Time Dependent Accessibility

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Abstract

Many place based accessibility studies ignore the time component. Relying on theoretical frameworks that treat distance between two fixed points as constant, these methods ignore the diurnal and seasonal changes in accessibility. Furthermore, network distances between two nodes are dependent on the network structure and weight distribution on the edges. These weights can change quite frequently and the network structure itself is subject to modification because of availability and unavailability of links and nodes. All these reasons, point to considering the implications of time variation in accessibility of a place. Using the case of transit, where all these feature are readily apparent simultaneously, I demonstrate the volatility in accessibility for two counties in North Carolina. Significant diurnal changes are observed in quarter of the locations and in the rest the changes are minimal mostly because of low levels of transit accessibility. I argue not for minimizing the volatility, but acknowledging its impacts on mode choices, location choices and therefore on spatial structure of cities.

1. Introduction

Many studies on transportation accessibility assume that the underlying spatial topology is invariant. Borne out of a Newtonian conceptualization of space, accessibility is measured as either as a cumulative measure of opportunities that are available from a location at a certain distance (or other appropriate metric such as travel time) or weighted measure usually based on gravity or a random utility (Handy and Niemeier 1997; El-Geneidy and Levinson 2006). In each of these approaches, there are no diurnal or seasonal changes in the distance metric between any two given points in the space. It is easy to think that the Euclidean/Manhattan distance between two points in a Cartesian plane is invariant. The differences in the accessibility of a location then usually stems from the changes of the attributes of the locations and attractors (e.g. employment, destination types, types of households etc.) and the interest is usually on relative accessibility of one location with respect to another (Dalvi and Martin 1976). In this paper, I want to argue that accessibility also depends upon the variable distance metric and should be given adequate attention.

A Leibnitzian conception of space, by contrast, is a conceptualization of space that dependent on locations of objects relative to one another (Galton 2001). Despite this abstractness, I argue that such mode of thinking allows us to rethink the distance metric as a variable and lends itself particularly well to a imagining a topological structure that changes over time. Space with variable topological structure is not uncommon. However, the network distance between two nodes is invariant, only if the underlying network structure is invariant. Many accessibility analyses not only focus on relative accessibility of locations, but relative changes in accessibility once a set of infrastructure investments are made (e.g. Golub, Robinson, and Nee 2013), which are inherently changes to the underlying network structure. Furthermore, when travel times are used as measure of impedance, the distance metric during peak and off-peak hours between any two given points are different even without any physical changes to the network; the edges shorten and lengthen depending on the time of the day. In other words, the weighted network changes with time (though the weights remain finite). Another obvious case of changing topology is the scenario where a particular node or edge of a network is no longer available. This situation is quite common during hazardous events (see e.g. Litman 2006) when some links and nodes disappear from the networks (or the weights become infinite) and therefore depending on their centrality can dramatically change the network distances between any two given nodes.

All the above examples presented make a compelling case for considering the variable distance metric. There is perhaps a no better use case than transit that encompass all the above situations. Even within an hour, the impedance between any two nodes (stops) is varying because of intermittent schedules and wait times. Infrastructure support for bread-winning is the norm because of gendered assumptions that undergird planning analyses (Law 1999), and therefore the level of service as evidenced by smaller headways is higher during the peak hours than the off-peak hours and on non-work days. Thus, impedance metric is fairly elastic throughout the day and among weekdays and weekends. Fundamentally, because the underlying network structure is dependent on un/harmonized schedules between different lines in the transit system that facilitate transfers, changes in these levels of service on a single line has ripple effects through the entire system. Depending on the time of the day, a line in the transit system may not be running and thus removing a set of links and nodes from the network. All these features make the case for using understanding the patterns of transit accessibility, as there are analogues in other situations described earlier.

It is, therefore, useful to study how the periodicity and breaks in the patterns of transit accessibility. It provides a starting point for understanding changes in other accessibility (such as auto) instead of relying on the maxmin approach that underlies the consideration of peak travel times, or worse using max approach that ignores congestion all together. Furthermore, accessibility that only accounts for invariant impedance is usually based upon the assumptions that travel to work, and more insidiously, travel to particular kind of work (regular shift) is singularly important. Using Current Population Survey data from 2004, McMenamin (2007) claims that almost 30% of the US workers are able or constrained to work in shifts other than regular shifts. Furthermore, accessibility to amenities other than work is also important (Handy and Clifton 2001) and because these amenities such as restaurants, retail establishments, hospitals have different rhythms than a traditional 9-5 job, changes in accessibility during the day and by seasons have implications both for users of as well as employed at these amenities (e.g. Weber and Kwan 2002).

In their wide ranging review, Guers and van Wee (2004) suggests that accessibility should account for land-use component, transportation component, temporal component and personal component. They suggest that each of these components is indirectly related to one another. In this paper, I want to argue that there are more direct relationships and should be accounted for our in our measures of accessibility. While the spatial distribution of opportunities is important, it is also related to the temporal dimensions of these distributed opportunities (activity hours, duration etc.) is also important (Crang 2004). The temporal component not only affects the time available for opportunities by a person, but whether or not such opportunities can be accessed by a person by a particular mode and with reasonable cost.

Furthermore, standard equity analysis for transit either measures the level of service in traditionally underserved areas by either measuring the headways or the number of jobs accessible via transit without actually accounting for whether such accessibility is constrained by time of the day. Such constraints are important to consider for equity analysis because, more often than not, persons in low income areas and underserved groups are likely to have non-traditional work arrangements and have significantly larger number of household maintenance trips that occur via transit and which may or may not be during regular 'peak' hours and therefore are more likely to suffer from low levels of transit service and large investments in auto-oriented development (Bullard, Johnson, and Torres 2004).

The paper is organized as follows. I begin by conceptualizing different accessibility measures and putting the place based accessibility measures into a single framework. I modify this framework to demonstrate that time could be readily incorporated and show for the case of transit how the method can be readily applied for much of the United States. I demonstrate the results of a specific case for two county region in North Carolina and draw some implications. I then suggest some limitations to this study.

2. Conceptual Overview and Methods

In their scathing critique, Kwan and Weber (2003) argue for the decline of the importance of distance[1] in our conceptual understanding and explanation of the urban spatial structure and transportation behavior and location choice. Giving examples of number of studies that showed mixed results about the relationship of distance to the central business district with level of employment, and housing values they argue that new models of accessibility are required that would account for the temporal constraints on different individuals as well the problems associated with place based accessibility measures. They advocate for a person based accessibility measures that follow from Hägerstrand (1970)'s conception of opportunities based on personal scheduling constraints (e.g. Miller 1999) and for explicitly accounting for the temporal changes in space.

However, accessibility analysis is replete with place-based models instead of person-based models. Some of the main reasons are 1) place is an important aggregative mechanism that summarizes the experiences of persons 2) planners and decision makers have abilities to affect places through infrastructure improvements, in a more direct way than they could affect persons 3) data to compute personal accessibility because of individual scheduling constraints are hard to come by. Therefore it is of no surprise that place based models are still a common theme in the literature. The method proposed here bridges place based accessibility and space-time based measures and require only readily available data.

In general, accessibility of a place i, with K as a set of destinations is defined as

$$A_i = \sum_{j \in K} g(O_j)\, f(\, d_{ij})$$

In a distance-based measure of accessibility, j refers to specific destinations such as central business district or bus stops, $g(O_j) = 1$ and $f(d_{ij}) = d_{ij}$ where d_{ij} is the distance between j and i. In cumulative opportunities and gravity based models, $g(O_j)$ is the number of opportunities (usually jobs) at location j or some other metric such as economic activity. Cumulative opportunities and gravity based measure are the same except for the weighting

[1] Because geographic distance and travel time are both distances in different metric spaces, Iuse distance to refer to them both in the rest of the paper.

function. In the former case, the weighting function *f,* is an indicator function $\chi_{d_{ij}<D}$, where D is the threshold distance and in the latter case, it usually is $e^{\beta d_{ij}}$, where β is the decay parameter. For the purposes of this analysis the functional forms of *f* and *g* are largely irrelevant. Therefore, I choose to demonstrate the concepts using the cumulative opportunities measure, though apart from computational considerations, there are no barriers in applying them to other place based accessibility measures. Accessibility of a place that is conditioned on time *t* is recast as

$$A_i^t = \sum_{j \in K} \chi_{t \in T}(O_j^T)\, \chi_{d_{ij}^t<D}(\, d_{ij}^t)$$

where O_j^T is the number of opportunities (jobs) at a location *j* with duration *T* and $\chi(.)$ is a indicator function. I use two modes (walking and bus) to compute d_{ij}^t, which could also be extended to use other compatible modes that would allow mode shifts such as bicycle. Since I am interested in place based accessibility and equity implications, I choose block group centroids as the origins and individual establishments as the set *K*. With appropriate modifications, the same analysis can be conducted for a purely zonal or purely point geographies conditioned on the availability of the data.

The algorithm follows roughly the same logic as Lei et. al. (2012) and heavily uses the python code from Morang and Pan (2013) (see Figure 1). The transit network is built from the Transit agencies' Generalized Transit File Specification (GTFS) files that are freely available online. Because in general, there are many transit agencies in a region that have operations that are complementary, I use multiple relevant GTFS files for a region to create a database for stops, links and schedules. The transit network is merged with road network from OpenStreetMap (OSM) that includes both limited access highways and local roads. To reach a transit station and other destinations from transit stations, I use a walking speed of a constant 4.8 km/hr on the road network. Then feasible origin destination pairs are calculated based on the schedule of the transit lines using Dijkstra's algorithm that is built in the ArcGIS™ Network Analyst. Block group centroids or Origins are attached to the nearest node on the merged network and service area buffers are computed for each origin for every 10 minutes in the day. Because GTFS identifies schedules by different days, I compute these buffers both for weekday, Saturday and Sunday. This could also be extended to include seasonal variations as long as the GTFS data has the information. To reduce the computational time, I limit the analysis only to block groups that are close (within 3.6 km) to transit stations. Employment within the buffers is calculated for each buffer and is assigned to block groups as a measure of accessibility for that particular time. Thus, creation of these buffers can be replicated anywhere in the United States where OSM and GTFS files are readily available.

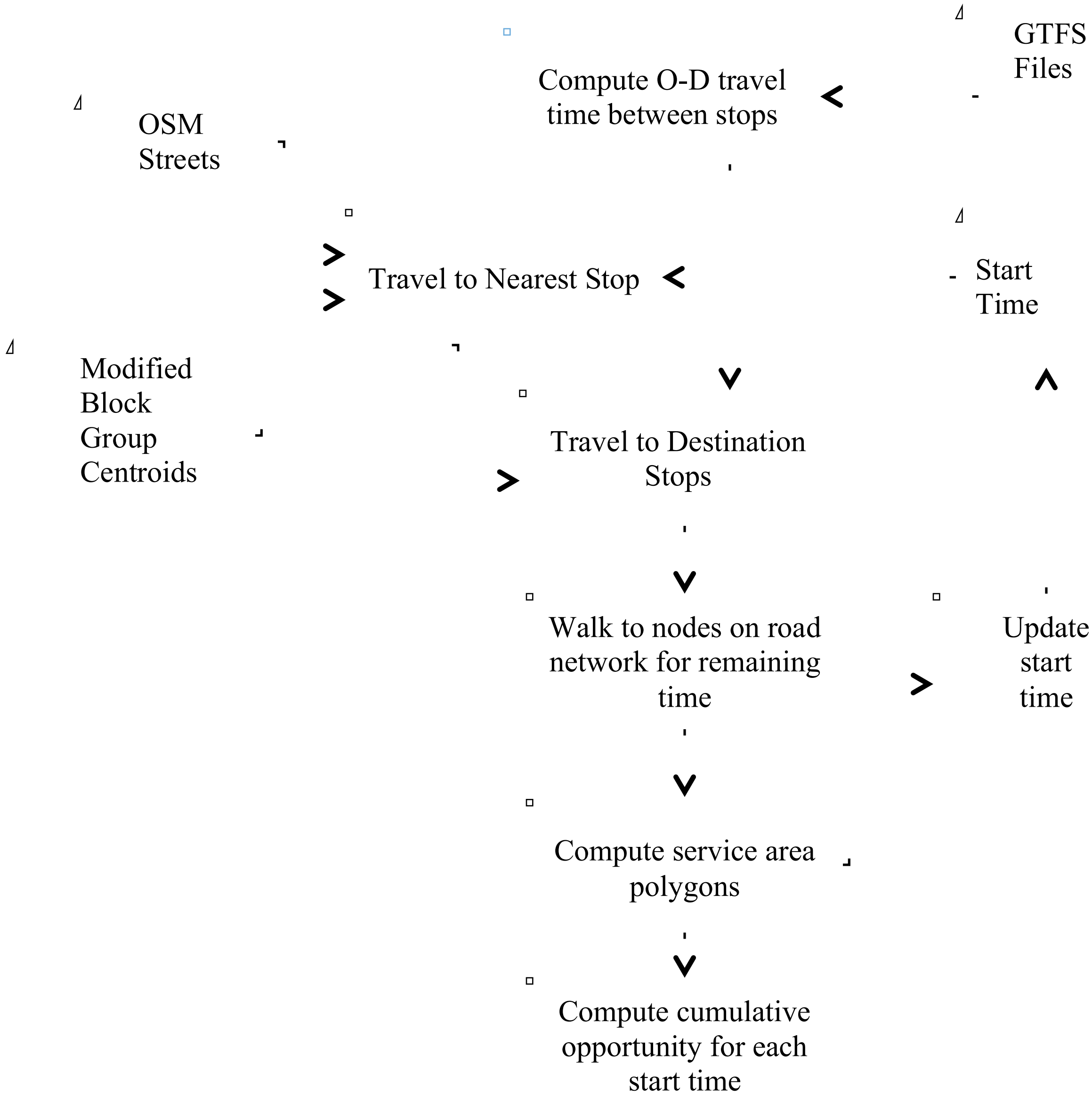

Figure 1 Schematic of the algorithm

While I do not use this dataset in this analysis, synthetic employment from Longitudinal Employer-Household Dynamics dataset can be used for destinations with information about their industry classification. Duration, *T,* as defined by facility opening hours are not comprehensive in standard data sources like Google or Yelp for all establishments in all industry types[2]. Therefore, broad activity hours are inferred for each of the industry classes: 9am–6pm for most industries, 6am–2am for food service (NAICS 722)[3], 11 am–10 pm for retail (NAICS 44-45) are used to categorize the establishments and employment. These times are inferred from queries using sample of names of the establishment to the Google places API[4]. This is not ideal unlike Ahas et. al (2010) study, which uses cellphone data to both spatially and temporally fix the activity patterns in the city. However, I believe this is a useful approximation given the data limitations.

3. An Use Case

The usefulness of the above concepts is demonstrated for a two county region; Orange and Durham Counties in North Carolina. These are the two main counties in the Durham-Chapel Hill-Carrboro Metropolitan Planning Organization (DCHC-MPO), which is responsible for transportation planning for the western part of the Research Triangle area in North Carolina[5]. Orange County is home to the University of North Carolina at Chapel Hill and Duke University is located in Durham County, both of whom are major employers in the region. The Research Triangle Park (RTP) is located Southern edge of Durham County, which is the home to many large employers and is not only the economic engine of the region, but also for the state. Collectively, 0.4 million people call these counties their home and 246,365 are employed in these two counties in 11,170 establishments. In total there are 228 block groups in the two counties region, and 18 of them are too far from transit stops so we ignore them from the

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[2] Industries such as NAICS codes 722 (Food Services) and 44-45 (Retail) are oversampled in Google and Yelp databases that are available through their Application Programming Interfaces (API).

[3] The North American Industry Classification System (NAICS) is the standard used by Federal statistical agencies in classifying business establishments and is developed by Office of Management and Budget (OMB). http://www.census.gov/eos/www/naics/

[4] https://developers.google.com/places/documentation/ (Accessed November 23, 2013)

[5] The MPO's jurisdiction is not exactly same as the study area. The jurisdiction covers all of Durham and the urbanized portion of Orange County and small portion of Chatham County. Since Chatham County does not have fixed route transit, it is not considered in the analysis.

analysis. In general, the transit provision seems to align with the density (see Figure 2); i.e. most of the jobs and households are relatively close to transit. However, as we will see later, that this does not translate to accessibility.

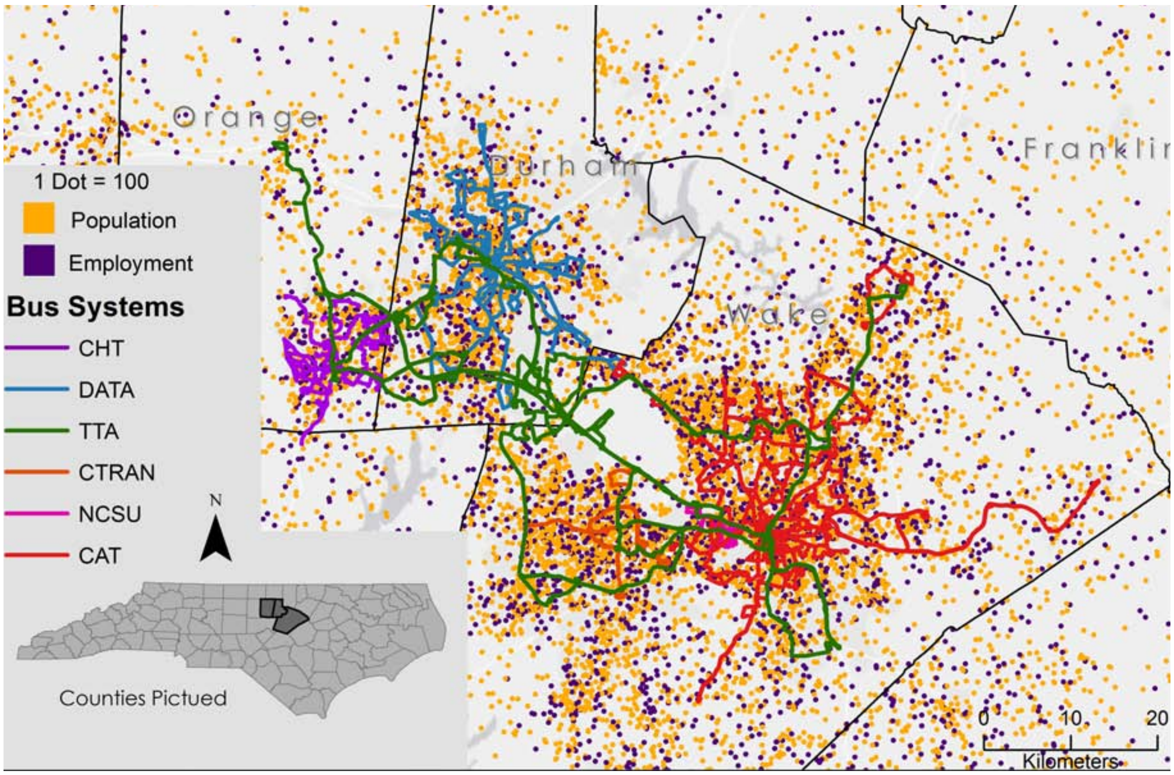


Figure 2 Regional context and transit systems in the study area. Wake county is shown for completeness, though is not used in the study area. The mixing of population and households are represented using a dot density plot; Bus lines from different transit agencies are also shown. (Source American Community Survey 2006-2010. GoTriangle.)

Like many regions, transit service in the triangle is splintered among multiple agencies (see Figure 2). The main agencies that provide transit are Durham Area Transit Authority (DATA), Chapel Hill Transit (CHT) and Triangle Transit (TTA). Because these transit systems connect up with other transit agencies in the region, we also consider Capital Area Transit (CAT) and C-Tran system to build a master regional transit service stops and lines, even though they are not considered in the set of origins. All these organizations run fixed line bus services[6]. While there

[6] There are other organizations that provide vanpools and paratransit, whom I will ignore as they are not widely used.

is regional effort underway to jointly plan for infrastructure improvements and provide a convenient trip planning interface, because of different mandates and organizational structures the operations are not necessarily coordinated. Chapel Hill Transit is a fare free system that relies on the contribution from the University where as the rest have fare structures that are not harmonized. Transfer from one system to the other is possible only with a regional bus pass, which is only sold online or at select stations. In this analysis, I will also ignore these limitations and consider only travel time as cost of travel instead of a generalized cost. I also limit the number of transfers to 1 and set the maximum travel time (D) to 45 minutes. The average commute time in the two county region is 23 minutes, so setting this upper limit is not unreasonable. Furthermore, this is a demonstration and therefore any arbitrary D can be chosen without loss of generality.

The GTFS files are available from http://www.gtfs-data-exchange.com/. The GTFS format is widely documented as they are used to create number of transit applications. In general, each agency provides a set of files that include “stops”, “routes”, “trips”, “stop_times” and “calendar” that combined together provide information on the schedule of every route during the day and the week.

I use the National Establishment Time Series (NETS) dataset to locate the employment and establishments. This proprietary dataset is from Walls & Associates, who convert Dun and Bradstreet (D&B) archival establishment data into a time series. For our analysis we ignore the longitudinal information in the dataset and focus on the establishments present in 2011 along with the number of employees and their industry category (NAICS 2007 definitions). Establishments near all transit stops (including outside the two counties) are extracted and are used in the analysis. As mentioned previously LEHD data could be substituted for this dataset.

4. Results

I will discuss the results for all jobs without considering the characteristic function *g*(.) first and then discuss the time dependent accessibility that constrains some sectors more than others. As can be expected in the use case, large percentage of block groups (162 or 77%) does not exhibit any variation even in a weekday where schedules vary dramatically and transit is oriented towards work travel. While, it might be tempting to think then that the above analysis is futile, it should be noted that the block group with the maximum value accessibility has a value 1,231 compared to a maximum value of 129,573. It should also be noted that the maximum value of the just over half the total number of jobs in the two counties; i.e. almost half of the jobs have no transit access at anytime of the day from any location. Other invariant block groups have substantially less accessibility with only 22 block groups (10%) greater than 100. This is reflective of low levels of transit accessibility for a large portion of the region, rather than conceptual issues with the analysis. In other words, even if the block groups were relatively close to the bus stops, the schedules were arranged in such a way that within 45 minutes of combined walk and bus travel, very few jobs are accessible to large areas in the region (see Figure 3). The block groups with relatively high accessibility are essentially downtown areas in Durham, Chapel Hill and Carrboro areas, though not all of central city locations have the same high accessibility. Unsurprisingly, the high accessibility areas are adjacent to the major transportation corridors and not necessarily all low income areas (see Figure 3).

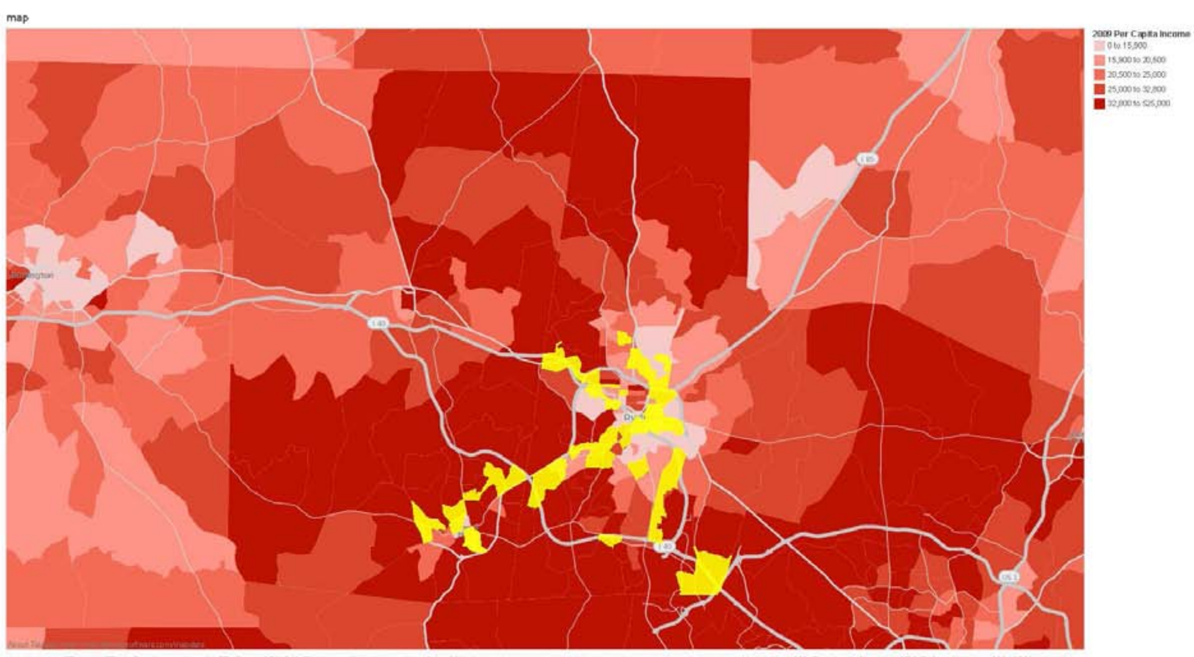
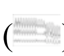


Figure 3 Block groups whose median accessibility during the weekday was above 1,500.

In the rest of the 49 block groups that do have relatively high levels of transit access, the accessibility shows a strong cyclical pattern, with significant changes in the structure throughout the day (). One of the advantages of considering a time varying measure is to determine, which areas have abrupt and dramatic shifts in accessibility and if that is consistent with the regional transit planning goals. Shifts in a univariate time series can be found using methods described in Verbesselt et. al.(2010). While the details of the method is beyond the scope of this particular paper, suffice it to say that the method uses iterative decomposition of the time series and detecting significant breaks using standard change detection methods (Zeileis et al. 2003). The advantage with the approach is the use of a harmonic seasonal model, which appropriate in our case given the nature of the data.

An example of break detection in the daily trend is shown in Figure 4(a) for a block group in Durham County. Significant reduction in accessibility happens right before 9 am and stays that way till 3 pm. Between 3 pm and 6 pm there is moderate level before reverting to almost 0. We can summarize the changes in the accessibility levels by visualizing the histogram of these breakpoints (Figure 4(b)). Block groups in Durham County (left) have greater number of changes in the accessibility levels and these break points are distributed throughout the day. Standard statistical models suggest that racial composition is not associated with the number of breaks. Plots of histograms of breaks by different levels of non-white population confirm these results.

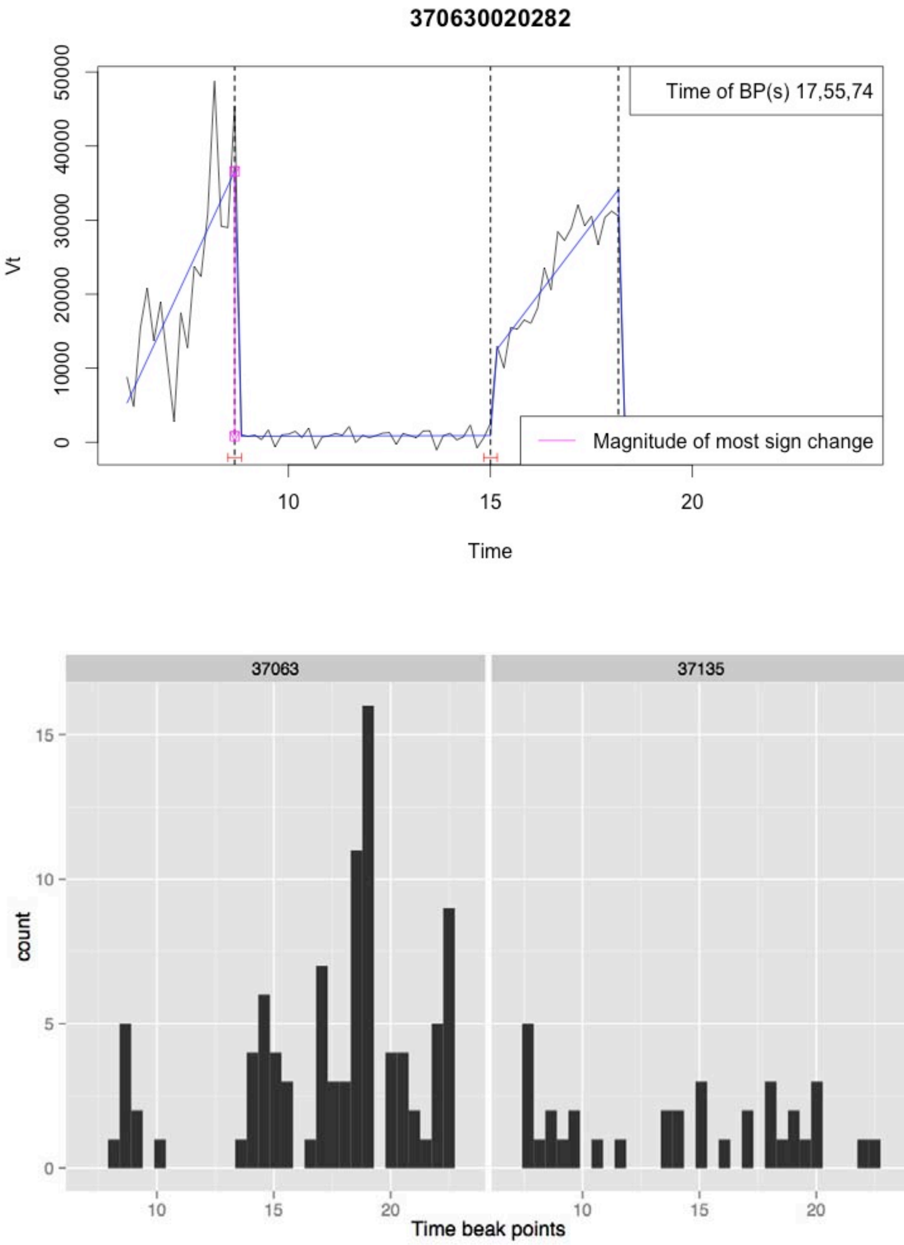


Figure 4 (a) Example of break point detection in the accessibility trend within a block group (b) histogram of break points during the day in Durham (left) and Orange (right) counties.

To visualize the changes in the trends, it may be much more useful to smooth out the hourly cycles with medians. The median while being unaffected by extreme values is relatively sensitive to changes in both amplitude and frequency of the cycles and therefore it is relatively easy to detect the trend. A noticeable and consistent pattern of change can be observed in the sharp dropoffs in the accessibility between 6 pm and 7 pm on weekday, reflecting significant changes in the level of service post evening peak (see Figure 5). In many cases, there is not a significant reduction in accessibility throughout the day post morning peak, though at least in a few block groups peaks are observed in the mid afternoon and around 10 am.

It should also be noted that the same block groups have markedly lower accessibility during the weekend and with different patterns. Almost all the block groups that have relatively higher accessibility for most of part of the Saturday and Sunday are blocks in central Durham County. This is partly explained by two phenomena. DATA, unlike CHT does not have dramatically marked reduction in service on Saturday. Triangle Transit, the regional transit agency does not run its express lines on Saturday, runs its other lines with lower levels of service and does not provide any service on Sunday, which puts residents in Orange county at a disadvantage in accessing the jobs in Durham County. This is assuming of course if the jobs are 'available' over the weekend.

Another way to visualize the differences over time is to use a multivariate time series plot (Peng 2012). It is easy to pick out the sharp drop off in the values for Orange county (in purple) in the post evening peak time period, compared to Durham (see Figure 6). However, when there is no such drop off, the right margin table indicates that the median over the day is relatively low suggesting low levels of accessibility over all. Thus the figure shows the tradeoffs between accessibility and quality. Reordering the rows of the plot by the decreasing order of the median value shows that for areas with very high accessibility (large daily median), the periodicity changes of the high values in the post evening peak compared to the rest of the day but nevertheless there are certain times of the night the accessibility is in the upper quintiles. This also explains the sharp drop in the hourly median of lines toward the top of the graph in Figure 5. In areas of very low accessibility (small daily median) the periodicity throughout the day is relatively constant.

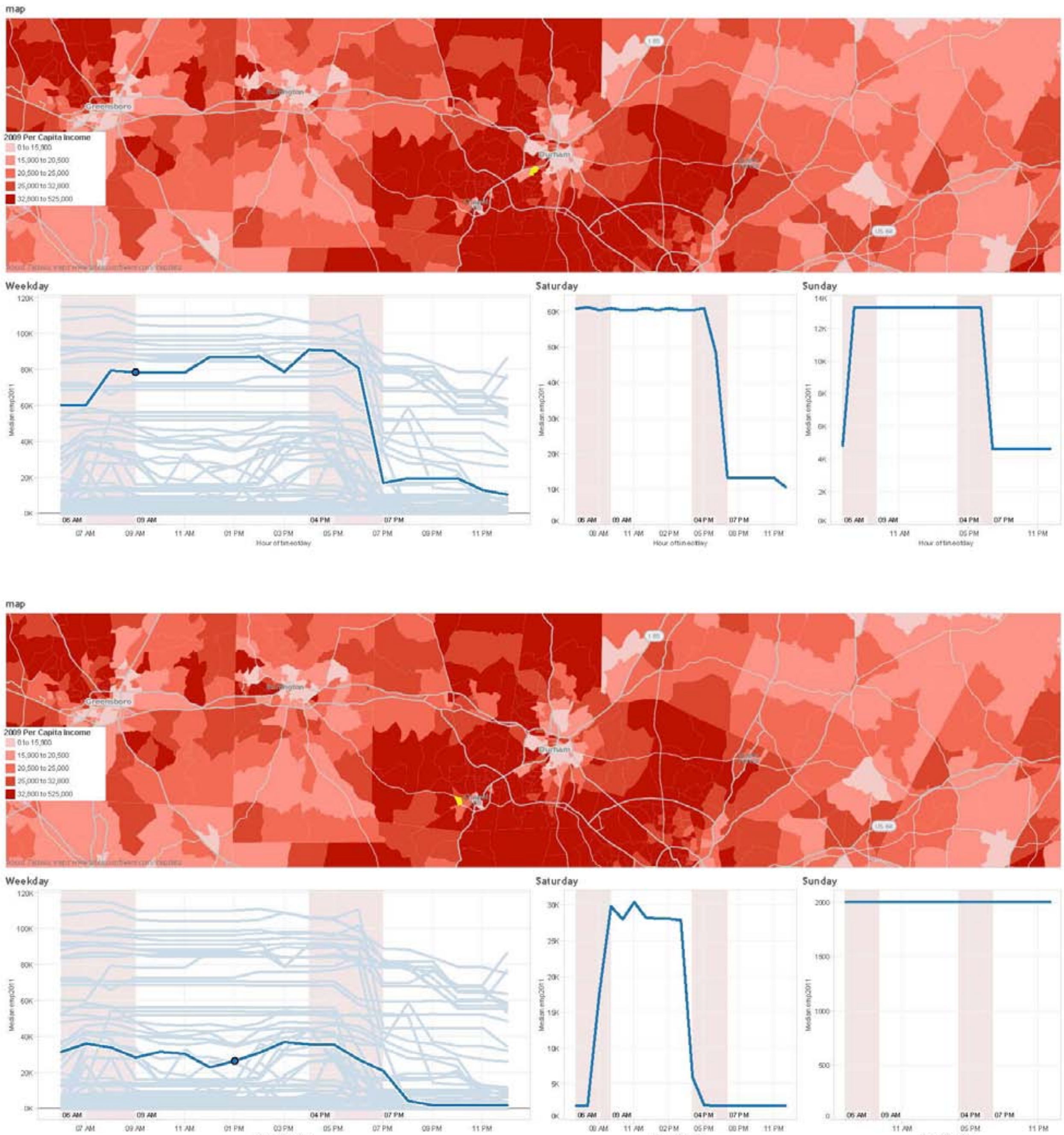


Figure 5 Variability in accessibility to all employment over the weekday and the weekend of two selected block groups. The graphs represent the hourly median accessibility over the day. Each line represents the accessibility in the block group and all the panels are linked to highlight the selected block group. The background in the map represents the per capita income.

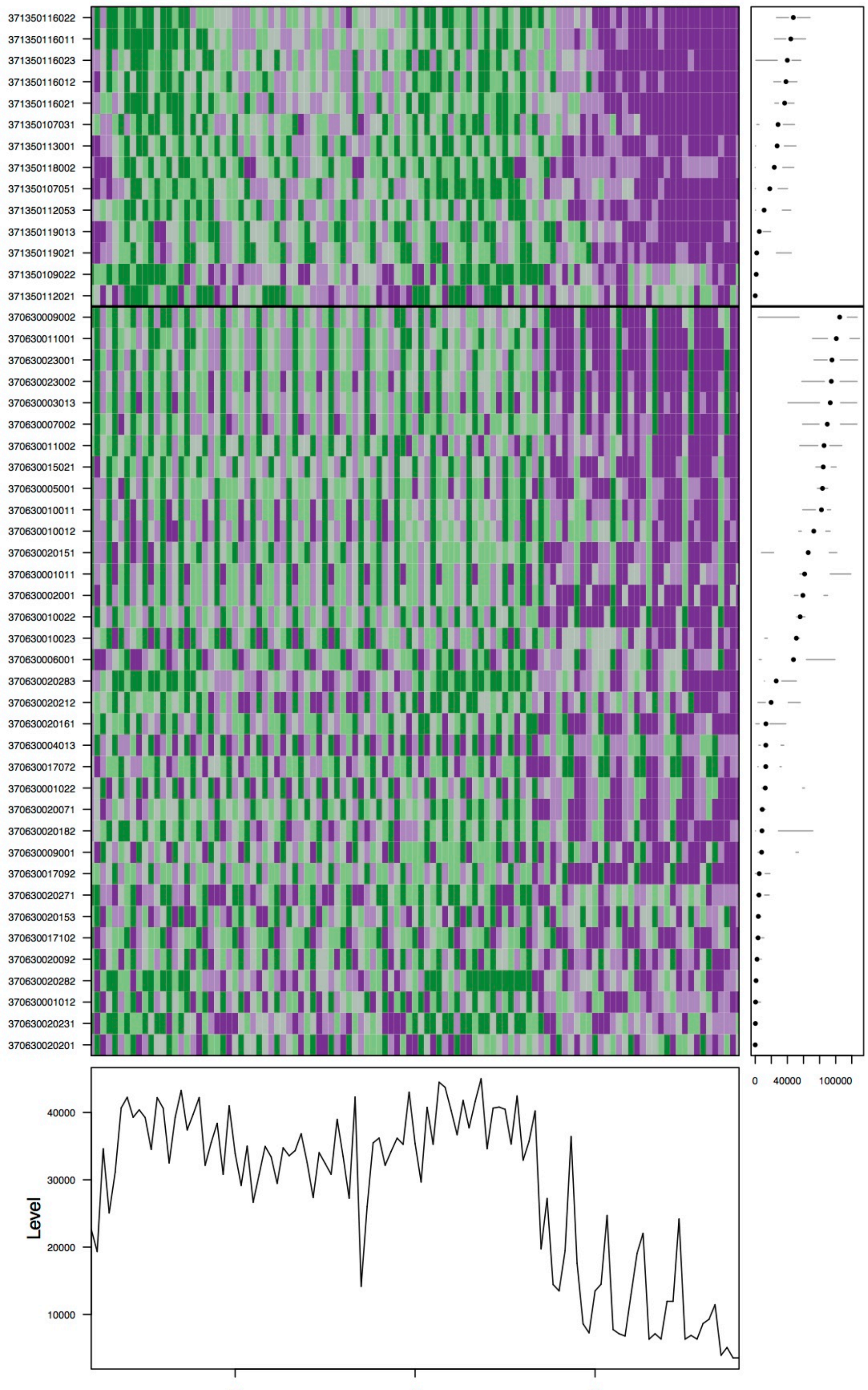
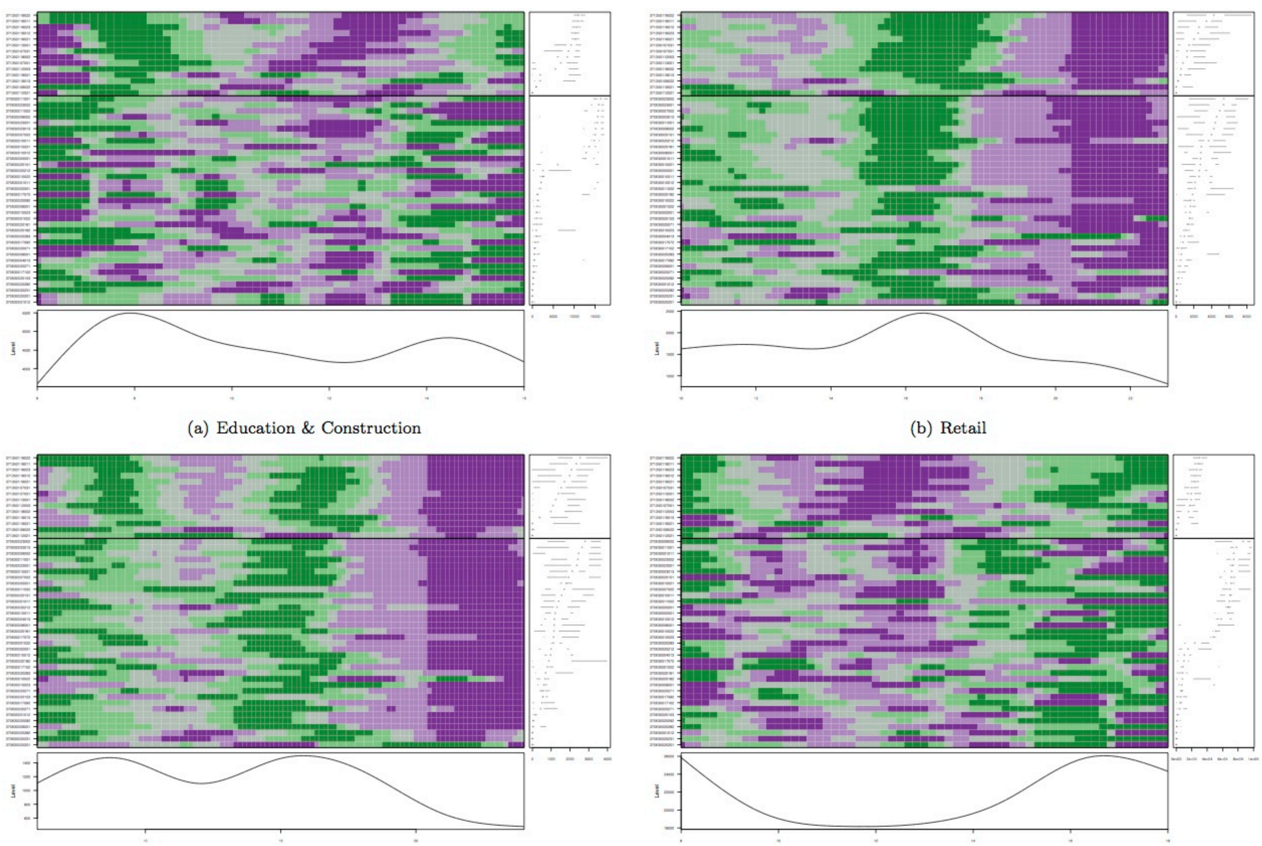


Figure 6 Multivariate time series plot of accessibility for the 49 block groups. Orange County block groups are at the top and Durham County is at the bottom. Shades of green (high) and purple (low) are used to describe within each block group time series. The right panel is the box plot for each block group; the bottom panel is the median for all block groups over time.

Till now, we have discussed the temporal trends focusing only on the variability of the distance metric. However, as discussed above different organizations and therefore different places in the region have different rhythms and impact the accessibility. Shopping is usually an after hours activity and therefore unavailability of transit to serve these uses across the region (see Figure 7(b)) contributes to the auto-orientation. Similarly, in the food service industry there are some establishments that cater to their customers during the day and others in the evening. Given the orientation of the transit system in the region, accessibility food establishments is relatively high throughout the day but declines quite rapidly post 6 pm (see Figure 7(c)) across the board except for few places in Durham. The accessibility as indicated by regular shift employment show low levels during the midday and high levels during morning and evening peak (see Figure 7(d)). Given that the orientation of the infrastructure provision towards supporting employees rather than users, this mismatch is perhaps inevitable.



(a) Education & Construction

(b) Retail

(c) Food

(d) Other

Figure 7 Multivariate time series plots of accessibility of different time constrained sectors for different block groups (smoothed with a spline of 6 degrees of freedom). Orange County block groups are at the top and Durham County is at

the bottom. Shades of green (high) and purple (low) are used to describe within each block group time series. The right panels are the box plot for each block group; the bottom panels are the median for all block groups over time.

5. Implications

Ignoring time variability in accessibility studies has several reasons. One reason is practical. While some regions may have high quality transit (small headways, wide coverage and high connectivity), such regions are few and far between in the United States. It is thus of no surprise that accessibility studies have auto orientation with a convenient assumption of invariant impedance between two points on network. In auto orientation, such assumptions are perhaps reasonable because network distances are fairly constant and impedance only depends on congested speeds. Congestion on one particular link does not dramatically affect the over all impedance of the paths unless the edge betweenness of the link is high. Given that in the US, only limited access highways have high edge betweenness, modeling accessibility by auto based on the congested speeds may give a reasonable picture of the relative desirability of places.

Another reason is conceptual. Because of high importance placed on work, infrastructure investments are focused on accessibility to jobs not on using jobs as proxy for desirability of the location for users. This is despite the overwhelming counter evidence. According to the 2009 national household travel survey (NHTS) that 83% of the trips in the US are non-work trips. A recent Brooking's study states that one of the common reasons for taking public transit is to go to work (Tomer et al. 2011), ignoring the fact that work related travel by public transit represented only 1/3 of the trips taken on public transit (Santos et al. 2011). Even while the neat division of breadwinning at work and caregiving at home has been upended since the World War II, yet transportation and transit investment decisions primarily are geared towards work-based travel. The rending of caregiving from home has important implications for travel behavior (on trip lengths, purposes and modes) and are yet to be systematically accounted for.

Concomitant to the focus on work, another conceptual blind spot is the time of work. While a vast majority of the workforce does work in regular shifts, a great number do not. Shopping assistants, restaurant cooks and servers, building custodians, factory workers, domestic workers and a number of others work different shifts than a regular shift and those employees who are mostly likely to benefit from transit provision are usually not ignored in the standard equity analysis by focusing on number of jobs available at a single time of the day.

While these reasons can partially explain why usually travel time variations are not considered in accessibility studies, until recently there has not been a widespread availability of networks with varying impedances and more importantly understanding of the temporal rhythms of a city. With the advent of ubiquitous personal tracking mechanisms via cellphone locations, we now see the city as a place not merely of economic activity, but of wide ranging sociocultural activities. This study aims to provide a framework using widely available datasets.

Ultimately, the measure of accessibility should be recognized as potential for interactions that are time sensitive. While, person based measures have long recognized the importance of time, constraints and budgets, place based measures have been reluctant to embrace them. Because person based measures require significant amount of data, it would be useful for land use and transportation planners to consider how the temporal patterns of activities might be affecting the spatial patterns. I have demonstrated in the use case that places with relatively high accessibility during certain portions of the day do not have the same levels, during other portions. Someone who is likely to make choices about locations or choices about modes, would not only consider the levels but volatility as well. Lei et. al (2012) posit that part of the explanation of low levels of transit usage in Southern California is because of comparatively low levels of transit accessibility to auto accessibility. However, another part of the explanation is the volatility of transit accessibility.

It is operationally infeasible to eliminate the volatility in the transit service given the densities and preferences of travellers. On average, 9 people are on a transit bus representing only 22% utilization rate. Thus, across the board increases in the levels of service to match auto-oriented accessibility are unwise. Such increases should only be justified with concomitant changes to land use patterns and activity patterns. What I am arguing for is a careful accounting of how temporal volatility might be affecting location choices of users. Furthermore, as I have demonstrated in the use case, since there are many transit operators with different mandates and funding mechanisms, the operational considerations of each one of them might dramatically affect the accessibility patterns of users that are not necessarily in their ‘jurisdiction’. Thus coordination is imperative.

6. Caveats

There are a number of caveats to this study that arise from practical data and computational considerations that warrant a brief mention. While I have argued that we should account for temporal variability, I have essentially sampled the times uniformly throughout the day. However, as it is apparent, the start time is of critical importance and can affect the nodes that can be reached within a certain time. Therefore, it might be useful to sample with as high a resolution as possible to get a more accurate picture, only to be limited by computational capabilities. However, much of this analysis can be naively parallelized by running the analysis for each hour on a different node in a cluster of computer and then aggregating the results back. However, since this analysis should be considered demonstrative, I believe a 10 min interval is sufficient.

Hewko et. al. (2002) argue that all accessibility analysis suffer from spatial aggregation errors and some spatial aggregation errors are more serious than others. They demonstrate for the case of Alberta that aggregation errors are a concern when calculating accessibility to amenities that have highly localized service areas such as playgrounds. In this analysis, I use a single point to represent block groups, which might have quite diverse distribution of population within them and therefore affect travel time to the nearest stop. Again this is an issue of resolution and computational limits force particular choices. Given the size of the block groups in urban areas and the demonstrative purposes of this exercise, this is not a serious concern but nevertheless should be acknowledged.

Putting the spatial and temporal resolution concerns aside, the area of most concern is the resolution of the industry categorization and the use of industry types of infer the activity durations. Given the lack of data, this is the best that is possible. Capturing the temporal patterns in standardly available datasets would be a useful addition that would increase the value of these types of analyses. Furthermore, there is no reason to limit to using jobs as an indicator or 'attraction' of a location. Other data are becoming increasingly widely available. These include 'sales', 'ratings' etc. If one of the critiques of this paper is to move away from conceptualizing accessibility of workers to accessibility of users then using jobs as a measure of quality of a place is perhaps not the most useful one. Furthermore, destinations such as playgrounds, daycare centers, hospitals, libraries, movie theaters and restaurants might be more important than across the board establishments.

7. Conclusions

While on a bus back from the airport during mid-afternoon, I overheard a conversation by a fellow passenger lamenting that it takes him about two hours to get to work during that time of day and he needed to get a car as soon as possible. Such a trip was not so burdensome, when alternative and faster routes were available during the peak hours, but he was limited to this option because of his shift. This snippet of conversation prompted me to rethink if the standard measures of accessibility captured the lived experiences.

What I have demonstrated in this paper, is that real distances vary over time even within a day and therefore, it is not unreasonable to expect that perceived costs are also quite different for different modes. Because transit is schedule dependent, it captures various features that are usually ignored in accessibility studies: We can easily visualize, in the case of transit, the changes in network structure and the associated robustness of accessibility and these can be ported to other modes. We can also examine which routes are central to determining the accessibility of the region by examining the changes in the accessibility when the level of service on the route changes and therefore determine the importance of particular links. Because institutional structure of transit provision is usually fragmented, studies such as this highlight the importance of coordination of schedules and operations.

Ultimately, any measure of accessibility is imperfect reflection of the lived experience of the people. However, ignoring a key aspect, volatility, and focusing only on the level, can lead us misfocus infrastructure investments and programs. The key point of this study is to demonstrate that such volatility matters and ignoring it is underpinned by larger theoretical assumptions. Challenging such theoretical frameworks could help us in uncovering the role of accessibility in location choices and spatial structure of our places.

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