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Private Motorization in Worldwide Developing Countries Metropolitan Areas: Patterns in the early 21st century

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Abstract. Urban growth is a global phenomenon challenging transportation systems. In developing countries, its effects are amplified by demographic and economic growth pressure. In order to prepare for private car motorization spread and to size transportation projects, it is necessary to re-evaluate the phenomenon in a new worldwide paradigm of digitalization and mobility services. So as to identify emerging motorization patterns and their differences from well-studied metropolitan areas in developed countries, this paper investigates the link between socio-economical characteristics at metropolitan scale and the development of private car motorization.

First, the scope of this research is set by a panel of 52 diverse metropolitan areas with a focus on developing countries. Second, a statistical analysis is conducted to investigate the private car motorization phenomenon. Relevant indicators are discussed with concerns about data availability before analyzing those in line with metropolitan level socio-economical characteristics. A focus on car ownership density dynamics with a consumption statistical model on 17 metropolitan areas concludes the analysis.

Results confirm that population densities, GMP per capita and income distribution are determinants of metropolitan private car motorization showing faster growth pattern for emerging countries than previously observed in western developed countries.

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. 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 developed public transportation networks sustaining their rapid demographic, the transportation demand increase mostly relies on the spread of motor vehicle use. The experience of developed countries in the second part of the 20th century shows that the private car had a prominent place in their metropolitan mobility systems. Private car ownership seemed to coincide socio-economic growth as can be seen in Cornut et al. (2014) for the case of Paris before the 1990s.

Therefore, previous analysis of motorization dynamics in occidental countries may not stand anymore for developing countries. Indeed, the current technological and socio-economic backgrounds has tremendously changed into a new paradigm. Digitalization is worldwide spread and some technologies have developed a lot faster in developing countries than in developed countries, such as the smartphone. The dynamical system balanced between technologic innovations and socio-economical behaviors evolutions is all the more difficult to assess as it keeps evolving without reaching a stable equilibrium. Data-oriented policies are also more spread and a shift from national transportation studies to metropolitan scale studies has happened.

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).

The private car motorization is studied here as a socio-economical phenomenon described by statistical analyses. First quantitative indicators of private car motorization are identified. Second, socio-economical features of metropolitan areas are set and compared to find correlations. Third, motorization dynamic is explored with time-series data employed to calibrate a statistical model to forecast motorization evolutions. The results enable to compare different trends according to metropolitan cases.

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. Analysis Perimeter

This paper is part of a research extending the meta-analysis of mobility conducted by Eskenazi et al. (2017) with a focus on private car motorization. As observed in this research, 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 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. This statement is especially true in low-income 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 decision to study 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.

But this metropolitan scale also shows limits. Some cities do not produce data at this scale. Even when metropolitan areas produce their own data, its range is not always the same. The median incomes 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 strongest limitation for using the metropolitan scale is the lack of general international data library at this scale. This generates two main difficulties for this research: the diversity of statistic organisms and data sources among and within metropolitan areas, and the languages in which the data is produced.

In order to overcome these limits, the first step has been to deal with large metropolitan areas. 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. Eventually, each metropolitan area has been individually studied by graduate students at ENPC with different languages skills enabling studying a wider number of cases.

The final selection of metropolitan areas is represented on Figure 1: 52 cases have been analyzed with a diversity intended to best represent developed and emerging countries. The selection is non-exhaustive but the coverage is larger than any metropolitan comparison study to the authors' knowledge.



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			

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

3. Motorization Indicators

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. Table 1 shows the identified private car motorization indicators.

Table 1: Candidate Private Car Motorization Indicators

	<i>Car density</i>	<i>Car ownership share</i>	<i>Car trip share</i>	<i>Car-kilometers</i>
Definition	Number of cars per 1,000 capita	Share of households owning a car	Share of the car trips in the modal mix	Number of kilometers driven by cars
Motorization Measure	Measures the local cars spread in the population market	Measures the penetration of the car good in the household market	Measures the car importance in the local mobility modal share	Measures the intensity of the car use on the local roads
Feature	Ownership	Ownership	Practices	Practices
Availability	Widely spread, in time-series	Uncommon, few time-series	Spread, few time-series	Rarely available, few time-series
Main Drawback	Rarely accounts for unregistered vehicles	Relies on the household definition which is not standardized	Measures the car use frequency but not its intensity	Does not differentiate intensity and frequency of use

The two widely available indicators are vehicle density and car trip share. They each represent a different expression of the motorization phenomenon, so it is expected there will be differences and no perfect correlation. Figure 2 shows these indicators comparison. It 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, fitting the hypothesis they do not exactly represent the same aspect of motorization. The final correlation factor is 0.84.

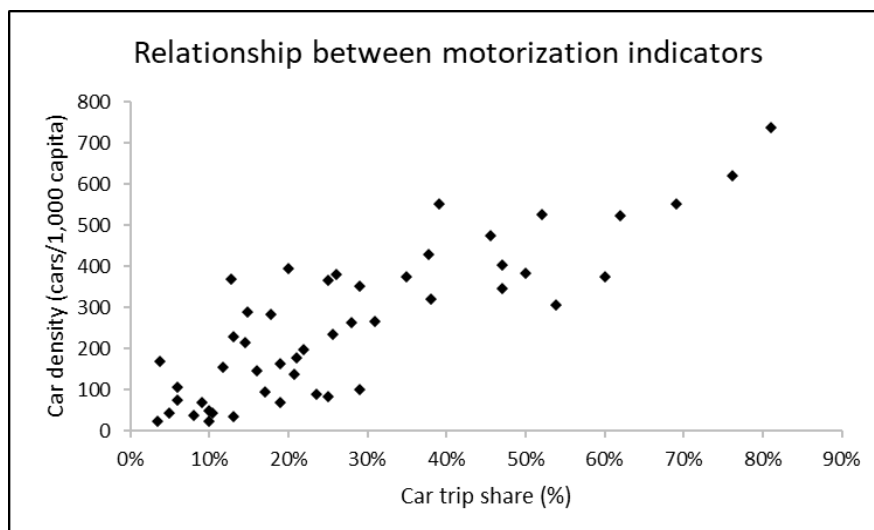


Figure 2: Relationship between car density and car trip share

4. Socio-economic Variables Describing Motorization

The most spread variable used to describe motorization is *the income*. It is based on a consumption conception of motorization where income is a measure of the purchasing power. A lot of studies such as in Dargay et al. (2017) or Dargay (2001) mainly rely on this indicator. But income can be analyzed from different perspectives: whether it is household or per capita income, whether it is the average, median or overall 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. An issue the income 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.

Analogous to income levels, *the Gross Metropolitan Product (GMP)* 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.

Population density could also be considered as an explanatory variable 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.

Other variables could also be used to explain motorization such as *urban form characteristics* (Tan et al., 2016). It suits disaggregated approaches more and is burdensome to use for comparing multiple metropolitan.

The public transit and the shared mobility services supplies could also be analyzed as mobility market competition indicators. But public transit supply does not work well in developing countries often lacking of it or not producing enough data on it. Shared mobility services supply is also difficult to quantify. *Transportation policy orientations and transportation restrictions* are also relevant indicators, especially with cities with very strong policies toward cars. But those qualitative indicators are difficult to compute and require extensive analysis.

Finally, the variables selected for the analysis are the *GMP per capita* as an indicator of metropolitan development and the *population 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.

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.

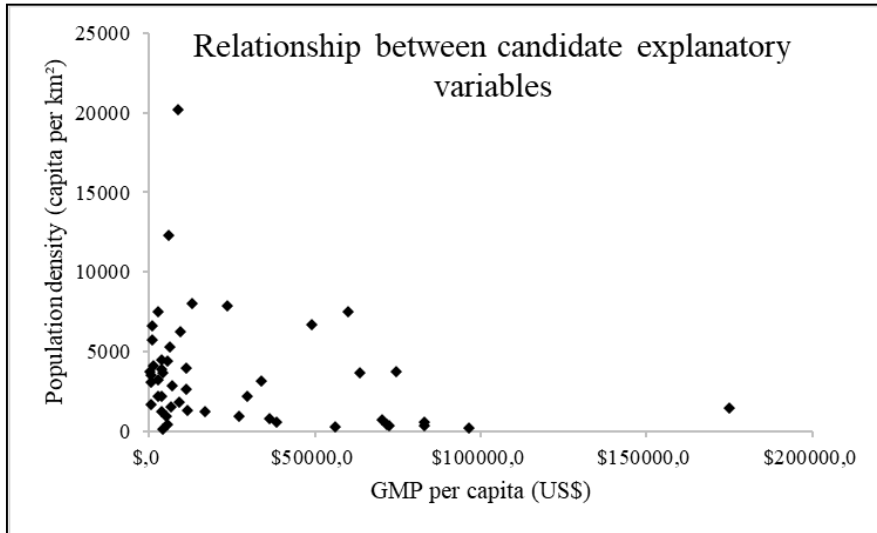


Figure 3: Relationship between population density and GMP per capita.

The comparison of car density and population density shows fitting pattern close to an inverse function in Figure 4. Population density clearly has a negative effect on car ownership similar to the one observed between annual gas consumption and population density in Newman and Kenworthy (1989). This observation seems to indicate that population 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.

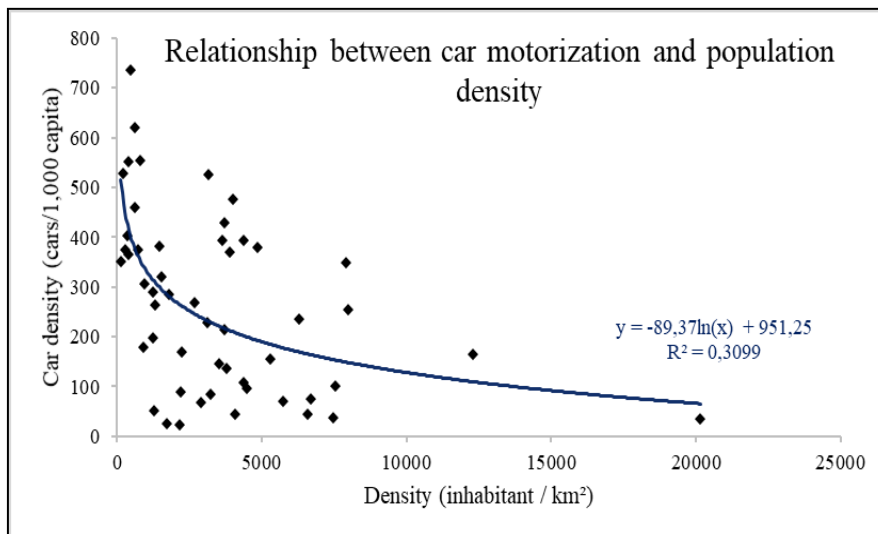


Figure 4: Relationship between car density and population density.

The relationship between car trip share 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.

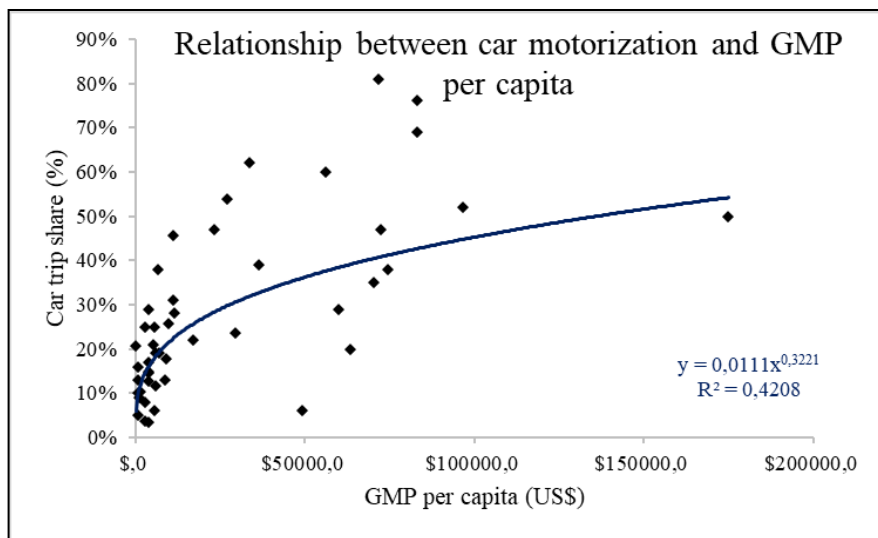


Figure 5: Relationship between car trip share and GMP per capita.

Population density and GMP per capita are relatively significant. Another important indicator to account for is the metropolitan income distribution. Indeed, income distribution takes into account the overall income level, but also the number of inhabitants above threshold income values where private car motorization is available. The next section analysis proposes to follow the evolution of this relationship with the years to access motorization dynamics.

5. Metropolitan Motorization 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. The research aim 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. The data collection being more burdensome, this motorization modeling step includes 17 metropolitan areas. South America is slightly overrepresented thanks to existing detailed statistical database easing the data collection process.

Many models have been developed to study dynamic motorization evolutions at an aggregated scale and Lescaroux (2010)'s model is efficient under those constraints. 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 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 in the population is lognormal and the consumption function is a lognormal cumulative distribution function of the income.

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. 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.

The results of the models are represented in Figure 6. The Medellin case is almost steady because of high variations of income level observed decreasing the quality of the income evolution estimation. 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.

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, 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% vehicle density growth expected between 2000 and 2025 each. The growth rates estimated from the dynamic model are gathered in Table 2. Even though those figures are approximations, they display general trends. It is clear that developing countries show the highest growth potentials.

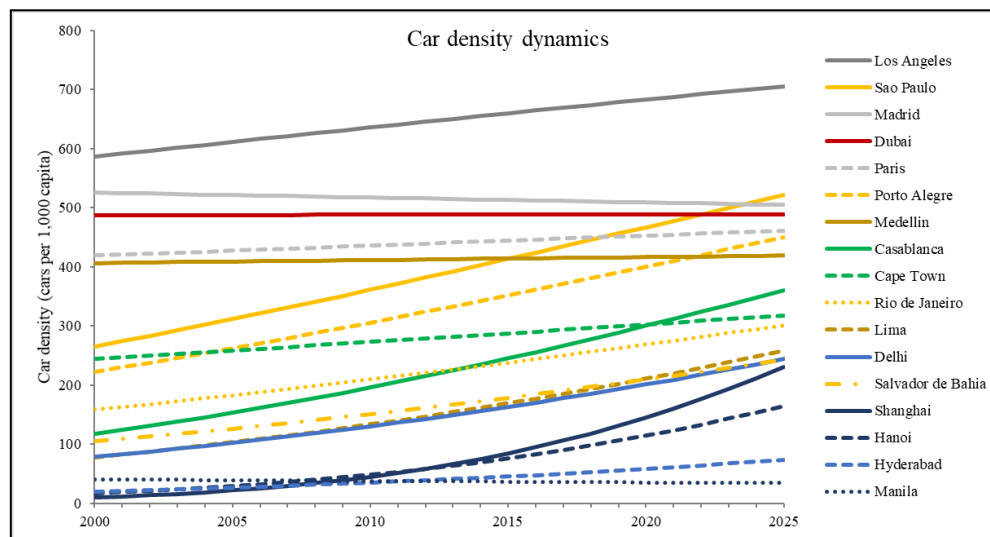


Figure 6: Vehicle density dynamics estimated for 17 metropolitan areas. Metropolitan areas from the same country or from the same world region have the same color. Dotted lines enables differentiating them.

Table 2. Estimation of car densities and car density growth rate.

	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%

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.

6. 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 52 cities, being one of the biggest metropolitan comparisons. Indicators of motorization and potential explainable variables have been derived and statistically analyzed enabling the identification of patterns of motorization following population density and 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, dynamic 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.

This paper contributes to the research by its emphasis on gathering data on private car motorization in multiple metropolitan areas around the world. The data comparison to assess indicators explaining motorization is another important contribution as the literature lacks international metropolitan comparisons. The use of a statistical model to forecast car densities on several metropolitan areas and to observe its growth contributes to the better understanding of private car motorization dynamics based on income distributions and should be applied to more cities of low-income countries. It would be interesting to extend the analysis 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.

A strong obstacle to this research has been the difficulty to collect reliable standardized data at the metropolitan scale to enable statistical generalization of such a dynamical phenomenon sensitive to technological and socio-economical system sustained growth. The authors encourage metropolitan and national organisms to pursue the development of open data statistical platforms to display metropolitan level data. Above the research interest, those data are key for driving the exponential urban growth in low-income countries and should interest urban planners for better understanding, forecasting and managing this phenomenon.

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