How much is accessibility worth? Utility-based accessibility to evaluate transport policies in Latin America

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Abstract

There is now a long tradition of accessibility research in Latin American cities, with an increasingly rich set of frameworks and methods from a distributional perspective. Despite such a positive outlook, most accessibility metrics deployed in research and practice do not consider the dimension of (dis)utility, which resonates more clearly with mainstream transport decision-making and planning. This paper seeks to contribute to debates about the use of utility-based measures as inputs for accessibility assessment of transport infrastructure investments in the Global South using discrete choice modeling and its potential as a bridging language between socially nuanced and economics-driven transport planning practices. This paper uses mixed revealed preferences and stated preferences data collected in Bogotá, Colombia. Then, it uses a logsum accessibility metric to estimate the differentiated impact of a set of infrastructure interventions on the accessibility of residents with different income levels and other socioeconomic conditions for accessing opportunities in the city. Particularly, the logsum accessibility metric analyses future innovations and structural additions to Bogotá public transport networks reflecting their effect on the accessibility and consumer surplus in the next 20 years. The proposed approach captures the benefits derived from the opportunity locations and transport infrastructure improvements, which has relevance for debates about transport policy and practice in this and similar urban contexts in the Global South. These accessibility gains could be assigned a monetary value to include in project cost-benefit assessments.

1. Introduction

Accessibility is a popular concept in current urban transport and mobility research and plays a relevant role in policymaking. In its simplest form, accessibility refers to the ‘ease’ with which people can reach the different opportunities (i.e., economic, education, leisure, health) offered in a territory. However, the slow progress in adopting an accessibility-oriented approach in policy and decision-making, particularly in Latin American urban contexts, has widened inequalities linked with mobility and caused declines in the quality of life of citizens across the region (Vecchio et al. 2020). This is partly due to a persistent utilitarian approach to transport planning and decision-making that tends to prioritize the ‘average’ user as a reflection of the population's travel needs (Oviedo and Nieto-Combariza 2021) as well as a lack of consensus on accessibility measures (Handy 2020). Accessibility is often defined and operationalized in diverse ways with several meanings. Effective accessibility-oriented policies can only become a reality if the concept is easy to interpret for planners and decision-makers and can be estimated with available data and tools to analyze land use and transport interaction (Geurs and van Wee 2004).

Several studies have contributed to quantifying different forms of accessibility measures. In practice, three accessibility measures are commonly found in the literature which are well documented and explained: contour, gravity-based, and utility-based measures (Hasnine et al. 2019). The first two measurements are popular in geography and urban planning studies due to their easiness of calculation, interpretation, and communicability. However, both measures assume that all opportunities are equally desirable, regardless of the transport mode used and the socioeconomic characteristics of the commuter. These are important limitations considering the increasingly complex environments for urban mobility in which these choices are made (i.e., people can choose between several modes, have multiple options for their trips, and value their time differently).

Utility-based measures can overcome some of these limitations by incorporating additional elements into the analysis of accessibility. These measures can be estimated through discrete choice models, which are based on Random Utility Maximization (RUM) behavioral theory (McFadden 2001), allowing to estimate consumer surplus using the logsum method (Ortúzar and Willumsen 2011). This approach allows to evaluate the maximum utility perceived in a travel choice situation considering the availability of transport alternatives, the combination modes in multimodal
trips, and the individual’s preferences, indicating the desirability of the full choice set (Ben-Akiva and Lerman 1985). In
addition, utility-based accessibility allows the assessment of the subjective nature of individual preferences in the
analysis of accessibility.

This paper aims to estimate a comprehensive utility-based accessibility indicator for Bogotá, Colombia, using a
multinomial logit model, estimated by combining revealed preferences (RP) and stated preferences (SP) data. The
utility-based accessibility approach allows researchers to quantify the welfare consequences of accessibility changes
in the study area due to transport investments in two hypothetical scenarios, which consider a set of transport
projects in line with the plans for the Bogotá region. It also allows evaluating distributional effects for different
population segments, accounting for the complexities of changes in the spatial distributions of origins and
destinations and the benefits for different commuters and diverse groups of citizens.

This research seeks to contribute to the literature by testing and implementing a more sophisticated accessibility
indicator for Bogotá compared to those used in earlier accessibility research in the local and regional contexts, using
a metric that focuses on understanding people’s benefits to reach their diverse destinations and allows expressing
accessibility in economic terms, considering a transport demand function. Such a measure has the potential to make
positive contributions to urban and regional planning and economic project appraisals by using a utility-based
accessibility measure to estimate welfare. As a consequence of this approach, the benefits of travel time and cost
reductions are represented by improved accessibility to opportunities, which is a transformed measure of time and
cost reduction on transport links.

Shifting our understanding of accessibility from travel costs to personal benefits, including users’ preferences,
presents an opportunity to plan and implement projects and policies that advance access to urban resources with a
focus on accessibility as an enabler of welfare. The analysis seeks to spark reflections about the subjective
dimension of accessibility and the differences between (dis)advantage and utility. Our case study interrogates
Bogotá’s private and public transport network, highlighting the strengths and limitations of the utility-based
accessibility measure.

2. The Utility-based Approach To Accessibility And Consumer Surplus

Accessibility has been extensively studied in international literature for over a century. However, a limited number of
studies have explored the links between accessibility and welfare using utility-based measures, especially in
developing economies. The utility-based accessibility is founded on microeconomic theory and overcomes some
limitations of traditional accessibility measures because it captures the heterogeneity of users’ preferences,
perceptions, and sociodemographic characteristics (Geurs and van Wee 2004). As a result, it is possible to assert the
degree to which accessibility is influenced by individual perceptions (Pot et al. 2021). Such type of metrics for
accessibility has not been used frequently in the Latin American context with even fewer applications considering
benefits from transport investments stemming from changes in consumer surplus induced by specific urban
interventions.

The definition of utility-based accessibility is based on the desirability of a complete choice set (Ben-Akiva and
Lerman 1985), namely, of transport alternatives. In other words, accessibility is measured at the individual level
considering commuters’ characteristics and modal attributes (Banister and Berechman 2001). Therefore, in a
standard multinomial logit (MNL) model, it is possible to use the logsum component as an accessibility measure,
which corresponds to the natural logarithm of the denominator of the MNL probability. This definition is consistent
with the key concept of the total consumer surplus (Niemeier 1997) (net benefit) in using the urban opportunities reachable within a given travel impedance.

From a behavioral perspective, the logsum can be understood as the expected worth of a set of alternatives or a measurement of the maximum utility expected from the choice set (Chorus 2012). If accessibility is interpreted as an outcome of a set of transport choices, the logsum term can be understood as a utility-based measure of accessibility (Geurs and van Wee 2004) depending on the demand functions estimated in the mode choice models. As the demand functions depend on the perceptions and preferences of the choice-maker, it has a subjective valuation component that drives the expected utility. Then, as the logsum represents the maximum expected utility, the higher the logsum, the higher the accessibility perceived by the traveler. Since travel is considered as a derived demand, the logsum represents a measure of the disutility experienced by an individual facing a trip, according to the available transport alternatives.

Few empirical studies capture the preference heterogeneity in accessibility regarding sociodemographic characteristics. For instance, Ziemke et al. (2018) compared two accessibility computation approaches: household-based and utility-based accessibilities in Nelson Mandela Bay, South Africa. They found that the latter needs much lower input data requirements and have advantages in terms of interpretability and policy sensitivity. Lu et al. (2014) present a utility-based measurement of accessibility to estimate the effects of different forms of information and communication technologies (ICT) on accessibility, trying to disentangle the effects of different ICT forms on accessibility. Nassir et al. (2016) capture public transport passengers’ behavior and their subjective perceptions of travel costs to measure the accessibility of the public transport network in the Brisbane metropolitan region of Australia. In Denizli, Turkey, and also in a public transport system, Gulhan et al. (2013) evaluate a utility-based accessibility indicator as a new parameter to support the decision-making process for investments and regulations, founding a more effective system in terms of accessibility. Hasnine et al. (2019) developed a discrete choice model-based measure of accessibility integrated into a GIS-based tool to explain the threshold of walking time in the public transport system in Toronto.

Despite these applications, no attempt has yet been made to generalize these insights into an accessibility-oriented approach to evaluate medium- and long-term urban plans. In Latin America, accessibility metrics have been applied to diagnose the current configuration of transport and land-use landscapes (Bocarejo and Oviedo 2012; Guzman et al. 2017b; Hernandez 2018; Herszenhut et al. 2022). To fill this gap, it is necessary to develop a localized framework for the analysis of accessibility, that enables evaluating a utility based-based accessibility indicator by different individual characteristics. Building on the literature, we propose that such differentiations include gender, income level, and occupation, taking a further step in the debate about the policy implication of accessibility in Latin America.

In addition to the state of the art of utility-based approach to accessibility, it is important to put consumer surplus into context. In welfare economics, the consumer surplus is measured in monetary terms, by the benefits received in a choice situation (i.e., the decision-maker chooses the alternative that provides the greatest utility) (de Jong et al. 2007). It is worth highlighting that the willingness to pay might not be equal to what people actually pay. Hence, the consumer surplus is linked to the willingness to pay for a good or service. It reflects the value individuals give to the good or service associated with the level of welfare they obtain by accessing it.

Examining accessibility in terms of welfare gains has an additional practical value since economic evaluation is the standard method to evaluate policy options and alternatives for public investment, which the accessibility literature has identified as a necessary area where gaps between theory and practice need to be narrowed. This leads to an explicit need to express accessibility effects in monetary terms (van Wee 2016). Utility-based measures capture the
valuation of accessibility by individuals, providing a valuable basis for cost-benefit analysis or multi-criteria analysis evaluations of transport investments (Geurs and van Wee 2004).

Beyond the traditional accessibility indicators, the inclusion of preference heterogeneity is a step further toward improving our understanding of utility-based accessibility measures. Discussion of accessibility in the academic literature is usually very technical, leaving aside the operational and planning implications of using such measures. It is therefore desirable to gain experience and weigh the pros and cons of using a utility-based accessibility approach to inform policy-makers in a developing country context. This accessibility-oriented approach could play a fundamental role in planning Latin American cities.

3. Accessibility In Bogotá

Bogotá, the capital of Colombia, is a very dense city, compared to urban areas with a similar population in both the Global North and South. In 2018, 7.42 million people lived in 380 km². About 16 million trips are made every day (pre-pandemic) in Bogotá. Most trips are made using active transport modes (approximately 42% of the daily trips), and public transport (nearly 26% of the trips). However, the mobility and accessibility gaps in the city are evident between the poor and the rich, who usually lives on the periphery and the eastern edge, respectively (Guzman et al. 2017b; Guzman and Bocarejo 2017). Due to the historical urbanization process of the city, the urban periphery does not have significant employment offers, education and health facilities, and other urban amenities (Guzman et al. 2017a). This urban structure affects more negatively the poorest residents of the city, who find themselves forced to travel for long periods and spend a large share of their income on the commute (Guzman and Oviedo 2018). The daily flow of commuters is pendular (periphery-center-periphery) with the eastern edge having the largest trip attraction for mandatory trips as it concentrates most employment, as shown in Fig. 2. The map also shows the location of the Central Business District (CBD), which corresponds to the zone of the highest concentration of employment (Peña et al. 2022).

These travel patterns imply an unequal distribution of accessibility levels, particularly for public transport users (86%), who mainly belong to the lower socioeconomic categories of the city (socioeconomic strata, SES, 1 to 3) and live on the periphery. SES is a residential land classification between 1 and 6, where 1 corresponds to the poorest zones and 6 to the wealthiest, and it is usually used as a proxy for the average household income level (Cantillo-García et al. 2019). These gaps have existed for many years in the city and, in some cases, they have worsened because lower-income populations cannot afford housing inside Bogotá and must therefore move to neighboring municipalities. For spatial analysis purposes and a clearer presentation of results, Bogotá is divided into 112 urban “zonal planning units” (UPZ), which are territorial units used to plan urban development and follow recognizable boundaries such as roads and natural barriers.

Accessibility in Bogotá has been previously studied by a growing number of urban and transport researchers over the years (Arellana et al. 2021; Bocarejo and Oviedo 2012; Guzman et al. 2018; Guzman et al. 2017b; Guzman and Oviedo 2018) highlighting the inequalities described above through different mechanisms. Most of these studies used potential accessibility and contour measures, which are better suited as diagnosis instruments, and are difficult to compare in certain contexts. Also, these measures do not necessarily provide a direct way to estimate changes in accessibility for changing conditions of land use and transport systems.

In this context, the national and local governments decided to launch an ambitious transport infrastructure plan for the year 2035, which consists of million-dollar investments in the construction and expansion of regional roads, improvement of access roads to Bogotá, and the construction of more cable cars and Bus Rapid Transit (BRT).
corridors, the first two metro lines and regional trains. However, this plan is still largely focused on enabling mobility rather than access. Given the scale and purpose of the proposed plan, this case presents an appropriate testing ground for the use of utility-based accessibility measures.

4. Methods

To estimate the accessibility measure, we use the mode choice utility functions estimated in Guzman et al. (2021). The MNL model considers the utility of using a particular transport mode alternative, given trip attributes and choice-maker characteristics. Then, the discrete choice model is linked to the consumer surplus concept (Niemeier 1997). It allows estimating the expected net benefits of transport users by monetizing consumer surplus using the cost parameter and subjective values of time from the choice model. Travel costs and travel times for each scenario are estimated using a four-stage classic transport.

From the perspective of welfare transport evaluation, investments in infrastructure and public transport services reduce generalized travel costs. In addition, there may be benefits for both existing and new users attracted by this cost reduction. Consumer surplus is easy to estimate when the demand function is assumed to be linear. The demand function in Fig. 2 intersects the marginal cost functions ($S^c$). The current supply function ($S_0$) is improved by implementing policies such as expanding the network's capacity or building new infrastructure. In this case, the supply curve moves downward to $S_1$, and the demand curve intersects in a new equilibrium price $P_1$, lower than $P_0$, resulting in a demand increase from $Q_0$ to $Q_1$. The benefits received by existing and new users together, between $S_0$ and $S_1$, are equal to the shaded polygon in Fig. 2, whose value is usually calculated using the Rule of Half (Tressider et al. 1968). This net benefit or welfare is called the consumer surplus.

However, travel demand functions are not usually linear. One of the most recognized approaches to evaluating travel demand is discrete choice modeling techniques (Ortúzar and Willumsen 2011). Discrete choice models assess the probability of selecting one alternative among a set of finite available options, considering choice-maker characteristics and attributes regarding the alternatives and the context. These methods also provide a robust framework to estimate substitution patterns such as willingness to pay and welfare change measures, allowing for the assessment of distributional effects by capturing preference heterogeneity considering different population segments. To observe the distributional effects, we disaggregated the results by gender, occupation, and income level.

4.1 Multinomial logit model specification

Grounded on the RUM economic theory, discrete choice modeling methods assume that the choice-maker is a rational agent that selects the alternative that maximizes his/her utility (McFadden 2001). The concept of utility can be associated with the satisfaction or benefits that the individual obtains by accessing the good or service selected. Then, the consumer surplus (CS) in a choice situation is the maximum utility perceived by the choice-maker, as seen in Eq. 1, where $\alpha_i$ is the marginal utility of income and $U_{ij}$ refers to the utility that individual $i$ obtains from a given alternative $j$. Note that $U_{ij}$ comprises a systematic utility ($V_{ij}$), observed by the modeler, and a random error component ($\epsilon_{ij}$) associated with the unknown and immeasurable component. The systematic utility is usually represented as a linear combination of observed attributes and a set of parameters to estimate, but it can assume diverse structures. Therefore, the expected consumer surplus might be calculated using Eq. 2 (Train 2009).

$$CS_i = \frac{1}{\alpha_i} \max_j (U_{ij}) \quad (1)$$

$$E(CS_i) = \frac{1}{\alpha_i} E \left[ \max_j (V_{ij} + \epsilon_{ij}) \right] \quad (2)$$
Under multinomial logit assumptions, $\varepsilon_{ij}$ is assumed independent and identically (IID) Gumbel distributed, utility is linear in income, and the probability of choosing alternative $j$ from a set of $N$ available alternatives is given by Eq. 3. It can be demonstrated that the expected value of the maximum utility perceived by the choice-maker can be expressed as in Eq. 4, a formulation known as the logsum, where $C$ is an unknown constant related to the fact that the absolute utility cannot be measured (Williams 1977). Assuming that $C$ is constant across scenarios, Eq. 4 might be used to evaluate changes in consumer surplus by estimating the difference as seen in Eq. 5. Note that this formulation allows estimating the net consumer surplus change between scenarios, represented as the shaded polygon in Fig. 2.

$$P_{ijk} = \frac{e^{V_{ij}}}{\sum_{j \in N} e^{V_{ij}}}$$  \hspace{1cm} (3)

$$E(CS_i) = \frac{1}{\alpha_i} \ln \left( \sum_j e^{V_{ij}} \right) + C$$  \hspace{1cm} (4)

$$\Delta E(CS_i) = \frac{1}{\alpha_i} \left[ \ln \left( \sum_j e^{V_{ij}^{after}} \right) - \ln \left( \sum_j e^{V_{ij}^{before}} \right) \right]$$  \hspace{1cm} (5)

The consumer surplus estimated through logsum differences in monetary terms refers to the amount needed to compensate individuals for enduring the policy change under evaluation (Zhao et al. 2012). Regarding the marginal utility of income ($\alpha_i$), it might be estimated as the negative of the parameter of a cost variable included in the systematic utility of the discrete choice model. By definition, the parameter associated with the cost attribute is the marginal utility of cost, which is the inverse of the marginal utility of income, as a cost reduction is equivalent to an equal increase in income (Train 2009).

Equation 3 relies heavily on the assumption that the marginal utility of income is constant. If this is not the case, a more complex formulation is needed. Fortunately, this is not an issue when evaluating consumer surplus changes relative to income generated by most urban transport policies and infrastructure investments since they are relatively small compared to the individual income, and the marginal utility could be assumed constant over the range of implicit changes generated by the policy under evaluation (Train 2009).

### 4.2 Accessibility measurement

The logarithm in Eq. 5 denotes the expected benefit for an individual in an MNL formulation and it is known as the logsum. In the context of a transport choice, the logsum can be used as a utility-based accessibility measure, since it represents the desirability of the complete set of available alternatives (Ben-Akiva and Lerman 1985; Geurs and van Wee 2004). Eq. 6 shows the logsum as a measure of accessibility ($A_i$), where $\mu$ is the scale factor associated with $\varepsilon_{ij}$ in the logit framework, usually assumed as 1 for identification purposes (Ortúzar and Willumsen 2011). Note that $A_i$ is the maximum expected utility of the choice situation, and it can be transformed into monetary units by dividing it by the cost parameter, resulting in a formulation analogous to Eq. 4. Individual accessibility can be aggregated among groups, either spatially or by population segments, by calculating the weighted mean, where the weights reflect the proportion of trips made during the studied period by individuals with the same representative utility (Zhao et al. 2012).

$$A_i = \frac{1}{\mu} \ln \left( \sum_j e^{\mu V_{ij}} \right)$$  \hspace{1cm} (6)

The utility-based accessibility can also be considered a measure of ‘experienced’ accessibility since it is calculated with information from the actual trips made by the individuals and considers the commuter preferences. Also, the utility-based accessibility measure from Eq. 6 has the same scale and units (‘utils’) of the utility functions. Even
though it is strictly an ordinal scale, the RUM framework allows for relaxing this requirement and treating it as a
cardinal variable for practical purposes (Batley 2008).

Note that the utilities and the accessibility measure can also take negative values. On one side, this is because only a
portion of the utility is observed. Moreover, if the transport demand is assumed to be a derived demand and the utility
function is specified to capture the ‘disutility’ experienced by the commuter (i.e., in formulations where the utility is a
function of the travel time and cost, are negative parameters), the utility domain could include negative values. It is
important to mention that one specific value of utility-based accessibility provides little information as the real scale
and magnitude of the utility are unknown. However, it can be used to compare the experienced accessibility between
population segments, assuming that the unobserved component of the utility is equal and considering that a higher
measure means higher accessibility.

4.3 Proposed scenarios

Two simulated scenarios are studied and processed to estimate the accessibility changes and consumer surplus
based on the 2019 baseline scenario. These scenarios represent the projected infrastructure building plans in the
study area in two-time horizons. The scenarios considered in this research and their characteristics are summarized
below and in Fig. 3:

- **Baseline scenario 2019.** There is 114.4 km of BRT corridors, covering just Bogotá and Soacha (a southern
  neighboring municipality) and one cable car (TransMiCable, see Guzman et al. (2022)). Bogotá’s road network
  comprises 13,970 lane-km with high levels of congestion. It is worth saying that currently in the study area, public
  transport only includes the BRT system and regular buses.

- **Scenario 2028:** The first metro line comes into operation. It includes two new BRT corridors (+ 24.4 km), the
  western regional train, and four new cable cars. In terms of new road infrastructure, there is a western perimeter
  road, an improvement of accesses to the north of the city, and several corridors to the south of the city, as is
  shown in Fig. 3 left.

- **Scenario 2035:** In addition to the projects in the previous scenario, public transport and road infrastructure
  projects are included, such as the green corridor of Carrera 7 (the most emblematic street in the city), the second
  metro line, more cable cars, the regional train of the city north and another expansion of the northern road
  accesses (see Fig. 3 right).

To evaluate these scenarios, we estimated travel demand for the horizon years. Since this accessibility approach is
part of a project to support local and regional governments’ decision-making and planning processes, we estimated
trip generations and attractions using an updated version of Bogotá’s Land-Use and Transport Interaction model
(Guzman 2019). These vectors generate the distribution of trips between the Origin-Destination pairs, the modal
choice, and the trip assignment in the network considering land-use changes over time. The final travel demand
estimation is 18.2 million trips/day in 2028 and 19.7 million trips/day by 2035. We then evaluate consumer surplus
and distributional effects by population segment and zone.

The consumer surplus differences between scenarios were estimated and aggregated in two ways by averaging by
population segments and by zone (UPZ). It is relevant to mention that the availability of private modes corresponds to
the reported vehicle ownership in the 2019 Household Travel Survey (HTS). In contrast, we determined the availability
of the public transport alternatives (i.e., regular bus, BRT, metro, and train) using GIS procedures joining the origin zone
and the availability of stations. Finally, cycling and walking are available for trips under 10 and 5 kilometers,
respectively.
5. Results

Our findings stem from the quantitative assessment of the distributional effects of welfare changes for the commuters in Bogotá in the above planned scenarios. We implemented the estimated utility-based accessibility (Eq. 6) and the consumer surplus change between scenarios using Eq. 5. As the utility functions depend on the choice-maker preferences, it has a subjective valuation component that could be interpreted as the individual perception regarding their trips.

The utility functions come from a multinomial logit model choice model calibrated using RP and SP data, implementing the data enrichment paradigm (Louviere et al. 2000). The combined data approach allows the evaluation of preferences towards new alternatives (metro and train) through the SP component while capturing the current behavior of individuals with the RP part, reducing the bias associated with the hypothetical nature of the SP data. Our model includes the alternatives car, motorcycle, public transport (i.e., bus, BRT, metro, and train), walking, and cycling. Note that metro and train are only available in the projected scenarios. Thus, the combined data model allows estimating the utility-based accessibility in the projected scenarios. The utility functions in the model include systematic taste variations to capture preference heterogeneity. Specifically, the model includes interactions of the constant with gender for public transport alternatives, travel cost with occupation and household size, and travel time with income level (SES). The general form of the systematic utility functions $V$ perceived by individual $i$ for alternative $j$ is described as follows:

$$V_j = ASC_j + (\beta c + \beta c_{NO} * NO + \beta c_{HS} * HS) * C_j + (\beta t + \beta t_{LI} * LI + \beta t_{HI} * HI) * T_j + \beta W_j * W * TP$$

(7)

Where $\beta$ is a set of parameters to estimate. $ASC$ is the alternative specific constant. $NO$ is a dummy that takes the value of 1 if the individual does not work or study (i.e., non-occupied). $HS$ is a dummy that takes the value of 1 if the household has more than three inhabitants. $LI$ and $HI$ are dummy variables that take the value of 1 if the individual belongs to a low- or high-income level respectively. $W$ is a dummy that takes the value of 1 if the individual is female. $TP$ is a dummy that takes the value of 1 if the alternative is public transport. Ultimately, $C_j$ and $T_j$ are the cost and travel times. This demand function allows disaggregating results considering systematic taste variations according to the transport mode used, gender, occupation, household size, and income level. The latter was categorized into three levels: low income corresponds to the lowest 20%, and high income to the top 20% according to the city’s per capita household income distribution. We also divided the sample into occupied (i.e., workers and students) and non-occupied.

The cost and travel time attributes for the scenarios come from a four-step transport model calibrated to reproduce the conditions observed for the study area in 2019. We also used a database from a large origin-destination (OD) survey collected in Bogotá in 2019, which is representative of Bogotá’s population and the daily travel demand. Using these tools and data, we estimated the utility-based accessibility (logsum) for each trip included in the 2019 HTS. Then, the consumer surplus between scenarios was estimated and aggregated in two ways: by population segments and by zone (UPZ).

Considering the above, Table 1 includes the subjective values of time (SVT) by income group and occupation according to the systematic variations for travel time and cost considered in the MNL formulation. Note that the SVT can be seen as the willingness to pay for a one-unit travel time-saving. The SVT increases with income and for those occupied. Further information regarding the choice model and the data can be found in Guzman et al. (2021).
Figure 4 shows the distribution and the average utility-based accessibility (Eq. 6) disaggregated by population segment for the baseline scenario. Higher-income and occupied individuals perceive lower accessibility compared to unoccupied and low-income commuters. In other words, wealthier and occupied individuals experience a higher disutility from their trips, which can relate to higher travel time valuations compared to the other segments, as seen in Table 1. In line with HTS 2019, the average distance traveled decreases with income for all transport modes.

In the low- and medium-income segments, the distribution of accessibility for female users is more dispersed toward lower values in comparison with males, especially for occupied segments (see Fig. 4). In the low-income segment, the average accessibility for female and male users is -0.59 and -0.45 (the difference in means is statistically significant with a p-value < 0.01 according to a two-sample t-test), while in the medium-income group the mean values are -1.28 and 1.13, respectively (p-value < 0.01). There are no significant differences in the high-income group. On average, females experience lower accessibility of -1.09, in comparison to males with -1.02 (p-value < 0.01). Some of these differences are explained by the fact that women experience a higher disutility for public transport alternatives, which can be associated with higher levels of insecurity and discomfort. This effect is captured in the mode choice model through a negative interaction term that affects the utility of public alternatives for females with respect to males (see Guzman et al., 2021). In addition, to reduce costs, as income decreases, commuters generally trade-off time, preferring more affordable alternatives such as public transport or active modes, which tend to have higher travel times. In this line, occupied users can have higher expectations toward transport services (Guzman et al. 2022) and higher subjective values of time, which translates into more penalizing utility functions. Considering the above, the differences in accessibility by sex, occupation, and income are related to differences in public transport preferences and level of use.

The interpretation of the utility-based accessibility measure poses various challenges. First, the units (‘utils’) might be considered a subjective scale to measure the utility experienced by the choice maker, making it difficult to interpret and communicate. This is overcome by transforming the utils into monetary terms by dividing the utility value per the associated attribute coefficient. In this case, the result can be interpreted as a measure of the total cost experienced by the choice-maker in a given situation.

Second, as there is an unobserved component in the utility functions, it is only possible to estimate a portion of the total desirability of the choice set. For these reasons, a unique value of utility-based accessibility provides limited information. Comparing measures between population segments requires the assumption that the unobserved utility
is equal between the segments under evaluation. This assumption can be relaxed when evaluating consumer surplus and policy implications among different scenarios, in which case it is less strong to assume that this unobserved component remains equal across population segments (de Jong et al. 2007).

Considering the above, we evaluated consumer surplus changes between the baseline and the projected scenarios after the accessibility estimation, using Eq. 5. The consumer surplus change refers to the difference, in monetary terms, of the logsums from the scenarios under comparison. It is relevant to mention that to calculate the average consumer surplus, we performed a weighted mean of the surplus experienced in each trip from the 2019 HTS, where the weights are the number of the daily trips made by individuals with the same representative utility, that is, from the same population segment. The average surplus is multiplied by the daily trips to obtain the aggregate consumer surplus change.

Results indicate that the new transport investment evaluated in the projected scenarios improves the consumer surplus associated with daily accessibility in Bogotá. The average logsum per trip in 2019 was 1.89 USD (6,206 COP), decreasing by 13% and 24% for 2028 and 2035, respectively. As the logsum in monetary terms indicates a cost, the decrease suggests a welfare improvement. Considering that the number of daily trips in 2019, 2028, and 2035 is 15.4, 18.2, and 19.7 million respectively, the aggregate consumer surplus change in a typical day in 2028 concerning 2019 is around 4.5 million USD, and in 2035 compared to 2028 is 4.0 million USD.

To evaluate distributional effects by population segments, we disaggregated the consumer surplus results by sex, occupation, and income level. These results are summarized in Fig. 5, which exposés the consumer surplus change between the projected scenarios compared to the baseline scenario. Most segments are better-off on average in the projected scenarios compared to the baseline, except for wealthy females, and wealthy occupied males in 2028, which experience a negative consumer surplus change. That is, high-income females experience their trips to be more expensive, in 2028 and 2035 compared to the baseline. In other words, the desirability of their trips is lower in the projected scenarios.

Results also suggest differences in income level and occupation. Higher benefits are experienced by low- and medium-income individuals, as well as by male-occupied commuters. This could be because the new infrastructure aims to improve the public transport system with new BRT, metro, and train corridors connecting Bogotá with neighboring municipalities to the north and west, where a sizeable proportion of the low-income population live. However, the road network does not have important improvements. Hence, the level of service of private vehicles improves at a smaller scale compared to public transport users. This could affect high-income users, which rely more heavily on private vehicles, as 41% of their trips are made by car, compared to 17% for medium-income and 4% for low-income. Furthermore, the proportion of trips made by public transport is 31%, 34%, and 25% for low-, medium- and high-income segments, while in the case of walking and cycling is 60%, 44%, and 34% respectively, according to Bogotá’s 2019 HTS.

Regarding the spatial distribution of benefits, Fig. 6 shows the average consumer surplus change between scenarios by zone. The consumer surplus for each zone is estimated by averaging the individual consumer surplus change by a trip, according to the travel demand distribution from each zone. Higher benefits are observed in zones belonging to corridors connecting the CBD area, located on the eastern edge (see Fig. 1 for CBD location), with zones to the south- and north-western. These benefits are directly associated with the implementation of the two metro lines. The spatial differences in consumer surplus are also associated with the socioeconomic characteristics of each zone. In Bogotá, the zones with a higher population of low-income residents are in the periphery, especially to the south and west, while
higher income is concentrated to the northeast. Considering this, Fig. 6 suggests that the investments in new public transport corridors aim to improve the accessibility from low- and medium-income zones to the CBD.

Consumer surplus results also align with the SVT presented in Table 1. As the SVT increases with income, the individuals experience lower welfare in their daily mobility, even though higher-income segments make shorter trips. In fact, in Bogotá, according to the 2019 HTS, the average distance traveled by high-income users in public transport is around 10 km, while for medium- and low-income is 11.3 and 12.2 km, respectively. In contrast, for car trips, the average distances are 7.9, 8.5, and 9.5 km for high-, medium-, and low-income segments, while for walking trips the average distances are 2.8, 3.4, and 3.7 km, respectively.

As mentioned in the accessibility analysis, higher SVT implies a higher disutility experienced in trips of the same length, compared to users with lower SVT. In other words, one unit of travel time saved by a higher-income user has a higher valuation in monetary terms. This means that the utility-based accessibility and welfare analysis estimated with logsum methods have a subjective component as it strongly depends on individual preferences. Therefore, in our analysis, the accessibility experienced by higher-income users is lower despite making shorter trips. If these issues are not considered, one might come to the wrong conclusion that high-income users have more transport disadvantages. Moreover, as with other accessibility frameworks, utility-based measures also rely heavily on travel patterns (origins and destinations), which define trip costs. Therefore, the perceived utility depends on where travel is.

The subjective nature of utility-based accessibility entails challenges when using these methods for project evaluation, especially when comparing benefits for different population segments. Although estimating consumer surplus might help capture the welfare changes in the context of transport policy evaluations, if the differences between preferences and subjective time valuations are not considered, it might lead to poor targeting of resources. This has implications for planning purposes, as it could lead to underestimating the benefits in low-income zones. We thus recommend complementing cost-benefit analysis by including evaluations using the accessibility appraisal for different population segments to minimize this bias.

Despite its practical challenges, utility-based accessibility methods help capture individuals’ subjective preferences that determine economic choices, which can contribute to the analysis of other urban aspects such as housing allocation, activity location, or explain the land value. This situation leads to rethinking the concept of accessibility by incorporating preference heterogeneity and framing the analysis in individual behavioral theories beyond traditional methods based on location and capacity. By considering the subjective nature of the preferences in the study of accessibility, it is possible to differentiate the aspects that determine the tastes and expectations of each population segment and identify the needs for connectivity for each group.

Our analysis suggests that the higher disutility that higher-income commuters perceive translates into a perception of higher costs for even shorter trips. Higher availability of opportunities leads to a higher marginal disutility for every additional unit of travel cost. Furthermore, findings also suggest that welfare benefits for wealthier populations are lower in comparison to low-income users in the evaluated scenarios. As income grows and more people transition into the middle class and higher-income groups, it is expected that they perceive a disutility shift, therefore influencing population expectations of the transport system. This will be discussed further in the following section.

6. Discussion

Our findings have implications for research and practice of accessibility planning and decision-making in Latin American and Global South cities. On the one hand, the use of utility-based metrics for the analysis of differentiated effects of planned infrastructure and public transport interventions adds depth and nuances to the influence of travel...
choices, proximity to more diverse and rich land uses, and socioeconomic conditions on the perceived disutility of accessing different opportunities. Incorporating preferences linked with specific socioeconomic characteristics into accessibility analysis also presents an opportunity for local practitioners and decision-makers to access relevant information about the distribution of accessibility gains and losses and the conditions explaining such a distribution. Findings are also consistent with previous accessibility research suggesting an effect of the subjective value of time in the perceived impedance between origins and destinations for different socioeconomic groups, which penalizes more trips by wealthier commuters while reflecting a higher willingness to tolerate higher costs by those belonging to more marginalized groups.

On the other hand, monetizable accessibility estimations can contribute to bridging the socially-oriented analysis of transport and mobility interventions with mainstream economic evaluation approaches. Building such a bridge has implications for shifting the approach to ex-ante analysis and feasibility assessment of public investment projects as suggested by previous research (Gulhan et al. 2013), and the analysis and evaluation of public investments in infrastructure and changes in the configuration of the urban transport network.

The practical advantages of utility-based measures of accessibility are illustrated by our analysis in the context of Bogotá’s plans for the development of transport infrastructure in the medium and long term. These advantages include interpretable and communicable information to both specialist and non-technical audiences. Furthermore, considering cities in the region tend to have access to the main inputs used in this paper such as travel demand data and traditional transport models, it is possible to produce monetizable accessibility analyses without increasing data requirements. Using technical tools already in use in transport planning practice reinforces findings from different empirical contexts suggesting the need for adapting and reinterpreting mainstream approaches to produce more nuanced social analysis (Ziemke et al. 2018). The use of behavioral models also helps define a common language with technical advisors and practitioners in different sectors, who often over-rely on these tools for supporting decisions. This has been raised in recent critiques of the mainstream approach to transport planning in cities of the Global South (Oviedo and Nieto-Combariza 2021). By leveling the playfield through the use of already accepted tools and information, it is possible not only to ease the transition of accessibility metrics into standard approaches to policymaking and evaluation but also to facilitate appropriation and deployment as part of standard models often used at the demand forecasting and feasibility stages of planning.

From a perspective of the operationalization of accessibility in the planning and assessment of public investments and infrastructure, our findings show that adding accessibility assessments at the planning and feasibility stages of future urban transport interventions can yield compelling results about potential inequalities. This approach can help unpack some of the aggregated results produced by traditional economic evaluations, which amalgamate costs and benefits without considering distributional impacts. Furthermore, an approach grounded in the notion of accessibility and related measures can help identify target areas or population groups that should be prioritized for public investment in transport or can challenge potential unintended (dis)benefits because of specific individual characteristics, preferences, or behaviors. As shown by other studies in the academic literature, this applies as much to infrastructure and other ‘heavy’ investments, as it does to operational decisions such as the introduction of ICTs into public transport (Lu et al. 2014). Such flexibility suggests that accessibility metrics can help inform structural changes in the transport network and minor adjustments that seek to improve efficiency, while still providing insights into their effects on social and spatial inequalities.

Considering accessibility can manifest at different scales (i.e., macro, meso, and micro), utility-based measures can inform decisions at all levels (Jones and Lucas 2012). On the one hand, utility-based accessibility metrics have been proven to inform strategic analyses at the city level, with applications to multi-modal public transport networks as
used in this study and previous research in different contexts (Nassir et al. 2016). On the other hand, as shown in our analyses, it is also possible to capture aspects related to access to infrastructure (mesoscale), which is consistent with previous applications (Hasnine et al. 2019). Finally, at the micro-level, it is possible to use utility-based metrics to dissect the preferences and experiences of different social identities, which align well with current concerns in the policy agenda in the region regarding gender inequalities and other social and spatial disadvantages, seeking to close the gaps in the urban transport landscape for different population groups. The analyses in this study illustrate the feasibility of doing so, evaluating utility-based accessibility by sex, socioeconomic level, and occupation, fitting with current debates in Latin America.

The accessibility-oriented approach suggested in this paper to economic evaluation of infrastructure and prospective planning could play a fundamental role in shaping rapidly growing Latin American cities. This presents a significant opportunity for changing research and practice in a context where there is an already solid tradition of its use since the early 2010s in assessing inequalities of the transport-land-use system.

7. Conclusions

The proposed utility-based accessibility captures the benefits derived from the spatial distribution of opportunities and transport infrastructure improvements using discrete choice modeling. The estimations of accessibility and welfare measures depend on individual preferences that determine utility functions, adding a subjective dimension to the estimation of accessibility and controlling preferences and perceived disutility by different socioeconomic groups. Although in a transport mode choice situation travel cost and travel time are two determinant attributes, they are certainly not the only ones nor do they have the same meaning and influence for all commuters.

The marginal utility of travel time tends to decrease with income (Guzman et al. 2021). That is, lower-income individuals are willing to accept higher travel times to save money. In this line, willingness to pay increases with income. This generates equality issues as limitations in the ability to pay for lower-income commuters force trade-offs between household location, travel costs, and travel times. In urban areas, these asymmetries result in lower-income population segments residing in deprived areas, usually far from the main opportunities, and experiencing higher travel times and lower accessibility to jobs and services, becoming trapped in a self-reinforcing cycle of disconnection and forced acceptance of increasing travel costs, which are reflected in the subjective value of time of poorer residents.

The approach based on logsum methods allows evaluation of a broader range of policy variables and scenarios than potential accessibility metrics since the flexibility of discrete choice modeling frameworks allows to specify any explanatory variable, as opposed to measures based on generalized costs (i.e., contour and gravitational accessibility measures), which are usually limited to travel time and cost. However, the subjective nature of many discrete choice experiments, especially when based on SP data or when evaluating new market contexts, might generate some bias, some of which could be overcome by complementing the SP with RP data through combined modeling techniques (Louviere et al. 2000). Moreover, the consistency of this framework with behavioral microeconomic theories, such as RUM, allows the evaluation of a wider range of welfare implications. Accessibility gains converted into monetary values can be useful in the practice of CBA, and therefore, incorporating accessibility in transport planning and economic evaluation of projects, considering equality issues, can lead to prioritizing the accessibility approach over the traditional mobility approach. This is in the interest of policy- and decision-making, as the proposed methods could contribute to evaluating the social implications of transport, such as the links with social capital, subjective well-being, and quality of life.
The proposed approach has the potential to inform deeper distributional analyses grounded in more complex frameworks such as transport-related social, exclusion, which have only been explored qualitatively in the local context (Oviedo Hernandez and Titheridge 2016). Discrete choice models enable the consideration of variables associated with social exclusion and the restriction of mobility by factors other than time, cost, and comfort. These include fear of crime, perceptions of road safety, vulnerability to harassment and other forms of violence, discrimination, time poverty, care responsibilities, and other factors that have been identified in the literature as significant determinants of access but that as of yet have not been incorporated in traditional metrics. While this study shares these limitations, it also opens a path for further research that explores these variables in discrete choice models that can later be translated into accessibility assessments of transport interventions.

**Declarations**

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**Conflict of interest statement**

On behalf of all authors, the corresponding author states that there is no conflict of interest.

**Authors’ contribution**

Luis A. Guzman: Conceptualization, manuscript writing, analysis of results, content planning and review (corresponding author). Victor Cantillo-Garcia: manuscript writing, analysis of results, methodology, and data curation. Julián Arellana: conceptualization, methodology, and literature search. Daniel Oviedo: resources, manuscript writing and review.

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Average consumer surplus by trip and origin zone with respect to baseline