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Analysis of road urban transport network capacity through a dynamic assignment model: validation of different measurement methods

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Abstract

Network capacity in a transportation system becomes an important measurement for transport planning and management because it addresses its capability to satisfy an efficient network traffic flow reducing the inefficiency of congestion phenomena.
This work provides a discussion of road urban transport network capacity including existing definitions in literature and the validation of new measurement methods. The study explores some of the properties of network-wide traffic flow relationships in a large-scale complex urban street network using real-time simulated results obtained from a dynamic traffic assignment model, periodically updated by data from radar sensors through rolling horizon technics.
The basic variables used in the methodology, such as network flows and speeds, are characterized using a network model calibrated in the urban area of Catania (Italy). For a comprehensive yet simple analysis, equations and graphs are utilized to resume the obtained results related to different days and several time intervals of the day.
This procedure proved to be suitable to investigate the properties of network-level traffic flow relationships and concluding remarks include suggestions for further research in this highly promising area.

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Keywords: Traffic-flow relation; Intelligent Transport System; Dynamic assignment model; Rolling horizon; Road urban transport network.

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1. Introduction

Capacity is an effective factor for evaluating traffic conditions and measuring network's performances. The proper definition and quantification of network capacity have been topics of debate among researchers for decades. This concept was introduced by Ford and Fulkerson (1956), developing an algorithm for the network maximum flow problem. Later, Iida (1972), Asakura and Kashiwadani (1993), and Akamastu and Miyawaki (1995) extended that notion and proposed different programming approaches to estimate the capacity of a road network. Yang et al. (2000) introduced the concept of "reserve capacity" defined as ''the maximum common multiplier that can be applied to a given O–D matrix subject to the flow on each link not exceeding its capacity when the multiplied O–D matrix is assigned to the network by some equilibrium model'' (Yang et al. 2000). More recently, Daganzo and Geroliminis (2008) used variational theory to develop analytical expressions for capacity of a street with blocks of diverse width and length with no turns.

However, actual urban networks are more complex. For highly idealized networks (completely homogenous and redundant) with slow-varying demand, Daganzo and Geroliminis (2008) suggested that if homogeneity conditions hold, these networks maximize their total flow for any given number of vehicles in the network. This can be referred to as ''theoretical capacity'' because it only depends on network structure and control and it is independent of O–D patterns. Nevertheless, in real-world urban networks, it is very likely that the required homogeneity conditions do not hold. More practically, network capacity can be defined as the ''observed'' maximum network flow. This suggests that the observed maximum flow in networks tends to be lower than the theoretical capacity confirming results of Knoop et al. (2013). As a matter of fact, the maximum flow varies over time on a given road link and it is influenced by a variety of factors that have especially to deal with congestion. Accordingly, in the context of networks, capacity is the complex measurement of the maximum amount of data that may be transferred between network locations over a link or network path. Because of the amount of intertwined measurement variables and scenarios, actual network capacity is rarely accurate.

Starting from these remarks, this paper aims to initiate a discussion on definition and quantification of urban transport network capacity, providing a talk of existing definitions in literature and the validation of new measurement methods. This study explores some of the properties of network-wide traffic flow relationships in a large-scale complex urban street network using simulated results obtained from a dynamic traffic assignment model. Using a calibrated network model of the Catania (Italy) urban area, the traffic flow relationships are explored, focusing on the effect of traffic congestion on network capacity.

The reminder of the paper is as follow. After a review of network capacity definitions in the general context of transportation, the second section discusses the methodological approach used to explore and subsequently calibrate network-wide traffic flow relationships. The third section presents the case study and describes the network simulation specifications. The fourth section shows the modelling results, indicating the effects of congestion on network capacity. The last section concludes the paper by summarizing the main findings and specifying directions for future research.

2. Methodology

2.1. Measuring the capacity of a rod network in a town centre

The origins of network traffic flow theory can be traced to the 1960's. Smeed (1966, 1968), Thomson (1967), Wardrop (1968), Godfrey (1969), and Zahavi (1972) were among the first studies to explore macroscopic relations of vehicular traffic in a network. These methodological approaches dealt largely with the development of macroscopic models for arterials, which were later extended to general network model, and today highly spread thanks to the current extraordinary availability of real time traffic data from sensors, floating car data and traceable personal mobile devices. Accordingly, the evaluation of capacity at network level has been receiving considerable attention in recent years (Mahmassani et al. (1984,1987) and Williams et al. (1987,1995)).

One of the early work in the literature, presented by Smeed (1966), considered the number of vehicles which can "usefully" enter the central area of a city and that the urban road system can accommodate, and defined N as the number that can use a single road. A number of investigations have been carried out and some results have emerged, finding a fairly definite relationship between the amount of traffic N on a road and the speed of traffic v between intersections.

This relationship is expressed in the form of the following Eq. (1):

$$N/w = 68 - 0.13\, v^2 \tag{1}$$

where N is the number of cars using the road per hour, w is the width of road (in feet) and v is the average speed of traffic (in miles per hour). Thomson (1967) extended this method by applying it to roads with approximate frequencies of intersections and widths found in the Central London (Fig.1) and many other towns.

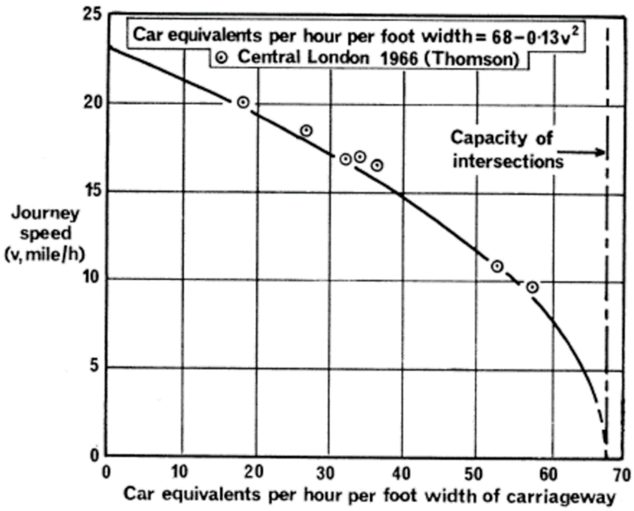

Fig. 1. Relation between speed and amount of traffic on main roads of Central London (Thomson 1966)

At the network level, it was found that traffic flow also tends to behave similarly to some aggregated physical systems, albeit with possibly different mechanism. For instance, various traffic flow models have been developed by analogy between vehicular flow and continuum compressible fluid or gas (Lighthill and Whitham 1955; Prigogine and Herman 1971; Helbing 1995, 1996).

Therefore, taking into account the analogy between hydrodynamic theory and traffic flows, the same methodological approach proposed by Smeed followed in this work, extending the calculation for single road by applying it to the entire network.

2.2. Dataset and model description

The proposed model explores the properties of network-wide traffic flow relationships in a large-scale complex urban street network using real-time simulated results obtained from a dynamic traffic assignment model (Meschini and Gentile, 2011), periodically updated by data from radar sensors through rolling horizon technics, as proposed by Mahmassani (2001), to reproduce the dynamic interaction between the level of congestion and users route choices (Torrisi et al., 2016).

Although many previous studies have focused on link or path analysis, this research performs an extended investigation and the methodology is tested at network level. Moreover, a day-to-day and a with-in day analysis of traffic flows and travel speeds relations are performed in order to analyse different traffic patterns and characteristics, particularly influenced by the phenomenon of congestion.

In this respect, the traffic data in use are estimated through the dynamic assignment model. In particular, the basic variables used are hourly average traffic flows and average travel speeds referred to the total amount of links that belongs to the simulated transport network.

The simulation model aggregates traffic data in 15-min intervals, and thus each day d is divided into 96 time intervals i-j, with i indicating the beginning of the time interval and j as the end of the same time interval. Further, fk,d,i-j is defined as the average flow at link k on day d during time interval i-j. Because of the graph representing the analyzed transport network is characterized by links with quite similar lengths, the values related to traffic flows and travel speeds of each network element are comparable to each other. Therefore, the computation of the average flow and travel speed of the traffic network is derived by a mathematical aggregation using the arithmetic mean method. From this remark, the dataset of network traffic flows, symbolised by $F_{d,i\text{-}j}$, is constructed for each time interval i-j for all analysed days d, through the average calculation of all these link-traffic flows $f_{k,d,i\text{-}j}$, presenting the average traffic flow of the considered traffic network, as shown in the Eq. (2):

$$\mathrm{F}_{d,i-j} = \frac{\sum_{\mathrm{k}=1}^{\mathrm{N}} \mathrm{f}_{k,d,i-j}}{N} = \bar{f}_{k,d,i-j} \tag{2}$$

where: $F_{d,i\text{-}j}$ is the average flow of the traffic network, on day d during time interval i-j, in vehicles equivalent units (VEU); $f_{k,d,i\text{-}j}$ is the average flow at link k on day d during time interval i-j, in vehicles equivalent units (VEU) and N is the total number of links that belongs to the network.
Similarly, the average travel speed can be calculated with the Eq. (3):

$$\mathrm{v}_{d,i-j} = \frac{\sum_{\mathrm{k}=1}^{\mathrm{N}} \mathrm{v}_{k,d,i-j}}{N} = \bar{v}_{k,d,i-j} \tag{3}$$

where: $v_{d,i\text{-}j}$ is the average travel speed of the traffic network, on day d during time interval i-j, in kilometers per hour (km/h); $v_{k,d,i\text{-}j}$ is the average travel speed at link k on day d during time interval i-j, in kilometers per hour (km/h) and, similarly to the above, N is the total number of links that belongs to the network.
The relationship between speed and the amount of traffic on which this study is based is represented by the following Eq. (4):

$$\frac{F_{d,i-j}}{L} = \alpha - \beta v_{d,i-j}^{2} \tag{4}$$

where $F_{d,i\text{-}j}$ and $v_{d,i\text{-}j}$ are respectively the traffic flow and travel speed aforementioned, L is the average width of the carriageway of the links belonging to the analyzed network and α and β are coefficient to be appropriately calibrated in order to produce more robust relations using the widespread traffic data across the entire network.

3. Case study

Catania is a city of about 300.000 inhabitants and it is located in the eastern part of Sicily; it has an area of about 183 km2 and a population density of 1.754,54 inhabitants / km2. It's 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 (Ignaccolo et al., 2017).

In this study, we used the network model of Catania urban area to calibrate the traffic flow relationships mentioned above, i.e. Eq. (4). The assignment road network is represented by the blue graph and it includes 8763 links (see Fig. 2).

As stated in section 2, the basic variables used are hourly average traffic flows and travel speeds. A simulation-based dynamic traffic assignment tool has been calibrated for this network using real-word observation, obtained from radar detector data. Computations are performed within the traffic supervisor centre realized by the Department of Civil and Architecture Engineering of Catania's University, where real-time sensor traffic data are combined with the simulated traffic data. (more details can be found in Torrisi et al., 2016 and Torrisi et al., 2017).

By explicitly simulating the interaction between travel demand and road networks through dynamic traffic allocation, it is able to reproduce explicitly the formation, propagation and dispersion of vehicle tails on the road network during the day, including spillback. This system propagates the spatial and temporal traffic flows measured in less than 1% of the network links, integrating available radar detectors' data and Floating Car Data (about 1500 cars). Corrections are applied locally to densities and capacities and are propagated on the network by the model.

Such system reaches a high level of accuracy of the propagation estimating traffic flows on links that are not monitored, fairly close to real values. It is also characterized by a good precision in short term traffic predictions over the whole graph, and calculating actual traffic state and predicting its development in the near future. It supplies traffic data including flow, speed, density and queue from simulations each 15 minutes' time intervals.

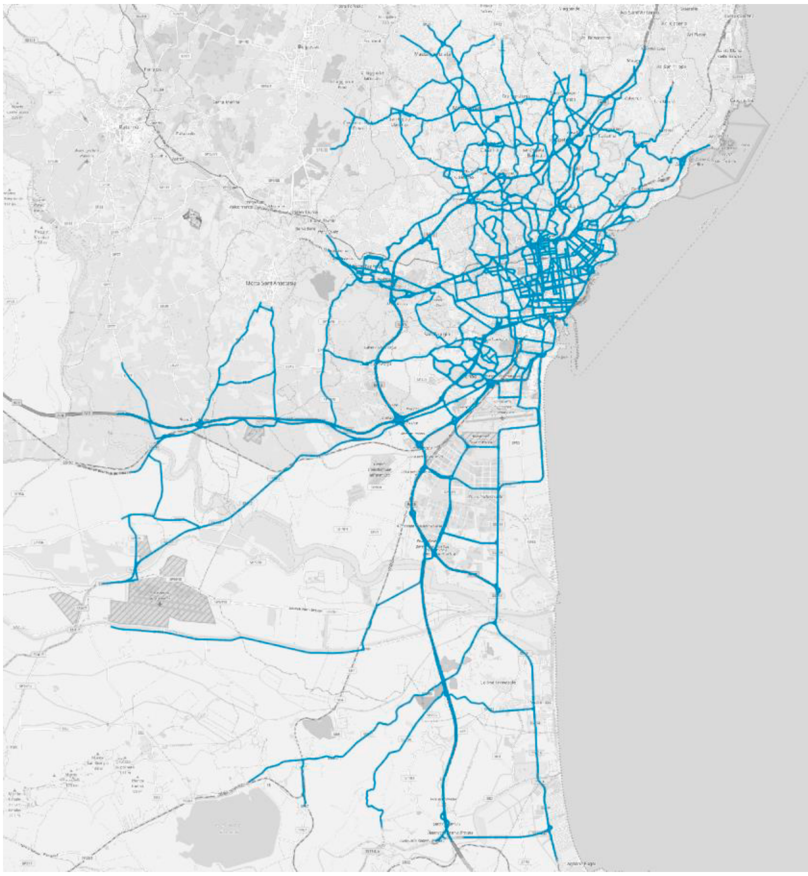

Fig. 2. Schematic view of Catania urban area: assignment network

Because the employed variables are referred to time intervals of one hour, simulated traffic data of each 15-min are aggregated, and the Eq. (2) and Eq. (3) are modified with according these following formulations (Eq. (5, 6)):

$$F_{d,i-j} = \frac{\bar{f}_{k,d,i-j}}{n} \tag{5}$$

$$v_{d,i-j} = \frac{\bar{v}_{k,d,i-j}}{n} \tag{6}$$

with n = 4 which represents the number of simulation during the time interval of one hour.

4. Results

This section attempts to point out to the effects of congestion phenomenon towards the properties of traffic flow relationships in a large-scale complex urban street network. The analysis at network level was performed by using average traffic flows and travel speeds calculated starting from the characteristics of each individual link that belongs to the considered transport network.

The network has been treated as a closed system, with a fixed number of vehicle maintaining a constant concentration throughout the observation period. A series of simulation runs were performed to evaluate the network speed-flow relations of interest. Each of these runs used the same basic network configuration with different vehicular concentration levels referred to each analyzed day and time interval, distinguishing between congested days (Cd) and uncongested days (UCd). The with-in day variation of average traffic flows and travel speeds is shown in Fig. 3: particularly at peak hours it happens that the performances of the network decrease (lower speed and level of service) when traffic flows have high values (reaching the capacity). This made it possible to detect in an immediate way that the higher gradients of travel speed occur in correspondence of congested days because both travel times and speeds increase with the high traffic flows.

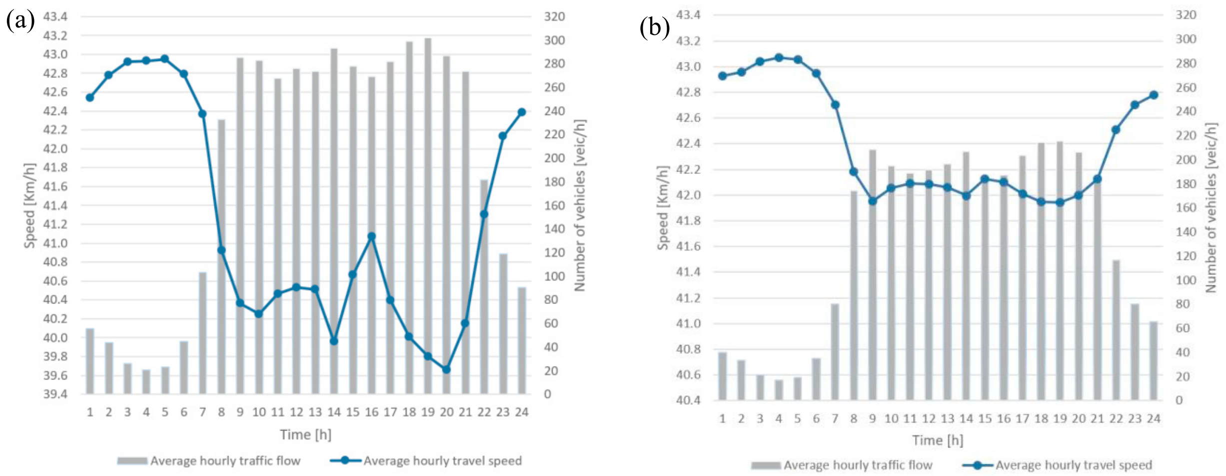

Fig. 3. With-in day variations of average travel times and traffic flows: (a) congested day; (b) uncongested day

These relationships between average traffic flows (along the horizontal axis, sorted in ascending order) and average travel speeds (along the vertical axis) are also depicted in Fig.4 and Fig. 5, respectively for a congested day and an uncongested day. As said before, it is immediately noticeable that with increasing traffic flows there is a decrement in travel speeds. This is less evident in the case of non-congested days.

By referring to these elaborations, the empirical relationships between flows and speeds have been appropriately obtained through the calibration of the two coefficients α and β, depending on the traffic condition analyzed.

In the first case, that is represented by a congested network (Fig. 4), the obtained relation flow-speed is similar to the recommended form of the applied model, i.e. Eq. (4), with α and β appropriately calibrated.

Instead, in the case of an uncongested network, given that there are no high increments of vehicular flows, the best functional form that better interpolate the dataset is a linear regression (as it is possible to see in Fig. 5).

By referring to the obtained results, the mathematical relations are synthetized in Table 1.

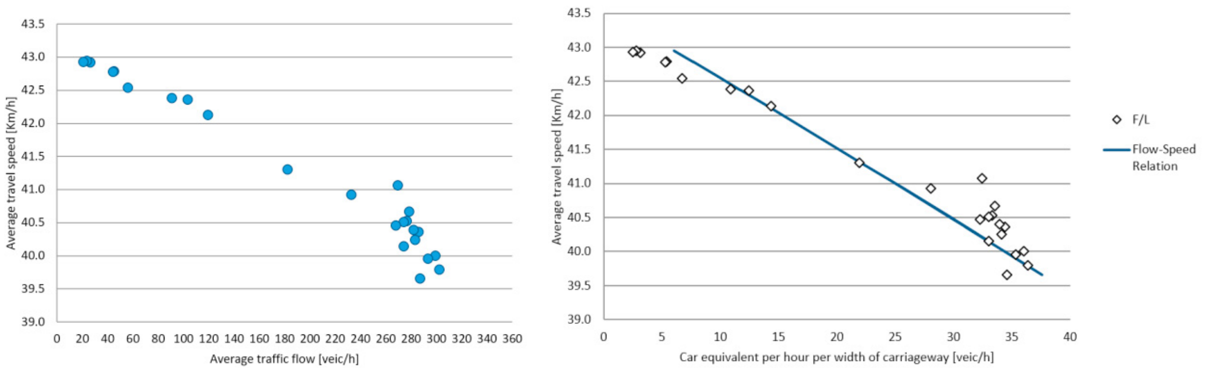

Fig. 4. Daily relationships between traffic flows and travel speeds for a congested day

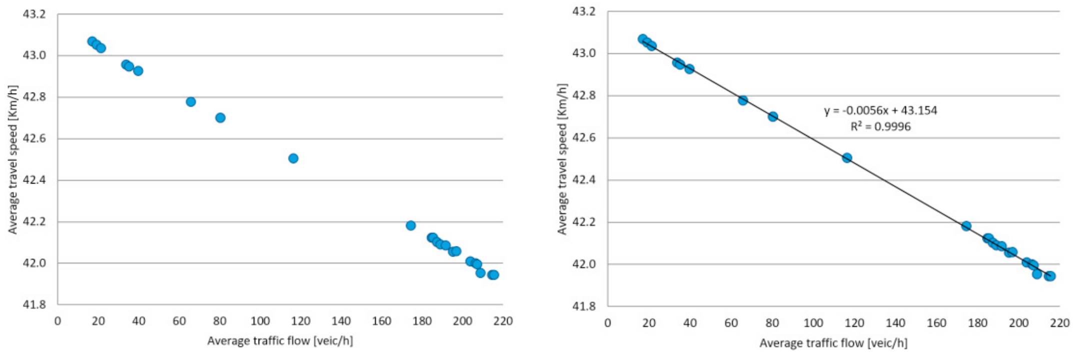

Fig. 5. Daily relationships between traffic flows and travel speeds for an uncongested day

Table 1. Formulations of network-wide traffic flow relationships

	Traffic flow relationships
Congested network (including all assignment links)	$\frac{TT_{Cd_i}}{L} = (217 \div 220) - 0.116\, v^2$
Congested network (excluding link with no flow)	$\frac{(TT_{Cd_i})_{f\neq 0}}{L} = (213 \div 223) - 0.116\, v^2$
Uncongested network	$v = 43.15 - 0.005\, TT_{UCd_i}$

5. Conclusions

Network capacity in a transportation system becomes an important measurement for transport planning and management because it addresses the question of whether or not the system has adequate ability to handle continuing economic surge and traffic congestion. In transportation, capacity has traditionally been measured at individual elements of the network, such as links and nodes, however these measures obviously do not constitute the network capacity. Therefore, recent studies in literature have suggested well-defined relationships between network-wide average flow, density and speed exist for urban networks.

In this context, this work provides a discussion of road urban transport network capacity including existing definitions in literature and the validation of new measurement methods. The study explores some of the properties of network-wide traffic flow relationships in a large-scale complex urban street network putting forward an innovative approach dealing with comprehensive data mining and analysis from different sources of data (radar sensors and floating car data) including real-time traffic estimations provided by a dynamic assignment simulation model. The basic variables used are traffic flows and travel speeds characterized using a network model calibrated in the urban area of Catania (Italy).

For a comprehensive yet simple analysis, equations and graphs are utilized to resume the obtained results related to different days and several time intervals. It was noticed that the network behaves differently depending on the traffic context and the corresponding flow-speed relationships were obtained for congested and uncongested conditions.

It is intended that the relations derived from this study are calibrated for our own traffic data set, but it is well conceivable that they can better describe datasets of other countries, with similar characteristics in term of network topology and transportation attitude.

Further research needs to be conducted to investigate the temporal and spatial stability of the proposed. Moreover, to account for heterogeneity of congestion, alternative traffic measures using trajectories might be examined in future studies.

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