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Carbon Pricing and Transit Accessibility to Jobs

Impacts on Inequality in Rio de Janeiro and Kinshasa

Andrew Nell
Daniel Herszenhut
Camilla Knudsen
Shohei Nakamura
Marcus Saraiva
Paolo Avner

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Abstract

Urban transport is a major driver of global carbon dioxide emissions. Without strong mitigation policies, rapid urbanization, especially in developing countries, is expected to exacerbate the problem. There is a growing consensus on the fundamental role of carbon pricing for achieving reductions in carbon dioxide emissions. However, carbon pricing policies are frequently criticized and resisted for having adverse distributional impacts, which could hinder their implementation, particularly when implemented as a fuel levy—which would impact private vehicle usage but may also affect transit services such as buses. Currently, there is a lack of evidence that quantifies these negative impacts, especially on people's ability to reach economic opportunities and services. To this end, this paper studies the impact of a uniform carbon price, as one of the most commonly discussed climate policies, on access to employment opportunities via transit services in Kinshasa and Rio de Janeiro. Reduced access to jobs would contribute to fragmented urban labor markets and thus lead to negative social outcomes. Unlike most previous studies, this study defines access as being constrained by both travel time and travel budget. The results indicate that fuel price increases (simulating increases induced by a carbon tax) reduce accessibility, but the effect is lower in more compact and walkable cities as well as in cities that have green transit options. The paper also shows that fuel price increases have spatially and socially disparate outcomes, with the lowest income communities not necessarily being the most affected, in part because even in the absence of carbon pricing, they are found to be priced out of using transit services. The results demonstrate the importance of strategies and investments, such as land use planning and decarbonized transit services, but also possibly complementary social protection programs (such as targeted subsidies, or even cash transfers), to mitigate the negative distributional consequences of carbon pricing policies.

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Andrew Nell, Daniel Herszenhut, Camilla Knudsen, Shohei Nakamura, Marcus Saraiva, Paolo Avner

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1 Introduction

Transport is a major contributor to climate change, accounting for 37 percent of global CO_2 emissions from end-use sectors (IEA, 2022). More alarmingly, transport is the fastest growing source of CO_2 emissions, especially in low- and middle-income countries, due to rapid urbanization and increasing motorization rates (Sims & Schaeffer, 2014). Despite technological improvements, urban transport—currently accounting for about 8 percent of world energy use—is expected to double its energy consumption by mid-century (IEA, 2013). Curbing emissions from urban transport is essential to achieving net zero emissions by 2050 and to limiting global warming to well below 2°C as called for in the Paris Agreement.

Carbon pricing, including carbon taxes and fuel excise taxes, is widely recognized in the economics literature as a cost-effective policy instrument to incentivize carbon abatement (Climate Leadership Council, 2019). A carbon tax sets a price on carbon by specifying a tax rate on the carbon content of fossil fuels (Pigato, 2019). In the transport sector, carbon taxes, like fuel excise taxes, effectively raise fuel prices, thereby reducing demand for overall travel, discouraging the use of private vehicles, and incentivizing other modes of travel or a shift to cleaner alternatives (Leard et al., 2020). However, while carbon pricing is an effective tool for shifting behavior towards low-carbon alternatives, there can be unintended negative socioeconomic impacts, especially in developing countries where there are higher levels of economic vulnerability and income inequality, and lower-cost alternatives often are not available (Carbon Pricing Leadership Coalition, 2020). As a result, carbon pricing policies can evoke strong public opposition and risk being withdrawn before being implemented.[1] Other less controversial policies, such as transit subsidies, could also help achieve a shift from cars to lower emitting transport modes. However, these have also been found to be associated to negative outcomes, such as a decrease in the quality of transit services, and they would in any case entail fiscal transfers, which may not be an option in countries with limited financial resources. This study, therefore, is focused on the impact of a carbon price induced increase in fuel prices on transit accessibility to jobs.

In many developing-country cities, low accessibility to economic opportunities contributes to fragmented urban labor markets, reduced productivity, and negative social outcomes (Franklin, 2018; Gulyani et al., 2010; Lall et al., 2017; Venables, 2017). Improving access to employment opportunities in cities is therefore key to achieving efficient labor markets, enhancing agglomeration economies, and ensuring inclusive economic growth. If a carbon or fuel excise tax is implemented uniformly (i.e., without exempting less carbon-intensive modes such as public transit) and the increase in fuel prices translates into a fare hike in public transit, carbon pricing, while incentivizing reduced use of cars, could potentially also reduce affordability of transit services and disrupt labor markets. Understanding and quantifying the potential impact of carbon pricing on access to employment is important to inform the development of mechanisms by which negative impacts can be mitigated, especially as an increasing number of low- and middle-income countries are considering carbon pricing policies (World Bank, 2022) or have commissioned carbon pricing studies (e.g., Telaye et al., 2019).

[1] Examples include the gilets jaunes protests in France which led the government to abandon the planned fuel tax increase, street protests in Ghana following the government's attempts at implementing a fossil fuel subsidy reform (Maria Vagliasindi, 2012), and protests and demonstrations in the Islamic Republic of Iran after the government introduced gasoline rationing and price hikes.

Accessibility to economic opportunities is widely regarded as an indicator of the ability of transport and land-use in cities to connect residents with its opportunities (Nakamura & Avner, 2021). Most studies measuring access to opportunities, however, focus only on travel time (El-Geneidy et al., 2016; Foth et al., 2013; Levinson, 2013; Peralta-Quiros et al., 2019; Wu et al., 2021). While travel time is an important factor that impacts travel decisions and limits accessibility, there are many other elements that affect people's travel behavior (Cui & Levinson, 2018), including the monetary cost of travel. Recent studies have started to incorporate monetary costs in accessibility analyses (Bittencourt & Giannotti, 2021; Conway & Stewart, 2019; Herszenhut et al., 2022; Oviedo et al., 2019), however they have focused on understanding existing relationships between travel times, travel costs, and other socio-economic factors, rather than assessing the impact of a policy mechanism.

In this paper, we quantify the impacts of a carbon price induced increase in fuel prices on transit services through a study on changes in access to employment opportunities and inequality in two cities: Kinshasa, Democratic Republic of Congo, and Rio de Janeiro, Brazil, leveraging General Transit Feed Specification (GTFS) data and socio-economic data. The aim is first to understand the magnitude of the impacts of an increase in transit fares on accessibility to jobs in both cities in aggregate, by income group and location; and, second to provide information to support the development of more targeted and nuanced policies that can offset negative distributional effects of carbon pricing policies on transit accessibility. The paper addresses four main research questions:

1. How do carbon price induced fuel price increases affect employment accessibility in aggregate?
2. Are any specific neighborhoods or socio-economic groups more severely affected?
3. In the absence of complementary measures, do carbon pricing policies further exacerbate existing inequalities?
4. Do carbon pricing policies risk further excluding some groups from participating in the local labor market?

Our results demonstrate that carbon pricing decreases accessibility to job opportunities. Communities in both cities that already had high levels of access to opportunities (generally higher income areas) saw the highest losses in accessibility, cautiously pointing to carbon pricing being progressive. However, we also found that some lower income residents located relatively close to jobs could be disproportionately affected, and that low-income residents lost more in relative terms in Rio but not in Kinshasa. We also found that increasing fuel prices (up to 500%) did not change the specific population groups that were impacted significantly; however, the severity of the impact increased. The effects were partly mitigated in Rio by the existence of non-petroleum-based services (such as rail and metro services) that were less sensitive to fuel price increases relative to the bus and Bus Rapid Transit (BRT). The compact nature of Kinshasa meant that the negative impacts of fare increases were mitigated to a certain extent because of the proximity between homes and jobs, which allows for walking to be an efficient way of maintaining good accessibility in large parts of the city. Kinshasa is however more sensitive to fuel price increases due to relatively high poverty levels and only gasoline-based services operating. The level of inequality (measured by the Palma ratio, which divides the average accessibility of the wealthiest 10% by the accessibility of the poorest 40%) and how it reacts to fuel price increases, crucially depends on the travel budget threshold selected. When considering commuting related spending below 30% of per capita income, inequality decreases with fuel prices, as the poorest could not afford transit services, and by construction only the middle income and wealthiest are affected. On the other hand, beyond 30% budget thresholds, inequality increases as some of the poorest could afford transit services in the baseline but get priced out with fare increases. Reduction in inequality, when observed, hides how much further from being able to afford transit services some of the poorest households are, an element that we also document in this study.

The paper is structured as follows. Section 2 presents the datasets and methods used to conduct the study, including the use of Pareto frontiers that represent specific itineraries that optimize for both travel costs and time. Section 3 presents the results of the study. It first presents how average accessibility varies as a function of travel budget and time thresholds in Rio de Janeiro and Kinshasa. Second it discusses how these average accessibility profiles are impacted by fuel price increases ranging from 0 to 500%. Thirdly, this section disaggregates these impacts both spatially and by income group, to document who and where are the most affected. The subsequent sub-section specifically looks into inequality in accessibility levels between the wealthiest 10% and the poorest 40% and how fuel price increases impact these as a function of travel budget thresholds. The fourth results sub-section looks specifically at households that might be excluded from using transit services altogether because of fare increases, where they reside and which income groups they belong to. Section 4 summarizes the rich set of results derived in this study, discusses them and points to some avenues for pushing ambitious climate targets while mitigating the negative consequences that they might entail.

2 Materials and methods

Socio-economic data, including the location of jobs and households, was derived from various household and travel surveys, and merged with transit data in General Transit Feed Specification (GTFS) format and street network information from OpenStreetMap (OSM). The transport data was processed using r5r (Pereira et al., 2021) to conduct baseline analyses of accessibility to economic opportunity and derive Pareto frontiers (all optimal itineraries between each origin-destination combination optimized on both travel time and travel budget) for every origin-destination combination within the two cities.

In order to better understand the nuance around the impact of fuel price increases and their impacts on specific communities as well as to identify potential mechanisms for reducing negative outcomes, the analysis was split into five components: Identifying baseline accessibility behavior, assessing the sensitivity of overall accessibility to fuel price increases across both cities, identifying specific locations within cities and income groups that may be more severely impacted, assessing inequality (utilizing the Palma ratio as a metric) and assessing the exclusion of residents from accessing jobs. Figure 1 shows a high-level overview of the workflow of this study. Each of these processes and the corresponding datasets are described in the data and methodology sections below, however, additional details are included in Appendix A – Detailed Data Description and Appendix B – Detailed Methodology.

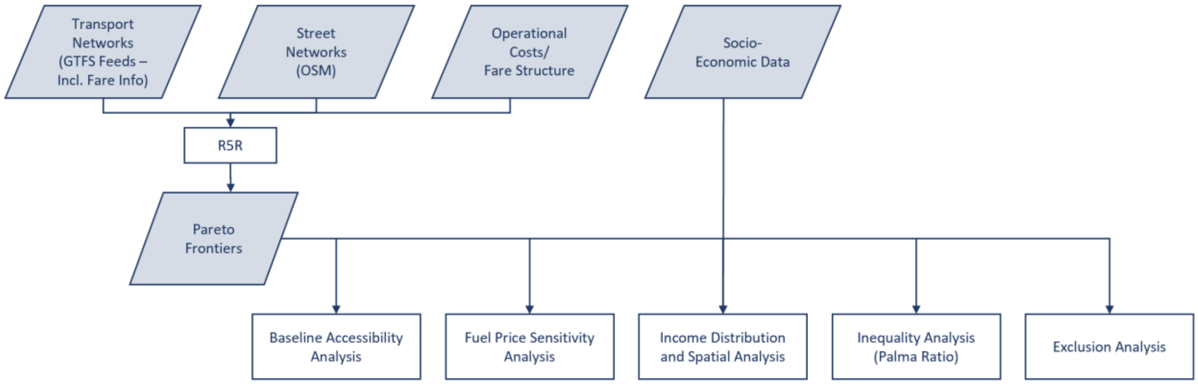

Figure 1: Methodology Overview

2.1 Data

2.1.1 Transport networks

The majority of daily trips in Rio are performed with public transport modes (47%), followed by non-motorized modes, walk and bike, which account for 28% of daily trips in the city (PMUS-Rio, 2015). Rio's public transport data were provided by transport operators (Fetranspor and SuperVia) in the General Transit Feed Specification (GTFS) format and represent a typical day of operations in November 2018 for the metro, rail, light rail, BRT, municipal bus, and ferry services operating within the municipal boundaries.[2] Fare information was incorporated based on the fares in effect in December 2021.[3] Rio's transit users can use a smartcard to enjoy fare discounts partly subsidized by the municipal and state government, but this study considered the full undiscounted fares to understand how carbon pricing policies may affect transit affordability and accessibility without government intervention. The available GTFS data does not extend across Rio's greater metropolitan region, meaning that the study needed to focus on the municipal boundary rather than the functional labor market.

Kinshasa transport system is highly dependent on non-motorized trips (around 50% of daily trips in the city are conducted by foot or bike), but transit trips also play a key role in the daily journeys of the citizens, with more than a quarter of all daily trips being conducted in collective modes (JICA, 2019). Kinshasa's public transport network data is also described in the GTFS format and was provided by GoMetro,[4] a service provider specializing in the mapping and quantification of transit networks - particularly in environments with high informality and data scarcity. Appendix A – Detailed Data Description has additional information on the data gathering process. The GoMetro team gathered data (including routes, stops, travel times and fare information) over three weeks between January and February 2020 representing typical operations over that period. Data included several services including Transco (the

[2] The provided GTFS data does not include moto taxis, municipal vans and informal public transport modes, such as moto taxis and vans run by non-formally-recognized operators. These modes are more frequently used by low-income citizens and are especially susceptible to carbon tax related fare increases due to their unregulated nature and the tendency of operators to distribute increasing costs to the service users. Not including such modes in our analyses is a limitation of this study that can be overcome in future similar research with more complete GTFS data.
[3] Please refer to the Riocard Mais website for the full set of up-to-date fares. Available at https://www.cartaoriocard.com.br/rcc/institucional/tarifas
[4] http://gometroapp.com/

formal public transport service), Esprit de Mort, Esprit de Vie, Taxi Jaune and in special cases moto taxis operating over fixed routes between specific locations, where congestion and road quality limit access for larger vehicles. Fares for public modes are set by the governor, while private modes are regulated by a private operator union, however, these private operators tend to overcharge for various reasons (7sur7, 2021; Deskeco, 2018; Heinze, 2018; MediaCongo, 2021) discussed in more detail in Appendix A – Detailed Data Description.

The various transport services active over the study periods in each city are visualized in Figure 2. Many of the services in Kinshasa overlap with each other (particularly in the city proper), while services in Rio operate in specific areas and generally connect with each other at specific points or interchanges. Walking speeds along the street network were assumed to be 3.6km/h.

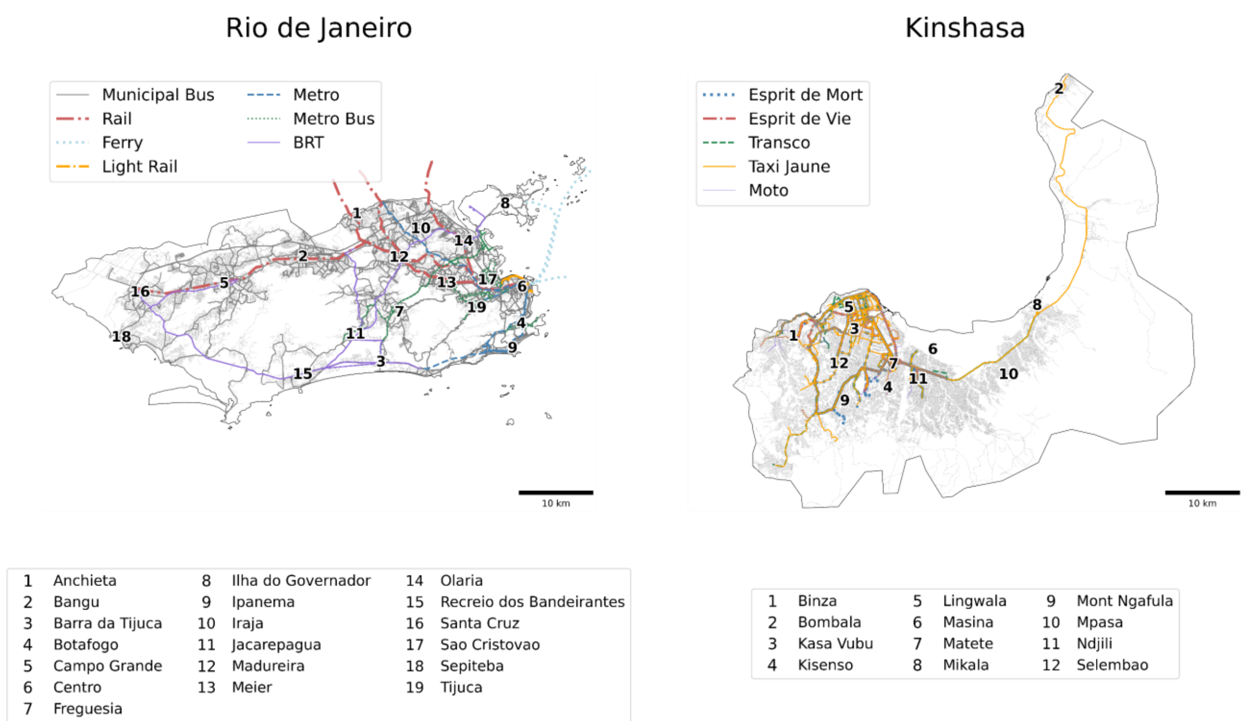

Figure 2: Transport Networks in Rio de Janeiro and Kinshasa

2.1.2 Socio-economic data

Socio-demographic and employment data for Rio de Janeiro were available from the 2010 Brazilian Census[5] and 2019 Annual Social Information Relation (RAIS)[6] respectively. These data sets are spatially aggregated and made publicly available by the Access to Opportunities Project[7] (Pereira et al., 2022).

[5] Available at https://censo2010.ibge.gov.br/.
[6] Available at http://pdet.mte.gov.br/rais/rais-2019. The available data includes only formal jobs. Even though a large share of Rio's workers declare to work on informal markets, the distribution of formal and informal jobs in the city is significantly correlated (Pereira, 2019). Not taking informal jobs into account in our study, therefore, should not drastically affect our results.
[7] Available at https://www.ipea.gov.br/acessooportunidades/en/sobre/.

Descriptive overviews of this data including population, employment opportunities, and income distributions are shown in Appendix A – Detailed Data Description.

Rio de Janeiro is the second largest city in Brazil, with more than 6 million inhabitants and the second largest GDP (IBGE, 2021a, 2021b). However, despite being relatively prosperous, it is characterized by high levels of inequality and large fragmentation (Ferreyra & Roberts, 2018), the latter being attributed to both morphological and geographic constraints (Ricky Burdett et al., 2013) as well as historical policies (Lago, 2015). Economic activity in Rio is heavily concentrated in the historic city center (Centro), with slightly lower levels of employment in directly adjacent areas and much lower levels across the rest of the city. This is contrasted with the population distribution across the city, which is relatively dense globally and extends across the municipal area with decreasing density as the city extends westward. The wealthiest residents are concentrated in low-density areas along the Southern coastline. Income tends to decrease the further North and West away from Centro, with the poorest residents generally living in the furthest North or Western parts of the city, except in the cases of some favelas with high concentrations of extremely poor residents in small areas of otherwise higher income regions.

Socio-economic data for Kinshasa was sourced from a Commuter Travel Survey conducted by the Japan International Cooperation Agency (JICA) in 2018, as part of ongoing work towards the Kinshasa Transport Master Plan (JICA, 2019). The survey was conducted for Traffic Area Zones (TAZ) and extended across the functional labor market of Kinshasa. However, the survey does not cover the full extent of Kinshasa's provincial boundaries. In addition, population data from WorldPop[8] was also used to complement the survey data and provide more detailed population information.

Kinshasa is the capital and economic center of the Democratic Republic of Congo (DRC) with a population in excess of 14 million (World Bank, 2019) and population growth rate of 5.1% per annum. It is expected to become the most populous megacity in Africa by 2030 (World Bank, 2018). Similarly to Rio, economic activity is concentrated in a small area, in Gombe, with some hyper-localized areas in Ndjili and Matete. However, despite Rio's relatively high density, the population of Kinshasa lives in an even more compact area with very high densities located relatively close to most economic activity. There are also smaller, slightly fragmented communities located further North-East along the river. The legacy of colonial spatial planning followed by extremely high rates of urbanization with insufficient investment in infrastructure have resulted in a few concentrated affluent areas (such as Gombe/Socimat and Mont Ngafula) and a high incidence of poverty (approximately 60% in 2012 (World Bank, 2018)), with large slums across much of the remainder of the city and many residents being unable to afford transport services (Beeckmans & Bigon, 2016). The lower earning residents are concentrated in Selembao and the Eastern edge of the city proper (Ndjili, Kisenso and Masina) with poorer residents also located along the Northeastern corridor towards Bombala.

In this study, all socio-economic data was aggregated to a hexagonal grid using Uber's H3 grid system (Brodsky, 2018). Each hexagon has a diagonal of approximately 900 meters and a total area of 0.7 km^2.

2.1.3 Operational costs and fare structure

In order to assess the impact of a fuel price increase on the fares of different transport services, we investigate existing operational costs, fare structures and mechanisms for increasing fares in each city.

[8] Available at https://www.worldpop.org/.

In the case of Rio de Janeiro, fare readjustments are set by different economic indices, determined in the concession contracts for the operation of each mode. The impact of fuel price increases on fare increases, therefore, is based on the share of fuel price changes to the composition of each one of these indices. These increases also affect the fares of services that are not directly reliant on fossil fuels to operate (Rail, Metro and Light Rail), albeit at a lower rate than services that are petroleum dependent. Table 1 summarizes the indices that control fare readjustments and the fuel price share on each one of them for each transit service considered in this study.

Table 1: Impact of fuel price increases on transit service fare in Rio de Janeiro due to fuel cost increases

Service	Base Fare Range		Share of fare price increase attributed to fuel price change	Explanation
	BRL	PPP $ (2018)		
Bus	4.05	1.84	21.00%	Based on a readjustment formula defined as part of the bus system bidding.[9]
Ferry	6.5	2.95	6.01%	Ferry price increase is set by the IPCA (Broad Consumer Price Index, in Portuguese).[10]
Rail, Metro, Light Rail	3.8 – 5.8	1.73-2.64	6.05%	These are adjusted based on the IGP-M (General Market Price Index, in Portuguese).[11]

However, there was limited literature on fuel price increases in Kinshasa. Leveraging information related to historical fare increases, historical prices of fuel locally and observing comparable cities (SSATP, 2001), the share of operating costs that could be attributed to fuel, and hence the expected rate at which fuel prices would impact fares, are documented in Table 2 below. Private minibus operators are more sensitive to fuel prices due to higher burden and risk on drivers, with the public bus service pricing linked to official changes, while the fuel component of moto taxis operating expenses was considered lower. There are no special rates or fare systems operating in Kinshasa where passengers could gain discounts or benefits for using specific services. Despite the system having some regulation through the governor and through a private operator union, there is widespread deviation from these practices, resulting in higher prices. More details on the method used to determine the share of operating costs attributed to fuel price in Kinshasa and on the fare readjustment process in the city are shown in Appendix A – Detailed Data Description.

[9] Detailed at https://www.rio.rj.gov.br/dlstatic/10112/4800832/4128528/ANEXOIX.pdf.

[10] The IPCA index composition is available at https://www.bcb.gov.br/conteudo/relatorioinflacao/EstudosEspeciais/EE069_Atualizacoes_da_estrutura_de_ponderacao_do_IPCA_e_repercussao_nas_suas_classificacoes.pdf.

[11] The IGP-M index is composed of 3 other indexes with different weightings - 60% IPA-M (Wholesale Price Index, in Portuguese), 30% IPA-C (Broad Producer Price Index, in Portuguese) and 10% INCC (National Construction Cost Index, in Portuguese). Each of these has a different fuel price component: 7.07%, 6.03% and 0%, respectively. These are then combined to determine an overall increase. Their compositions are respectively available at https://portalibre.fgv.br/sites/default/files/2020-03/altera_o-de-pondera_es-do-ipa-2013.pdf, https://portalibre.fgv.br/sites/default/files/2020-03/an_ncio-novos-pesos-ipc-jan_2020-_005_-1.pdf and https://portalibre.fgv.br/sites/default/files/2020-03/metodologia-igp-m-maio-de-2014.pdf.

Table 2: Service Price increases per Fuel Cost Increase in Kinshasa

Service	Base Fare Range		Share of Operating Cost attributed to fuel price	Explanation
	CDF	PPP $ (2018)		
Transco	500-1000	0.61-1.22	30%	Bus Service
Esprit de Vie	500-1000	0.61-1.22	30%	Bus Service
Esprit de Mort	300-1000	0.37-1.22	40%	Private Minibus Service
Taxi Jaune	300-2500	0.27-3.06	30%	4-Seater Sedan Service
Moto Taxi	100-2000	0.12-2.44	20%	Motorbike Service

2.2 Methodology

2.2.1 Accessibility

For any origin area *i*, accessibility is calculated as the sum of jobs across destination areas $j = \{1,2,3\ldots,n\}$ where at least one travel itinerary *k* satisfies both the travel time and travel cost thresholds (Equation 1). To calculate overall accessibility for an urban area that comprises multiple origin and destination pairs, accessibility in each origin area is weighted by the share of the population in that area. This accessibility measure does not indicate a decision process for commuting but it indicates potential access given selected thresholds and is a useful tool for planners and policy makers.

$$A_i = \sum_{j=1}^{n} O_j \max_{k \in K} \left(f(t_{ijk}) g(b_{ijk}) \right) \tag{1}$$

$$f(t_{ijk}) = \begin{cases} 1, & if \;\; t_{ijk} \leq T \\ 0, & if \;\; t_{ijk} > T \end{cases} \tag{2}$$

$$g(b_{ijk}) = \begin{cases} 1, & if \;\; b_{ijk} \leq B \\ 0, & if \;\; b_{ijk} > B \end{cases} \tag{3}$$

A_i is the total number of jobs accessible in origin area *i*; O_j is the number of jobs in destination area *j*; *K* is the total set of possible itineraries between origin *i* and destination *j*; t_{ijk} and b_{ijk} represent the travel time and travel cost, respectively, of itinerary *k* between origin *i* and destination *j*; *T* and *B* are travel time and travel cost thresholds, respectively, which define binary functions $f(t_{ijk})$ and $g(b_{ijk})$.

As part of the assessment of monetary costs, it was felt that a more suitable metric of affordability was a monetary cost relative to an average monthly income or travel budget of different areas. Single trip costs were adjusted assuming two trips a day for 22 business days in a month and then dividing these by the monthly income as shown in Equation 4.

$$b_t = \frac{c_t \times 2 \times 22}{I_i} \tag{4}$$

Where b_t is the travel budget to complete a trip *t*, c_t is the absolute cost of a trip *t* and I_i is the average income of origin area *i*.

Thus, the travel budget required to complete a trip that costs BRL 4.00 for an individual that earns BRL 600.00 is approximately 29.3% of their monthly income, if they were to use that trip to get to work throughout a month.

A notable problem for this type of analysis is the modifiable temporal unit problem (MTUP) (Cheng & Adepeju, 2014; Conway et al., 2018), which refers to the arbitrary selection of departure times and the inherent variation in accessibility with different times and the arbitrary selection of cutoff thresholds for travel times or travel budget thresholds which differ across cities and socio-economic groups (Herszenhut et al., 2022; Pereira, 2019). The MTUP was addressed by calculating results along a 2-hour time window, from 7 to 9 am, with departure times distributed every 15 minutes, after which the median number of jobs reachable across this time window were calculated. Sensitivity analysis was also conducted for a range of travel time thresholds (between 5 and 120 minutes for every 5 minutes) and travel budget thresholds (between 2.5% and 100% of monthly income in increments of 2.5%) and incorporated into the results.

Due to data availability, monthly income was derived from monthly income per capita, where the total income of each area is divided by the number of people living there - i.e. the income is evenly shared by all members of a household. In practice, however, the income of a household is not evenly shared by all household individuals, with some family members requiring larger personal budgets to fulfill their activities. In order to address this issue, we have set a maximum travel budget threshold of 100% of income per capita because we wanted to assess the accessibility impacts of fuel price increases when allowing for progressively larger affordability thresholds and to account for cases where households may be allocating larger portions of income to a specific breadwinner. Further studies could try to understand how transit monetary costs and household income (rather than income per capita) should be considered in accessibility studies.

2.2.2 Pareto Frontiers

Historically, accessibility analysis has been conducted by calculating a travel time matrix between every possible combination of origin-destination (OD) pair, after which one could easily determine the number of jobs accessible within specific thresholds. However, this approach only considers the fastest trip between each OD pair. In order to accurately account for the impact of both travel time and monetary cost restrictions on accessibility, it is important to consider a wide set of itineraries that range from the fastest (usually the most expensive) to the slowest (and usually cheapest) trips between each OD pair.

Recent studies have adopted different strategies while trying to consider a wide set of different itineraries between OD pairs. For example, Herszenhut et al. (2022) calculated up to 20 different itineraries between two points, and Da Silva et al. (2022) calculated travel times with and without ‘premium’ services that offer faster trips at higher costs. None of these approaches, however, exhaust the full set of itinerary options that may exist between two points, which could lead to less accurate accessibility estimates, and, therefore, policy assessment.

Another recent study has proposed a strategy to exhaust the list of itineraries between OD pairs using a multi-objective optimization or pareto frontier approach (Conway & Stewart, 2019). This strategy relies on finding the fastest trips between each Origin-Destination pair for each possible combination of fares in the transit network. An example pareto frontier is shown in Figure 3, that outlines the trip options that dominate the rest of the alternatives either in terms of monetary cost or travel time. In the example below, walking from origin to destination takes about 110 minutes. This travel time can only be reduced (to about 100 minutes) when spending 4.05 BRL, with which a transit user can ride a bus. Spending anything less than 4.05 BRL would not bring any benefits to the user in comparison to the walking-alternative. The travel time can be further reduced to 95 minutes by spending 8.10 BRL and using the Bus and BRT, and further still by using more money and different services.

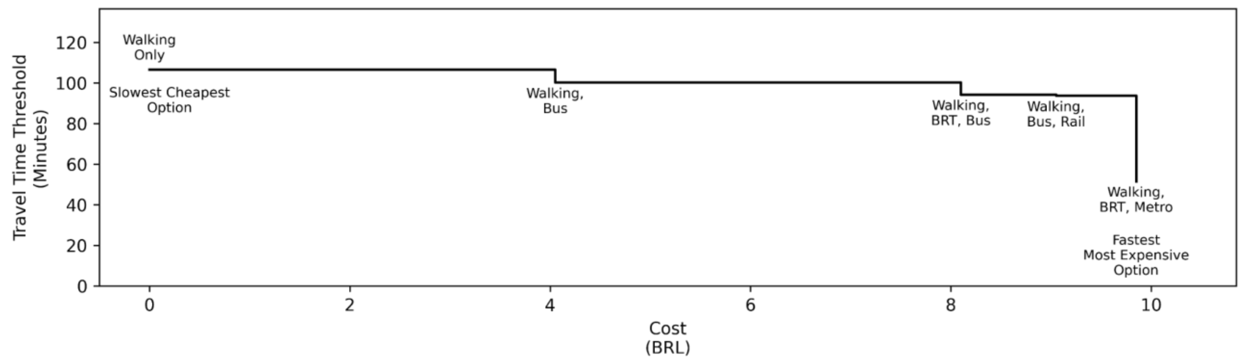

Figure 3: Pareto Frontier Example for single OD pair

To estimate the Pareto frontiers in both cities we used several R functions that allow us to use the R5 multi-modal routing engine developed by Conveyal.[12] These functions are now integrated to the development version (as of June 2022) of the R package r5r (Pereira et al., 2021), an R wrapper to R5, which has a built-in Pareto frontier function.

2.2.3 Inequality

Palma ratio (Palma, 2006, 2011) was chosen to quantify inequality in a single, easily interpretable metric. This metric was originally developed to compare the income of the wealthiest 10% of the population with the poorest 40%. However, it has been adapted in a few transport accessibility studies (Guzman & Oviedo, 2018; Herszenhut et al., 2022) to compare the average accessibility of the wealthiest 10% with the poorest 40%, as shown in Equation 5. While this measure can be criticized for using arbitrary cutoff points when defining who should be considered as the wealthiest and the poorest of a given population, it clearly reflects how accessibility changes for some people in each group and provides an estimate of inequality levels.

$$Palma\ Ratio = \frac{\overline{A}_{w10\%}}{\overline{A}_{p40\%}} \qquad (5)$$

Where $\bar{A}_{w10\%}$ denotes the average accessibility of the wealthiest 10% of the population and $\bar{A}_{p40\%}$ denotes the average accessibility of the poorest 40% of the population.

3 Results

3.1 Baseline accessibility

Before assessing the impacts of carbon taxes on accessibility within the selected study cities, it is important to understand the baseline sensitivity of accessibility to both travel time and travel budget

[12] Available at https://github.com/conveyal/r5.

thresholds. This sensitivity informs the existing constraints on residents and helps to frame how fuel price increases may affect the average accessibility levels in each city, and more specifically, different locations and population groups. In addition, it also provides some understanding of acceptable thresholds to use when investigating the impacts of fuel price changes in each city.

Figure 4 shows the sensitivity of average accessibility with varying travel times and travel budget thresholds for Rio de Janeiro (a and b) and Kinshasa (c and d). The left two subplots (a and c) show how accessibility levels vary when increasing travel time thresholds (shown on x-axis) for different travel budget (as a percentage of monthly income) scenarios (shown with different colors). We compute average accessibility in both Rio de Janeiro and Kinshasa for 41 travel budget threshold scenarios ranging from 0 percent to 100 percent of household income in increments of 2.5 percent. The right two subplots (b and d) show how accessibility levels vary when increasing travel budget thresholds (shown on x-axis) for different scenarios of travel time (shown with different colors). We compute average accessibility for 25 travel time threshold scenarios ranging from 0 minutes to 120 minutes in increments of 5 minutes.

The highest average accessibility in both cities is approximately 60% of total jobs, but this is only when the travel time and budget thresholds are at 120 minutes and up to 100% of income respectively. However, residents are unlikely to be able to spend 100%[13] of their income and travel for 2 hours when commuting. Calculating accessibility in the two cities at 60 minutes (a travel time cutoff frequently used in the literature) while still allowing trips that may cost up to 100% of citizens' income makes the average accessibility peak around 15% and 20% of opportunities in Rio and Kinshasa, respectively. Lowering the travel budget to 20% of income while maintaining the 60 minutes cutoff, results in even smaller accessibility levels of approximately 10% of total jobs. This suggests that many citizens are already excluded from using transport services in both cities before any form of carbon tax on fuel.

[13] Note however that incomes are expressed per capita due to data availability. Results were tested with thresholds up to 150% of income to account for this with no major changes above 100% of income per capita.

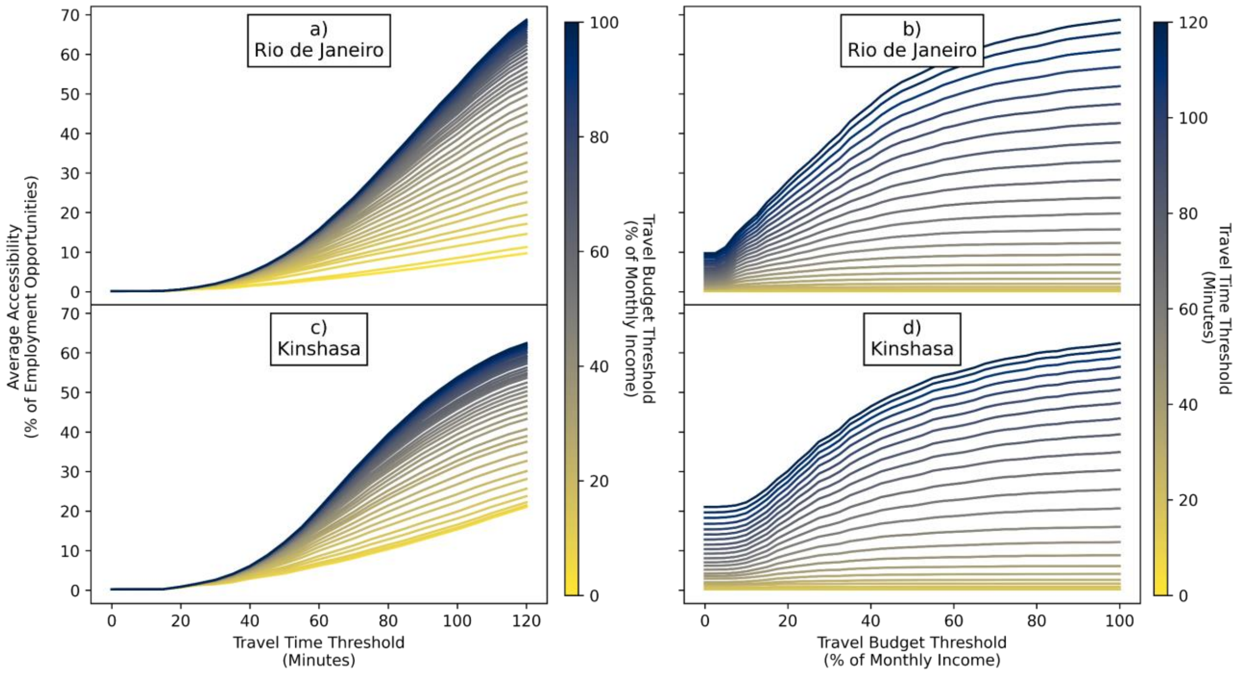

Figure 4: Average Accessibility Baseline Sensitivity to travel time and travel budget threshold

Note: Left hand side subplots a) and c) show average accessibility (in percent of total accessible jobs), for Rio de Janeiro and Kinshasa respectively, as a function of travel time thresholds (x-axis) for various travel budget threshold scenarios (shown in colours) ranging from 0 to 100 percent of per capita income in increments of 2.5 percent. Right hand side subplots b) and d) show average accessibility (in percent of total accessible jobs), for Rio de Janeiro and Kinshasa respectively, as a function of travel budget thresholds (x-axis) for various travel time threshold scenarios (shown in colours) ranging from 0 to 120 minutes in increments of 5 minutes.

In Figure 4 a and c, average accessibility levels hardly increase up until the 30-minute mark. The accessibility curves of both cities have an inflection point at 30-minutes, when the ability to ride transit starts bringing significant accessibility benefits when compared to a walking-only scenario (the equivalent of setting a 0% travel budget limit). In Kinshasa, there is another inflection point around 80 minutes, above which increased travel times thresholds have less impact on average affordability. This may be indicative of an affordability constraint but may also be due to the nature of the spatial distribution of people and economic opportunities in Kinshasa, with most residents that can afford to use transport having already reached the majority of the concentrated employment opportunities. Rio's curves do not show a second inflection point as pronounced as Kinshasa's, but slightly diminishing benefits can be observed with travel times higher than 110 minutes. This difference may be attributable to the more fragmented nature of Rio's labor market, with higher shares of the population living spread out across the study area. Many residents live very far away from the highly concentrated employment opportunities, which results in high accessibility increases at high travel time thresholds.

In Figure 4 b and d, the accessibility curves of both Rio de Janeiro and Kinshasa remain constant with increasingly higher travel budgets until thresholds of 5% and 15% of monthly income, respectively. None of the residents of both cities would be able to afford transit services before these points, so reaching any employment opportunities would only be possible by walking. The higher average walking accessibility in Kinshasa (approximately 20%) relative to Rio (approximately 10%) highlights the compactness of Kinshasa. The inflection points represent when some residents (the wealthier ones) start being able to afford transit services, suggesting that the barrier to use transit is higher in Kinshasa. The average accessibility curves ascend from the inflection point onward, however, not at the same rate. Increasing travel budget thresholds result in smaller increases in average accessibility in Kinshasa than in Rio, and above the 80 minutes threshold Kinshasa's curves begin to plateau with increasing travel budgets. In Rio there are consistent increases in accessibility with both increasing affordability and travel time.

In summary, we can extract three main messages from Figure 4. First, travel time thresholds are the main driver of accessibility in Kinshasa, as can be seen in Figure 4d. When households accept to travel for 120 minutes, average accessibility in Kinshasa is only multiplied by approximately 3 when they spend 100% of their income on commuting instead of 0% (a little over 60% vs 20%, respectively). This is a testimony to the power of compactness and density in enabling connections between households and job opportunities. Second, both travel time and travel budget thresholds are important for average accessibility in Rio, but travel budgets have a much stronger role in Rio than in Kinshasa as can be seen by the much larger spread of accessibility values in Rio for the 120-minute time threshold than in Kinshasa (Figures 4a and 4c). This is indicative that transit and its affordability play a large role in compensating for Rio's fragmented spatial layout (relative to Kinshasa). Third, transit is much more affordable in Rio than in Kinshasa on average. Figures 4b and 4d indeed show that accessibility starts increasing when households can spend about 5% of their income on transport in Rio, whereas this only manifests itself around the 10% mark in Kinshasa.

In cases where comparisons of the two cities will be undertaken, a travel time threshold of 75-minutes will be used. This threshold provides a cross-section where residents are able to use transit services for mobility, there is clear variation between the travel budget thresholds and no secondary inflection point with respect to travel time and travel budget threshold increases has been reached, which could potentially convolute results.

Figure 5 shows the accessibility spatial distribution in Rio de Janeiro and Kinshasa, with increasing travel budget thresholds. This analysis is further supported by baseline accessibility distributions per income decile, which are shown in Appendix C – Baseline Accessibility per Income Decile. At low travel budget limits, accessibility is concentrated around the economic centers (Centro and Gombe) of both cities. However, as the limits get higher, accessibility levels increase along key transit corridors away from the economic hubs. This is particularly concentrated along rail, metro and BRT corridors in Rio and along the N1 between Bon-Marche and Matete in Kinshsasa. Residents located at the peripheries of both cities generally have very low accessibility to economic opportunities.

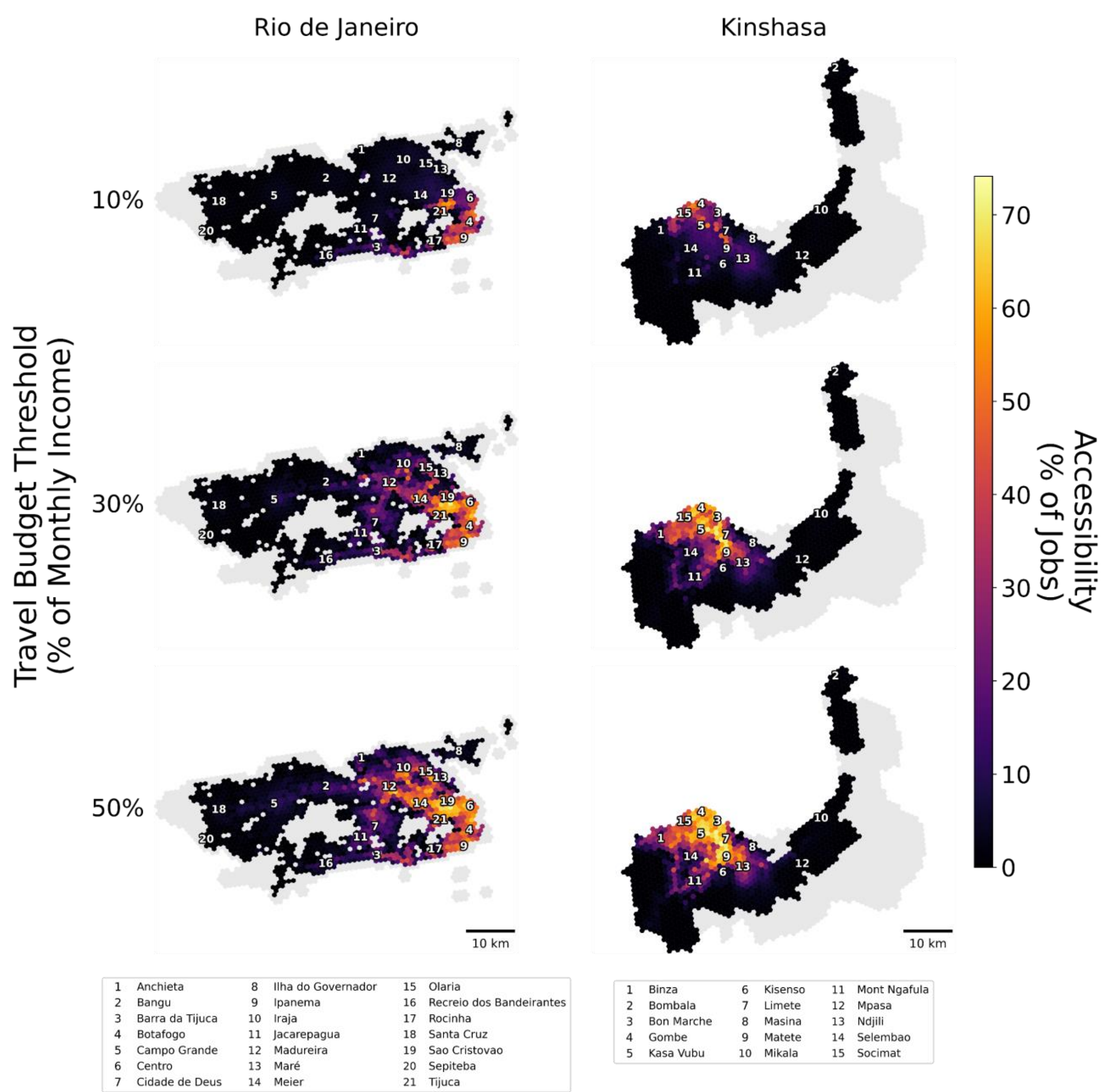

Figure 5: Accessibility in Rio de Janeiro and Kinshasa with increasing travel budget thresholds and a maximum travel time of 75 minutes

3.2 Fuel price sensitivity analysis

Figure 6 shows how the average accessibility in both cities vary in different travel budget scenarios with increasingly higher fuel price increases.

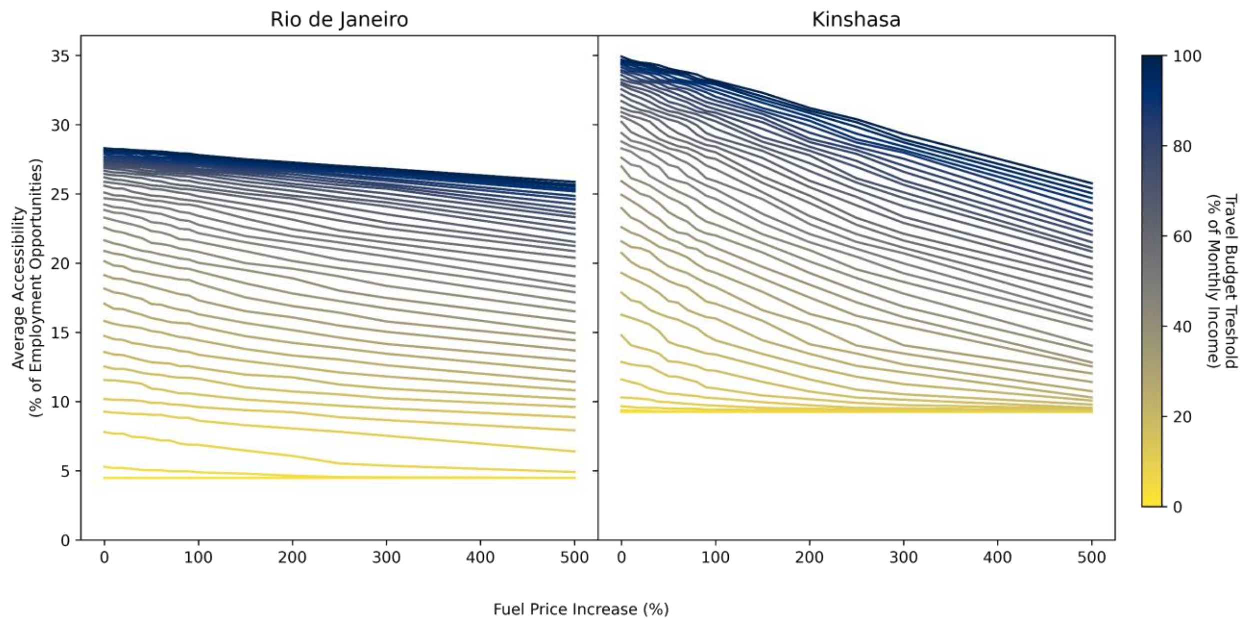

Figure 6: Average accessibility for various travel budget thresholds with an increasing fuel price and 75-minute travel time threshold

Note: Each color-coded curve shows average accessibility (share of total jobs accessible) as function of fuel price percent increases (percent increase with respect to the baseline on the x-axis) for a specific travel budget threshold scenario and for a 75-minute travel time threshold. Travel budget threshold scenarios range from 0 percent of per capita income (bright yellow curve) to 100 percent (dark blue curve at the top).

There are two striking facts in Figure 6: first, accessibility levels in Kinshasa are almost always above those observed in Rio for varying travel budget thresholds and increased fuel prices, with the exception of very high fuel price increases and very high travel budget threshold scenarios. Second, accessibility levels in Kinshasa are more sensitive to fuel price increases than in Rio, as can be observed by much steeper negative slopes on the right-hand figure.

The first point reinforces the previous message that the compactness of Kinshasa and the relatively small average distances between homes and jobs are powerful means not only of connecting households to the labor market but also to mitigate against the negative consequences of higher transport prices.

The second point indicates that households' ability to use transit services is more sensitive to fares in Kinshasa than in Rio, as can be observed from steeper declining slopes in the right-hand side of Figure 6 compared to the left-hand side. In Kinshasa, increasing fuel prices leads to higher average accessibility decreases and larger losses (up to a 10% loss between the highest and the lowest fuel price increase, with travel budgets above 60%) when compared to Rio (up to 4% with travel budgets above 60%), which is indicative of a higher sensitivity to fuel price increases. To illustrate, transit services may be 'just about' affordable for baseline fuel prices for many households in Kinshasa but become unaffordable for marginal increases, where households have to renounce one or all motorized trip legs with higher fares. The lower sensitivity in Rio is indicative of many households having a budget buffer allowing them to absorb fare price increases while remaining within their allocated travel budget threshold. It is also indicative of fuel price increases translating to lower fare hikes because of the availability of several low carbon or decarbonized transit modes (rail, light rail, and metro). These key corridors mitigate the impact of the fuel price increases on average accessibility.

With lower travel budgets, the decline in average accessibility with fuel price increases is less marked. Once budget thresholds are below 10% of income, there is almost no variation in average accessibility with increasing fuel prices. Losses in accessibility are greatest for lower fuel price increases, after which most citizens are unable to afford any transit at such low travel budget levels.

3.3 Income distribution and spatial analysis

The previous section describes how fuel price increases may impact average accessibility levels in both cities and suggests measures to mitigate the loss of accessibility that carbon taxes would trigger. However, this analysis does not assess how specific neighborhoods, communities or socio-economic groups may be more severely impacted than others. Further analysis in subsequent sections investigates how accessibility losses caused by fuel price increases are distributed both spatially and between income groups.

For different fuel price increase levels (20%, 50% and 100%) we calculated the average accessibility level in each hexagon across all travel budget thresholds[14] and the difference between this value and the average accessibility in the baseline scenario (prior to any fuel price increase). The accessibility loss data is then combined with income data to assess the impact on specific socio-economic groups.

The losses in average accessibility for Rio de Janeiro with increasing fuel prices and a maximum travel time of 75 minutes are shown spatially on the left side of Figure 7 below. The middle box plot describes the reductions in accessibility per income decile in absolute terms (% of jobs no longer accessible), while the right-most box plot shows a similar figure with loss of accessible jobs shown in relation to baseline accessibility, i.e., the loss in percent accessible jobs is divided by each income decile's baseline accessibility (percent of total jobs accessible). The red line indicates the population weighted median, while the upper and lower limits the 25th and 75th percentiles. The blue dots indicate the hexagons that compose each decile, irrespective of population.

[14] This was calculated for all travel budgets between 0 and 100% of monthly income (in 2.5% increments) with each travel budget weighted equally.

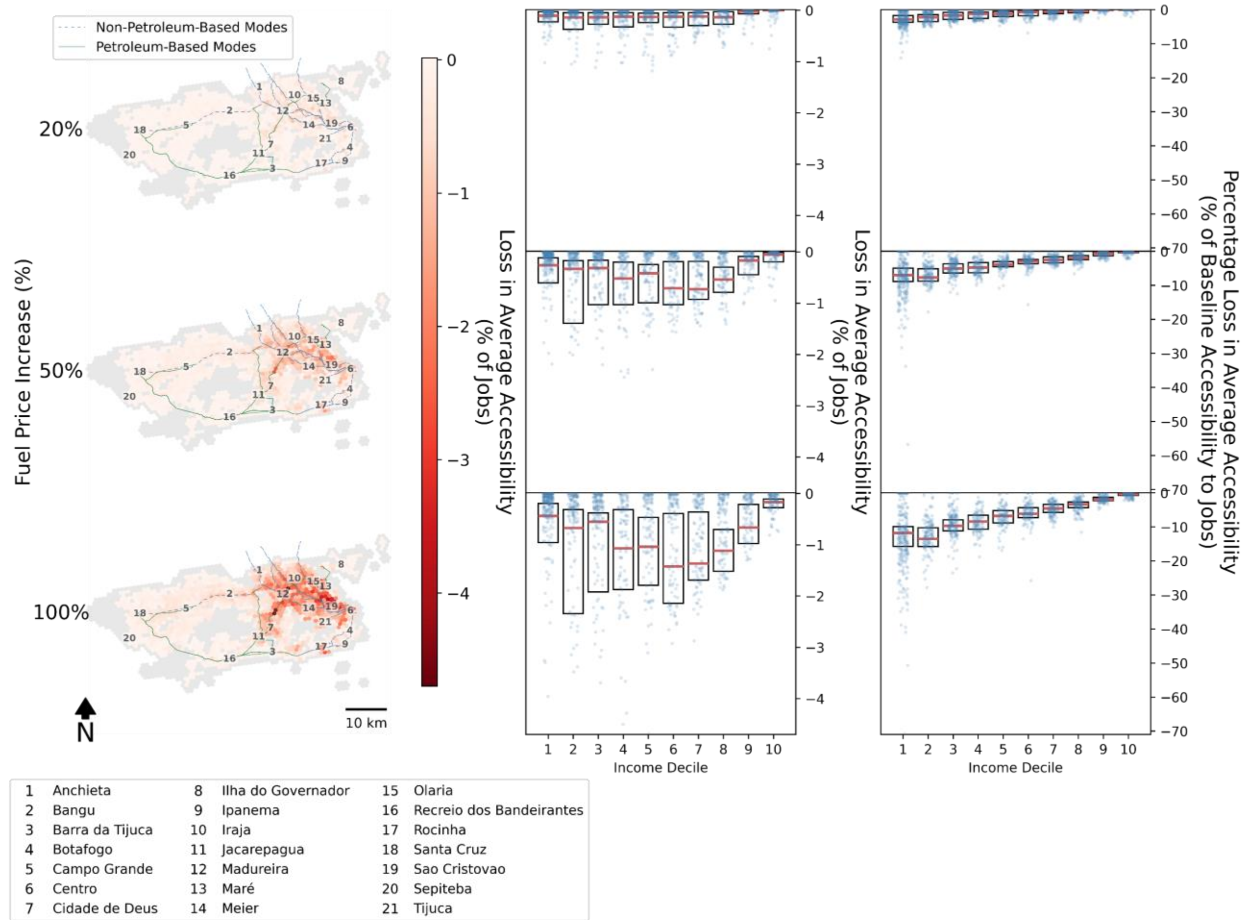

Figure 7: Losses in average accessibility in Rio de Janeiro for increasing fuel prices with a 75-minute maximum travel time

Note: The left-hand side column shows maps of the spatial distribution of loss in average accessibility at the hexagon level for three fuel price increase scenarios represented on each row: 20, 50 and 100 percent of baseline fuel price. The intensity of the loss in accessibility is color coded with dark red representing higher average accessibility losses. The central column shows boxplots of the average accessibility aggregated by income decile for three fuel price increase scenarios represented on each row: 20, 50 and 100 percent of baseline fuel price. The right-hand side column shows boxplots of losses in average accessibility triggered by fuel price increases by income decile relative to each income decile's initial average accessibility level (losses in average accessibility divided by baseline average accessibility). Rows also correspond to three fuel price increase scenarios: 20, 50 and 100 percent of baseline fuel price. The red line in each individual boxplot shows the population weighted median loss in accessibility. The upper and lower limits of the boxplot show the interquartile range between the 25th and 75th population percentile (in terms of average accessibility losses). The blue dots represent average accessibility losses of each hexagon.

Focusing on the left-hand figures, there are areas of Rio that appear to be mostly unaffected by fuel price increases, particularly along the Southern coastline where most of the wealthier residents live. This is confirmed when looking at the highest income groups of both box plots, who appear to be largely unaffected. The maps also show that people on the Western end of the city, where many lower income residents live, appear to be unaffected. However, these residents need to spend more time and money to commute than most of the selected travel time and budget thresholds and are hence relatively unaffected by incremental fuel price increases because they are in fact excluded from using transit services even in the baseline conditions.

The neighborhoods that are most impacted appear to be common spatially across the different fuel price increases, with the severity increasing as the fuel price increases. The areas North-West of Centro tend to be the most affected, particularly along some of the rapid transit corridors that cross the city. Although this whole area suffers relatively high accessibility losses, the segments with the highest losses appear to be in lower income areas, and particularly along the BRT corridor between Jacarepaguá and Olaria. Areas adjacent to non-petroleum-based services (such as the rail and subway) have lower losses. These are confirmed through several regressions (see Appendix D – Supplementary Regression Analysis for further details) which show that income has a strong inverse relationship with losses in accessibility, proximity to non-petroleum-based modes has a weaker inverse relationship and proximity to the BRT (one of the key petroleum-based modes) has a direct relationship. These relationships become more robust and stronger with higher fuel price increases. In other words, income and proximity to non-petroleum-based modes act as cushion against fuel price increases. However, even though the rail and the subway are not as severely impacted by fuel prices as petroleum-based modes, they are the most expensive modes to ride in Rio. Low- and middle-income residents' accessibility, therefore, tend to rely on cheaper and petroleum-based alternatives such as the BRT and the municipal buses to travel, which explains the relatively widespread accessibility loss in northern Rio. Thus, effective ways to mitigate against the impacts of a carbon tax on transit services in Rio include increasing electrification of specific modes[15] and subsidizing cleaner transport modes that remain as viable options to low-income transit users and to people who would be likely to shift away from private vehicles. Offering targeted subsidies to low-income people can also help mitigate the negative impacts of fuel price increases on the most financially vulnerable citizens without requiring the same economic resources of non-targeted subsidies and fleet electrification.

The two sets of boxplots explore how the loss of accessibility is distributed across income deciles. The middle boxplot indicates that loss of accessibility in absolute terms is U-shaped across income groups with the upper-middle-income deciles being most affected (deciles 4, 5, 6, 7 and even 8) and increasingly so with higher fuel price increases. These are income groups which can afford transit services but can be priced out as fares increase. The higher income groups can absorb the fare increase within their travel budget and are therefore less impacted. Finally, the poorest income deciles are only marginally impacted in aggregate absolute terms, as many of them are already excluded from using transit in the baseline for affordability issues and therefore experience no losses. However, it should be noted that whereas poorer income households appear reasonably unaffected as a group, there are quite a few outliers, as demonstrated by the outlier points indicated as blue dots for deciles 1 through 4.

The loss of accessibility in relative terms (right-hand boxplot) shows a different picture, where the impacts are highest for low-income group and decrease with increasing income levels. These impacts also increase with fuel price increases. This complements the previous observation: while the poorest lose little in absolute terms, they are the most impacted in Rio in relative terms.

Figure 8 shows a similar set of figures and metrics for Kinshasa.

[15] This is assuming that electricity is not reliant on carbon-based generation or would not be affected by carbon pricing and hence not susceptible to price increases as carbon pricing is implemented. In 2021, around 80% of all electricity generated in Brazil came from renewable sources, such as hydroelectric plants and biomass (EPE, 2022).

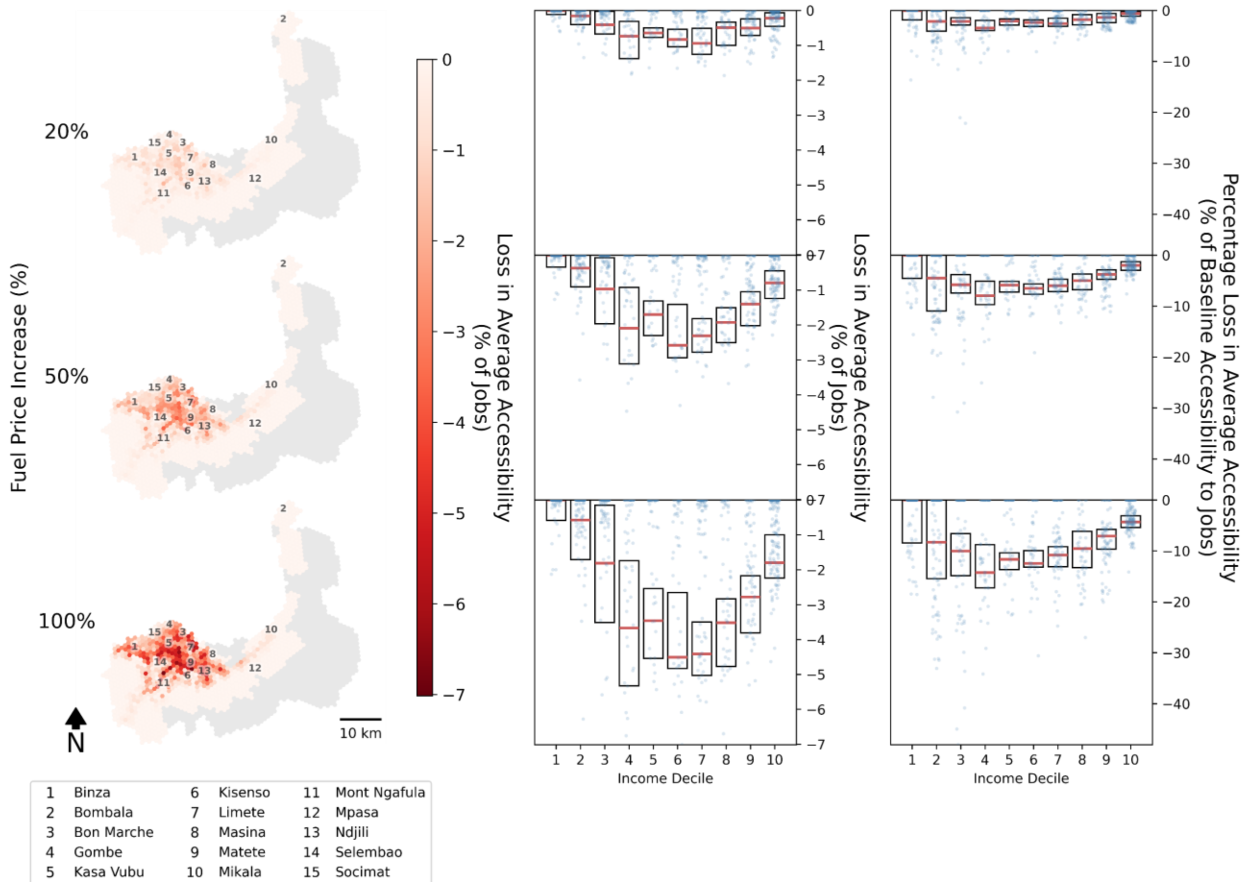

Figure 8: Losses in average accessibility in Kinshasa for increasing fuel prices with a 75-minute maximum travel time

Note: The left-hand side column shows maps of the spatial distribution of loss in average accessibility at the hexagon level for three fuel price increase scenarios represented on each row: 20, 50 and 100 percent of baseline fuel price. The intensity of the loss in accessibility is color coded with dark red representing higher average accessibility losses. The central column shows boxplots of the average accessibility losses aggregated by income decile for three fuel price increase scenarios represented on each row: 20, 50 and 100 percent of baseline fuel price. The right-hand side column shows boxplots of losses in average accessibility triggered by fuel price increases by income decile relative to each income decile's initial average accessibility level (losses in average accessibility divided by baseline average accessibility). Rows also correspond to three fuel price increase scenarios: 20, 50 and 100 percent of baseline fuel price. The red line in each individual boxplot shows the population weighted median loss (absolute or relative) in accessibility per income decile. The upper and lower limits of the boxplot show the interquartile range between the 25th and 75th population percentile (in terms of average accessibility losses). The blue dots represent average accessibility losses of each hexagon.

It is important to note that the severity of the losses experienced in Kinshasa is much higher than that of Rio – both in absolute (7% of jobs, compared to 4%) and relative terms (with the lower limits around 30%, compared to 15%) – with transit services being completely reliant and more sensitive to the fuel price in Kinshasa. The nature of the average loss of access in Kinshasa follows a similar trend to that of Rio, in that the trends are consistent spatially and across income groups, with only the severity of the losses increasing with increasing fuel prices. As with Rio, peripheral residents (who are also mostly lower income) do not lose much accessibility because they were already excluded in the baseline scenario. However, the map shows less clear trends in terms of absolute losses, as residents appear to be losing accessibility along all transit routes. This can be attributed to the high overlap of different services within the city and the high sensitivity that all these services would have to fuel price increases. Noticeable deviations include slightly higher losses in parts of Limete (where residents are not located close to any transport) and slightly lower losses along the N1 – a major arterial road - between Gombe and Matete/Ndjili that has good walkable proximity to most jobs. Wealthier residents in parts of Gombe, Socimat and Mont Ngafula - where price is less of an issue- appear to be slightly less impacted.

The boxplots indicate that the middle-to-higher earning deciles (specifically the 6th and 7th deciles) are more severely impacted than lower income deciles. Unlike in Rio, the lower income deciles are mostly unaffected when accessibility is considered in both absolute and relative terms, cautiously pointing to carbon pricing possibly having some progressive impacts in Kinshasa. This message, of course, needs to be nuanced to account for the fact that higher impacts on the rich are also driven by the exclusion from transport options based on affordability of the less wealthy and those living in the periphery of the urban area, who were completely unaffected by fuel price increases. As well as the highest income deciles being less affected. There are also a high number of outliers in these lower income groups (see blue dots) that had higher losses (particularly in relative terms) than all other income groups, which shows that the few very low-income residents that can afford transit are severely affected by the fuel price increases.

3.4 Inequality analysis

Another way of interpreting the impact of increasing fuel prices on accessibility is to assess the changes in inequality within each of our cities, as measured through the Palma ratio. The Palma ratio compares the average accessibility of the wealthiest 10% of the population with that of the poorest 40%. Before deriving the Palma ratio, the average accessibility for these two groups were assessed to better understand the factors that impact the two groups and thus contribute to the inequality levels in each city.

Figure 9 shows the average accessibility for the wealthiest 10% (a and c) and the poorest 40% (b and d) against increasing fuel prices with different travel budget thresholds indicated by color. Generally, average accessibility decreases for all groups with increasing fuel price, as can be observed from downward sloping curves in panels a to d. There are two exceptions: first, in cases where the travel time threshold is the limiting factor for accessibility, in which case an increase in fuel prices and travel costs does not affect accessibility levels (see Rio's wealthiest residents above 25% travel budget); and second, for very low travel budget thresholds, in which case residents cannot afford to use any transit services and rely solely on walking, with fuel price having no impact on accessibility (below 10% travel budget for the richest 10% and below 30% for the poorest 40% in both cities).

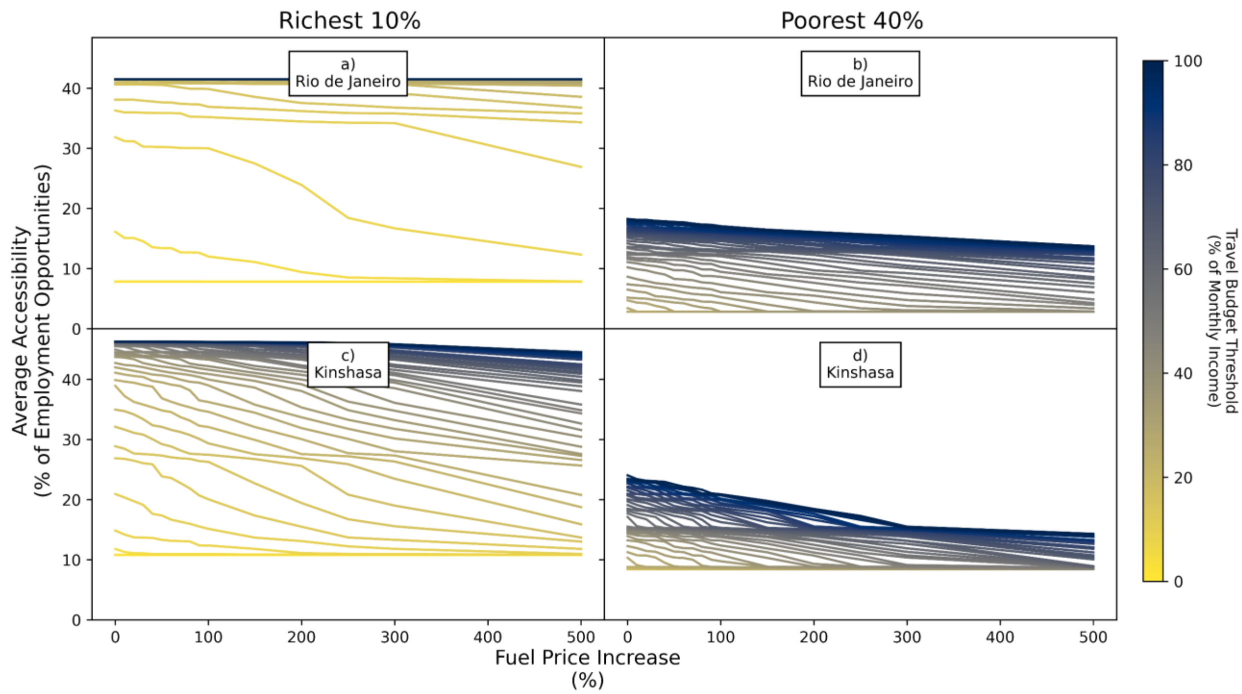

Figure 9: Average accessibility for the richest and poorest population groups with varying travel budget thresholds and increasing fuel prices and a 75-minute travel time limit

Note: The left-hand side subplots a) and c) show the average accessibility of the richest 10 percent households against fuel price increases ranging from 0 to 500 percent in Rio de Janeiro and Kinshasa respectively. The right-hand side subplots b) and d) show the average accessibility of the poorest 40 percent households against fuel price increases ranging from 0 to 500 percent in Rio de Janeiro and Kinshasa respectively. Each color-code curve corresponds to a specific travel budget threshold scenario ranging from 0 (bright yellow) to 100 percent (dark blue) of per capita income.

The maximum average accessibility for the wealthiest residents is higher in Kinshasa than in Rio, likely due to a more fragmented labor market in Rio in comparison to Kinshasa[16] and the choice to look at the 75-minute travel time threshold in this analysis. The wealthier citizens in both cities have greater average accessibility with larger travel budgets (over 40% of jobs). More specifically in Rio, travel budget thresholds of 25% ensure that the wealthiest can reach 40% of the jobs on average. Beyond that, increases in allocated budget thresholds do not translate into higher accessibility, indicating that the limiting factor for accessibility increases is travel time thresholds. Increases in fuel prices in Rio also have mostly limited impacts on the accessibility of the wealthiest, due to the high affordability of transit services for these residents and their proximity to non-petroleum-based services (particularly the metro) that are not highly impacted by fuel price increases. This highlights the benefit that multiple decarbonized transit options have on reducing the impacts of price increases. In Kinshasa, in comparison, increases in travel budget thresholds always translate into accessibility gains even for the wealthiest. This is attributed to the higher levels of poverty, the reliance of transit services in Kinshasa on petroleum-based fuels and the location of some of the wealthiest residents relatively far from economic opportunities, despite the compact nature of the city.

[16] The extraordinary compactness of Kinshasa and population densities mean that average distances between homes and jobs are small. Rio is also a relatively dense city but more fragmented and sprawled out in comparison to Kinshasa.

The poorer residents in both Kinshasa and Rio de Janeiro only have the option to walk until the travel budget thresholds are increased above 30% of income. Their respective average walking-only accessibility are approximately 10% and 5% of total jobs, respectively. Even when travel budget thresholds extend beyond the 30% mark and some of the poorest citizens of both cities start being able to afford transit services, their highest average accessibility (approximately 20% of jobs) is much lower than that of the richer citizens. Contributing to this behavior is the fact that not only the poorest residents tend to live farther from the big employment centers of both cities, but also the fact that even at very high travel budget thresholds many of the poorest citizens are still unable to afford any services, and thus are only able to walk and are consequently unaffected by fuel price increases.

The average accessibility of the richest and poorest citizens is then combined in Figure 10 to calculate the overall Palma ratio for each study area against increasing fuel prices and travel budget thresholds indicated by color. The Palma ratio is calculated by dividing the average accessibility of the richest 10 percent by the average accessibility of the poorest 40 percent households.

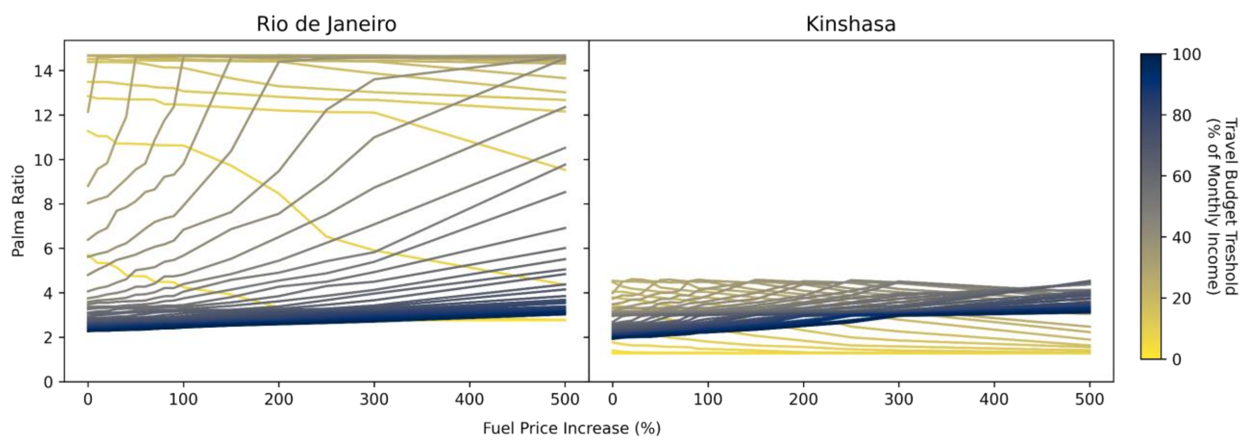

Figure 10: Palma ratio for different travel budget thresholds with increasing fuel prices and a 75-minute travel time limit

Note: Figure 10 presents the Palma ratios of average accessibility, an inequality metric, against fuel price increases ranging from 0 to 500 percent of their baseline value (x-axis) for Rio de Janeiro on the left-hand side and Kinshasa on the right-hand side. Each color-coded curve corresponds to a specific travel budget threshold scenario ranging from 0 percent (bright yellow) to 100 percent (dark blue) of per capita income. Palma ratios are computed by dividing the average accessibility of the richest 10 percent households by the average accessibility of the poorest 40 percent of households.

Figure 10 paints a complex picture of inequality in accessibility to jobs depending on budget thresholds and fuel price increases in Rio de Janeiro and Kinshasa. Before considering the impact of fuel price increases, and in order to make sense of Figure 10, let us focus on how inequality, as measured by the Palma ratio, differs depending on travel budget thresholds and across both cities focusing only on the baseline scenario with fuel price increases of 0%.

The first striking element is the difference in spread of the Palma ratios in Kinshasa and Rio. While in Kinshasa the Palma ratio varies between 1.5 and approximately 5, depending on travel budget thresholds, numbers in Rio range from 3 to approximately 15. This means that an average resident belonging to the wealthiest 10%, under some circumstances, can access 15 times as many jobs as a resident belonging to 40% poorest household. In comparison, that number is 5 in Kinshasa, meaning that maximum inequality, while significant, is 3 times lower than in Rio.

The second striking element of Figure 10 is that when walking is the only option for all households (0% travel budget threshold), the Palma ratio in Rio is 3 while it is 1.5 in Kinshasa. This indicates that richer and poorer households in Kinshasa are on average located nearly as equally close to jobs. In Rio, the richer households are much closer to employment opportunities, reaching as many as three times more opportunities than the poorer households on average.

Thirdly, the level of inequality is highly dependent on the travel budget thresholds. Inequality levels are unsurprisingly lowest when this threshold is set to 0, meaning that all citizens can only commute by foot. Inequality levels (focusing on 0% fuel price increases) have an inverted U-shape with travel budget thresholds. They increase in both cities as travel budget thresholds increase to approximately 30%, and then decrease as budget thresholds increase from 30% to 100% of per capita income. As discussed previously, only the richest residents can afford transport services when considering travel budgets from 0% to 30%, so the inequality levels increase, as the accessibility levels of the rich increase. Beyond 30%, the poorer households can increasingly afford transport services, so the accessibility inequality decreases. It should be noted that for Rio, inequality levels for the travel budget thresholds corresponding to above 60% of income are very close to the inequality levels when all households walk.

But how are these inequality levels affected with increasing fuel prices? For budget thresholds up to 30%, increasing fuel prices decrease inequality levels, as the rich are hit by the fuel price increase but the poorest are still priced out of using transit services. At 30% travel budget thresholds, inequality levels in Rio, and to a lesser extent in Kinshasa, are virtually flat with increasing fuel prices, indicating that both the wealthiest 10% and the bottom 40% are equally affected. Above 30% travel budget thresholds, inequality levels rise with fuel prices, however, these rise more steeply closer to 30% travel budgets with the steepness of the increase decreasing with increasing travel budgets This is indicative that the bottom 40% can be priced out of transit with increasing fuel prices when they can only allocate slightly more than 30% of their incomes to commuting.

3.5 Exclusion analysis

As noted, in both sections 3.3 and 3.4, there are groups of the population that are excluded from using transit services and are hence unaffected by fuel price increases. Additional analysis was conducted to identify the excluded population by assessing the equivalent travel budgets needed to access 10% of employment opportunities. The 10% access to jobs threshold was selected as an arbitrary, but easy to comprehend, value that would indicate some basic level of potential participation in the urban labor market.

Figure 11 shows the equivalent travel budgets required to reach 10% of employment opportunities both spatially (left) and across the income distribution (right) with increasing fuel prices shown from top to bottom in Rio de Janeiro. In the maps on the left, the excluded population that would never have access to 10% of jobs are indicated by black hexagons, whereas the population that could always reach 10% of jobs, irrespective of travel budgets, because they could access 10% of the jobs by walking, are shown with yellow hexagons. Finally, the population that would require a specific travel budget threshold to reach 10% of the jobs are shown with various levels of red. The income distribution figures have stacked bar charts that indicate the percentage of the population in each decile that are either always excluded, always within reach of 10% of total jobs or sensitive to the travel budget threshold.

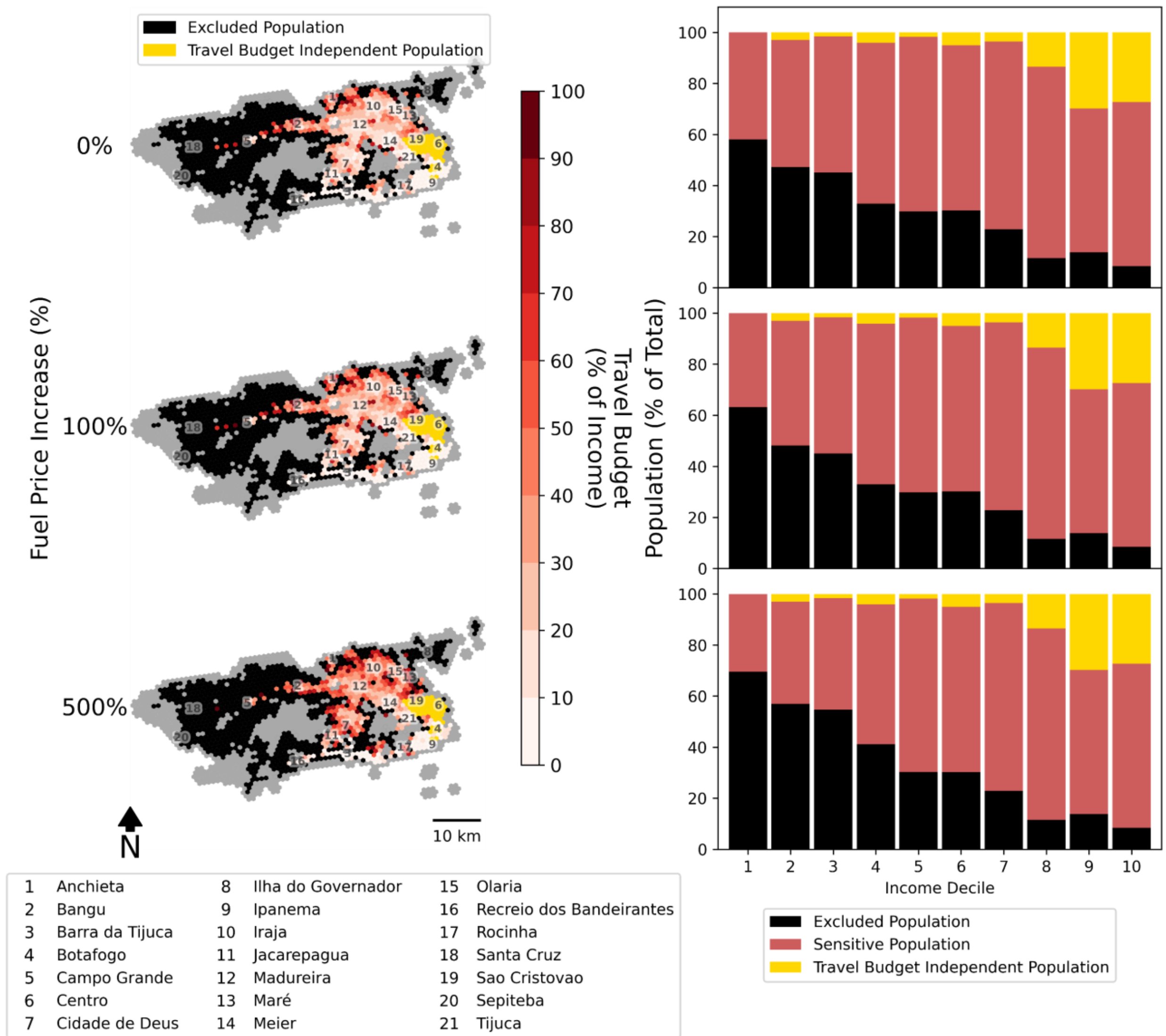

Figure 11: Equivalent travel budget thresholds to reach 10% of employment opportunities in Rio de Janeiro (with a 75-minute travel time threshold)

Note: The left-hand side figure shows the spatial distribution of three categories of population in Rio de Janeiro: in yellow the locations of households that can always access 10 percent of total jobs irrespective of fuel price increases and travel budget thresholds because they can access 10 percent of total jobs by walking ("travel budget independent population"); in black the location of households that can never access 10 percent of total jobs in the urban area, irrespective of how much they are willing to spend on transport because accessing 10 percent of jobs would absorb more than 100 percent of the per capita income ("excluded population"); in red the location of households that can access 10 percent of total jobs through spending a share of their income on transport ("travel budget sensitive population"), with the shade of red indicating the extent of the spending required ranging from light pink (just above 0 percent of per capita income) to dark red (100 percent of per capita income). Each row shows this information for different fuel price increase scenarios ranging from 0 percent (baseline) to 500 percent. The right-hand side uses the same color code to represent the share of the population in each income decile that is "travel budget independent" (yellow), "excluded" (black), or "travel budget sensitive" (red).

Within Figure 11, the excluded areas are predominantly on the peripheries or in areas that have poor access to transit services. Inversely, travel budget independent areas, as indicated in yellow, are concentrated around Centro, where most jobs are located in Rio. The corresponding equivalent travel budgets necessary for different people to reach 10% of opportunities are indicated with varying degrees of red, where a darker red indicates a higher travel budget, with some residents needing to spend 100% of per capita income to reach opportunities.

While there are clearly higher travel budgets required with increasing fuel price scenarios, the spatial trends associated with each scenario consistently suggest that the fuel price increases would exclude already vulnerable communities. The same areas need higher travel budgets and are located in lower income neighborhoods (such as Maré, Cidade de Deus, Rocinha, etc.). Areas along key transit corridors (Rail, Metro, BRT) with reasonable access to the CBD, however, generally need less than 30% of income, even in the 500% fuel price scenario. However, much of the population located along rail stations further West remain excluded.

The exclusion of vulnerable people is even clearer in the distribution of population in each group within income deciles on the right. Even though the charts show almost no changes between scenarios, there are some increases to the excluded population in the lower income deciles with an increase from 55% to 70% of the poorest decile's population. Inversely, the percentage of the population that is independent of travel budgets account for over 20% of the top 2 deciles, decreasing to 0% of the lowest income deciles, with no changes to these groups with increasing fuel prices. Wealthier residents along the South coast require the lowest budgets and appear to have almost no changes in travel budget requirements with increasing fuel prices.

These suggest that the fuel price increases will disproportionately increase the required travel budgets of lower income communities to access opportunities in Rio and that there are large portions of the population that are already economically excluded independently of a fuel price change. Fuel price increases, therefore, will further increase the share of Rio's population (located almost exclusively in the poorest neighborhoods) excluded from transit services.

Similar analysis was conducted for Kinshasa, shown in Figure 12.

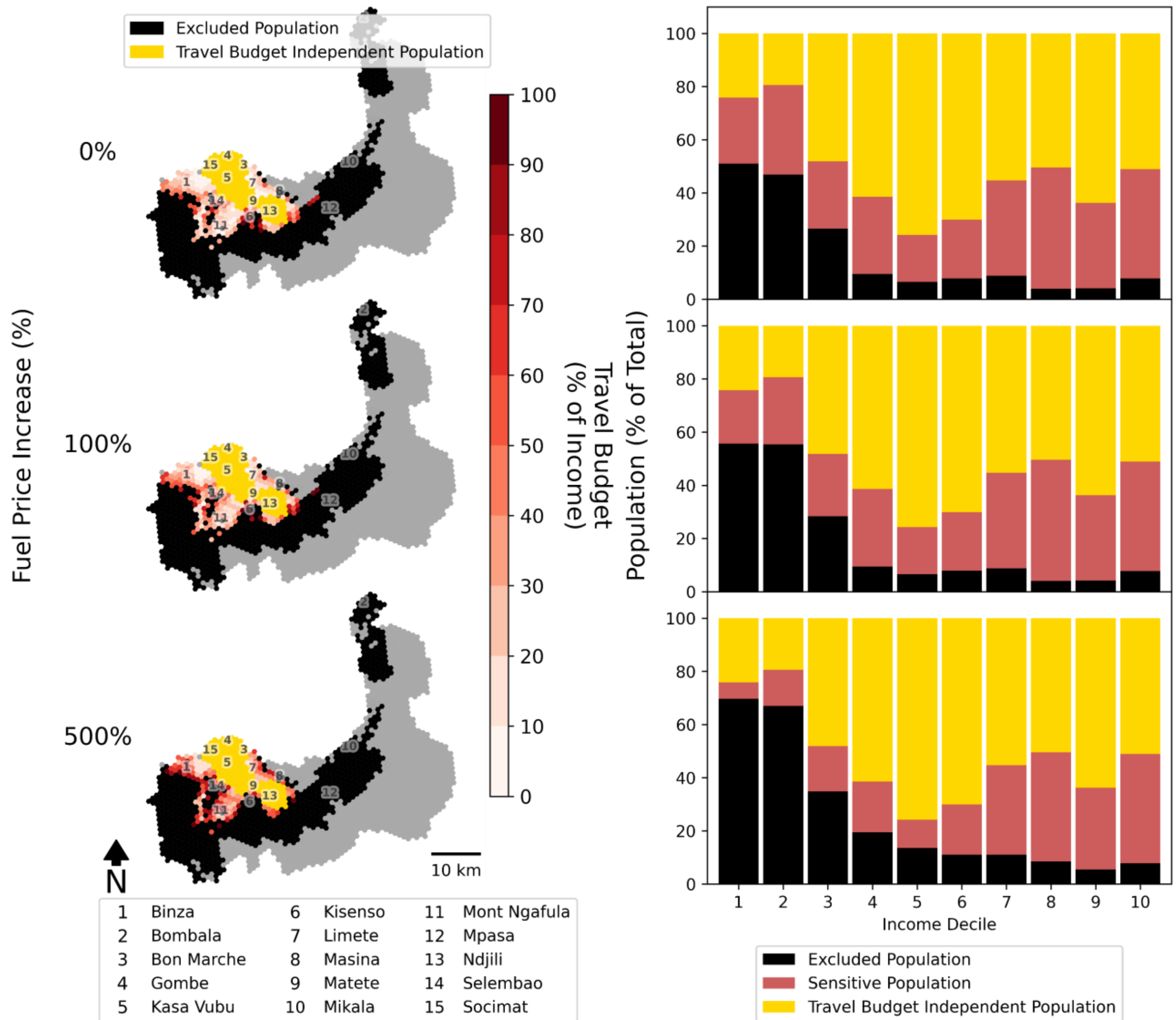

Figure 12: Equivalent travel budget thresholds to reach 10% of employment opportunities in Kinshasa (with a 75-minute travel time threshold)

Note: The left-hand side figure shows the spatial distribution of three categories of population in Kinshasa: in yellow the locations of households that can always access 10 percent of total jobs irrespective of fuel price increases and travel budget thresholds because they can access 10 percent of total jobs by walking ("travel budget independent population"); in black the location of households that can never access 10 percent of total jobs in the urban area, irrespective of how much they are willing to spend on transport because accessing 10 percent of jobs would absorb more than 100 percent of the household income ("excluded population"); in red the location of households that can access 10 percent of total jobs through spending a share of their income on transport ("travel budget sensitive population"), with the shade of red indicating the extent of the spending required ranging from light pink (just above 0 percent of per capita income) to dark red (100 percent of per capita income). Each row shows this information for different fuel price increase scenarios ranging from 0 percent (baseline) to 500 percent. The right-hand side uses the same color code to represent the share of the population in each income decile that is "travel budget independent" (yellow), "excluded" (black), or "travel budget sensitive" (red).

Firstly, the yellow area showing residents who would always be able to reach 10% of jobs regardless of travel budget is much larger than in Rio and accounts for a much larger percentage of the population (approximately 60% of the population from income deciles 4 to 10). This area also largely coincides with the area that loses less relative average accessibility along the N1 corridor and covers a large part of the city proper, which is indicative of the compactness and walkability of Kinshasa. The lowest two income deciles, whose population tend to live farther from the main opportunity centers, only have 20% of their population independent of travel budget to reach 10% of the total jobs in the city. Although lower than other income deciles, this share of the population is much higher than in the case of the same income deciles in Rio, which highlights the role a compact city can play in mitigating the impacts of fuel price increases on people's ability to reach jobs, particularly the most economically vulnerable.

The excluded population is concentrated on the periphery of the city limits and stretches Eastward through the satellite settlements in Mikala and Bombala. Many of these residents would need to spend substantial amounts of time and money to reach their jobs in the city and do not have many transit services operating in these areas. There are some slightly better located, lower income areas around Selembao and Mpasa, that become excluded with high fuel price increases, and while there is not much change in the excluded population between fuel price increase scenarios, there are increases in these areas raising the excluded population in the bottom two deciles from approximately 50% to 70% of the population. These are people that have limited access to transit services and have lower incomes and are particularly sensitive to fuel price increases. While we had previously showed (See section 3.3) that the lowest income deciles were less impacted in Kinshasa, this was because many of these residents were excluded and this excluded population will increase in these deciles with the fuel price increases, suggesting that they will be disproportionately impacted without any intervention in the event a carbon tax is introduced.

As with Rio, the areas that were sensitive to fuel price increases remained the same across scenarios. However, the population living in these areas were much more sensitive to fuel price increases than their Rio counterparts, resulting in much higher travel budgets required to reach 10% of total jobs at higher fuel prices. This highlights the sensitivity of Kinshasa residents to fuel price increases, as transport is relatively expensive against incomes and all modes are dependent on fossil fuels. The only area that was relatively unaffected was parts of Socimat and Binza, where some of the wealthiest residents that cannot walk to 10% of jobs live.

4 Discussion and conclusion

This study evaluated how transit-based access to economic opportunities are impacted by carbon pricing in the form of a fuel-based levy in Kinshasa and Rio de Janeiro with varying travel time and budget thresholds. The goals of this study were to assess how average accessibility would be impacted in two cities of different economic status and with different spatial layouts, to understand which were the heaviest hit communities both in terms of their locations within the urban area and their economic status, to investigate how carbon pricing would impact inequality in accessibility, and shed some light on who and where the households excluded from the use of transit services are located. An overarching goal of the study was to understand whether the most commonly discussed climate policy, a carbon tax, would be regressive or progressive on accessibility to job opportunities, keeping in mind the fact that regressive policies tend to be resisted, regardless of their aggregate economic impacts.

The usage of Pareto frontiers to identify the optimal different itineraries between different origin-destination pairs provides a computationally efficient way to conduct this analysis using both travel time and travel budget thresholds and could be used to assess the impacts of different pricing mechanisms or proposed new services in different cities. While GTFS feeds and socio-economic survey information that provide details related to people’s income and commuting patterns are not available for all cities across the world, this type of analysis would be transferable to any city where this information is available.

Accessibility is concentrated along key transit corridors with the BRT, Metro and Rail services in Rio, and along major arterial roads in Kinshasa, particularly roads that were serviced by multiple modes and had close proximity to economic hubs, forming the backbone of transport systems in both cities. Calculating average accessibility using a combination of walking and transit services for the maximum, and unlikely, budget and time thresholds (100% of per capita income and 120 minutes), we find that an average resident could reach 60% of all jobs in both cities. However, baseline accessibility (prior to fuel price increases) displays different profiles in both cities, when varying the travel time and budget thresholds. In Kinshasa, an extremely compact and dense city, walking alone for two hours could allow an average resident to access 20% of all jobs. On the other hand, a person walking in Rio, less dense and more fragmented than Kinshasa, can only reach 10% of the total jobs in the city on average. For this reason, travel budgets play a larger role in Rio, and transit systems, being relatively more affordable, play a key role in overcoming physical distances and connecting residents with employment opportunities.

With carbon pricing, we observe that Kinshasa’s average accessibility remains above Rio’s for most of the travel budget thresholds and fuel price increases, except at very high values, another testimony to the benefits of compactness in absorbing price shocks. But we also observe that average accessibility in Kinshasa is more sensitive to fuel price changes than in Rio. This is linked to a greater affordability of transit services in Rio, with more households being able to continue using transit services with fare hikes, but also to the greater availability of low-carbon or even decarbonized travel modes (rail and metro) in Rio, for which carbon pricing will only marginally translate into higher fares. This is indicative of another policy-relevant avenue to combine ambitious climate targets and high accessibility to employment: the decarbonization of travel modes. The BRT system in Rio appears as a potential candidate for such an intervention.

Disaggregating the impacts of fuel price increases on accessibility spatially, we find that both in Rio and Kinshasa the hardest hit communities are those that had high accessibility levels in the baseline scenario, because they were relatively close to jobs and major transit services. It is however important to note that communities in the vicinity of the rail and metro systems in Rio are relatively unaffected because they can rely on decarbonized transport systems to reach jobs. The impacts per income group are more contrasted between Rio and Kinshasa. In Rio, deciles 4, 5, 6 and 7, middle income groups, are the most heavily impacted in absolute terms (loss of access in number of jobs), but the lowest income deciles (1, 2, 3) are the most heavily impacted in relative terms (in % of their baseline accessibility). In Kinshasa, income deciles 8 and 9, among the wealthiest, are the hardest hit both in absolute and relative terms, cautiously pointing to fuel price increases having progressive impacts in Kinshasa, although many outliers were also found in deciles 1 and 2 as being severely impacted.

Inequality levels are much higher in Rio than in Kinshasa, as they reach values of 15 and 5 respectively. The impact of fuel price increases on these inequality levels is also complex. When travel budget thresholds are below 30%, fuel price increases reduce inequality because most of the poorest cannot afford transit and the fare increases only weigh on the richer income deciles. Beyond 30% budget thresholds, inequality increases as some of the poorest could start affording transit services in the baseline fuel scenario, but get priced out with fare increases.

Inequality levels are mainly driven by the chosen travel budget thresholds, because depending on these the low- and middle-income populations can be excluded from using transport systems, even prior to any fuel price increases, and therefore do not appear to lose accessibility. However, with fuel price increases they are further away from being able to afford transit services, something that we equally document in our study, in the form of the share of their monthly budget they would need to spend to reach at least 10% of the jobs in each area, and the share of households that would never be able to reach 10% of jobs irrespective of their travel budget. There is a clear negative relationship between income and the share of excluded population, with the excluded population increasing with increasing fuel prices only for the lowest income residents in both cities.

The study has also highlighted two avenues through which the negative impacts of carbon taxes on accessibility to jobs can be mitigated. First, a compact and dense urban form, as is the case of Kinshasa, protects against large losses in accessibility levels because the average distance between households and jobs is smaller, all else equal. This means that walking alone can put you within reach of many opportunities, and that fewer transit legs, and therefore lower travel costs, are needed. Land use planning and efficient land markets can help achieve such outcomes, but the existence of path dependence in urban forms suggests that such tools are most useful in early stages of urban growth, before a city has sprawled. Secondly, the case study of Rio demonstrated that low carbon or even decarbonized transport modes (rail and metro systems powered by electricity) can protect residents against higher carbon taxes, provided that the electricity is itself decarbonized. The electrification of the current BRT system in Rio seems like a promising avenue to decouple carbon taxes from increased transit fares.

More fundamentally, this study has investigated the impact of carbon taxes on accessibility to jobs using transit services. Carbon taxes are the most discussed climate policy, as they are relatively easy to implement, particularly in resource constrained environments with no capital requirements, but they do not equate to climate policies. Many scholars have discussed the benefits and drawbacks of public transport subsidies (Gwilliam, 2017), with one view being that they could constitute an important tool to ensure that transit use is encouraged, in the context of the fight against climate change, especially at the expense of cars, and would be better able to articulate climate ambition and social impact concerns. In fact, examples abound of transit systems and fares being heavily subsidized: Paris, London, some of the largest cities in the United States, with various schemes, some targeting the poorest users, some targeting the most frequent users, and finally some schemes being applied to all users. The impacts of transit service subsidies were not looked into here, but could constitute an important extension of this paper.

5 References

7sur7. (2021). *Le plus grand site d'information en république démocratique du congo*. https://7sur7.cd/index.php/2021/06/24/kinshasacovid-19-le-gouvernement-ngobila-met-en-garde-contre-la-hausse-du-prix-de

Barrington-Leigh, C., & Millard-Ball, A. (2017). The world's user-generated road map is more than 80% complete. *PLOS ONE*, *12*(8), e0180698. https://doi.org/10.1371/journal.pone.0180698

BBS Foundation. (2018, November 9). Sud-Kivu: L'association des chauffeurs du Congo souhaite le «réajustement» des frais de transport en commun. *La PrunelleRDC*. https://laprunellerdc.info/sud-kivu-lassociation-des-chauffeurs-du-congo-souhaite-le-reajustement-des-frais-de-transport-en-commun/

Beeckmans, L., & Bigon, L. (2016). The making of the central markets of Dakar and Kinshasa: From colonial origins to the post-colonial period. *Urban History*, *43*(3), 412–434. https://doi.org/10.1017/S0963926815000188

Bittencourt, T. A., & Giannotti, M. (2021). The unequal impacts of time, cost and transfer accessibility on cities, classes and races. *Cities*, *116*, 103257. https://doi.org/10.1016/j.cities.2021.103257

Brodsky, I. (2018, June 27). *H3: Uber's Hexagonal Hierarchical Spatial Index*. Uber Engineering Blog. https://eng.uber.com/h3/

Carbon Pricing Leadership Coalition. (2020). *Distributional Impacts of Carbon Pricing on Households* [Brief]. World Bank. https://doi.org/10.1596/33686

Cheng, T., & Adepeju, M. (2014). Modifiable Temporal Unit Problem (MTUP) and Its Effect on Space-Time Cluster Detection. *PLOS ONE*, *9*(6), e100465. https://doi.org/10.1371/journal.pone.0100465

Climate Leadership Council. (2019). *Economists' Statement on Carbon Dividends*. Climate Leadership Council. https://clcouncil.org/economists-statement/

Conway, M. W., Byrd, A., & Eggermond, M. van. (2018). Accounting for uncertainty and variation in accessibility metrics for public transport sketch planning. *Journal of Transport and Land Use*, *11*(1), Article 1. https://doi.org/10.5198/jtlu.2018.1074

Conway, M. W., & Stewart, A. F. (2019). Getting Charlie off the MTA: A multiobjective optimization method to account for cost constraints in public transit accessibility metrics. *International Journal of Geographical Information Science*, *33*(9), 1759–1787. https://doi.org/10.1080/13658816.2019.1605075

Cui, M., & Levinson, D. (2018). Full Cost Accessibility. *Journal of Transport and Land Use*, *11*, 661–679. https://doi.org/10.5198/jtlu.2018.1042

Deskeco. (2018, October 1). *Prix du carburant: A Kinshasa, l'Association des Chauffeurs n'envisage pas encore de hausser le prix du transport*. Deskeco - Premier site d'information 100% économie de la RDC. https://deskeco.com/prix-du-carburant-a-kinshasa-lassociation-des-chauffeurs-nenvisage-pas-encore-de-hausser-le-prix-du-transport

El-Geneidy, A., Levinson, D., Diab, E., Boisjoly, G., Verbich, D., & Loong, C. (2016). The cost of equity: Assessing transit accessibility and social disparity using total travel cost. *Transportation Research Part A: Policy and Practice*, *91*, 302–316. https://doi.org/10.1016/j.tra.2016.07.003

EPE. (2022). *Balanço energético nacional 2022: Ano base 2021*. Empresa de Pesquisa Energética.

Ferreyra, M. M., & Roberts, M. (2018). *Raising the Bar for Productive Cities in Latin America and the Caribbean*. World Bank. https://doi.org/10.1596/978-1-4648-1258-3

Foth, N., Manaugh, K., & El-Geneidy, A. M. (2013). Towards equitable transit: Examining transit accessibility and social need in Toronto, Canada, 1996–2006. *Journal of Transport Geography*, *29*, 1–10. https://doi.org/10.1016/j.jtrangeo.2012.12.008

Franklin, S. (2018). Location, Search Costs and Youth Unemployment: Experimental Evidence from Transport Subsidies. *The Economic Journal*, *128*(614), 2353–2379. https://doi.org/10.1111/ecoj.12509

Gulyani, S., Talukdar, D., & Jack, D. (2010). *Poverty, Living Conditions, and Infrastructure Access: A Comparison of Slums in Dakar, Johannesburg, and Nairobi*. World Bank. https://doi.org/10.1596/1813-9450-5388

Guzman, L., & Oviedo, D. (2018). Accessibility, affordability and equity: Assessing 'pro-poor' public transport subsidies in Bogotá. *World Transit Research*. https://www.worldtransitresearch.info/research/6951

Gwilliam, K. (2017, July 24). Transport pricing and accessibility. *Brookings*. https://www.brookings.edu/research/transport-pricing-and-accessibility/

He, Y., Thies, S., Avner, P., & Rentschler, J. (2021). Flood impacts on urban transit and accessibility—A case study of Kinshasa. *Transportation Research Part D: Transport and Environment*, *96*, 102889. https://doi.org/10.1016/j.trd.2021.102889

Heinze, R. (2018). "Taxi Pirates": A comparative history of informal transport in Nairobi and Kinshasa, 1960s–2000s. In *Transport, Transgression and Politics in African Cities*. Routledge.

Herszenhut, D., Pereira, R. H. M., Portugal, L. da S., & Oliveira, M. H. de S. (2022). The impact of transit monetary costs on transport inequality. *Journal of Transport Geography*, *99*, 103309. https://doi.org/10.1016/j.jtrangeo.2022.103309

IBGE. (2021a). *2021 Population Estimates*. https://ftp.ibge.gov.br/Estimativas_de_Populacao/Estimativas_2021/estimativa_dou_2021.pdf

IBGE. (2021b). *Produto interno bruto dos municípios 2019*. https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=2101896

IEA. (2013). *A Tale of Renewed Cities—A policy guide on how to transform cities by improving energy efficiency in urban transport systems*. https://iea.blob.core.windows.net/assets/0f4ded88-91b4-429c-b636-66b239929253/Renewed_Cities_WEB.pdf

IEA. (2022). *Transport*. IEA. https://www.iea.org/topics/transport

JICA. (2019). *Project for Urban Transport Master Plan in Kinshasa City—Volume 1: Urban Transport Master Plan in Kinshasa City*. https://openjicareport.jica.go.jp/pdf/12340303_01.pdf

Lago, L. C. do. (2015). *Desigualdades e segregação na metrópole: O Rio de Janeiro em tempo de crise* (2nd ed.). Letra Capital.

Lall, S. V., Henderson, J. V., & Venables, A. J. (2017). *Africa's Cities: Opening Doors to the World*. World Bank. https://doi.org/10.1596/978-1-4648-1044-2

Leard, B., Linn, J., & Cleary, K. (2020). *Carbon Pricing 202: Pricing Carbon in the Transportation Sector*. Resources for the Future. https://www.rff.org/publications/explainers/carbon-pricing-202-pricing-carbon-transportation-sector/

Levinson, D. M. (2013). *Access Across America* [Report]. Center for Transportation Studies, University of Minnesota. http://conservancy.umn.edu/handle/11299/199892

Maria Vagliasindi. (2012). *Ghana | Implementing Energy Subsidy Reforms*. https://elibrary.worldbank.org/doi/abs/10.1596/9780821395615_CH02

MediaCongo. (2021). *Actualités—Hausse des tarifs de transport en commun: La population face au silence radio des autorités !* https://www.mediacongo.net/article-actualite-90633_hausse_des_tarifs_de_transport_en_commun_la_population_face_au_silence_radio_des_autorites.html

Nakamura, S., & Avner, P. (2021). Spatial distributions of job accessibility, housing rents, and poverty: The case of Nairobi. *Journal of Housing Economics*, *51*(101743). https://doi.org/10.1016/j.jhe.2020.101743

OpenStreetMap. (2022). *OpenStreetMap*. https://www.openstreetmap.org/about

Oviedo, D., Scholl, L., Innao, M., & Pedraza, L. (2019). Do bus rapid transit systems improve accessibility to job opportunities for the poor? The case of Lima, Peru. *Sustainability*, *11*. https://doi.org/10.3390/su11102795

Palma, J. G. (2006). Globalizing Inequality: ‘Centrifugal’ and ‘Centripetal’ Forces at Work. In *Working Papers* (No. 35; Working Papers). United Nations, Department of Economics and Social Affairs. https://ideas.repec.org/p/une/wpaper/35.html

Palma, J. G. (2011). Homogeneous Middles vs. Heterogeneous Tails, and the End of the ‘Inverted-U’: It’s All About the Share of the Rich. *Development and Change*, *42*(1), 87–153. https://doi.org/10.1111/j.1467-7660.2011.01694.x

Peralta-Quiros, T., Kerzhner, T., & Avner, P. (2019). *Exploring Accessibility to Employment Opportunities in African Cities: A First Benchmark* [Working Paper]. World Bank. https://doi.org/10.1596/1813-9450-8971

Pereira, R. H. M. (2019). Future accessibility impacts of transport policy scenarios: Equity and sensitivity to travel time thresholds for Bus Rapid Transit expansion in Rio de Janeiro. *Journal of Transport Geography*, *74*, 321–332. https://doi.org/10.1016/j.jtrangeo.2018.12.005

Pereira, R. H. M., Herszenhut, D., Braga, C. K. V., Bazzo, J. P., Oliveira, J. L. A., Parga, J. P., Saraiva, M., Silva, L. P., Warwar, L., & Tomasiello, D. B. (2022). Distribuição espacial de características sociodemográficas e localização de empregos e serviços públicos das vinte maiores cidades do Brasil. *Texto para Discussão IPEA*, *2772*, 28. https://doi.org/10.38116/td2772

Pereira, R. H. M., Saraiva, M., Herszenhut, D., Braga, C. K. V., & Conway, M. W. (2021). r5r: Rapid realistic routing on multimodal transport networks with r 5 in r. *Findings*, 21262. https://doi.org/10.32866/001c.21262

Pigato, M. A. (2019). *Fiscal Policies for Development and Climate Action*. World Bank. https://doi.org/10.1596/978-1-4648-1358-0

PMUS-Rio. (2015). *Resumo do Diagnóstico*. https://www.rio.rj.gov.br/documents/5450795/7289444/IX+.+Resumo+do+Diagn%C3%B3stico.pdf

Radio Okapi. (2018, May 22). *Kinshasa: Le gouverneur André Kimbuta insiste sur le respect des prix du transport en commun*. Radio Okapi.

https://www.radiookapi.net/2018/05/22/actualite/societe/kinshasa-le-gouverneur-andre-kimbuta-insiste-sur-le-respect-des-prix-du
RFI. (2018, May 4). *RDC: Augmentation des prix des transports à Kinshasa*. RFI. https://www.rfi.fr/fr/afrique/20180504-rdc-augmentation-prix-transports-kinshasa
Ricky Burdett, Ömer Çavuşoğlu, Savvas Verdis, Thomas Matussek, Deyan Sudjic, David Harvey, Susan S. Fainstein, Edgar Pieterse, Richard Sennett, Rahul Mehrotra, Enrique Peñalosa, Andy Altman, & Catarina Heeckt. (2013). Urban Age—City Transformations Conference—Rio de Janeiro—24-35 October 2013. *City Transformations*. https://lsecities.net/wp-content/uploads/2013/10/city-transformations-newspaper_en.pdf
Sims, R., & Schaeffer, R. (2014). *IPCC - AR5 Climate Change 2014: Mitigation of Climate Change*. IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf
SSATP. (2001). *SSATPWP54.pdf* (Working Paper No. 54). The World Bank and Economic Commission for Africa. https://www.ssatp.org/sites/ssatp/files/publications/SSATP-WorkingPapers/SSATPWP54.pdf
Telaye, A., Benitez, P., Tamru, S., Medhin, H., & Toman, M. (2019). *Exploring Carbon Pricing in Developing Countries: A Macroeconomic Analysis in Ethiopia*. World Bank. https://openknowledge.worldbank.org/handle/10986/31717
Venables, A. J. (2017). Breaking into tradables: Urban form and urban function in a developing city. *Journal of Urban Economics*, *98*, 88–97. https://doi.org/10.1016/j.jue.2017.01.002
World Bank. (2018). *Democratic Republic of Congo Urbanization Review: Productive and Inclusive Cities for an Emerging Congo*. World Bank. https://doi.org/10.1596/978-1-4648-1203-3
World Bank. (2019, October 17). *Democratic Republic of Congo—Overview* [Text/HTML]. World Bank. https://www.worldbank.org/en/country/drc/overview
World Bank. (2022). *Carbon Pricing Dashboard*. https://carbonpricingdashboard.worldbank.org/
WorldPop. (2022). *WorldPop*. https://www.worldpop.org/
Wu, H., Avner, P., Boisjoly, G., Braga, C. K. V., El-Geneidy, A., Huang, J., Kerzhner, T., Murphy, B., Niedzielski, M. A., Pereira, R. H. M., Pritchard, J. P., Stewart, A., Wang, J., & Levinson, D. (2021). Urban access across the globe: An international comparison of different transport modes. *Npj Urban Sustainability*, *1*(1), Article 1. https://doi.org/10.1038/s42949-021-00020-2
ZoomEco, L. (2018, December 29). *RDC: Carburant, le prix du litre a augmenté de 29,5% en 2018 !* https://zoom-eco.net/economie/rdc-carburant-le-prix-du-litre-a-augmente-de-295-en-2018/

Appendix A – Detailed Data Description

Street Networks

Data for the street networks for pedestrians for both Rio de Janeiro and Kinshasa were extracted from OpenStreetMap (OSM). A global collaborative community of mappers who all contribute and maintain publicly available data related to roads, points of interest and administrative boundaries (OpenStreetMap, 2022). Researchers estimate that approximately 80% of the street grid is accounted for on OSM and it is widely accepted as a reliable source of road network data (Barrington-Leigh & Millard-Ball, 2017). A base walking speed of 3.6km/h was used across the road network. Digital Elevation Models (DEM) for both cities were also incorporated into the street networks to account for the impact that slopes might have on walking speed with these being adjusted through Conveyal's R5 engine using Tobler's hiking function.[17]

Transport Networks

Transit networks in both cities are described in the General Transit Feed Specification (GTFS) format. GTFS is a standardized framework for transit service schedules and geographic information. It was created with the intention of standardizing the way public transit data is published and used (particularly for software applications) globally and utilizes a series of relational .txt files to efficiently store this data (Google, 2021). It includes data related to the stops, schedule (frequency-based or specific schedules), and routing related to different services within a transit system and can often include other supplementary information such as fares or details regarding informal modes of transit. It is generally used to support navigation for familiar software applications such as Google Maps, Waze, CityMapper, etc. and has also been used extensively in the study of transit networks (Barbeau & Antrim, 2013).

Rio's feeds were provided by transport operators (Fetranspor and SuperVia) and represent a typical day of operations in November 2018 for the metro, rail, light rail, BRT, municipal bus, and ferry services operating within the municipal boundaries. The municipal buses provide the most comprehensive service across all areas of the city acting as both trunk and feeder services, however, the metro, rail and BRT services provide more efficient access along key trunk routes. Fare information was incorporated based on the fares in effect in December 2021.[18] Rio's transit users can use a smartcard to enjoy fare discounts partly subsidized by the municipal and state government, but this study considered the full undiscounted fares to understand how climate change-related fuel taxing policies may affect transit affordability and accessibility without government intervention. Unfortunately, the available GTFS data does not extend across Rio's greater metropolitan region, meaning that the study needed to focus on the municipal boundary rather than the functional labor market.

Data for Kinshasa was provided by GoMetro, a service provider specializing in the mapping and quantification of transit networks - particularly in environments with high informality and data scarcity as part of work carried for a study completed for the World Bank (He et al., 2021). Kinshasa has several transit services including a public bus operator (Transco), public minibus operators (Esprit de Vie), private

[17] Details of which are described on the Conveyal website and github repository. Available at https://docs.conveyal.com/learn-more/generalized-cost and https://github.com/conveyal/r5/blob/43068e168138bc5636d895861209c1c0049e0f1a/src/main/java/com/conveyal/r5/rastercost/ToblerCalculator.java#L32

[18] Please refer to the Riocard Mais website for the full set of up-to-date fares. Available at https://www.cartaoriocard.com.br/rcc/institucional/tarifas

minibus operators (Esprit de Mort), 4–5-seater taxi service running along specific routes (Taxi Jaune) as well as motorcycle taxis (referred to as Moto's in Kinshasa) which account for many first and last mile trips, however, do also operate along fixed routes between locations where congestion and road conditions are an issue for larger vehicles. There are no special rates or fare systems operating in Kinshasa where passengers could gain discounts or benefits for using specific services. Despite the system having some regulation through the governor, there is widespread deviation from these practices, and while private operators are governed by the ACCO these drivers also tend to deviate from standards resulting in higher prices. Approximately 80% of the road network is unpaved.

The GoMetro team gathered data (including routes, stops, travel times and fare information) for all modes over three weeks between January and February 2020 representing typical operations over that period. After identifying all transport services and their operational routes, the team used their proprietary GoMetro Pro mobile phone application to map each route. Enumerators ride round trips of each route at least once documenting information related to location, fares, stops and deviations.

Hexagonal Grid

Uber's publicly available H3 framework [Brodsky, 2018] was utilized in order to analyze accessibility across each of the cities, using the level 8 aperture (corresponding to approximately 900m diagonals and $0.7km^2$ areas). The study areas for each city were similar in size with $1552km^2$ and $1200km^2$, corresponding to 1853 and 2018 hexagons in Kinshasa and Rio de Janeiro respectively.

Socio-Economic Data

Understanding the socio-economic conditions in each city was integral to how the city's transit systems currently functioned and how they were impacted by fuel price increases. Figure 13 below shows the number of employment opportunities aggregated per hexagon in both study areas. Economic activity is concentrated in the historic city center (Centro), with lower levels of employment sightly North and South of this region, and to a lesser extent in parts of Barra de Tijuca. In Kinshasa employment is concentrated in Gombe and surrounds and lower levels of employment in Ndjili and Matete.

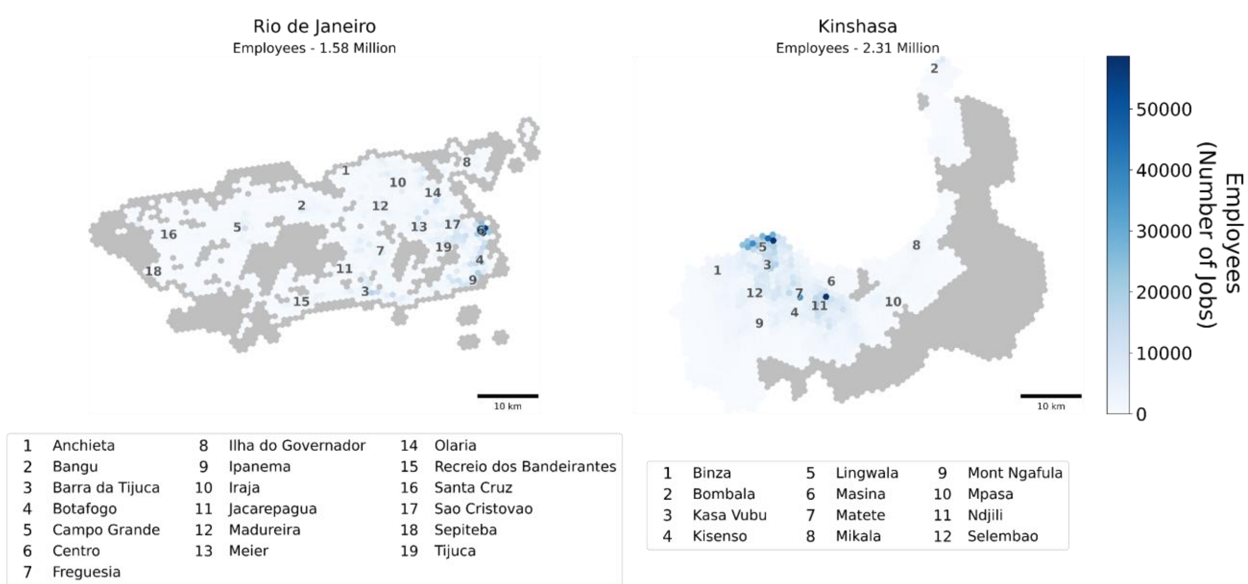

Figure 13: Employment in Rio de Janeiro and Kinshasa

An important component of the intended analysis was to compare the cost of transit services relative to incomes in an area. However, it is important to note that amounts that individuals are prepared to spend on mobility varies across cities and income groups. Analysis was conducted with relative affordabilities between 0 and 100% of income per capita to account for this. Income per Capita information was available from the Access to Opportunities project in Brazil and this could also be calculated for Kinshasa per TAZ based on the survey information. However, there are limitations to using income per capita as a measure of individual spending, particularly when focusing on commuting to economic opportunities, which would assume that each household would split their income between all members and use that equally for all costs including transport. In practice this may differ with households allocating more to breadwinners, however, it was selected as a metric due to data availability.

The income distributions in each city are quite different as shown in Figure 14 below. Notably, Kinshasa is relatively poorer with a very small wealthy population. This is contrasted with Rio de Janeiro, whose entire income distribution is shifted up the income bands and has two distinct peaks at 200-300$ and 1000-1500$ and a longer tail, which is characteristic of the inequality that exists within Brazil.

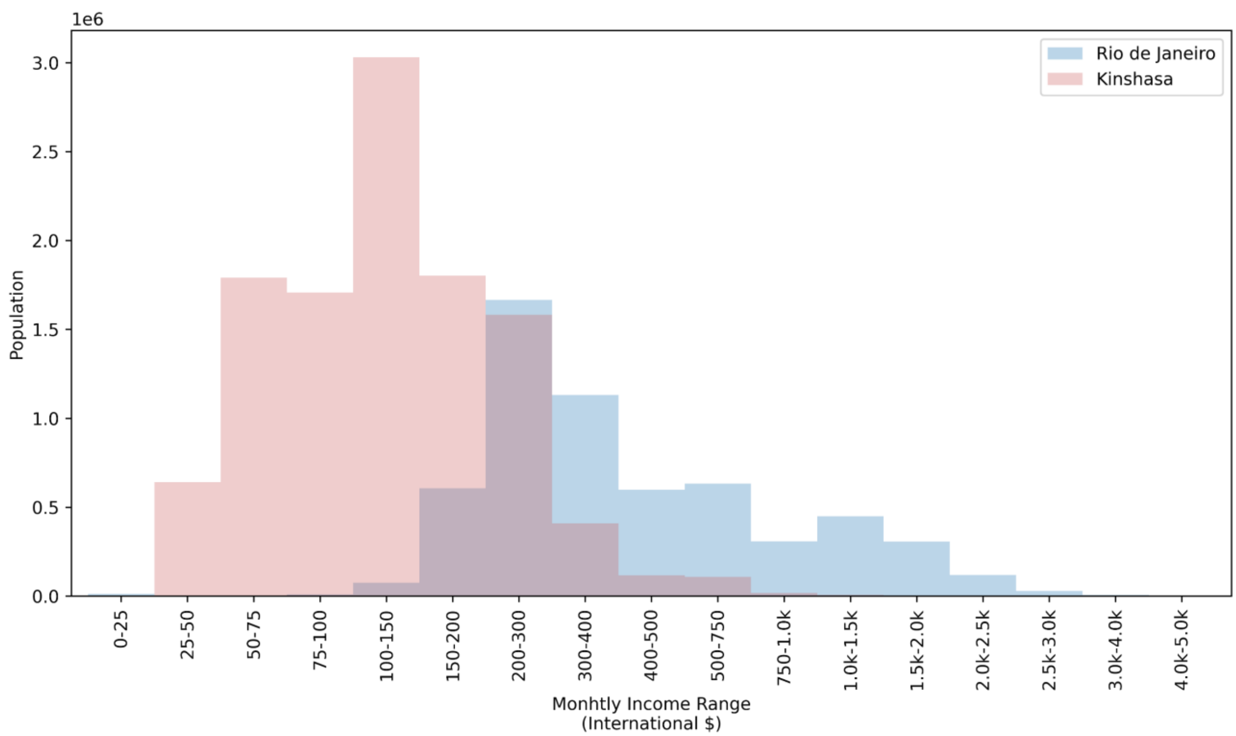

Figure 14: Income Distributions (Converted to PPP)

Income deciles spatially for each city are shown in Figure 15 below. Rio de Janeiro's high earners are concentrated on the Southern coastline from Botafogo across to Recreio dos Banderantes. Income generally decreases as you move further North and further West away from Centro. Kinshasa has high income earners concentrated around Lingwala and in Mont Ngafula. Lower income residents are concentrated between Selembao and Ndjili, with poorer residents located along the Northeastern corridor towards Bombala.

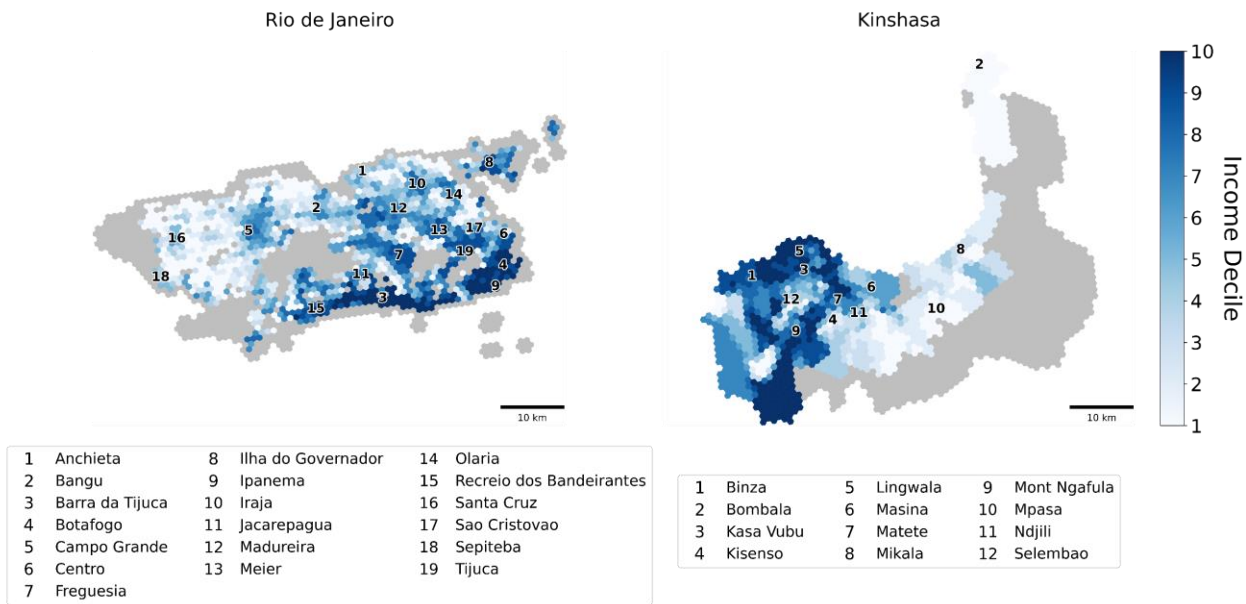

Figure 15: Income Deciles in Rio de Janeiro and Kinshasa

In addition, population data from WorldPop (WorldPop, 2022) was also used comparatively to ensure that the survey information aligned to expected population figures in both cities, but particularly for Kinshasa. The population in both Rio and Kinshasa, according to WorldPop, aggregated to equal area hexagons are indicated in Figure 16 below. While Rio is considered a dense city globally, relative to the denser parts of Kinshasa it has lower levels of population concentration. Rio's population is spread out over a larger area extending over much of the Eastern part of the city decreasing further North and West, away from employment and the historic city center. It is important to note the high densities of people in Kinshasa within the city proper all have reasonable proximity to economic opportunities, however there are specific communities that live further away along the North-Eastern Corridor.

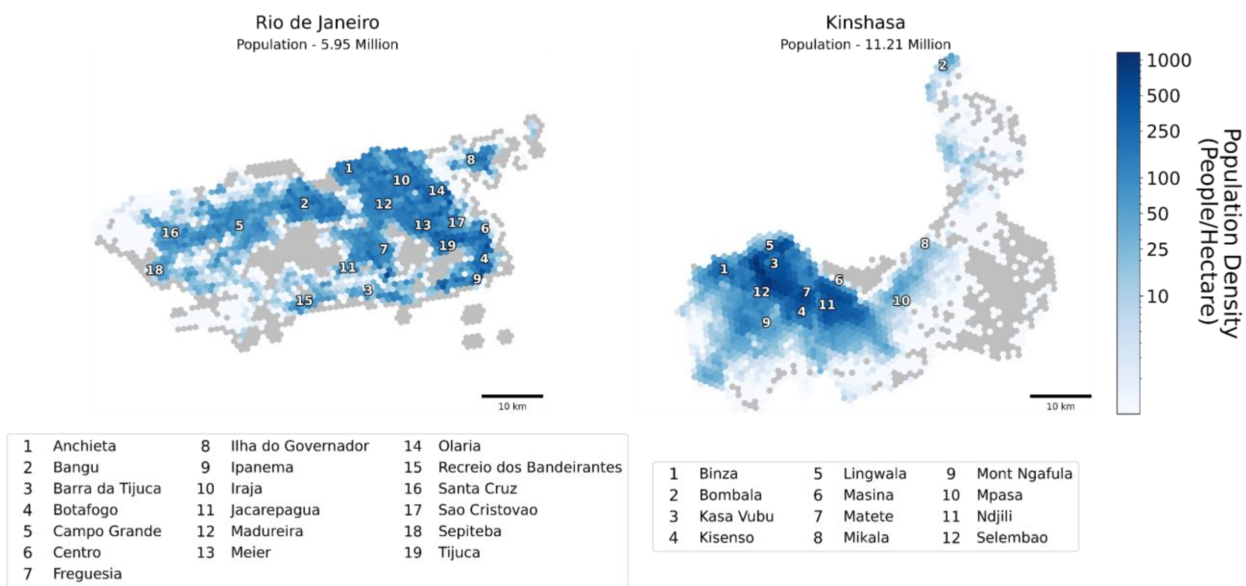

Figure 16: Population in Rio de Janeiro and Kinshasa

Fare Composition for Kinshasa

While the fares for public services in Kinshasa are regulated by the Governor, this information could not be found publicly. Similarly, evidence suggests that private operator fares are regulated to some extent by a private operator union, l'Association des Chauffeurs du Congo (ACCO) (Deskeco, 2018), which could also not be found publicly. However, it is important to note that private service providers often do not adhere to the governors or associations regulations with drivers typically earning income through commission after operating expenses (fuel, small repairs, tips for touts, bribes to police) (Heinze, 2018) which can significantly affect their earnings. Drivers are incentivized to hike prices wherever possible. and typically charge higher fees during peak hours, suggesting higher sensitivity (relative to the proposed fuel cost composition proposed) to the petrol and diesel prices for these services (7sur7, 2021; MediaCongo, 2021).

Historically, the two most recent adjustments to the price regulations by the governor were made in 2011 and 2018 which were attributed to both fuel price and inflation. The 2018 adjustment corresponded to between a 30-40% price increase for different services from the 2011 regulations (Radio Okapi, 2018; RFI, 2018). Over this same period, despite high volatility, the price of fuel increased from 920 CDF to 2000 CDF per liter (BBS Foundation, 2018; ZoomEco, 2018), suggesting that an approximate 100% fuel price increase corresponds to a 30-40% service price increase (some of which may be attributed to inflation).

In order to further verify the implications of a fuel price increase on services, similar investigations were conducted to identify the cost component of fuel in operational costs for potentially similar cities. These included: Abidjan – 40%, Bamako – 40%, Nairobi – 30% and Harare – 35% (SSATP, 2001).

Based on the above information, the service price increases associated with a fuel price increase in Kinshasa were assigned Table 3 below with services prices adjusted based on the type of vehicles and services provided.

Table 3: Service Price increase per Fuel Price in Kinshasa

Service	**Base Fare Range (CDF/ International $)**	**Share of Operating Cost attributed to fuel**	**Explanation**
Transco	500-1000/0.61-1.22	30%	Bus Service
Esprit de Vie	500-1000/0.61-1.22	30%	Bus Service
Esprit de Mort	300-1000/0.37-1.22	40%	Private Minibus Service
Taxi Jaune	300-2500/0.27-3.06	30%	4-Seater Sedan Service
Moto Taxi	100-2000/0.12-2.44	20%	Motorbike Service

Appendix B – Detailed Methodology

Palma Ratio

The regions defined as the poorest 40% and richest 10% of the population are shown in Figure 17 below for Kinshasa and Rio respectively. While the lower income areas are significantly larger than the highest income regions, with the lower income areas being concentrated on the outskirts of both cities there are large lower income regions that are well-located and have higher proportions of the poorest population.

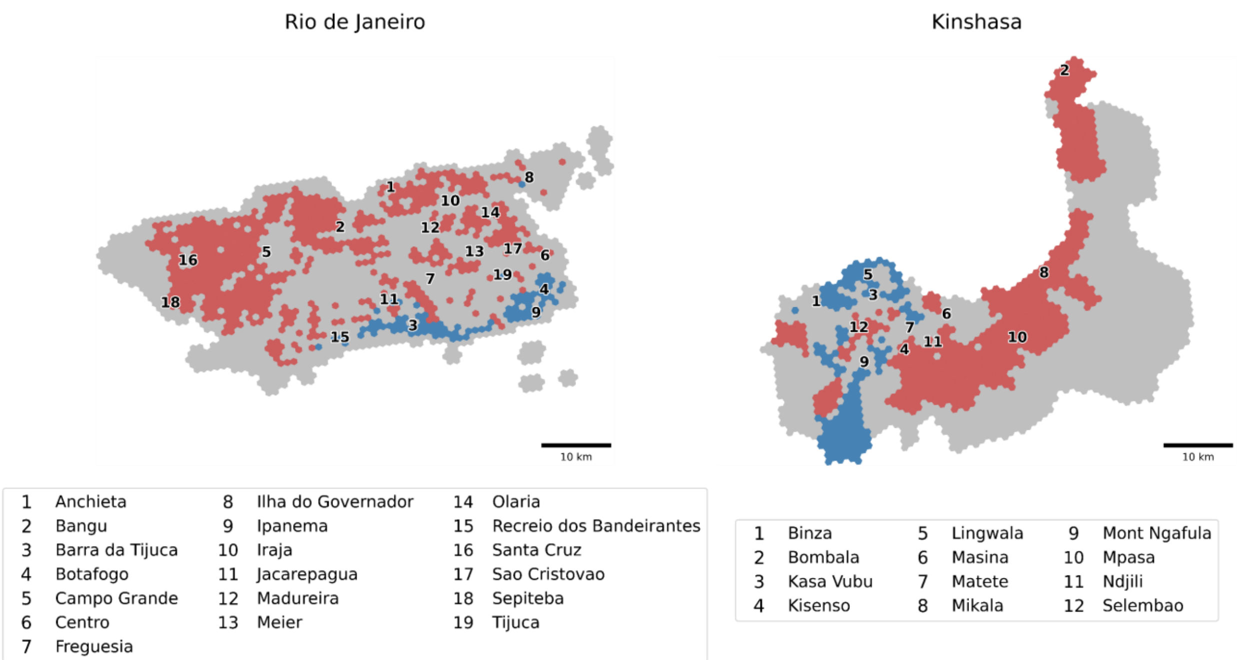

Figure 17: Palma Regions in Rio de Janeiro and Kinshasa

Appendix C – Baseline Accessibility per Income Decile

Further baseline accessibility analysis was conducted to identify the baseline trends in accessibility per income decile across each of the study cities. This is shown in Figure 18 below, where the box plots indicate the 25th, 50th (in red) and 75th population weighted percentiles per income decile, with the blue dots indicative of each hexagon within each decile and the corresponding accessibility.

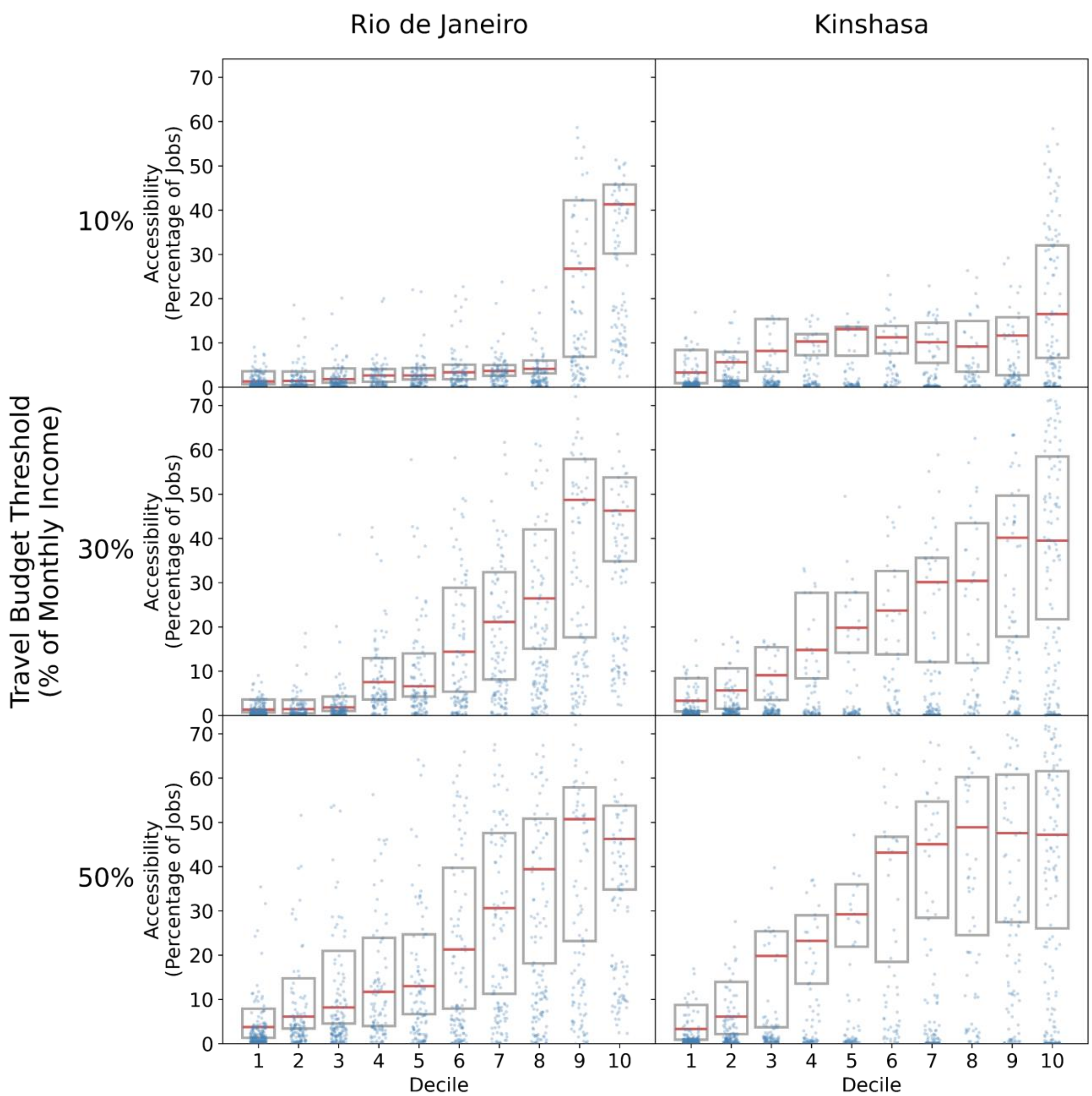

Figure 18: Population Weighted Baseline Accessibility per Income Decile

There are three clearly defined groups within Rio, regardless of the travel budget threshold. The high-earning group in the two highest income deciles - who always have much higher accessibility than the others. The middle-income group (between the 4th and 8th deciles) – who cannot afford to use transit in the 10% travel budget scenario, but see large changes with higher travel budgets. Finally, the low-income group (The 3rd decile and below) – who can only afford to use transit once the travel budget threshold is increased above 50%.

In Kinshasa, there are not necessarily clearly defined groups with more continuity across the income deciles. However, apart from the top decile, almost no one can afford transit in the 10% travel budget scenario. When this is increased to 30%, each decile shows increases in accessibility, with the higher income deciles showing much higher increases. At the 50% travel budget, this same trend continues, however, deciles 7-10 appear to have leveled out and are not increasing with any increased travel budget limits.

Appendix D – Supplementary Regression Analysis

Additional analysis was undertaken to assess how the proximity of petroleum- and non-petroleum-based modes may be impacting the losses in accessibility experienced by residents in Rio de Janeiro. It was hypothesized that the decarbonized modes were mitigating the impacts of the fuel price increases to some extent. Initial ordinary-least squares and weighted ordinary-least squares regressions provided evidence of this relationship and so no further spatial regressions were conducted.

Non-Petroleum Based Modes Proximity and Income controls

Initial regressions assessed the relationship between losses in accessibility with the proximity (defined as the travel time through walking) to non-petroleum-based modes with additional controls for baseline accessibility and income.

$$\begin{aligned}(\text{Accessibility loss})_{i,j} &= \alpha + \beta_1(\text{Travel time to decarbonized transport})_i \\ &+ \beta_2(\text{Baseline accessibility})_i + \beta_3(\text{Income})_i + \varepsilon_i\end{aligned} \tag{6}$$

Where the outcome variable (Accessibility loss)i, j is the percentage reduction (in absolute terms) in accessibility for pixel i due to j percent increase in fuel prices. For the purposes of the regression, we only consider 10% to 100% increases in fuel prices as the relationship is consistent.

Table 4 summarizes the regression results. The coefficients estimates for the income variable are strongly negative and relatively robust (with p-values below 0.01) suggesting that the higher the income in an area, the lower the losses in accessibility. This suggests that wealthier residents do not experience losses in accessibility as they can afford to use transport regardless of the budget threshold selected. However, the proximity to non-petroleum-based modes, has a small positive coefficient and despite not being a robust variable, this does improve with higher fuel price increases. This positive relationship means that the further away from a non-petroleum-based mode a resident is located, the higher losses in accessibility they would experience – which suggests that the proximity to these modes mitigates the impact of fuel price increases (albeit with a relatively small effect). In the case of 20% fuel price increase, in which the average loss in job accessibility is 1.495%, every 10-minute increase in travel time to the nearest decarbonized transport is associated with 0.017% loss in job accessibility.

Table 4: Non-Petroleum-Based Modes Proximity and Income Controls regression

	Fuel Price Increase=				
	10%	20%	30%	40%	50%
Constant	5.2189***	7.5109***	12.2724***	16.1463***	21.0351***
	(0.5677)	(0.7159)	(1.0394)	(1.3744)	(1.7595)
Baseline Accessibility	-0.0049	-0.0064	-0.0128**	-0.0179**	-0.0178**
	(0.0034)	(0.004)	(0.0055)	(0.007)	(0.0089)
Travel time to non-petrol-based modes	-0.0002	0.0017	0.0019	0.0034	0.0056**
	(0.0013)	(0.0013)	(0.0016)	(0.0021)	(0.0025)
Ln(Income)	-0.613***	-0.9005***	-1.4535***	-1.9115***	-2.5126***
	(0.0905)	(0.1155)	(0.1681)	(0.2236)	(0.2859)
Average loss in job accessibility (%)	1.077	1.495	2.523	3.341	4.362

Adjusted R^2	0.194	0.323	0.435	0.483	0.496
Observations	1001	1001	1001	1001	1001

Note: Robust standard errors in parentheses. * p < 0.1, ** p < 0.05, *** p < 0.01

	Fuel Price Increase=				
	60%	**70%**	**80%**	**90%**	**100%**
Constant	23.2495***(1.9142)	27.1896*** (2.2518)	31.7407*** (2.6005)	33.3762*** (2.7276)	37.9368*** (3.1221)
Baseline Accessibility	-0.0234** (0.0098)	-0.0231** (0.0114)	-0.032** (0.0131)	-0.0328** (0.0137)	-0.034** (0.0157)
Travel time to non-petrol-based modes	0.0045 (0.0027)	0.0077** (0.0032)	0.0063* (0.0036)	0.008** (0.0038)	0.0094** (0.0044)
Ln(Income)	-2.7491*** (0.3119)	-3.2487*** (0.3674)	-3.7539*** (0.4244)	-3.9551*** (0.4455)	-4.5043*** (0.5101)
Average loss in job accessibility (%)	4.827	5.666	6.593	6.97	7.866
Adjusted R^2	0.513	0.52	0.535	0.544	0.545
Observations	1001	1001	1001	1001	1001

BRT Proximity and Income controls

A separate regression was assessed using the relationship between losses in accessibility with the proximity (defined as the travel time through walking) to the BRT system – which is one of the main trunk-based services that relies on petroleum-based fuels. The results are shown in Table 5, where the results follow a similar trend to the previous regression in terms of the relationship between baseline accessibility and income. However, the proximity to a BRT stop has a small negative coefficient, which suggests that the closer a resident is to a BRT stop the higher the losses in accessibility, which is likely due to the fuel price increases being higher for this type of mode. Although the robustness of the relationship between the proximity to the BRT variables is lower than other variables.

Table 5: BRT Proximity and Income Controls regression

	Fuel Price Increase=				
	10%	**20%**	**30%**	**40%**	**50%**
Constant	6.0814*** (0.6283)	8.8763*** (0.7736)	14.3253*** (1.1493)	18.6223*** (1.4892)	23.9993*** (1.8928)
Baseline Accessibility	-0.0017 (0.0025)	-0.0052* (0.0029)	-0.0103*** (0.0035)	-0.0167*** (0.0042)	-0.0166*** (0.0053)
Travel time to BRT	-0.0007 (0.001)	-0.0022** (0.0011)	-0.0028* (0.0017)	-0.0039** (0.0019)	-0.0057** (0.0025)
Ln(Income)	-0.7508*** (0.0944)	-1.0799*** (0.1185)	-1.7357*** (0.1795)	-2.2356*** (0.2324)	-2.8797*** (0.2952)
Average loss in job accessibility (%)	1.062	1.514	2.522	3.358	4.358
Adjusted R^2	0.167	0.281	0.381	0.422	0.427
Observations	1126	1126	1126	1126	1126

Note: Robust standard errors in parentheses. * p < 0.1, ** p < 0.05, *** p < 0.01

	Fuel Price Increase=				
	60%	**70%**	**80%**	**90%**	**100%**
Constant	26.6383***(2.0787)	30.6898*** (2.4159)	35.9902*** (2.8148)	37.6913*** (2.9399)	42.7047*** (3.3307)
Baseline Accessibility	-0.0192*** (0.0059)	-0.0234*** (0.0067)	-0.0258*** (0.0077)	-0.029*** (0.0081)	-0.0284*** (0.0091)
Travel time to BRT	-0.006** (0.0028)	-0.0061* (0.0031)	-0.0085** (0.0034)	-0.0083** (0.0036)	-0.01** (0.0041)

Ln(Income)	-3.1922*** (0.3255)	-3.676*** (0.3778)	-4.2984*** (0.4391)	-4.494*** (0.4596)	-5.0898*** (0.5197)
Average loss in job accessibility (%)	4.846	5.676	6.608	6.996	7.872
Adjusted R²	0.436	0.437	0.455	0.457	0.463
Observations	1126	1126	1126	1126	1126

Proximity of Non-Petroleum Based Modes and BRT with income controls

The variables of the previous two regressions were combined to see if the relationship was still true when considered altogether. The results are shown in Table 6, where these relationships do hold true, although the relationship between the losses in accessibility and proximity to each type of mode is not as robust.

Table 6: Proximity to Non-Petroleum-Based Modes and BRT with Income Controls regression

	Fuel Price Increase=				
	10%	**20%**	**30%**	**40%**	**50%**
Constant	5.7551*** (0.7739)	8.5701*** (0.9972)	13.8378*** (1.497)	18.2618*** (1.9877)	23.4318*** (2.5188)
Baseline Accessibility	-0.004 (0.0039)	-0.004 (0.0046)	-0.0101 (0.0063)	-0.0143* (0.0081)	-0.0129 (0.0102)
Travel time to non-petrol-based modes	0.0002 (0.0014)	0.0025* (0.0014)	0.0031* (0.0018)	0.005** (0.0025)	0.0073** (0.0029)
Travel time to BRT	-0.0001 (0.0011)	-0.0013 (0.0012)	-0.0013 (0.0019)	-0.0019 (0.0021)	-0.0032 (0.0027)
Ln(Income)	-0.6996*** (0.1268)	-1.0608*** (0.1657)	-1.6946*** (0.2521)	-2.2369*** (0.3356)	-2.8708*** (0.4244)
Average loss in job accessibility (%)	1.14	1.592	2.68	3.553	4.634
Adjusted R²	0.154	0.275	0.381	0.428	0.431
Observations	909	909	909	909	909
	Note: Robust standard errors in parentheses. * p < 0.1, ** p < 0.05, *** p < 0.01				
	Fuel Price Increase=				
	60%	**70%**	**80%**	**90%**	**100%**
Constant	25.7193*** (2.739)	30.0218*** (3.2505)	34.9514*** (3.7304)	36.6066*** (3.9225)	41.5761*** (4.4563)
Baseline Accessibility	-0.0182 (0.0111)	-0.0175 (0.0131)	-0.0241 (0.0149)	-0.0254 (0.0156)	-0.0238 (0.0177)
Travel time to non-petrol-based modes	0.0062* (0.0032)	0.0098** (0.0038)	0.0085** (0.0043)	0.0102** (0.0045)	0.012** (0.0052)
Travel time to BRT	-0.0031 (0.003)	-0.0027 (0.0034)	-0.0048 (0.0037)	-0.004 (0.0039)	-0.0055 (0.0044)
Ln(Income)	-3.1203*** (0.4631)	-3.6835*** (0.5497)	-4.2302*** (0.6295)	-4.4422*** (0.663)	-5.0461*** (0.7523)
Average loss in job accessibility (%)	5.135	6.01	7.01	7.406	8.36
Adjusted R²	0.444	0.449	0.462	0.469	0.468
Observations	909	909	909	909	909