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An analysis of day-to-day variations in individual space-time accessibility

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Abstract

Traditional studies about the planning and equality of public service delivery have treated accessibility of services as if it were a static concept of physical proximity. This paper extends and empirically substantiates the conceptual argument for the incorporation of time in measures of accessibility. It does so by examining the variability in person-based accessibility to urban opportunities over a one-week period. Accessibility is specified on the basis of persons rather than places and measured for each day of the week rather than for a single day. An empirical case of government offices in the city of Ghent (Belgium) is used to demonstrate how space-time accessibility may fluctuate between persons and per person from day to day. The case study provides evidence that, even for fulltime workers on weekdays, considerable day-to-day variability in the accessibility level of a single person can exist as a consequence of differences in space-time constraints.

Keywords

Space-time accessibility; time geography; inter-personal variability; public services

1. Introduction

Accessibility is an integral concept of evaluative studies of public service delivery. In this context, accessibility is generally understood as the ease with which individuals can participate in desired activities given the available transportation system and land-use pattern (Pirie, 1979; Hero, 1986; Pooler, 1987). Traditionally, a place-based perspective is taken to measure accessibility. Place-based indicators assess accessibility in terms of the spatial proximity of services vis-à-vis the home or work location. Common examples of such indicators include the minimum network distance from the residence to the closest service and the number of accessible services within a given travel time. Place-based indicators are overwhelmingly favored in the public service delivery literature (see e.g. Talen and Anselin, 1998; Tsou et al., 2005; Langford and Higgs, 2010) because they yield valuable insights with relatively little data collection effort, are easy to implement using geographical information systems (GIS), and can be interpreted by policymakers without much prior knowledge of complex concepts or theories (Geurs and van Wee, 2004).

A major inadequacy of place-based indicators, however, is that they are static in the sense that they fail to account for the fact that accessibility levels may fluctuate over time as a consequence of day-to-day heterogeneity in time use and mobility patterns of individuals. Since the schedules of individuals are structured around well-established temporal rhythms of mandatory activities (e.g. working, chauffeuring children), time budgets to travel and engage in discretionary activities may vary substantially between days and across individuals. Furthermore, opening hours of urban opportunities also vary from day to day and often run parallel to individuals' working schedules.

The importance of such temporal constraints for accessibility analysis has been acknowledged in the strand of accessibility literature that has evolved around time geography (Hägerstrand, 1970). In particular, recent years have seen a modest but growing number of studies that have sought to use the time geographic framework to compute person-based measures of accessibility on the basis of detailed observations of individual activity and travel behavior (Neutens et al., 2011). These measures have proved particularly valuable in revealing individual differences in access to urban opportunities that would go unrecognized when conventional place-

based measures are employed (Kwan, 1998; Weber and Kwan, 2003; Casas, 2007; Kwan and Weber, 2008; Casas et al., 2009; Neutens et al., 2010b). However, while much progress has been made in operationalizing these measures (Miller, 1991; Kim and Kwan, 2003; Neutens et al., 2008; Neutens et al., 2010c), empirical work to date has used pooled samples of separately observed activity-travel days and generally do not make an explicit distinction between persons who are sampled at different days of the week. This implies that the individual differences in accessibility levels estimated in these studies may not reflect sheer inter-personal differences but are rather a corollary of the fact that people experience different space-time constraints on different days of the week.

This study has a dual aim. First, it seeks to develop and compute insightful measures of person-based accessibility that account for an individual's activity-travel patterns over an entire week. Second, it uses one-week activity-travel diaries to explore to what extent differences in individual accessibility may be attributed to inter-personal and intra-personal variability, respectively. These objectives are addressed in a case study of accessibility to government offices in the city of Ghent. This particular case was chosen because it is of interest to the local policy makers who are currently reexamining the spatiotemporal organization of their urban services within the framework of the LEO (Loket en Onthaalbeleid – Dutch for 'Office Window Services Policies') project.

2. Relevant literature

2.1. Day-to-day variation in observed travel and activity behavior

For several decades, multi-day analysis of individual travel characteristics has been an active research topic in travel behavior research. The need for a better understanding of day-to-day fluctuations of individual activity-travel patterns has emerged in tandem with a paradigm shift in transportation planning from capacity expansion to travel demand management (Pendyala et al., 2000). Using longitudinal activity-travel diary surveys, past studies have probed into the repetitive use of activity locations and the temporal stability of activity-travel decisions regarding *inter alia* mode choice, route choice, timing, duration, and trip frequency (Hanson and Huff,

1982; Pas, 1983; Huff and Hanson, 1986; Pas and Koppelman, 1986; Ma and Goulias, 1997; Buliung et al., 2008; Roorda and Ruiz, 2008; Kang and Scott, 2010). Empirical evidence has repeatedly shown that, besides *inter-personal* variability (differences in the behavior of different persons), activity-travel behavior also exhibits considerable *intra-personal* variability (differences in the behavior of one person over time), challenging the existence of an archetypal travel day and thus the value of models and policies based on single-day samples of travel behavior.

Along this line of inquiry, much attention has been devoted to the quantification of the spatial extent of revealed long-term mobility patterns of individuals and households. Drawing on insights from centrographic statistics (Beckmann et al., 1983b, a) and spatial ecology (Jennrich and Turner, 1969), researchers have sought to model the size of activity spaces of quotidian life. An activity space circumscribes the area where a person's activities are concentrated within a given time period (Newsome et al., 1998). Schönfelder and Axhausen (2003), for example, have used a six-week travel diary survey (*Mobidrive*) conducted in two German cities to explore the relationship between a respondent's activity space, measured through a confidence ellipse, a bivariate kernel, and a minimum spanning network, and his/her personal attributes. Their analysis showed that the size of an activity space is influenced by variety-seeking behavior as well as by the socio-demographic characteristics of the respondents. Using the same data set, Susilo and Kitamura (2005) revealed that inner-city residents tend to have larger variations in activity spaces than those who live in other areas of the city, and that the activity spaces of workers are more consistent over time than those of non-workers and students. Recently, Buliung et al. (2008) have found significant weekday-to-weekend and day-to-day variations in the geographical properties of activity-travel behavior measured through minimum convex polygons.

2.2. Day-to-day variations in potential travel and activity behavior

While the analysis of day-to-day variability of observed activity-travel behavior has received much attention in transportation studies, little is known about the implications of this variability for individual accessibility (i.e. an individual's ability to reach desired activity locations). Nevertheless, day-to-day variations in mobility

resources and the timing and location of mandatory commitments are likely to generate day-to-day differences in individual accessibility because these factors tend to act as capacity and coupling constraints on potential activity-travel behavior (Cullen and Godson, 1975; Schwanen et al., 2008). These personal constraints additionally interact in complex ways with the spatial and temporal constraints offered by the institutional context (e.g. shopping acts), the transportation system (e.g. congestion), and the urban environment (e.g. the spatial distribution and operating hours of urban opportunities).

The interplay of these constraints in shaping potential activity-travel behavior has long since been epitomized by the construct of a space-time prism (Hägerstrand, 1970) which represents a direct measure of an individual's accessibility. The operationalization of prism-constrained accessibility has nevertheless only recently received increased momentum thanks to advances in geographical information systems (GIS) and the availability of disaggregate travel data (Miller, 1991; Kwan and Hong, 1998). From an empirical point of view, temporal variations in the size of space-time prisms have been studied in two ways. Some scholars – among them Pendyala et al. (2002), Yamamoto et al. (2004), Kitamura et al. (2006) and Soo (2009) – have used stochastic frontier models to estimate the temporal distribution of a commuter's earliest possible departure from home (origin vertex of a morning prism before work) and latest possible arrival at home (terminal vertex of an evening prism after work). These estimations are based on observed timings of commuting trips and a range of socio-economic attributes. While these studies have generated useful insights into social differences in the timing flexibility of before-work and after-work trips, they did not consider individual accessibility to urban opportunities as such.

Others have used a more pragmatic approach by deriving the prism vertices from start and end times of mandatory activities reported in travel diaries (e.g. Kwan, 1999, 2000; Weber and Kwan, 2002; Kim and Kwan, 2003; Neutens et al., 2010b, a). These empirical investigations (*ibid.*) have relied on pooled samples of single-day or two-day observations, but did not consider explicitly the variations of a person's accessibility over a longer time horizon. This is to be considered a critical shortcoming since – as argued earlier – the accessibility level observed at a particular day may not be representative for an individual's accessibility at other days

of the week because of day-to-day differences in space-time constraints. Measures that summarize an individual's accessibility over a longer time horizon (e.g. one week) are expected to be more stable and would be useful to verify accessibility criteria specified over multiple days (e.g. an individual should be able to reach at least one opportunity on a weekday). Also, these measures would enable detailed evaluations of temporal policies that affect weekly repetitious regimes of constraints (e.g. opening hours of urban opportunities).

3. Person-based accessibility

An essential step in measuring person-based space-time accessibility is to derive space-time constraints retrospectively from observed activity-travel behavior of individuals. Following the time geographic tradition, we employ a space-time prism (*STP*) to express the role of these constraints on individual activity participation on a given day of the week. A *STP* gathers all space-time points (x, t) where an individual i could have been during a time budget between two fixed activities (Figure 1). Fixed activities are generally defined as commitments with high priority and a mandatory character that are difficult to replace and/or reschedule, at least in the short run. Examples of fixed activities typically include work, education, medical appointments, and chauffeuring children. The locations and times where an individual undertakes these activities limit to a large extent the number and kind of services that the individual can reach. Let (o, d) denote a pair of consecutive fixed activities o and d at locations x_o and x_d , respectively. The ending time t_o of the first fixed activity marks the starting time of the time budget, whereas the starting time t_d of the next fixed activity denotes the ending time of the time budget.

Having introduced these basic time geographic concepts, the *STP* can more formally be defined as:

$$STP(i, (o, d)) = \{(x, t) \mid T(x_o, x) \leq (t - t_o) \wedge T(x, x_d) \leq (t_d - t)\} \quad (1)$$

where $T(x_o, x)$ is the travel time from x_o to x and $T(x, x_d)$ is the travel time from x to x_d .

The spatial footprint of a *STP* is termed the potential path area (*PPA*) and is given by:

$$PPA(i, (o, d)) = \{x | \exists t: (x, t) \in STP(i, (o, d))\} \quad (2)$$

Figure 1 depicts an example of a *STP* and its *PPA* in an isotropic travel environment under the assumption of a constant maximum travel velocity.

(insert Figure 1)

Since an individual may have a set K of fixed activity pairs (o, d) during the course of a day k , we superimpose the *STPs* associated with all (o, d) in K to obtain a day-covering *STP* (*KSTP*):

$$KSTP(i, K) = \cup_{(o,d) \in K} STP(i, (o, d)) \quad (3)$$

Importantly, the general equations (1)-(3) above only account for the space-time constraints on the part of an individual on a given day of the week but do not reflect the locations and temporal constraints of service delivery on that day. Therefore, we denote a set S of services s at location x_s , a set O_s of opening hour intervals $[t_{s,b}, t_{s,e}]$ of s on day k , and a minimum visitation time \bar{T} required to enjoy a meaningful service at s . Using these notations, we define a feasible opportunity set (*FOS*) as follows:

$$FOS(i, (o, d), S, O_s, \bar{T}) = \{s | T(x_o, x_s) \leq (t - t_o) \wedge T(x_s, x_d) \leq (t_d - t) \wedge \exists t_{s,b}, t_{s,e}: F([t_o + T(x_o, x_s), t_d - T(x_s, x_d)], [t_{s,b}, t_{s,e}]) \geq \bar{T}\} \quad (4)$$

where F denotes a function which returns the length of the overlapping time interval between two time intervals.

In other words, FOS represents the set of services that can be visited by an individual during a time budget for at least a predefined period of time. The set of services that an individual can visit during an entire day is then given by:

$$KFOS(i, K, S, O_s, \bar{T}) = \bigcup_{(o,d) \in K} FOS(i, (o, d), S, O_s, \bar{T}) \quad (5)$$

Based on equations (4) and (5), we can specify four day-specific measures which are used in section 5.1 to explore the day-to-day variability in individual levels of accessibility. These measures are formally given by:

$$POS(i, K, S, O_s, \bar{T}) = \begin{cases} 1 & \text{if } KFOS(i, K, S, O_s, \bar{T}) \neq \emptyset \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

$$SC(i, K, S, O_s, \bar{T}) = \sum_s G(s) \text{ with } G(s) = \begin{cases} 1 & \text{if } s \in KFOS(i, K, S, O_s, \bar{T}) \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

$$SP(i, K, S, O_s, \bar{T}) = \min_{(o,d) \in K} \min_{s \in FOS(i, (o,d), S, O_s, \bar{T})} (T(x_o, x_s) + T(x_s, x_d)) \quad (8)$$

$$TE(i, K, S, O_s, \bar{T}) = \max_{s \in KFOS(i, K, S, O_s, \bar{T})} \sum_{[t_o, t_d] \times [t_s, b, t_s, e]} F([t_o + T(o, x_s), t_d - T(x_s, d)], [t_s, b, t_s, e]) \quad (9)$$

where $[t_o, t_d] \times [t_s, b, t_s, e]$ denotes a combination of a time budget and an opening hour interval.

The above measures have been selected because they provide complimentary insights into various aspects of accessibility (see Neutens et al. (2010a)). These aspects include possibility (POS), spatial choice (SC), spatial proximity (SP) and temporal extent (flexibility) (TE). They should be interpreted as follows:

- i. POS examines whether or not an individual is able to visit a service for a certain period of time, given the set of constraints (s)he experiences on day k ;
- ii. SC tallies the different services that an individual can visit during day k ;
- iii. SP represents the minimal travel time that is required in order for an individual to reach a service on day k ;

- iv. TE expresses the total time that an individual would be able to maximally spend at a service on day k .

The procedures to calculate these measures have been coded in Visual Basic.

4. Case study

To illustrate the importance of day-specific accessibility measures in a longitudinal analysis of individual accessibility, a case study is elaborated.

4.1. Data

The study area is the city of Ghent, which is the third largest city in Belgium and capital of the province of East-Flanders. Ghent has a population of approximately 245,000 inhabitants on an area of nearly 160 km². It is an important tourist destination and a trading center on a par with Hamburg (Germany) and Le Havre (France), with an industrial concentration in the port zone in the northern part of the city. Within this study area, data were obtained about the urban opportunities, the transportation network, the activity-travel behavior of the inhabitants and the transportation system.

Urban opportunities

The set of urban opportunities in the study area consists of 15 government offices (Figure 2). These offices take care of the citizens' administration concerning marriage, birth, cohabitation, death, travel, residential moves, elections, etc. The current opening hours of the government offices are given in Table 1 as background information for interpretation of the results. While the different offices offer a comparable set of services, they can differ much in terms of opening hours. Table 1 shows that opening hours of offices 4-15 are quite generous, whereas those of offices 1-3 in the sparsely populated northern part of the city are rather limited. These differences in opening hours as well as the spatial distribution of the offices induce

important spatiotemporal differences in service levels within the city, which are accounted for by the accessibility measures specified in section 3.

(insert Figure 2)

(insert Table 1)

Activity-travel behavior

The visitor population of the government offices consists of all inhabitants of Ghent. To obtain a sample of the activities and travel patterns of this population, we have used an activity-travel data set consisting of a seven-day consecutive diary of out-of-home activities of 717 persons aged 12 to 75 living in Ghent, of whom 50.3% are male and 49.7% are female. The data set was collected from September to December 2008 within the framework of the BMW (Behavior and Mobility within the Week) project. After comparison with demographic statistics for Ghent, the household structure of the BMW sample appears to reflect quite faithfully that of the actual population (Castaigne et al., 2009): 18% of the surveyed individuals live alone, 26% in a two-persons household, 20% in a three-persons household, and 37% in household consisting of four persons or more. For a detailed description of the BMW data set, the reader is referred to Castaigne et al. (2009).

After removing incomplete and erroneous observations, 605 individuals, whose activity locations were geocoded at the address level, were retained for further analysis. Given that within the BMW project individuals were randomly sampled on the basis of census data of Ghent, the spatial distribution of the home locations of the individuals closely mirrors the population density (Figure 3). In line with research about the space-time rigidity of activity participation (Cullen and Godson, 1975; Kwan, 2000; Schwanen et al., 2008), the activities belonging to the categories 'work', 'education', and 'pick up/drop off' were considered fixed. The addresses of the reported locations of these fixed activities were geocoded at the street level. Figure 4 shows a map of the fixed activity locations of the considered sample in Flanders (Belgium) over the entire week. The lion's share of fixed activities is clearly

concentrated in and around the city of Ghent, but some important concentrations are also observed in Brussels and other provinces' capitals. Although the map represents only the fixed trips in Flanders and Brussels, we would like to emphasize that we have also accounted for the few fixed trips individuals undertook in other parts of the country as well.

(insert Figure 3)

(insert Figure 4)

Transportation system

The third source of data is the TeleAtlas® MultiNet™ (version 2007.10) road network data for Belgium. Based on this data set, travel times were estimated using ESRI®'s Network Analyst (ArcGIS™ 9.3). The two predominant transport modes in Ghent – car and bicycle – are considered in this case study. 53% of all trips in the BMW data set are made by car versus 19% by bicycle. Public transportation accounts for 9% of all trips and has not been addressed because of a lack of appropriate data. In order to account for individual differences in mobility resources, it was assumed that an individual could travel by car if (s)he possesses a driver's license and there is at least one car in the household. Otherwise, an individual was supposed to be able to travel by bicycle. Travel times by car and bicycle from/to all fixed activities of individuals in the sample to/from all government offices have been calculated on the basis of the procedures and assumptions outlined in earlier work by Neutens et al. (2010b).

4.2. Analysis

Day-specific accessibility levels

Based on the theoretical framework introduced in section 3 and the data sets described in section 4.1., we have calculated individual levels of accessibility per day of the week. For these calculations, we have imposed a minimum visitation time (see

equation (4)) of 20 minutes required to perform an average transaction at a government office. This value has been determined in consultation with the local authorities on the basis of visitation time statistics, which have been collected in the scope of the LEO project. Also, only physical access to the government offices is looked at in this study; accessibility of services by virtual means (e.g. e-services) has not been considered at this stage.

Figure 5 represents accessibility in terms of the number of days per week at which an individual is able to visit a government office for at least 20 minutes. This graph was obtained by calculating *POS* for each individual in the sample and adding up the value of *POS* per person over the entire week. Figure 5 shows that over 40% of the population sample is able to visit a government office on six days in the week, given the constraints resulting from fixed activity participation, the performance of the transportation system, and the locations and opening hours of the government offices. Since all offices are closed on Sunday, there is no one in our sample who can reach an office at each day of the week. Furthermore, it can be seen that only 0.2% cannot reach a government office during the whole week and about 10% of the population is denied access to an office for at least five days a week. However, overall, these figures tend to suggest that the majority of Ghent's inhabitants have several alternatives within the week to combine public service visits with paid employment, education or other fixed activities.

It is important to note that these figures could not have been obtained through the use of pooled samples of person-days. Should we have considered our sample as independent observations of person-days, we only could have been concluding that 34% of the persons are not able to reach an office at the day they were sampled. This percentage reduces to 26% when only persons sampled at weekdays are considered. It is clear that these percentages do not express individuals' ability to access services as detailed and qualified as do longitudinal statistics of day-specific accessibility levels.

(insert Figure 5)

In addition to the possibility to visit a government office, we have also explored the spatial choice component of accessibility using the number of accessible offices (*SC*). Table 2 reports the percentage of sampled individuals and the number of offices they can visit for each day of the week. While on Saturday only one government office is available for 94% of the population, spatial choice is much larger on Wednesdays when almost 80% of the inhabitants can reach more than 12 offices. There are also slight differences in spatial choice between Monday, Tuesday, Thursday, and Friday, which are strongly influenced by the number of available offices and their opening hours. Table 2 further shows that the number of inhabitants who are unable to reach an office is significantly lower on Saturday and Wednesday compared to other days of the week. On Saturday this can largely be explained by the fact that people have fewer fixed activity engagements resulting from employment, while on Wednesday it can be explained by a combined effect of extended opening hours (see Table 1) and a decrease in the number of fixed activity engagements (many part-time employed parents in Belgium do not work on Wednesday afternoon so that they can spend time with their children).

(insert Table 2)

Next, we have examined the temporal flexibility to schedule a service visit by means of *TE*. Figure 6 shows the average possible visitation time per person per day of the week relative to the total possible visitation time (i.e. the amount of non-overlapping opening hours of all offices). Performing an ANOVA followed by Tukey's post-hoc test, significant differences in average possible visitation time were observed across different days of the week (Table 3). For example, average possible visitation time on Wednesdays differs significantly from that on other days of the week. The same is true for Thursday. Differences across different days of the week are largely proportional to the corresponding differences in the total possible visitation time of the offices. While on average, people would be able to spend 288 minutes at government offices on Wednesday, possible visitation time drops to just over two hours on Thursday. Remarkably, on Saturday, when only one office is open during 150 minutes, the average possible visitation time per person amounts to almost 137 minutes. Again, this reflects the fact that people experience fewer constraints during the weekend relative to weekdays.

However, some reservations are necessary here because our data set did not contain the in-home fixed activities of the sampled individuals. This data limitation may result in inflated individual accessibility in evening periods, or other periods spent at home, when a person may not be able to leave the home to perform an activity, despite him/her being 'free' as far as this data are concerned. However, in this specific example, many of the government offices are closed during the evening hours when the majority of individuals may have 'non-reported' fixed activities, thus greatly limiting the effect of the data weakness. For case studies where the ignorance of in-home activities tends to be more harmful, researchers may implicitly account for non-reported space-time constraints by incorporating people's timing preferences regarding when they would like to participate in the type of activity under consideration. These can be derived from observed timings available in standard travel diary data sets (see Neutens et al. (2010b)).

(insert Figure 6)

(insert Table 3)

It should be noted that Table 2 and Figure 6 can also be achieved by grouping a pooled sample of person-days per day of the week. However, this approach would imply that average day-specific accessibility levels are calculated on the basis of different subsamples with potentially different social compositions, and may therefore result in inconsistent comparisons across different days of the week.

Finally, spatial proximity (measured using *SP*) to government offices has also been calculated for each day of the week. However, the average *SP* did not show significant differences across different days of the week and has therefore not been taken up in a graph.

Mean and variability

Having gained insights into the day-specific accessibility levels of our sample, we now examine the mean and variability of the four day-specific measures described in section 3. Table 4 shows the number of observations, the mean¹, and the intra-personal and inter-personal variability of person-based accessibility over the whole week and on weekdays, respectively. The table is stratified socially in terms of gender and employment status. Readers should appreciate that these are important but not the only axes of social differentiation along which differences in (variability of) person-based accessibility can be observed (see Neutens et al. (2010b)).

In our sample, 63% is gainfully employed, of which 77% is employed full-time and 33% is employed part-time. Female workers represent 40% and 81% of the full-time and part-time employed population, respectively. The remaining category of 37% not gainfully employed persons includes slightly more women (54%) than men (46%). Table 4 shows that the means of *POS*, *SC*, *SP* and *TE* per person over the entire week are systematically higher for those who devote less time to paid employment or education. This means that people who face more time constraints experience more difficulties to access services, can reach fewer service facilities, have less temporal flexibility but have to travel shorter distances. This last effect is presumably because they can combine spatially a service visit before and after engagements in fixed activities which typically take place in and around Ghent (see Figure 4). Gender differences in mean accessibility over the week are also observed. In particular, it is found that *POS*, *SC*, *SP* and *TE* are somewhat higher for female students and employed women relative to their male counterparts. However, it is emphasized that our data set did not include in-home activities such as domestic responsibilities, which may have certain fixity in space-time as well and are still disproportionately undertaken by women (Schwanen et al., 2008).

In the category of the unemployed on the other hand, higher levels of accessibility are obtained for men. One potential explanation can be found in gender differences in mobility resources: driver's license possession in our sample is significantly higher for men than women and this disparity is particularly pronounced for unemployed persons (45% of women vs. 35% of men in our data set have no driver's license in

¹ Observations of individuals that cannot access a facility were excluded before calculating the mean of *SP*.

this category). Similar trends can also be observed for the means of the considered accessibility measures on weekdays, but now their absolute values are systematically higher. This can in part be explained by the current set of opening hours of the government offices which considerably limit the possible visitation time and the number of available offices in the weekend.

Finally, we have examined the day-to-day variability in individual levels of accessibility. The analytical approach taken in this study is based on the seminal work of Pas (1987) and Sundar and Pas (1995). The approach consists of the decomposition of the total variability in individual levels of accessibility into two major components: (i) within-person (intra-personal) variability and (ii) between-person (inter-personal) variability.

The total variability is represented by the total sum of squares (*TSS*):

$$TSS = \sum_i \sum_k (A_{ik} - \bar{A})^2 \quad (9)$$

where A_{ik} is the accessibility level of individual i on day k and \bar{A} is the overall sample mean accessibility level per individual per day.

The inter-personal and intra-personal components of the *TSS* are respectively calculated by the within-person sum of squares (*WPSS*) and the between-person sum of squares (*BPSS*) which can be defined as follows:

$$WPSS = \sum_i \sum_k (A_{ik} - \bar{A}_i)^2 \quad (10)$$

$$BPSS = m \sum_i (\bar{A}_i - \bar{A})^2 \quad (11)$$

where \bar{A}_i is the mean level of accessibility of individual i per day and m is the number of days in the study period (*in casu* seven).

Table 4 shows the *WPSS* and *BPSS* (in %) over the entire week and on weekdays for the different categories of employment status and gender. At least four interesting findings can be drawn from this table. First, in general, a considerable proportion of the total variability in individual levels of accessibility is due to intra-personal differences within the week. Second, it is found that intra-personal variability is significantly smaller on weekdays but still accounts for an important share of variability across the four accessibility measures. Third, inter-personal variability tends to be highest with respect to the temporal extent measure (*TE*), while spatial proximity (*SP*) exhibits the least inter-personal variations. Fourth, the proportion of intra-personal variability may differ between men and women and is lowest for full-time employed persons across all four accessibility measures.

Taken together, these findings suggest that comparisons of individual levels of space-time accessibility inferred from pooled samples of person-days may be biased because (i) differences in individual space-time accessibility levels can, to a significant degree, be attributed to intra-personal rather than inter-personal variations, and (ii) the relative importance of the intra-personal component may be different for people with different socio-economic attributes. Hence, space-time accessibility analyses using pooled samples of activity-travel diary data should control explicitly for the day of the week at which individuals are sampled if the goal is to measure true variations in accessibility levels between individuals. Furthermore, that *SP* exhibits the least inter-personal variation and *TE* exhibits the most is an extremely important finding. Not only does it show that personal temporal constraints are highly heterogeneous, thus necessitating the time-use approach, it also tends to suggest that the government offices are conveniently located, while temporal policies need working on.

(insert Table 4)

4. Conclusion

For more than a decade, researchers have sought to implement time-geography's space-time prism as an analytical method for measuring space-time accessibility using activity-travel diary data. These measures capture a wide range of individual, land use and transport-related constraints affecting a person's access to urban opportunities in both space and time and so reveal inter-personal variations in accessibility that cannot be articulated using conventional place-based measures. However, presumably because of data and computational limitations, previous empirical studies in this area have considered either a single representative person-day (e.g. Kim and Kwan, 2003; Schwanen and De Jong, 2008) or have employed pooled samples of one-day or two-day observations of activity-travel behavior of individuals (e.g. Casas, 2007; Kwan and Weber, 2008; Neutens et al., 2010b). This paper set out to examine to what extent person-based levels of accessibility may fluctuate from one day to the next. It constitutes the first study that has analyzed space-time accessibility over a period of an entire week. To this end, a particular case study of access to government offices in the city of Ghent has been elaborated using a one-week activity travel-diary data set of 605 persons living in Ghent. This specific case is easily interpretable and relatively straightforward to compute, but the reader should be cautioned that it does not provide insights into the overall accessibility of individuals within the entire study area.

However, notwithstanding the specificity of the results reported in this paper, we were able to point out at least three general arguments as to why more circumspection is warranted regarding the use of pooled samples in space-time accessibility analysis. First, the case study provides evidence that considerable day-to-day variability in the accessibility level of a single person can exist as a consequence of differences in space-time constraints. Thus, accessibility differences between two individuals sampled at a particular day may be totally different from those found at another day of the week. Second, it was shown that the degree of intra-personal variability can be different when different aspects of accessibility are considered (e.g. spatial proximity vs. spatial choice) and varies with employment status and gender. Third, this study has proposed and implemented day-specific accessibility measures and demonstrated that these can yield additional insights into the degree to which space-

time constraints on a particular day of the week affect a population's average level of accessibility.

The above findings call for a more explicit consideration of the time interval during which a person's accessibility is measured. Not only will this enable to make true inter-personal comparisons on an equal time scale, but it will also allow expanding the current application scope of space-time accessibility measures to the evaluation of the impact of urban time policies on people's quality of life. Such policies have gained increased momentum in recent years (see e.g. Moccia (2000); Healey (2004); Boulin (2006); Zandvliet et al. (2008)). They seek, among others, to respond to the time-space inequalities that have emerged from particular macro changes in society including the diversification of lifestyles and the rise in dual-earner families. In this context, time-specific accessibility measures, as those suggested in this paper, may help to achieve a deeper understanding of the ways in which opening hours of urban service delivery can be better attuned to the changed activities and travel patterns of citizens (Delafontaine et al., 2011). Likewise, they may help to obtain a better grasp of the temporal aspects of mobility-related social exclusion (Lyons, 2003; Kenyon and Lyons, 2007; Farber and Paez, 2009; Farber et al., 2011). We hope our study may inspire time geographers and researchers alike to further integrate time and space in empirical studies of accessibility along these lines.

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Captions of figures

Figure 1. Space time prism (*STP*) and potential path area (*PPA*).

Figure 2. Study area and location of government offices in Ghent (Belgium).

Figure 3. Home locations of sampled individuals in Ghent (Belgium).

Figure 4. Location of fixed activities of sampled individuals.

Figure 5. Number of days during the week with access to a government office.

Figure 6. Average possible visitation time per person per day of the week.

Captions of tables

Table 1. Current opening hours of government offices in Ghent (Belgium).

Table 2. Percentage of the sampled population that can reach a specific number of offices.

Table 3. Statistical differences in average possible visitation time by day of the week employing Tukey's post-hoc test.

Table 4. Number of observations, mean, intra-personal and inter-personal variability in individual accessibility to government offices in the city of Ghent (Belgium).