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Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

Worldwide Investigation of Private Motorization Dynamics at the Metropolitan Scale

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Abstract

Urban growth and the development of metropolitan areas are global challenging phenomena putting pressure on the development of transportation systems. In developing countries, its effects are often amplified by exponential growth and limited existing public infrastructures. Therefore, metropolitan growth is strongly linked with private motor vehicle ownership dynamics. In order to assess and quantify this statement, this paper investigates the link between socio-economical characteristics of metropolitan areas and the development of private car ownership to better explain and guide current motorization patterns in developing countries.

First, the panel of analyzed metropolitan areas is presented to define the scope of this research. The final perimeter represents a diverse set of metropolitan areas with a focus on developing countries where private motor vehicles ownership dynamics seem to be the most significant. Data from up to 52 metropolitan areas have been used in selected analyses. Second, the identification of relevant indicators of private cars ownership is discussed with concerns about data availability in relation with geographical and temporal scales. This paper especially proposes to focus on metropolitan level indicators that better describe local mobility and socio-economical characteristics instead of the traditional national indicators. A consumption statistical model is applied to explore the dynamic relationship between household income distribution evolutions and private motor cars ownership and to realize general trend forecasts for a shortlist of 17 metropolitan areas.

The results confirm the importance of population densities, income distribution and GMP per capita for explaining metropolitan private motorization dynamics, especially for developing countries metropolitan areas.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: Private Motorization ; International Metropolitan Comparison ; Socio-Economical Impacts ; Developing Countries ;

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Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY

1. Introduction

With the current demographic and economic growth centered on cities, metropolitan area development is a major challenge faced by urban planners all around the world. This challenge is all the more important because it has strong effects on local economic development and on greenhouse gases emissions, a major concern of the XXIth century. Indeed, it is established that cities with very low population densities and housing neighborhoods, far from work and leisure places, generate a high transportation demand leading to increased traffic congestion and energy consumption, at the root of a high share of greenhouse gases emissions. Studying transportation systems with regard to metropolitan and urban characteristics seems a relevant approach enforced by previous studies conducted by Gwilliam (2002) or Tana et al. (2016).

The metropolitan area development challenge is emphasized in developing countries where those growths levels are much higher. Berg et al. (2017) illustrate the need for designing efficient urban development policies to manage economic growth, social inclusion or sustainability in these countries. As those metropolitan areas do not often have a developed public transportation networks sustaining their rapid demographic growth and as those take a lot of time to design and implement, the transportation demand increase mostly relies on the spread of motor vehicle use. The experience of developed countries in the second part of the XXth century shows that cars had a prominent place in their metropolitan mobility systems. Private car ownership seems to coincide socio-economic growth as can be seen in Cornut et al. (2014) for the case of Paris before the 1990s. Thus, this paper aims on describing private motor vehicle ownership dynamics in light of socio-economic characteristics evolutions of metropolitan areas around the world with a focus on developing countries cases.

This approach provides an opportunity to question the place of the private car in line with socioeconomic development and political conditions and whether the motorization dynamics in developing countries follow the same pattern than previous motorization trajectories in developed countries such as suggested in Kuhnimhof et al. (2013). Nowadays, it seems developing countries metropolitan areas follow the previous motorization dynamic trend observed in developed countries. But two-wheeled and three-wheeled motor vehicles appear to be a step before car motorization, and the peak car phenomenon might not appear in the same way. This phenomenon is still not settled: while in developed countries Goodwin (2012) suggests a trend toward a stabilization or even a decrease of motorization, Klein and Smart (2017) propose an economic explanation linking motorization overall steadiness to delays for young adults' access to economic independence contradicting the peak car threshold theory. Investigating motorization dynamics with demographic evolutions and income growth patterns seems all the more important to highlight the phenomenon's evolution since the first motorization spread in occidental countries.

In order to reach this paper's objective, a first part describes the research scope by assessing which metropolitan areas are analyzed. The aim is to get cities widely spread around the world and representative of the metropolitan areas with a focus on developing countries. So as to get data and relatively similar cases, only urban areas above one million inhabitants are considered in this analysis. A second part is dedicated to the identification of relevant private motorization indicators available at specific geographical and temporal scales within data availability constraints. A quantitative approach assesses the relationship among private car density, household income characteristics and demographic growth. This part draws patterns of international metropolitan motorization developments. A final third part shows the use of a consumption statistical model linking household income distributions evolution to private cars ownership evolution. It enables the study of metropolitan growth through its income distribution evolution with the motorization growth within the limits of the model's assumptions.

Three principal contributions of this research can be identified: (i) The data collection on metropolitan areas with different statistical processes and communications in different languages, (ii) The comparison of the results among the different metropolitan areas giving hints of international patterns of the motorization phenomenon, (iii) The implementation of a consumption statistical model accounting for motorization dynamics enabling motorization trends forecasts for 2020 and 2025.

2. Metropolitan Areas Panel and Analysis

This research can be regarded as an extension of the meta-analysis of mobility at city and country scales conducted by Eskenazi et al. (2017) with a focus on private motorization. As observed in this paper, most of the international analysis of mobility are conducted at the national scale (not evaluating individual cities). These approaches are facilitated by the open access to reliable data gathered by reference international and national organizations such as the World Bank, the CIA or the OECD and also pay access to private organization databases such as the International Road Federation. As a result, many studies on motorization are conducted at the national scale: Dargay and Gately (1999), then Dargay et al. (2007) and Lescaroux (2010) are reference research at the national scale dealing with more than 45 countries each. Kuhnimhof et al. (2014) also has a national scale approach on the developing BRICS countries.

Yet, motorization seems to be a local phenomenon rather than a national one. Indeed, the national scale encompasses very different local cases: rural and urban areas do not show the same motorization patterns as they do not have the similar transportation supply and socio-economic characteristics within a country. This concept is especially true in developing countries where the gap between urban and rural developments is wider. As data at the metropolitan scale is increasingly becoming available, lack of data availability is no longer an obstacle in conducting metropolitan scale analysis. The present choice of studying motorization at the metropolitan scale follows the need for international comparison among cities stated in Robinson (2011) and a recent metropolitan comparison by McFarlane et al. (2017) on Mumbai, Delhi and Cape Town. The metropolitan scale was selected instead of the urban scale as administrative urban limits are often too restricted for studying the structural importance of the suburbs on mobility.

But this metropolitan scale also shows some limits: some cities just don't produce data at this scale. This is the case for smaller cities where the cost of producing, processing and maintaining data is too important compared to the outcome of data access. Even when a metropolitan area produces its own data, its range is not always the same than at the administrative city, regional or national scale. The average and median incomes per capita or per household are sometimes available at the national scale while only per capita data exists for the metropolitan scale. The current approach must then be conducted on relatively general variables often available at the metropolitan scale. The final and probably strongest limitation for using the metropolitan scale is the lack of general international data library at this scale. This limitation generates two main difficulties for this research: the diversity of statistic organisms and data sources among metropolitan areas and within a metropolitan area, and the languages in which the data is produced. Indeed, within the same country data on two metropolitan areas often rely on at least two different local statistical organizations. And when looking for data in a metropolitan area, it has been very common to use data from at least two different sources on income, population and number of registered vehicles for example.

In order to overcome these limits in this paper, the first step has been to choose to only deal with metropolitan areas usually over one million inhabitants. This decision is convenient as it enables getting rid of most of the situations where data does not exist at the metropolitan scale while still enabling to deal with a large share of the population as UN's 2018 World Urbanization prospects states more than half of the urban population lives in urban areas over 500,000 inhabitants. Concerning the different analysis scales, the choice has been to get data at the city, metropolitan or regional scale where the data range was sufficient enough, with preferences for the metropolitan scale. This choice relies on the metropolitan area characteristics and is also based on the local observations: getting regional data for Paris is not that different from the metropolitan area scale and has a larger range so this level has been selected in this research, but it would not have been the case with a larger region and encompassing several metropolitan areas. Eventually, each metropolitan area has been individually studied by graduate students at ENPC with different languages skills enabling studying a wider number of cases, to deal with the diversity of metropolitan areas.

The final selection of metropolitan areas is represented on Figure 1: 52 metropolitan areas have been analyzed with a diversity intended to best represent developing countries and places where the urban growth mainly occurs as can be seen with the high number of African, Asian and South American cases. The selection is obviously non-exhaustive but the coverage is larger than any metropolitan comparison study to the authors' knowledge. The range of available cases is expected to grow with each passing year to better cover the world, within existing open data limits.

North America (2)	South America (7)	Europe (11)	Africa (14)	Middle East (3)	Southern and Eastern Asia (13)	Oceania (2)
Guatemala city	Porto Alegre	Copenhagen	Algiers	Riyad	Hong Kong	Melbourne
Washington DC	Rio de Janeiro	Paris	Luanda	Abu Dhabi	Shanghai	Sydney
	Salvador de Bahia	Dublin	Kinshasa	Dubai	Wuhan	
	Sao Paulo	Amsterdam	Cairo		Zhengzhou	
	Santiago	Oslo	Addis Ababa		Bangalore	
	Medellin	Lisbon	Accra		Delhi	
	Lima	Bucarest	Abidjan		Hyderabad	
		Moscow	Nairobi		Kolkata	
		Madrid	Casablanca		Kuala Lumpur	
		Stockholm	Tangier		Manila	
		Birmingham	Maputo		Singapore	
			Dakar		Seoul	
			Cape Town		Hanoi	
			Dar es Salaam			

Fig. 1. World map and list of the metropolitan areas included in the analysis.

3. Indicators of Motorization at the Metropolitan Scale

In order to study the facts, phenomena and causality of private motorization, private motorization indicators must first be defined. A first subpart is then dedicated to the quantitative representation of private motorization. A second subpart describes the possible metropolitan socio-economic variables linked to private motorization. The last subpart shows results of observed trend in the dataset collected and enables identifying relationships between the selected explanatory variables and private motorization.

3.1. Private Motorization Description

Private motorization can be defined as the motor vehicles degree of penetration within a private transportation system. It appeared with the invention of motor vehicles and it encompasses any motorized vehicle. The most studied ones are cars and motorcycles, but the term motorization is often used with the implicit meaning of car motorization. As less data is available on motorcycle or other motorization, the analysis concerns only car motorization. This part examines private motorization dynamics drivers at the metropolitan scale. Which can also be formulated as analyzing the influence of socio-economic characteristics of metropolitan areas on the evolutions of private car motorization. To meet this expectation, a first step is to set which indicators best measure motorization.

The most common measure of private car motorization is the *average number of private cars per 1,000 capita* that will be referred to as *vehicle density* for the rest of this paper. This indicator sometimes has another unit, the number of vehicle per 1,000 households related to the former by the average capita per household ratio. It is a way of measuring the capacity of the car mode on a territory even though it does not capture car uses. It is very often produced and can be analyzed in time series. From a metropolitan mobility perspective, this indicator illustrates the spread and the rank of those private motorized modes in the transportation modes mix. It is the motorization indicator that is favored in this study, especially as it is the most easily found or computed for studying many metropolitan areas. One issue with it is that it often does not account for unregistered vehicles or for vehicles registered in neighboring geographical areas.

The *households owning a car share* is a second motorization indicator which can also be called motorization ownership rate. It is less produced than the previous ones and is rarely frequently produced so as to be studied within time series. Households owning a car share relies on the definition of households that is sometimes not clear such as observed by Randall and Coast (2015) in Africa or with the variety of close but not identic term such as “hogar” and “familia” in South America. It also does not show the overall car mode capacity. Instead it results from a consumption approach of car ownership and it is an evaluation of the penetration of the car good in the household market. It is important to notice that the motorization rate is based on households, relying on the assumption that cars are expensive and durable goods which are bought at the household level and not at the individual level.

The *percentage of car trips* is not often used under the meaning of motorization but it is definitely a measure of car use importance through its modal share. This indicator is generally produced by household travel surveys which are rarely conducted more frequently than once every decade. The percentage of car trips in a weekday can then be considered as a spread indicator but not produced enough to include in time series. Its main drawback is that is does not evaluate well the physical impact of cars on the transportation system as it accounts for the frequency of car use and not really its intensity. It is also heavily linked to it measurement period: even though it is generally measured on the morning peak period of a weekday to avoid week-end effects, it is heavily subject to exceptional local events.

The *average number of car-kilometers* or car-miles is another indicator of motorization. It is the number of kilometers of car use, resulting from the multiplication of the average number of kilometers per car by the number of cars. It completes the last indicator by incorporating the notion of the intensity of the car use. This indicator is rarely available at the metropolitan scale for developing countries and cannot be used in time series.

In order to include the maximum number of metropolitan areas in this study, the two indicators of motorization analyzed in this paper are the vehicle density and the percentage of car trips. After describing private car motorization, the next subpart describes the potential metropolitan socio-economical explanatory variables of the phenomenon.

3.2. Socio-Economic Explanatory Variables

The first and most spread variable used to describe motorization is the *income*. It is based on a consumption view of motorization considering the car as a good to consume. Income being a measure of wealth, it is a measure of the population purchasing power. A lot of studies such as the one conducted by Dargay et al. (2017) or Dargay (2001) mainly rely on this indicator. But income can be analyzed from different perspectives: whether it is the household or the per capita income, whether it is the average, median or overall income. As explained for the household motorization rate, cars seem to be household goods rather than individual goods, so household income should be more relevant for studying motorization. This statement might not be true for developed countries where multi-motorization is common, but as this research focuses on developing countries, it is valid. Between median, average or overall income, the median income seems to best fit the need for analyzing motorization as it incorporates an income distribution sensitivity the average and overall motorization lack. Yet it is not always as often available as the average income. The average income can be coupled with inequality measure such as the Gini coefficient or inter-quantile ratios to compensate its lack of income distribution data. Another issue with the income variable is that it has a monetary unit dependent on the metropolitan area studied. In order to draw an international comparison, each income is converted into US dollars, the international reference currency. But converting each currency into US dollars captures variations of the local currency value and also variations of the dollar, so there still can be very wide variation not always reflecting the real change of purchasing power.

Analogous to income levels, the *GMP* – Gross Metropolitan Product – variable is sometimes used to describe motorization. It is generally employed as an approximation of the income variable when it is not available and it has the same characteristics, except that it is not as good an estimator of purchasing power as income is. *Expenditures* are also sometimes used to replace income, but it is theoretically questionable as it effectively uses the overall consumption to explain the evolution of the consumption of a specific good, thus using the consumption value to explain consumption.

Tan et al. (2016) use urban form characteristics to explain motorization. This variable is the equivalent of the urbanization rate when studying motorization at the national scale. This is practically realized by considering the distance to activity centers or the urban spread shape and structure. Taking into account this variable is theoretically complicated and requires a lot of data on the metropolitan area. It suits disaggregated approaches more and is burdensome to use for comparing 52 metropolitan areas with each its own expanding borders.

Population or *density* could also be considered as an explanatory variables of motorization, or at least its dynamics. On one hand, population growth might be linked to economic development and thus consumption evolution. On the other hand, density is known for having an impact on motorization among developed countries metropolitan areas such as observed in Bertaud and Richardson (2004). Density can also be interpreted as an indirect estimator of other transportation modes competition. Indeed, public transit is more efficient and easier to organize while there is often a lesser need for travelling long distances, making walking and biking become more attractive in dense areas. The immediate advantage of those variables is that they are the most easily accessible, their drawback being their indirect relationship with motorization.

The *public transit* and the *shared mobility services supplies* could also be analyzed as indicators of the competition on the urban mobility market. Public transit supply is not an appropriate indicator in developing countries often lacking of it or not producing enough data on it. Shared mobility services supply is difficult to quantify and data is all the more difficult to get than it is divided among the different existing mobility services.

The *transportation policy orientations*, the *transportation restrictions* are also relevant indicators, especially with cities with very strong policies toward cars. A good example is Singapore with its restriction on car driver’s license numbers that manages to have low income densities compare to its very high average GDP per capita. Other common policies are the use of special pricing strategies on car parking, uses, energy consumption. They can target either the ownership or the use of specific transportation vehicles or modes. But those qualitative indicators are difficult to compute and each require extensive analysis of the metropolitan areas to take into account every aspects of the different policies implemented.

The variables selected for the analysis are the *GMP per capita* as an indicator of metropolitan development, the *population growth* as an indicator of metropolitan development dynamics and the *density* representing local modal competition against car ownership. The income is not accounted for as too many metropolitan areas didn’t propose an easy access to those data.

3.3. Dataset analysis

This subpart is dedicated to the analysis of the 52 metropolitan areas dataset. In order to assess how the selected variables influence motorization, the different motorization indicators are first compared, before looking for candidate explanatory variables correlations and finally relationships between the potential explanatory variables and the motorization indicators.

Relationship between motorization indicators

This first step is conducted to ensure that vehicle density and the percentage of car trips are two indicators representing motorization. This statement should appear through a strong relationship between these variables. But as explained when selecting the motorization indicators, they each represent a different expression of the motorization phenomenon, so it is expected that there will be differences and no perfect correlation. The Figure 2 shows the comparison of these two indicators.

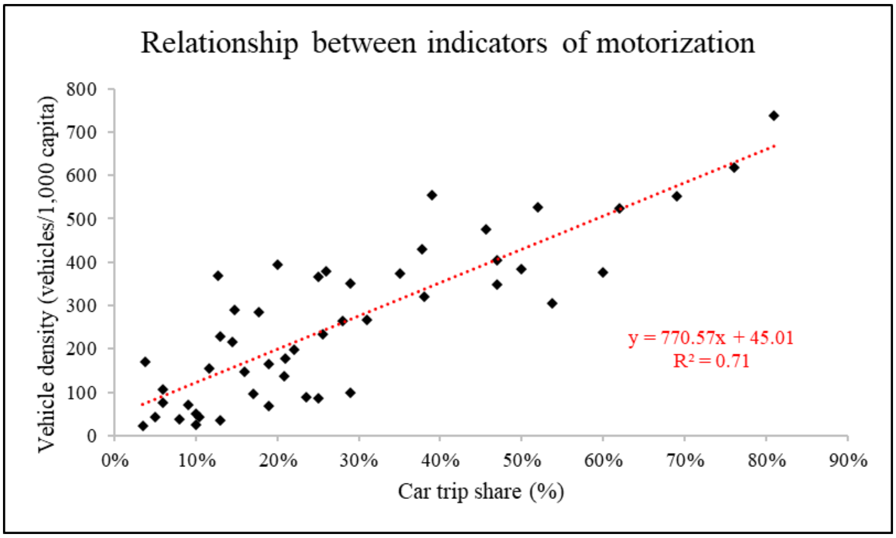

Fig. 2. Relationship between *Car density* and *Car trip share*

The comparison of the two motorization indicators clearly shows an almost linear relationship between car density and car trip share. Yet some noise can be observed and the data points are not perfectly aligned, corresponding to the second hypothesis that they do not exactly represent the same aspect of motorization. The final correlation factor is 0.71, a value validating the hypothesis of a high association between the two variables.

Relationship among candidate variables

A first comparison of GMP growth with population growth does not show any easy close-form interpretation with a correlation factor of 0.17, letting think those two variables are uncorrelated. This observation is not straightforward for the comparison between Population density and GMP per capita, as there seems to be an inverse function relationship. But this interpretation is biased by the data used focusing much more on metropolitan areas in developing countries not showing the diversity of such cities. The inverse function interpretation also mainly comes from three extreme data points and does not appear for the rest of the graph. The results of this comparison appear in Figure 3.

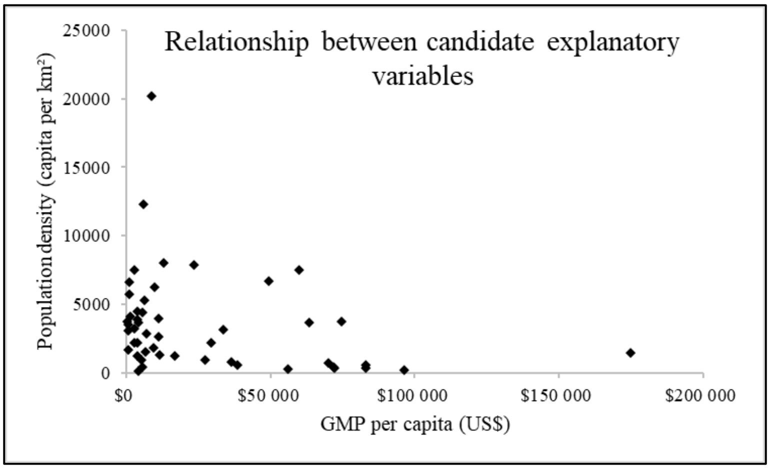

Fig. 3. Relationship between candidate explanatory variables.

The results show the candidate explanatory variables are likely not correlated. This result seems a bit disappointing but it is convenient for the interpretation of the following tests of those explanatory variables to explain motorization, without cross-correlation effects.

3.4. Results

The comparison of the two private car motorization indicators and density show some noise around a decreasing function in Figure 4. Even if the exact function for explaining this relationship is not self-evident, the results clearly show that density has a negative effect on car ownership – through the car density indicator – and on car use – through the car trip share indicator –. This graph is very similar to the one between annual gas consumption and population density in Newman and Kenworthy (1989). This observation seems to corroborate the previous observation that density could be interpreted as an indicator of other modes competition, as the development of proximity transportation modes, services and public transit is more economically viable.

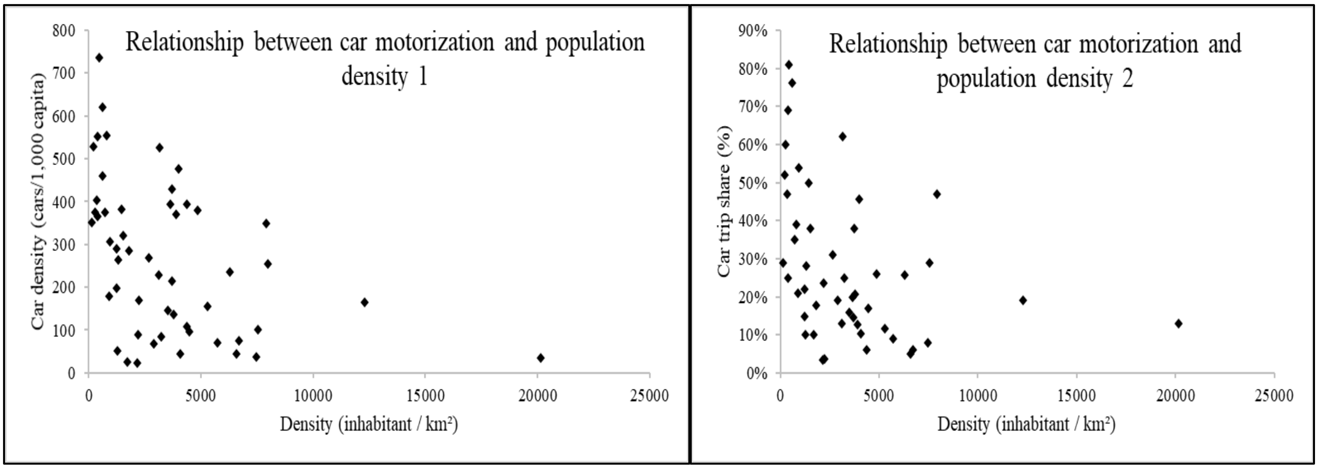

Fig. 4. Relationship between private car motorization and population density.

The relationship between car motorization and GMP per capita shown in Figure 5 is the reverse, with an increase of private car motorization with the GMP per capita. This observation fits the expectations that metropolitan areas in developed countries with higher GMP per capita are more motorized than cities in developing or underdeveloped countries. Yet it can also be interpreted as a higher car motorization amplitude for high GMP per capita. It probably comes from that such metropolitan areas have a socio-economic structure enabling high private car motorization but can limit it with other factors such as the policy indicators not encompassed in this analysis. The Singapore case with a high GMP per capita and only 100 cars per 1,000 capita coming from its car limitation policy is striking for illustrating this observation.

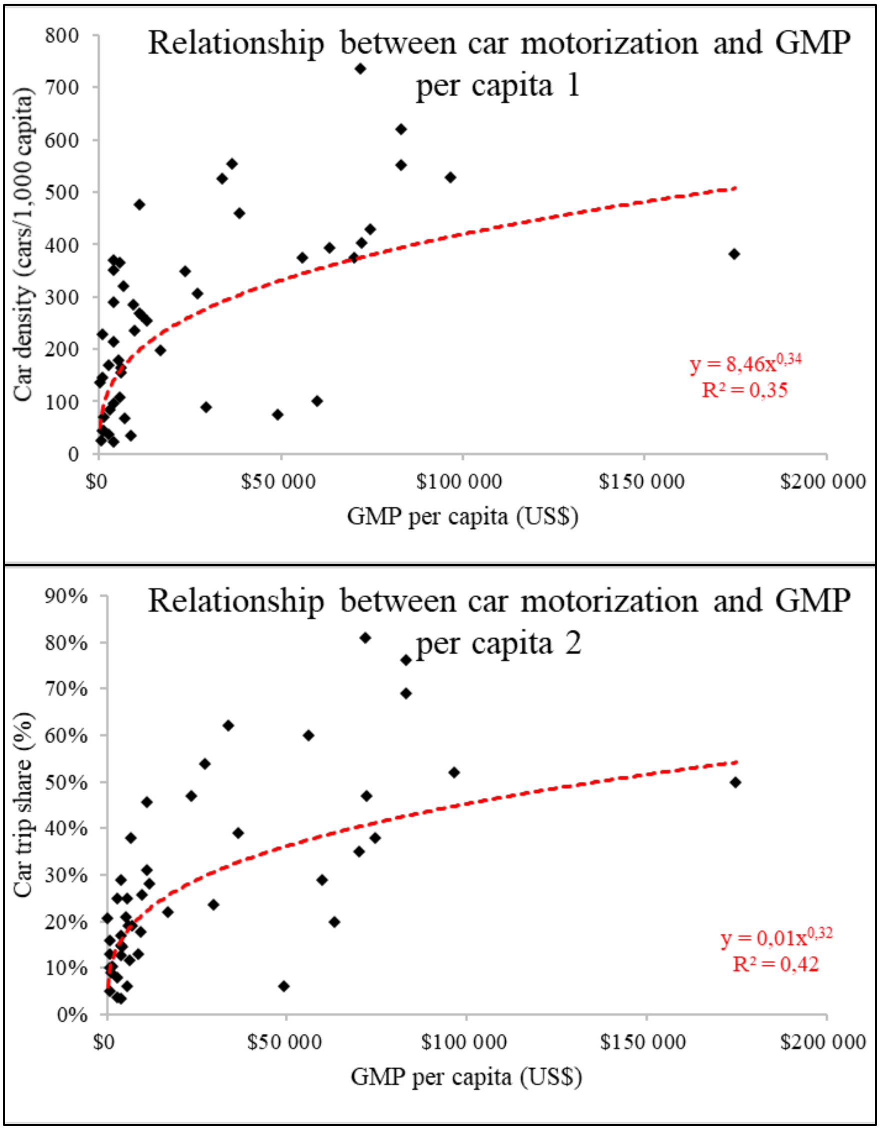

Fig. 5. Relationship between private car motorization and GMP per capita.

So the effect of population density and GMP per capita is well illustrated by this analysis. Another indicator to account for is the metropolitan income distribution. Indeed, Income distribution take into account the overall income level, but also the number of inhabitants above threshold income values where private car motorization is available. The next analysis also proposes to follow the evolution of this relationship with the years to access motorization dynamics.

4. Motorization and Income Distribution Dynamics

Income levels have often been used to forecast motorization evolutions at a national scale, but a lot less at the metropolitan scale, or only on models applied to one metropolitan area with available disaggregate data. This part's goal is to use aggregate data on income at the metropolitan scale to reproduce the income distribution evolutions over time. This income distribution evolution is then used to forecast vehicle density evolution. This approach is standard for studying consumption goods such as explained in Trognon (1978), but it has not been used for studying motorization at the metropolitan scale and on a lot of candidate cities.

As this approach is dynamic, it requires income and motorization data on at least three time periods to calibrate a model. This implies getting data on income level and distribution and motorization for several years, which is more challenging. The data collection being more burdensome, this motorization modeling step includes 17 metropolitan areas instead of the 52 previously used. Yet, those 17 cases have been selected with the same goal as the selection of the first 52 sample: being representative of the diversity of the world regions, with a focus on developing countries, for cities with enough official data accessible at the fitting scale. The final selection for the application of a statistical dynamic consumption model is presented in Figure 6. South America is slightly overrepresented because of the existence of detailed statistical database easing the data collection process, compared with Africa for example.

North America (1)	South America (6)	Europe (2)	Africa (2)	Middle East (1)	Southern and Eastern Asia (5)
Los Angeles	Porto Alegre	Paris	Casablanca	Dubai	Shanghai
	Rio de Janeiro	Madrid	Cape Town		Delhi
	Salvador de Bahia				Hyderabad
	Sao Paulo				Manila
	Medellin				Hanoi
	Lima				

Fig. 6. World map and list of the metropolitan areas selected for the motorization dynamic modeling.

Many models have been developed to study dynamic motorization evolutions at an aggregated scale and Lescaroux (2010)'s model is efficient under those constraints. Its main advantage is that it incorporates lagged variable such as the previous year's vehicle density. This diminishes the effect of the volatility of income, a variable varying a lot more quickly than the number of cars per 1,000 capita. But implementing this model takes a long time to process. The final model choice has been set on Cramer (1959)'s model, a model similar to Lescaroux's one but without accounting for lagged variables. Its main advantage is the need of few aggregate data to produce motorization forecasts.

Cramer's Model

Cramer's model is a consumption model based on the evolution of income distribution over time to forecast the share of consumed goods. It relies on two main assumptions:

- The income distribution is lognormal and its standard deviation is a constant over time;
- The consumption function is a lognormal cumulative distribution function of the income.

In order to apply Cramer's model, first the income distribution parameters must be determined. Then the consumption function parameter must be determined to calibrate the model. In order to apply this function to a number of consumed units instead of its share, thresholds are set. The process is as follows:

- The income distribution parameters are determined through several methods depending on the available data. In this research, the parameters are determined through the median income, the average income, the Gini coefficient or the inter-quantile ratio, with the following formula standing for lognormal distributions:

  $$MedianIncome_t = \exp(m_t)$$

  $$AverageIncome_t = \exp(m_t - \sigma_t{}^2/2)$$

  $$InterdecileRatio_t = \exp(2.56 \times \sigma_t) \text{ and } InterquantileRatio_t = \exp(1.68 \times \sigma_t)$$

  $$Gini_t = 1 - 2 \times \Phi(-\sigma_t/\sqrt{2})$$

  with (m_t, σ_t) the parameters of the lognormal distribution of incomes for each year t, and Φ the standard normal distribution.

- Then a constant σ is estimated by averaging the values of σ_t on the time periods. The consumption share is made equal to the vehicle density divided by a threshold simulating the maximum value of the vehicle density if every member of the population had the highest income. This threshold will be determined from an initial value set at 1,000 vehicles per 1,000 capita.

  $$ConsumptionShare = VehicleDensity / Threshold$$

  The consumption cumulative distribution of parameters (m_c, σ_c) appear in the formula:

  $$ConsumptionShare = \Phi((m_t - m_c)/\sqrt{\sigma^2 + \sigma_c{}^2})$$

  The (m_c, σ_c) parameters can be evaluated by running a linear regression of Φ^{-1}(ConsumptionShare) by m_t. The (a,b) coefficient of the linear regression y = a.x + b are related to (m_c, σ_c) such as follows.

  $$a = 1/\sqrt{\sigma^2 + \sigma_c{}^2}) \text{ and } b = -m_c/\sqrt{\sigma^2 + \sigma_c{}^2})$$

  Now that (m_c, σ_c) are available, the threshold is determined by an optimization process minimizing the sum of the squared errors with the threshold as unique variable.

- Since the threshold is available, it is possible to implement a dynamic Cramer's model. First, the m_t of the income distribution are assumed to be linear and are modeled over the analysis period with a linear regression of the years t. Then (m_c, σ_c) are assumed to be constant too. Eventually, the threshold, the m_t for every year t and (m_c, σ_c) are available. The vehicle density for each year t is computed with the formula:

$$VehicleDensity_t = Threshold \times \Phi((m_t - m_c)/\sqrt{\sigma^2 + \sigma_c{}^2})$$

The main issue with Cramer's Model is its high sensitivity to income variations that triggers high variation in vehicle densities while cars are long-term goods not bought or sold immediately after one year of general income increase or decrease. It also considers only the income effect with no regard for local policies that could limit or foster car ownership, such as downtown car or diesel car bans. As a result, Cramer's model better suits metropolitan areas in developing countries where the income growth is very significant and where other policies that could impact car ownership are not yet implemented or are not as strong as in developed countries.

Model implementation

The first step of Cramer's model where the income's lognormal distribution parameters are calculated has been realized on the collected data, with income converted into US dollars, the world reference currency. Thus the means of the distribution can be compared in the Table A.1 of the Appendix A. The poorest metropolitan area of our panel is definitely Hanoi with a mean under 0 while developed countries have means above 7. Standard deviation above 1 seems to indicate countries with high income distribution spread i.e. inequalities, the highest being Dubai with a 1.84 standard deviation. This last result is not very surprising EAU have very different income policies for each ethnic group, the Emirati households having a lot higher incomes than immigrants from other Asian countries.

When observing the m values in Table A.1, the reader can notice their overall constant or decreasing value between 2008 and 2009. This observation is caused by the 2008 world economic crisis that had a strong impact on income levels. Unfortunately, this strong shift from the general trend of increasing incomes highly impacts the model estimation, especially as a lot of data points happen to be around 2008. In metropolitan areas with many data points available this is not such a big issue as for cases with less than 6 data points, but it has an effect on the final quality of the model nonetheless.

The results of the model calibration are detailed in Table A.2 of Appendix A. The threshold values obtained are generally very close to 1,000 vehicles per 1,000 capita, so it seems there naturally is a convergence to 1 vehicle per capita. Yet the optimization didn't always converge: in these cases, the threshold value of 1,000 vehicles per capita was kept to avoid infinite or null thresholds. For the cases of Madrid and Manila, the vehicle density slightly diminishes with income increase on the observation period. This yield an inverted model for those, where income increase is associated to vehicle density decrease. It can be explained for Madrid as it is a metropolitan area of a developed country, with other factors than income influencing vehicle density and the potential peak car phenomenon appearance. For Manila, it probably comes from the few data available showing a steady vehicle density while income was perturbed by the 2008 economic crisis, highly deteriorating the model efficiency. More data would probably automatically solve this issue. Or it could also be linked to the motorcycle motorization and that owners of motorcycles are less likely to buy a car even though their income increases.

Model results

The results of the models are displayed in Table A.3 of Appendix A and represented in Figure 7. The Medellin case is almost steady because of high variations of income level observed decreasing the quality of the income evolution estimation. The final m calculated are almost flat and do not much evolve over time, so the model only yields the average vehicle density value on the observed periods. This example illustrates well the vulnerability of the model to high and not regular income variations. Except for this case, the model seems to fit the observations well for metropolitan areas between 50 and 500 vehicles per 1,000 capita and without much income variations. Note that 500 cars per 1,000 capita often means 1 car per household for the regular case of metropolitan areas with more than 2 capita per household. Yet one should be careful as this does not mean that every household owns a car. Los Angeles is the highest car density case, representative of the extremum cases of a metropolitan area completely built around car use.

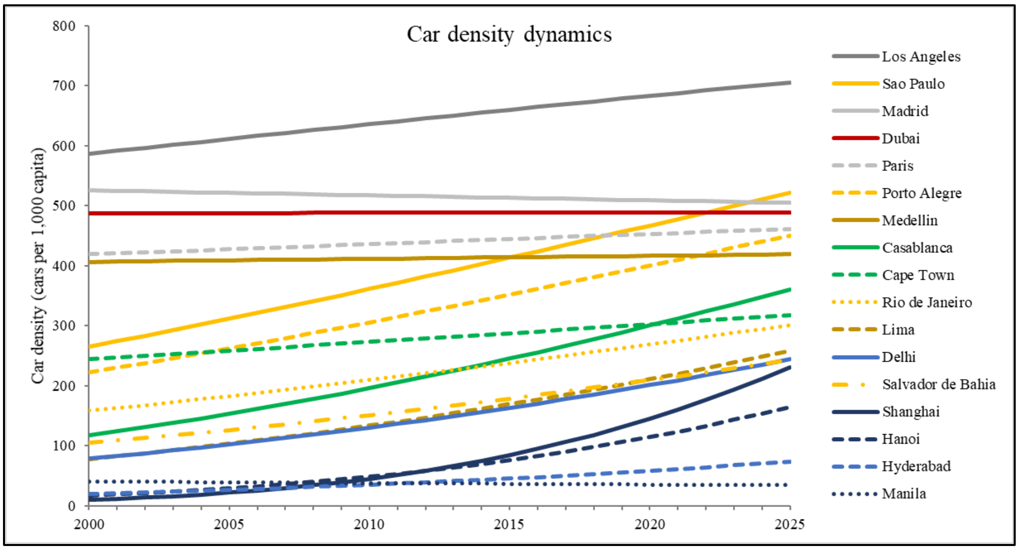

Fig. 7. Vehicle density dynamics estimated for 17 metropolitan areas.

The case of Dubai is also specific as it is disturbed by big vehicle density variations which is quite unexpected. This probably comes from the quality of the original data that was difficult to find for this metropolitan area, highlighting the need for better input data. Yet some examples such as the two cases in India show that even with little data, the proposed model enables drawing general trends matching observed data.

The metropolitan areas with the highest vehicle density growth potentials are Shanghai, Hanoi, Hyderabad, Delhi and Casablanca with more than 20 percentage points of vehicle density growth expected between 2000 and 2025 each. This comes from the high income growth perspectives for those metropolitan areas. It is quite surprising to see similar evolutions for Hanoi and Shanghai which are different cities: Shanghai has a much more developed public transit system while Hanoi mainly relies on private transportation, especially motorcycles and mototaxis. This highlights the model limits: even though both cities have similar income distribution growth patterns, the motorization growth will probably be also impacted by public transit supply. The growth rates estimated from the dynamic model are gathered in Table 1. Even though those figures are approximations, they display general trends. It is quite clear that the developing countries identified as BRIC – Brazil, Russia, India, China – clearly shows the highest growth potentials.

The four Brazilian cities in this study show quite different vehicle density levels justifying the metropolitan approach for studying motorization. Yet it seems the growth levels are similar, suggesting motorization dynamics might be similar for cities above one million inhabitants in the same country.

Table 1. Estimation of car densities and car density growth rate for 17 metropolitan areas.

	Estimated car density in 2000	Estimated car density in 2025	2000/2025 growth rate	Expected 2020/2025 growth rate
Shanghai	10	231	2266%	59%
Hanoi	17	165	869%	44%
Hyderabad	20	74	273%	27%
Lima	78	258	231%	22%
Delhi	79	244	209%	21%
Casablanca	117	361	208%	20%
Salvador de Bahia	105	243	133%	16%
Porto Alegre	222	450	102%	12%
Sao Paulo	265	521	97%	12%
Rio de Janeiro	158	301	90%	12%
Cape Town	245	318	30%	5%
Los Angeles	586	706	20%	3%
Paris	419	461	10%	2%
Medellin	406	419	3%	1%
Dubai	487	489	0%	0%
Madrid	525	505	-4%	-1%
Manila	40	34	-15%	-3%

5. Conclusion

This research's initial objective was to analyze private car motorization dynamics at the metropolitan scale with a focus on developing countries cases. It has been tackled by first identifying candidate cities over one million inhabitants and representative of the diversity of world regions. 52 Cities were selected, being one of the biggest metropolitan comparisons as far as the authors are aware of. Then indicators of motorization and potential explainable variables have been derived. Their relationship was studied on graphs with analysis of the correlation factors, enabling the identification of patterns of motorization according to population density and the GMP per capita as indicators of socio-economic metropolitan development. The results show that population density has a negative effect on private car motorization that could be linked to its interpretation as other modes competition while GMP per capita enables higher motorization levels. A final, more detailed, approach of the effect of household income distribution evolutions on the vehicle density was conducted on a 17 metropolitan areas shortlist because of a need for more extended time-series data. The dataset has been used to implement a consumption model enabling to draw vehicle densities estimation and forecasts between 2000 and 2025. The developing countries metropolitan areas clearly show the strongest growth potential on this period, reasserting the relationship between income distribution evolutions and motorization.

The paper contributes to the research by its emphasis on gathering data on private car motorization in multiple metropolitan areas around the world and includes data from very diversified sources in many languages. The synthesis of the comparison of these data to assess indicators explaining motorization is another important contribution as the literature lacks international metropolitan comparisons. Finally, the use of a statistical model to forecast car densities on several metropolitan areas and observe its growth contributes to the better understanding of private car motorization dynamics based on income distributions.

To put the work into perspective, socio-economic characteristics were used to determine private car motorization. But the assessed relationships between socio-economic variables and motorization indicators goes both ways. Thus this paper also indirectly shows private car motorization can be seen as an indicator of metropolitan development.

This subject can be further extended by increasing the number of analyzed metropolitan areas first to get more significant results and to be able to draw a motorization typology. Second, the number of metropolitan socio-economic variables that could be used as private car motorization explanatory variables should grow to look for other possible causal links. Finally, the statistical model employed could be developed to be less sensitive to uneven income or motorization variations. Eventually, this analysis can be extended to the study of private motorcycle motorization and its relationship with private car ownership so as to state whether or not motorcycle spread is an intermediate motorization step before car motorization.

Acknowledgements

This work relies on the contributions of the graduate students of the TRADD master at ENPC. The authors thank them for their help with data collection, Renault ParisTech's Institut de la Mobilité Durable (IMD) for financing the meta-observatory of mobility at the origin of this research, and Chaire Ile-de-France Mobilités - ENPC funding financing Mallory Trouve's research position.

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Appendix A. Model Results

This appendix gathers the data generated in order to implement the car density forecast model.

A.1. Step 1: Income distribution parameters

Table A.1. Income lognormal distribution parameters calculated from observed income data.

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Porto Alegre	m		5.68	5.56	5.61	5.74	6.04	6.24	6.38	6.55	6.55		6.89	6.85	6.85	6.84	6.53			
	sigma		1.23	1.22	1.19	1.17	1.17	1.15	1.12	1.13	1.10		1.11	1.09	1.11	1.08	1.07			
Rio de Janeiro	m		5.63	5.50	5.52	5.68	5.95	6.14	6.26	6.50	6.48		6.69	6.72	6.70	6.66	6.36			
	sigma		1.23	1.22	1.22	1.20	1.20	1.22	1.22	1.19	1.20		1.21	1.16	1.16	1.19	1.21			
Salvador de Bahia	m		5.25	5.16	5.05	5.24	5.56	5.76	5.99	6.15	6.18		6.50	6.41	6.43	6.41	6.08			
	sigma		1.32	1.35	1.32	1.27	1.28	1.29	1.29	1.30	1.27		1.25	1.26	1.28	1.24	1.20			
Sao Paulo	m		5.81	5.71	5.67	5.76	6.08	6.29	6.48	6.63	6.61		6.97	6.91	6.91	6.89	6.58			
	sigma		1.23	1.23	1.20	1.18	1.21	1.16	1.16	1.12	1.11		1.11	1.12	1.15	1.16	1.10			
Medellin	m					6.44	6.68			6.43	6.53	6.81	6.88	7.00	6.95	6.77	6.45	6.48	6.50	
	sigma			1.77	1.38	1.09	0.95			1.22	1.24	1.04	0.98	0.95	0.98	1.02	0.93	0.91	0.87	
Lima	m											6.71	6.82	6.88	6.88	6.92	6.98			
	sigma										0.82	0.80	0.78	0.76	0.76	0.74	0.74			
Shanghai	m					5.70	5.83	5.97	6.19	6.38	6.49	6.64	6.82	6.93	7.04	7.13	7.04			
	sigma					0.94	0.93	0.93	0.91	0.91	0.88	0.85	0.84	0.84	0.86	0.80	0.91			
Hanoi	m											-1.91		-1.61		-1.36		-1.26		
	sigma											1.30		1.27		1.27		1.27		
Madrid	m									7.66	7.61	7.54	7.46	7.44	7.65	7.45	7.29	7.23		
	sigma									1.03	1.10	1.06	1.08	1.11	1.08	1.11	1.15	1.18		
Paris	m		7.22	7.24	7.25	7.26	7.30	7.34	7.38	7.41	7.40	7.42	7.45							
	sigma		0.76	0.76	0.77	0.77	0.77	0.77	0.77	0.78	0.78	0.78	0.79	0.78	0.79	0.79	0.80			
Manila	m	5.85			5.71			6.00			6.18			6.37			6.37			
	sigma	0.83			0.75			0.74			0.76			0.75			0.72			
Dubai	m	6.46								7.09						7.43				
	sigma									1.84										
Delhi	m					6.23	6.31	6.38	6.59	6.67	6.86	7.05	7.08	7.16	7.15	7.21	7.26	7.35		
	sigma												0.64							
Hyderabad	m		4.18	4.21	4.32	4.43	4.46	4.55	4.75	4.57	4.68	4.79	4.67	4.68	4.61	4.65	4.67			
	sigma		1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34			
Casablanca	m					6.22			6.35		6.44	6.43								
	sigma	0.75							0.76											
Cape Town	m		6.00									6.87	6.80	6.58						
	sigma		1.19						1.17			1.12						1.14		
Los Angeles	m	8.24										8.51	8.53	8.53	8.50	8.53	8.56	8.61		
	sigma														0.87	0.85	0.82	0.80		

A.2. Step 2: Model calibration

Table A.2. Application of the model on observed data to evaluate the threshold and the consumption parameters.

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Sum of squared errors	Threshold
Porto Alegre	Model		234	224	228	239	264	280	293	309	309		340	336								
	Observed		223	232	240	248	258	266	277	292	308		345	366								
	Delta²		114	59	149	88	34	209	243	287	1		20	873							2078	1001
Rio de Janeiro	Model		165	158	159	168	183	194	201	216	215		228	230								
	Observed		156	164	169	173	178	184	192	201	213		236	251								
	Delta²		80	30	94	29	18	108	92	228	5		63	442							1190	1001
Salvador de Bahia	Model		112	108	104	112	125	135	146	154	156		173	168								
	Observed		104	109	112	117	122	129	137	145	155		175	186								
	Delta²		62	0	77	25	9	29	82	91	2		5	341							724	1002
Sao Paulo	Model		282	272	269	277	309	331	350	366	364		403	397								
	Observed		266	276	284	292	302	315	333	352	371		405	424								
	Delta²		268	13	232	227	48	244	317	194	45		3	755							2346	1000
Medellin	Model						414			386	398	429	437	451	445	424	388					
	Observed						238			335	369	400	430	460	489	506	547					
	Delta²						30978			2564	835	852	55	74	1916	6700	25083				69056	1006
Lima	Model											128	144	153	152	159	169					
	Observed											131	139	149	152	164	170					
	Delta²											9	22	22	0	31	1				85	1000
Shanghai	Model					17	20	24	30	37	41	47	57	63	69	75	69					
	Observed					17	22	26	30	34	39	45	51	59	68	76	86					
	Delta²					0	2	5	0	9	6	5	31	11	2	0	301				372	1000
Hanoi	Model	17									44						76					
	Observed	17									47						74					
	Delta²	0									10						3				13	991
Madrid	Model									512	513	514	516	516	512	516	519	520				
	Observed									538	513	511	512	506	501	505	519	533				
	Delta²									682	0	15	16	94	131	130	0	189			1256	1000
Paris	Model		421									435	437	439	441	443	444					
	Observed		420									430	440	444	448	443	435					
	Delta²		1									26	7	24	46	0	78				183	1000
Manila	Model													37	37	37	37	36				
	Observed													37	37	37	37	36				
	Delta²													0	0	0	0	0			1	1000
Dubai	Model								488	488	488	488	488	488	488	488						
	Observed								484	518	493	470	462	473	499	504						
	Delta²								10	891	31	324	682	229	121	255					2544	978
Delhi	Model					94	98	102	113	118	130		144	149	148	153	156					
	Observed					97	98	104	111	117	124		140	145	150	156	164					
	Delta²					8	0	3	6	1	29		18	19	4	12	51				153	1001
Hyderabad	Model		17	18	21	26	27	32	43	32	38	46	38									
	Observed		17	19	20	22	25	28	32	38	42	46	51									
	Delta²		0	1	1	10	4	12	120	28	16	0	167								360	1000
Casablanca	Model					144			170		193	190										
	Observed					144			169		188	196										
	Delta²					0			1		29	41									71	1000
Cape Town	Model													269	282	285	287	290	293	296		
	Observed													269	278	285	293	293	291	293		
	Delta²													0	10	0	28	9	4	9	60	1000
Los Angeles	Model	582	591	596	601	606	611												669			
	Observed	562	578	601	595	634	629												658			
	Delta²	390	183	21	36	786	301												117		1835	1000

A.3. Final Step: Results of the dynamic model

Table A.3. Observed and estimated car densities evolution with the estimated mean of the income distribution.

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Porto Alegre	Observed		223	232	240	248	258	266	277	292	308		345	366													
	Estimated m	5.53	5.63	5.73	5.83	5.93	6.03	6.12	6.22	6.32	6.42	6.52	6.62	6.72	6.81	6.91	7.01	7.11	7.21	7.31	7.41	7.50	7.60	7.70	7.80	7.90	8.00
	Model	222	230	238	246	254	262	271	279	288	297	306	315	324	333	342	352	361	371	380	390	400	410	420	430	440	450
Rio de Janeiro	Observed		156	164	169	173	178	184	192	201	213		236	251													
	Estimated m	5.50	5.59	5.68	5.77	5.86	5.95	6.03	6.12	6.21	6.30	6.39	6.48	6.57	6.66	6.75	6.84	6.93	7.02	7.11	7.20	7.28	7.37	7.46	7.55	7.64	7.73
	Model	158	163	168	173	178	183	188	193	198	204	209	215	220	226	232	238	244	250	256	262	269	275	281	288	295	301
Salvador de Bahia	Observed		104	109	112	117	122	129	137	145	155		175	186													
	Estimated m	5.07	5.17	5.27	5.37	5.47	5.58	5.68	5.78	5.88	5.98	6.09	6.19	6.29	6.39	6.49	6.60	6.70	6.80	6.90	7.01	7.11	7.21	7.31	7.41	7.52	7.62
	Model	105	109	113	117	122	126	131	136	141	146	151	156	162	167	173	179	185	191	197	203	209	216	223	229	236	243
Sao Paulo	Observed		266	276	284	292	302	315	333	352	371		405	424													
	Estimated m	5.63	5.72	5.82	5.91	6.01	6.11	6.20	6.30	6.39	6.49	6.58	6.68	6.77	6.87	6.96	7.06	7.15	7.25	7.34	7.44	7.53	7.63	7.72	7.82	7.91	8.01
	Model	265	274	283	293	302	312	321	331	341	351	361	371	382	392	403	413	424	435	445	456	467	478	489	499	510	521
Medellin	Observed						238	270	309	335	369	400	430	460	489	506	547										
	Estimated m	6.61	6.62	6.62	6.62	6.63	6.63	6.64	6.64	6.65	6.65	6.66	6.66	6.66	6.67	6.67	6.68	6.68	6.69	6.69	6.69	6.70	6.70	6.71	6.71	6.72	6.72
	Model	406	407	407	408	408	409	409	410	410	411	411	412	412	413	413	414	414	415	415	416	416	417	417	418	418	419
Lima	Observed	100	101	103	104	104	105	106	110	117	123	131	139	149	152	164	170										
	Estimated m	6.29	6.34	6.38	6.43	6.48	6.52	6.57	6.61	6.66	6.70	6.75	6.80	6.84	6.89	6.93	6.98	7.02	7.07	7.12	7.16	7.21	7.25	7.30	7.35	7.39	7.44
	Model	78	83	87	92	98	103	109	114	120	127	133	140	147	154	162	169	177	185	194	202	211	220	229	239	248	258
Shanghai	Observed					17	22	26	30	34	39	45	51	59	68	76	86										
	Estimated m	5.22	5.35	5.49	5.63	5.76	5.90	6.04	6.17	6.31	6.45	6.58	6.72	6.86	6.99	7.13	7.27	7.40	7.54	7.68	7.81	7.95	8.08	8.22	8.36	8.49	8.63
	Model	10	12	14	16	19	22	25	29	34	39	45	51	58	66	75	84	95	106	118	131	145	160	176	194	212	231
Hanoi	Observed	17									47						74										
	Estimated m	-2.97	-2.86	-2.75	-2.64	-2.53	-2.42	-2.31	-2.20	-2.09	-1.98	-1.87	-1.76	-1.65	-1.54	-1.43	-1.32	-1.21	-1.10	-0.99	-0.88	-0.76	-0.65	-0.54	-0.43	-0.32	-0.21
	Model	17	19	21	24	26	29	33	36	40	44	48	53	58	64	70	76	83	90	98	106	114	123	133	143	154	165
Madrid	Observed	536	547	550	500	518	520	518	547	538	513	511	512	506	501	505	519	533									
	Estimated m	8.02	7.97	7.93	7.88	7.84	7.80	7.75	7.71	7.66	7.62	7.57	7.53	7.48	7.44	7.39	7.35	7.30	7.26	7.21	7.17	7.12	7.08	7.03	6.99	6.94	6.90
	Model	525	524	524	523	522	521	520	519	519	518	517	516	515	514	514	513	512	511	510	510	509	508	507	506	505	505
Paris	Observed		420									430	440	444	448	443	435										
	Estimated m	7.18	7.21	7.23	7.26	7.28	7.31	7.33	7.36	7.38	7.41	7.43	7.46	7.48	7.51	7.53	7.56	7.58	7.61	7.63	7.66	7.68	7.71	7.73	7.76	7.78	7.81
	Model	419	420	422	424	426	427	429	431	432	434	436	437	439	441	443	444	446	448	449	451	453	455	456	458	460	461
Manila	Observed													37	37	37	37	36									
	Estimated m	5.74	5.79	5.83	5.88	5.92	5.97	6.01	6.06	6.10	6.15	6.19	6.24	6.28	6.33	6.37	6.42	6.46	6.51	6.55	6.60	6.64	6.69	6.73	6.78	6.82	6.87
	Model	40	40	40	40	39	39	39	39	38	38	38	38	37	37	37	37	36	36	36	36	35	35	35	35	34	34
Dubai	Observed								484	518	493	470	462	473	499	504											
	Estimated m	6.48	6.55	6.62	6.69	6.76	6.83	6.90	6.97	7.04	7.11	7.18	7.25	7.32	7.39	7.46	7.52	7.59	7.66	7.73	7.80	7.87	7.94	8.01	8.08	8.15	8.22
	Model	487	487	487	487	487	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	488	489	489	489
Delhi	Observed		70	86	91	97	98	104	111	117	124		140	145	150	156	164										
	Estimated m	5.90	6.00	6.09	6.19	6.29	6.38	6.48	6.58	6.67	6.77	6.87	6.97	7.06	7.16	7.26	7.35	7.45	7.55	7.64	7.74	7.84	7.94	8.03	8.13	8.23	8.32
	Model	79	83	88	92	97	102	107	113	118	124	130	136	143	149	156	163	170	178	185	193	201	209	217	226	235	244
Hyderabad	Observed		17	19	20	22	25	28	32	38	42	46	51														
	Estimated m	4.27	4.31	4.34	4.38	4.41	4.44	4.48	4.51	4.55	4.58	4.62	4.65	4.68	4.72	4.75	4.79	4.82	4.85	4.89	4.92	4.96	4.99	5.03	5.06	5.09	5.13
	Model	20	21	22	24	25	26	28	30	31	33	35	37	39	41	43	45	48	50	53	55	58	61	64	67	71	74
Casablanca	Observed					144	148	163	169	178	188	196	205	209	212	215											
	Estimated m	6.08	6.12	6.15	6.19	6.23	6.27	6.30	6.34	6.38	6.42	6.45	6.49	6.53	6.56	6.60	6.64	6.68	6.71	6.75	6.79	6.83	6.86	6.90	6.94	6.97	7.01
	Model	117	124	131	138	145	153	161	169	178	187	196	205	215	225	235	245	256	266	278	289	300	312	324	336	348	361
Cape Town	Observed													269	278	285	293	293	291	293							
	Estimated m	5.98	6.04	6.11	6.18	6.25	6.32	6.39	6.46	6.53	6.60	6.67	6.73	6.80	6.87	6.94	7.01	7.08	7.15	7.22	7.29	7.35	7.42	7.49	7.56	7.63	7.70
	Model	245	247	250	253	256	259	261	264	267	270	273	276	279	282	285	287	290	293	296	299	303	306	309	312	315	318
Los Angeles	Observed	562	578	601	595	634	629												658								
	Estimated m	8.26	8.28	8.30	8.32	8.34	8.37	8.39	8.41	8.43	8.45	8.47	8.49	8.51	8.54	8.56	8.58	8.60	8.62	8.64	8.66	8.68	8.71	8.73	8.75	8.77	8.79
	Model	586	591	596	601	606	611	616	621	626	631	636	641	645	650	655	660	664	669	674	678	683	688	692	697	701	706