ACCESSIBILITY IMPACTS OF TOD EXPERIENCES IN EUROPEAN METROPOLITAN AREAS

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Keywords: Transit Oriented Development TOD; Accessibility

Abstract
The study investigates how Transit Oriented Development - TOD structure affect accessibility in cities with the aim of establishing whether TOD patterns of urban expansion, in terms of network connectivity and inhabitants and job density, could be associated with measures of rail accessibility. In particular the paper addresses the following overarching questions: is TOD informed structure related to high accessibility by rail public transport? Which features of TOD structure affect accessibility? The paper provides a cross- comparative empirical analysis of six metropolitan areas in Europe, where the TOD degree is measured as the amount of urban development clustering along rail corridors and stations; this feature is then related to cumulative opportunity measures of accessibility to jobs and inhabitants.
The research demonstrate that accessibility increases in cities that are developed around the rail network and with higher value of network connectivity, but no correlation is found between accessibility and mean density values. The research furthermore provide an application of the node-place model demonstrating its useful potential in accessibility planning processes.

1. Introduction

A big interested has spread around TOD planning strategy (Bertolini, 1999; Curtis et al., 2009; Knowles 2012; Bertolini et al. 2012) which is based on the concept of clustering urban developments around railway stations and is viewed, under the right conditions, as offering the potential to shape polycentric cities and regions, mitigate urban sprawl, boost public transport ridership, increase biking and walking, while accommodating economic growth and creating attractive places. Since 1990, TOD has become the dominant urban growth planning paradigm in the United States, where the concept of Transit Oriented Development is closely connected with the Smart Growth (SG) and New Urbanism (NU) approaches (Cervero, 2004; Dittmar & Ohland, 2004, Newman & Jennings, 2008). The same concept has been applied in Europe, with a regional or network approach since the late 19th and early 20th centuries with the development of streetcars routes and star-shaped urban forms. After the Second World War, and until at least the 1970s, European planners were able to channel suburban development into satellite suburbs along transit served corridors. In recent years a "third generation" of European TOD is spreading in many European metropolitan areas (Crawford, 2000; Givoni & Banister, 2010; Bertolini et al. 2012), partly stimulated by the European Spatial Planning Framework indicating polycentric development as a tool (and, at the same time, a target) to achieve more cohesive territories (European Commission, 1999), and also influenced by new emerging challenges: the growth of the post-industrial service economy than in a way counterbalanced decentralisation tendencies, central expansion of mixed use development in inner city locations in ex centrally located industrial areas, urban shrinking phenomenon and the growing attention to urban retrofit practices.

There is already ample literature on TOD strategies assessment and TOD impacts analysis, but much of the interest in TOD relates to issues of travel behaviour. Specifically, the efficiency of TOD and urban rail polycentrism, in terms of commuting distances and times is at the heart of the debate (Schwanen et al., 2001). This mobility-based approach doesn't take into account the broader concept of accessibility, or in other word the degree of interaction people can accomplish in a given time. Accessibility, as an interface between the transport and land use interactions, provides a useful framework for the integration of transport and land use planning (Bertolini, Le Clercq, & Kapoen, 2005) at the regional level. Furthermore, improving accessibility has recently re-emerged as a central aim of urban planners and aligned disciplines (Lacono, Krizek, & El-Geneidy, 2010).
For this main reason, in this research we use accessibility as a tool for studying the land use and transportation system structures and in particular the TOD grade of a city, defining accessibility as the ease of reaching valued destinations and the TOD grade of a city as the measure of how much the distribution and the centrality of urban densities of inhabitants and jobs are connected to the rail network density. According to that, we study the way in which TOD polycentric urban structures affect accessibility in six European metropolitan areas, answering the following research questions: does TOD shaped urban structure has an impact on accessibility? Which features of TOD urban structure, as average density, network connectivity and shape, affect a city rail accessibility? In other word, what we aim to answer is the being and the extent of a correlation between the TOD and the rail accessibility, and to analyse how different rail network structure, density and network centralities affects accessibility values.
Grid-based data available from our cases has been organised in a systematic spatial database; an integrated data structure for subsequent analysis has been set up, with the use of a detailed spatial scale (grid cells of 1km by 1km). Regression analysis is then performed by means of suitable statistical software, using as dependent variable the cumulative rail accessibility to inhabitants and jobs and as as independent variable the TOD degree of a city, defined as the extent of how much the urban structure is developed along rail transit (tram, metro and regional rail) corridors. Geographical information systems (GIS) are used here as a powerful tool, allowing for spatial analysis and comparison, as well as visualisation of results
This research present some innovation points.
The first main innovation of this work regards the use of accessibility in analysing the land use and transport structure of cities. A large number of empirical studies on the impact of the transport and land-use factors on travel behaviour exists (Kockelman, 2007; Ewing and Cervero, 2010). However, the impact of the transportation system and land use structure on urban accessibility has attracted much less attention from researchers (Levine, 2012).
Further, accessibility metrics, while increasing in importance in transportation practice and research are rarely used to compare metropolitan areas and most empirical research measuring accessibility has been focused on case studies of single metropolitan regions (e.g., Benenson, Rofe, Martens, & Kwartler, 2010; Cheng, Bertolini, & le Clercq, 2007; Grengs 2010; Scott & Horner, 2008; Shen, 1998); while in this study we compare accessibility and TOD degree values in six different cities. Cross analysis are in fact central to moving accessibility to a more central position in transportation policy and to inferring the determinants of accessibility and accessibility change (Levine, 2012).
Another innovation is using European study cases. Empirical studies are overwhelmingly focused on the North American context and here is as yet no systematic, quantitative analysis on TOD in the European context. The paper brings in more evidence from Europe, as the pattern of urbanisation and histories and diverse spatial planning differs radically from that in the USA.
As regards the innovation point in the analysis methodology, the paper uses of a "network" approach for the analysis of TOD strategies and the application of network indicators for the measure of TOD and propose an innovative application of the node-place model (Bertolini, 1998), not just considering the station areas, but the all the accessibility zones in the study area.

The following methodological steps are undertaken in this study:

- design of methodology for data-based inspection of the relationships between TOD degree and accessibility;
- analysis of the statistical relationships between TOD degree and accessibility for each city under consideration;
- comparison between the various case studies, and interpretation of results.

The paper is organized into four sections. In Section 1 we review the relevant literature on the impacts of urban form on travel behaviour and accessibility. In the Section 2 an overview of the data and methods used of a cross-comparative analysis of six study cases in Europe is presented. Then we turn to a discussion of the results, over Section 3. On the basis of the evidence we go on to formulate some conclusion in Section 4

2 TOD urban form and accessibility in literature

The interaction between urban form and mobility has attracted much attention in the scientific literature worldwide and a growing number of empirical studies have been produced on the analysis of city morphology factors affecting travel behaviour and mobility (see Crane, 2000, Ewing and Cervero, 2001 and Ewing and Cervero, 2010 and National Research Council Committee (2009) for reviews of this literature).

In most of the study a mobility-based perspective prevails, in the sense that urban strucure is usually studied in relation to travel behaviour and mobility patterns. Accessibility measures are on the contrary less analysed, especially in cross- comparative studies.

The produced literature on this theme can be articulated as showed in the Figure 1 and five main classes can be recognized: studies on the impacts of transport system on mobility behaviour (relation 1: Crane, 1996; cite); studies on the impacts of land use on mobility behaviour (relation 2: Rickaby, 1991; Van der Valk & Faludi, 1992; Cooper et al., 2001; Lloyd-Jones et al., 2001; Schwanen et al., 2001; Dieleman et al., 2002; Banister 1997; Ewing 1995; Frank and Pivo 1994; Meurs and Haaijer 2001; Naess and Sandberg 1996; Stead 2001; Gordon et al. 1989; Kitamura et al. 1997; Van wee, 2002; Naess 2003, 2005; Schwanen and Mokhtarian, 2003, 2004, 2005; Solutions project, 2011; van Wee 2013); studies on the impact of accessibility on travel behaviour (relation 3: cite); studies on the interrelation on land use and transport (relation 4: Keyes 1976 Bruinsma and Rietveld, 1997; Miller et al. 1998; Willigers et al. 2002; Mikelbank 2004, among others); studies of the impact of urban form on accessibility (relation 5: cite). For a wider review see for example Crane, 2000, Bagley, 1999 or Handy 1996)

As regards in particular the impact of urban form on travel behaviour, with respect to the specific TOD structure, some author assert that polycentric developments around transit nodes is the urban development strategy most able to sustainably accommodate growth by reducing car use and travel distances and conserving land, but credible supportive evidence remains limited (cite). Some authors (Gordon and Richardson, 1997; Levinson and Kumar, 1994) suggest that a deconcentrated structure tends to reduce commuting distance and commuting times. The scholars in this group adhere to the `co-location' hypothesis, which states that firms and households periodically readjust spatially to achieve balanced average commuting distances and duration (Gordon et al., 1991). Other authors (e.g., Cervero, 1996; Newman and Kenworthy, 1989; Ewing, 1997) refute this positive view of the effect of policentricity on travel behaviour.

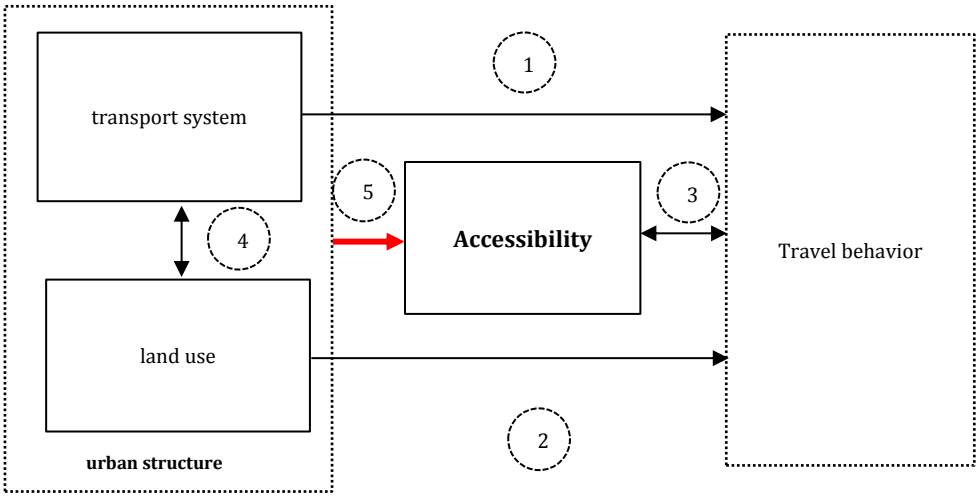


Figure 1. Literature framework on the impact of urban form on travel behaviour

Some other studies emphasise the join effect of transport / land use in analysis and focus on accessibility (Bertolini Le Clerck, 2003; Bertolini Le Clerck, 2005; Bertolini, Le Clercq, & Kapoen, 2005). Improving accessibility has recently re-emerged as a central aim of urban planners and aligned disciplines (Lacono, Krizek, & El-Geneidy, 2010).

3 Research design

There are a variety ways of measuring accessibility, networks connectivity, and density developed in the field of transportation geography and network science (cite). Selected methodology used in this paper are discussed below.

3.1Data set and spatial analysis areas and units

The GEOSTAT 1A project population grid dataset (GEOSTAT Project Team, 2012), which provides an integrated 1 km grid population dataset from national census data and the European disaggregated dataset, was used for the analysis. This grid dataset provided by the GEOSTAT project was updated with National statistical datasets, and integrated with the total number of jobs. As regards the geodataset, from OpenStreetMap (OSM) databases were derived the rail, metro and tram networks. As regards the workplaces, datasets for each study cases were constructed from the Census databases of the single Countries.

The boundaries of the study areas correspond with the circumference of 30 km radius, centred in the main station of the city centre. This distance corresponds with the average commuting distance in the different city (rif). The definition of this areas, even it differs in part with the DUS Daily Urban System functional boundaries of the metropolitan areas as defined by Eurostat's Urban Audit (RIF), allows a more systematic comparison between the study cases.

The study areas have been divided into Accessibility Zone AZ, which correspond to the grid cell measuring 1km². To each AZ socio-economic characteristics have been joined.

3.2 Study cases panel

We selected six European study cases with a total population between 1 and 4 million inhabitants, according to the main criterion of getting an heterogeneity of key land use and mobility variables: population, jobs and relative densities as regards the land use characteristics (see Table 1) and modal share of home-to-work trips as regard the transport system features (see Table 2). Total areas also differ because water and other natural unbuilt areas are not computed in the sum. This heterogeneity has to be borne in mind when interpreting the results.

Table 1 – Structural land use variables of the study cases (Source: Eurostat's Urban Audit)

	Area	**Inhabitants and jobs**	**Average Population ad jobs density**
	[sqkm]	*[inh + jobs]*	*[inh + jobs / sqkm]*
		2011	*2011*
Amsterdam	1,973	4,207,435	1,714
Helsinki	2,147	1,596,723	744
Munich	2,219	3,528,261	1,590
Naples	1,906	4,627,604	2,428
Rome	2,321	4,500,970	1,939
Zurich	2,647	2,337,367	883

Table 2 – Structural mobility variables of the study cases (Source: Eurostat's Urban Audit [(a)]2004; [(b)]2011; [(c)]2001)

	Transport supply			**Modal share journey to work**						**Congestion level (tom tom)**
	number of registered cars per 1000 inhabitants	Rail network		car	PT	motorcycle	foot	bicycle	Average home to work journey time	
	[n]	*[Km/ mln inh]*	*[n. stations/ mln inh]*	*%*	*%*	*%*	*%*	*%*	*[min]*	
	2009	*2013*	*2013*						*2009*	*2001*
Amsterdam	257	18	13	41[(a)]	30 [(a)]	3[(a)]	4 [(a)]	22[(a)]	31	17%
Helsinki	408	15	16	51.4[(b)]	30.8[(b)]	0.3[(b)]	9.8[(b)]	7.7[(b)]	27	17%
Munich	354	28	16	41 [(a)]	41.3[(a)]	0.4[(a)]	9.1[(a)]	8.2[(a)]	26	24%
Naples	575	15	6	53.9[(c)]	26.1[(c)]	6.9[(c)]	13[(c)]	0.1[(c)]	31	23%
Rome	698	14	8	57.4[(c)]	23.3 [(c)]	11.7[(c)]	7.4[(c)]	0.2[(c)]	37	36%
Zurich	361	26	26	23.7[(c)]	62.6[(c)]	1.3[(c)]	7.5[(c)]	4.9[(c)]	26	n.d.

3.3 Dependent and independent variables

The independent variable is the TOD level of a city, defined as the extent of how much the urban structure is 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 settlement along the rail transit transport networks that serve them.
We measure this value with the use of the Node-place model (Bertolini, 1999): for each Accessibility Zone AZ we measure a "node index" and a "place index" and we analyse the bivariate scatterplot distribution in a xy graph of the value assumed for each AZ belonging to the study area. The TOD grade is then described by trend and the strength of the relationship of the two variables.
The node index for a zone is calculated as the inverse of the average of cumulative distance required to reach from that zone from all the zones in the analysis area along the shortest paths measured along to the public transport network (regional rail, metro and tram). The node index for each Accessibility Zone AZ is based on the measure of two components, considering the trips from each zone is composed on two aliquots: the trip on the rail, metro and tram network; the trip from / to the AZ to the nearest station.

$$node\_index_{AZ} = \frac{1}{station\_dist_i + \beta \cdot dist_{iAZ}} \quad (1)$$

where:

$$station\_dist_i = \sum_{j=1}^{N} \frac{d[i,j]}{N} \quad (2)$$

where:
$d[i,j]$ is the shortest path distance between the $station_i$ and $station_j$ measured on the rail transit network (regional rail, metro and tram);
N is the total number of station;
$dist_{iAZ}$ is the distance from the AZ to the nearest station *i*;
β is a parameter that takes into account the difficulty of reaching the station increasing with the distance itself.
In order to compare the different cities, a normalized node_index has been calculated for each city according to (3), where N_{max} is the maximum number of stations within the study cases.

$$node\_index_{AZnorm} = \frac{1}{\frac{N_{max}}{N} \cdot station\_dist_i + \beta \cdot dist_{iAZ}} \quad (3)$$

The place index of a AZ is the density of inhabitants and jobs of each zone AZ, according to the following formula:

$$place\_index_{AZ} = \frac{inh_{AZ} + jobs_{AZ}}{Sup_{AZ}} \quad (4)$$

For each city the resulting scatterplot has been analysed in order to evaluate the correlation of the two variables and to identify the regression model that better describes the distribution of the variables. In particular the R2, the correlation index, the maximum and mean values of the node and place indexes, has been analysed (see table x).
The dependent variable is an accessibility measure. A cumulative opportunities measure of accessibility is implemented at the AZ level, measured as the number of inhabitants and jobs reachable in 30min by rail public transport (rail, metro and tram). The time limit of 30 min has been defined according to the average time of journey to work in the different cities (see Table 2).
The PT accessibility index of a AZi has been measured according the following formula:

$$AccPT_{AZ}^{30} = \sum_{AZ \in G, t_{AZ} \leq 30\min} (inh_{AZ} + jobs_{AZ}) \quad (5)$$

where:

t_{AZ} is the average shortest time to reach the zone AZ and is given by the sum of two component of two components: the average shortest time to reach the station on the regional rail, metro and tram network and the time to reach the AZ from / to the nearest station.

$$t_{AZ} = station\_t_i + \beta \cdot t_{iAZ} \quad (6)$$

where:

$station\_t_i$ is the shortest time to reach the station i measured on the rail transit network (regional rail, metro and tram);

t_{iAZ} is the distance from the AZ to the nearest station i;

β is a parameter that takes into account the difficulty of reaching the station increasing with the distance.

4 Cross-sectional comparison - outputs

The cross-sectional analysis was made in two steps. In the first phase the dependent and independent variables for the different study cases have been calculated and analysed. In the second step the focus is set on the correlations between the two.

4.1 Outputs of cross sectional TOD degree and accessibility analysis in the study cases

The independent variable analysis for each study case lead to the definition of six node-place model scatterplots where on the x axis is set place index, and on the y axis is set the node index (Figure 4). In all diagrams the maximum x and y values are set on the same value in order to allow the visual comparison of the scatterplots. (Figure 4). For each scatterplot the correlation index, the r squared, the maximum of node and place indexes, and the coordinates of the scatterplot centrum are calculated (Table 3). It is important to underline that the measure of the r2, that quantify the degree to which the regression equation matches the scatterplot, has not the scope of analysing the correlation between the node and the place index, but to synthetically describe the scatterplot shape, and the inclination of the scatterplot line model. Also a geo representation of the place and node indexes is shown in Figure 2 and 3. The scatterplot help to compare the different interrelation and scatter distributions in the six study cases, while the maps allows to visualized the different spatial distribution of node and place indexes in the Accessibility Zones.

The dependent variable measurement is reported in form of maps for each study case (Figure 5) and summarized in Table 4.

From the comparison of the TOD degree in the different cities, it is clear how TOD polycentricity has extremely different forms in the analysed study cases. The patterns of deconcentration differ significantly across the six urban systems, ranging from the “strong core structure” (i.e. Munich and Rome), to the “fully networked city-region” (i.e. Amsterdam, Zurich and Naples), to the “corridor structure” of Helsinki. The scatterplots clearly show the differences within cities even belonging to these three main categories, with a prevalence of “unbalanced places” in the cases of Naples, where the urban activities are relatively more developed than the transport systems, or a prevalence of “unbalanced node”, where the opposite is true as in Zurich. The average values foe each study cases in terms of maximum and mean values of node and place indexes.

As regards the values of the TOD degree in the six study cases, cities with higher correlation between the node and the places indexes, or in other words cities that are more developed around rail network

are Amsterdam (R = 0,74) and Munich (R = 0,74), while the city with the lower value is Naples (R=0,54).

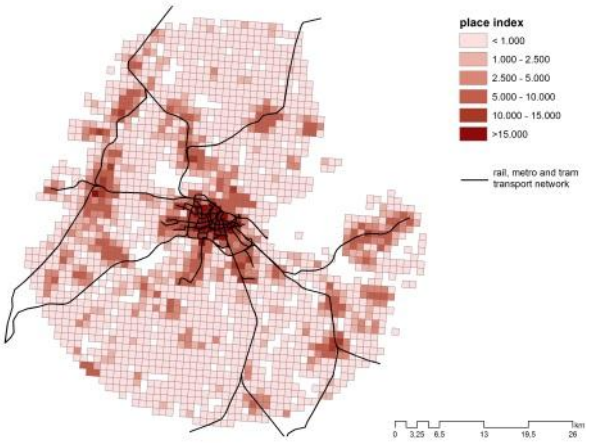
Table 3 – Comparison of the independent variables in the study cases: the TOD grade

	R	R2 linear	R2 Polynomial (2)	Linear regression line slope	Max value of node index	Mean value of node index	Max value of place index	Mean value of place index
Amsterdam	0.74	0.55	0.56	2.53E-06	0.074	0.020	31,389	1,712
Helsinki	0.62	0.39	0.43	2.72E-06	0.055	0.012	19,924	744
Munich	0.74	0.54	0.56	2.62E-06	0.071	0.024	23,733	1,589
Naples	0.54	0.29	0.32	5.11E-07	0.026	0.012	48,453	2,427
Rome	0.70	0.49	0.53	1.79E-06	0.063	0.017	47,405	1,939
Zurich	0.62	0.38	0.39	3.24E-06	0.061	0.024	16.296	883

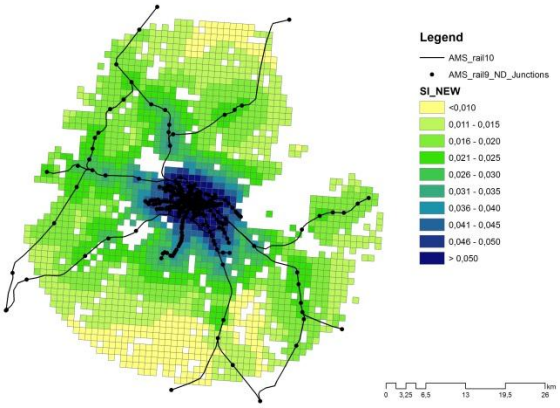
As regards the values of accessibility in the six cases, the mean values are summarized in Table 4 and shown in figure 5 for the single grid elements. Amsterdam is again the study case with the higher mean value (75%), and Naples is the city with the lower value of average accessibility (11%).

Table 4 – Comparison of the dependent variables in the study cases: the accessibility to jobs and population by rail, metro and tram within 30 minutes

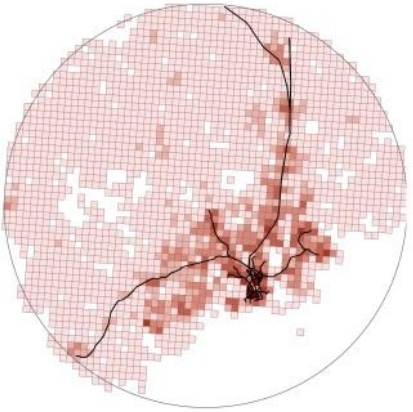
	Accessibility to jobs and inhabitants by rail, metro and tram within 30 minutes
Amsterdam	74,99%
Helsinki	55,45%
Munich	44,95%
Naples	10,82%
Rome	50,94%
Zurich	31,05%



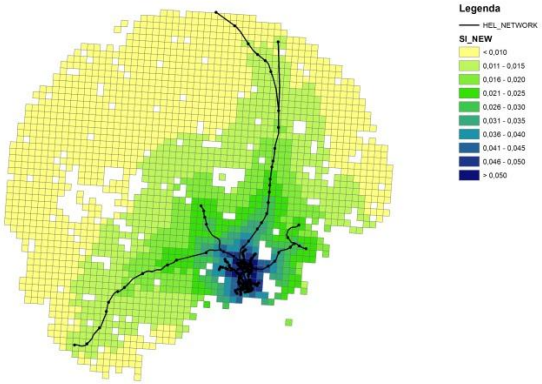
Amsterdam place index



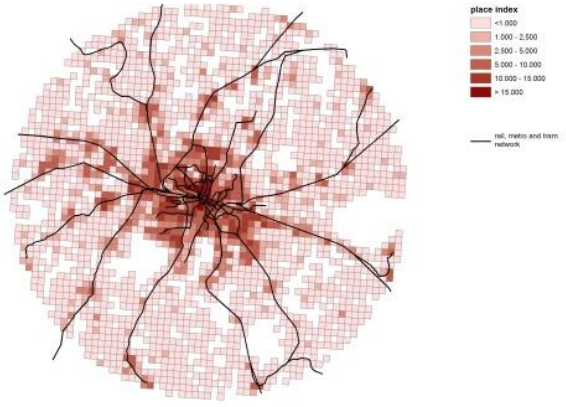
Amsterdam node index



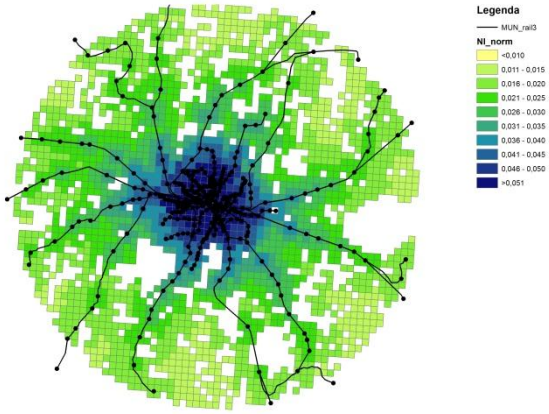
Helsinki place index



Helsinki node index

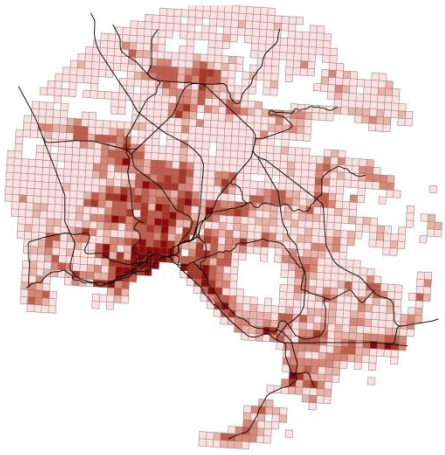


Munich place index

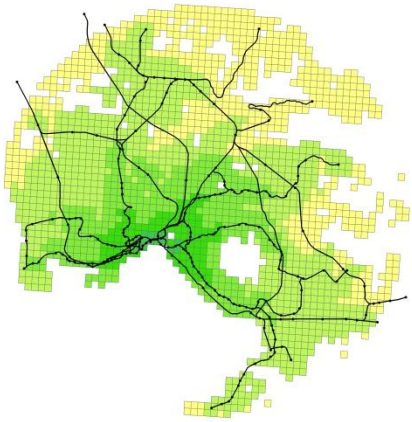


Munich node index

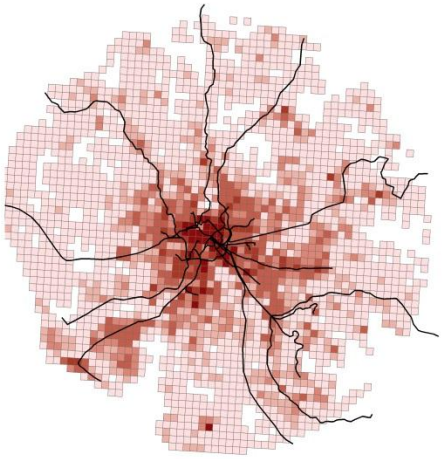
Figure 2 – the node and the place index (Amsterdam, Helsinki and Munich)



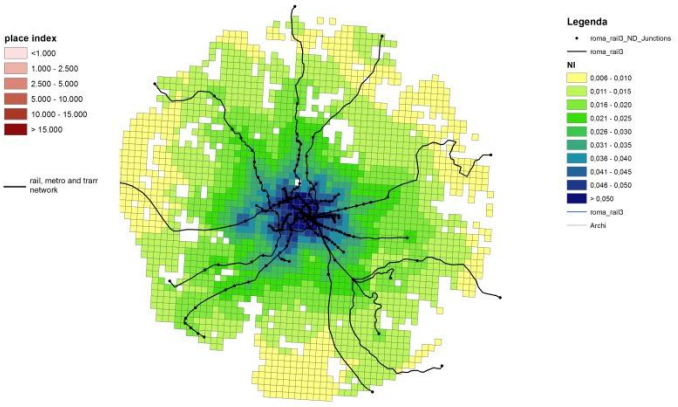
Naples place index



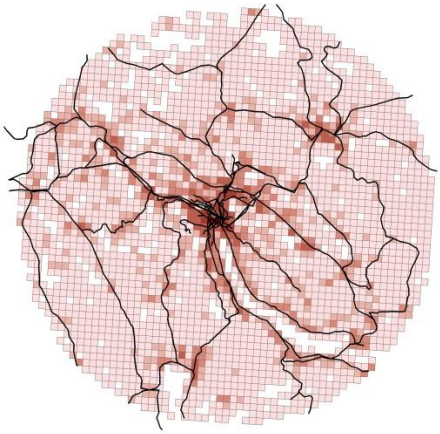
Naples node index



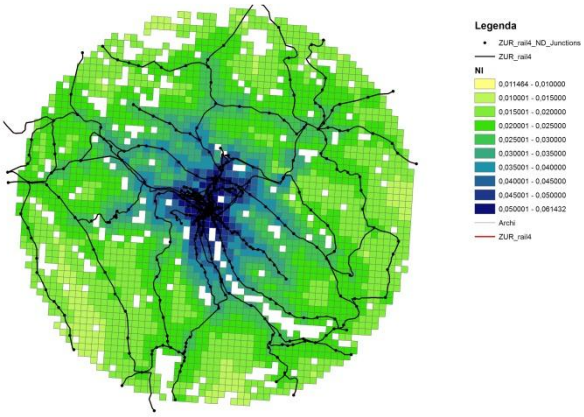
Rome place index



Rome node index



Zurich place index



Zurich node index

Figure 3 – the node and the place index (Naples, Rome and Helsinki)

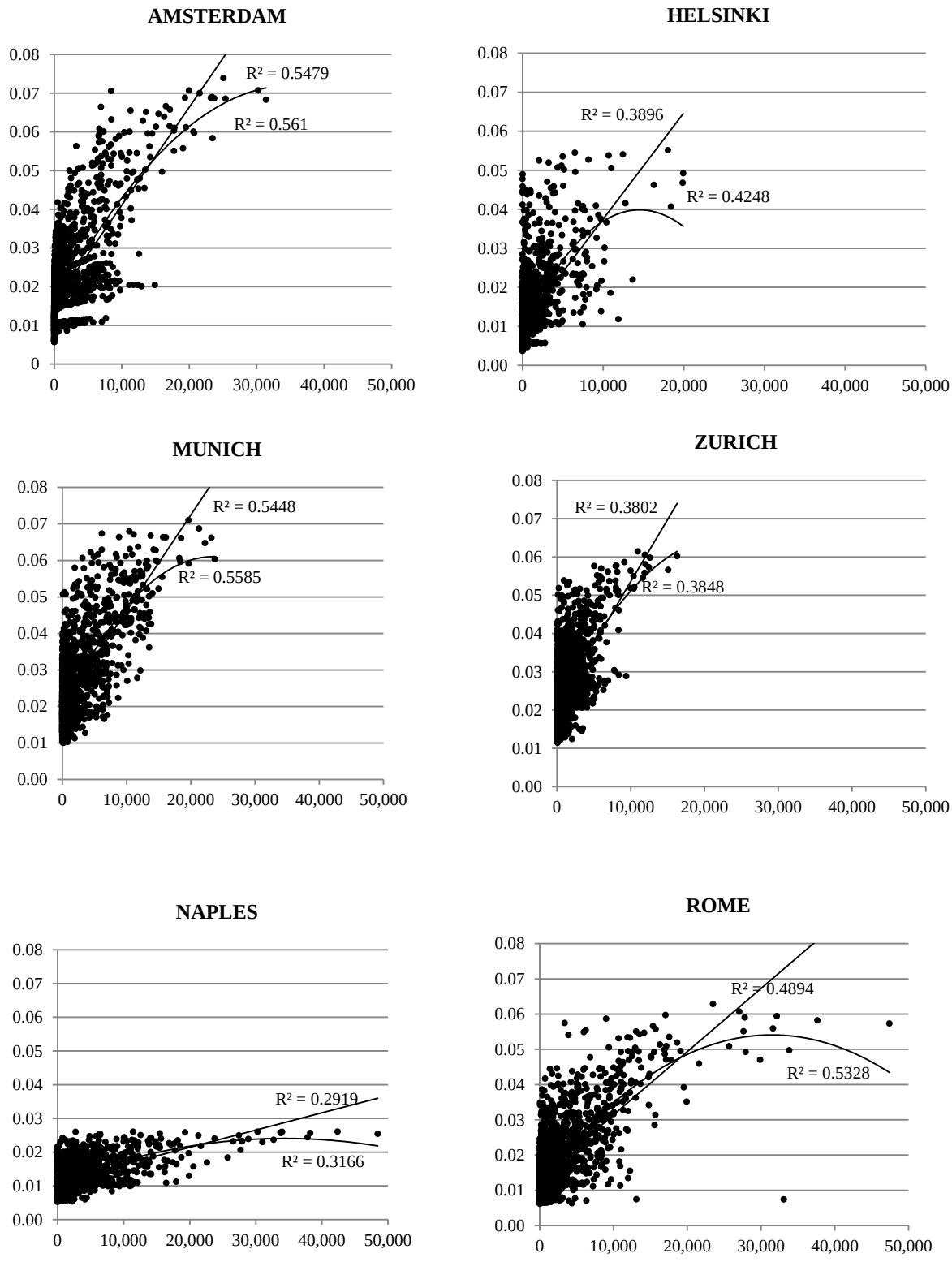
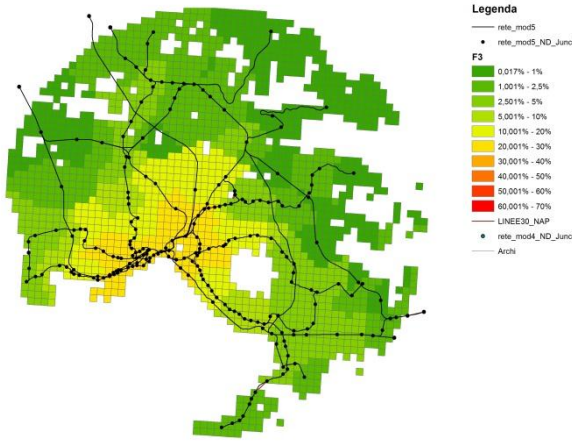
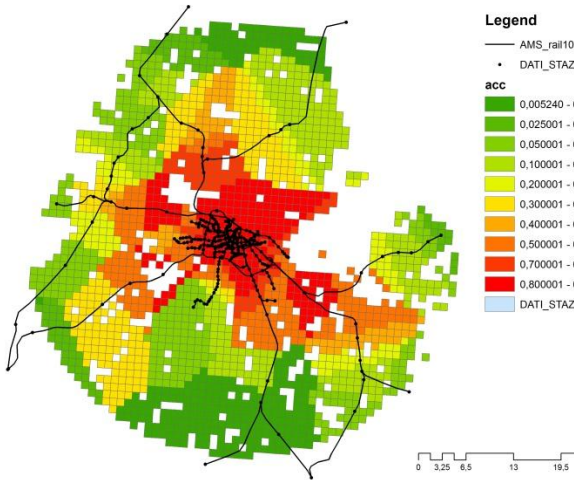


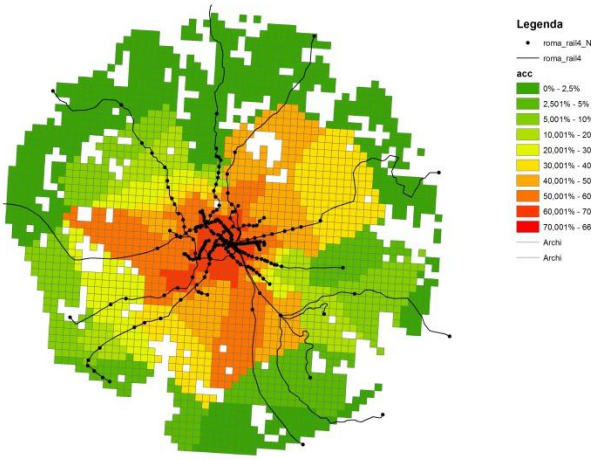
Figure 4 – the node - place model for each study case



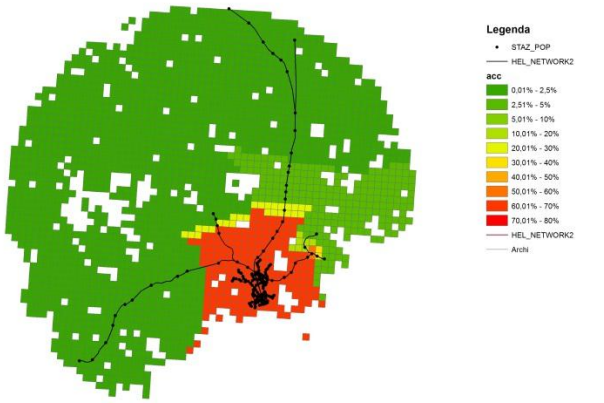
Naples accessibility



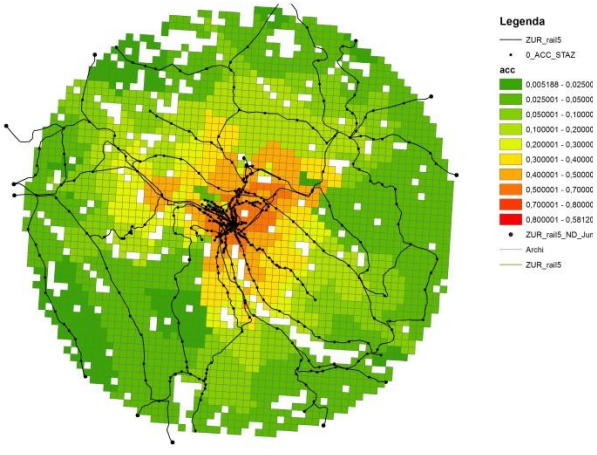
Amsterdam accessibility



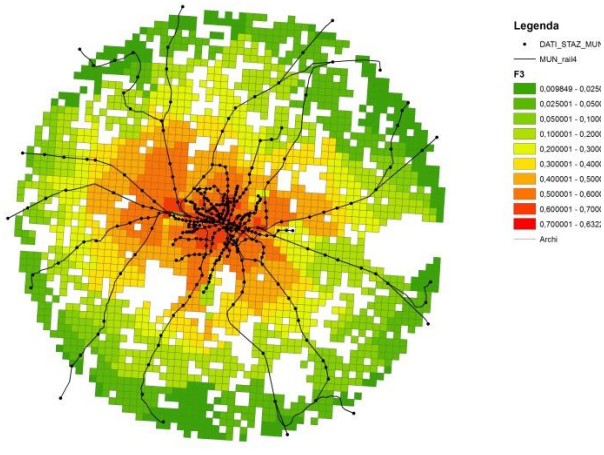
Rome accessibility



Helsinki accessibility



Zurich accessibility



Munich accessibility

Figure 5– the accessibility measure in the different case study

4.2 Outputs of correlation analysis

The outcome of the correlation analysis is summarized briefly as follows (see Table 5):

- a significant direct relationship was found between the index measuring TOD degree (in term of correlation index R, R2 linear and R2 polynomial) and accessibility, in line with the expectations expressed in the international literature.
- a less strong positive relationship also exists with the variables representing the mean and the maximum node index and the accessibility indicating that the accessibility impact was higher when the network connectivity was higher
- on the other hand together with the size of the urban areas in terms of absolute population and jobs, average density appears to have no effect on the accessibility values.

Here we have two interesting results: accessibility is strongly affected by the TOD level of a city. In fact, accessibility increases, when the form of development becomes structured along the rail network (the node index and the place indexes are correlated) and the node indexes values increase. Accessibility values, on the other hand, do not react either to density or compactness of development.

Table 5– Correlation indexes (power function)between the variables

	R	**R2 linear**	**R2 polynomial**	**regression line slope and accessibility**	**Mean value of node index**	**Max value of node index**	**Mean value of place index**	**Max value of place index**
R2 with accessibility	0,93	0,92	0,86	0,32	0,49	0,72	0	0,02
R with accessibility	0,92	0,93	0,90	0,31	0,81	0,54	0,01	0,15

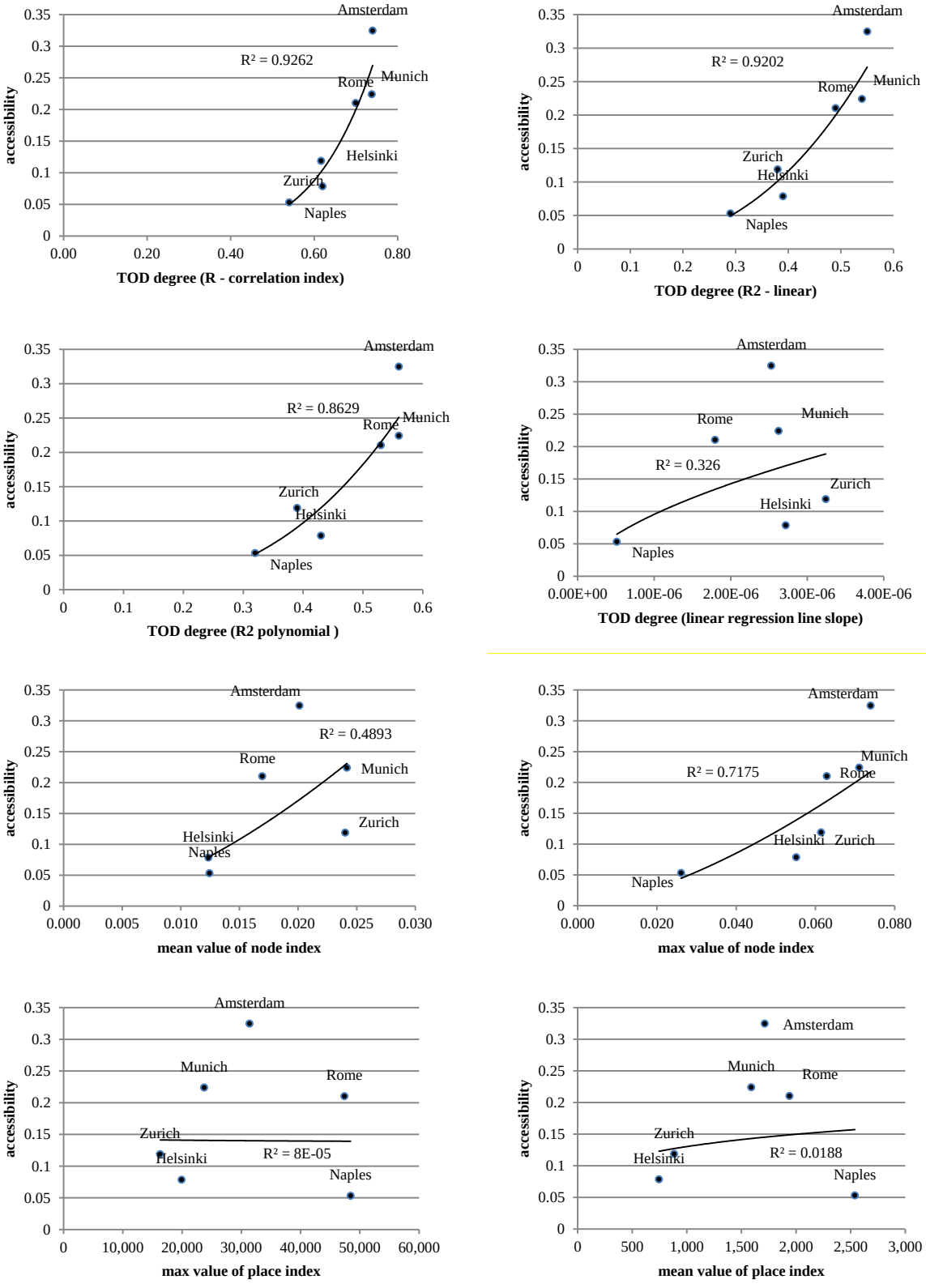


Figure 6– correlation analysis

5 Conclusion

TOD city structure is becoming one the most used development strategy for city region. Furthermore accessibility is being used by transportation and urban planner as a tool for assess and plan new urban development solutions. Accessibility metrics, while increasing in importance in transportation and spatial planning practice and research, are rarely used to compare metropolitan areas.
It was in this context that the present empirical analysis was developed, with the aim of establishing, whether TOD patterns of urban expansion, in particular in terms of network connectivity and inhabitants and job density could be associated with measures of rail accessibility.
This research provides a new methodology and dataset to enable metropolitan comparisons of network connectivity, density and accessibility in a way that is clearly understood and explainable, and that does not require complex mathematical calculations.
The paper provide empirical evidence to the existing literature, according to which an auto-oriented metropolitan form is also a low-accessibility form (Curtis & Scheurer, 2010; Ewing, 1994). As far as TOD degree is concerned, in fact the research demonstrate that accessibility increases in cities that are developed around the rail network and which have higher value of network connectivity. This was in line with expectations. According to this the developed methodology and the TOD degree measure as proposed in this paper, can be a useful tool for measuring accessibility at the metropolitan scale. Furthermore the study demonstrate that the node-place model can be used in the accessibility planning processes as a powerful tool to identify the land use or network connectivity intervention for each spatial zone within the city, directly related the single intervention to the whole city accessibility level. The study furthermore enlighten that while the connectivity of the rail transit network has a key role in gaining accessibility level, it is not the same for the average density distribution of activities.
No relations can be found with the values of rail accessibility and the modal share journey to work. This result is coherent with the some studies (Schwanen et al., 2001; altri) that demonstrate that travel behaviour and transit modal share depends on the nature of the polycentrism.
This research has several implications for urban and transportation planning. The network structure and its connectivity has a main role in increasing urban accessibility rather than the increase of densities. Planners can intervene to make cities more (or less) inter-connected through design and investment decisions, with a direct implications for resultant urban accessibility, how individuals use cities, the scope of their activity space.

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