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Influence of Accessibility, Land Use and Transport Policies on the Transport Energy Dependence of a City

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Abstract

Transports can be considered as the main contributors of climate change and cities' total energy consumption. In order to reduce transport energy, which is mainly influenced by urban form and available systems, three strategies can be adopted: a land use distribution lowering the need of motorized mobility; adoption of measures fostering low impact transport modes; promotion of energy efficient vehicle fleets. The aim of this paper is to evaluate the suitability of accessibility measures as a planning tool to evaluate the effectiveness of integrated transport and land use policies adopted to reduce the transport energy dependence of an urban area.

Keywords: transport energy; sustainable mobility; accessibility; land use; transport planning.

1. Introduction

Nowadays it's widely recognized the need for a change of approach in the discipline of transport planning from the traditional one towards sustainability, well explicated in the "paradigm of sustainable mobility" (Marshall, 2001; Banister, 2008). Planning should be based on the desired level of connectivity between urban functions and improving the quality of life rather than on predictions of future levels of congestion (Banister, 2002).

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A radical change in the approach towards sustainable mobility is also needed to ensure a more energy-efficient and climate proof transport system. In 2011 transport used one third of all energy and 70% of all oil in EU (EC, 2013). Urban areas produce 25% of all CO2 transport-related emissions (EEA, 2013) and they are home to 70% EU population and generate 85% of the Union's GDP (EC, 2009) so meeting the climate change targets and reducing energy oil dependency is primarily a role of local communities.

The ASIF framework (Activity – modal Share – fuel Intensity – Fuel type, Schipper et al., 2000) is the most recognized methodology used to define the relation between transportation energy consumptions and urban policies. Working on the two first components means looking for some correlation between transport system and activities; some of the available models make aggregated statistical correlations among urban density and fuel consumptions. Others are based on sophisticated transport demand behavioral approaches to transport mode choice and transport energy consumption.

Yin et al. say that there are two reasons for analyzing consequences of urban form by energy consumption. First, from the physical stand point, the urban spatial configuration and land use affect the total amount of energy consumption. Second, the density and intensity of activities, such as traffic and industry, is a major factor influencing energy consumption. Actually those issues have been long debated among supporters and detractors of the compact city (Breheny, 1994, 1995; Owens,1995; Haugton and Hunter,1996; Newman and Kenworthy,1999; Camagni et al.,2002). At the same time, it's very difficult to understand what type of transport and land – use policies are most efficient to achieve the target level of energy consumption and how to incorporate transport energy into urban planning (Saunders et al., 2008).

To this aim a simple land use and transport model is presented to calculate a transport energy indicator to support the delivery of sustainable urban and transport plans. Besides the correlation between different accessibility measures and transport energy at the scale of neighborhood is explored. The transport model is based on a mathematical description of the transport system, while the land use model consists of geographically-based socioeconomic data and demand flows according to the travel purpose at the traffic zone scale. Transport mode choice follows ideal simple rules based on the minimum distance from origin to destination and zone accessibility. Assignment of flows among origin and destination zones to minimize transport energy and CO2 emissions is formulated as a standard transportation problem. The model has been applied to the urban area of Catania simulating different planning scenarios, and the results are in terms of transport energy consumption, CO2 emissions, travelled distance, modal share for each transport mode at different scales, both at the traffic zone level and at the urban area. Statistical correlations are found among low transport energy neighborhoods and accessibility measures. The results at the zone level are used to compare the different scenarios within the same area, but they can also be used to compare different cities or the same city over time according to its forecasted evolution.

The paper is structured as follows: in the following section a literature review of past research is discussed. Then the methodology is illustrated with reference to the method used to estimate the energy consumption and the accessibility index. In the case study section, a description of the study area is given, with the indication of selected statistics and figures regarding the input data. Model is applied and its empirical results are presented. The final chapter will give conclusive reflections and policy implications.

2. Literature review

The urban mobility patterns and related energy consumptions are affected by the dimension, density, design and transport level of service of the city, as well as by socio-economic features.

Newman and Kenworthy (1989) found that transport related fuel consumption is reduced by urban density. The idea is that higher density increases the probability of shorter trips' length and then walking and public transport use. Karathodorou et al. (2010) estimated a fuel demand model and found that urban density affects fuel consumption, mostly through variations in the car stock and in the distances travelled, rather than through fuel consumption per kilometer. In Lefèvre (2008) through the application of an integrated ''transport–land uses'' model, TRANUS, it's demonstrated that transit technologies can significantly curb the trajectories of energy consumption and the ensuing carbon dioxide emissions, if and only if they are implemented in the framework of appropriate urban planning. Furthermore, the study establishes that there are tools which are available to facilitate the necessary policy-making processes and can allow stakeholders to discuss different political alternatives integrating energy issues, based on quantitative assessments. Wang et al. (2015) propose a new approach for reducing both the energy and resulting carbon emissions from urban travel, in the form of a personal transport energy quota, using a unique cloud technology based intelligent navigation system.

Compact, transit accessible, pedestrian oriented, mixed use development patterns and land reuse epitomize the application of the principles of Smart Growth and other popular movements and planning approaches for urban sustainable development, such as New Urbanism and Transit Oriented Development (La Greca et al., 2011). Planning for high density has two main goals in the context of transport energy consumption: reducing trip length and total mobility by concentrating residential, employment and services areas (Cervero, 1988); changing the modal split to reduce the share of the private car use in relation to public transportation, walking and cycling (Barrett, 1996). The effectiveness of a land use policy towards higher densities and mixed use is affected by the willingness of the population to accept high levels of density and by their social attitude towards a change in modal split from the private car to public transportation and non-motorized modes. Mode choice behaviour is also affected by the level of service and accessibility provided by low energy transport modes, by car ownership rate and by the transport demand measures adopted to limit the use of cars. Besides, a non-compatible planning of mixed land use might result in higher values of vehicle kilometers travelled to reach activities that may be located far away (Mindali et al., 2004).

In this respect it seems interesting the concept of transport energy specification that Saunders et al. (2008) introduced as a tool to incorporate transport energy into urban planning. It is calculated as a function of the land use and the transport system of an urban area with the aim to ensure development occurs within a defined design boundary. The transport energy specification is not bound to the complex modeling described above. It is a simple indicator of the minimum transport energy used if people would select the most energy efficient mode of transport available according with simple rules based on the distance between land use locations. In synthesis it is not an estimate of the real transport energy consumption but a calculation of transport energy dependence.

Based on Saunders' approach, in previous studies (Inturri et al., 2014, Ignaccolo et al. 2015), the authors built a new methodology to calculate a transport energy dependence (TED). The TED index is applied to a whole urban area. And it's applied using an optimal assignment model to distribute flows of workers to their workplaces in order to minimize the total transport energy used in the whole urban area. As in the work of Saunders, we use a mode choice model based on simple rules, but it is also conditioned by the accessibility of all different transit system which are explicitly represented; the option of intermodal trips is included.

In this work relationship among accessibility index and TED index will be investigated, in order to verify if there's a significant statistical correlation between them as to prove that information on accessibility measures can facilitate a transport energy evaluation.

3. Methodology

Planning for accessibility requires indicators of adequate accessibility that can include the quantity and quality of opportunities that can be achieved within a fixed threshold time or distance or cost, available for a given social group. There is indeed a growing literature on indicators of accessibility (Bruinsma and Rietveld, 1998; Geurs and van Wee, 2004; El-Geneidy and Levinson, 2007) and each indicator refers to one or more components that can affect accessibility: transport system and its impedance; spatial distribution of activities in the study area; spatial distribution of the different social classes (demographics, income, car ownership, age, etc.); time threshold, seen as availability of services and territorial opportunities.

An ideal measure of accessibility should take into account all the components and their impact on sustainability; in practice the measures generally focus some aspects, typically those related to the perspective used (transport, land, geography, economy) and will neglect the other in varying degrees.

In this study we decided to compare the results from two different accessibility gravity measures. Hansen's Accessibility Measure (Hansen, 1959), which defines accessibility as the potential of opportunities for interaction, as indicated in equation 3.1:

$$A_i = \sum_{j=1}^{n} \frac{O_j}{d_{ij}} \tag{3.1}$$

According to this formula, the accessibility for each zone *i* is given by the summation of opportunities *O* available at each zone *j* divided by the impedance *d* to go from *i* to *j*.

In order to compare results from two different accessibility measures, we also applied Agyemang-Duah and Hall Accessibility Measure (Agyemang-Duah and Hall, 1997), as indicated in equation 3.2:

$$A_i = \sum_{j=1}^{n} O_j \cdot e^{-d_{ij}} \tag{3.2}$$

According to this formula, the accessibility for each region is given by the summation of opportunities *O* available at each zone *j* multiplied by an exponential negative function of the impedance *d* to go from zone *i* to *j*.

The TED calculation methodology is based on three interacting models: land use, transport and energy. The land use model specifies the number of residents and activities present in each traffic zones the urban area has been subdivided in. Each traffic zone is assumed to generate a demand flow to all other zones as a function of the number of residents and a fixed trip weekly frequency for each type of destination (workplace, retail, services, etc.). The transport model provides a mathematical description of the road, transit, pedestrian and cycling networks and calculates the shortest distance between each OD pairs for each transport mode. Then the transport mode choice model assigns a transport mode to each OD pair following a set of simple fixed rules based on the length of the trip and transit accessibility. Then the optimal distribution of demand flows among ODs is calculated by solving a standard transportation problem (Hillier and Lieberman, 2001) to minimize the total transport energy in the urban area. Then, for each planning scenario s, the total amount of transport energy of the urban area, the so called "Transport Energy Dependence" TEDs (MJ) can be calculated with the following expression:

$$TED_s = \sum_o \sum_d t_{od} \cdot l_{od} \cdot \frac{e_v}{c_v \cdot LF_v}$$

being

t_{od} number of trips assigned from zone o to zone d to minimize Z (passengers)

l_{od} shortest distance between zone o and zone d (km)

e_v unit energy consumption of the transport mode chosen (MJ/km)

c_v capacity of the vehicle (spaces)

LF_v load factor (passengers/spaces)

For a given scenario, TEDs is the minimum energy that in a week would have been consumed if, given a fixed distribution of population and urban functions, and transport mode options, every person could work in the nearest workplace and would choose the best available transport mode for each distance range to be travelled. Of course the model can be easily extended including other weekly trips made by the population for other reasons (school, shopping, entertainment, etc.). If TED (MJ/week) is divided by the total number of urban population N and expressed in MJ/person/week, it can be used to compare different cities or the same city over time according to its forecasted demographic evolution. When TED is divided by total travelled distance and expressed in MJ/pax-km it can represent a clear indicator of the energy efficiency of the transport system in the urban area. When different scenarios have to be compared within the same urban area, TED_i (MJ/person/week) can be computed for each traffic zone i according to the number of residents Ni.

Correlation between the two different accessibility measures and transport energy both at the globally and at scale of neighbourhood will be explored in the Catania's urban area case study presented in next section. The methodology has been tested to evaluate the transport energy dependence related to university students' and workers' daily trips.

4. Case Study

4.1. General Features from the urban area of Catania

The methodology has been applied to the urban area of Catania, a medium-sized city (300,000 inhabitants) located in the eastern part of Sicily, Italy. The city is part of a greater Metropolitan Area (750,000 inhabitants), which includes the main municipality and 26 surrounding urban centers, some of which constitute a whole urban fabric with Catania. The case-study can be considered as quite significant for similar urban areas, which are characterized by medium population density (about 7,000 people per km2 in the urban area of Catania) and size (about 45 km2), a strong attraction towards the central business district from the surrounding areas, heavy car traffic volumes along radial routes mainly for commuting purposes (about 20,000 vph during the peak hour of the average working day) and a limited public transport ridership. The main city contains most of the working activities, mixed with residential areas. Even if several attraction polarities (hospitals, main schools, shopping centers) are spread over the whole territory, the transport demand pattern is mostly radial. The modal share for public transport is about 15%, while the amount of travelled kilometers by bicycle is negligible (even if increasing), thus leading to a modal share of individual transport close to 85%. Regarding transport supply, the urban road network is about 700 km long, and it consists of a highway ring connecting all radial highways to the other Sicilian towns, few internal major roads (as 'extensions' of the main highways and rural roads) and an internal road network, which lacks a complete hierarchical organization. The urban public transport consists of an extensive regular bus services network (about 250 km long), and a short metro line, mainly underground, of less than 4 km, which is going to be extended to 11 km within a couple of years. Traffic congestion, limited public transport utilization, little diffusion of cycling and walking for systematic trips, inefficiency of the parking management, absence of city logistics measures are the main critical issues for the transport system of Catania.

4.2. Transport system

The transport model consists of:

- Transport demand: only commuting flows are considered; a frequency of 5 home-to-work trips/week is assigned to all employed population; a frequency of 5 home-to-school trips/week is assigned to all university students population.

- Transport supply: the road network is composed of 516 nodes and 1122 links; transit network considers 49 bus lines, 4 BRT lines and 1 metro line. The transport network is implemented within PTV VISUM software package used to compute the shortest path between all origin and destination pairs by all modes of transport. When more transit systems are available, the shortest path is a combination of them, thus including the option of transit intermodality.

Fig. 1a shows the coverage of the transit network operated with regular bus lines, Fig. 1b is the road network available for private transport, walking and cycling.

Bus network (a) Road Network (b)

Fig. 1. (a) Bus network and (b) road network in Catania.

The land use model considers a subdivision of the urban area in 50 traffic zones (Fig. 2). For each zone the following information are available: households, employed population, non-working population, number of activities and number of workplaces. In both cases (students and workers) we defined the opportunities *Oj* as the total number of employment/study positions in *j* and the impedance *d* as the distance between *i* and *j* as calculated by the transport mode choice model included in the TED calculation.

Fig. 2. Zoning of the urban area of Catania.

4.3. Transport mode choice model

Transport modes considered are: walking, cycling, regular bus transit, Bus Rapid Transit, metro and private car. The shortest distance among each pair of traffic zones is calculated; distances are measured on the road network and are assumed to be the same for walking, cycling and car modes. Then for each OD pairs of zones, the following simple mode choice model is adopted:

- If the distance to the first available workplace (or university) is less than 500 m, then walking is the chosen mode;
- If the distance to the first available workplace (or university) is less than 1000 m, then cycling is the chosen mode;
- If conditions 1 and 2 do not occurs and the zone transit network density (both in origin and in destination zones) overcomes a "transit network density threshold" (calculated as described soon after), then transit is used;
- If none of the previous conditions occurs, then private car is used.

There is not an explicit representation of the internal pedestrian and cycling paths within each zone, so the "equivalent radius" of each traffic zone is calculated as the radius of the circle having the same area. As far as the number of workers does not exceed the available workplaces of a zone, they are assumed to reach their works by walking or cycling within their origin zone, if the equivalent radius is less than 500 m or 1000 m respectively; otherwise, motorized modes are taken into consideration.

The transit network density threshold is calculated as the one corresponding to the maximum distance a person is willing to walk to access a transit stop, assuming a uniform distribution of the lines along a grid street pattern within the zone, according with the scheme in Fig. 13. In Table 1 the threshold is calculated for the bus, BRT and metro considering an increasing willingness to walk to the stop as a function of the transit system performance (Dittmar et al., 2004). For each zone and each transit system the transit network density is calculated as the ratio between the total extension of the transit lines crossing the zone and its area. It is expressed in km/km2.

Fig. 3 Transit density threshold to walk to stop

4.4. Scenarios

Methodology is applied to test the land use and transport planning strategies described in four different scenarios for worker's trips. Scenario 0 represents the present situation and the baseline for evaluating other scenarios. Scenario 1 represents a short term transport policy, where the catchment area of the bus system is enlarged by improving the easiness to access the transit stops, through better pedestrian infrastructures, pedestrian safety measures and car traffic calming measures meant to favor walking to transit. Using the concept of equivalent distance (Wibowo et al., 2005), it is assumed that all measures adopted will increase the maximum willingness to walk to the nearest transit stop from 300 m of the scenario 0 up to 400 m in the scenario 1. The consequence is that the bus network density threshold is reduced and the number of zones overcoming the limit is increased from 10 of scenario 0 to 26 in scenario 1 (Fig. 14).

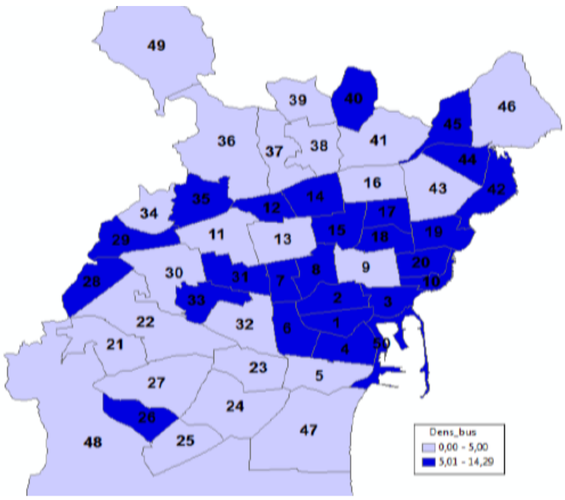

Fig. 4 Distribution of bus network density in scenario 1

Scenario 2 is a medium-long term transport policy where the transit network is enhanced by the introduction of four BRT lines and the extension of one metro line (Fig. 15). Again, the transit density thresholds are lowered.

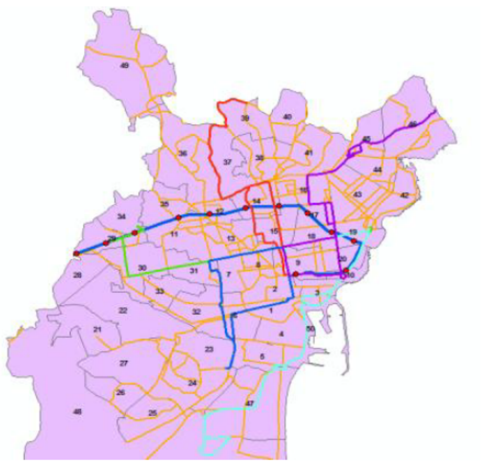

Fig. 5 Transit network in scenario 2: regular bus (orange), metro (thick blue), BRT (other colours)

Scenario 3 represents a long term spontaneous land use change. It assumes a 10% increase of density in the zones directly served both in origin and destinations by the metro line as a consequence of the re-locations of households from all other zones attracted by the accessibility improvement. The scenario may simulate the effect of adopting the so called Transit Oriented Development policies.

4.5. Results

4.5.1. Correlation between TED and Accessibility Measures at neighborhood level

As expected, in all analyzed cases, a correlation has been found between transport energy dependence measure and accessibility measures. In particular, for both Hansen's (Fig. 5) and Agyemang-Duah and Hall's (Fig. 6) index, for low accessibility values, TED values are decreasing through a wide range, assessing in more stable low values for high accessibility index.

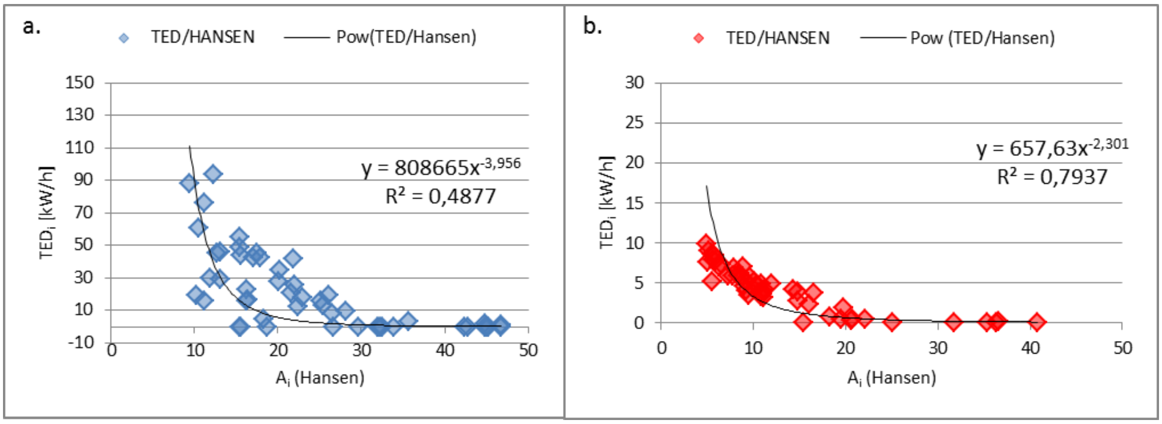

Fig. 5 Relation between TED and Hansen's Index in workers' case study (a) and students' case study (b)

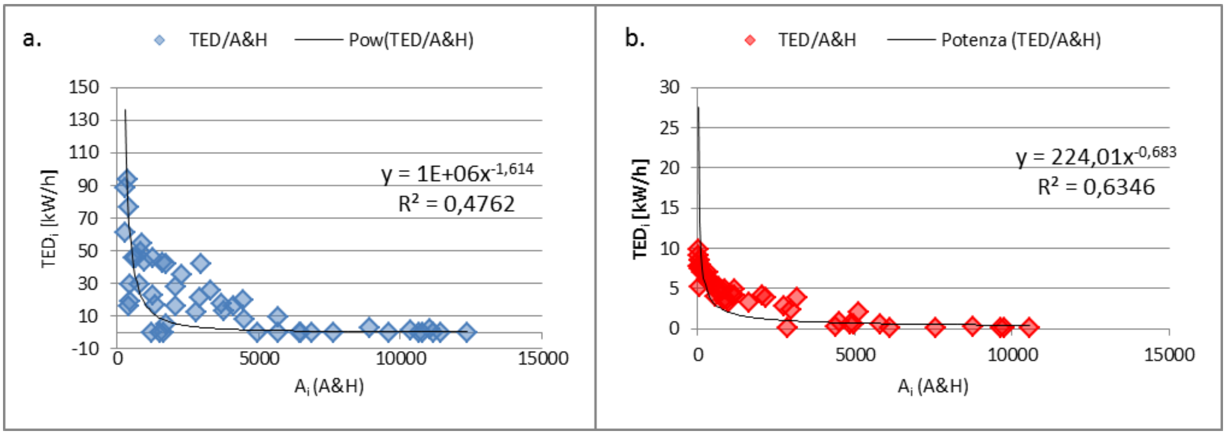

Fig. 6 Relation between TED and Agyemang-Duah and Hall's Index in workers' case study (a) and students' case study (b)

Variation of correlation has been also analyzed with reference to the different four scenarios of workers' case study (Fig. 7 and Fig. 8) for both accessibility measures. Improvements in pedestrian movements, introduction of new public transport lines and a transit oriented development policy take to both higher accessibility and lower energy consumption, maintaining and improving their power function correlation.

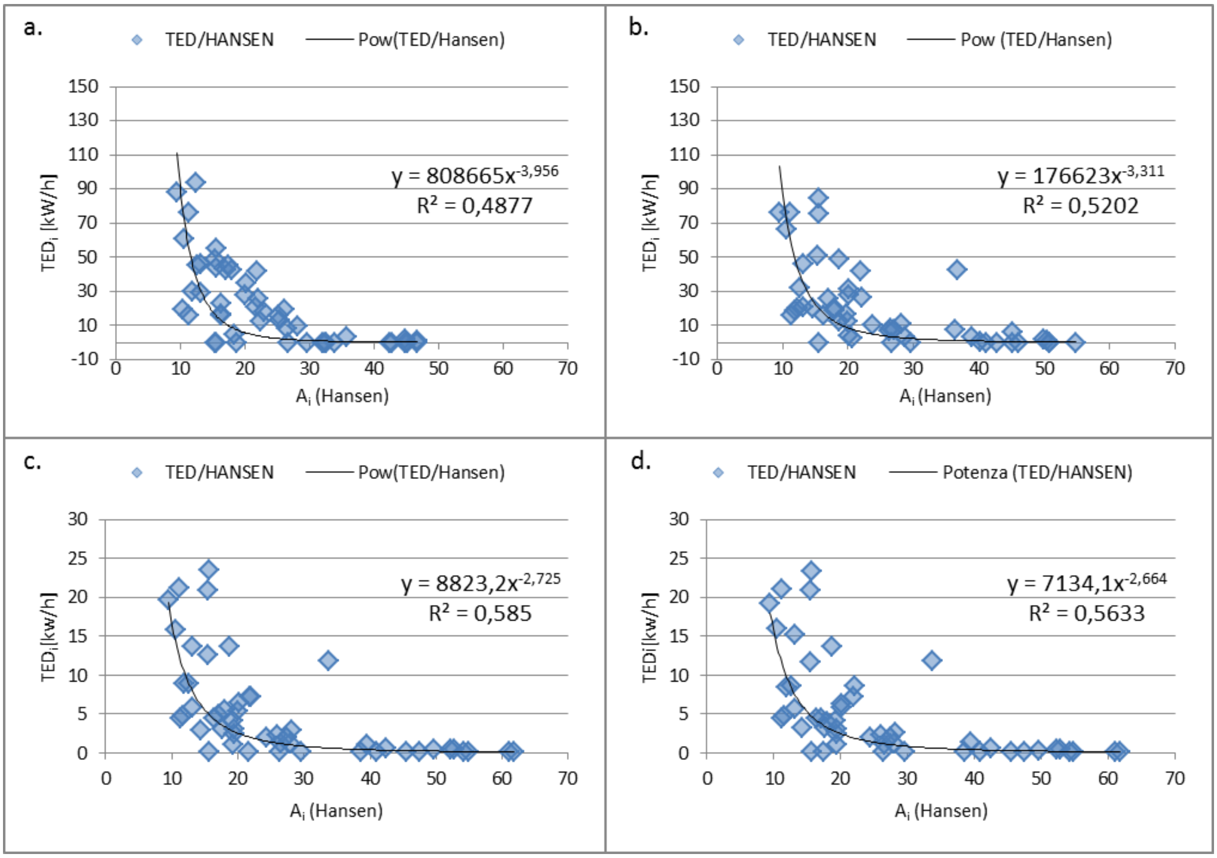

Fig. 7 Relation between TED and Hansen's Index in the 4 workers' scenarios 0 (a), 1 (b), 2 (c), 3 (d)

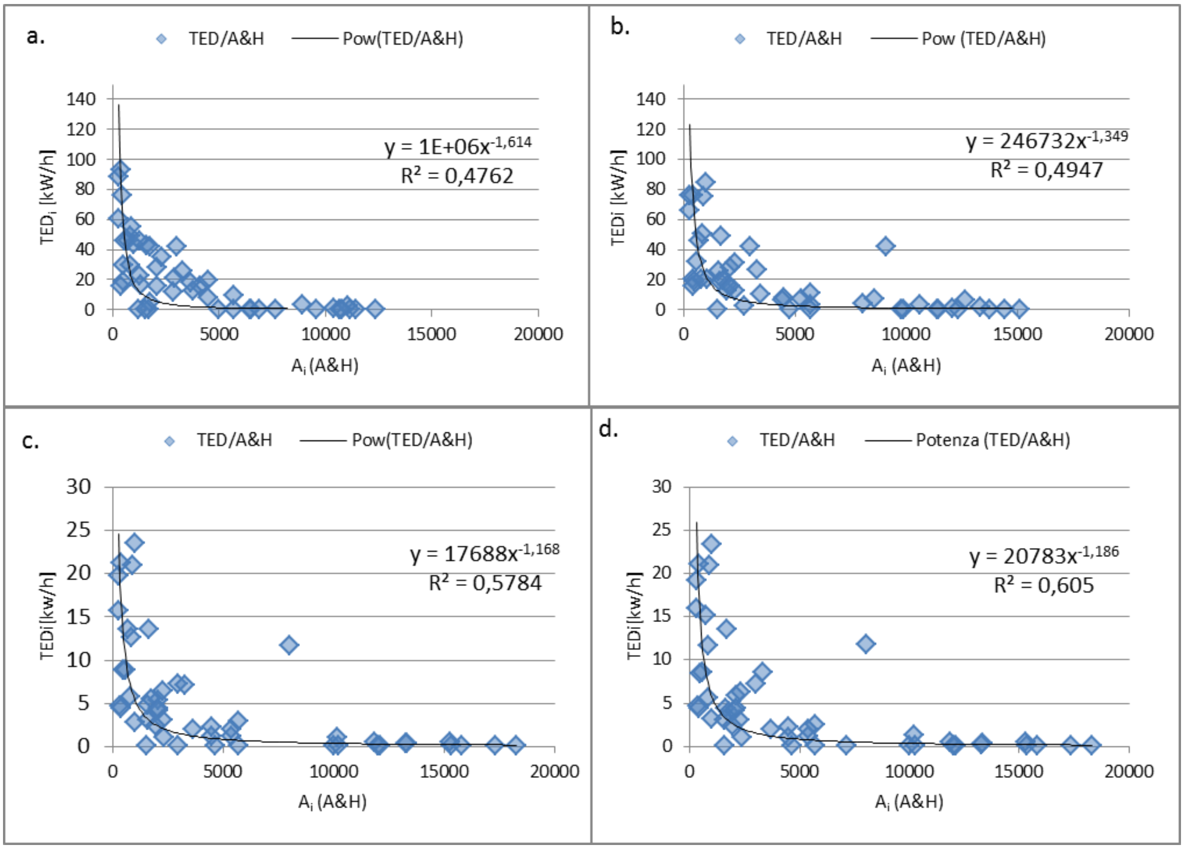

Fig. 8 Relation between TED and Agyemang-Duah and Hall's Index in the 4 workers' scenarios 0 (a), 1 (b), 2 (c), 3 (d)

4.5.2. Correlation between TED and Accessibility Measures at urban level

Relationship has been investigated also among both indices at urban level, computing TED urban index and a weighted average value of accessibility for the whole urban area. The analysis of the couple of values for the four different workers' case scenarios confirms the tendency seen at neighborhood level with improvements in sustainable mobility taking to a better accessibility and lower energy consumption also at urban level.

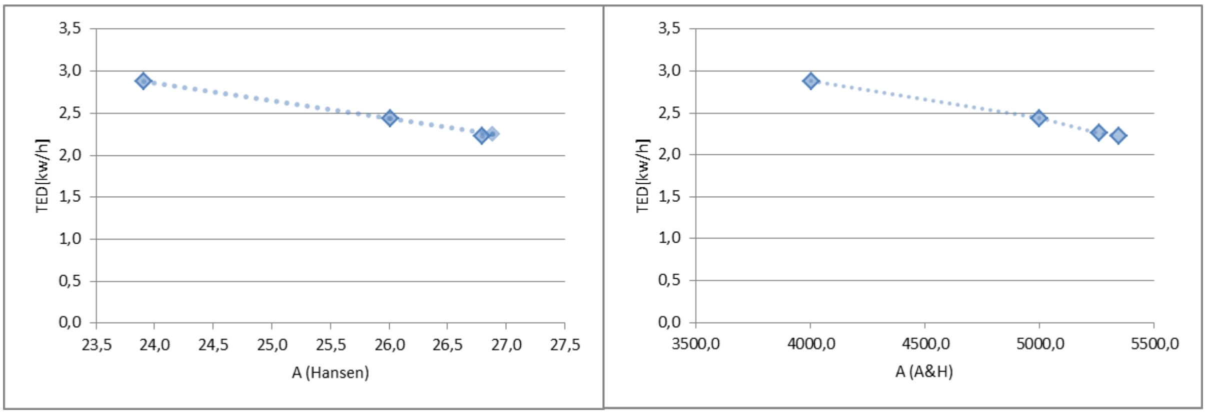

Fig. 9 Relation between Global TED and Accessibility Measures in the 4 workers' scenarios at urban level

5. Conclusions

The thesis of the authors is that a transportation planning based on objectives of accessibility is a key success factor to achieve social, environmental and economic sustainability. In particular, the influence of accessibility as an indicator of environmental sustainability is proven: high-density urban areas, close destinations and accessible with a broad spectrum of opportunities for low-impact transport (public transport, cycling, walking), reduce environmental impacts and transport externalities.

The paper presented the application of a simple land use and transport model to calculate a commuting transport energy indicator to support the delivery of sustainable urban and transport plans. The model is based on a mathematical description of the transport system, where transport mode choice follows ideal simple rules based on distance from home to work and study place and transit network density.

The TED model has been applied to the urban area of Catania and the impacts of different planning scenarios has been tested, reflecting some of the main measures of the urban mobility and land use plans which are under discussion. Two different accessibility gravity measures have been calculated at neighborhood and urban level for the four different scenarios and the relationship between TED and accessibility values have been investigated. Results showed that there's a good correlation between the two indices and, in particular, that better values of accessibility take to lower transport energy consumption.

The methodology proved to be suitable to evaluate the potential impact of land use and transport policies in terms of transport energy consumption and confirmed the suitability of accessibility as an effective urban and transport planning tool.

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