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Accessibility across transport modes and residential developments in Nairobi

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Abstract

A key goal of urban transportation planning is to provide people with access to a greater number of opportunities for interaction with people and places. Measures of accessibility are gaining attention globally for use in planning, yet few studies measure accessibility in cities in low-income countries, and even fewer incorporate semi-formal bus systems, also called paratransit. Drawing on rich datasets available for Nairobi, Kenya this analysis quantifies place-based accessibility for walking, paratransit, and driving using three different measures: a mobility measure quantifying how many other locations in Nairobi can be reached in 60 minutes, a contour measure quantifying the number of health facilities that can be reached in 60 minutes, and a gravity measure quantifying the number of health facilities weighted by a time-decay function. Health facilities are used because they are an essential service that people need physical access to and as a representation of the spatial distribution of activities more broadly. The findings show that place-based accessibility is highest for driving, then paratransit, then walking, and that there are high levels of access to health facilities near the Central Business District (CBD) for all modes. Additionally, paratransit accessibility is comparatively better in the contour and gravity measures, which may mean that paratransit is efficiently providing access based on the spatial distribution of services. The contour measure results are also compared across different residential levels, which are grouped based on neighborhood characteristics and ordered by income. Counterintuitively, the wealthiest areas have very low levels of place-based accessibility for all modes, while poor areas have comparatively better walking access to health facilities. Interestingly, the medium low residential level, characterized in part by tenement apartment buildings, has significantly higher accessibility than other residential types. One way to reduce inequality in access across income groups is to increase spatial accessibility for the modes used by low- and middle-income households, for example with policies that prioritize public transport and non-motorized travel, integrate paratransit with land use development, and provide safe, efficient, and affordable options.

Keywords: accessibility, Nairobi, semi-formal transit, paratransit, transportation planning

1. Introduction

A key goal of urban transportation planning is to provide people with access to a greater number of opportunities for interaction with other people and places, a goal which supports the creative dynamics, liveability, and productivity of cities. The concept of accessibility based on this insight has been used in transportation planning since Hansen (1959). Despite the growing interest in accessibility and related measures globally, many cities continue to focus on increasing travel speeds and reducing congestion (UN Habitat, 2013; Sclar and Lönnroth, 2014). This appears to be the focus in Nairobi, Kenya where road and highway construction has been prioritized over non-motorized and mass transportation (Hagans, 2013; Klopp, 2012; Porter, 2016). Rather than improve accessiblity, this focus is likely to exacerbate high levels of fragmentation and social and spatial inequality and affect the ability to meet Sustainable Development Goal 11.2 of providing 'access to safe, affordable, accessible and sustainable transport systems for all' (Hagans, 2013; Lall et al., 2017; UN Habitat, 2016). To bring more discussion of accessibilty into this context, this research explores the relationship between housing and access to health facilities in Nairobi, Kenya, specifically, using place-based accessibility measures we explore how accessibility varies spatially across Nairobi, across transport modes, and across different types of residential developments. Given that mode used and type of residential development are strongly linked to income, the resulting spatial inequality in accessibility has implications for social equity and exclusion.

Nairobi presents a number of fundamental differences compared to cities typically studied in the United States and Europe (Cervero, 2013). The first difference is the predominance of the paratransit system (Behrens et al., 2016; Cervero, 2000). Common to many cities in low- and middle-income countries, the paratransit system in Nairobi is made up of minibuses, often 14 seaters, called matatus, which are privately owned and operated by individuals or cooperatives. As opposed to a formal public transit system, this semi-formal system of matatus runs on flexible schedules, stops, and sometimes routes. Little is known about how well paratransit systems provide for increased accessibility citywide. Another crucial difference between cities in high-income countries versus cities in low-income countries, is mode share. In Nairobi, the majority of people rely on the paratransit system, which accounts for 40.7% of all trips (Nairobi City County, 2014b). Walking accounts for 39.7%, private automobiles (including taxis) account for 13.5%, and two-wheelers account for 5.4% of trips (Nairobi City County, 2014a). Given that paratransit and walking make up 80% of all trips, accessibility metrics based solely on driving, as often happens in the literature, would capture only a small portion of the overall level of accessibility and exclude consideration of accessibility for the majority of citizens (Lucas, 2011).

Finally, the way that transport access interacts with residential development in Nairobi is unexplored.

From 800,000 residents in 1980, Nairobi grew to 3.1 million in 2009 and the city is expected to grow to 5.2 million by 2030 (Nairobi City County, 2014a). Development is expanding outward, maintaining fairly low density in high-income areas in the western part of the city and car ownership rates have been on the rise. For example, the Westland Division of the city has maintained a low density of 2,539 persons per sq km compared to the average density for the city of 5,429 persons per sq km (excluding the Nairobi National Park). At the same time, a substantial portion of the population who cannot afford motorized transportation often live within walking distance of employment opportunities in slum conditions near the city center (Salon and Aligula, 2012), where density can be in excess of 25,000 persons per sq km. How transport and land use interact to influence suburbanization, gentrification, and equity in Sub-Saharan Africa needs more attention.

In an effort to address gaps in what we know about transport access in low-income cities, this research draws on rich datasets available for Nairobi to measure and visualize place-based accessibility using three different metrics and to compare levels of accessibility across different types of residential development. In one metric, referred to as the mobility measure, we focus on how the different transport modes (walking, paratransit, or driving) enable travel to other locations throughout the city. We then incorporate the location of health care facilities into a contour measure and a gravity measure to examine how physical characteristics of the transport system interact with land use. Health facilities are used because they are an essential service that people need physical access to and as a representation of the spatial distribution of activities more broadly. Given that, in general, the poorest depend on walking, the poor and middle classes take paratransit, and the wealthy tend to drive, unequal levels of access by mode serve as a rough proxy for inequality in physical access across socio-economic groups. Using the contour measure we also compare access to health facilities across seven different residential levels based on neighborhood characteristics and ordered by median income. This analysis highlights how income is interconnected with transport, land use, and housing, which suggests that different metrics and a different guiding vision in planning may be required if social equity is a goal.

2. Literature Review

Accessibility can be defined and operationalized in a number of different ways. We adopt the commonly used definition of accessibility as the "potential of opportunities for interaction" (Hansen, 1959) and focus on place-based measures. Place-based measures can be thought of as showing the potential access to destinations that an individual has at a given location (Handy and Niemeier, 1997; Geurs and van Wee, 2004). It is important to note that these measures do not capture actual travel behavior or other constraints individuals face such as time, affordability, or physical limitations (Curl et al., 2011; Weber, 2006; Odoki et al., 2001;

van Wee, 2016) but is still a neccessray condition for a more holistic, person-based accessibility.

In this paper, we show that place-based accessibility even with its limitations can be used to begin to understand spatial inequality and social equity. We follow the concepts as laid out by Teunissen et al. (2015) and use spatial inequality when referring to unequal levels of place-based accessibility across mode or residential type and use equity when referring to issues of fairness in the distribution of levels of accessibility. Accessibility is also linked to social exclusion, because households with low levels of access are socially excluded, unable to perform the activities and access the services deemed normal for the society in which they live (Páez et al., 2010).

Travel survey and focus group research demonstrates how residential location can limit the opportunities available to low-income households in Sub-Saharan Africa. In a study in the Tshwane region of South Africa, an urban area similar to Nairobi in terms of poverty and paratransit use, Lucas (2011) explores transport disadvantage and social exclusion. Through the qualitative analysis of a series of focus groups, she finds that cost and lack of transport limit the ability of low-income households from participating in key activities including employment, education, health services, and social networks.

In another study using a survey of 1,751 slum households in Nairobi, Salon and Gulyani (2010) find that poor residents often have physical access to transit, but affordability remains a major issue. Only 38% of slum households have at least one member who regularly uses motorized transport compared to 80% of households citywide. In fact, matatus are the only form of motorized transport that slum residents report using for any trip. The researchers highlight that slum residents in Nairobi have limited mode 'choice'; they take matatus very infrequently and walk practically everywhere because they cannot afford other options. In a second travel survey of 2,105 households throughout Nairobi, Salon and Aligula (2012) link transport options to income and residence. With low car ownership rates, they demonstrate that the middle-income group is dependent on the matatu system. They also find that a large number of households must live within walking distance of work because they cannot afford any motorized transport options. This means that households may be choosing to live in slums in order to be close to opportunities. The tradeoff between residential quality and transportation is one that we explore further in this paper.

There is a small but growing body of empirical research on accessibility in cities in low- and middle-income countries. Melbye et al. (2015) map accessibility in Dar es Salaam and compare free-flow conditions to periods with significant traffic congestion. This research identifies locations where congestion has the largest adverse effect on the accessibility of motorized vehicles. Ziemke et al. (2017) compare two different accessibility computation approaches for Nelson Mandela Bay in South Africa, noting the usefulness and policy relevance of the different measures. A study in Buenos Aires, uses the OpenTripPlannerAnalyst tool to calculate employment accessibility by car and public transit (Quirós and Mehndiratta, 2015). Comparing the accessibility of cars to transit for different neighborhoods, they find that jobs are predominantly accessible by car; only in the city center does the transit system provide similar levels of access. They also find that growth is happening in places with very low levels of public transport access, particularly in gated communities. In Accra, Moller-Jensen et al. (2012) map accessibility by time of day and at different directions, incorporating congestion levels and traffic flows. Additionally, in a report for the Gauteng City-Region in South Africa, Gotz et al. (2014) study the relationship between residential typology and travel patterns and use a gravity measure to capture access to jobs. The report highlights the lack of local amenities in peripheral locations and the advantages that centrally located households have in terms of access to public transport, lower costs, and shorter travel distances. Their results, using an accessibility measure for a subset of townships, show that low access to jobs is a combination of peripheral location, lack of transit access, and few economic opportunities nearby.

In the past, lack of data would have been a barrier for accessibility planning in Nairobi but paratransit and land-use data are now available (Klopp et al., 2015; Williams et al., 2014, 2015) and are being used to study walkability and accessibility (Leis, 2014; Avner and Lall, 2016; The World Bank, 2016). The World Bank's Kenya Urbanization Review, uses this data to analyze access to jobs, parks, hospitals, and schools across modes. They find that access to jobs differs spatially between cars and transit, with cars able to reach more formal economic opportunities within 30 minutes (The World Bank, 2016). This analysis relies on a number of uncertain assumptions to quantify the number of jobs, which may bias their analysis. In an extension of this work, Avner and Lall (2016) explore if the transport-land use relationship is efficient. By simulating a number of counterfactual scenarios of the location of jobs and households, they find that better coordination between land use and transport can increase the share of overall opportunities accessible within a given timeframe (Avner and Lall, 2016). Our study builds on this work by looking directly at spatial inequality in place-based accessibility across types of residential development. We compare all three modes of transport incorporating congestion, and focus on access to health facilities where the georeferenced data is more reliable and as an example of an important service that people need and must be able to physically access in a timely manner (as do the workers in these facilities to make them work). The extent to which the spatial distribution of health facilities is an approximation of opportunities more broadly, is an area for future research.

By measuring and visualizing place-based accessibility in Nairobi we contribute to the literature in the following ways. First, we add to what is currently known about the relationship between transport and land use in Nairobi by analyzing place-based accessibility across the entire city for the three primary modes of travel: walking, paratransit, and driving. The richness of data available makes it possible to measure place-based accessibility generated by the paratransit system, which has rarely been studied. Although this kind of semi-formal transit system is common to cities in the Africa, Asia, and Latin America, Nairobi is one of the only places where the entire system has been mapped and put into a data format that can be used for measuring accessibility (Williams et al., 2015; Klopp et al., 2015). A privately operated system could offer some benefits in terms of flexibility and demand responsiveness or it could focus and limit its service to only the most profitable subsets of the population (Mutongi, 2006; Woolf and Joubert, 2013). A question remains about how well this system, and paratransit systems in general, provide for greater urban accessibility. Finally, unlike previous studies, we compare the provision of transportation and access to health facilities across types of residential development with a focus on understanding if there is spatial inequality in access to health facilities across the city, across modes, and across income groups.

3. Methodology

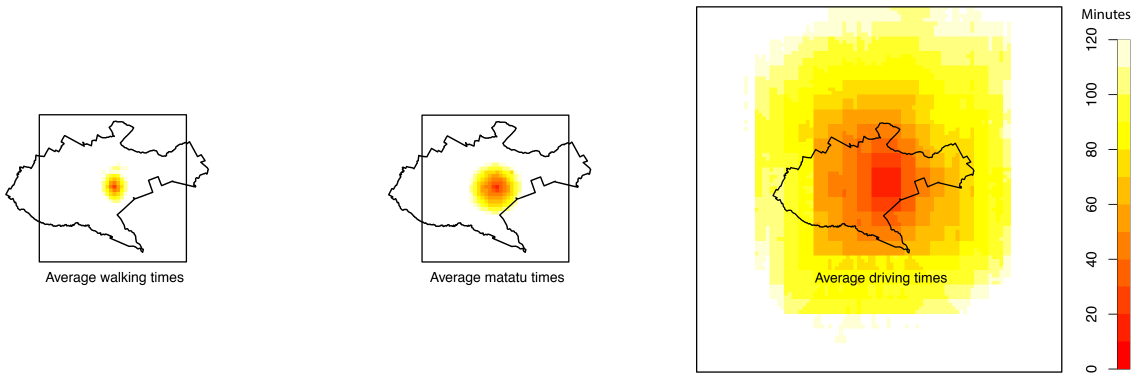
This section describes the methods used to generate travel times for each mode across a grid over Nairobi, the three different metrics used to measure accessibility, how locations are classified based on a residential typology and income, and how levels of accessibility are compared across residential developments.

3.1. Compiling Travel Times

Travel times for walking, paratransit, and driving are computed on a grid of travel origins and origin-specific grids of travel destinations. For each mode, a grid of origins specifies the sampled locations where accessibility is to be measured. To perform the measurement, a second grid is created for each origin location, centered on the origin location. This grid specifies possible destinations to be reached from that origin. The primary quantity we calculate for each pair of origin and destination points is the time required to traverse the distance using the given mode, using paths appropriate to that mode as defined below. The origin grid for all modes consist of points spaced 0.01 ° (about 1 km) over Nairobi City County (1.15 °S to 1.40 °S and 36.65 °E to 37.17 °E).

The radius of the destination grids for each origin point differs by mode, such that the furthest destinations are about two or more hours distant. For walking and paratransit, destinations 0.16 ° or about 18 km distant are sampled. For walking, this results in grids for which the shortest time to the furthest sampled point is 6.8 hours and the median furthest point time is 12.4 hours distant. For paratransit, the minimum furthest time is 4.1 hours and median time is 7.9 hours. For driving, destinations 0.40 ° or about 44 km distant are sampled, and the minimum furthest time is 1.9 hours and median furthest time is 3.2 hours. These minimum furthest times ensure that we do not exclude any relevant destinations due to unsampled data. Destination grids have a higher resolution than origin grids, with grid points 0.004 ° or about 400 m apart. Figure 1 shows the average travel time to each point in an origin's destination grid, across all origin points. Colors fade to white at a distance of 2 hours. Boxes denote the range of sampled destinations, relative to the origin location. The three maps are centered at an arbitrary example origin point in Nairobi, consistent across the three modes.

Figure 1: Example of Travel Time Data for a Given Origin Point



Walking times are retrieved from the MapQuest transit route matrix interface, which draws upon OpenStreetMap data[1]. The MapQuest route matrix reports the estimated time to walk the fastest route between two points, avoiding limited access roads for pedestrian timing. If the destination is unreachable, MapQuest will sometimes report the time to the closest reachable point. If the distance reported for such a partial route is less than the straight-line distance from the origin to the destination, the observation is dropped. Origin locations for which over 50% of destinations are unreachable or dropped are retrieved using the Google Maps distance matrix interface instead, as described for driving, and the maximum of the two results is used. An example of the sampling process is shown in AppendixA.

Driving times are collected using the Google Maps distance matrix interface[2]. The Google Maps distance matrix provides shortest driving distances using the road network and walking distances using sidewalks and pedestrian paths. MapQuest and Google Maps routes are similar, with Google Maps providing complete routes from origins to destinations more often. Google Maps limited data collection more than MapQuest, motivating the use of both services.

We query driving times with and without congestion. The effects of congestion are estimated by the Google distance matrix based on historical average speeds, drawing from data for the same day of week and time of day. In the absence of congestion, driving times are based only on the road class, with an assumed velocity for that class. Driving duration with traffic is based on historical traffic conditions for a given day

[1]MapQuest transit route matrix interface is described at `http://www.mapquestapi.com/directions/#matrix`. MapQuest relies on OpenStreetMap data (`https://www.openstreetmap.org/`) where it is more detailed than their own.

[2]Google Maps distance matrix interface is described at `https://developers.google.com/maps/documentation/distance-matrix/intro`.

of the week and time of day. We assume a departure time of 7:30 am (local time) on a Tuesday, representing regular weekday commuting traffic.

Walking and driving times are first queried at 100 locations for each origin point, and then extended to the entire destination grid by a daisy-chaining process. The initial 100 points are arranged in a 10 x 10 grid, extending 0.04 ° (4.4 km) from the origin for walking and 0.16 ° (18.9 km) for driving. The entire collection of destination grids for each origin point is then used to determine times to further locations and interpolated to higher resolution. The total time required to travel from an origin point to a destination point in the final grid is the shortest time to leapfrog from one origin point to another, summing the origin-to-destination times in each step.

Paratransit connections are detailed in the form of a General Transit Feed Specification (GTFS) and made open and available by the Digital Matatus Project, a research consortium, which generated and disseminated the data (Williams et al., 2015; Klopp et al., 2015). The GTFS data includes waiting, departure, and estimated transit times from each stop, and describes transfer points and transfer times between the routes. We find the minimum time to travel from an origin point to a destination point by estimating the walking time from the origin to each matatu stop, followed by all possible rides and connections, followed by the walking time from each final stop to the destination. Walking times for paratransit are estimated using a straight-line path at an average speed of 4 km per hour. If this total is greater than the time to walk from the origin to the destination without using paratransit, then the walking time is reported instead. We only consider paratransit trips with boarding times between 7am and 9am on Mondays, but allow the trip to start at any time in this span that minimizes total travel time. The GTFS schedule was estimated from data collected on board vehicles. For both the paratransit data and the driving data, we estimate the travel times during the morning peak period to capture effects that incorporate historical traffic conditions. Paratransit transit times are queried at the full resolution of the destination grids, rather than using a daisy-chain approach.

3.2. Calculating Accessibility

In this analysis we use three different place-based accessibility measures: a mobility measure that quantifies how many other locations in Nairobi can be reached in 60 minutes, a contour measure that quantifies the number of health facilities that can be reached in 60 minutes, and a gravity measure that quantifies the number of health facilities weighted by a time-decay function that penalizes facilities that are further away.

To understand how service provision varies across modes, we use a measure that takes into account only characteristics of the transport network, excluding land use interactions. We call this the mobility measure and approximate it at each grid point in Nairobi using the following formula:

$$M_i^v = \sum_{j \in J(i)} I(t_{ij}^v \leq t_{max}) \tag{1}$$

where M_i^v is the level of mobility (measured in number of grid points) at origin location i for transport mode v, $J(i)$ is the set of destination points for origin point i, t_{ij}^v is the travel time in minutes between points i and j on mode v, and $I(\cdot)$ is an indicator function that is 1 if t_{ij}^v is less than or equal to t_{max} of 60 minutes. We use the travel times generated across a grid as explained previously. We use origin points i that fall within Nairobi City County. Destination points j can be outside the city limits. This measure counts the number of other grid points that an individual can reach in 60 minutes from a given grid point, without taking into account the types of activities at each grid point.

Next, we use a contour measure to understand how access to specific activities varies. The following contour-based accessibility measure, also referred to as a cumulative opportunities measure, is used to approximate access to health facilities at each grid point in Nairobi:

$$C_i^v = \sum_{j \in J(i)} O_j \cdot I(t_{ij}^v \leq t_{max}) \tag{2}$$

where C_i^v is the level of contour-based accessibility (measured in number of health facilities) at origin zone i for mode v, O_j is the number of opportunities near destination point j, and $I(\cdot)$ is an indicator function that is 1 if the time (t_{ij}^v) to get from origin zone i to destination zone j using mode v is less than or equal to t_{max}, which we set to 60 minutes. A variety of opportunity types can be used, but for this analysis we focus on medical facilities including hospitals (private or public), health centers, dispensaries, private clinics, nursing homes, and institutional health facilities (such as at schools, universities and prisons). In the main specification we use a 60 minute cutoff, because it is larger than the average travel time of 47 minutes per trip in Nairobi (The World Bank, 2016). We also test the results at 20, 40, 80, and 100 minute time bands. This measure is often used in accessibility analyses because it is easy to calculate and interpret. The downsides are that the cutoff point (60 minutes in our study) is arbitrary and that it gives equal weight to opportunities, whether they are 1 minute or 60 minutes away.

Finally, we use a gravity measure, also referred to as a potential accessibility measure, which incorporates a time-decay function. This has the benefit of giving less weight to locations that take a long time to reach and, with a big enough travel time window, minimizes the impact of the choice of cutoff point. In this case, we employ the commonly used negative exponential cost function in the gravity-based accessibility measure as follows:

$$G_i^v = \sum_{j \in J(i)} O_j \cdot e^{-\sigma^v t_{ij}^v} \tag{3}$$

where G_i^v is the level of gravity-based accessibility (measured in number of health facilities) at origin zone i for mode v, O_j is the number of opportunities (in this case health facilities) near destination point j, σ^v is the impedance parameter (also called the cost sensitivity parameter) for mode v, and (t_{ij}^v) is the time it takes to get from origin zone i to destination zone j using mode v.

We estimate the impedance parameter, σ^v, from travel surveys using the frequency distribution of trip time fit to an exponential distribution for each mode. Travel survey data was prepared by JICA in 2013 for the Nairobi Master Plan and included a survey of 10,000 households and 38,634 trips. In this data, one trip can be composed of more than one mode, so we classify a trip as a walking trip if it includes only walking; a paratransit trip if it includes any combination of walking, matatu, or bus; and a driving trip if it includes a car or motorcycle. We exclude trips where primary mode used was ambiguous, which happened in less than 1 percent of the cases. The resulting estimates are 0.0303 for walking, 0.0165 for paratransit, and 0.0195 for driving. These correspond to an average trip length of 33 minutes for walking, 61 minutes for transit, and 51 minutes for driving. The impedance parameters used in this analysis were calculated without distinguishing trips based on trip purpose, so represent an average across all reasons for traveling. Separately, we estimated the impedance parameters using only trips classified as "medical" and found similar, albeit slightly higher, point estimates that were not statistically different than the values reported here.

To calculate the number of opportunities, we associate each facility of interest, such as a hospital, to a point on the destination grid. Facilities are associated with the destination grid point closest to their centroid, excluding points beyond the range of the sampled destination points. Data on health facilities is for 2007 and comes from the Kenya Bureau of Labor Statistics[3]. Additionally, we only include medical facilities that fall within Nairobi's city boundaries. All accessibility calculations were performed in R using a number of packages[4].

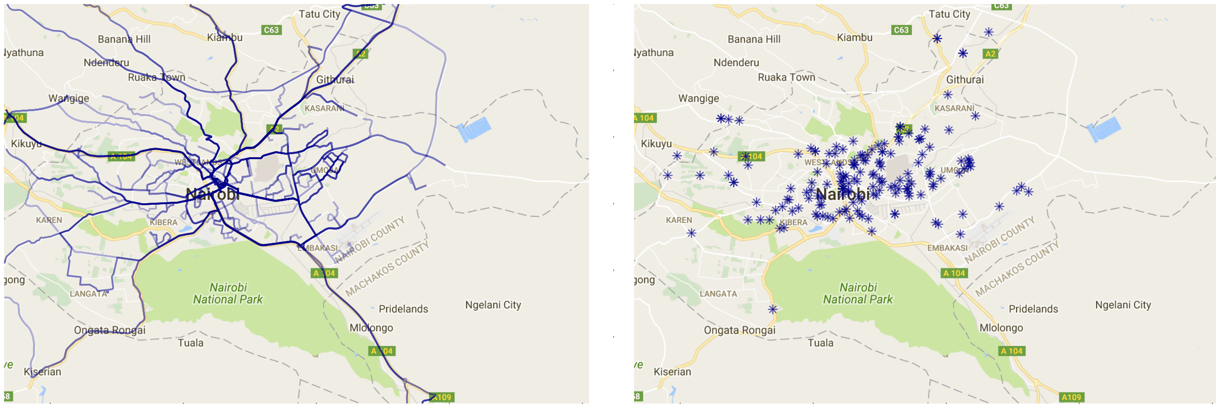
Maps of the paratransit routes and the health facilities in Nairobi are shown in Figures 2a and 2b, respectively. For the paratransit map, darker lines indicate that there are more routes operating along that road. The paratransit network is dense close to the CBD. Routes primarily run from outlying areas into downtown. In terms of the spatial distribution of health facilities, there are more health facilities around central Nairobi. Excluding the National Park and the eastern part of the city, health facilities are disbursed

[3]This data was downloaded from Kenya Open Data (`http://www.opendata.go.ke/`) on May 20, 2016.

[4]Packages used include ggplot2, data.table, rgdal, RColorBrewer, ggmap, raster, maptools, stargazer, and PBSmapping. R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. `http://www.R-project.org/`.

across Nairobi.

Figure 2: Health Facilities and Paratransit Routes in Nairobi



(a) Paratransit Network (b) Health Facilities

Note: The underlying basemap is from Google Static Maps API using the R package ggmap. The dashed grey line denotes Nairobis city limits, but is incorrectly displayed due to an error in Google's encoding.

3.3. Comparing Across Residential Levels

Data on residential types comes from the UN Habitat Global Water Operators Partnerships Alliance's (GWOPA) pilot project on Access to Water in Nairobi (Ledant, 2013)[5]. Using a set of composite Quickbird satellite images from October 2009, their work classified land cover into different land uses in Nairobi. Residential plots were further classified into 17 distinct categories of housing based on having particular combinations of physical characteristics. Physical characteristics included density of vegetation, plot size, attached or detached housing, single or multiple stories, gated space, and roof material. In March and April 2011, they conducted a survey of 817 households, sampling across the different residential categories. They assigned all neighborhoods of a given type the mean socioeconomic characteristics of the surveyed locations. They further grouped the neighborhood types into 7 aggregated classes based on income. In the survey, income ranges were recorded based on respondents' estimation of household income. The median value was normalized by the number of household members and extrapolated to the neighborhood level. For the purpose of our study, we take these seven aggregated classes and order them from very low to very high. These residential levels and a description of the neighborhood typology is shown in Table 1 and mapped in Figure 3. The list of physical characteristics and income that define each neighborhood typology can be found in the GWOPA report.

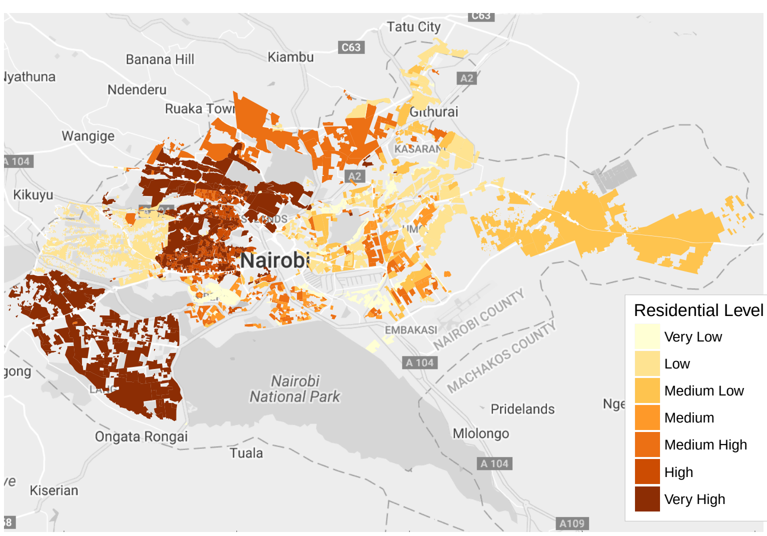
[5] See http://access-to-water-in-nairobi.gwopa.org/

Table 1: Ordering of Residential Levels

Level	Income*	Description of Neighborhood Typology from Ledant (2013)
Very High	39,890 KES	Detached housing on very large plots in intense vegetation
		Detached housing on large plots in lush surroundings
High	22,084 KES	Attached housing on medium plots in lush surroundings
		Moderate density apartment buildings
Medium High	13,352 KES	Attached housing on small sized plots with some vegetation
		Detached housing on large plots in lush surroundings
Medium	6,153 KES	Attached housing on small-sized plots with some vegetation
		Moderate-density apartment buildings
Medium Low	3,854 KES	Institutional housing
		Scattered detached housing
		Attached housing on small-sized plots with some vegetation
		High-density lower-quality tenement buildings
Low	2,165 KES	Institutional housing
		Institutional housing
		Rural low-quality housing
		Lower-quality housing under development
		Planned lower-quality housing
Very Low	1,301 KES	Very low-quality housing (slums)

* *Income is the median value of per capita income from each neighborhood type that makes up the aggregated class.*

Figure 3: Map of Residential Levels



To analyze how accessibility varies by residential level and location we perform the following regression:

$$C_p^v = \beta_0 + \beta_1 distCBD_p + \sum_{L \neq \text{medium}} \beta_L R_p^L + \varepsilon_p \tag{4}$$

where C_p^v is the value of the contour measure at residential plot p for mode v, distCBD$_p$ is the straight-line distance (in kilometers) from the centroid of residential plot p to the CBD given by the coordinates 1 °16'59.99"S, 36 °49'0.01"E, R_p^L are indicator variables set to 1 if residential plot p is of residential level L, and ε_p is the residual error. There are 1,598 distinct residential plots in the dataset, which are mapped by residential level in Figure 3. Residential levels L include "very low", "low", "medium low", "medium high", "high", and "very high", as defined in the first column of Table 1. "Medium" is the reference level. Taking the "low" residential level as an example, the interpretation of the coefficient on R_p^{low} is that on average at a residential development in the "low" category, one can reach β_{low} more health facilities than from a residential development in the "medium" category at the same distance from the CBD. A positive coefficient means that, on average, a residential development of level L has greater access to health facilities within a travel time radius of 60 minutes than would be expected for a "medium" level residential development.

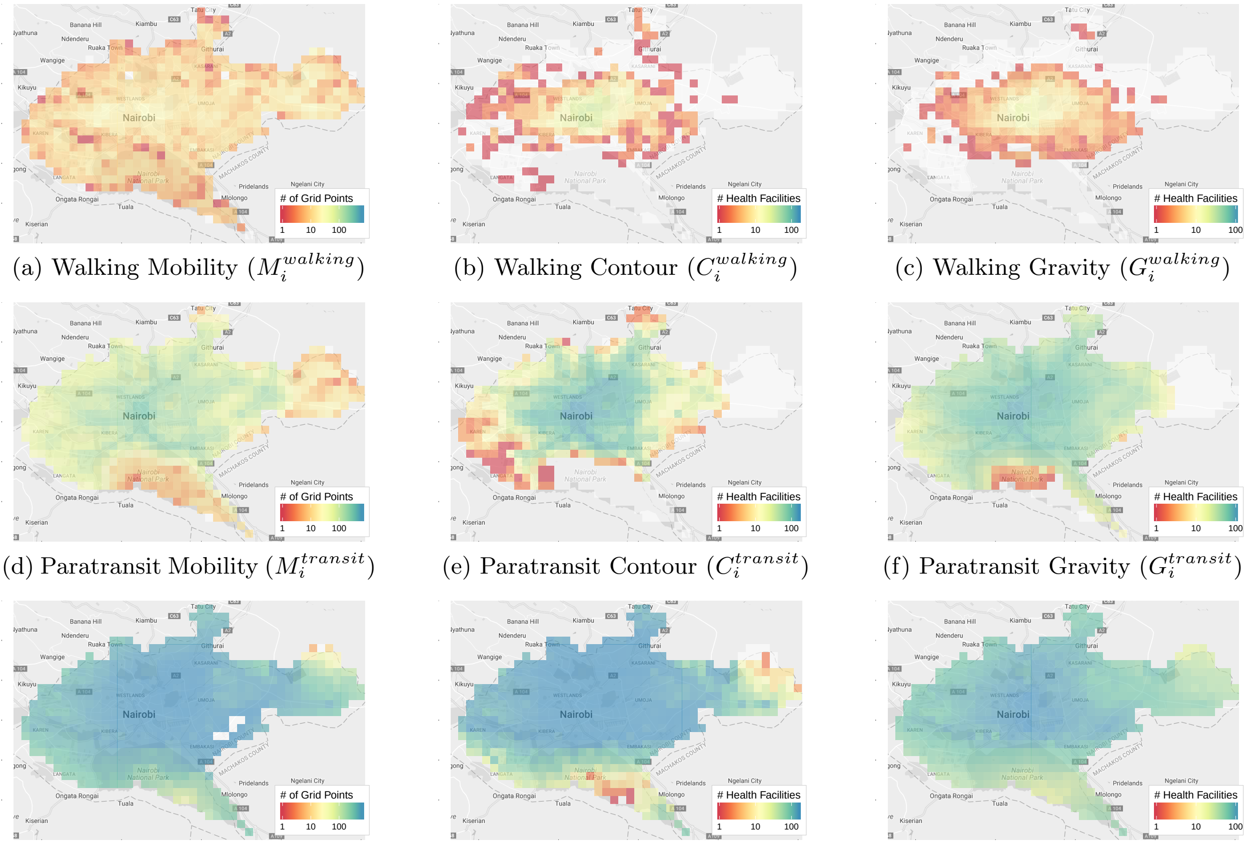
4. Results

The results are organized into two subsections. In 4.1, the three accessibility measures are mapped in Figure 4 and descriptive statistics are presented in Table 2. The graphs in Figure 5 show the cumulative distribution of values in each measure by mode. We compare place-baed accessibility across modes and review the findings. In 4.2, the results for access to health facilities using the contour measure are compared across different residential levels, where residential level is based on neighborhood characteristics and ordered by income. The relationship between accessibility and residential level is shown graphically in Figures 6 and 7 and the regression results are shown in Table 3. The results using the gravity measure are similar, so are presented in AppendixD.

4.1. Accessibility by Mode

The maps in Figure 4 show the results for each accessibility measure by mode. The mobility measure (M_i^v), presented in the first column, shows the total number of grid points j that are reachable within 60 minutes of travel from each origin point i using a given mode. The mobility measure is essentially a description of the characteristics of the transport system, or the ability to reach one location from another location. In the second column, the contour measure (C_i^v) shows the total number of health facilities reachable within 60 minutes of travel from each origin point i. This measure incorporates the spatial distribution of health

Figure 4: Spatial Variation in Accessibility by Mode for Each Accessibility Measure

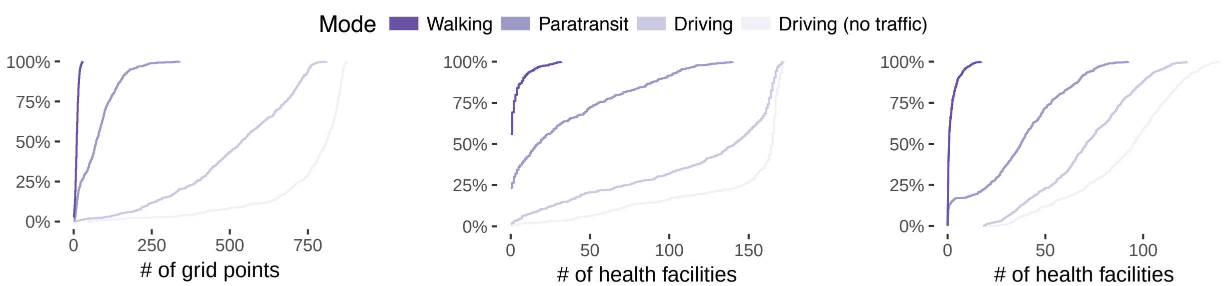


(a) Walking Mobility ($M_i^{walking}$) (b) Walking Contour ($C_i^{walking}$) (c) Walking Gravity ($G_i^{walking}$)

(d) Paratransit Mobility ($M_i^{transit}$) (e) Paratransit Contour ($C_i^{transit}$) (f) Paratransit Gravity ($G_i^{transit}$)

(g) Driving Mobility ($M_i^{driving}$) (h) Driving Contour ($C_i^{driving}$) (i) Driving Gravity ($G_i^{driving}$)

Figure 5: Cumulative Distributions of Accessibility Data



(a) Mobility Measure (M_i^v) (b) Contour Measure (C_i^v) (c) Gravity Measure (G_i^v)

Table 2: Summary Statistics of Accessibility Measures By Mode

	Mobility Measure (M_i^v)				Contour Measure (C_i^v)				Gravity Measure (G_i^v)			
Mode	**Mean**	**St.Dev.**	**Min**	**Max**	**Mean**	**St.Dev.**	**Min**	**Max**	**Mean**	**St.Dev.**	**Min**	**Max**
Walking	10.3	5.6	0	29	2.6	5.4	0	32	2.0	2.9	0.0	17.2
Paratransit	79.0	60.0	0	340	33.0	37.5	0	140	36.7	23.1	0.0	92.5
Driving	513.3	189.1	0	810	115.5	56.0	0	172	70.4	24.3	18.1	122.5
Driving (no traffic)	751.3	155.2	46	874	143.2	43.0	0	172	89.9	27.2	20.9	139.6

Note: Sample includes 566 origin points in Nairobi.
The units for the mobility measure are number of grid points (including destination grid points outside of Nairobi).
The units for the contour and gravity measures are number of medical facilities (with 172 total health facilities in Nairobi).

facilities throughout the city, and so presents one way to conceive of the interaction between transport and land use. Results using other time bands is in AppendixB. The gravity measure (G_i^v), in the third column, shows the number of health facilities reachable from each origin point i, weighted by the time-decay function. This is an improvement over the contour measure in that it penalizes health facilities that take longer to get to, and is not sensitive to a 60 minute threshold. The first row of maps shows the results for walking for each measure, the second row shows paratransit, and the third row shows driving. The accompanying Table 2 provides summary statistics, including for the results for driving without traffic, which is not mapped here. Additional information on the effects of congestion are available in AppendixC.

Overall, there are similar trends in place-based accessibility by mode in the three different measures used. In terms of paratransit access, the outline of the paratransit network is apparent, with high levels of accessibility along transit routes. A second trend throughout the maps is that the southern and eastern-most parts of Nairobi City County have low levels of accessibility, which makes sense because these areas have few roads, no paratransit routes, and no health facilities. The southern part is Nairobi National Park.

A third trend is that driving provides very high levels of accessibility, often an order of magnitude higher than other modes (note that the scale is logarithmic). For example in the mobility measure, walking values range from 0 to 29 with a mean of 10.3; paratransit values range from 0 to 340 with a mean of 79.0; and driving values are much larger with a range from 0 to 810 and a mean of 513.3. On average one can reach 2% (10.3/513.3) of the locations (grid point centroids) on foot as by car and 15% (79.0/513.3) by paratransit as by car in one hour. Furthermore, traffic congestion has a large impact. Using our estimates, it reduces the mean number of locations reachable in 60 minutes by a third (from 751.3 to 513.3). Clearly, driving has an advantage over walking and paratransit in reaching more points throughout the city. Similar patterns can be seen in the contour and gravity measures.

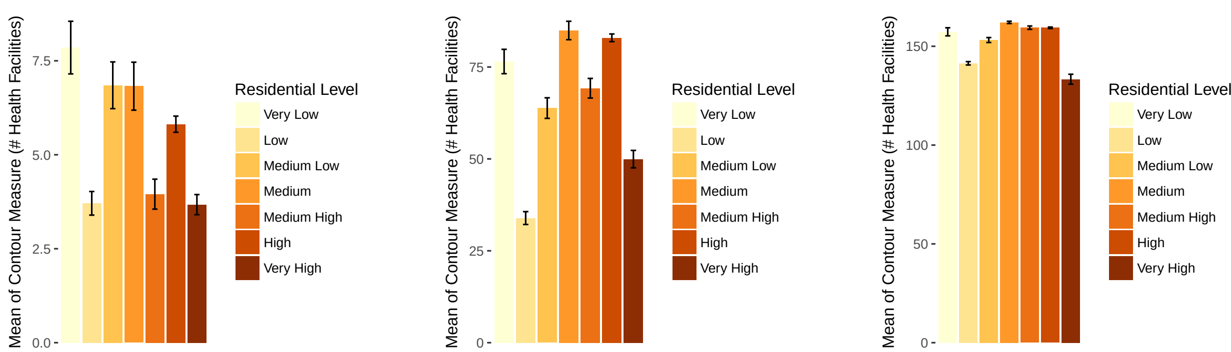
A final trend apparent in the maps is that central city locations have a comparative advantage for all modes, and especially for walking in the contour and gravity measures where walking accessibility is very low outside of the CBD. It is informative to compare the results for walking in the mobility measure to the contour and gravity measures, which take into account the spatial distribution of health facilities. When land use factors are considered, then there are few locations outside of the CBD with even moderate levels of access to health facilities by walking.

In comparison to the contour measure, the gravity measure tends to give less variation when levels of access are high (such as in the results for driving), and a more radially uniform result for lower levels of access. This reflects the smoother weighting applied to distant health facilities given by the gravity measure. Whereas the contour measure applies a discrete cutoff at 60 minutes, facilities at 90 minutes still have a weight of 0.17, under transit, for the gravity measure.

In Figure 5, the empirical cumulative distribution function of the data is computed for each accessibility measure and for each mode. The x-axis is the value of the accessibility measure and the y-axis is the proportion of observations in the data with that level of accessibility or less. Reading across the graph at 50%, these values correspond to the means shown in Table 2. As an example for how to interpret the graph using the contour measure in Figure 5b, reading across at 75%, we see that 75% of locations have access to 2 health facilities or fewer by walking (or alternatively that 25% of locations have access to more than 2 health facilities); 75% of locations have access to 55 or fewer health facilities by paratransit; and 75% of locations have access to 163 or fewer health facilities by driving.

How the shapes of the cumulative distribution curves and the comparisons between modes changes based on the measure used, shows that it is important to consider the distribution of activities when comparing driving to paratransit. In the cumulative distribution function of the mobility measure (Figure 5a), driving has a huge advantage over paratransit in terms of having more locations that are able to reach more grid points throughout the city, but this advantage becomes less pronounced in the contour and gravity measures, Figures 5b and 5c, respectively. In particular, when we take into account where health facilities are, we see that, because paratransit serves the areas where there are more health facilities, the comparative advantage of driving compared to paratransit is reduced. In the mobility measure the average level of accessibility by paratransit is 15% (79.0/513.3) as high as the average level of accessibility by driving, in the contour measure the average level of accessibility by paratransit is 29% (33.0/115.5) as high as the average level of accessibility by driving, and in the gravity measure the average level of accessibility by paratransit is 52% (36.7/70.4) as high as the average level of accessibility by driving. Paratransit provides comparatively better accessibility when the location of health facilities is taken into account.

Figure 6: Contour-Based Access to Health Facilities (C_i^v) by Residential Level

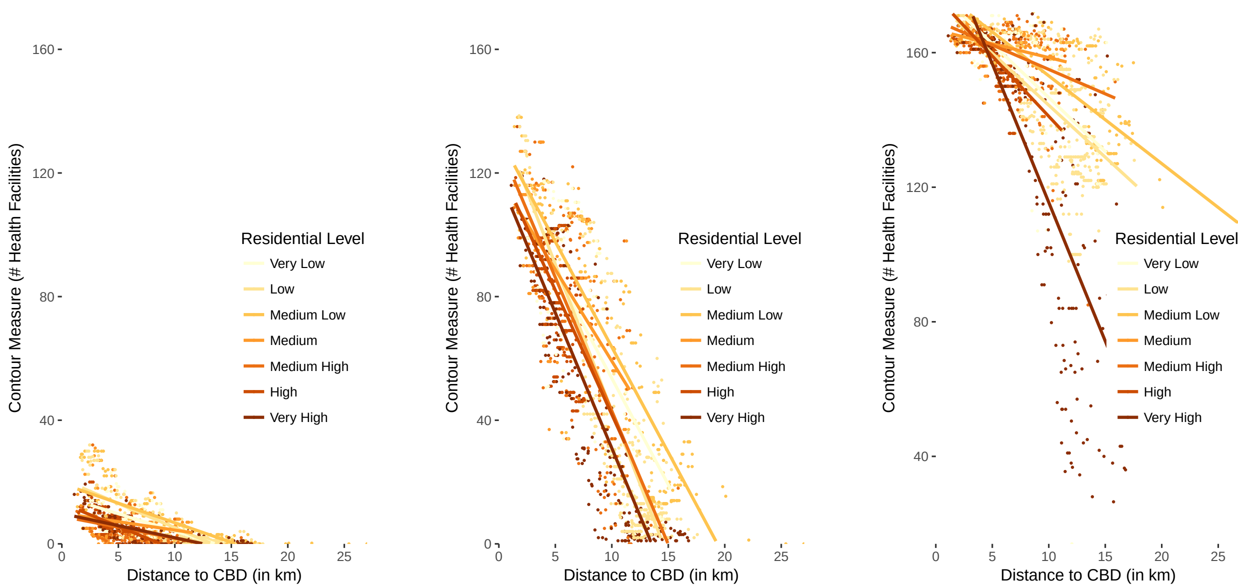


(a) Walking (b) Paratransit (c) Driving

4.2. Accessibility by Residential Level

Figure 6 shows the mean and standard error of the contour measure (C_i^v) by residential level for each mode. How residential levels were generated from neighborhood characteristics and ordered by household income is explained in Section 3.3. Because the results are so similar whether using the contour or gravity measure, the main analysis uses the contour measure and the results for the gravity measure are in AppendixD. In general, the contour measure for walking is higher for lower residential levels. The "low" level is the main exception with very low contour-based access to health facilities. It is also, on average, the furthest from the central business district (CBD) at 11.0 km away versus 6.7 km for the "very low" and 10.0 km for the "medium low" residential levels. This is due in part to the residential developments on the western side of the city, in the neighborhoods of Kawangware, Kangemi, and Riruta. They make up a large proportion of the observations for the "low" category. Trends are less obvious for driving and paratransit, except that the "very high" and the "low" residential levels have much lower contour-based accessibility than other categories.

Figure 7: Contour-Based Access to Health Facilities (C_i^v) by Residential Level Plotted by Distance to CBD



(a) Walking (b) Paratransit (c) Driving

Figure 7 shows the relationship between the contour measure (of access to health facilities) and distance to the CBD by residential level for each mode. The graph includes a scatterplot of the data and a linear regression line. The regression results are shown in Table 3. The slope of the regression line represents the change in the number of health facilities reachable in 60 minutes for a 1 kilometer change in the distance to the CBD. The negative slope means that the value of the contour measure is lower on average for locations

Table 3: Regression of Contour Measure (C_i^v) on Residential Level

	Dependent Variable (Contour Measure):		
	Walking Access	Paratransit Access	Driving Access
	(1)	(2)	(3)
Distance to CBD	-1.148^{***}	-8.058^{***}	-3.968^{***}
	(0.034)	(0.142)	(0.124)
Very Low	2.200^{***}	-0.207	-0.716
	(0.640)	(2.667)	(2.335)
Low	2.993^{***}	-8.166^{***}	0.406
	(0.517)	(2.153)	(1.885)
Medium Low	4.999^{***}	13.802^{***}	8.259^{***}
	(0.555)	(2.312)	(2.024)
Medium High	-1.357^{*}	-5.073^{*}	2.566
	(0.559)	(2.327)	(2.037)
High	-1.878^{***}	-8.070^{***}	-5.718^{**}
	(0.502)	(2.091)	(1.830)
Very High	-0.639	-17.369^{***}	-20.081^{***}
	(0.517)	(2.154)	(1.885)
Constant	13.309^{***}	130.435^{***}	184.494^{***}
	(0.469)	(1.955)	(1.712)
Observations	1,598	1,598	1,598
Adjusted R^2	0.446	0.751	0.503
Residual Std. Error (df = 1590)	4.630	19.286	16.884
F Statistic (df = 7; 1590)	184.920^{***}	688.476^{***}	232.310^{***}

Note: *p<0.05; **p<0.01; ***p<0.001

further from the CBD. The average slope is steepest for paratransit (-8.058), followed by driving (-3.968), and walking (-1.148), and each is statistically significant. Notably, access to health facilities decreases more quickly going away from the CBD for paratransit than for the other modes, likely because the paratransit system is characterized by fixed routes that converge on and are very dense in the CBD. Furthermore, the ability to transfer between routes is easier near the CBD, which is another factor increasing center city accessibility. The results also show the large comparative advantage of paratransit travel. Switching from walking to paratransit provides a 10-fold (130.435/13.309) increase in access to health facilities, while switching from paratransit to driving only provides 1.4 times (184.494/130.435) higher level of access to health facilities on average.

The regression results in Table 3 also demonstrate that, controlling for the distance from the CBD, higher residential levels tend to have lower accessibility than other residential levels. High residential levels ("medium high", "high", and "very high") reach up to 1.878 fewer health facilities in an hour by walking, between 5.073 and 17.369 fewer by paratransit, up to 20.082 fewer by driving than the "medium" residential level (which is the reference category in the regression), although the results are not statistically significant for walking accessibility for the "very high" level or driving accessibility for the "medium high" level. On the other hand, lower residential levels ("very low", "low", and "medium low") are able to reach between 2.200 and 4.999 additional health facilities in an hour by walking than the "medium" residential level given the same distance from the CBD. Overall patterns for paratransit and driving are less clear for lower residential levels.

Of particular note are the exceptionally high levels of the contour measure for the "medium low" residential level and the exceptionally low levels for the "very high" residential level. Controlling for distance from the CBD, the "medium low" residential level has the highest average contour-based accessibility compared to other residential developments for all three modes. The "medium low" residential level includes large-scale multi-story tenement buildings such as in Huruma, Pipeline, Umoja, Inner Core, and Eastleigh; institutional housing such as in the neighborhoods of Bahati, Pangani, and Eastleigh including the old Indian quarters and housing developed during colonial rule to house African railway laborers; and the eastern part of Nairobi where private developers have built low-density single family homes. The tenement buildings are notable because of their very high population densities and poor conditions. A sample in Huruma estimates densities of approximately 5,242 people per hectare, which is extreme, even compared with late nineteenth century New York City tenements that reached 1,294 people per hectare (Huchzermeyer, 2007).

The other housing category that stands out is the "very high" residential level because the contour measure is exceptionally low. This category includes detached housing on very large (often gated) plots of land. It is likely that this dispersed and land-intensive development leads to low physical access. It is also due to the lack of health facilities in these exclusive areas, likely a result of their restrictive zoning.

5. Discussion

These findings add to the small but growing body of research measuring accessibility in low-income countries, research made possible by open and available data on paratransit. The results concerning the spatial distribution of access to health facilities are similar to what Avner and Lall (2016) find in access to jobs. Our findings are also in line with the analysis of travel surveys by Salon and Gulyani (2010), who show that living in slums near the CBD may be the only feasible option for low-income households who cannot afford motorized transport and need to be able to walk everywhere they want to go.

We add to this body of research by making explicit the relationship between housing and transportation's contribution to access to health facilities, quantified using a contour measure and gravity measure. In addition to finding that lower residential types have better walking accessibility, we find notable results for the "medium low" and "very high" types, as compared to the "medium" residential type. The "very high" residential level stands out for having much lower driving and paratransit accessibility, even after we control for the distance from the CBD. This is a somewhat counterintuitive result that the housing type with the highest median income has access to the fewest number of health facilities within 60 minutes. This type is representative of detached single-family housing on very large (often gated) plots of land. It may be that this dispersed and land-intensive development leads to lower accessibility. It could also represent a preference not for access, but for seclusion, a point made by Couclelis and Getis (2000). In addition to being built for cars, some of these neighborhoods also ban matatus from entering. Although these neighborhoods often employ domestic workers, the ability of domestic workers to get there is severely limited. This type of urban development appears to contribute to spatial segregation.

Our findings also highlight the issue of tenement housing, a rapidly growing residential form in Nairobi. The "medium low" residential level has significantly higher levels of access to health facilities and is characterized by both colonial-era institutional housing and by privatized high-rise apartment buildings. Huchzermeyer (2007) draws attention to the growth in large-scale privately owned apartment buildings, likening them to modern-day tenements with extremely high population densities, insufficient planning and regulation, and driven by profit-maximization. However, we find that the location of this residential type near transport networks has a significant advantage in accessibility which may explain their attraction.

The mobility, contour, and gravity measures used here are estimates and do not capture all the factors that influence individual travel decisions or health care service. For example, we do not take into account quality of care, the variation in services offered at each health facility, or how the ratio of health facilities per person in high-density slum areas may limit provision of service. Additionally, these place-based measures do not account for the variation across individuals such as how access differs by age, gender, or physical ability, which are important when considering health care accessibility (Guagliardo, 2004; LaMondia et al., 2011). We also do not take into account financial constraints, such as the ability to pay for paratransit or a car or to pay for health services upon arrival at a health facility, which is a limitation of the data. The only "cost" that is currently captured is the time spent traveling. The results presented here are useful in understanding how the potential for physical access compares across neighborhoods (also called "nominal" access), and if used in practice should be compared with actual travel behavior and realized benefits (or "effective" access). In particular we recommend further study on the complex factors that affect travel behavior and the use of person-based accessibility measures. One area for future research is further incorporating travel survey data into these measures and analysis in a way that reflects the different constraints that individuals face. Since access is a function not only of location, but also of personal characteristics, person-based measures would provide information about additional factors contributing to transport-based social exclusion (Páez et al., 2010; Preston and Rajé, 2007).

Another limitation is the lack of high-quality land parcel data, which, for political reasons, is rarely made public (Williams et al., 2014). As a proof of concept, we focus on health care facilities, but future work should be done to understand how the distribution of health care facilities compares to other destination types and if health care facilities are an appropriate proxy for access to opportunities more broadly. Health facility data tends to be more readily available than local land use data, so this is an important area for future research in low-income countries. Additionally, we do not take into account the variation in quality of health care facilities, which future research should explore. Furthermore, the residential typology data is an estimate. In creating the residential typology data, field surveys were conducted and income was extrapolated to all neighborhoods within the same category. The accuracy of the extrapolation has not been verified and has an unknown influence on our results (Ledant, 2013).

The quality of walking infrastructure may have a larger negative impact on location-based accessibility than is captured here. Using travel surveys with the frequency distribution of trip time by mode, we find an impedance parameter of 0.0303 for walking, which is much higher than the parameters estimated for paratransit (0.0165) or driving (0.0195), and higher than what is commonly used in the literature in high-income countries. This means that the time-decay penalty for walking in the gravity measure is higher than for the other modes, although the actual pedestrian environment on each route is still not captured; it is assumed that if the MapQuest transit route matrix interface can calculate a path, then it is walkable. The Nairobi Master Plan highlights how sidewalks are narrow and in many places do not exist at all, particularly not as a formulated pedestrian network, and that there is insufficient pedestrian signage and crossing signals.

These street-level characteristics may have a huge impact on accessibility and safety that we do not fully capture and deserves further attention.

Finally, although we take into account traffic congestion, there are a number of other factors that impact transportation service. For example, future research could look at how accessibility varies over a 24-hour period and how reliability and safety vary across modes. These may be important when considering paratransit access and important features for understanding how equitable accessibility is across groups (El-Geneidy et al., 2016; Fransen et al., 2015; Klopp and Mitullah, 2016). In addition, one might be able to explore how a more optimal paratransit network might generate better place-based accessibility.

6. Conclusion

Our findings show how place-based accessibility, calculated using mobility, contour, and gravity measures, varies spatially across Nairobi and across modes, and the results make explicit the relationship between residential developments and physical access to health facilities. In particular we find that the mobility, contour, and gravity measures are highest near the Central Business District (CBD) for the three modes: walking, semi-formal transit (or paratransit), and driving. The central location may be particularly advantageous to people who walk because walking accessibility (and access to health facilities) is very low outside this area.

We also find significant variation in accessibility across residential levels where levels are grouped based on similar physical characteristics and then ordered by income. Lower residential levels are found to have better physical access to health facilities by walking than higher residential levels. It is important to note that higher place-based accessibility does not imply a socially just situation in terms of actual access to health care. For example, it may be that some clinics are in low-income neighborhoods to specifically cater to them, while wealthier residents living in more stringently zoned residential neighborhoods drive to clinics that offer higher quality care. However, it does tell us something about the character of different neighborhoods. Poor neighborhoods, which are not typically regulated, have a larger variety of land use types in close proximity (residential and health services) than high-income neighborhoods. In addition, the highest residential level has the lowest access to health facilities for paratransit and walking. Wealthier residents tend to drive, which may discourage public transit, investment in walking paths, or mixed use development in these neighborhoods. We note that this raises problems for the many low-income people living and working in these areas or who must pass through them. We also find that the "medium low" residential level, which includes tenement style apartments, offers significantly better place-based access to health facilities than other residential types after controlling for distance from the CBD. Whether this kind of accessibility tends to increase density as a market response to demand for housing near mixed land uses needs further exploration.

Focusing on accessibility and the interaction between transport and land use is important for understanding how well transport systems serve the needs of urban populations. We found that although driving provides much higher levels of mobility than paratransit, the advantage of driving over paratransit is smaller when we incorporate land use information. Evaluating transport projects based solely on physical characteristics of the system such as travel time savings, underestimates the importance of paratransit and other systems that work in conjunction with land use and policy instruments to produce not just mobility but accessibility, greater opportunities for interaction. Indeed, a breakdown of mobility and accessibility by mode as a proxy for socio-economic status can also highlight where increasing mobility for some (for example by banning matatus from wealthy neighborhoods to reduce congestion or putting high speed highways through poor neighborhoods) creates serious accessibility barriers for others.

Furthermore, we show that there are potential tradeoffs that households are facing between housing quality and place-based accessibility. For example, low-income households may live in lower quality housing precisely because it gives them walking access when no other modes are affordable. Middle-income households may compromise on private tenement-like apartments also because it provides better access to urban opportunities based on the modes available to them. Finally, at the highest end of the spectrum, residential developments for the wealthy are built in ways that limit access to these neighborhoods but have real drawbacks for residents in terms of convenience and congestion, which may be one reason some entrepreneurs are looking into van pooling or other ways to share mobility in wealthy neighborhoods[6]. If access to transport modes is limited by income, then a first order condition for equitable access is for better equality in spatial access across modes and across residential developments.

The recent Master Plan for Nairobi recommends public transport development policies including supporting a modal shift to public transport, examining ways to improve the existing matatu and bus services, strengthening the existing rail service, and promoting Transit Oriented Development. The master plan also acknowledges that a developed non-motorized transport network is a prerequisite. Yet in practice, transportation planning in Nairobi continues to be skewed towards the implementation of road development plans with a focus on the mobility of wealthier car users (Klopp, 2012; Hagans, 2013). Transport investments which focus on highways for rapid car travel do not always enhance accessibility for the majority and, in fact, can make walkablity worse for those who do not own cars, exacerbating inequality in access to the city. Our work demonstrates that paratransit and walking provide crucial access, particularly to low- and middle-income neighborhoods, and especially given that these modes are used by the vast majority of citizens. Investments

[6]See https://nairobiplanninginnovations.com/2016/11/12/ubabi-vanpooling-shared-mobility-for-nairobis-driving-class/

that may increase place- and person-based accessibility such as mixed land-use and affordable fares, tend to be neglected within current transportation planning. Even in the new Non-Motorized Transport (NMT) policy adopted by the Nairobi City County, only 20% of the transportation budget is allocated to NMT and public transit, whereas 80% of the people use these modes (Nairobi City County, 2014b). Careful interventions that focus on improving the way the modes used by the majority interact with land use is one path to increasing access for all.

In conclusion, in line with new global thinking, cities are beginning to move from theory to practice by mainstreaming accessibility and social equity as goals in transport and land-use planning and by supporting these goals through related investment. Critical to this effort is the movement to leverage technology to create vital data on public transport, housing, and land use (Klopp et al., 2015; Williams et al., 2014, 2015). This data is essential for measuring, analyzing, and visualizing accessibility. In addition, this study underscores the value of open data which allows for more and richer analysis, transparency, and debate around accessibility, spatial inequality, and social equity in our transport systems and cities. Overall, this push for data and metrics and a stronger focus on accessibility instead of mobility, must also reach planning discussions in cities like Nairobi, which are rapidly growing and building transport infrastructure with large impacts into the future. This is particularly the case in light of the Sustainable Development Goals, including target 11.2 that aims to 'By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons' (United Nations, 2015). Finally, this study also demonstrates that accessibility issues, and approaches to addressing them, may look different depending on the historical dynamics and context of particular cities.

7. Acknowledgments

Removed for Blind Review

8. Online content

Removed for Blind Review

9. References

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AppendixA. Sampling process for walking and driving

Figure A.8 shows an example of the sampling process employed for a point, 1.3° S, 36.8° E, shown with a green marker. Holding the origin point fixed, we sample travel times from it to a grid of destination points, shown with red markers. The actual route is determined by MapQuest or the Google Distance Matrix to minimize travel time.

These are spaced 0.04 ° apart. This grid spacing is one tenth the resolution of the final grid used in the paper. The result is a matrix of travel times, as shown below. Note that the travel time from the origin point to the same point, in the center of the grid, is 0 min.

201 min	99 min	111 min
90 min	0 min	88 min
145 min	145 min	228 min

In some cases, the travel route only gets as close as possible to the destination point, within the limits of the mapping system.

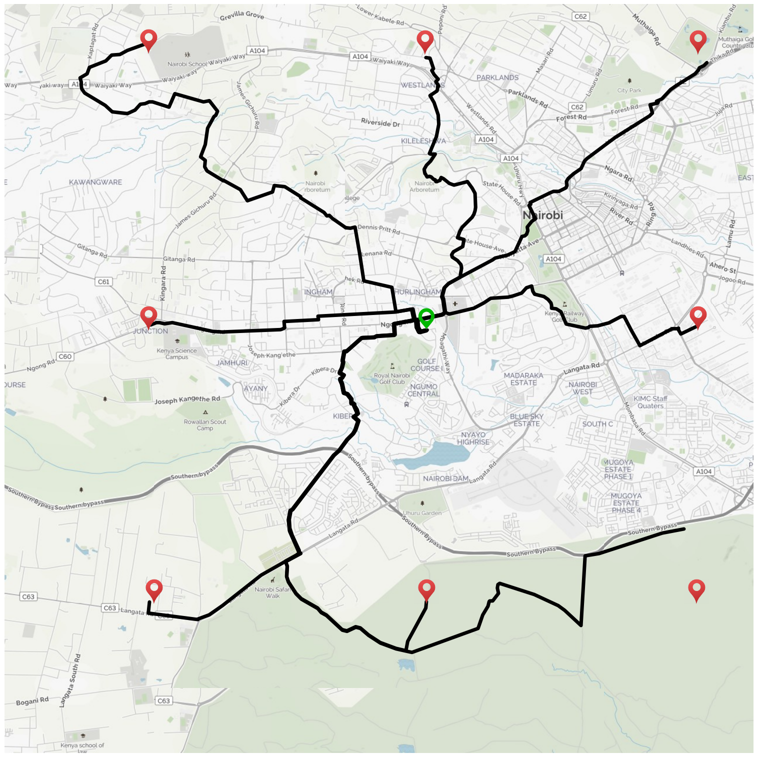


Figure A.8: An example grid of destination points (red markers) from a common origin point (green marker). These are spaced 0.04 ° apart, ten times farther than the grid used in the paper.

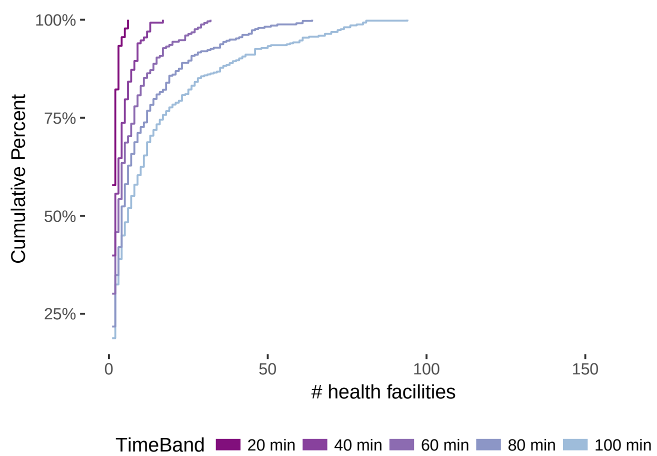
AppendixB. Sensitivity to Time Threshold

Figure B.9 plots the cumulative distribution function of the access data from the contour measure calculated using time bands of 20, 40, 60, 80, and 100 minutes with each graph displaying a different mode. The 60-minute threshold is used in the main results. As seen in the graphs, the higher time bands increase the magnitude of the results. In the walking and paratransit graphs the relative distribution of the data is similar for each time band used. For driving, at higher time bands, there is less variation in the access at different origins; most locations have only very high levels of access. We interpret these graphs as demonstrating that the choice in time cutoff is more of a scaling than censoring issue.

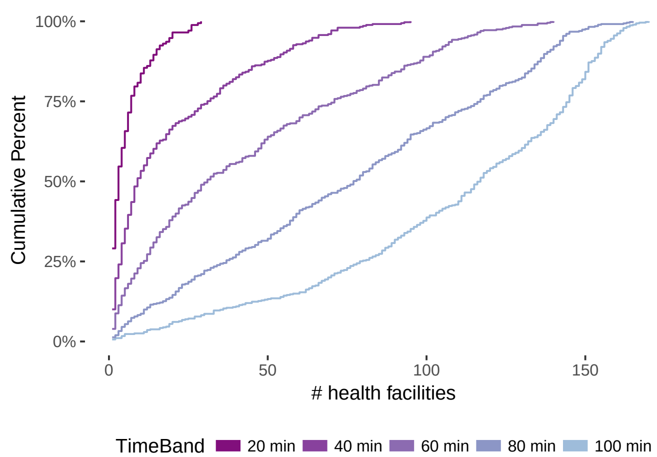
AppendixC. Effects of Congestion

We estimate the effects of congestion in two ways. First, we compute the average ratio of congested driving time to uncongested driving time in the vicinity of each origin point, during the morning rush-hour period used in the paper. This is shown in figure C.10. This shows ratios from 50% to over 1000%. The median ratio of congested driving times to uncongested times in the city is 176%, meaning that it takes 76% longer to travel in the city than would be possible just by the grading or speed limits of the roads. Ratios

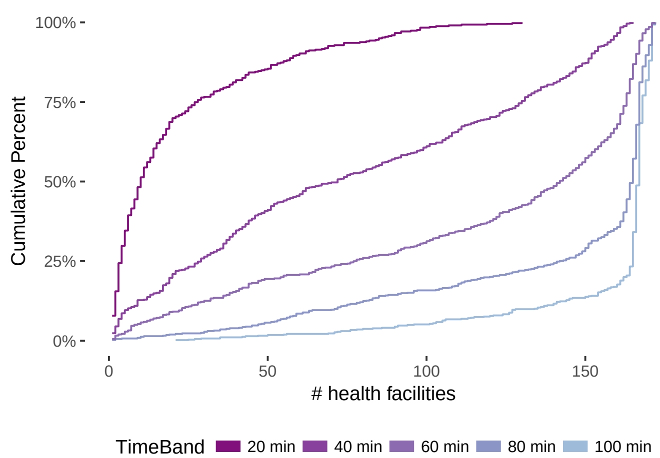
Figure B.9: Various Time Bands Used for the Contour Measure



(a) Walking



(b) Paratransit



(c) Driving

that are less than 100% imply that cars are able to move faster than the roads are graded for, which only occurs near Nairobi National Park and outside the city.

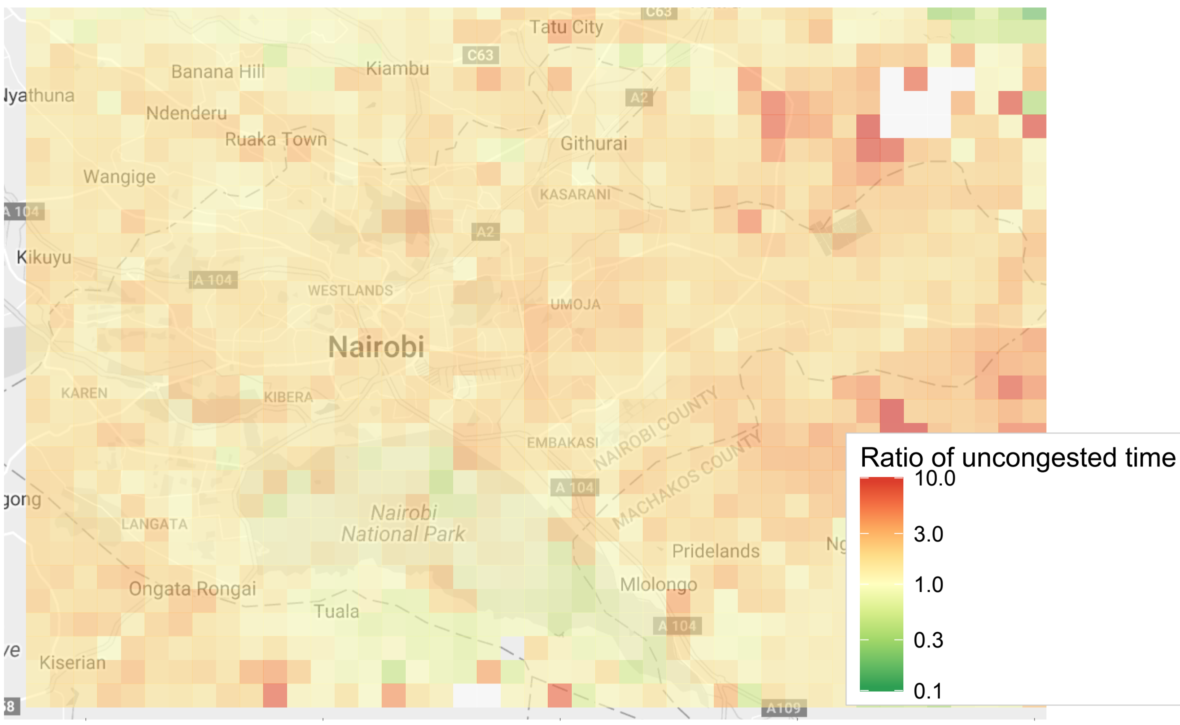


Figure C.10: The ratio between travel times to points near each origin point including historical traffic to travel times to the same points excluding traffic.

Second, we compare the mobility measure for driving with and without the historical effects of traffic, to estimate the effects of congestion. The percent ratio of mobility including traffic to the mobility without traffic describes the losses to congestion, where a ratio of 0% implies a complete stand-still in all directions. Across Nairobi City County, the average ratio is 67%, implying that about a third of mobility is lost. Figure C.11 shows how this measure varies across our study region. Interestingly, the area where traffic has the least affect is in the city center. This is because much of the city is accessible even with traffic to those in this area. Areas in the east have the largest mobility losses from congestion, with some having only a quarter of the mobility they would have otherwise.

AppendixD. Regression Analysis Using Gravity Measure

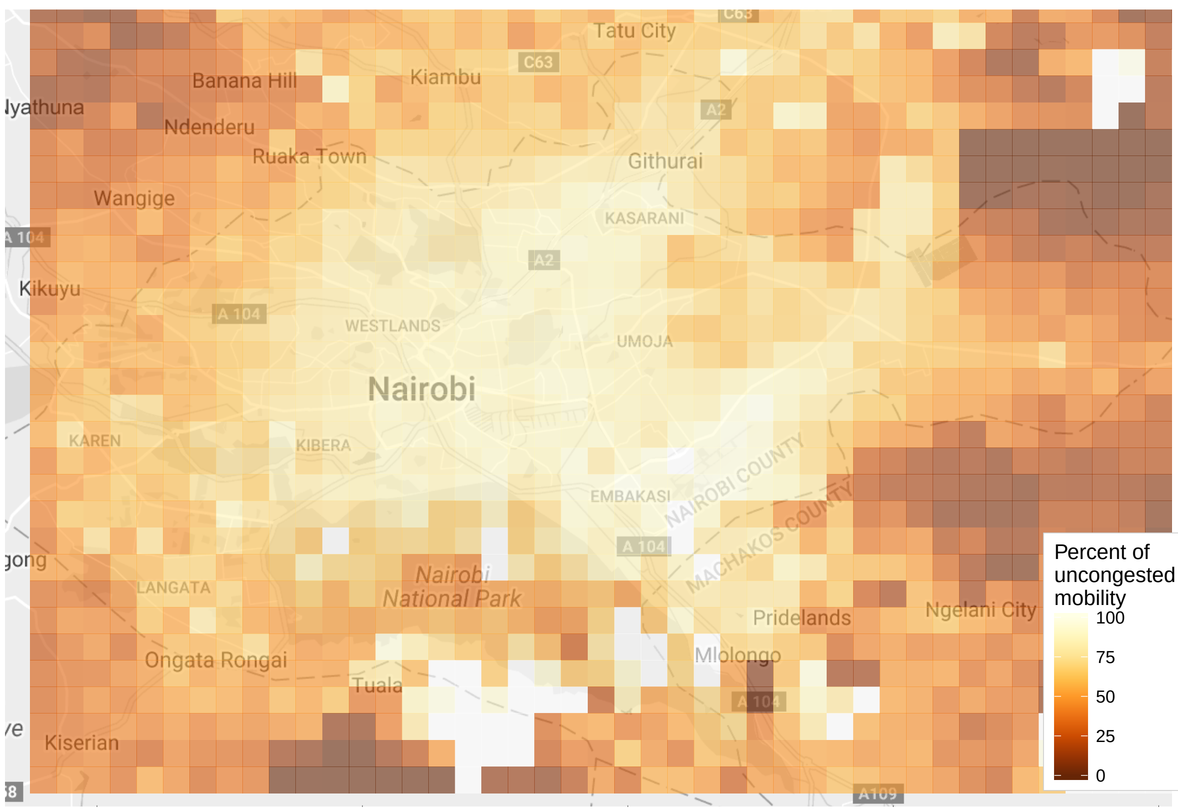


Figure C.11: The ratio of the mobility measure (points reachable in 60 minutes) including historical traffic and excluding traffic, expressed as a percent.

Table D.4: Regression of Gravity Measure (G_i^v) on Residential Level

	Dependent Variable (Gravity Measure):		
	Walking Access	Paratransit Access	Driving Access
	(1)	(2)	(3)
Distance to CBD	-0.625^{***}	-3.888^{***}	-3.419^{***}
	(0.017)	(0.061)	(0.061)
Very Low	1.091^{***}	0.109	0.147
	(0.318)	(1.154)	(1.146)
Low	0.922^{***}	-4.047^{***}	-0.576
	(0.257)	(0.931)	(0.925)
Medium Low	2.346^{***}	7.526^{***}	4.703^{***}
	(0.276)	(1.000)	(0.994)
Medium High	-0.830^{**}	-1.866	-1.815
	(0.278)	(1.007)	(1.000)
High	-1.437^{***}	-3.557^{***}	-7.554^{***}
	(0.250)	(0.905)	(0.898)
Very High	-0.975^{***}	-7.597^{***}	-10.972^{***}
	(0.257)	(0.932)	(0.925)
Constant	8.312^{***}	86.268^{***}	117.270^{***}
	(0.233)	(0.846)	(0.840)
Observations	1,598	1,598	1,598
Adjusted R^2	0.506	0.791	0.726
Residual Std. Error (df = 1590)	2.303	8.345	8.287
F Statistic (df = 7; 1590)	234.576^{***}	862.949^{***}	604.734^{***}

Note: *p<0.05; **p<0.01; ***p<0.001