USING DATA SCIENCE TECHNIQUES TO ASSESS THE MARGINAL EFFECTS OF PUBLIC TRANSIT INVESTMENTS ON EMPLOYMENT ACCESSIBILITY: THE CASE OF BOGOTA'S FIRST AERIAL CABLE-CAR

Manuel Santana Palacios, Corresponding Author
Department of City & Regional Planning, University of California, Berkeley
Email: manuel.santana@berkeley.edu

Brian Hill
Department of Civil and Environmental Engineering, University of California, Berkeley
Email: brianwhill@berkeley.edu

Logan Ritter
Department of Electrical Engineering and Computer Science, University of California, Berkeley
Email: lritter@berkeley.edu

Jarvis Yuan
Department of Civil and Environmental Engineering, University of California, Berkeley
Email: jarviskroos7@berkeley.edu

Word count: 4,856 words text + 1 table(s) × 250 words (each) = 5,106 words

Submission Date: August 1, 2020

ABSTRACT

Public transit data released by cities following the General Transit Feed Specification, combined with employment data, and open-access network analysis tools have allowed researchers to estimate the marginal effects of investments in public transportation on employment accessibility at a consistent and high spatial fidelity. One popular tool among the transport data analytics community to estimate accessibility is the OpenTripPlanner router engine. Despite the rising popularity of the tool for accessibility analyses, there is little work published in the transport academic literature documenting how to use it, along with how to wrangle the data needed to produce employment accessibility metrics. Using Bogota's public transport and employment, we tested OpenTripPlanner to estimate the marginal effect of the city's first aerial cable-car line, TransMiCable, on employment accessibility. We provide insights on how to wrangle and generate data that can be used with this router engine to estimate the marginal effects of public transit investments on employment accessibility. Our analysis suggests that by investing in TransMiCable, Bogotá dramatically changed the distribution of employment accessibility in the project's area. The localized marginal effect ranges from 2 to 63 percent, depending on factors such as pre-existing bus service quality. Our analysis also uncovers improvements in employment accessibility in low-income areas located at the south-wester and south-eastern corners of the city.

Keywords: Employment Accessibility, Public Transport, OpenTripPlanner, GTFS, Urban Data Analytics

INTRODUCTION

Improving employment accessibility, broadly defined by Hansen (*1*) "as the potential of opportunities for interaction," is a goal that many urban and transport planning scholars promote. During the last decade, the transport data analytics community has capitalized on standardized data on public transportation data schedules and trip planning tools like OpenTripPlanner to estimate employment accessibility indexes. Despite the rising popularity of these resources, there is little work on documenting how to use them to assess the impact of investments of public transportation on employment accessibility. Using OpenTripPlanner and data on Bogota's public transport and employment, we estimate the marginal effect of the city's first aerial cable-car line, TransMiCable, on employment accessibility. We also provide insights on how to wrangle data for conducting these types of analysis when data is incomplete, our experience using OpenTripPlanner, and some cautionary notes.

After more than three decades of research on equity and accessibility, analyses are often conducted to assess the level of inequality in employment accessibility, and not to evaluate the extent to which investing in transport infrastructure reduces gaps in employment accessibility. However, the open data revolution, along with increasing access to open-access transportation network analysis tools, and the standardization of transit data has opened new frontiers to understand how investments in public transport could change the geography of employment accessibility (*2*, *3*).

Using public transport data feeds in the GTFS format and travel data provided by the city of Bogota, along with OpenTripPlanner, we assessed the marginal effects of the city's first aerial cable-car, TransMiCable on employment accessibility. Despite the high expectations the project will have, there are no studies detailing its effects on employment accessibility. Our analysis of the marginal effects of TransMiCable on employment accessibility captures both localized and regional effects. We uncover marginal localized effects ranging from 2 to 63 percent in areas close to one of the aerial cable-car stations. Our analysis also reveals increases in employment accessibility in low-income areas located at the south-wester and south-eastern corners of the city, along with improvements in areas where higher-income residents, including the financial district and other employment hubs. We also provide insights on how to wrangle data for conducting these types of analysis when data is incomplete, our experience using OpenTripPlanner, and some cautionary notes.

BOGOTA'S FIRST AERIAL CABLE-CAR LINE

In part as a recognition of the mobility needs of geographically marginalized residents in Bogota, the city invested in building its first aerial cable-car line in Ciudad Bolivar - one of the poorest districts in the city. One-quarter of the population makes minimum wage, and half make less than twice the minimum wage. The peripheral location of Ciudad Bolivar, along with its challenging topography and inadequate public transport provision, constitutes one of the main barriers for residents to reach employment hubs and other destinations in Bogotá.

After more than ten years of planning and more than two years of construction, Bogota's first aerial cable-car line, known as TransMiCable, opened to the public in December of 2018. With the inauguration of this aerial cable-car, Bogota joined the growing number of Latin American cities investing in cable-propelled transit to improve the lives of thousands of inhabitants living in low-income peripheral settlements with challenging geographies. Other cities that have invested in urban gondolas include Medellin, La Paz, Cali, Caracas, and Rio de Janeiro. At least a dozen more are planning on deploying these infrastructures to improve low-income constituents’ access to public transportation and employment.

TransMiCable consists of a single 3.4-kilometer line, 163 cabins, and four stations: El Mirador-Paraiso, Manitas, Juan Pablo II, and Portal Tunal (Figure 1). In Portal Tunal, TransMiCable passengers can transfer to BRT services that reach multiple areas within Bogotá. The line connects with the city's Bus Rapid Transit, which reaches most employment hubs in the city. Because TransMiCable flights over a dense section of Ciudad Bolivar, it can operate at a constant speed of approximately 15 kilometers per hour. Its constant 10-seconds headway and 10-passenger maximum capacity per cabin can move up to 3,600 passengers per hour per direction.

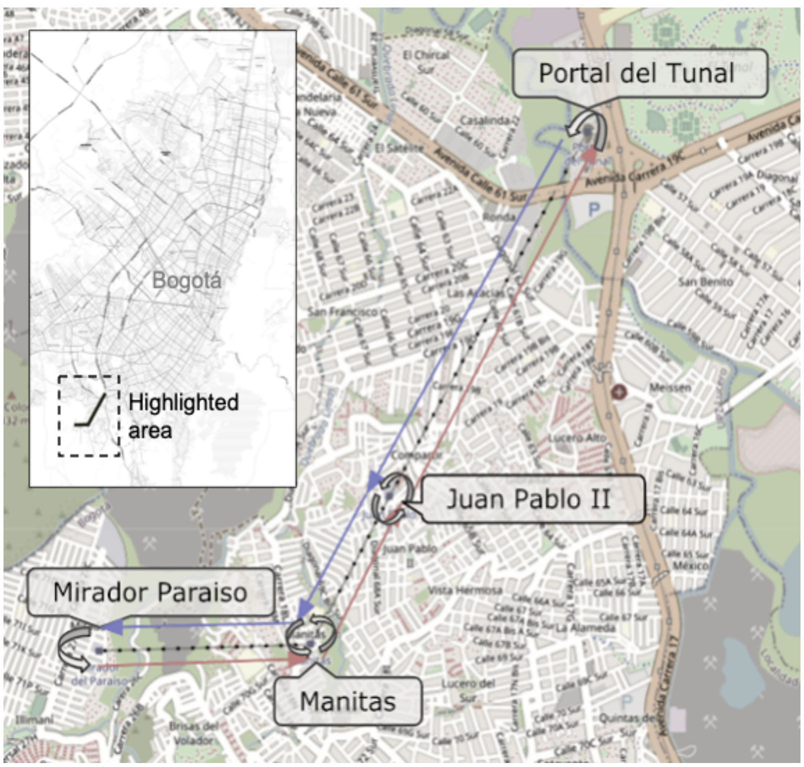

FIGURE 1 - Bogota’s TransMiCable location

DATA AND METHODS

Our analysis capitalizes on multiple data sources and tools that allow us to create employment accessibility indexes for small areas. On the transportation supply side, we downloaded the city’s public transport network published following the General Transit Feed Specification (GTFS) format from OpenMobiltyData and the walking network from OpenStreetMap (OSM). Employment location was imputed from the most recent travel survey available when we started working on the project. These data sets are the fundamental building blocks to estimate access to jobs using a combination of open-source tools such as OpenTripPlanner. Below we provide more information about these data sources, the methods we employed to process the data, and the tools used to estimate employment accessibility.

Obtaining Bogota's Public Transportation and the Walking Network

A critical element of our analysis is the public transit network. Modern open-access network analysis tools such as OpenTripPlanner take public transport data in the GTFS format, along with a pedestrian network, to estimate the best route from a provided origin and destination. The General Transit Feed Specification or GTFS, for short, is, according to its creators, "a data specification that allows public transit agencies to publish their transit data in a format that can be consumed by a wide variety of software applications."

The GTFS consists of a collection of at least 6 (with up to 13) text files linking to each other with primary keys (Figure 2). Altogether, these files represent a transit system's scheduled operations and provide sufficient functionalities for building trip planning web applications and conducting network analysis - such as estimating travel times from and to all parcels in a city. Transportation network analysis tools such as OpenTripPlanner only require some text files to generate origin-destination travel times.

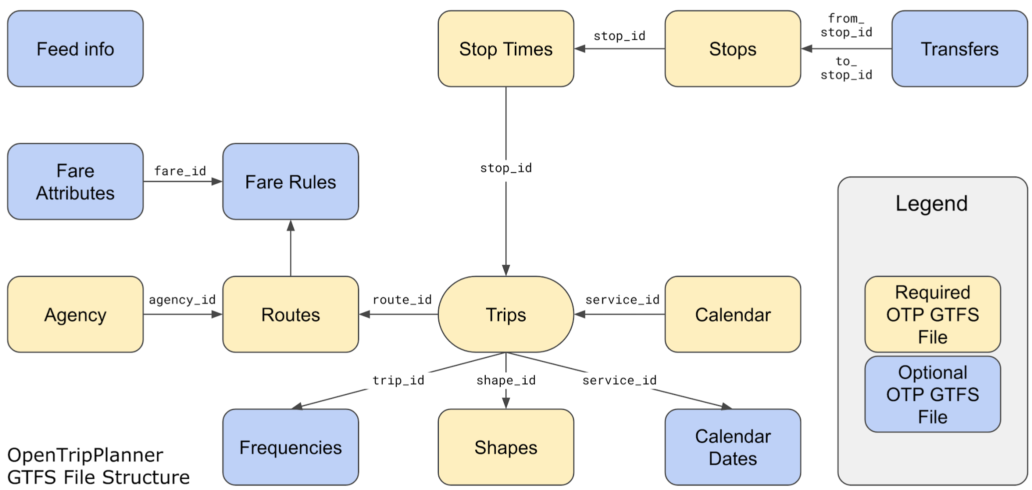

FIGURE 2 - General Transit Feed Specification structure and required files by OpenTripPlanner

Much of Bogota's transit network is covered by its Integrated Public Transport System (SITP in Spanish), including multiple bus rapid transit (BRT) corridors, feeder, and direct-route services. Bogota's SITP bus network is available to download from OpenMobilityData and follows the General Transit Feed Specification. The feed contains approximately 500 bus routes and more than 12,000 stops. Bogota's GTFS does not include TransMiCable.

Since we were interested in estimating the marginal effect of TransMiCable on employment accessibility, we generated the cable-car line's GTFS using information about its daily operations available from Bogota's BRT agency TransMilenio. Going uphill from the city's BRT terminal, Portal Tunal, are stations Juan Pablo II, Manitas, and Mirador-Paraiso. We acquired their exact coordinate locations from Google Maps. We treated the gondola as a 'loop route' and assigned each cabin to a different trip id with a loop stop sequence, operating with fixed headways upon arriving and departure. Following this approach, we ended up with a total of trips corresponding to the number of cable-car cabins operating on the same loop route.

Then we estimated a fixed headway based on operational features available from one of the city's transit agencies. According to the TransMilenio website, the system has 164 cabins, travel time between Portal Tunal and Mirador-Paraiso station is approximately 14 minutes, so the whole loop takes 1,680 seconds. With that information, we estimated that the headway between cabins was approximately 11 seconds (see Equation 1).

$$t + (s * h) = c * h \tag{1}$$

Where t is the time in seconds one cabin takes to complete a loop, s is the number of stations the gondola passes through to complete the loop c is the number of cabins h is the headway in seconds.

With a fixed headway, operation time, and the numbers cabins, we generated TransMiCable's GTFS using Python script in case we needed to replicate the process once validating the feed. We tested the GTFS feed using the validator script from Google's TransitFeed package. One last check was to map the entire transit network once we added TransMiCable (Figure 3). One downside of the package is the lack of capabilities for generating the 'shapes.txt' file. Although this file is not mandatory for the functionality of using the feed for most applications, it is required by OpenTripPlanner to visualize and describe the path of vehicles traveling along route alignments (Figure 3). Our solution to this problem was to generate the file using straight-line geometries between the stops and appended the additional *shape_id* column onto *trips.txt*, which is readable by OpenTripPlanner.

A pedestrian street network is integral for accessibility analyses. It serves as the knitting between layers of transit nodes and edges, just as we walk from our homes to transit stations in real life. OpenTripPlanner uses the walking network to plan the shortest walking path to reach transit stops. Acquiring such a pedestrian network in Python has become much easier with the implementation of OSMnx, developed by Boeing (*4*), which can create automated methods to transform OpenStreetMap (OSM) street networks into valid graph objects. We used OSMnx to parse directly and download the street network of Bogota to feed it into OpenTripPlanner in conjunction with the GTFS feeds of the TransMiCable and bus network.

FIGURE 3 - Bogota's public transit network visualization based on the GTFS feeds. Bus routes are in red; the TransMiCable line is in yellow. The color intensity of routes represents their planned frequency.

Wrangling employment data

Using travel data available through Bogota's open data portal, we generate a data set with the spatial distribution of employment in the city. Despite most employment accessibility analyses drawn from formal employment counts available from government databases, Bogota does not provide such data in their open data portal. Our solution was to use the most recent travel survey, conducted in 2019, a few months after TransMiCable opened to the public. In this data set, the city is subdivided into polygons known as transport analysis zones (TAZs), which the starting and ending points of each trip are assigned to. The dataset also provides a weighting factor for each journey and the corresponding trip purpose.

If analyses were to be conducted using large irregular TAZs, highly localized changes in travel times, like those expected from TransMiCable, would likely be missed in the accessibility analyses. We parsed all trips reported on the travel survey whose purpose was 'go to work,' aggregated the number of jobs by destination, and passed the information on employment from TAZs to smaller and consistent polygons. Drawing from a Python script shared by Mohan in his GitHub page, we subdivided the city into a grid composed of approximately 4,600 400-meter hexagons to reduce the bias induced by using a surface made of irregular zones.

A final step was to pass the employment data from TAZs to over smaller hexagons. This task was conducted using an aerial interpolation technique provided in the Tobler Python package developed by Cortez et al. (*5*). The Tobler package takes in two sets of polygons representing the same geographical area and creates a third union geometry. It returns two mappings: one from the source data to the union geometry and one from the union geometry to the destination data. Through matrix multiplication, we calculate the proportion of the area of each source polygon that falls into each destination polygon, which can then be used to distribute the jobs into the new polygons. Passing employment data from larger irregular TAZs to smaller hexagons provides the benefit of smaller geographical areas that provide more granular, accurate analysis, and using hexagons provides uniformity.

Setting Open Trip Planner to Estimate Travel Times

With information on the transit network, employment distribution, and the walking network, we ran OpenTripPlanner to estimate inter-hexagonal travel times by public transport and, ultimately, employment accessibility for each hexagon in the grid. The main benefit of using OpenTripPlanner over other tools is that, besides being open access, it allows automated queries to quickly estimate travel times between all polygons in the city by executing a few lines of code while customizing our query. For example, it is easy to specify minimum transfer times, wheelchair accessibility requirements, and preferred routes.

To estimate the marginal effect of TransMiCable on employment accessibility, we executed our script first without the gondola GTFS, and then a second time with the Gondola GTFS. The script we employed to facilitate the calculation of a travel time matrix built on work done by Pereira and Grégoire (*6*). We modified the script to run using multiple cores in parallel over network nodes, and to save intermediate values to avoid running out of memory. Our script ultimately estimated travel times by public transport in each direction between all of the hexagons in which we subdivided the city.

For our analysis, we assume most residents in the study area start their commutes by 6 am. We also checked the *calendar_dates* file to confirm that there is no variability in public transport operations in the city between weekdays and no significant changes between different times in the morning peak. We expect to repeat this analysis for other times within the morning peak to account for schedule variability, as suggested by Conway et al. (*7*).

Since OpenTripPlanner was designed primarily to build routing applications, it assumes people have enough information on public transport networks and chose the best time to start their trip to minimize waiting times. We modified this default feature better to represent the reality of residents of Ciudad Bolivar. Anecdotal evidence suggests that busses in this area are rarely on schedule, and there is no in-real-time information available. However, aerial cable-car lines are unique because they operate with very low headways, which translate into short waiting times and should be captured in accessibility calculations. In light of that reality, we force a departure time to 6 am by setting the parameter *req.setClampInitialWait* equal to cero

Another critical factor to consider when estimating accessibility is boarding times. One factor affecting boarding times during peak hours is crowding. From our observations in the area of study, we learned that, during peak times, busses were often full, which may require some users at the end of the queue to wait for the next bus to arrive. One way to account for crowing with OpenTripPlanner is to set an average boarding time per mode. For our analyses, we use a conservative estimate of 5 minutes of additional boarding time for busses. However, this value may vary depending on unexpected conditions such as bus delays and bunching, not captured in static GTFS data.

Another essential factor to consider is that OpenTripPlanner selects the route that minimizes the generalized cost of each trip, allowing users to customize the weights of the generalized cost function. For our test, we configured the OpenTripPlanner router to weigh all travel times (in-vehicle, wait, walking time) equally, so the router captures the travel time advantage TransMiCable delivers. Once we set the parameters discussed, we ran the script that executes the OpenTripPlanner router to estimate travel times from and to all hexagons in the grid using the with and without TransMiCable public transportation network, and the walking network.

From Travel times to accessibility indexes

Our final step was to estimate employment accessibility for each hexagon in the grid. One of the most widely used accessibility metrics is the cumulative opportunities measure, which calculates how many opportunities can be reached within a predetermined travel time or threshold (see Equation 2 and 3). We decided to estimate accessibility using a cumulative opportunity index because it is easier to interpret than other measures such as utility-based or gravity-based measures (*8*).

$$A_i \; = \; \sum_i^n O_i \; f\left(C_{ij}\right) \qquad (2)$$

$$f\left(C_{ij}\right) = \; 1 \; if \; C_{ij} \; \leq t; \; 0 \; otherwise \qquad (3)$$

Where A_i is accessibility at point i to all jobs at zone j, O_j the number of jobs in zone j, $f(C_{ij})$ the weighing functions with C_{ij} being the travel time from i to j, and t the travel time threshold.

With that in mind, we started by first setting a fixed travel time threshold and created a new data frame that includes only those origin-destination pairs in which travel time is equal or below that threshold. Travel times were estimated for both the with and without the TransMiCable scenarios, assuming no changes in the spatial distribution of jobs. The next step was to group the number of jobs by trip origin. Our final data frame includes only the origin id, number of jobs, and the geographical data for each origin hexagon and for the with and without TransMiCable data sets, which we merged to finally calculate the change in the number of jobs for each hexagon.

Limitations

Our estimations may be improved if more and better data becomes available. For example, our model included only the formal public transit options in Bogota available in the GTFS data we had access to. However, we recognize that there are hundreds of fixed-route but semi-formal (authorized by the city but with no fixed stops) and informal services not included in the GTFS we obtained. Adding these services may help paint a better picture of employment accessibility.

We are currently working on including the semi-formal and informal transit network following a GTFS flexible format that allows for non-fixed stops, as proposed by Williams et al. (2015 - digital matatu), to improve our estimations further.

Another critical point to make is that while OpenTripPlanner produced expected outcomes, we identified in analysis three outliers; two suggesting travel times decreased despite our network only improved travel times, and the spatial distribution of jobs remains the same. When we reduced the hexagon size to 250 meters, a considerable number of negative changes in travel times emerged. We report our results using the 400-meter hexagon grid, excluding outlier values. This apparent sensitivity to spatial granularity requires further investigation.

RESULTS AND DISCUSSION

Our results from imputing employment using travel data and areal interpolation are consistent with other studies on Bogota that use different methods or datasets (*9*, *10*). As we expected, employment is heavily concentrated in the central business district in the East of the city, while identifying some other employment clusters, such as the Historical Center and the Corabastos Market (Figure 4). Within Ciudad Bolívar, our approach captures some heterogeneity within Ciudad Bolivar as well, with a higher concentration of jobs in hexagons located to the north of the district.

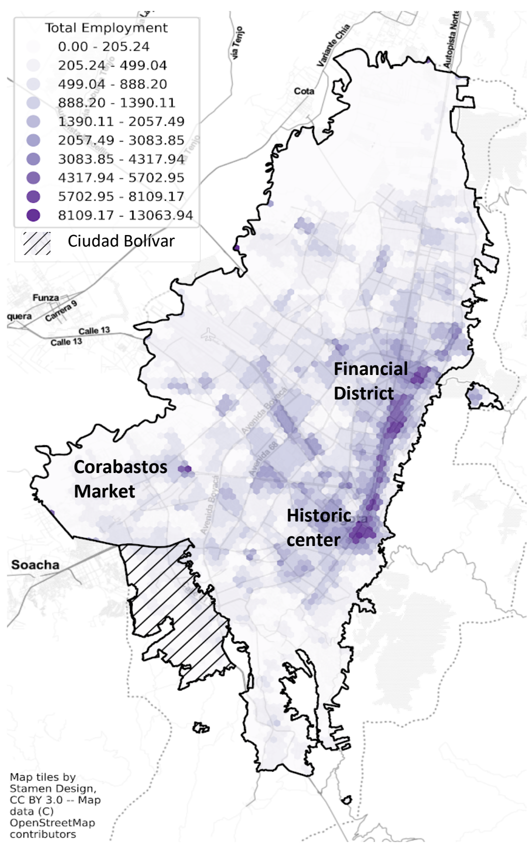

FIGURE 4 - Spatial distribution of employment in Bogota. Own elaboration with data from the city's 2019 travel survey

Using Bogota's public transport, walking network, and employment data, we estimated travel time savings enabled by TransMiCable. Our analysis assumes that residents walk at an average speed of 3 miles per hour. Under those assumptions, our study suggests that, for example, a trip from the Manitas station to Portal Tunal takes approximately 21 minutes with no aerial cable-car and about 13 minutes with TransMiCable. Travel time savings from the Mirador-Paraiso to Portal Tunal are estimated at 8 minutes (Table 1).

TABLE 1 - Travel times estimates between TransMiCable stations. Note: Origins are approximated to the centroid of the hexagon containing each station

Station	Travel Time to Portal Tunal (min)		
	With No TransMiCable	With TransMiCable	Absolute Change
Juan Pablo II	20.9	8.1	-12.8
Manitas	20.9	12.5	-8.3
Mirador-Paraiso	26.2	17.9	-8.3

For this paper's purposes, we are using a travel time threshold of 60 minutes, since it best displays the variation in employment accessibility across the city and within Ciudad Bolivar before adding TransMiCable (Figure 5). A 60-minute threshold guarantees that residents of the more peripheral areas of Ciudad Bolivar can access the multiple employment hubs, including the financial district. We believe it is a reasonable travel time, considering the urban extend of Bogotá. Our city-wide employment accessibility map largely mirrors the spatial distribution of employment, with a pattern of radiating rings around the financial district and capturing the public transportation network effects, with higher employment accessibility figures near significant bus corridors. Our baseline analysis also captures the disparities between residents living in the outskirts of Ciudad Bolivar and those closer to Portal Tunal.

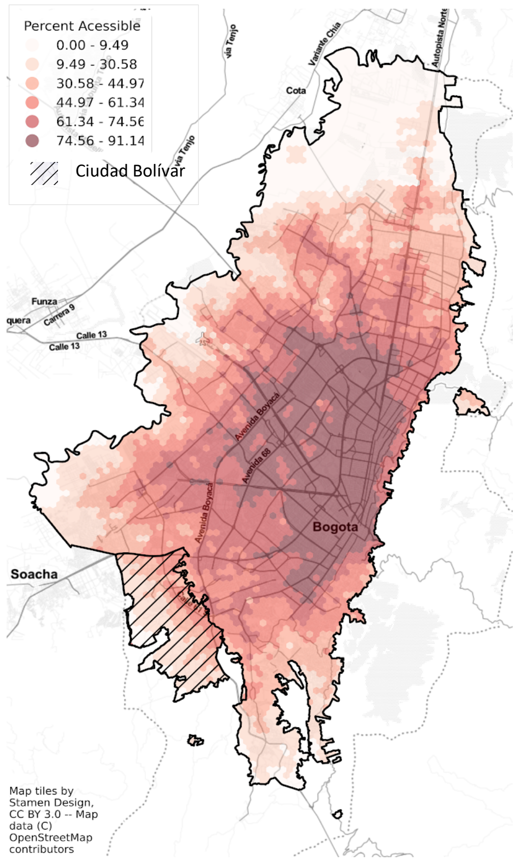

FIGURE 5 - Percent of jobs accessible by public transit within 60 minutes and without TransMiCable

Our analysis of the marginal effects of TransMiCable on employment accessibility also provides expected outcomes when examining city-wide changes. Figure 6 depicts the darker red hexagons nearby the project, representing high increases in employment accessibility. Our analysis also captures increases in employment accessibility in low-income areas. For example, our analysis shows benefits for communities located south-western and south-eastern corners of the city, along with improvements in areas where higher-income residents live, such as the district of Chapinero, which encompasses the financial district and other employment hubs.

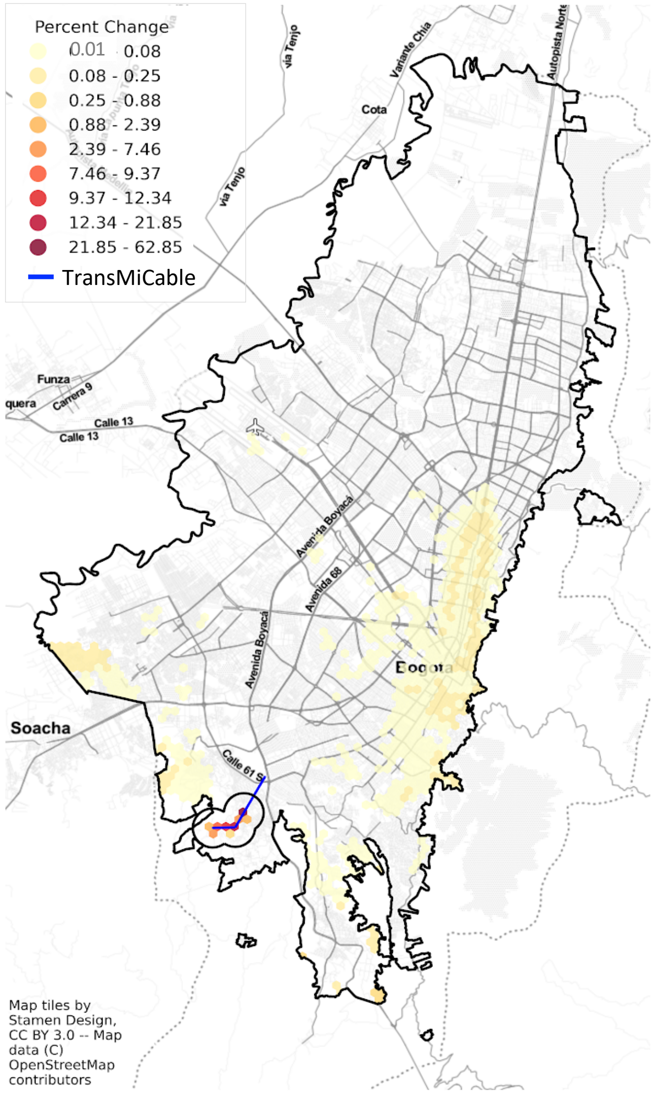

FIGURE 6 - Percentage change in employment accessibility after adding the TransMiCable and using a 60-minute threshold

Looking more closely at TransMiCable's area of influence, our analysis uncovered that the spatial distribution of changes in employment accessibility neither uniformly decreases as one gets closer to the urban fringe (nearby Mirador-Paraiso station), nor exhibits a gradual decrease in access as the distance to stations increases (Figure 7). The most significant improvement was observed in the hexagon that contains the Juan Pablo II station, which added approximately 435,000 jobs now accessible within a 60-minute trip by transit, representing a 62.9 percent increase in employment accessibility. Second in the list is the hexagon that contains the Manitas station, which experienced a rise in employment accessibility of approximately 21.9 percent. The hexagon where the Mirador-Paraiso station is located experienced a 2.4 percent increase, where now almost 9,600 additional jobs can be reached within a 60-minute commute.

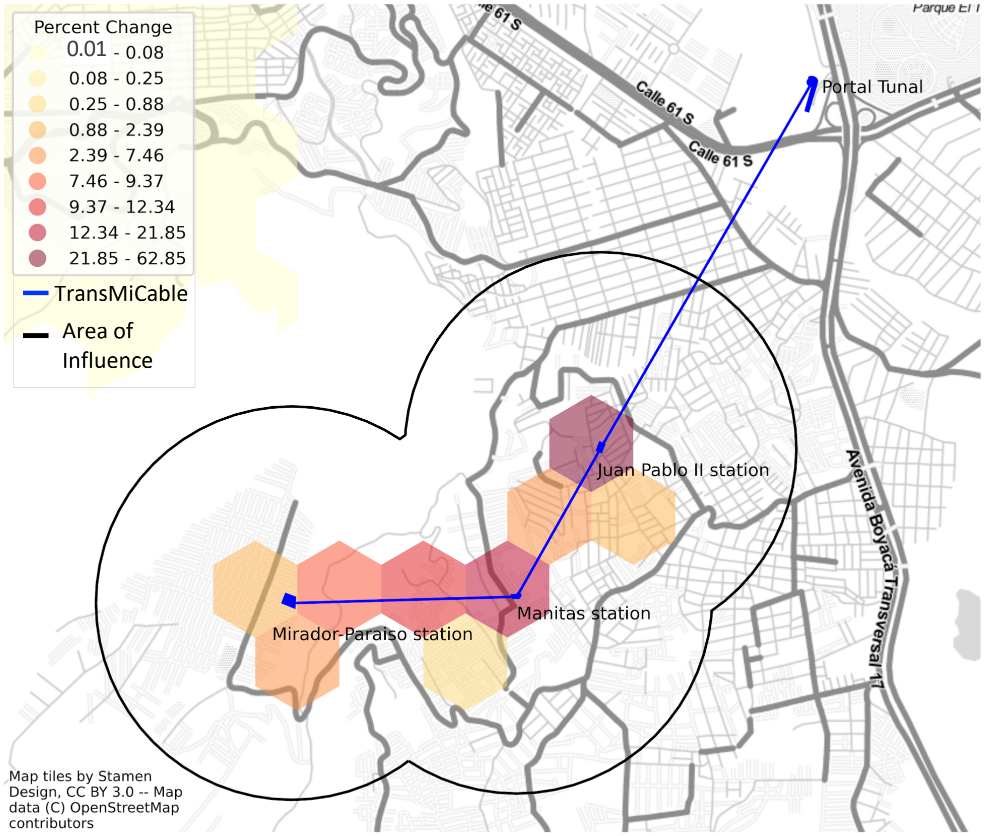

FIGURE 7 - Change in employment accessibility within TransMiCable's area of influence (800-meter buffer around stations).

The spatial pattern of change in employment accessibility is explained by the presence of several bus routes that happen to serve some areas better than others. For example, the significant increases around Juan Pablo II station are partly explained by the lower level of bus services in this area, allowing more room for TransMiCable for improvement. However, this not seems to be the case for hexagons nearby the Mirador-Paraiso, which are served by faster bus routes.

Another factor to consider is that OpenTripPlanner assumes the origin of each trip is located at the centroid of each polygon in the grid. In addition to the winding road infrastructure, it may also help explain the spatial distribution of change in employment accessibility in the area of influence of TransMiCable. For example, the centroid of the hexagons nearby Mirador-Paraiso station are further from the station compared to the centroids of hexagons nearby Manitas and Juan Pablo II stations.

CONCLUSION

The emerging field that uses data science tools, particularly the open-source router OpenTripPlanner and GTFS and OpenStreetMap data, has advanced in demonstrating the capabilities of these resources for transportation policy and planning. Despite the rising popularity of OpenTripPlanner for accessibility analyses, there is little work published in the academic literature documenting how to use these resources, along with how to wrangle the data needed to produce employment accessibility metrics at a high and consistent spatial fidelity. Using public transport data feeds in the GTFS format and travel data provided by the city of Bogota, along with OpenTripPlanner, we assessed the marginal effects of the city's first aerial cable-car, TransMiCable on employment accessibility. Despite the high expectations from the project, there are no publications on the impact it has on employment accessibility.

Our analysis capitalizes on multiple data sources and tools that allow us to create employment accessibility indexes for a small and consistent grid of 400-meter hexagons in which we subdivided the city. On the transportation supply side, we downloaded the city's public transport network published following the General Transit Feed Specification (GTFS) from OpenMobiltyData, and the walking network from OpenStreetMap (OSM). We imputed employment location from the 2019 travel survey available via the city's open data portal. We documented how we wrangled the available data, including our approach to impute employment data from travel surveys to hexagons using aerial interpolation. We also document how we generated TransMiCable's data following the General Transit Feed Specification and using information about the project available on the city's transit agency website.

Our analysis suggests that by investing in TransMiCable, Bogotá improved the distribution of employment accessibility in the project's area of influence with a marginal effect ranging from 2 to 63 percent. The spatial pattern of change in employment accessibility is, in part, explained by the presence of several bus routes that happen to serve some areas better than others. Besides, these results could be explained by the poor connectivity the walking network has in some areas. We also uncover increases in employment accessibility in low-income areas located at the south-wester and south-eastern corners of the city, respectively, along with improvements in areas where higher-income residents, including the financial district and other employment hubs.

Despite the advantages of the approach we employed, we noted some limitations. One limitation consists of the size of the areas used. It is evident that the smaller the polygon, the better the analysis to capture localized effects. One advantage of the method we used was that we passed employment data from larger transportation analysis zones to smaller 400-meter hexagons to reduce the bias potentially induced by using a surface made of irregular polygons. However, we noted that the distance from the centroids of our hexagonal grid to their closest TransMiCable station significantly varies, something that could also have influenced our results. Another important cautionary note relates to an apparent sensitivity of OpenTripPlanner to the spatial granularity of the analysis. When we reduced the hexagon size to 250 meters, OpenTripPlanner suggested travel times decreased in some areas of the city. This apparent sensitivity to spatial granularity requires further investigation.

REFERENCES

1. Hansen, W. G. How Accessibility Shapes Land Use. *Journal of the American Institute of Planners*, Vol. 25, No. 2, 1959, pp. 73–76. https://doi.org/10.1080/01944365908978307.
2. Pereira, R. H. M. Transport Legacy of Mega-Events and the Redistribution of Accessibility to Urban Destinations. *Cities*, Vol. 81, 2018, pp. 45–60. https://doi.org/10.1016/j.cities.2018.03.013.
3. Pereira, R. H. M., D. Banister, T. Schwanen, and N. Wessel. Distributional Effects of Transport Policies on Inequalities in Access to Opportunities in Rio de Janeiro. *Journal of Transport and Land Use*, Vol. 12, No. 1, 2019. https://doi.org/10.5198/jtlu.2019.1523.
4. Boeing, G. *Osmnx V0.4.1*. Zenodo, 2017.
5. Cortes, R. X., E. Knaap, S. Rey, and J. Gaboardi. V0.3.0. *Pysal/Tobler: Version 0.3.0*. Zenodo, 2020.
6. Pereira, R. H. M., and L. Grégoire. V1.1. *Rafapereirabr/Otp-Travel-Time-Matrix: Tutorial with Reproducible Example to Estimate a Travel Time Matrix Using OpenTripPlanner and Python*. Zenodo, 2019.
7. Conway, M. W., A. Byrd, and M. Van Eggermond. Accounting for Uncertainty and Variation in Accessibility Metrics for Public Transport Sketch Planning. *Journal of Transport and Land Use*, Vol. 11, No. 1, 2018. https://doi.org/10.5198/jtlu.2018.1074.
8. Handy, S. L., and D. A. Niemeier. Measuring Accessibility: An Exploration of Issues and Alternatives. *Environment and Planning A: Economy and Space*, Vol. 29, No. 7, 1997, pp. 1175–1194. https://doi.org/10.1068/a291175.
9. Guzman, L. A., and D. Oviedo. Accessibility, Affordability and Equity: Assessing 'pro-Poor' Public Transport Subsidies in Bogotá. *Transport Policy*, Vol. 68, 2018, pp. 37–51. https://doi.org/10.1016/j.tranpol.2018.04.012.
10. Guzman, L., D. Oviedo, and R. Cardona. Accessibility Changes: Analysis of the Integrated Public Transport System of Bogotá. *Sustainability*, Vol. 10, No. 11, 2018, p. 3958. https://doi.org/10.3390/su10113958.