes

Table 5

Correlation between TOD degree and cumulative rail-based accessibility (average citywide value).

R	R2	Correlation line linear slope and accessibility	Mean value of node index	Max value of node index	Mean value of place index	Max value of place index
0.93	0.92	0.32	0.49	0.72	0	0.02

more structured along the rail network (i.e. when the node index and the place indices are more strongly correlated). Second, accessibility also increases, but to a lesser extent, when railway network connectivity increases (i.e. when the average and maximal node index values increase). Third, accessibility values are not correlated with maximal or average density of the study area.

Fig. 6. Correlation analysis: TOD degree of urban structure and rail-based cumulative accessibility.

Table 6
Multiple regression analysis results.

Regression statistics					
Multiple R					0.94
R square					0.89
Adjusted R square					0.44
Standard ERROR					0.08
Observations					6.00
ANOVA					
	df	SS	MS	F	Significance F
Regression	4.00	0.05	0.01	1.97	0.48
Residual	1.00	0.01	0.01		
Total	5.00	0.05			
	Coefficients		Standard error	t Stat	P-value
R		1.24	0.77	1.61	0.35
Mean value of node index norm		1.06	9.04	0.12	0.93
Mean value of place index norm		0.04	0.69	0.06	0.96
Line slope		0.03	0.66	0.04	0.97

In order to explore these relationships further, Table 6 shows the result from a multiple regression model. Results confirm positive relationships between node index and accessibility.

5. Conclusions

Transit-Oriented Development is one the most commonly used development strategies for metropolitan areas. Furthermore, accessibility is increasingly being used by transportation and urban planners as a tool for identifying and assessing integrated urban and transport development solutions. However, accessibility metrics, while increasingly important in transportation and urban planning practice and research, are rarely used to compare and assess metropolitan areas, especially TOD urban structures. In this context, we developed the above empirical analysis to examine whether TOD patterns of urban expansion, in particular in terms of correlation between railway network connectivity and inhabitants and job density, could be associated with measures of cumulative rail-based accessibility.

The empirical evidence supports some of the claims made in the literature. Our research demonstrated that cumulative rail-based accessibility is higher in cities with a higher TOD degree, almost in direct proportion. This result is not unexpected and in some respects tautological. However, we also believe that the two measures are still conceptually distinct: the former is a condition, or quality from a system user's point of view, the second a characteristic of urban form. Cumulative rail-based accessibility is also positively correlated with railway network connectivity, but to a lesser extent.

As a contribution to the academic body of knowledge, we were able to specify how the transport and land use characteristics of TOD are related to accessibility. Of prior importance is the degree of TOD, i.e. the degree to which the spatial distribution of jobs and population densities matches the hierarchies (i.e. the degree of connectivity of nodes) in the public transportation network. Second, our analysis showed high correlations between overall network connectivity levels and accessibility. On the contrary, we could find hardly any correlations between maximal or average densities and cumulative rail-based accessibility. The latter point supports the claims made by others that density alone is not enough, but it further specifies these claims by stating that *maximal or average density* does not matter, whereas the *distribution* of density relative to the railway network does.

It is important to stress that the proposed correlation analysis is exploratory and hypothesis-generating rather than explanatory or

hypothesis-testing. In accordance, our research provides a new methodology and dataset, which enable systematic comparisons of metropolitan network connectivity, density and accessibility in a way that is clearly understood and explainable, and that does not require complex calculations. The information and visualisations can be used as a platform to understand the relationships between transport and land use features and accessibility. More proactively, it can be used as a platform to explore the relationships between accessibility and land use or transport network interventions in a whole urban region or in a specific zone. For example, it can show the relationships between whole-city accessibility, and the density or connectivity of a single urban area and vice versa.

In terms of implications for urban and transportation planning, this study suggests that strengthening the relationship between the railway network and land uses is an effective measure for increasing cumulative rail-based accessibility; improving railway network connectivity is also important, but just increasing densities is not. A key role is played by the correlation between railway system connectivity values and land use densities, what we term the TOD degree of the urban structure. Planners wishing to enhance the cumulative rail-based accessibility of an urban area should primarily focus on transport and land use interventions that improve this correlation. In particular, this can be done by targeting density increases towards areas with relative high connectivity, and targeting connectivity increases towards areas with relative high density, as already suggested by Bertolini (1999). The city-wide analysis we proposed is a useful tool for exploring which specific measures could be employed and how to guide planning in a given context not only for station areas but for all the spatial units in the study area. Furthermore, the approach can be used as a planning support tool, to explore the relationships between levels of connectivity and density of each AZ in the metropolitan area, the TOD degree and hence rail-based accessibility of that area. The possibilities and constraints for implementing such measures will, of course, depend on the broader characteristics of that context, including non-physical, institutional factors.

In terms of follow-up research, a limitation of this research is the use of an aggregate accessibility indicator without taking into account the subjective dimension of individual mobility choices. Thus, it would be interesting to extend the methodology with more sophisticated accessibility measures, for instance acknowledging distance decay and competition effects, or focusing on specific segments of the population. Another direction of improvement could be adding more detail to the node and place indices. For instance, data on frequency of service, inter-modal transfers, and parking could be integrated in the node index. Data on walkability and land use diversity could be integrated in the place index. Further, an important improvement of the work would be to include a fine-grained measure of density, in order to better measure its distribution and articulation in the study area.

Next, a larger sample of cities would make the results more robust, and we believe that our method provides an approach to systematically add more cases in future steps of the research or by other authors. Finally and importantly, our analysis could just show correlation not causation. In order to explore the latter, future research could adopt a different methodology to further investigate these functional interdependences.

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