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Marginal Activity Access Cost (MAAC): a new indicator for sustainable Land Use/Transport (LUT) planning

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Abstract

The paper presents the 'Marginal Activity Access Cost', an accessibility indicator providing estimation in monetary terms of the impacts on mobility and on the environment of locating a single new activity in a specific zone of the urban area. In the first part of this paper, the new indicator is presented and compared to other accessibility indicators proposed in literature. In the second part, the MAAC is validated through an application to the urban area of Rome. The paper concludes with brief remarks on using the proposed accessibility indicator as index of performance for sustainable spatial planning.

Keywords: Accessibility planning; accessiblity measures; external transport costs; sustainability assessment.

1. Introduction

Accessibility expresses the relationship between the land use system and the transportation system serving it. Accessibility measures have widely been used by transportation and land use geographers, engineers and planners for several purposes: a) to understand and model land-use and transport interactions; b) to assess transports plans with respect to equity and sustainable planning goals; c) to solve optimal activity location problems. In a broader perspective several authors believe that accessibility measures can play a key role for designing land use and transport integrated policies (Bertolini *et al.*, 2005). However, while on the one hand accessibility issues has long been discussed in the academic debate, the interpretation of such concepts in performance measures that could be effective in practice to improve the integration of Land Use and Transport (LUT) plans, on the other hand, is still limited (Curtis, 2008; Silva, 2013). Some authors affirm that this is due to the absence of operational forms of accessibility measures for planning and policy design purposes and to the lack of consensus on the best accessibility measures to be used. In the Accessibility Instrument Survey (Hull *et al.,* 2012), developed for the COST Action "Accessibility Instruments for Planning Practice", some interesting remarks have been highlighted:

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accessibility measures are in some cases too complex, abstract, hard to comprehend and to interpret for non-modelers, including planners. Researches on the usability of accessibility measures in the UK and in the Netherlands confirm these weaknesses and identify other implementation barriers in existing tools. These include inadequately supporting the generation and testing of new strategies and projects, and not providing insights into land use and transport dynamics. As a result, land-use and transport plans are often evaluated with accessibility measures which are easy to interpret for researchers and policy makers, such as congestion levels or travel speed on the road network, but which have strong methodological drawbacks.

According to several authors, indicators must remain sufficiently simple and intuitively meaningful to be used in public forums and to be widely accepted (El-Geneidy, *et al.*, 2011; Handy & Niemeier, 1997; te Brömmelstroet & Bertolini, 2010). Two additional specific characteristic in our opinion are required for accessibility measures to be efficiently used in LUT planning processes. The first regards the need of accessibility measures to assess location choices from a public decision makers' perspective (system optimum), while most used indicators are in general defined from the single user's point of view, measuring the ease of an activity to be reached from potential users (user optimum) with a subjective perspective (usually private). Another essential characteristic an accessibility measure should have is a clear unit of measure: accessibility indicators are in general a-dimensional, usually corresponding to an index varying in a numeric scale that does not have any unit of measure, especially the most sophisticated one.

With a view to give an answer to these requirements, this paper proposes an indicator, i.e. the "Marginal Activity Access Cost" (MAAC), that can support integrated land use and transport decision making process, filling the gap between strong theoretical basis and the usability in practice, overcoming some limitations of the existing accessibility measures.

The remaining of the paper is organized as follows. A brief review of accessibility measures is presented in Section 2 compared to the proposed one, i.e. MAAC. Section 3 shows the results from a test application to the realistic case-study of Rome (Italy), whose objective, at current research stage, is to exploring the potentiality of the measures compared to the existing accessibility ones. Section 4 sums up some conclusions.

2. Accessibility measures versus Marginal Activity Access Cost

In literature several accessibility taxonomies have been proposed, according to different criteria (Geurs & van Eck, 2001; Geurs & van Wee, 2004; Curl *et al.*, 2011). Here we propose a classification of accessibility measures (Table 1) depending on whether they do include or not behavioral components; as a result, they can be divided in the following two clusters:

- Behavioral (or individual-based) accessibility measures, that define accessibility from a single user/activity subjective perspective;
- Not-Behavioral (or zone-based) accessibility measures, that define accessibility based on potential opportunities spatially distributed in the zones of the study area.

Such classification is consistent, and partly derive from the assumption that accessibility measures can be defined either from the particular individuals viewpoint (behavioral measures), or from a geographical impersonal perspective, relating accessibility values to urban zones (not-behavioral measures).

To the first cluster, belong the "utility-based" accessibility measures, derived from Random-Utility Maximization (RUM) theory (Ben-Akiva & Lerman, 1979), and the "contour measures", also referred to as "opportunity-based" measures.

Utility-based measures are founded on the paradigm that individuals aim at maximizing the net utility of participating in activities located in an area. They can be further classified into "trip-based" and "activity-based". Trip-based measures consider one trip at a time, not taking into account the daily schedule of the activities or any trip chaining. They assume each trip is independent from the others made not only in the same day, but also in the same journeys. On the other hand, activity-based measures (Dong *et al*., 2006) also defined in literature as "time-space" measures (Kwan, 1998), do estimate accessibility in terms of individual ease of access to activities, taking into account the daily activity schedule and the related trip chain as well as the spatial and temporal constraints of each activity. They contributed to extent the definition of accessibility by incorporating innovative concepts such as trip chaining, daily schedule and duration of the activities undertaken.

Utility-based measures are formally very robust and are based on strong theoretical paradigms. They can represent accessibility at individual level according to discrete preferences, but have some drawbacks: complexity and data requirement are the main barriers to their implementation. Moreover, the results are not expressed into physical units of measure, so that they cannot be easily interpreted and are difficult to be transferred across different territorial contexts.

Contour measures define accessibility as the number of opportunities that can be accessed within a given distance or travel time or generalized travel cost, from a specific location in the study area (e.g. a station, a building, etc.). These measures require the definition of the threshold of the maximum travel times (or generalized cost) acceptable for individuals to reach the opportunities (Ingram, 1971). They here classified as behavioral, because they include a subjective component (although this is not fully and immediately recognized) in that the threshold values vary with individuals' preferences, taste and habits.

While easy to understand and to compare, contour measures have a high sensitivity towards such threshold values, which need to be calibrated upon disaggregate individual data and are difficult to be computed in practical application. In fact, not all the opportunities are perceived in the same way by individuals. To overcome such drawback, Cascetta et al. (2013) have introduced the concept of perceived opportunities in the definition of this type of accessibility measures.

To the second cluster of accessibility measures, belong the "network-based" and the "gravity-based" measures. These classes of indicators define accessibility in relation to the potential opportunities available in the zones spatially distributed in a given study area.

Network-based measures, founded on graph theory, are based on the characterization of the topological (relational) properties of spatial networks; according to them, accessibility is directly related to the concept of the network centrality of a node. Five different measures of centrality can be defined: degree, closeness, betweenness, straightness and information (Crucitti et al., 2006). Degree centrality defines accessibility of a node proportional to the number of links connecting that node to all the others. Closeness centrality compute to what extent a node *i* is close to all the other nodes along the shortest paths in the network. Betweenness centrality is based on the definition that a node is central as much as it is crossed by shortest paths connecting origin-destination pairs. Straightness centrality, originates from the assumption that the efficiency in the communication between two nodes *i* and *j* is equal to the inverse of the shortest path length d_{ij}. Information centrality relates node significance to the ability of the network to respond to the deactivation of the node itself. Network measures, can have important shortcomings for accessibility, social and economic evaluations, but they ignore potential land-use impacts of transport strategies.

Gravity-Based measures, so-called according to Isaac Newton's Universal Law of Gravitation, define accessibility proportional to the number of activities/users that can be reached, and inversely proportional to travel distance or travel times or generalized travel costs (Hansen, 1959). Gravity-based measures depends on two factors: an attractive factor (i.e. the mass) measuring the total number of potential users located in the zones of the study area *d*, and an "impedance function" representing the generalized travel cost between the zone *o* (for which accessibility is computed) and all the other zones *d*. One of the major difficulties of this accessibility measure is the need to estimate the parameters to weight masses and impedance factors.

Moreover, the concept of accessibility can be defined in a twofold way. On the one hand, it can be related to the ease of reaching the activities/opportunities located in different specific points or zones of the study area for a given purpose (active accessibility); on the other hand it can be related to the opportunity of an activity located in a given location to be reached from the potential "consumers" coming from all the other zones (passive accessibility) (Cascetta, 2009).

In Table 1 we propose a comparison between the classified accessibility measures and the "Marginal Activities Access Cost" (MAAC) we propose in this work, according to the principles of theoretical basis, communicability, operationalization and usability for sustainability assessment.

Table 1. Accessibility measures comparison

Cluster	Accessibility measures		Theoretical basis[a]	Communicability[b]	Operationalisation[c]	Usability for sustainability assessment[d]
Behavioral (individual - based)	Utility-Based/Random utility measures	Trip-based random utility measures	±	-	-	-
		Activity-based random utility measures (time-space)	±	-	-	-
	Contour /cumulative opportunity		-	+	±	±
Not behavioral (zone – based)	Network-based		-	+	+	-
	Gravity-based		±	-	-	±
	MAAC		+	+	±	+

a Score: + strong theoretical bases ; ± moderately strong; - weak theoretical basis;
b Score: +easy to communicate or interpret; ±moderately difficult; - difficult;
c Score: +easy to operationalize; ±moderately difficult; - difficult;
d Score: +easy to use; ±moderately difficult; - difficult;

The MAAC is an indicator conceptually different from accessibility but that can be used for the same purpose of supporting the spatial planning process in light of sustainability goals. MAAC is an aggregate (zone-based) indicator (expressed in monetary terms) aiming at estimating the costs people perceive from travelling (i.e. internal costs) and the cost they generate on the environment (i.e. external costs), due to the location of a new single activity in a given zone. In fact, locating new activities in a zone can modify the potential the zone has to satisfy travelers' needs (i.e. the attractiveness of the zone), and thus, can not only alter flows to and from the zone itself, but can also modify the mobility patterns in the whole study area. Activities are expressed in terms of people employed; "one single new activity in the specific zone *o*", thus, means an increment of *n* employees in zone *d*, *n* being the number of employees of the activity itself.

The MAAC is computed as the difference of access cost to the zone d, with and without the new activity, under the assumption that the Origin-to-Destination (OD) generalized travel costs is constant; in other terms, the additional mobility induced by the activity has no impacts on network links congestion and on the spatial distribution of other activities in the study area. To keep this assumption valid, the number of employee of the new activity should be small enough, e.g. be equal to one.

The MAAC of a zone *d* includes two components: the internal costs, i.e. the generalized travel cost (times and cost on auto and public transport) both of people employed in the new activity (i.e. commuting costs) and of people "attracted" by that activity for other purposes (e.g. shopping); and the external costs, e.g. the pollutant emissions related to the additional trips those people make by car. Therefore, MAAC can be computed as:

$$MAAC(d) = IMC(d) + ETC(d)$$

where the first component, "Induced Mobility Costs" (IMC), measures the incremental mobility costs due to trips generated by the activity (i.e. for commuting and other purposes), and the second component, "External Transport Costs" (ETC), measures the impacts that such induced trips generate on the environment, e.g. in terms of air pollution and noise.

2.1. Induced Mobility Costs (IMC)

The induced mobility costs (IMC) component is measured as the incremental generalized travel cost induced by the location of one single new employee in a given zone *d*, keeping constant the distribution of other activities and the transport network performances (link travel times). It consists of two terms:

- commuting mobility cost, related to the home-to-work trips of the new employee in the activities of zone *d*;
- other purposes mobility costs, related to the flows of users attracted by the zone for other purposes (e.g. for shopping and leisure).

Thus, the IMC component can be expressed as:

$$IMC(d) = \sum_{O} \Delta d_{Od} \cdot C_{Od} \tag{1}$$

where:

- Δd_{Od} is the sum of the commuting trips and those trips made for other purposes, induced by the location of the new employee in zone *d*;
- C_{Od} is the average travel cost from *O* to *d* using the available transport modes (e.g. auto and public transport).

The induced demand, Δd_{Od}, can be computed as follows:

$$\Delta d_{Od} = p_{loc}(O \mid d) + \sum_{s} \left[E_s(O) \cdot \Delta p_{other}(d \mid O) \right] \tag{2}$$

where:

- $p_{loc}(O|d)$ is the probability of residing in zone O of the new employee in zone *d* ; this can be estimated using residential location models conditional to workplace (Nuzzolo & Coppola, 2011);
- $E_s(O)$ is the number of trips generated from zone O for purpose *s*, *s* being several purposes but commuting; this estimated by trip frequency models;
- $\Delta p_{other}(d|O)$ is the variation in the probability of choosing zone *d* as destination for several purpose but "work", conditional to living in zone O; this can be estimated by trip distribution models.

To perform the computation of the MAAC, spatial Land-Use Transport Interaction (LUTI) models, particularly residential location models, trip generation-attraction and modal split models, are needed. In the application presented in the next paragraph, the LUTI model STIT (Nuzzolo & Coppola, 2005) is adopted. This allows estimating the spatial distribution of the residents' conditional to workplace and the origin-destination matrices for by mode and purpose use random utility models.

The OD travel cost, C_{Od}, is expressed in monetary term, and can be estimated as follow:

$$C_{Od} = \%auto_{Od} \cdot (tt_{Auto,Od} \cdot VOT_{Auto} + mc_{Auto,Od}) + \%PT_{Od} \cdot (tt_{PT,Od} \cdot VOT_{PT} + mc_{PT,Od}) \tag{3}$$

where:

- $\%auto_{Od}$, $\% PT_{Od}$ are the modal shares of auto and public transport modes on the OD pair *Od*;
- VOT_{Auto}, VOT_{PT} are the values of times for travelers using auto and public transport modes respectively (in Euro/hour);
- $tt_{Auto, Od}$ is the travel times (in hour) by auto on the OD pair *Od*;
- $tt_{PT,Od}$ is the travel times (in hour) by public transport on the OD pair *Od*, including on-board time, waiting time and access-egress time;
- $mc_{Auto, Od}$ $mc_{PT,Od}$ the monetary costs using auto and public transport modes respectively, on the OD pair *Od*.

2.2. External Transport Costs (ETC)

External Transport Costs (ETC) component, usually referred to as "externalities", measures wider impacts on economy, environment and public health: pollution, noise, climate change, vibration, severance, visual intrusion, loss of important sites, resource consumption, impairment of landscape, soil and water pollution. European-wide reviews of external costs of transportation are provided in several studies including IMPACT (Mailbach *et al*., 2008) and HEATCO (Odgaard *et al*., 2005).

In this study, the external transport costs component is measured as the incremental external cost due to additional distances travelled by car, induced by the location of one new employee in a given zone *d*. It includes climate change, air pollution, noise, road safety and congestion. The External Transport Costs (ETC) component can be expressed as:

$$ETC(d) = \sum_O \sum_i \Delta veich_{Od} \cdot dist_{Od} \cdot \alpha^i \quad (4)$$

where:

- $\Delta veich_{Od}$ is the sum of the induced trips by car (converted into vehicles), including commuting trips and those for other purposes, induced by the location of the new employee in zone *d*;
- $dist_{Od}$ is the distance on the road network between zone *O* and zone *d*;
- α^i is the unitary external cost (expressed in Euro/Vehicle-Km); this value has been adapted to the case study based on the literature.

2.3. Remarks

MAAC depends on the typology of activity to be located, e.g. commerce, education, services which may attract a differentiated number of trips. Therefore, several types of MAAC indicators can be defined according to activity sectors. Moreover, since such impacts vary from zone to zone, the proposed indicator gives an estimation of the differentiated impacts of locating activities in different zones of the urban area, and could be useful to assess land-use and transport development policies in compliance with the goal of reducing the overall transport cost.

With respect to other (passive) zone-based accessibility measures proposed in the literature, the MAAC does not measure the “opportunities” of an activity to be reached but the global cost (internal + external) the community has to pay if a new activity is located in an urban zone. Indeed, it considers not only the “users costs” to reach the new activity (such as some aggregated accessibility measures do) but also the external transport costs related to the atmospheric and noise pollution.

In converting such cost components in monetary terms (i.e. Euro), the MAAC has a clear and easy communicable unit of measure which constitutes a great advantaged for the stakeholders engagement and in sharing results, as it can be easily understood.

3. Application to the case study of Rome

The application to the realistic case study here presented aims at exploring the potentiality of the new MAAC indicator and to compare it to the gravity-based passive accessibility index. The test-site area corresponds to the urban area of Rome, i.e. the European most populated urban area, with 2.8 million residents in 1,285.3 sqkm and 1.1 millions of employees. We here refer to a zoning of the study area consisting of 463 zones.

To the scope of our analysis, a set of zones has been selected according to proximity to city center (CBD) and to zonal access to Public Transport (PT), measured as the connectivity of the zone by metro.

It can be observed that the MAAC is inversely correlated to the proximity to CBD (Figure 1): the more a zone is far from the city center, the bigger is the MAAC. This depends on the fact that central zones are located in barycentric position with respect to residents and to other activities, and, therefore, the average trips length, and consequentially the (internal and external) travel cost to access these zones is lower than to access peripheral zones. With respect to the zonal access to Public Transport Accessibility index a similar pattern can be identified only for peripheral zones, while a null correlation can be observed for central zones, i.e. the zones with higher access to Public Transport. This depends on the fact that the increase of mobility due to a single new activity in central areas is marginal with respect to the demand volumes already attracted by such zones in the base scenario (i.e. without the new activity). Moreover central zones have lower External Transport Costs (ETC) due to less volume of vehicles directed towards these zones: fewer trips by car means lower emissions and therefore smaller external costs.

This is confirmed also by the fact that zones with higher connectivity by public transport present a lower External Transport Costs (ETC) relatively to the Induced Mobility Costs (IMC) components (Figure 2), due to preeminent access to public transport towards such zones.

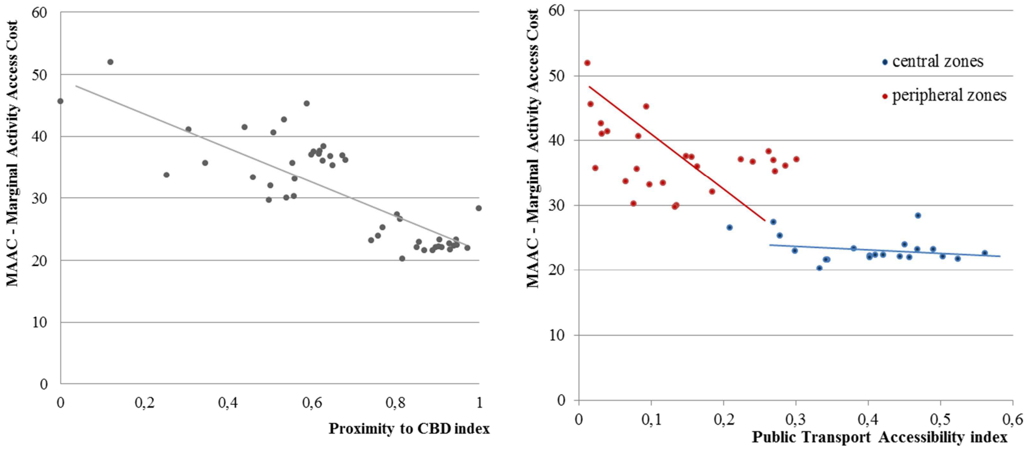

Fig. 1. Scatterplot between MAAC and the Proximity to CBD and Public Transport Accessibility indexes.

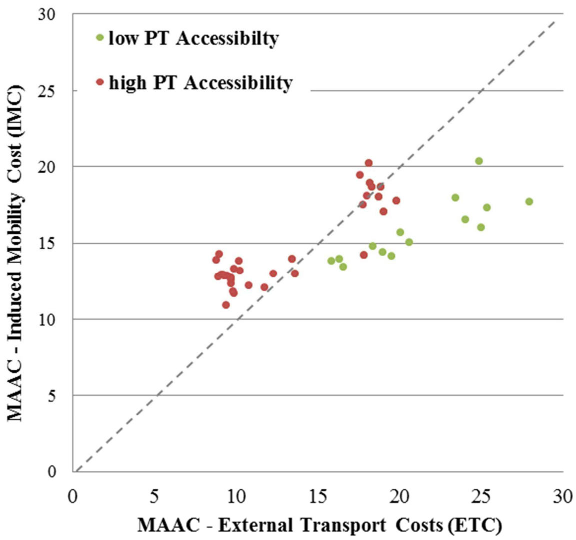

Fig. 2. External Transport Cost (ETC) vs. Induced Mobility Cost (IMC).

The scatterplot in Figure 3 shows a comparison between the component of Induced Mobility Cost (IMC) related to the commuting trips and the component of Induced Mobility Cost (IMC) related to the trips for other purposes. Three main clusters of zones can be identified for central areas, semi-peripheral areas and peripheral areas of the study area.

For central areas the two components of the MAAC are well balanced: the component for other purpose is slightly higher than the one for commuting, but this difference is not very substantial due to the fact that the average travel distance towards central zones is similar for commuting and for other purposes.

On the other hand, in semi-peripheral zones the "other purposes" component is preeminent to the commuting component. The explanation arises from the consideration that the distance of the residence zone from the workplace zone is within a range that does not vary with the distance from the city center; in other terms wherever the workplace is located, either in the city center or in the suburb area, the average distance home-to-work (and thus the average commuting access cost) is almost invariant. This is not true for other purposes trips where the average access distance is greater for peripheral zones than for the more central zones.

For peripheral area the commuting cost is higher than the cost of trips for other purposes, since in such area the mobility volumes induced by other purposes is very low due to the absence of agglomerations (i.e. low number of activities) and the distance to residential zones; therefore, the induced mobility cost are mainly related to commuting. These results are confirmed by the distribution of the ICM component by purpose among disaggregated clusters of zones (see Coppola & Papa, 2013).

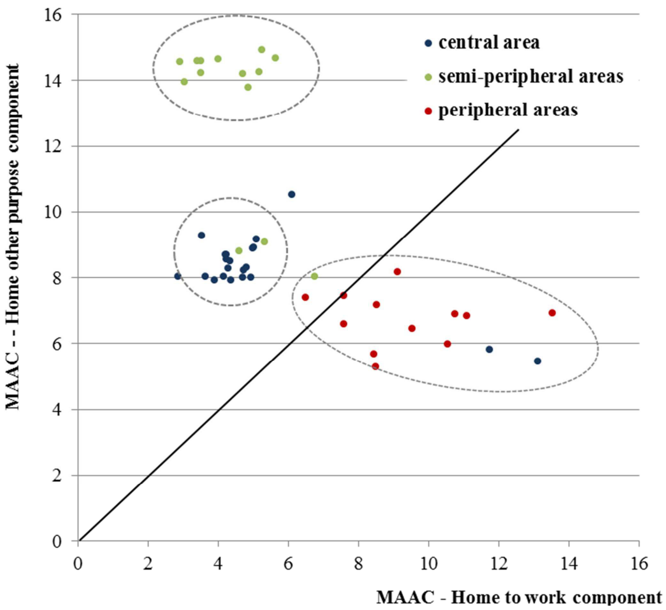

Fig. 3. MAAC component: commuting trips vs. to trips for other purposes

A final step of the application consists into the comparison of the MAAC values with an accessibility index. The latter has been computed as the gravity-based passive accessibility of the firms to the households (Coppola & Nuzzolo, 2011):

$$Passive\_Acc(d) = \sum_{o} HH(o)^{\alpha_3} \cdot \exp\left(\alpha_4 \cdot C(o,d)\right) \quad (5)$$

where:

- HH(o) is the number of households (expressed in thousands) in the zone "o";
- C(o,d) is the generalised travel cost between zones "o" and "d";
- α_3 α_4 are two estimated parameters.

In order to compare the values of these two different indicators, they have been normalized in a (0,1) scale. Table 2 denotes the average values of the indexes for five zone clusters identified according to proximity to city center (CBD) and to connectivity by Public Transport (PT):

- cluster A: consisting of traffic zones close to the CBD, with low connectivity by Public Transport (PT);
- cluster B: consisting of traffic zones close to the CBD, with high connectivity by PT;
- cluster C: consisting of traffic zones far from the CBD, with high connectivity by PT;

- cluster D: consisting of traffic zones far from the CBD, with low connectivity by PT;
- cluster E: consisting of suburban areas, very far from CBD and very low connectivity by PT.

The MAAC is by definition dual to accessibility, i.e. zones with higher accessibility should correspond to zones with lower MAAC. This is confirmed by the average index values reported in Table 2 where it can be observed that zones with higher proximity to CBD and high connectivity by PT (cluster B) are those with lower MAAC and higher accessibility, as well as peripheral zones with very low connectivity by PT (cluster E) are those with lower accessibility and higher MAAC.

Moreover, it can be observed that MAAC is more affected by the proximity to CBD than to accessibility. Indeed, the MAAC index for central zones (cluster A and B) is five times greater than for peripheral ones (clusters C, D and E), whereas the accessibility indexes for central zones is 1.3-1.5 times those for peripheral zones. This is due to the fact that MAAC includes also external transport costs which are higher for peripheral zones where the mobility by car is preeminent than for central zone, and such component is typically not included in accessibility measures. As consequence, also the differences in MAAC between different clusters present a higher degree of variance, while accessibility differences among clusters are more uniform.

Table 2. MAAC index (IMC plus ETC) vs. Passive (Gravity-based) Accessibility index for zones clusters.

Cluster zone	Gravity-based passive accessibility index	MAAC index
A	0,75	0,10
B	0,78	0,09
C	0,65	0,52
D	0,57	0,48
E	0,40	0,57

4. Conclusions

Taking into account the main limitation of the existing accessibility measures reviewed in literature, in this paper an aggregate (zone-based) indicator, i.e. the Marginal Activities Access Cost (MAAC), is proposed in order to measure the impacts of locating new activities on transport system and related externalities. In line with the goals of accessibility planning, aiming at sustainable and integrated Land-Use and Transport (LUT) development, this indicator represents a useful tool to assess the location choices of new activities.

Results show that the proposed indicator allows overcoming some limitations of existing approaches: unlike the typical accessibility measures, the MAAC takes into account not only individual travel time and costs (IMC) but also external costs (ETC) and has a clear and communicable unit of measure (Euro). At the same time it has a strong theoretical base, as it is constructed with the use of widely consolidated Land Use and Transport Interactions models.

An application to the urban area of Rome have been presented aiming at validating the proposed tool through its application to zones characterized by different connectivity by public transport and different proximity to CBD. This application helped to explore the potentiality of the new indicator compared to the classic gravity-based accessibility measure. It results that proximity to city center (i.e., in the mono-centric case study of Rome, proximity to more densely urbanized districts) is a key factor in determining the MAAC: the areas close to city center present values of both IMC and ECT lower than the zones far from the city center with low density of settlements. Moreover, zones with high connectivity by public transport present MAAC values lower than those characterized by prevailing connectivity by car, due to less volume of vehicles directed towards these zones: fewer trips by car correspond to lower emissions and therefore smaller external costs.

Compared to passive gravity-based accessibility, the MAAC present a broader range of variation across zones with different proximity to city center, due to the inclusion of the external cost which are not taken into account by other accessibility measures.

The results obtained are strongly related to the spatial structure and to the transport networks of the case study of Rome, which presents a strongly mono-centric urban form. Further researches and improvements will regard the validation of the proposed measure to metropolitan areas with polycentric urban pattern in order to verify usability and transferability of the proposed tool to different urban contexts (mono-centric vs. polycentric urban areas). Adding an energy cost component in the external transport costs ETC will also be subject of future research.

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