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Mobility in Cities: Distributional Impact Analysis of Transportation Improvement in São Paulo Metropolitan Region

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Abstract:

This paper evaluates the impacts of transportation investments/policies using a spatial computable general equilibrium (SCGE) model integrated to a travel demand model. In order to enhance our understanding of the distributional impacts of transportation improvements in Brazilian cities, we simulate the impact of different types of mobility investments in the São Paulo Metropolitan Region (SPMR). To explore further the income effects of infrastructure investments, we also conduct microsimulation exercises integrated to the SCGE results. We look at 10 different scenarios, ranging from a series of infrastructure-related interventions – considering the expansion of the mass-transit public transportation network – to policies that focus on monetary disincentives to the use of cars. The simulations results suggest trade-offs between efficiency and equity.

Keywords: General equilibrium; urban mobility; accessibility; productivity; transportation infrastructure.

JEL Codes: C63; C68; R13; R42.

Mobility in Cities: Distributional Impact Analysis of Transportation Improvement in São Paulo Metropolitan Region[1]

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1. Introduction

Good connectivity within cities is an essential input for productivity and livability in cities, but the distributive impacts of improvements in within-city mobility are not well understood. This work aims at filling this gap by exploring the impacts of alternative infrastructure investments and mobility policies on economic growth, income distribution of households and internal distribution of economic activity.

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This paper focuses on the estimation of the impacts of transportation investments/policies using a spatial computable general equilibrium (SCGE) model integrated to a travel demand model, following the methodology presented in Haddad et al. (2015). In order to enhance our understanding of the distributional impacts of transportation improvements in Brazilian cities, we simulate the impact of different types of mobility investments in the São Paulo Metropolitan Region (SPMR). To explore further the income effects of infrastructure investments, we also conduct microsimulation exercises integrated to the SCGE results.

We look at ten different scenarios, which are divided into main categories: ranging from a series of infrastructure-related interventions on the mass-transit, and policies that create disincentives to the use of private cars. In the first group, the expansion of transportation infrastructure tends to reduce the average travel time in public transportation, representing a reduction in the generalized cost[9] of public transportation to individuals. Therefore, travelers gain an incentive to substitute away from private modes, potentially reducing congestion. The second group of interventions relates to policies that restrict car access to the city, increasing the generalized cost of individual transportation. In such cases, potential mode switch away from cars also tends to reduce congestion. The simulations results suggest potential trade-offs between efficiency and equity in the case of policies that restrict cars' access to the city. However, infrastructure-related interventions, not surprisingly, are associated with increases in GDP and, while their impacts on income distribution are relatively more modest, they suggest that improvements in the overall economy brought by transportation investments are not coming at the expense of lower-wage workers.

In what follows, we discuss the motivation for this study in section 2. We then present some stylized facts regarding the internal organization and commuting patterns at the SPMR in section 3, and discuss the main methodological aspects of the integrated modeling system in section 4. Results from the integrated modeling framework, focusing on the SCGE outcomes, are presented and discussed in section 5. Section 6 concludes.

[9] The term "generalized cost" refers to the weighted sum of the monetary and non-monetary costs of a journey.

2. Motivation and Background

Cities come in different sizes and forms. However, cities that have been able to grow large and remain productive and competitive such as London, Singapore and New York, all have one thing in common: good connective infrastructure has allowed all areas of the city to remain connected. Connectivity has allowed the city to grow as a single entity.

Connectivity is essential for the success of a city for several reasons. First, firms benefit from good links to their input and output markets. A well-connected city provides firms with a larger pool of labor and bigger markets to sell their products. Second, households also benefit from good connections in a city. They can reach more opportunities in shorter times, and have access to larger pools of goods, including housing, to choose from. When households and firms are well connected, productivity and livability can be higher (Fernald, 1999; Ghani et al, 2012; Rospabé and Selod, 2006; Gobillon et al 2007; Gobillon and Selod, 2014).

Improvements to connectivity can be achieved in at least two ways. First, by reducing the cost of transportation per unit of distance traveled. This can be done either through infrastructure investments that reduce commuting times between different points in the city, through subsidies that reduce the fare paid by consumers, or through demand management instruments that reduce congestion and commuting times. Second, policymakers can also reduce the distance between jobs and households locations, by providing incentives for the co-location of these two types of actors through zoning and land use planning decisions. Policies and investments along these two lines should be seen as complements rather than substitutes, as coordinated land use and transportation planning could help increasing densities that allow the economies of scale needed in transportation systems to be exploited, while also managing the negative externalities that arise from concentration of firms and people, such as congestion and pollution.

Computable general equilibrium (CGE) models have been used in the literature to estimate the effects of improvements in transportation infrastructure and transportation policy changes on macroeconomic variables as well as to assess the impact that such investments may have on the overall income distribution (World Bank, 2008; Haddad and Hewings, 2005; Haddad et al., 2011; Kim et al., 2004, among others). More recently, a SCGE model integrated to a transportation model that measures accessibility in the SPMR has been applied to estimate the economic impacts of the subway system, and to assess the impacts of alternative investments on the local and national economy (Haddad et al., 2015).

In this paper, we take a step forward in trying to understand the impacts of improvements to intra-city connectivity on household income distribution, by combining the SCGE model with a microsimulation model that evaluates the impact of investments and other policy changes on households' incomes. We also extend previous work by considering improvements to the city transportation network that go beyond the existing metro infrastructure and include scenarios that consider both improvements to the transportation network and demand management alternatives.

As mentioned above, policymakers have two main sets of instruments at hand to improve connectivity in a city: on one hand, investments in the physical infrastructure and demand management strategies that reduce the cost of transportation per distance travelled, and on the other hand, land use policies that reduce the distance traveled. To keep results tractable, in this work we focus on the first of these two sets, specifically investigating the impacts of infrastructure investments that reduce the generalized cost of public transportation and the use of regulations deterring the use of private vehicles in the central areas of the SPMR. Hence, we leave aside the second set of instruments related to land use management policies. However, we recognize this as a limitation of the current exercise and we highlight this as an important extension that can be considered in future work.

Transportation challenges in São Paulo Metropolitan Region

As cities grow in size and income, connectivity challenges become more complex. For example, demand for private cars increases with income, and hence pollution and congestion tend to rise. Similarly, as demand for land increases with more people and firms coming to the city, the poor are often forced to locate in peripheral areas where land is cheaper but opportunities are limited. São Paulo is no exception. A large proportion of the poorest households are located in peripheral areas, where density of employment is low and connective infrastructure is weak (Villaça, 2011). Forced to live in areas where land is affordable but opportunities are limited, these households are left behind bearing high costs (monetary as well as non-monetary, e.g. time) remaining in poverty.

To tackle connectivity challenges, the City of São Paulo together with the State government have taken important steps to improve connective infrastructure in the metropolitan area, investing in the construction and expansion of the underground metro system, improving the existing suburban rail network, and physically integrating the various modes of public transportation. However, challenges remain. Today, about 31 percent of trips are done in private vehicles, 37 percent with public transportation, and 32 percent with non-motorized vehicles (METRO, 2013). The metro system is 78.5 km in length, and, while it is one of the most productive in the world in terms of passengers per kilometer and passengers per car-kilometer, its mode share is still low when compared to other metropolitan areas of similar size, mainly because of its limited extension. The metro is complemented by 261 km of suburban railways and a municipal bus system with around 4,500 km of routes and 15,000 vehicles. The city also has a roadway network of about 17,000 km, and the municipality has recently invested on a significant expansion of the bikeways and bus corridors, adding 400 km of bikeways and 400 km of bus-only lanes on existing roadways (World Bank, 2016; São Paulo City Study, 2011).

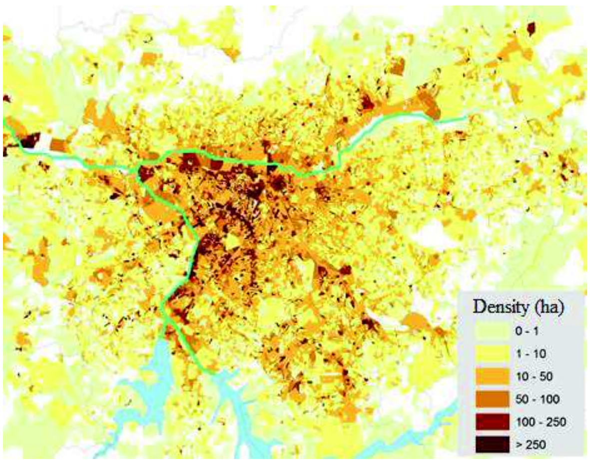
There are currently different investments under consideration and planned for the next 10-15 years. However, the impacts of infrastructure investments on employment and on household income distribution are yet to be understood. By defining different scenarios of infrastructure investments and mobility policies, this work assesses the impacts of transportation-related interventions in the SPMR on growth, household income distribution, the location of economic activities within the metropolitan area, as well as CO_2 emissions.

3. The Study Region

The Internal Structure of the SPMR – Some Stylized Facts[10]

SPMR, the main economic and financial center of Brazil, consists of 39 municipalities in an intense process of conurbation. It is the fourth largest urban agglomeration of the world, and the largest in the country, with about 10% of the national population (around 20 million inhabitants), and 19% of Brazilian GDP. The city of São Paulo is the core of the metropolitan area and accounts for about 56% of its population. From a stylized perspective, the internal organization of the SPMR may be approached by a Muth-Mills-Alonso urban model, having as the central business district (CBD) the extended center of the city of São Paulo (Haddad et al., 2015). Even though the broadly-defined CBD concentrates a great proportion of the jobs, a considerable level of employment decentralization is observed in the region (Figure 1). Households spread across the territory, mainly located in the areas surrounding the center, with population density declining in the boundaries of the territory of the metropolis (Figure 2).

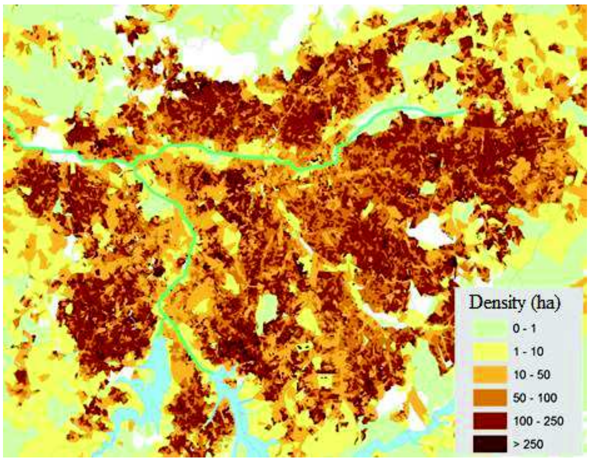
Figure 1. Employment Density in the SPMR, 2008



Source: Authors' elaboration using data from RAIS, Ministry of Labor, IBGE

[10] This section draws on Haddad and Barufi (2017).

Figure 2. Population Density in the SPMR, 2010



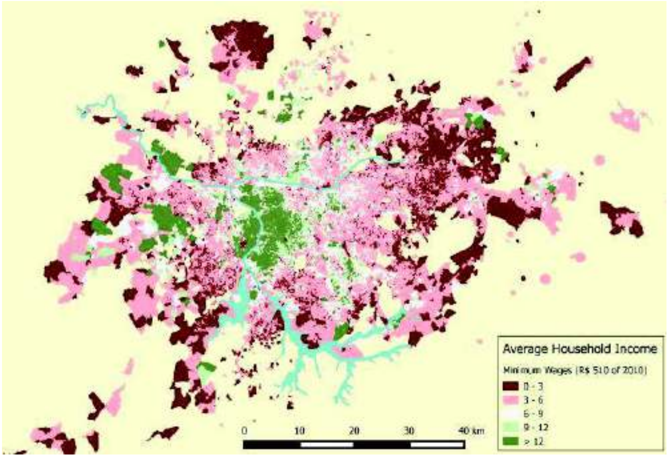
Source: Authors' elaboration using data from Demographic Census, IBGE, 2010

The great majority of commuters' flows in the SPMR are from peripheral regions to the metropolitan business centers in the central and western zones of São Paulo city moreover, according to the 2010 Population Census, the city of São Paulo – the core of the SPMR – received daily an inflow of almost one million commuters from other municipalities, representing 15.4% of workers in the city.

Low-income residents are overwhelmingly concentrated in the periphery (Figure 3), where connectivity is weaker. Facing larger commuting times and relying more on public transit (Figure 4), lower income residents tend to have lower access to jobs.

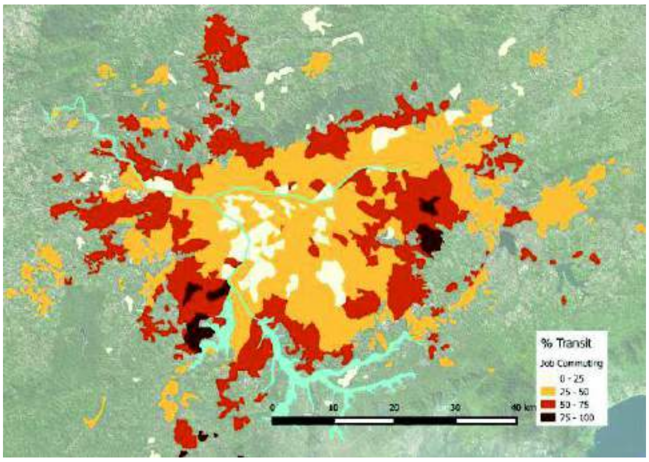
Moreover, the somehow diffuse pattern of job decentralization makes it harder for workers with no car to reach potential employers that are located far from the focal points of accessibility associated with the public transit infrastructure. This spatial mismatch makes it much harder for low-income workers to find employment since they traditionally reside in the less central parts of cities (Figure 5).

Figure 3. Average Household Income in the SPMR, 2010



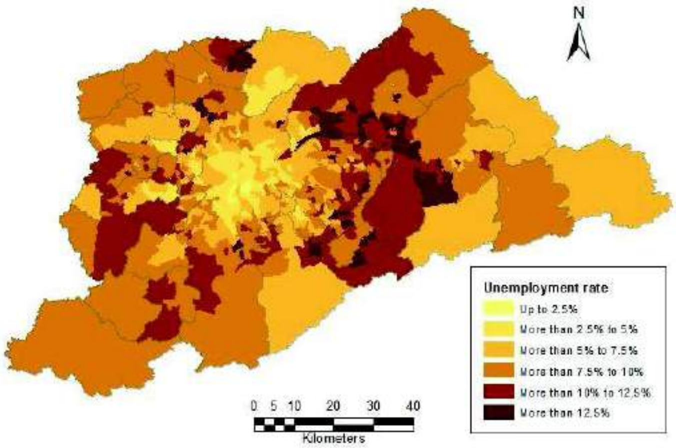
Source: Demographic Census, IBGE, 2010

Figure 4. Share of Commuting by Public Transportation in the SPMR, 2007



Source: OD Survey, 2007

Figure 5. Unemployment Rate in the SPMR, 2010



Source: Demographic Census, IBGE, 2010

Commuting Patterns in the SPMR – Some Stylized Facts

The commuting data used in this study comes from the most recent Origin Destination (OD) Survey of 2007, carried out by the São Paulo Metropolitan Company – Metro, which interviewed around 30,000 households in the SPMR and it was designed to be representative of all trips made in a regular weekday in the metropolitan area. The information collected in the survey includes trip duration, purpose, mode, origin, destination, and socioeconomic characteristics of households. The OD Survey divided the SPMR into 460 traffic zones (TAZs).[11]

We also use a time-equivalent transportation generalized cost matrix for each pair of TAZ, both in the case of trips made by auto and public transportation. The estimation, carried with the software *EMME*, is based on an aggregated trip-based classic four-step model for traffic estimation (Ortúzar and Willumsen, 2011). This model is used to

[11] The sample of the OD Survey is based on a stratification of households according to their consumption of electricity as a proxy for income levels. Households were divided into 5 consumption levels: 0-100, 100-200, 200-300, 300-more kwh/month. Therefore, the sample for each Traffic Zone (TZ) was randomly selected conditional on the share of households in the population within each consumption bin. Data was collected for all individuals living in selected households. Information about trips was related to the day immediately before the interview. For example, Saturday interviews collected information about trips made on Friday. The Metropolitan Region was divided into 460 TZs, and the number of households in the sample was defined such that the margin of error for the number of trips originated in each TZ would be inferior to 5% at 95% confidence. The final sample included 30,000 households.

identify the routes with the lowest generalized cost between each pair of zones. In what follows, we present the descriptive statistics of job commuting trips extracted from the 2007 OD Survey.

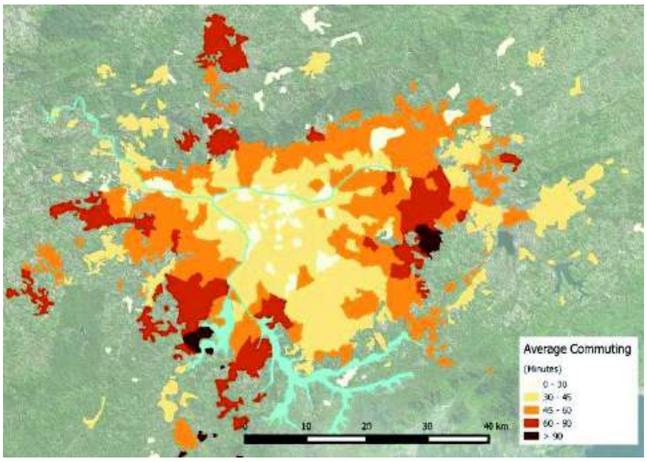
On an average weekday of 2007, there were about 38 million trips within SPMR, out of which 15.7 million were work (commuting) journeys. Table 1 shows the mode share distribution of commuting trips and the average commuting time of each mode. Mass transit accounted for 58.6% of commuting trips, private vehicle for 32.3% and other modes (mostly walking) accounted for 21.4%. Such distribution is drastically different from what is observed in developed countries, particularly the United States, where the vast majority of trips are made by car. Not surprisingly, motorized trips are considerably longer than trips made by non-motorized modes. However, within the group of motorized trips, journeys made by public transit are on average 86% longer than trips made by private vehicle. Figure 6, which complements the information previously shown in Figure 4, shows that average commuting time increases as the distance to the CBD rises.

Table 1. Mode Share and Average Commuting Time (Home to Work Trips)

	Nº of Trips	% of Trips	Average Trip Duration (minutes)
Transit	**7,393,206**	**58.6%**	**68.2**
Bus	6,872,412	43.8%	67.8
Subway	1,354,285	8.6%	66.0
Rail	969,525	6.2%	81.5
Private Vehicle	**4,548,993**	**32.3%**	**36.5**
Car Driver	3,682,845	23.5%	37.4
Car Passenger	834,739	5.3%	35.3
Táxi	31,409	0.2%	30.4
Motorcycle	519,916	3.3%	28.1
Other	**3,355,176**	**21.4%**	**16.3**
Walking	3,097,319	19.7%	16.2
Bicycle	214,416	1.4%	20.4
Other	43,441	0.3%	73.6
Total	**15,693,904**	100%	44.1

Finally, Table 2 shows the differences in commuting patterns by income strata. Higher income workers are more likely to commute by private vehicle. Meanwhile, the lower household income, the higher are the mode shares of transit, walking and bike. Such pattern is observed across all income groups, except for workers in the lower income bracket (0 and 1 minimum wages)[12], for which the mode share of public transit is lower than in the case of individuals in the income bracket of 2-5 minimum wages. This pattern reversal may suggest that for the poorest, affordability of public transportation may be still a concern.

Figure 6. Average Commuting Time in the SPMR, 2007



Source: OD Survey, 2007

Table 2. Mode Share and Commuting Time by Income Group (Home to Work Trips)

Household Income (MWs)	Mode Share: Transit	Mode Share: Private Vehicle	Mode Share: Walking	Mode Share: Bike	Average Duration (Minutes)
0 - 1	48.8%	14.9%	33.3%	3.0%	47.6
1 - 2	56.3%	15.1%	26.2%	2.4%	56.0
2 - 5	54.1%	22.5%	21.9%	1.5%	52.5
5 - 10	41.5%	43.4%	14.5%	0.6%	47.4
> 10	22.7%	68.2%	8.9%	0.3%	42.3

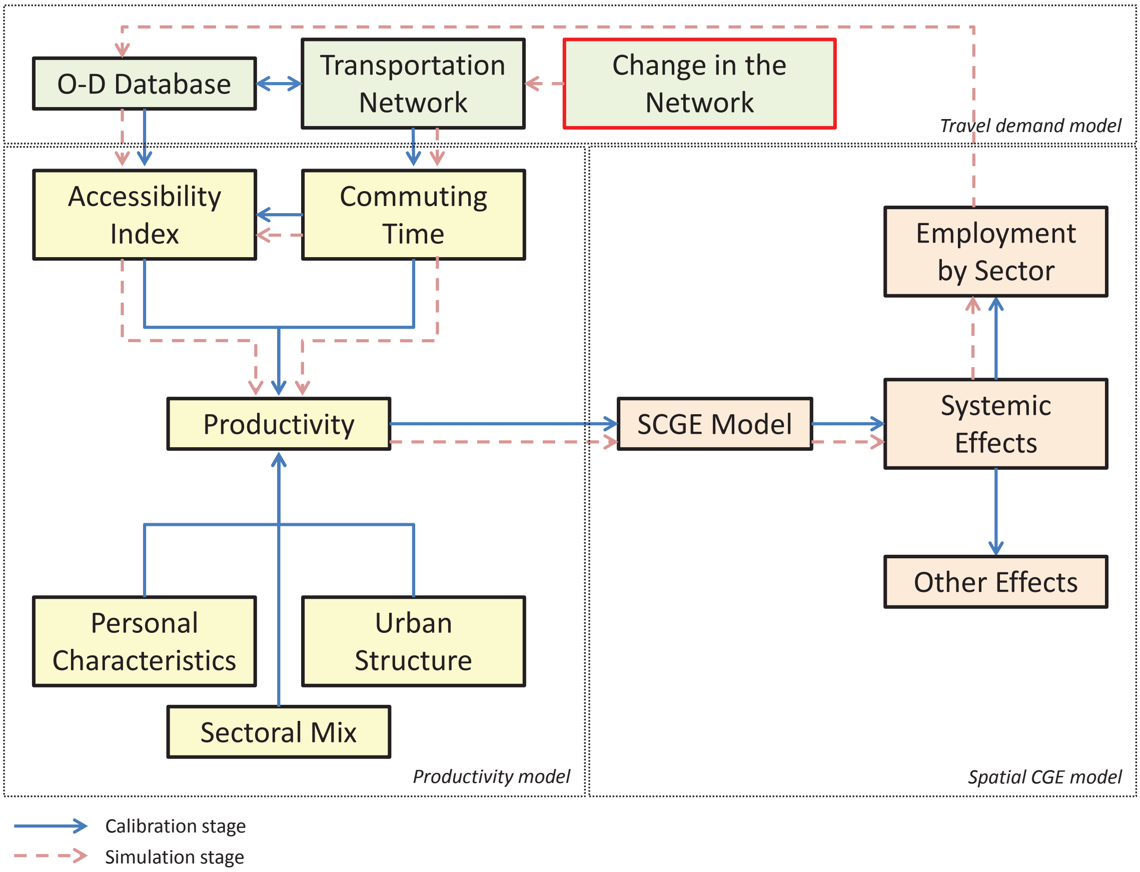
[12] The Brazilian minimum wage in 2012 was equal to R$ 510 or US$ 271 of 2007.

4. Overview of the Methodology

The methodology followed in this work has two main stages, calibration and microsimulation. In the first stage, a travel demand model, a wage equation and a SCGE are defined using the baseline data for the SPMR. In the second stage, the policy and investment scenarios are defined. For each scenario, the transportation model is used to calculate the changes on travel time and mode demand. These results are used as inputs to calculate productivity shocks through the wage equation estimated in the previous stage. The results of this simulation feed the SCGE model, which computes the effects of productivity chocks on sectoral output, income and employment in different parts of the metropolitan region. Through microsimulation techniques, the results of the SCGE are then used to assess the equilibrium impacts on income inequality.

The travel demand model allows identifying the initial causality path of the different scenarios of infrastructure investments and mobility policies estimating econometrically initial individuals' reactions on transportation decisions, which in turn can be fed into a SCGE model to capture the system wide impacts. By doing so, the paths of reaction can be revealed and modified where necessary, taking into consideration changes in individual behavior rather than assuming a constant induced change in accessibility or commuting time and costs. The main channels from the travel demand model to the SCGE model are through labor productivity changes associated with changes in commuting time and accessibility to jobs. Figure 7 describes the path followed in the modeling framework and the integration of all its parts, discussed in detail in Haddad et al. (2015), and Vieira and Haddad (2015). In what follows, we discuss in further details the second stage of our methodology, that is, the microsimulation steps.

Figure 7. The Integrated Modeling Framework



<u>Source</u>: Haddad et al. (2015)

Estimating the Distributional Impacts of Transportation Policy Changes – The Microsimulation Module

Microsimulation is a technique commonly used to model the behavior of individuals by evaluating the observed attributes of a representative population that are jointly distributed (Clarke and Holm, 1987). In our framework, microsimulation is used to estimate how productivity and labor income of workers would be affected by changes in transportation policies and infrastructure investments, using information from the OD Survey. While the OD Survey in São Paulo is not designed to collect detailed income or consumption information, the income variable does appear to provide a good approximation to the income distribution in the SPMR when compared to PNAD data.[13]

[13] PNAD is a national household survey conducted yearly by the Brazilian Institute of Geography and Statistics (IBGE) that is focused on demographic and socioeconomic information of the population.

Our microsimulation, as it interacts with the SCGE model results, can be divided into two steps. First, with the definition of the investments and policy changes in each scenario, we use the transportation model to forecast changes on travel time and mode demand. Based on the estimated parameters of the wage equation, these results lead to direct impacts on workers' productivity. In the second step, this variation in productivity is an input for the SCGE model, which interacts back with the microsimulation by shifting the distribution of employment over the urban area, altering the accessibility of individuals. Then the results on workers' income and commuting time are further evaluated.

Step 1 – Using the results of the transportation model

For each scenario, the transportation model estimates a matrix of travel time changes for each pair of TAZs in the SPMR. While the baseline travel time by mode m between each pair of TAZ is defined as $t^0_{od,m}$, the new travel times in each scenario are described by $t'_{od,m}$. Thus, the travel time change that is simulated for each worker i, is computed based on their observed baseline travel time $t^0_{i,m}$ and the ratio between $t'_{od,m}$ and $t^0_{od,m}$ for the workers TAZs of residence (o) and employment (d).

$$t'_{i,m} = t^0_{i,m}\left(\frac{t'_{od,m}}{t^0_{od,m}}\right) \tag{1}$$

Additionally, the transportation model also estimates, for each scenario, the new mode demand $Y'_{od,m}$ for each pair of TAZ. By adding the mode demand of all TAZ pairs, we have the total mode demand Y'_m in the whole SPMR.

$$Y'_m = \sum_{od} Y'_{od,m} \tag{2}$$

The new mode demand in each scenario is distributed throughout workers by an adjustment on their sample weights ϕ_i.

$$\phi_i' = \phi_i^0 \left(\frac{Y_{od,m}'}{Y_{od,m}^0} \right) \quad (\forall \quad i \quad | \quad m_i = m\,) \tag{3}$$

A RAS iterative proportional fitting method is then used to keep constant the share of residents and workers in each TAZ.

$$Y_{od}' = Y_{od}^0 \tag{4}$$

Moreover, the new travel times from the transportation model lead to a new value for the accessibility a_i of workers.

$$a_i' = \sum_d \frac{E_d^0}{\delta(t_{od}')} \tag{5}$$

Where E_d^0 is the baseline number of jobs in each TAZ and $\delta(\,)$ is a deterrence function capturing the effect of travel time on accessibility.

Using the estimated coefficients of the wage equation from the calibration stage, we calculate the impact of new travel times and accessibility values on workers' productivity w_i.

$$w_i' = \hat{\beta}_a \frac{a_{od}'}{a_{od}^0} + \hat{\beta}_t \frac{t_{od}'}{t_{od}^0} \tag{6}$$

Finally, we calculate the average productivity variation W' for each municipality mun, both in terms of workers' place of residence and employment. This matrix of productivity changes is used as input for a SCGE model shock.

$$W_{mun}' = W_{mun}^0 \left(\frac{\sum_i w_i' \phi_i'}{\sum_i w_i^0\, \phi_i^0} \right) \tag{7}$$

Step 2 – Using the results of the SCGE model

From the productivity shocks described above, the SCGE model produces a vector of employment and population changes for each municipality. This vector is used to recalculate the sample weight ϕ_i of workers according to their city of employment and residence. The redistribution of employment leads to a new vector of accessibility, which is used to calculate a new productivity shock, which is again aggregated and used as input in the SCGE model. This process is repeated until convergence is reached, and then the wages of workers are adjusted so the overall real income by municipality is equivalent to the values calculated by the last iteration of the SCGE model.

CO_2 Emissions Module

Furthermore, we have implemented a module for computing vehicle emissions in each simulated scenario. Despite its relatively simplistic approach, such calculations generate partial estimates that provide initial insights on the effects on CO_2 emissions associated with different mobility policies.

Data from CETESB were used to compute CO_2 emission factors (g/l) by type of fuel used in vehicles. The amount of gas emitted depends directly on the amount of fuel consumed (in liters) by the vehicle on its journey. The following factors were adopted in this study: (i) Automobiles – 1.91 g/l (average consumption of alcohol (41%) and gasoline (59%) in BOE (barrel of oil equivalent) in 2015; (ii) trucks – 2.6 g/l.[14]

We have considered that CO_2 emissions depend directly on the amount of fuel consumed by vehicles. Fuel consumption, on its hand, depends on distance traveled and on average speed (km/h).

Performance curves (fuel consumption (l) x average speed (km/h)) were estimated using the software *HDM-VOC*. In this analysis, four types of vehicles were considered: (i) small cars; (ii) large cars; (iii) light trucks (2 and 3 axles); and (iv) heavy trucks (4 or more axles).

The average distances and speeds reached in each trip were obtained from the traffic simulation model. From these data, the average fuel consumption in each scenario was calculated and, subsequently, the resulting CO_2 emissions were estimated.

[14] It was considered that trucks runs only on diesel, and automobiles runs on both gasoline and alcohol. For the latter, an average emission factor was estimated based on the total gasoline and ethanol consumption throughout the year of 2015, according to the National Agency of Petroleum, Natural Gas and Biofuels (ANP).

5. Results

We evaluate the impact of the following ten scenarios, as described in Table 3. The first four policy scenarios refer to infrastructure investments in the expansion of metro, train, and bus corridors. The definition of these scenarios was based on current investment plans to 2020 and 2025. Scenarios 6 to 10 focus instead on demand management policies that impose out-of-the-pocket payments mainly to private vehicle users. Scenario 5 provides a combination of the two, including investments in infrastructure and an increase in fuel prices.

Table 3. Investment and Policy Scenarios

Investments Only	Scenario 1 – Metro and Train developments until year 2020
	Scenario 2 – Metro, Train and Bus corridor development until year 2020
	Scenario 3 – Metro and Train developments until year 2025
	Scenario 4 – Metro, Train and Bus corridor development until year 2025
Investments + Tax	Scenario 5 – Metro, Train and Bus corridor development until year 2025, and 30% increase in fuel price
Changes in policies (fees, toll, tax)	Scenario 6 – 30% increase of in fuel prices
	Scenario 7 – Implementation of urban toll (R$5,00)
	Scenario 8 – 50% increase in parking cost in the entire SPMR
	Scenario 9 – 50% increase in parking cost in the extended CBD
	Scenario 10 – 50% increase in parking cost in the core of the CBD

Figure 8 presents the main causal relationships embodied in the SCGE model underlying the results of a hypothetical simulation exercise that generates increases in labor productivity of workers.[15] According to the SCGE model structure, this represents, on one hand, decreases in the prices of composite commodities, with positive implications for real regional income (price change channel): in this cost-competitiveness approach, firms become more competitive – as production costs go down (inputs are less costly); investors foresee potential higher returns – as the cost of producing capital also decreases; and households increase their real income, envisaging higher consumption possibilities. Higher real income generates higher domestic demand, while an increase in the competitiveness of national and regional products encourages external demand. This creates room for increasing firms' output – destined for both domestic and international markets – which requires more inputs and primary factors. Increasing demand puts pressure on the factor markets for price increases, with a concomitant expectation that the prices of domestic goods would increase.

On the other hand, the increase in labor productivity is also associated with a decrease in the labor requirement per unit of output in those sectors that employ workers that are affected by the changes in commuting time. As production becomes less labor-intensive, *ceteris paribus*, demand for labor decreases generating excess supply of labor in the economic system (technical change channel). This creates a downward pressure on wages as well as on capital rentals due to imperfect substitutability between the primary factors, which are passed on in the form of lower prices. Second-order price changes go in both directions., with the net effect being determined by the relative strength of the countervailing forces. Figure 8 summarizes the transmission mechanisms associated with major first-order and second-order effects in the adjustment process underlying the model's aggregate results.

Table 4 presents the results for the main impacts generated by the simulations, considering long run impacts of each scenario. In what follows, we present estimates for different indicators for the SPMR, highlighting some of the results that shed light on the potential trade-offs of the distributional impacts.

[15] Effects of decreases in labor productivity go in the opposite direction.

Figure 8. Causal Relations underlying the System of Equations of the SCGE Model

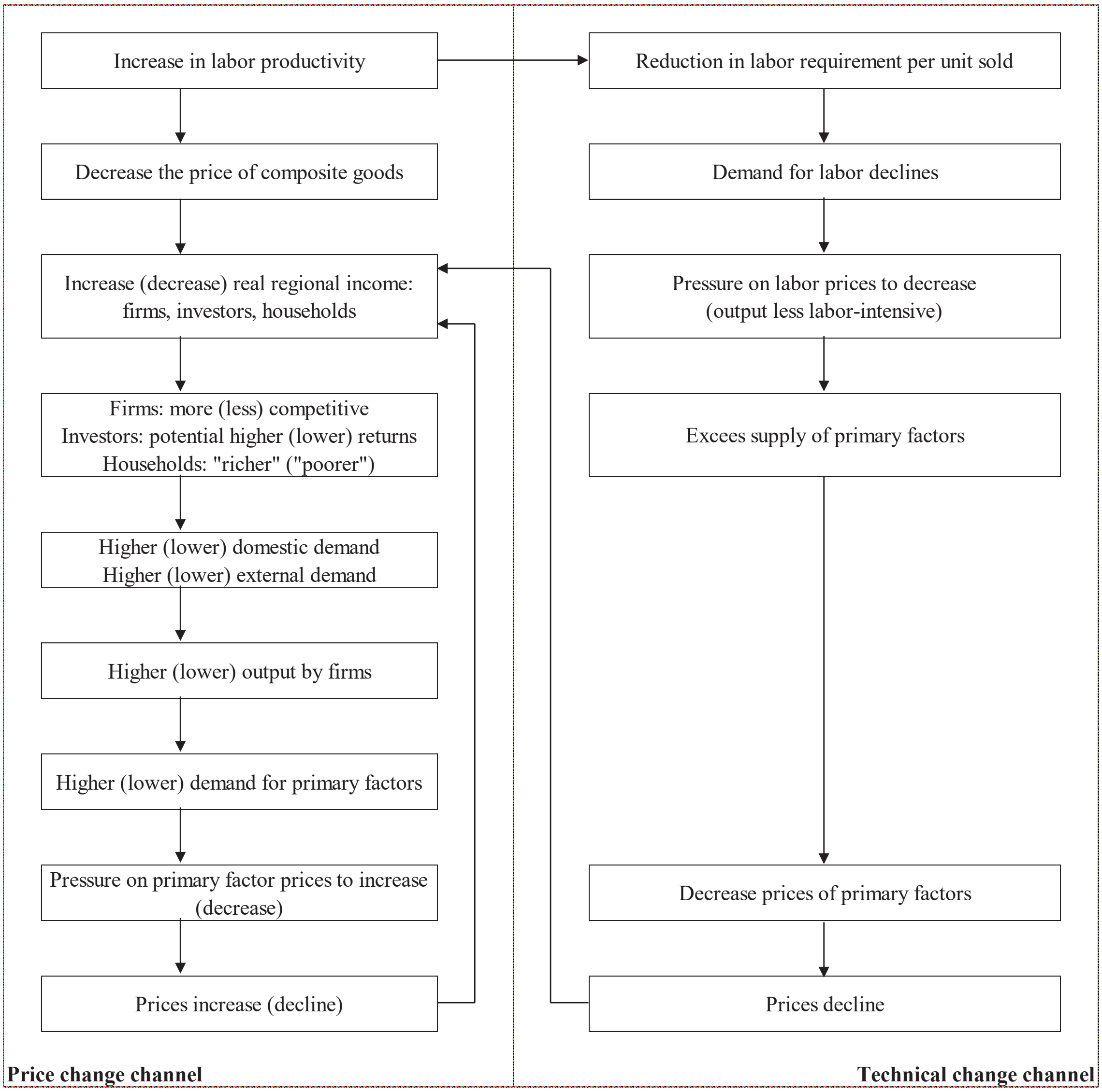


Figure 9 reveals the direct relationship between average commuting time and real GRP growth. Commuting time affects productivity through two main channels. Long commute is expected to decrease workers' productivity as longer commuting time may induce workers to arrive late at work, or leave earlier, and increase the number of absent days (Van Ommeren and Gutièrrez-I-Puigarnau, 2009); moreover workers experiencing longer commuting trips may also become less productive as they provide lower effort levels than those residing closer to jobs (Zenou, 2002). Agglomeration economies are also expected to positively influence workers' earnings. Workers are paid more in larger and denser markets because they are more productive there due to the presence of agglomeration economies (Melo and Graham, 2009). In this case, better mobility improves accessibility to job, which approaches workers and firms favoring a more efficient matching in the urban labor market. Since productivity is inextricably linked to long-term growth, the relationship depicted in Figure 9 follows.

Figure 10 summarizes some of the main results of Table 4, considering selected indicators. The graph contains information on three different dimensions. The x-axis presents the growth impacts on the SPMR GRP, and the y-axis presents the percentage change in the Gini for labor income. The third piece of information relates to the locational Gini calculated using population weights: warmer colors (*reddish*) represent increases in concentration of economic activity, while cold colors (*green*) are associated with dispersion of the activity level within the SPMR – in both cases, darker colors refer to stronger effects

Overall, the impacts of the two main groups of interventions point in two different directions. First, scenarios 1 to 4, which are associated with infrastructure investments on public transportation, are all pro-growth and reduce overall commuting time. It is also clear that, as the portfolios of investments considered include a larger array of interventions (both in terms of different types of infrastructure and over time), the effects are magnified, with larger impacts for scenarios 3 and 4 which consider expansions planned until 2025. We find that investments in transportation contribute to equalizing wages across space, as barriers to mobility decline, favoring concentration of economic activity.

Second, scenarios 6-10, which are associated with mobility policies that impose out-of-the pocket payments mainly to private vehicle users, point to effects that reduce economic growth of the SPMR. They contribute to reducing inequalities in accessibility and labor income and to promoting decentralization of the economic activity within the SPMR. They do so with increases in overall average commuting times and lower levels of overall welfare, as measured by the average real wage. Scenario 5, which represents a mix between the two groups of interventions, shows stronger effects on public transit demand, income and spatial inequality but lower impacts on GRP growth and smaller reductions in overall commuting times.

One dimension that is not included in the model but that is also important to consider is the political economy of the policy changes included in the scenarios. While for the group of infrastructure interventions the financial cost may be high, the political cost is relatively low. Instead, for policies that impose extra costs to car users, such as the urban toll, the political costs may be very high, despite the relatively low financial cost related to the implementation of such set of policies.

Finally, the results also show that the most significant changes toward mass transit modes are seen in scenarios 5, 6, and 7 as they impose restrictions to auto use. The fact that scenarios 1 through 4 are not reflecting the largest changes in public transit demand confirms the well-known fact that supply side efforts are not enough to encourage users to substitute from private vehicle trips to mass transportation modes. These results have direct implications to the results related to CO_2 emissions, which also show scenarios 5, 6 and 7 as those with higher potential to reduce transit-related pollution in the SPMR.

Table 4. Summary of Long-run Impacts

	Baseline	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Scenario 6*	*Scenario 7*	*Scenario 8*	*Scenario 9*	*Scenario 10*
Travel Demand											
Transit trips (% in total)	56.99	56.97	57.03	57.27	57.38	61.04	60.28	60.42	58.00	57.67	58.86
Generalized cost of private vehicle trips (in % change)	-	-0.095	-0.202	-0.457	-0.739	16.827	18.136	17.820	-0.599	-0.754	-0.555
Generalized cost of transit trips (in % change)	-	-4.721	-4.985	-6.716	-7.077	-7.601	-0.892	-0.344	-0.311	-0.262	-0.526
Gini											
Wage	0.6006	0.5976	0.5970	0.5957	0.5948	0.5847	0.5907	0.5893	0.5982	0.5990	0.5959
Commuting time	0.4120	0.4020	0.4010	0.3990	0.3973	0.3904	0.4044	0.3979	0.4094	0.4104	0.4061
p 90 / p 10											
Wage	4.65	4.66	4.65	4.74	4.54	4.25	4.63	4.67	4.65	4.65	4.66
Commuting time	11.00	8.07	8.07	10.93	8.56	9.12	11.00	13.05	10.47	10.81	11.04
Average Indicators											
Wage (BRL)	761.91	783.03	784.41	793.29	796.24	781.85	748.90	746.38	760.91	761.70	759.27
Commuting time (min)	52.14	50.25	50.07	49.55	49.23	50.57	53.41	54.50	52.33	52.20	52.70
RMSP GRP (in % change)	-	0.879	0.919	1.259	1.362	0.205	-1.049	-1.278	-0.166	-0.092	-0.354
Locational Gini											
Equal weights	0.8461	0.8460	0.8460	0.8461	0.8460	0.8457	0.8457	0.8455	0.8460	0.8460	0.8459
Population weight	0.1602	0.1604	0.1604	0.1605	0.1602	0.1581	0.1583	0.1563	0.1595	0.1597	0.1589
CO2 Emissions (kg per type of vehicle)											
Automibiles (in % change)	-	-5.685	-5.801	-6.714	-7.094	-16.811	-13.737	-9.589	-2.090	-1.595	-3.505
Trucks (in % change)	-	-0.042	0.084	0.139	0.042	-0.042	-0.014	-0.097	-0.014	0.125	-0.028
Qualitative indicators											
Political cost	-	Low	Low	Low	Low	High	High	High	High	High	High
Financing cost	-	High	High	High	High	High	Low	Low	Low	Low	Low

Figure 9. Commuting Time and GRP Growth

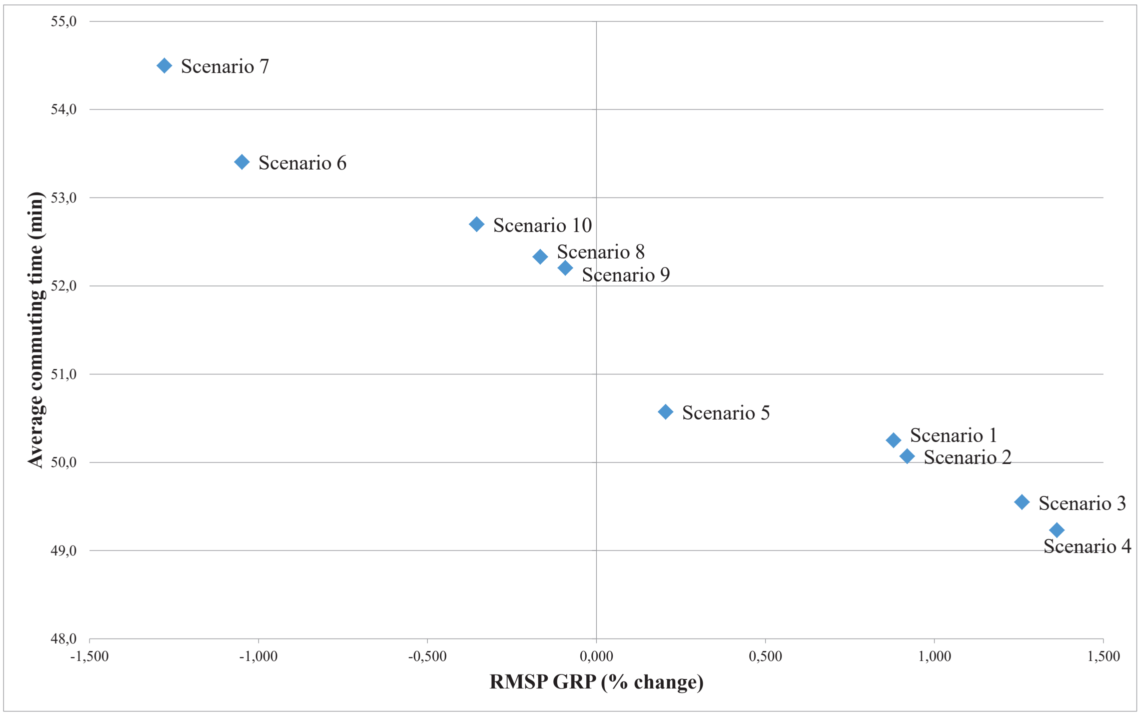


Figure 10. Summary of Aggregate Results

6. Conclusion

This work simulated a set of alternative mobility policies and investments for the São Paulo Metropolitan Region. The analysis was based on a framework that integrates a transportation model, capturing the structural effects of each policy, with a SCGE model that allows the assessment of the economic impacts of such changes. Further exploration of the income effects of the policies was done to assess their distributional impacts.

The results from this work suggest, not surprisingly, that investments in transportation infrastructure are associated with increases in GDP. Further, while the impacts of such investments on income distribution are relatively modest, they do suggest that improvements in the overall economic efficiency brought by transportation investments are not coming at the expense of the lower income workers. Results indicate that investments in the infrastructure of mass transportation systems can lead to substantial economic gains for the metropolitan area. For all infrastructure investment scenarios, average increases in GRP throughout the region fall above 0.8%. Impacts in commuting times and income vary across the region but on average, larger decreases in commuting times are achieved through the infrastructure scenarios. On the other hand, in the case of policies that increase the individual cost of private vehicle users, the overall impact on economic growth is negative, while their distributional impacts are relatively stronger in favor of income equity and spatial cohesion.

As previously stressed, this work does not take into account the land use patterns of the city, which could contribute to strengthening or weakening the observed impacts. While coordinated land use planning and transportation planning can make the layout of the city more conducive to shorter commutes than transportation investments alone, constraints in the housing market can act as barriers to the internal mobility of households and firms. Recent work for Chicago provides evidence that zoning had a broader and more significant impact on the spatial distribution of economic activity than geography or transportation networks (Shertzer et al., 2016). The jury is still out on the net effect that these may have in an urban area like the SPMR.

Finally, by accounting for the impact that the infrastructure and policy changes may have on emissions, and hence pollution and health, we add another dimension of the impacts. A move to mass transportation is usually associated with a reduction in emissions. However, this is only true when mass transportation is cleaner than cars. In cities where the bus fleet is outdated and remains unchanged, a move toward mass transport modes may in fact increase pollution and health issues may worsen. Extending the current work along these two lines can help better inform the tradeoffs that policymakers face in supporting economic growth by enhancing efficiency of the city while maintaining and improving livability.

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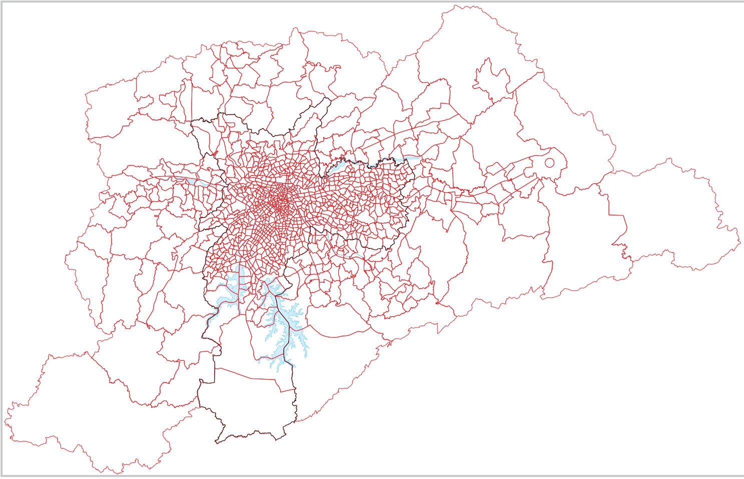
Annex A1. Transport Modeling Framework

To assess the impacts of changes in infrastructure and operations of the transport system within the SPMR, we used a travel demand model for personal travel developed and implemented by the engineering company *TTC – Engenharia de Tráfego e de Transportes*, São Paulo, Brazil. The model consists of an aggregated trip-based classical four-step model that takes into consideration socioeconomic data, survey data, transportation infrastructure characteristics, and operational information to produce trip flows and times. The four steps included in the model are: (i) *Trip Generation*, which determines the number of trips (by origin and destination from/to each pre-defined zone) within a period of time, by trip purpose; (ii) *Trip Distribution*, which determines the origin-destination (OD) pairs, based on the total origin and destination trips of each zone; (iii) *Mode Choice*, which defines the proportion of trips for each OD pair that uses automobiles or public/mass transport modes; and (iv) *Assignment*, which selects which paths will be used by each OD pair and transport mode.

The variable used to quantify travel time and travel cost is referred to as the generalized cost, which is a linear combination of the weighted components of travel time (walking, waiting, in vehicle, etc.), distance, and monetary costs (fuel costs, public transportation fare, parking costs, etc.) spent on each trip.

The zone system adopted in this study is the same used in the household survey carried out by the São Paulo Metropolitan Company (Metro) in 2007 (OD 2007), in which the SPMR was divided into 1,895 micro traffic zones, from the original 460 TAZs. Figure A1.1 illustrates the zone system used for the SPMR (in red), and the city borders of São Paulo (in black).

Figure A1.1. Zone System



Source: TTC

This first step in the modeling exercise attempts to estimate the total number of trips going out and to every single zone within the study area. This is referred to as the trip generation model. In this stage, regression models are used to relate socioeconomic and geographic variables to travel vectors obtained from the OD 2007 and the updated version for 2012 (OD 2012), grouped into 460 macro zones. Two sets of equations are estimated: (i) travel generation equations, which feature the following independent variables: income, self-ownership, population and family structure; and, (ii) travel attraction equations, which use employment and public and private enrollment as independent variables. These equations are then used to estimate trip generation and attraction for each zone.

In the second step, the vectors of trip generation and attraction obtained in the first step are used in a gravity-type model to estimate the number of trips between origin and destination pairs, creating an O-D matrix using a travel distribution model. Trips for each O-D pair are hence estimated as proportional to the number of trips leaving the origin zone and the number of trips arriving at the destination zone, and inversely proportional to the generalized travel cost between two zones.

The equation used in the calculation of the number of trips per stratum between pairs of zones is as follows:

$$T_{ij}^{stratum} = O_i^{stratum} * D_j^{stratum} * e^{(-1/\beta * GC_{ij})}$$

where:

$T_{ij}^{stratum} = Trips\ between\ zones\ i\ and\ j\ per\ stratum;$

$O_i^{stratum} = Number\ of\ trips\ leaving\ origin\ zone\ i\ per\ stratum;$

$D_j^{stratum} = Number\ of\ trips\ arriving\ at\ destination\ zone\ j\ per\ stratum;$

$\beta_k = Constant\ adopted\ for\ the\ \ k_{th}\ group\ of\ origins;$

$GC_{ij} = Generalized\ cost\ between\ zones\ i\ and\ j.$

The generalized cost between pairs of zones was calculated using a network model for both automobile and mass transit modes. For automobiles the operational cost of the vehicle, the occupation (people-automobile ratio), travel time, and distance were considered in the calculation. For mass transit, the generalized cost considered the average walking distance, waiting time, travel time, and cost of the fare.

Calibration of the distribution model is made by comparing the travel frequency histogram obtained from the observed OD 2007/2012 surveys with the histogram obtained from the estimated matrix. The distribution model is adjusted in an iterative manner varying the parameter β until both histograms are superimposed. It is an iterative process in which the constant β converges to a single value. Another convergence parameter is the average cost of travel. Over the iterations, this cost is recalculated until it matches the observed value.

In the third step, travel flows need to be broken down by mode (mass transit and automobile). A mode choice model is estimated using a binomial logit function which uses as explanatory variables for the probability of using different transportation modes the following variables: reason for travel, income, cost and time of travel, car ownership, travel time, frequency, among others, are used.

Finally, the software *Emme 4* is used for the assignment of paths by OD pair and mode of transport.[16] As previously mentioned, the simulation model used for this study covers the main roads of the SPMR, in addition to all subway and rail networks. Each link has information attached on length, number of lanes, hierarchical classification, capacity, maximum speed, etc. The simulation model includes the municipal bus lines of São Paulo (regulated by SPTrans) and other 38 cities of the SPMR, intercity bus lines in the SPMR (regulated by EMTU), metropolitan passenger trains operated by the São Paulo Metropolitan Trains Company (CPTM), and the Metro lines. Each of the transit lines has information on its physical and operational characteristics, such as itinerary, frequency, fare, vehicle type, capacity, etc. A total of 3,044 unidirectional transit lines, among municipal, intercity, trains and subway are included in the model.

The simulation model uses specific travel time functions, or volume delay functions (VDF), for calculating the distribution of automobile demand. The route assignment algorithm for automobiles assumes every car seeks to improve its travel time in each iteration until alternatives routes do not produce improvements in travel time. For mass transport, the transit time of a line at each link is computed taking into consideration the automobile time at that link. For links where there are no automobiles, the transit time is computed using a constant speed instead.

[16] This Canadian software has been widely used for analytical work in Brazil, and has been the choice of most transit agencies in São Paulo for planning purposes.

Annex 2. Comparing the Income Distribution from PNAD and OD 2007 surveys

In this annex, a comparison between the income variables obtained from the 2007 OD survey and the 2007 PNAD is carried out to assess how different the two distributions are. PNAD is the preferable database used for studying poverty and income inequality in Brazil. The analysis suggests there is no major difference between the two surveys, validating the analysis in this work that uses information from the OD survey to estimate changes in income inequality derived from the policy scenarios analyzed. In order to account for inflation, all values were adjusted using IBGE's IPCA inflation index. The baseline period was defined as September 2007 since most of the data from PNAD was collected in that month.

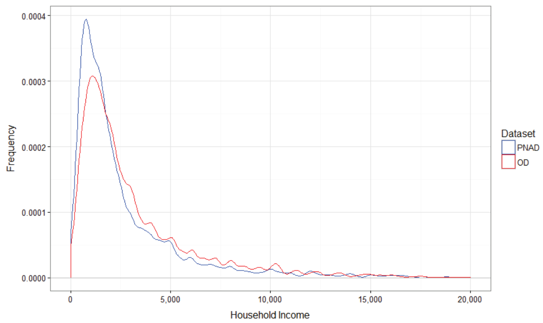
PNAD: Household income was calculated as variable V4614, which includes the income from all individuals in the household except pensioners, domestic workers, domestic worker relatives and individuals younger than 10. Lines with income reported as 999,999,999,999 were transformed into NA and subsequently excluded from the analysis. Data was restricted to *estrato* 3539 which corresponds to the Metropolitan Region of São Paulo.

OD: Household income was calculated as the sum of the income from all household members who were part of the same family (RENDA_FA). For one particular household, date was registered as "1582-12-05". This was substituted by the date from the mode of observations ("2007-10-01"). The same procedure was applied to observations with missing dates.

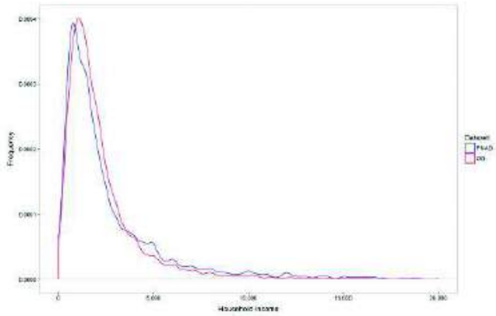
Figure A2.1 compares the two distributions both for the unweighted and weighted samples. These statistics and depictions suggest that, overall, inequality tends to be underestimated when using the weighted OD data. Looking at the distribution suggests that some important individuals seem to be missed at the two extremes of the distribution in the OD survey, hence suggesting lower inequality than in PNAD. The unweighted data from the OD survey provides a closer estimate of inequality for 2007.

Figure A2.1. Density Estimate of Household Income (PNAD vs OD 2007)

PNAD vs OD 2007 unweighted



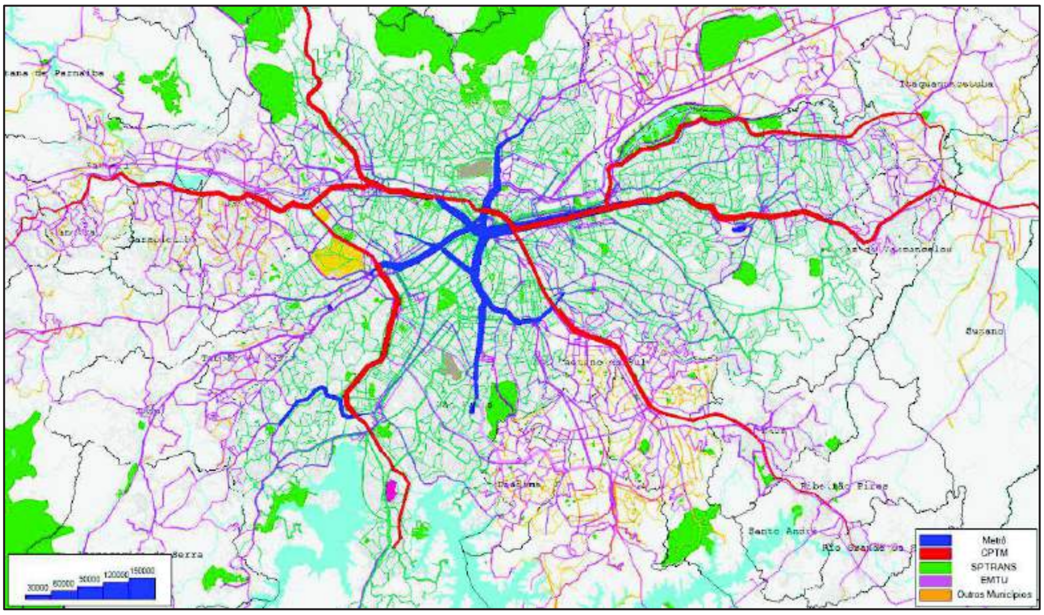
PNAD vs OD 2007 weighted



Source: Author's elaboration using PNAD 2007 and OD 2007 Survey

Annex 3. Definition of Investments and Policy Scenarios

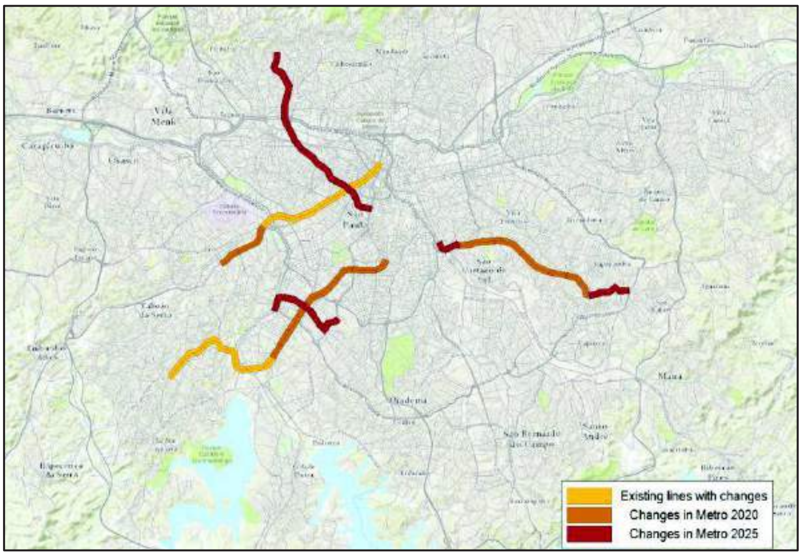
Figure A3.1. Current Public Transportation Network (transit volumes)



Source: TTC

Plans for future railway network were obtained from Metro and CPTM, and show the planned expansion of metro, train and monorail in the metropolitan region of São Paulo for years 2020 and 2025. Based on these data, the implementation schedule presented by the government was compared with the history of construction and opening of railway lines, in order to establish an implementation schedule as realistic as possible, to be used in the analysis.

Figure A3.2. Planned Extensions of Metro



Source: TTC

Table A3.1. Changes in Metro network until 2020

Line	Path	Plus extension (km)
Line 4 - Yellow	Vila Sônia - Luz	3.8
Line 5 - Lilac	Capão Redondo - Chácara Klabin	9.9
Line 15 - Silver	Vila Prudente - Sapopemba	9.3
TOTAL		23.0

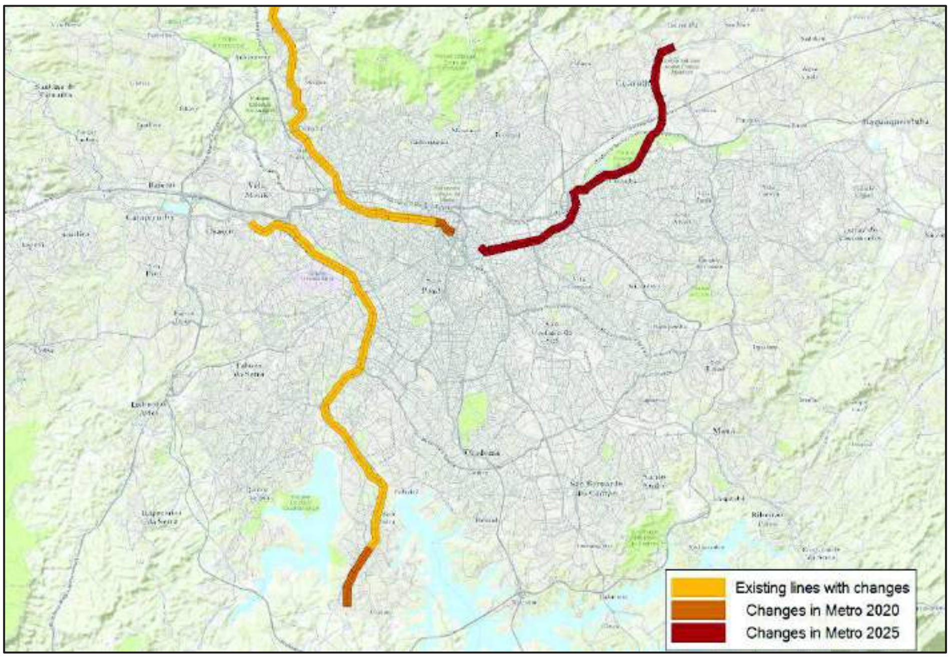
Source: TTC

Table A3.2 – Changes in Metro network until 2025

Line	Path	Plus extension (km)
Line 4 - Yellow	Vila Sônia - Luz	3.8
Line 5 - Lilac	Capão Redondo - Chácara Klabin	9.9
Line 6 - Orange	Brasilândia - São Joaquim	13.5
Line 15 - Silver	Ipiranga - São Mateus	12.1
Line 17 - Gold	Jardim Aeroporto - Congonhas - Morumbi (L9)	6.7
TOTAL		46.0

Source: TTC

Figure A3.3. Planned Extensions of Urban Rail (CPTM)



Source: TTC

Table A3.3. Changes in Urban Trains (CPTM) network until 2020

Line	Path	Plus extension (km)
Line 7 - Ruby	Francisco Morato - Bom Retiro	2.1
Line 8 - Diamond	Itapevi - Bom Retiro	2.1
Line 9 - Emerald	Varginha - Osasco	4.2
	TOTAL	8.4

Source: TTC

Table A3.4. Changes in Urban Trains (CPTM) network until 2025

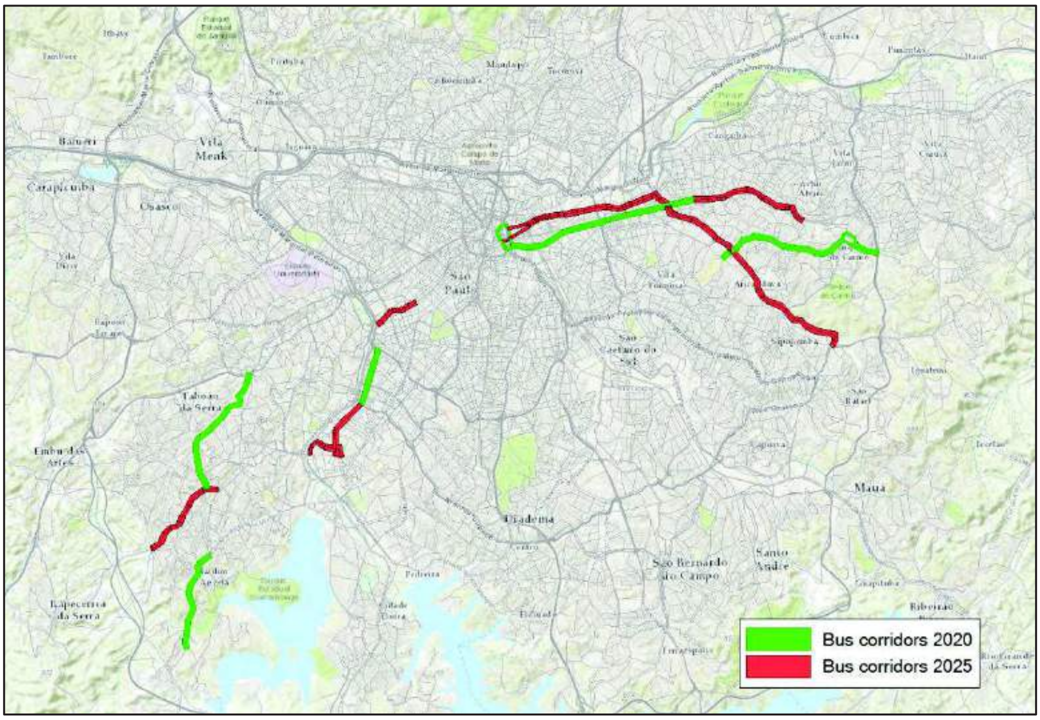
Line	Path	Plus extension (km)
Line 7 - Ruby	Francisco Morato - Bom Retiro	2.1
Line 8 - Diamond	Itapevi - Bom Retiro	2.1
Line 9 - Emerald	Varginha - Osasco	4.2
Line 13 - Jade	Aeroporto - Brás	24.9
	TOTAL	33.3

Source: TTC

Expansion plans for the bus network of São Paulo come from the investment plans on corridors collected from São Paulo Transportation – SPTrans (see figure A3.4). As it was done for the case of the rail system, a comparison with the historical implementation schedule was used to adjust the planed schedule to a more realistic implementation plan. This adjusted schedule is presented in the figure and tables included below.

For bus corridors implemented on existing roads where the road hierarchy remained unchanged, the changes in the simulation were limited to increases in commercial speeds over the line on said link, untying such speed to the speed of the general traffic. Further, for bus corridors implemented on new roads or in roads where the functional hierarchy was changed, adjustments on the itineraries of routes where made so as to account for the new connections in addition to the adjustments made to speed.

Figure A3.4. Planned Extensions of Rapid Bus Lanes



Source: TTC

Table A3.5. Changes in bus corridors until 2020

Corridor	Main roads	Plus extension (km)
Berrini	Av. Berrini (Trecho 1)	3.6
Campo Limpo (Capelinha - V. Sônia)	Av. Carlos Lacerda / Estr. Campo Limpo / Av. Fco. Morato	12.2
Itaquera - Líder	Av. Itaquera / Av. Lider / Rua São Teodoro)	10.4
Radial Leste	Av. Alcantara Machado / R. Melo Freire (Trecho 1)	9.9
M´Boi Mirim	Estr. M´Boi Mirim (extensão)	5.3
TOTAL		41.5

Source: TTC

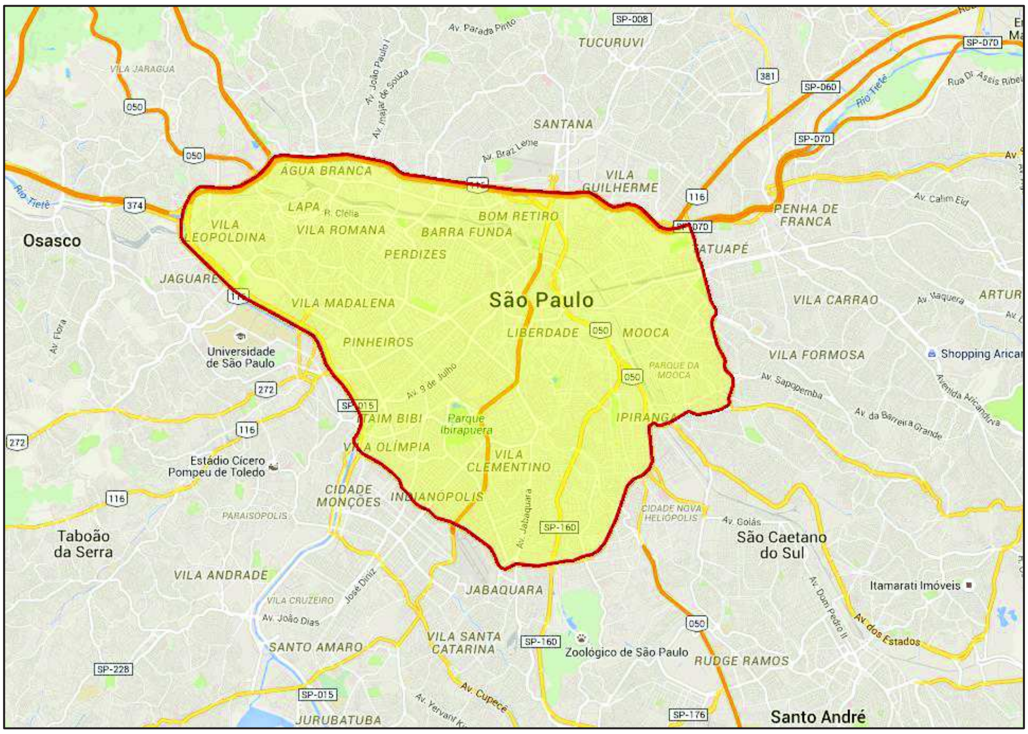
Table A3.6. Changes in bus corridors until 2025

Corridor	Main roads	Plus extension (km)
Aricanduva	Av. Aricanduva	13.7
Berrini	Av. Berrini (Trecho 1)	3.6
Berrini	Av. Chucri Zaidan / viário novo (Trecho 2)	3.5
Campo Limpo (Capelinha - V. Sônia)	Av. Carlos Lacerda / Estr. Campo Limpo / Av. Fco. Morato	12.2
Nove de Julho - Santo Amaro	Av. Cidade Jardim (extensão)	2.2
Itaquera - Líder	Av. Itaquera / Av. Lider / Rua São Teodoro)	10.4
Ponte Baixa	Rua Antonio Aranha / Av. Tomás do Vale / viário novo	4.6
Radial Leste	Av. Alcantara Machado / R. Melo Freire (Trecho 1)	9.9
Radial Leste	Av. Luiz Ayres (Trecho 2)	7.1
Celso Garcia - São Miguel	Av. Celso Garcia / até Penha (Trecho 2)	9.5
Itapecerica	Estr. de Itapecerica (extensão)	4.5
M´Boi Mirim	Estr. M´Boi Mirim (extensão)	5.3
TOTAL		86.5

Source: TTC

To estimate the impacts of the implementation of an urban toll in the city of São Paulo, the expanded center of the city was used to define the CBD, which outlined the area for which the toll would be charged. Such area is identified by the shaded area within the red line in figure A3.5 below. This area is known as "expanded center" of São Paulo, and currently traffic restriction program (where only allows vehicles whose license numbers end with certain digits to drive on particular weekdays). The toll is assumed to be charged to all cars driving into the restricted area. Further, all trips originating within the area will pay the toll at the origin link, while trips beginning outside the area will pay the fare at the first link of the restricted area.

Fiigure A3.5. São Paulo Extended CBD

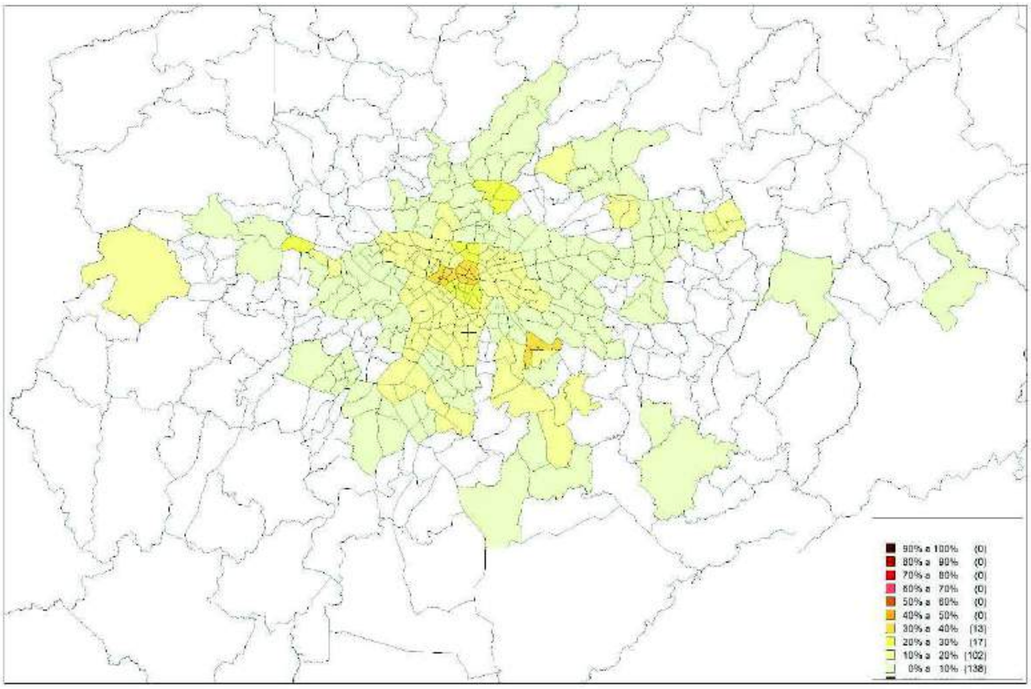


Source: CET.SP – Companhia de Engenharia de Tráfego de São Paulo

Finally, the scenario where parking costs increase leads to increases in overall transportation costs as parking costs by region are used for the calculation of generalized transportation costs matrices. The average cost of parking in the trip destination zone is considered in the generalized costs travel to that area, therefore affecting the decision of travelers to go to that area. The average parking cost per destination in calculated as a weighted average of the prices of that area by the number of trips that use parking. Thus, areas with few trips using parking has average costs of travel greatly reduced by trips that do not pay for parking.

Data from the OD / 2007 survey suggests that only 8.3% of MRSP car trips pay for parking. Figure A3.6 below, shows the proportion of trips that pay for parking. Among those paying are users of the Blue Zone (similar to a parking meter), public parking lot users paying by the hour and monthly users. Among the non-paying are those using curb side parking, own parking spaces, sponsored (parking available at no cost) and those who do not park at all. Further, only car trips for work/study are included in the calculation, disregarding the trips made to drop another person to a destination. Trips using paid parking overnight at the residence location were also excluded from the simulation.

Figure A3.6. Percentage of trips that pay for parking



Source: TTC

Table A3.7. Proportion of average auto trips by parking type

Proportion of trips paying for parking by area (%)				
Type	**Category**	**MRSP**	**Expanded center**	**Center**
Blue zone	Paying	0.7%	1.7%	2.4%
Parking lot (hourly+monthly)	Paying	7.6%	15.2%	22.6%
Paying for parking		**8.3%**	**16.9%**	**25.1%**
Weighted average costs for parking		**R$ 0.70**	**R$ 0.93**	**R$ 1.11**
Sponsored parking lot	Not paying	52.9%	48.7%	46.4%
Own parking	Not paying	11.9%	9.5%	9.0%
Curb parking	Not paying	25.4%	23.9%	18.3%
Not parking	Not paying	1.5%	1.1%	1.2%
Not paying for parking		**91.7%**	**83.1%**	**74.9%**
Total of trips		**2,181,308**	**652,478**	**179,530**

Source: TTC

Table A3.8 below summarizes the impacts on generalized costs and number of auto and transit trips for each scenario.

Table A3.8. Summary results per scenario

Scenario	Auto generalized costs (min)	Var. (%)	Transit generalized costs (min)	Var. (%)	Auto trips	Transit trips	Percentage of transit trips (%)
Scenario 0	49,393,784	-	51,055,637	-	1,211,347	1,605,276	57.0%
Scenario 1	49,346,714	-0.1%	48,645,136	-4.7%	1,211,951	1,604,674	57.0%
Scenario 2	49,293,780	-0.2%	48,510,714	-5.0%	1,210,189	1,606,436	57.0%
Scenario 3	49,168,278	-0.5%	47,626,573	-6.7%	1,203,601	1,613,022	57.3%
Scenario 4	49,028,855	-0.7%	47,442,580	-7.1%	1,200,579	1,616,044	57.4%
Scenario 5	57,705,139	16.8%	47,174,920	-7.6%	1,097,304	1,719,319	61.0%
Scenario 6	58,351,603	18.1%	50,600,088	-0.9%	1,118,669	1,697,954	60.3%
Scenario 7	58,195,915	17.8%	50,879,975	-0.3%	1,114,858	1,701,766	60.4%
Scenario 8	49,097,676	-0.6%	50,896,886	-0.3%	1,182,994	1,633,630	58.0%
Scenario 9	49,021,173	-0.8%	50,921,652	-0.3%	1,192,138	1,624,486	57.7%
Scenario 10	49,119,771	-0.6%	50,786,838	-0.5%	1,158,818	1,657,807	58.9%

Source: TTC

The result suggest that the most significant change toward mass transit modes is seen in scenarios 5,6, and 7 as these implement restrictions to auto use. The fact that scenarios 1 through 4 are not reflecting the largest changes of transportation mode confirms the well-known fact that supply side efforts are not enough to encourage users to move to mass transportation modes.