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Measuring accessibility: positive and normative implementations of various accessibility indicators

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ABSTRACT

Accessibility is a concept of continuing relevance in transportation research. A number of different measures of accessibility, defined as the potential to reach spatially dispersed opportunities, have been proposed in the literature, and used to address various substantive planning and policy questions. Our objective in this paper is to conduct a review of various commonly used measures of accessibility, with a particular view to clarifying their normative (i.e. prescriptive), as well as positive (i.e. descriptive) aspects. This is a distinction that has seldom been made in the literature and that helps to better understand the meaning of alternative ways to implement the concept of accessibility. Our discussion of the positive and normative aspects of accessibility measurements is illustrated using the city of Montreal, Canada, as a case study. The example highlights the differences in the measured levels of accessibility depending on implementation. Comparison of the two by means of a relative indicator of accessibility helps to identify the gap between desired (as normative defined) and actual (as revealed) accessibility levels.

1. Introduction, motivation, and objectives

Accessibility, defined as the potential for reaching spatially distributed opportunities (for employment, recreation, social interaction, etc.), can be considered one of the main outputs of spatial development, the joint result of a transportation network and the geographical distribution of activities. The concept of accessibility has long been central to transportation and regional research (Martellato and Nijkamp, 1998), and the analysis of accessibility continues to be central to a host of urban and regional research endeavors. Whether in the study of transportation-related social exclusion (e.g. Páez et al., 2009; Scott and Horner, 2008), the analysis of service areas for health care facilities (e.g. Apparicio et al., 2008; Horner and Mascarenhas, 2007; Páez et al., 2010a), the definition of functional commute sheds (e.g. Reggiani et al., 2011), the economic impact of transportation infrastructure (e.g. Ozbay et al., 2003; Páez, 2004; Ribeiro et al., 2010), the effect of public transit on employment outcomes (e.g. Blumenberg and Shiki, 2003), or the existence of food deserts (e.g. Apparicio et al., 2007; Bertrand et al., 2008; Clarke et al., 2002; Larsen and Gilliland, 2008; Páez et al., 2010b), it is reasonable to anticipate that as long as the friction of distance continues to exist, accessibility will remain a relevant component of transportation studies.

A longstanding preoccupation of accessibility researchers has been the utility of accessibility research to inform urban and regional planning and policy. While the basic notion of accessibility, or perhaps more accurately, the use of the term, has long been a staple of discourses in planning, it has not always been translated into performance measures to more concretely direct planning efforts (Handy and Niemeier, 1997). Effective use in planning has been hampered in the past by limited understanding of the measures, definitional issues, and measurement problems. These are all matters that have led to the use in practice of simple but partial performance measures, such as congestion levels or travel speeds (Geurs and van Wee, 2004). Indeed, Handy and Niemeier (1997) note that performance measures such as level of service or the distribution of land uses variously used by transportation engineers and planners, have the distinct disadvantage that they represent isolated aspects of more complex transportation and land-use systems. Accessibility's strongest suite, on the other hand, is that it combines not only these two aspects of development (state of the network and land uses), but also, potentially, how they are perceived and effectively utilized by individuals in the population with differing characteristics.

The value of accessibility as an integrative device, in particular its ability to establish a connection between transportation and

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land use, has recently gained ground on institutions that can most effectively wield it as a planning tool. Farrington (2007), for instance, explains how the concept of accessibility has been embraced by the UK government. In particular, work in the UK by the Social Exclusion Unit (2003) accomplished much in terms of establishing accessibility as a valuable instrument for the analysis and design of social policy – including recommendations for specific ways to develop performance measures. Still, the debate on how to make accessibility notions more applicable in practice continues, and researchers remain keenly aware of the need to promote measures that are intuitive and highly communicable (e.g. Straatemeier and Bertolini, 2008; Vandenbulcke et al., 2009). The task seems all the more urgent given the host of environmental, social, and economic efficiency issues that argue for the use of accessibility as a planning tool. The connection between accessibility and social ideals of inclusion, in particular, has in recent years prompted conceptual and empirical investigations that have contributed to advance both our understanding of the mechanisms that influence accessibility, the accessibility situation of disadvantaged populations, and the implications of limited accessibility (e.g. Casas, 2007; Casas et al., 2009; Miller, 2006; Páez et al., 2009).

Given developments in the past few years, including theoretical advances, significant gains in the quality and the quantity of information available for accessibility analysis, and an increased interest in the application of accessibility measures to evaluate plans and assess performance, the objective of this paper is to review and discuss the recent literature on accessibility measurements and their application. Previous reviews of accessibility indicators, in particular those due to Handy and Niemeier (1997), Kwan (1998), Geurs and van Wee (2004), and Guagliardo (2004), were concerned with various conceptual and computational issues of relevance for the implementation of accessibility measures. The review by Handy and Niemeier (1997) advocated increased efforts to translate concepts into operational measures, and provided a conceptual framework to facilitate this translation that covered the specification, calibration, and interpretation of various accessibility measures. Many of the issues identified by Handy and Niemeier were still current at the time of Guers and van Wee's (2004) review, including the need to improve land use and transport appraisal. Guers and van Wee adopted a broad base for their review, and considered the theoretical basis, operationalization, interpretability, communicability, and usability for evaluation purposes of various measures of accessibility. The review by Kwan (1998), on the other hand, concentrated on the comparison of place-based and personal measures of accessibility, including their computational and data requirements, as well as the degree of agreement or correlation between measures in practice. Guagliardo (2004) discussed the fundamental concepts and emerging challenges for accessibility research from the specific viewpoint of access to healthcare.

The studies cited above provide a valuable reference that helps to clarify the role and appropriate use of accessibility indicators. The present review, in addition to updating these works, takes an alternative perspective, in that our interest is focused on the utility of accessibility measures, in particular the way they are implemented, to address positive and normative analysis needs. In our work, normative accessibility measures are defined in terms of how far people *ought* to travel or how far it is *reasonable* for people to travel whereas positive accessibility measures are defined in terms of how far people *actually* travel. In other words, normative accessibility is defined in terms of an expectation on the part of the analyst or policy maker – an expectation that may be informed by some understanding of the behavior in question. Positive accessibility, on the other hand, reflects no such expectation – it is based on the actual experiences of individuals traversing space to engage in out-of-home activities. As such, the travel cost underlying the derivation of positive accessibility can vary from one individual to another. This is not typically the case for normative accessibility, which assumes a reasonable or desired cost of travel, which moreover is uniform across individuals as a way to establish a standard.

The positive and normative aspects of measuring accessibility have seldom been explicitly considered and discussed. A more or less isolated example where they are, is the paper by Farrington (2007) that describes the discursive use of the accessibility terminology and its connections with ongoing geographical debates. Said paper, despite its thematic concurrence, is curiously divorced from a parallel literature stream that can chronicle its history by the development of particular accessibility measures (Weber, 2006). The literature on accessibility measures, on the other hand, is not clear about the distinction between positive and normative ways of implementing and interpreting various accessibility measurements. In our view, this perspective provides a much needed clarification regarding how several measures are reported and interpreted. In this respect, whereas Farrington (2007) contends that the concept of accessibility is at its most useful when applied normatively (p. 321), our view is that positive and normative approaches are useful in that they help to address specific research, policy, and planning needs – say, by helping to understand in a positivistic way the current situation (e.g. identification of issues of possible policy interest), or to design, given a desired (i.e. normative) outcome, policy and planning interventions.

In order to illustrate the differences between these approaches, we present an empirical illustration using Montreal, Canada, as a case study. The example shows that it is possible to derive great benefit from the synthesis of both perspectives, by applying the concept of relative accessibility to the assessment of accessibility differentials, or in other words, by comparing accessibility as *is* (in terms of revealed behavior) to what it *ought to be* (from normative policy and/or planning perspectives).

2. Measuring accessibility

2.1. Definitions

Accessibility measures are typically comprised of two basic components, the cost of travel (determined by the spatial distribution of travelers and opportunities) and the quality/quantity of opportunities. These two components can be deployed in a number of different ways to produce location- or person-based indicators of accessibility, a distinction that depends to a large extent on the degree of detail available concerning the situation of the network, different modes of transportation, and inherent differences in the mobility of individuals. Conjointly, accessibility can be measured from the perspective of the location of origin, or the originator, of potential trips, or from the standpoint of the destination/objective of these trips (Islam et al., 2008, term this distinction "supply of opportunities" and "demand of participants"). Examples taken from the recent literature illustrate different instances of these alternative ways of defining accessibility:

- Accessibility defined as the (population-weighted) mean number of supermarkets within 1000 m of census tract i (location-based, from the perspective of trip origin; Apparicio et al., 2008).
- Availability of at least one dentist within a distance of 10 miles of county i (location-based, from the perspective of trip origin; Horner and Mascarenhas, 2007).
- Number of grocery stores that are within the typical trip distance of an individual with profile p, centered at the place of residence (person-based, from the perspective of trip origin; Páez et al., 2010b).

- Number of people within 500 m of a food shop, divided by total population (location-based, from the perspective of the destination; Social Exclusion Unit, 2003).
- Number of welfare recipients within 0.25 miles of a transit line, divided by total number of recipients (location-based, from the perspective of destination; Blumenberg and Shiki, 2003).

Previous typologies of accessibility measurements identify three broad classes of indicators: cumulative opportunities, gravity-based, and utility-based (q.v. Geurs and van Wee, 2004; Handy and Niemeier, 1997). Cumulative opportunities and gravity-based measures are specific instances of a more general formulation:

$$A_{ik}^{p} = \sum_{j} g(W_{jk}) f(c_{ij}^{p}) \tag{1}$$

Eq. (1) gives the accessibility from the standpoint of (origin) location i, to opportunities of type k, from the perspective of individual p. This measure of accessibility is a function of the number of opportunities W of type k at location j, and the cost of moving between i and j as perceived/experienced by person p. Function $f(\bullet)$ defines a kernel around location i, usually symmetric if c_{ij} is given by Euclidean distance, but not necessarily, for instance if c_{ij} is measured over a network. In order to accommodate more advanced concepts, such as space–time accessibility, the measure can be formulated using map algebra concepts as follows:

$$A_{ik}^{p} = \sum_{j \in R_i^p} g(W_{jk}) \tag{2}$$

where R_i^p is a region defined for individual p based at location i. Eq. (2) represents the overlay of region R and a layer containing the spatial distribution of opportunities W. Region R can be determined by the potential path area (PPA) corresponding to the individual, the set of destinations that an individual subject to space–time constraints can potentially reach (Hägerstrand, 1970; Scott, 2010). This area can be calculated using any of a number of available algorithms (e.g. Kwan, 1998; Miller, 1991). Interpretation of the index is as the number of opportunities, total length of road, etc., found within the PPA of the individual. PPAs can be calculated for specific periods of time during the day, or aggregated to obtain daily PPAs and daily accessibility indicators. Furthermore, authority constraints such as store operation hours can also be implemented (e.g. Weber and Kwan, 2003).

Measures of accessibility that adopt the perspective of the destination more closely resemble market/service/catchment areas or shares, and can likewise be defined in the following way:

$$M_{kj}^{p} = \sum_{i} g(P_{ik}^{p}) f(c_{ij}^{p}) \tag{3}$$

Eq. (3) summarizes the size of population segment p with access to opportunity of type k at location j. This measure is a function of the size P of population segment p at i, meant to be served by opportunity k, and the cost of traveling between i and j as perceived/experienced by members of population segment p.

A third class of accessibility measures, namely utility-based measures, is based on the log-sum of discrete choice models applied to destination choice analysis (Ben-Akiva and Lerman, 1977). Despite their theoretical appeal, application of discrete choice models to destination choice is currently limited in terms of the spatial resolution of alternative destinations (destinations must be aggregated in order to reduce the size of the choice set), or depends on a randomly selected set of alternatives in a common but dubious practice due to spatial autocorrelation concerns and the implications for the Independence of Irrelevant Alternatives property of multinomial logit models (Páez, 2009). In this paper, we will not be concerned with this (essentially positivistic) approach.

Table 1 illustrates how different measures of accessibility can be obtained by defining the functions $g(\bullet)$ and $f(\bullet)$ in various ways. Note that the subscript k and superscript p are not shown in the table. In principle, a location-based measure can be converted into a person-based measure by considering: (1) the differing individual profiles, including location; (2) how these profiles affect the way people perceive or experience space; and (3) authority constraints that may prevent certain segments of the population to access some types of opportunities, or at specific times.

2.2. Positive and normative implementation of measures

Since accessibility measures are comprised of two parts, opportunities and cost of travel, there are four normative–positive combinations depending on how the transportation and land-use components of accessibility are implemented (see Table 2). A vast majority of accessibility research is concerned with applications where the distribution of opportunities is given, in other words, with a positive implementation of the land-use component. There are a few examples where the desired distribution of opportunities is cast within an accessibility framework, including the analysis of dental services in Ohio of Horner and Mascarenhas (2007), and the method proposed by Horner (2008) to generate optimal accessibility landscapes. More frequently, this class of problems is covered in the location–allocation literature, where objective functions typically involve cost of travel as one of various criteria. In what follows, we concentrate on measures that deal with the actual distribution of firms and services, and on the transportation side with normative/positive implementations of the cost of traveling. It is important to note that these measures could be used to analyze the accessibility impacts of proposed new services – however, not in the sense of optimally allocating them.

From the perspective of the cost of transportation, accessibility measures are frequently implemented based on assumed values of distance or time traveled – a fact that presumably underlies the assertion that: "[a]ccessibility is a measure of supply, namely potential mobility, is not a descriptor of behavior" (Salomon and Mokhtarian, 1998, p.131). Indeed, a review of the literature finds that in a large number of applications, the transportation component of accessibility measures is often assumed based on conventions, reasonable expectations on the part of the analyst, or a desire to highlight patterns – and less frequently on actual measures of travel behavior.

Conventions develop as early research is published and the results are adopted in the literature. For instance, in order to define accessibility to transit stops "[t]he user must be able to get to the origin transit stop and from the destination transit stop in a reasonable amount of time (5 min or [400 m] distance is a typical standard for walking)" (Beimborn et al., 2003, p. 3). Once in print, "reasonable" values have a tendency to become conventional. Consider, as an example, the use by Smoyer-Tomic et al. (2008) of various distances from Census Block centroids (500, 800, 1000, and 1500 m). These values are selected because they "correspond with those used in related literature" (p. 742). The works referenced in support of this selection include Apparicio et al. (2007), who use a distance of 1000 m (corresponding to a 15 min walk for an adult in an urban setting – Montreal), and Block et al. (2004) who "chose…1-mile and 0.5-mile buffers because of uncertainty of how far individuals were willing to routinely travel outside their census tract to purchase food".

Even considering the caveat concerning uncertainty about travel behavior, there appears to be little agreement in terms of what a "reasonable" distance is. For instance Ball et al. (2009) choose for their analysis of suburbs in Melbourne "[a] 2 km buffer zone…since this had been suggested as a reasonable travel distance to food outlets" (p. 579). The relevant reference is Donkin

Table 1
Examples of accessibility measures: formulation and applications.

Accessibility from the origin	$g(W_j)$	$f(c_{ij})$	Examples
Cumulative opportunities	*General formulation*: W_j *Relative supply*: $W_j = \frac{S_i}{D_j}$ S_i: supply of a service (e.g. number of beds at hospital) D_i: demand of a service (e.g. population in catchment area)	$I(c_{ij} \leqslant \gamma_i) = \begin{cases} 1 & \text{if } c_{ij} \leqslant \gamma_i \text{ (threshold value)} \\ 0 & \text{otherwise} \end{cases}$	Gutiérrez and Gómez (1999): Number of jobs within 20 and 30 min of i O'Kelly and Horner (2003): Population within 50 miles of i Apparicio et al. (2007): Number of supermarkets within 1000 m of i, divided by share of population Sharkey et al. (2009): Number of food stores or fast food restaurants within 1, 3, and 5 mile network distance from population weighted center of Census Block Group i
Gravity	*General formulation*: W_{ij}^{θ} **Specific cases:** *Cost weighted opportunities*: $\theta = 1$ *Agglomeration*: $\theta > 1$ opportunities exert a more than proportional effect on accessibility *Congestion*: $\theta < 1$opportunities exert a less than proportional effect on accessibility	*General formulation*: $K(\frac{c_{ij}}{\gamma})$ **Specific cases:** *Negative exponential*: $\exp(-\gamma_i c_{ij})$ *Inverse cost*: $c_{ij}^{-\gamma_i}$	Gutiérrez and Gómez (1999): Inverse-cost weighted population and number of jobs ($\theta = 1$, $\gamma = 1$) Parks (2004): Gaussian-cost weighted number of jobs ($\theta = 1$, γ empirically calibrated using a gravity model) Holl (2007): Inverse-cost weighted population ($\theta = 1$, $\gamma = 1$) Scott and Horner (2008): Gaussian-cost weighted number of opportunities ($\theta = 1$, γ empirically calibrated using a gravity model) Cervigni et al. (2008): Pediatrician/children ratios within a 10 km radius of child population centroids
Mean travel cost to k nearest facilities	$I(c_{ij} \leqslant c_{ij}^{*}) = \begin{cases} 1 & \text{if } c_{ij} \leqslant c_{ik}^{*} \text{(cost of traveling to } k\text{th nearest facility)} \\ 0 & \text{otherwise} \end{cases}$	$\frac{t_{ij}}{k}$	Stanilov (2003): Distance to CBD, distance to nearest freeway, distance to nearest arterial ($k = 1$) Armstrong and Rodriguez (2006): Distance to nearest rail station by foot or car ($k = 1$) Apparicio et al. (2007): Distance to nearest supermarket ($k = 1$; population weighted) Scott and Horner (2008): Travel time to nearest facility ($k = 1$) Sharkey et al. (2009): Distance from population weighted center of Census Block Group i to nearest food store or fast food restaurant ($k = 1$) Hare and Barcus (2007): Mean travel time from zone centroid to 10 nearest general and surgical hospitals ($k = 10$)
Presence of at least one facility within predetermined distance	$I(c_{ik}^{*} \leqslant \gamma) = \begin{cases} 1 & \text{if } c_{ik}^{*} \text{(cost of traveling to } k\text{th nearest facility)} \leqslant \gamma \\ 0 & \text{otherwise} \end{cases}$	1	Smoyer-Tomic et al. (2008): Access to supermarkets ($\gamma = 800$ m), access to fast food restaurants ($\gamma = 500$ m) Horner and Mascarenhas (2007): Access to dental services ($\gamma = 10$ mile)
Accessibility to the destination	$g(P_j)$	$f(c_{ij})$	Examples
Population serviced or market shares	*General formulation*: P_j *Market share*: $M_j = \frac{P_j}{\sum_j P_j}$ P_j: Population serviced by facility	$I(c_{ij} \leqslant \gamma_i) = \begin{cases} 1 & \text{if } c_{ij} \leqslant \gamma_i \text{ (threshold value)} \\ 0 & \text{otherwise} \end{cases}$	Grengs (2001): Percentage of population *beyond* transit service buffer Martin et al. (2008): Travel time to hospital from addresses in 30 km buffer Islam et al. (2008): Number of individuals within travel time of various opportunity locations Islam et al. (2008): Number of individuals within travel time of various opportunity locations Cervigni et al. (2008): Number of children within a 10 km radius of hospital Cinnamon et al. (2008): Proportion of total population within 1 h driving time of facility

Table 2
Normative and positive implementations of accessibility.

		Cost of travel	
		Normative	Positive
Distribution of opportunities	Normative	• Desired/assumed location of firms or services • Desired/assumed behavior of travelers	• Desired/assumed location of firms or services • Actual/observed behavior of travelers
	Positive	• Actual/observed location of firms or services • Desired/assumed behavior of travelers	• Actual/observed location of firms or services • Actual/observed behavior of travelers

et al. (1999) who select a 2 km radius as a reasonable walking distance in their analysis of two wards in London (this distance was confirmed by participatory appraisal work). Occasionally efforts are made to confirm the relevant parameters used in the analysis. Examples of this, in addition to Donkin et al. (1999), include Lovett et al. (2002) who use "[a] radius of 800 m... to represent a distance that the great majority of the population would find acceptable to walk... [this distance] was arbitrary but was informed by advice from local bus operators and transport planners." (p. 103). Despite this use of expert opinion, there are still important differences in values reported in the literature (compare to the 400 m used by Beimborn et al. (2003)).

The lack of agreement in conventionally used values is perhaps not surprising when one considers that travel behavior may not be constant between regions, or even locations within regions (see Morency et al., 2011; Roorda et al., 2010). On the other hand, this arouses questions regarding the transferability of "reasonable" values between case studies, and at a different level, whether the values used for the cost of travel reflect actual behavior, or rather the beliefs of the analyst with regards to needs satisfaction, as in the following case:

> "[W]e believe that an individual wishing to satisfy his desire to play a [Video Lottery Terminal] will tend to go to the establishment closest to his place of residence, above all when he is walking" (Robitaille and Herjean, 2008, p. 5).

In other instances, values are selected in order to emphasize variability. For instance, Pasch et al. (2009) study access to alcohol outlets within a 3000 m buffer. Selection of this buffer is "largely due to the suburban geography" and follows a desire "to maximize variability" in the representation of accessibility. The analysts also believe that "the youth in our sample are more mobile and may be better able to travel further from the home or school environment, therefore, the 3000 m buffer was also chosen to reflect this potential increased exposure" (p. 643). Smoyer-Tomic et al. (2006), in their analysis of food deserts in Edmonton, report on the use of buffers of 1 km radius after examining 500 m and 800 m buffers that resulted in minimal accessibility differences within the city.

Now, we do not mean to suggest that using such values is improper, but rather that the interpretation of the resulting measures of accessibility needs to be clarified. Along this lines, Straatemeier and Bertolini (2008) note that statistics are readily available for accessibility analysis involving travel times when commuting to work. However, when asked, experts had difficulties in setting the requirements "for other activities...because they appeared not to know the actual behavior related to these types of activities. This resulted in more *normative* or *impressionistic* statements about the required access to certain activities with different transport modes" (p. 5; our emphasis). This suggests that measures implemented in the way described above should be interpreted as normative, and most definitely not as indicators of behavior. This distinction, alas, is seldom made in the literature. Dunkley et al. (2004) pinpoint the issue when stating that:

> "[t]he two [measures] used [in the analysis]...do not incorporate either subjective preferences or objectively measured differences among individual persons or households. Thus, they use the same standard of access to groceries for everyone, consistent with the view that *everyone ought to have some minimal access to food*, which is a necessity" (p. 395, our emphasis).

In other words, the measure is not about actual travel behavior, but rather about a situation that is seen as desirable in a normative way – that everyone should have, as a standard, some minimal level of access to food. A second lonely example where the difference is explicitly made is Smoyer-Tomic et al. (2004) who use for their analysis a distance of 800 m from parks because:

> "[This distance] corresponds to Edmonton's specification of the maximum distance residents would have to travel to reach a neighbourhood park" (p. 292).

Again, this measure does not in any way reflect how far members of the public are willing to travel in order to use recreational facilities, but is rather a normative statement that nobody should have to go more than 800 m before finding a park. A key difference then emerges about how far people *ought* to travel (normative) and how far they *actually* travel (positive). Thus, a measure could be implemented based on the normative objective that every resident should have (for instance) a food store within 800 m of their residence. If no stores are found at that distance from a given location, the established norm is violated, and this situation may prompt policy intervention. The measure, on the other hand, does not imply that people are not willing to travel longer to find a food store. Alternatively, measures could be implemented to test whether access at different scales correlates with other forms of behavior (e.g. alcohol consumption, use of VLT). It is important to note that the differences between normative implementations and those based on actual behavior can be substantially large (e.g. Zhao et al., 2003).

As shown in Table 3, there are multiple examples of studies where accessibility is implemented in a definitely positivistic way with regards to the cost of travel. These are cases where the cost of travel reflects actual behavior – for example, actual distance traveled during the day by specific individuals, as revealed in surveys (e.g. Islam et al., 2008; Pasaogullari and Doratli, 2004). This type of implementation is common in empirical time geography research (e.g. Casas, 2007; Kwan, 1998). Direct use of distance or travel time reported in surveys retains a high degree of specificity with respect to individual accessibility, but does not lend itself for generalization. Other approaches that allow for generalizations include the estimation of spatial interaction (gravity) models as in Scott and Horner (2008), Minocha et al. (2008), Ozbay et al. (2003), and Clarke et al. (2002). Regression analysis can also be used to obtain estimates of distance or time traveled, as in Páez et al. (2010b) and Zhao et al. (2003). Zhao et al. (2003), for example, estimate a distance decay function of transit use based on regression analysis. The results are indicative of how far people are willing to walk to a transit stop. The function is then used to weight population around transit stops, substituting the typical ¼ mile (1320 ft) buffer in the analysis of accessibility in this type of application. The findings indicate large differences in potential users when revealed behavior is considered, as opposed to the typical "reasonable" values of buffers. This implementation of accessibility

Table 3
Summary of selected applications.

Cost of travel	
Normative (no behavioral content)	Positive (behavioral content)
• Ribeiro et al. (2010): Population within 60, 90, 120 min travel time of municipality i	• Páez et al. (2010b): Number of opportunities within distance d of place of residence. Distance d is estimated based on travel diary survey data
• Sharkey et al. (2009): Number of facilities within 1, 3, and 5 mile network-based buffers	• Scott and Horner (2008): Number of employees at opportunity j. Exponential decay function of travel time is calibrated using a gravity model
• Sharkey et al. (2009): Distance from Census Block Group centroid to nearest supermarket/fast food restaurant is calculated	• Islam et al. (2008): Distance traveled by individuals to various opportunity locations is directly obtained from survey
• Vandenbulcke et al. (2009): Spatial distribution of towns and rail stations is given. Travel time to nearest opportunity is measured	• Minocha et al. (2008): Employment distribution is given. Exponential distance decay function from origin i is calibrated using gravity model
• Ball et al. (2009): Number of fruit and vegetable stores, and chain supermarkets within a 2 km network-based buffer	• Chang and Lee (2008): Location of rapid rail transit stations are given. Exponential cost decay function is calibrated based on the generalized cost of various access modes
• Pasch et al. (2009): Number of alcohol outlets within 3000 m buffer	• Casas (2007): Number of opportunities within distance d of place of residence. Distance is maximum distance traveled by individual during the day
• Pasch et al. (2009): Distance from respondent's place of residence to nearest alcohol outlet is calculated	• Shin et al. (2007): From Traffic Analysis zone i, estimated number of commute trips ending in zone j, with estimated shortest travel time between i and j in free-flow and peak-hour conditions
• Pearce et al. (2009): Travel time (by car – assumptions not explained) from population-weighted center to nearest tobacco outlet is calculated	• Tanser et al. (2006): From homestead i, travel time to nearest clinic. Theoretical travel time models calibrated with survey data
• Macintyre et al. (2008): Mean distance to nearest opportunity of each class (libraries, parks, etc.) is calculated	• Horner (2004): Estimated average cost of trips produced or attracted by zone. Exponential distance decay function is calibrated using a gravity model
• Larsen and Gilliland (2008): Population within 1000 m distance of supermarkets (based on comparisons and empirical results), or within 10 min bus ride plus 500 m walk	• Pasaogullari and Doratli (2004): Travel time to public space, explicitly asked in utilization survey
• Cervigni et al. (2008): Population within 10 km buffer from hospital	• Rosero-Bixby (2004): Medical doctor-hours at distance d from place of residence. Inverse distance function and congestion effect calibrated using a discrete choice model
• Robitaille and Herjean (2008): Distance to nearest Video Lottery Terminal is calculated	• Zhao et al. (2003): Frequency distribution of transit use at different distances to stop. Distance decay function estimated based on survey data
• Smoyer-Tomic et al. (2008): Number of supermarkets/fast food restaurants within 500, 800, 1000, and 15,000 m of Census Block centroid	• Wang (2003): Ratio of jobs available at j to residents of zone i, accounting for residents of other zones. Travel time and parameter of decay function are estimated from Census Transportation Planning Package data
• Raja et al. (2008): Number of food destinations within 5 m travel time of neighborhood centroid i by different modes	• Ozbay et al. (2003): Proportion of total number of jobs reached by commuter from zone i within 60 min travel time, calibrated based on origin–destination matrix
• Chen et al. (2008): Distance to current employment location (revealed) from alternative residential locations is calculated	• Clarke et al. (2002): Retail floor space at j. Exponential decay function of distance d is calibrated using a gravity model
• Lopez et al. (2008): Total population within 4 h travel time of population center i	
• Lopez et al. (2008): Distance weighted population using exponential decay function with $\beta = 1$ (by convention)	
• Straatemeier (2008): Number of inhabitants requiring a service within reasonable travel time of service location (30 min by car, 45 min by transit). Distance traveled is based on modeled travel speed	
• Straatemeier (2008): Number of jobs within 15 min travel time of population center. Distance traveled is based on modeled travel speed	
• Shin et al. (2007): Walking time from real estate property to nearest subway station	
• Shin et al. (2007): Distance from real estate property to Central Business District	
• Lin et al. (2007): Number of electronic-related professionals in institutions located in zone j within 10 km of i	
• Lin et al. (2007): Distance weighted number of professionals using exponential distance decay with $\beta = 2$ (selected to improve the fit of innovation model)	
• Hare and Barcus (2007): Area covered by 15 min travel bands from general and surgical hospitals	
• Escalona-Orcao and Diez-Cornago (2007): Travel time from population center to designated health care facility	
• Martin and Reggiani (2007): Travel time to urban agglomeration and local share of GDP at agglomeration	
• Ozmen-Ertekin et al. (2007): Mean travel time to all counties in sample	
• Chin and Foong (2006): Number of school in zone of real estate property	
• Chin and Foong (2006): Distance from real estate property to nearest subway and CBD	
• Zenk et al. (2005): Manhattan distance from Census Tract to nearest supermarket	
• Wang and Luo (2005): Population within 30 min travel time from physician location j. Travel time based on nominal speed limits	
• Smoyer-Tomic et al. (2004): Distance from postal code centroid to nearest playground	
• Smoyer-Tomic et al. (2004): Number of playgrounds within 800 m buffer of postal code centroid	
• Guagliardo et al. (2004): Number of primary care providers for children in a small cell (0.1 square mile) divided by population in cell	
• Dunkley et al. (2004): Number of stores within 5 min travel time (by various modes) of population weighted centroid	
• Rosero-Bixby (2004): Nearest outpatient care/hospital facility is within 4 km/25 km of place of residence	

Table 3 (*continued*)

Cost of travel	
Normative (no behavioral content)	Positive (behavioral content)
• Beimborn et al. (2003): There is at least one transit stop within ¼ mile of place of residence • Lovett et al. (2002): Distance to nearest surgery from residential postcode (population weighted) • Lovett et al. (2002): Population within 800 m buffers around transit routes that passed within 800 m of at least one surgery • Hyndman and Holman (2001): Population at distance *x* to nearest surgery • Talen (2001): Network-based distance from Census Block centroid to location of school in district	

does not carry any normative value – while it indicates the distance that transit users actually walk (a majority of them no more than 300 ft, and very few more than 2400 ft), it does nothing to establish value in terms of what the situation ought to be. On the other hand, the measure provides a more refined planning tool to assess catchment areas (which are grossly overestimated by the buffers method), and can in fact feed into a more normative exercise, by informing, based on evidence of travel behavior, the possible distribution of stops to increase the potential population served.

In the following section, a comparison between positivistic and normative implementations of accessibility measures will further serve to illustrate the differences between these two approaches. As well, the example will show how the two approaches can be fruitfully used in combination to better understand the gaps between desired and actual patterns of accessibility.

3. Example: accessibility to day care facilities in Montreal

In this section, we illustrate the differences between positive and normative implementations of a common accessibility measure. We use as an example the case of accessibility to day care facilities in Montreal, Canada.

Traditionally, the provision of child day care services in Canada was perceived as important only in exceptional circumstances, for lone parents or in periods of national crisis (Rose, 1990). With greater participation of women in the workforce and an increase in the number and proportion of lone parent families, day care use has increasingly entered the mainstream. Daycare is, in fact, thought to be a key balancing factor that can influence production–reproduction decisions of policy relevance (Joshi, 2002; Van Ham and Buchelz, 2006). On the one hand, there is the decision whether to participate in the labor force, which is essential for lone parents, and increasingly important as well for dual-earner families: according to recent statistics, female labor contributed approximately 33% of family income in an average dual-earner family (Gascon et al., 2007). The decision whether to have children is also of policy interest, given Canada's sub-replacement fertility rate. Further to production-reproduction decisions, day care attendance is also thought to have a positive effect on children over the lifespan (Havnes and Mogstad, 2011; Kohen et al., 2008).

Accessibility to day care is broadly understood to have a financial component. In the case of Quebec, as the first jurisdiction in North America to institute universal child care, subsidies for regulated care succeeded in increasing participation rates, in particular for low-income families (Baker et al., 2008; Kohen et al., 2008). It is also recognized that accessibility to day care has a spatio-temporal component that is particularly critical to understand life and work-balance issues for females (Schwanen and de Jong, 2008). There have been, however, very few studies that investigate the geography of accessibility to day care: besides the work of Schwanen and de Jong (2008) in the Netherlands, these include the analysis of day care accessibility and labor-market participation in the UK of Webster and White (1997), the investigation of deprivation and accessibility to community resources in New Zealand due to Pearce et al. (2008), and the studies of Kawabata (2009, 2010, 2011) in Tokyo. In the specific case of Montreal, prior to 1990 no research existed on the location of day care facilities and the impact on accessibility (Rose, 1990, p. 367). No research on the geographical accessibility of day care services in the region appears to have been conducted in the intervening time.

3.1. Data

In order to implement accessibility using a positive approach, we employ data extracted from Montreal's Household Travel Survey of 2003 (see http://www.cimtu.qc.ca/EnqOD/Index.asp). This survey was collected by means of Computer Aided Telephone Interviews with approximately 70,000 households or about 5% of all households residing in the survey area. Information was collected regarding the travel behavior of every participating household member 4 years and older. This includes number of trips, purpose of trips, and location of the destinations. In addition, socio-economic and demographic information was collected. Place of residence and destinations were geocoded using structured databases on addresses, intersections, and trip generators. The database is comprised of 122,420 records corresponding to individuals who performed out-of-home activities during the day of the survey.

Day care facilities in Montreal were extracted from a business point database. This database is prepared by InfoCanada, a firm that collects industrial information and verifies it annually for accuracy. Environics Analytics, a marketing firm based in Toronto, further processes and packages this information to create a georeferenced set of business points (latitude and longitude) with business profiles. Day care facilities can be identified by their Standard Industrial Classification (8351: Services-Child Day Care Services). A total of 1131 sites are identified for Montreal.

3.2. Estimates of travel behavior

One way to introduce behavioral content in the calculation of a positivistic measure of accessibility is by using estimates of trip length. An attractive way to obtain estimates of this travel behavior is by applying the spatial modeling approach known as the expansion method (Casetti, 1972). The expansion method is a simple tool to generate models with spatially-varying coefficients, which allow the analyst to obtain location- and person-specific estimates of distance traveled (Morency et al., 2011). These estimates, in turn, define spatially-varying threshold values for deriving cumulative opportunity indicators of accessibility. The expansion method offers some attractive features. At each location in space individuals are differentiated by their socio-demographic characteristics (e.g. age, income, household structure, mobility tools, etc.), and can be compared explicitly in terms of their accessibility. In turn, this may suggest reasons why observed differences exist, and thus inform any location-specific actions to be taken by planners and policy makers to mitigate the experiences of presumably disadvantaged individuals.

Implementation of the expansion method requires detailed travel survey data. In addition to socio-demographic information, these data must include geocoded locations for which the accessibility values will be calculated, such as residential or work locations. Also, trip distances must be provided with the data or generated by the analyst. Normative implementation of accessibility, in contrast, requires only a standard value or a reasonable supposition of cost. In other words, the expansion method approach can be considered 'data hungry' compared to the normative approach.

The expansion method is implemented as follows. Beginning with an initial model of trip length d (log-transformed to compress the long tail usually displayed by this variable):

$$\log(d_i) = \beta_0 + \sum_j X_{ij}\beta_j + \varepsilon_i \tag{4}$$

an expanded model can be defined to incorporate interactions between the location of an observation (i.e. a contextual factor) and all or some variables of substantive interest X as follows:

$$\log(d_i) = \sum_j X_{ij}\beta_j + \sum_s Z_{is}\theta_{is} + \varepsilon_i \tag{5}$$

In Eq. (5), Z is a substantive variable associated with a spatially expanded coefficient θ. Please note that the expanded coefficients θ, unlike spatially-fixed coefficients β, are specific to location i. Coefficient expansion is achieved by defining the coefficient as a function of contextual variables, in this case the coordinates u_i and v_i (e.g. northing and easting, or latitude and longitude) of the observation. The expansion takes a linear form if we define:

$$\theta_{is} = \theta_{s1} + \theta_{s2}u_i + \theta_{s3}v_i \tag{6}$$

or a quadratic form by introducing squared terms:

$$\theta_{is} = \theta_{s1}1 + \theta_{s2}u_i^2 + \theta_{s3}u_i + \theta_{s4}u_iv_i + \theta_{s5}v_i + \theta_{s6}v_i^2 \tag{7}$$

Higher order expansions can be defined easily by using higher order polynomials.

Average trip length is used as a basic indicator of individual mobility (Morency et al., 2011). This variable is defined as the average straight line from place of residence to destination for all trips and purposes, excluding only the return-home trip. Straight line distance is simple to compute, and is highly correlated with network distance (Apparicio et al., 2008). Explanatory variables used to estimate the model are selected based on theoretical considerations and a survey of the previous literature on distance travelled. Detailed discussions concerning the selection of variables appear in Páez et al. (2009) and Morency et al. (2011). The results of estimating a spatially expanded model of average trip length for Montreal appear in Table 4.

The coefficients of the model can be used to obtain estimates specific to a socio-economic and demographic profile p and location i. For instance, if the desired profile p is a 38-year old female, living with a couple and children, who is employed full time, with a household income of \$45,000, who has a driver's license and a household car, the estimate can be calculated as:

$$\hat{d}_i^p = e^{-2.1698-0.1349-0.1333+0.2844+0.1729+0.5448-22.0461\mathrm{PopDen}_i+4.2953\mathrm{DistCBD}_i-4.0270u^2+5.5544u-0.3891uv+4.8903v-5.4417v^2} \tag{8}$$

It can be seen that the estimate for a specific socio-economic and demographic profile will vary by location, when distance to CBD, and the coordinates u and v are introduced to evaluate the profile at different locations. By purposefully varying the personal profile and using the appropriate coefficients, spatial and personal variations in travel behavior can be estimated. For the example, we use the three different profiles shown in Table 5.

As seen in the table, the profiles are young females (age 20–35) living in different household types: Profile 1 is a couple with children, whereas Profiles 2 and 3 are lone mothers. The income level of lone mothers is slightly lower than for a family with a couple (20–40 thousand dollars and 40–60 thousand dollars respectively). Further, Profile 2 is a lone mother who owns a vehicle and holds a driver's license, while Profile 3 is a lone mother who lacks these mobility tools. The estimates of average trip length for these three profiles are shown in Fig. 1. In general, trips tend to become longer as the place of residence is located farther away from the central part of the city. More specifically, important variations in average trip length can be observed, with lone mothers having more limited geographical range than comparable females living with a couple, a situation exacerbated by the lack of mobility tools.

3.3. Accessibility to day care: implementations

We illustrate the differences between normative and positive implementations of a cumulative opportunities indicator of accessibility. The general formulation of this indicator is as follows:

$$A_{ik}^p = \sum_j W_{jk} I(c_{ij} \leqslant \gamma_i^p) \tag{9}$$

where W_{jk} indicates the presence of a facility of type k at location j, c_{ij} is the cost of moving between i and j, and γ_i^p is a threshold value.

Normative implementations of the accessibility indicator could be as follows. A reasonable distance (i.e. a buffer) for calculating accessibility is, say, 3.6 km (e.g. the average trip length of females aged 20–35 with children in the region). Alternatively, one could follow a policy goal that families should have a reasonable choice of day care facilities within a distance of (for the sake of the example) 3.6 km from their place of residence. The normative indicator of cumulative opportunities has a fixed threshold, and is calculated as:

$$A_i = \sum_j W_j I(d_{ij} \leqslant 3.6) \tag{10}$$

The results of calculating this accessibility indicator for a fine (1 km) grid in Montreal appear in Fig. 2.

The map in Fig. 2 is the typical output of an analysis of accessibility. Clearly, the density of opportunities (the number of day care facilities) is lower in the peripheral areas of Montreal Island, thus revealing the spatial disparities in terms of the number of opportunities available at various locations. This map could be used by an analyst to normatively assess the number of opportunities available at a variety of locations within the study area, and contrast them against policy goals – for instance, to recommend infrastructure planning objectives. Alternatively, the map could be interpreted as the number of opportunities available within what the analyst considers a reasonable distance from the place of resi-

Table 4
Spatial expansion model of average trip length, Montreal 2003 (u and v are the geographical coordinates).

Variable	Estimate	p-Value
Constant	−2.1698	0.0000
Gender		
Female	−0.1349	0.0000
Age		
Age <20	−0.4418	0.0000
Age 20–35	0.0497	0.0000
Age 36–50	Reference	
Age 51–64	−0.0309	0.0009
Age 65+	0.3920	0.0130
Income		
Income refuse/do not know	0.0190	0.0292
Income <20 K	−0.8890	0.0001
Income 20–40 K	−0.0624	0.0000
Income 40–60 K	Reference	
Income 60–80 K	0.0835	0.0000
Income 80–100 K	0.1358	0.0000
Income >100 K	0.1925	0.0000
Household structure		
Couple with children	−0.1333	0.0000
Other multi-person household	0.0354	0.0000
Mobility tools		
Driver license	0.2844	0.0000
Household owns vehicle	0.1729	0.0000
Transit within 500 m	−0.0879	0.0000
• Age 65+	−0.1561	0.0069
• Low income	0.0943	0.0277
Free parking at work	0.2183	0.0000
Occupation		
Full-time employment	0.5448	0.0000
• Age 65+	−0.1014	0.0187
• Low income	−0.0573	0.0134
Part-time employment	0.1839	0.0000
• Low income	0.1211	0.0031
Student	0.5154	0.0000
Urban form		
Population density	−22.0461	0.0000
Spatial expansion		
Distance to CBD	4.2953	0.0000
• Age 65+	−0.3689	0.0138
• Single parent	−1.2410	0.0000
u^2	−4.0270	0.0000
• Low income	−3.3371	0.0000
• Single parent	2.1180	0.0052
U	5.5544	0.0000
• Age 65+	−0.2930	0.0009
• Low income	4.3100	0.0000
• Single parent	−3.7163	0.0034
$u * v$	−0.3891	0.0011
• Low income	−0.6588	0.0478
• Single parent	1.6555	0.0035
v	4.8903	0.0000
• Age 65+	−1.0728	0.0354
v^2	−5.4417	0.0000
• Age 65+	1.0570	0.0425
• Low income	−0.5575	0.0028
• Single parent	0.8873	0.0074

$R^2_{adj} = 0.201$, $s^2 = 1.204$, $s = 1.097$, $n = 122{,}420$.

dence. Note that this implementation of accessibility reflects a normative position, a relatively simple assumption about travel behavior, or the beliefs of the analyst, and is insensitive to variations in travel behavior by population segments, such as illustrated in Fig. 1. A positivistic implementation of the cumulative opportunities indicator would be as follows:

$$A_i^p = \sum_j W_j I(d_{ij} \leqslant \hat{d}_i^p) \tag{11}$$

Table 5
Examples of personal profiles.

Variable	Household structure		
	Profile 1: couple with children	Profile 2: lone parent	Profile 3: lone parent
Gender			
Female	✓	✓	✓
Age			
Age 20–35	✓	✓	✓
Income			
Income 20–40 K		✓	✓
Income 40–60 K	✓		
Mobility tools			
Driver license	✓	✓	
Vehicle own	✓	✓	
Occupation			
Full time employment	✓	✓	✓
Urban form			
Population density	✓	✓	✓
Spatial expansion			
Distance to CBD	✓	✓	✓
• Single parent		✓	✓
u^2	✓	✓	✓
• Single parent		✓	✓
u	✓	✓	✓
• Single parent		✓	✓
$u * v$	✓	✓	✓
• Single parent		✓	✓
v	✓	✓	✓
v^2	✓	✓	✓
• Single parent		✓	✓

The threshold in Eq. (11) replaces the normative value with a behaviorally derived measure, such as the estimate of average trip length for personal profile p at location i. Since the threshold now adapts to reflect variations in travel behavior, the indicator of accessibility now is superscripted by profile p.

The maps in Fig. 3 show the results of implementing the indicator of accessibility in a positivistic way, for the Profiles 1–3 shown in Table 5. The general patterns of accessibility are similar for the three profiles. This is due to the underlying opportunity landscape. However, there are important differences that reflect the way individuals of the selected profiles typically use space. Profile 1, a female with access to a vehicle and driver's license, living in a household with a couple and children, tends to have a longer range. This is clearly reflected in the number of opportunities that can be reached within the distance of a typical trip. A lone mother (Profile 2) has access to a much smaller set of opportunities, as expected due to their more limited range. Lack of mobility tools (Profile 3), further reduces the number of opportunities available that a lone mother can reach within the distance of a typical trip.

Due to the differences in travel behavior, there are large differences between the normative implementation of the accessibility indicator and the accessibility calculated using behavioral input. As an exploratory tool, the normative and positive versions can be combined to derive insights about how well behavior conforms to an established norm. Relative accessibility is calculated as follows (using the estimate of trip length for the positive version, and a distance of 3.6 km for the normative):

$$RA_i^{p/N} = \frac{A_i(\hat{d}_i^p)}{A_i(3.6)} \tag{12}$$

Profile 1 consistently exceeds the levels of accessibility derived in a normative way. As shown in Fig. 4, this is not the case for lone mothers. The maps in the figure show the ratio of positive accessi-

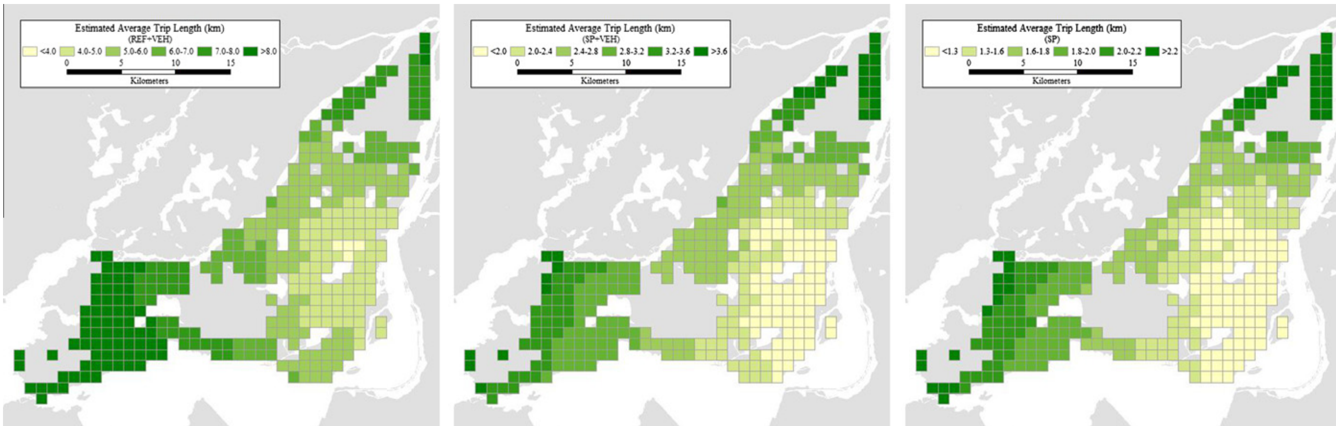

Fig. 1. Estimates of average trip length for Profiles 1: Female living with a couple and children (left); 2: Female, lone mother (center); and 3: Female, lone mother, no auto or driver license (right).

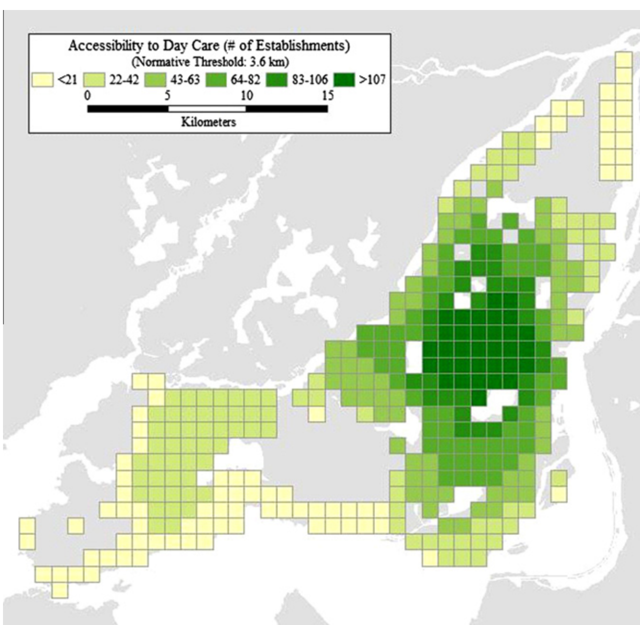

Fig. 2. Normative cumulative opportunities indicator.

bility (Profiles 2 and 3) to normative accessibility. There are sites where lone mothers with mobility tools can reach more opportunities within the length of a typical trip than stipulated by the normative accessibility, but more generally this is not true. As seen in the figure, there are no sites where the accessibility profile of a lone mother without mobility tools reaches 100% of the normative accessibility (the maximum value is 85.7%), and demonstrates a general lack of conformity with the stipulated norm.

4. Summary and conclusion

In this paper, we have conducted a review of the literature on accessibility measurements, with a view to clarify an issue that has not previously been explicitly discussed. Accessibility measures can be implemented using indicators of travel behavior, such as parameters derived from the calibration of gravity models or estimates of distance traveled. When implemented in this fashion, the indicators can be interpreted as positivistic approaches to measuring accessibility, or accessibility *as is*. More common in the literature is the implementation of accessibility using assumed reasonable values or occasionally values that correspond to some desired situation. In this case, we argue, the indicators must be seen as normative (accessibility as it *ought* to be or what is *reasonable*), recognizing that such indicators may be informed by some understanding of the behavior in question. In the latter case, the distinction between positive and normative is not completely

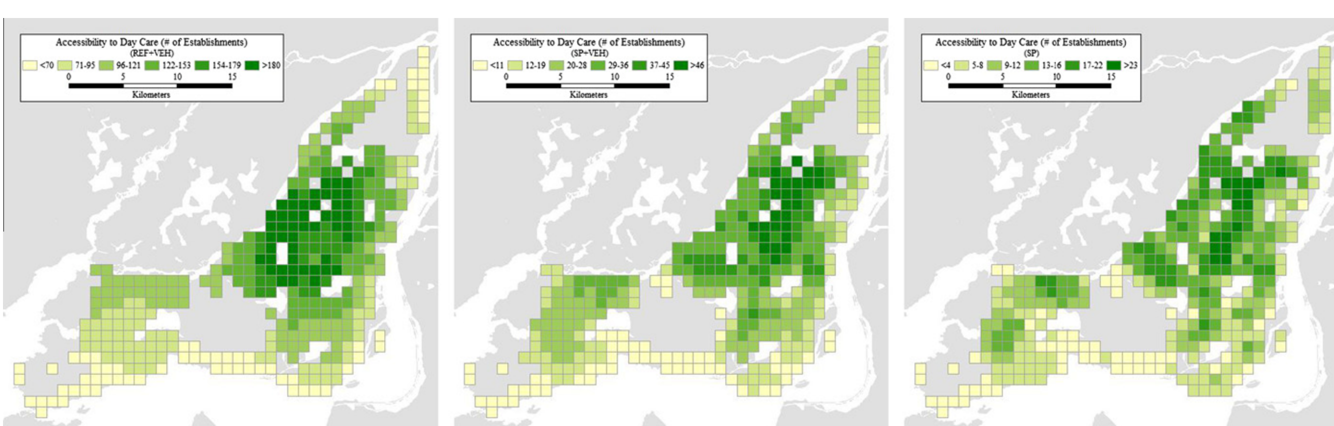

Fig. 3. Positivistic cumulative opportunities indicator for Profiles 1: Female living with a couple and children (left); 2: Female, lone mother (center); and 3: Female, lone mother, no auto or driver license (right).

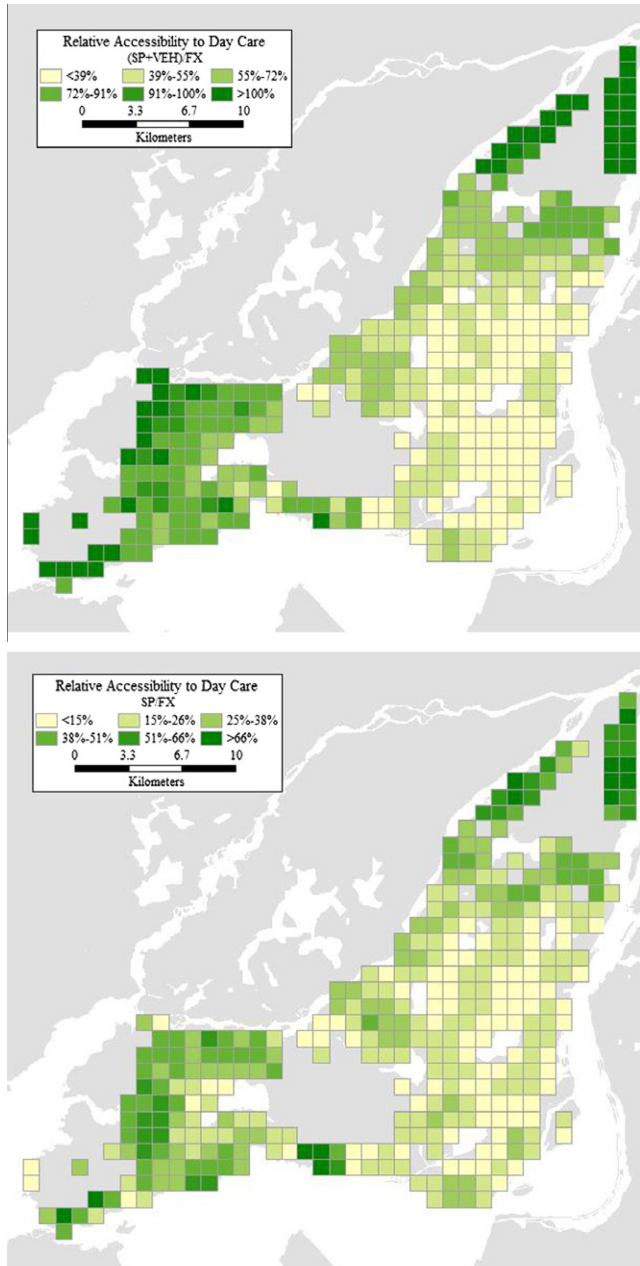

Fig. 4. Relative accessibility: Profiles 2 (top) and 3 (bottom) compared to normative (fixed threshold).

clear-cut, and may depend on the ability or willingness of the analyst to verify the assumptions underlying conventional, reasonable, or preferred values.

In order to illustrate the differences between normative and positive accessibility we also report the example of access to day care in Montreal, Canada. The comparison is based on one form of accessibility measure, cumulative opportunities, which enumerates the number of opportunities within a given threshold relative to an origin location. In the example, the opportunities are day care establishments, the threshold is defined by trip length, and the origin locations are defined by the geocoded locations of residences. Since there was no official value indicating how far an individual should have to travel to access day care, we set the normative accessibility threshold to 3.6 km, which is the average trip length of females aged 20–35 with children in the Montreal region as ascertained from the 2003 Montreal Household Travel Survey. In other words, our normative accessibility indicator is based on how far it is *reasonable* to travel, not how far people *ought* to travel. The expansion method is used to obtain positive accessibility thresholds. These thresholds, which are estimates of actual trip length, are location and person specific. Our comparison illustrates how different types of women conform to what we, the analysts, define as what is a reasonable distance to travel to access daycare. Obviously, these differences are likely to vary according to the value of the normative threshold chosen. Also, they will vary according to model fit. It is important to remember that the trip-length values derived from the expansion method are *estimates* of actual behavior, not actual trip lengths themselves. In turn, this means that the fit of the estimated model to the original data, as determined by the *r*-squared value, is important. Therefore, the objective of the analyst should be to achieve the highest *r*-squared value possible given the available data.

The comparison discussed in this paper illustrates how positive and normative accessibility indicators can be used in tandem –

that is, how a positive accessibility indicator can be used to test the extent to which the behavioral experiences of individuals conform to an existing policy or suggested norm. Differences between the two can be used to either alter existing policy or develop new policy. In turn, this suggests that the coupling of positive and normative accessibility can lead to better policy outcomes.

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