The impact of urban density on car dependency and related energy consumption

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I. Introduction

Cities are the drivers of economic growth in the current world economy and this will increasingly be the case in the decades to come. More than half of the world's population lives in cities at the moment and this number will grow to around three-quarters in 2050 (Shell 2014). This growth will mainly take place in the developing world; until 2050 the urban population of developing cities will increase with 2.5 billion, whereas for developed cities this will be less than 150 million (UN 2007). This enormous prospected growth in urbanization in developing cities brings about several challenges, one of which is the increase in transport related energy consumption. Currently, cities account for 70% of global energy consumption and related greenhouse gas emissions, of which around 23% are due to transport (LSE Cities 2014: 28; IPCC 2014b). Moreover, those transport related emissions are growing faster than the emissions of any other sector. Under a business as usual scenario, they are expected to have doubled by 2050 (Dulac 2013; IPCC 2014b).

The way these future cities will be shaped and the spatial structure they will take will be crucial for the amount of greenhouse gasses they will emit. Research has shown that low urban density is strongly related to high levels of car dependency and that urban form is the main determinant of the amount of transport related greenhouse gasses cities emit (e.g. Newman and Kenworthy 1999). Figure 1 shows this strong negative correlation between urban density and transport energy usage for a sample of cities around the world. Currently, US cities have the lowest densities and are by far the most car dependent, followed by Australian and Canadian cities. European and Asian cities are on average denser and more public transport-based (Kenworthy and Laube 1999). Low-density cities are usually associated with an increase in average trip lengths and high levels of private car usage, which causes more greenhouse gas emissions. Although compact city growth seems desirable to reduce emissions, most of current urban growth is increasingly sprawling, as can be seen in figure 2. Since 1990, worldwide city densities have been declining with 2 percent per year

(Angel 2001). If this trend continues in the decades to come, urban land cover could triple by 2030 and the number of cars could double (LSE Cities 2014).

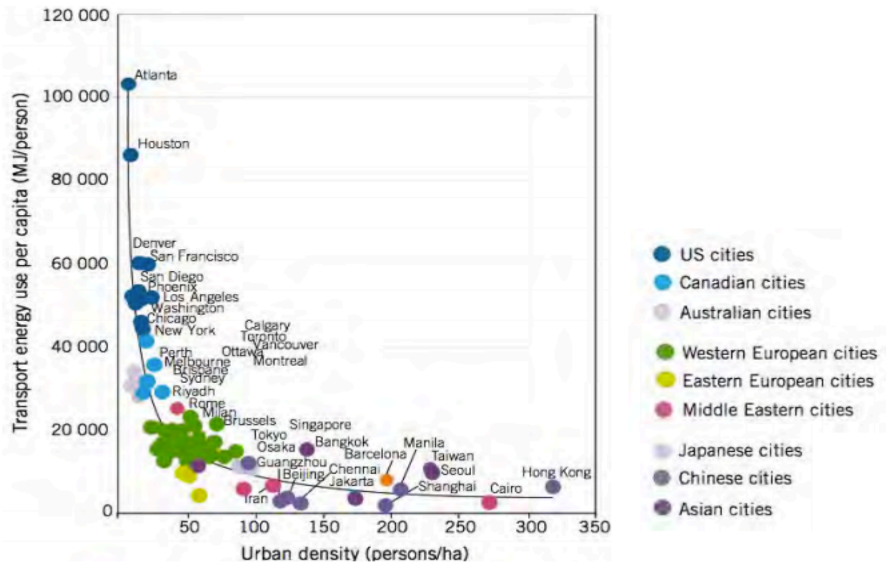

Figure 1: Urban density and transport energy use per capita
Source: WHO 2011

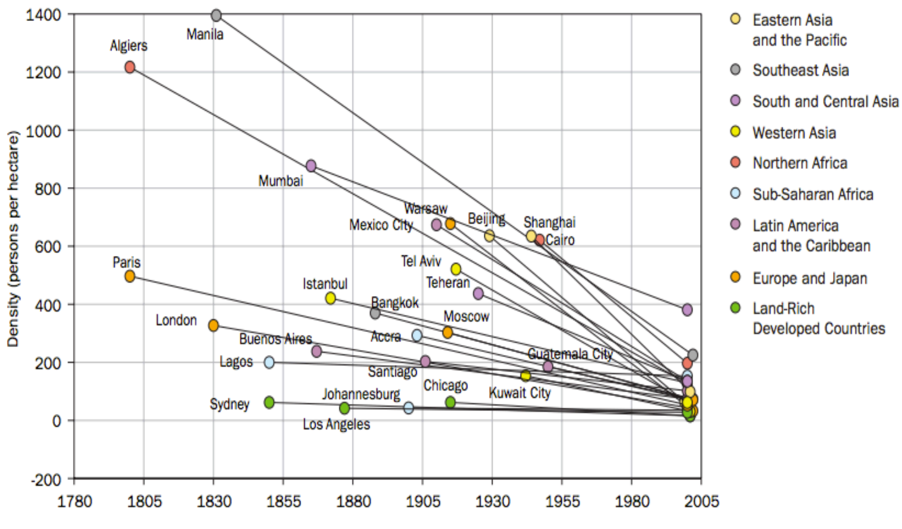

Figure 2: The general decline in built-up area densities in 25 representative cities, 1800-2000
Source: Angel, 2011

Most of the worldwide growth in car dependency and transport related energy consumption is expected to take place in emerging economy megacities; figure 3 shows the expected growth pattern (Darido, Torres-Montoya et al. 2009). A good understanding of the impact of urban spatial structure on car dependency in those cities is thus very important to face the challenges that lie ahead. However, most research on this issue that has been conducted so far has focused on the developed world only (e.g. Badoe and Miller 2000; Bart 2010; Bento et al. 2005; Brownstone and Golob 2009; Dieleman et al. 2002; Hankey and Marshall 2010; Potoglou et al. 2008). These findings show that the strongest determinant of the level of car dependency of a city is urban density (e.g. Cameron et al. 2000; Potoglou et al. 2008) and other possible factors, such as the city's gross regional product (GRP), are of much less influence (e.g. Bart 2010; Kenworthy and Laube 1999). However, for developing cities the effect of the several factors that determine the level of car dependency of a city might be different than is the case for developed cities. Data on developing Asian cities, for example, revealed that although those cities are denser than their wealthier neighbors, they also have higher levels of car dependency (Newman and Kenworthy 1999); which is not in line with the relation found for developed cities. A better understanding of the determinants of car dependency in emerging economy megacities might have important policy implications. For example, densification might be a good way to reduce car dependency in developed cities, but this strategy might have a different impact on developing cities, that usually already have very high densities.

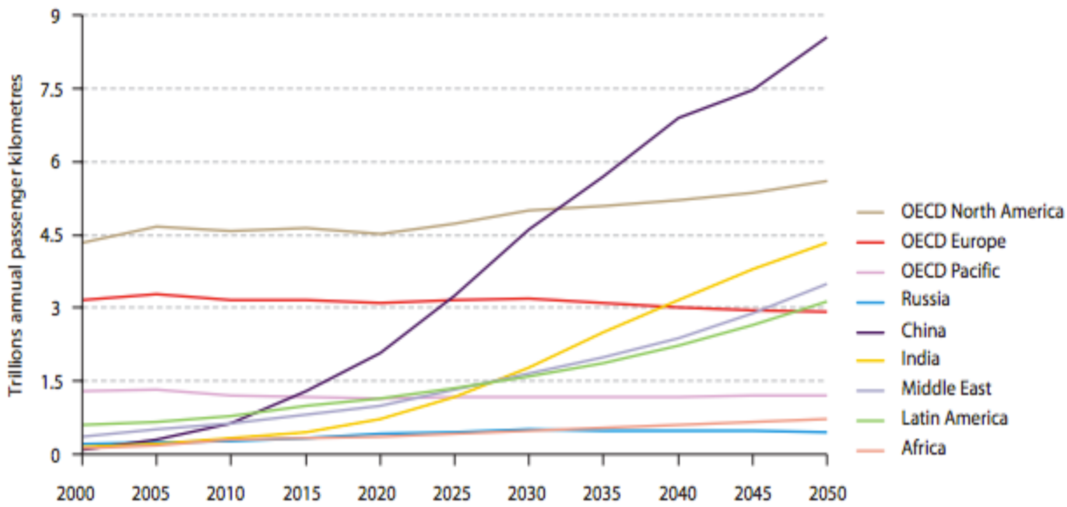

Figure 3: Expected urban private motorized travel (in passenger kilometers)
Source: IEA data

This paper is organized as follows. First, a general overview is provided over the most important factors that contribute to car dependency. Section 2 then focuses on the rich literature from the developed world that analyses the most important factor determining this car dependency: urban density. The empirical findings on the strength of this relation between urban density and car dependency will afterwards be discussed in section 3. Section 4 will argue why and how these relations might differ for developing cities. The last section concludes and gives some possible directions for future research.

II. Which factors determine the level of car dependency of a city?

There is a range of factors that determine how car dependent a city is. Those factors are usually related to the cost of public transport and car use, public transport provision and urban form. Urban economic theory predicts that the mode choice and vehicle miles traveled by a household depend on the size of the city, the distribution of employment and population and the public transport and road network (Bento 2004). Newman and Kenworthy (1999) were the first researchers to examine those relations on a large scale; for more than seven years they collected data on transportation and land use in 46 cities in North America, Australia, Western Europe and Asia, divided into developed and developing Asian cities. In this section those relations will be discussed.

Relative share of public transport on motorized travel

The relative share of public transport on motorized travel depends on the marginal time cost and price relative to the cost of driving. This marginal time cost in turn depends on how dense the road network is and on the population density (Bento 2004). Figure 4 shows the share of public transport on total motorized travel for the different regions. Dependence on the car is by far the largest in U.S. cities, followed by Canadian and Australian cities, and with European and Asian cities having relatively low dependence on the car and much higher usage of public transport. Additionally, though not included in figure 4, European and Asian cities make much more use of non-motorized transport such as cycling and walking compared to U.S., Canadian and Australian cities (Kenworthy and Laube 1999).

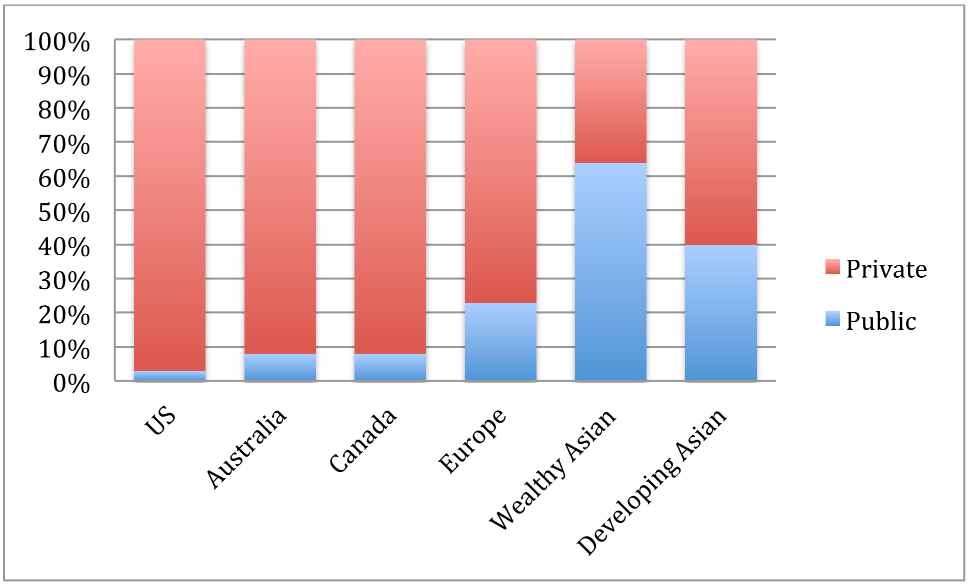

Figure 4: Relative shares of public transport on total motorized travel, 1990

Source: adopted from Kenworthy and Laube, 1999

Journey-to-work-time and length

The large worldwide differences in modes of transport for the journey-to-work might lead to the expectation that the times of those trips differ widely as well. This is however not the case; the average journey-to-work time of 30 minutes is similar across cities around the world and has remained stable for around six centuries (SACTRA, 1994). Marchetti, who also found that across history, city dwellers have had an average daily travel time of one hour, has described this pattern. He explains how cities can sprawl as long as they stay within the one-hour daily travel boundary; with this benchmark, car dependent cities can spread much more (50-60 kilometers in diameter) than transit oriented (20-30 kilometers) or walking (5-8 kilometers) cities (Marchetti 1994). This is furthermore in line with research that found that the construction of new highways leads to more traffic instead of reducing congestion (Baum-Snow 2007). Nevertheless, in contrast to the similarity of journey-to-work times, the lengths of those trips differ widely across cities and are strongly related to the level of car dependence.

Public transport operating costs

Figure 5 shows that the cities with the lowest densities and highest car dependency have the worst operating cost recovery of public transport. Those cities have much higher cost structures for transit companies because of the low occupancy per kilometer (Tong and Wong 1997). The only cities where transit companies make a profit are the high-density Asian cities (Kenworthy and Laube 1999). A more recent McKinsey report (Woetzel et al. 2009) found as well that high-density urban areas can provide mass-transit systems at much lower costs than less compact cities.

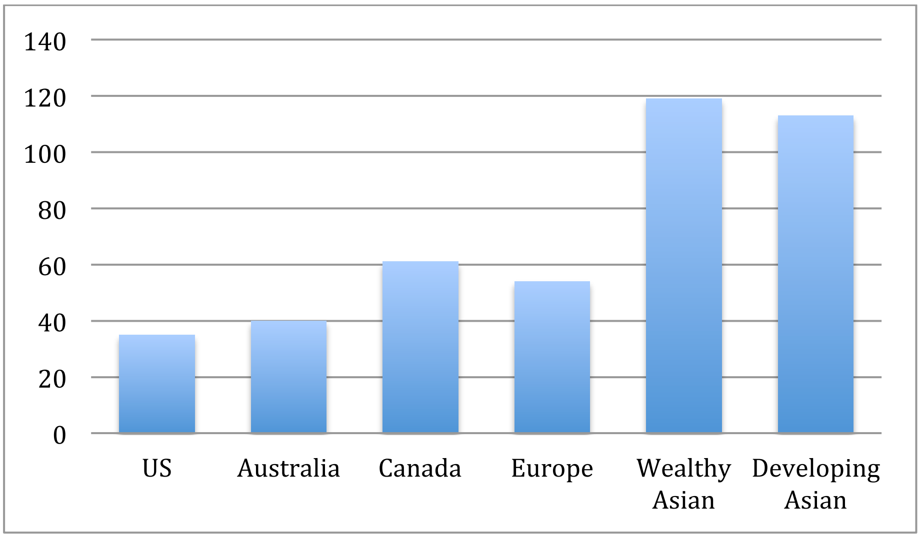

Figure 5: Public transport operating cost recovery in percentages

Source: adopted from Kenworthy and Laube, 1999

Share the city spends on operating passenger transportation

The higher costs of operating a public transport system for low-density cities is also reflected in a higher share of the GRP those cities spend on operating all modes of passenger transportation, as figure 6 shows. Kenworthy and Laube (1999) found a positive, though not very strong, correlation for developed cities (R^2 = 0.59). For the developing Asian cities this relation does however not hold; although the developing Asian cities are denser than the wealthier Asian cities, the share of their GRP spent on operating passenger transportation is much higher. This is not surprising considering the very low GRP of those cities, though it is an interesting finding when investigating the determinants of car dependency in developing cities.

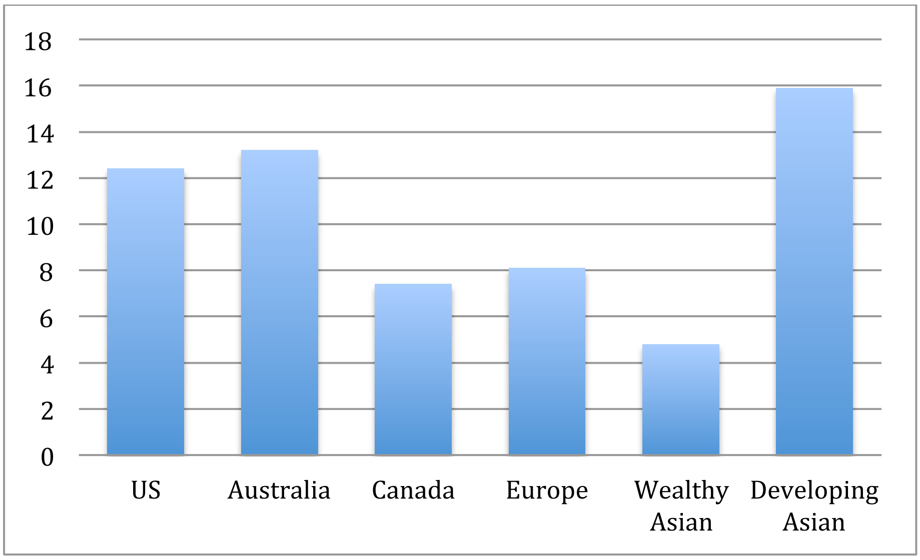

Figure 6: Percentage of GRP spent on operating all modes of passenger transportation, 1990

Source: adopted from Kenworthy and Laube, 1999

Cost of owning and running a car

The cost of owning and running a car are not related to the city's level of car dependency when these costs are not adjusted for wealth. If they are adjusted for wealth, there is, as might have been expected, a negative relation (R^2=0.56), a finding that is also supported by Giuliano and Dargay (2006). However, there is quite some scatter in this relation; for example, the cost of owning and running a car in Toronto is very similar to the average U.S. city, though Toronto is half as car dependent. The costs that are included in this analysis are the fuel price, taxes related to car purchase and usage, maintenance costs and tolls (Kenworthy and Laube 1999).

GRP

Probably the most surprising finding; if GRP is correlated with per capita car use in developed cities, there is virtually no relation between car use and wealth (R^2=0.07) (Kenworthy and Laube 1999; Bart 2009). This is the case for car usage as well as car ownership. Taking as an example cities in the U.S., with the highest levels of GRP and car dependency in the world and compare them to Zurich, a city that is equally wealthy but has a very low level of car dependence and the second highest worldwide public transit usage (after Hong Kong). However, if the developing Asian cities are included in the analysis, the relation between car use and GRP becomes much stronger, which indicates that although the wealth of a city is of no influence in developed cities, it does have a large influence in developing cities (Kenworthy and Laube 1999).

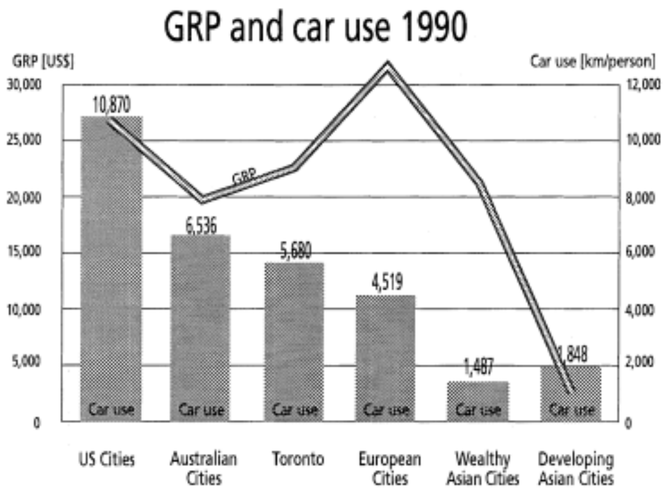

Figure 7: GRP and car use, 1990

Source: Kenworthy and Laube 1999

Urban density

In contrast to the absence of a relation between car use and GRP in developed cities, urban density has a very strong negative relation with car use, the strongest of all investigated factors (R^2=0.82). This strong correlation holds for different measures of density such as density of the whole city and density of specific parts of the city (such as the inner area and the central business district). Low densities are associated with higher average trip distances, less public transport options and lower viability of cycling and walking.

III. How strong is the relation between urban density and car dependency in developed cities?

This section focuses on the factor that was found to have the strongest impact on car dependency in the sample of developed cities: urban density. Several empirical studies, of which by far the majority is on U.S. datasets, have attempted to measure how strong this relation is. This section will first compare the different measurements of urban density that are being used and will in turn discuss the different empirical findings on how strong the impact of urban density on car dependency is in developed cities.

Measures of urban density

The most common way to measure urban density is the number of persons per hectare in the metropolitan area (e.g. Kenworthy and Laube 1999). Some later work uses a measure of urban intensity instead, which means the number of residents and jobs per hectare (e.g. Newman and Kenworthy 2006). It could be argued that other factors of urban form should be taken into consideration as well when analyzing the effects on urban transportation patterns. Some studies have used various measures of urban form such as city shape, density of the road network, spatial distribution of population and jobs-housing balance (e.g. Bento 2005). These factors all influence the length of trips within a city. However, it seems that land use density is highly correlated with almost all other measures of urban form, so it might be sufficient to use the simple measure of urban density (Badoe and Miller 2000). However, when using land use density, it is important to take geographic heterogeneity into account.

Empirical research on the relation between car dependency and urban density can be divided into research that uses aggregate and disaggregate data. Aggregate measures use averages per city instead of data on the household level. Whereas aggregate types of data have the drawback that it is not possible to infer how individuals behave, they have the big advantage that there are less econometric issues with selection effects that might occur if disaggregate data is used. Limiting, for example, endogeneity issues that may occur when people that live further away from the city center are more inclined to drive a lot in general.

Empirical estimates

One of the most cited articles that uses aggregate data is from Newman and Kenworthy (1999). They use total urbanized land in their definition for urban density; thus not only residential density, but also urban open spaces, roads, industrial and commercial land uses. In their analysis for 37 cities, they find a strong negative relation between urban density and car usage (R^2=0.82). Table 1 gives an overview of the findings. Additionally, in a later analysis of the same dataset, the researchers found a threshold of urban intensity above which the level of car dependency is significantly reduced. This threshold is an urban intensity is 35 persons and jobs per hectare. Above this threshold, people tend to use much more non-motorised modes of transport. They also found a threshold for which it becomes much more viable to operate a public transit system; this threshold is similar at 35-40 persons per hectare (Newman and Kenworthy 2006).

Density (population + jobs per hectare)	Annual energy consumption for travel (mega joules per inhabitant)	Cost of transport (% of GDP)
< 25	55 000	12.4
25 to 50	20 200	11.1
50 to 100	13 700	8.6
> 100	12 200	5.7

Table 1: Population density, energy consumption and cost of transport

Source: adopted from Newman and Kenworthy, 1999

Brownstone and Golob (2009) used disaggregate data for almost 70.000 households across the U.S. to investigate the relation between residential density and vehicle usage and fuel consumption, controlling for social-demographic variables. Note that residential density is a slightly different measure than urban density, as used by e.g. Newman and Kenworthy, as it excludes other urban land uses than residential. They made a comparison between households that live in dense areas to households that are similar in all other factors but live in less dense areas. It turned out that the household that lives in the denser area (1000 housing units per square mile denser) drives on average 7.8% per year less and uses 7.5% less fuel than the household in the less dense area. Additionally, they did a simulation that moved a household from a suburban to an urban area and found that this would reduce the yearly miles driven by 15%.

Another study that uses disaggregate U.S. data was performed by Bento et al. (2004). This research uses several measures of urban form to estimate the effect on commute mode choices and vehicle miles traveled for households living in 114 suburban areas in the U.S. They find a small but significant effect of urban form on household's travel demand. "In cities where the spatial distribution of population is more compact, households are less likely to own a car. The quantitative effect of these variables on annual average VMTs is, however, small: a 10% increase in population centrality, through its effect on vehicle choice, reduces annual VMTs by only 1.5%" (Bento et al. 2004: 477). This small estimated effect might be explained by the different measures of urban form that are used in this research. The researchers also found that if those measures change simultaneously, the effect on VMT and mode choice is much larger.

Bart (2010) investigated which factors might have caused the increase in transport related greenhouse gas emissions in the EU between 1990 and 2000. He found that the main cause has been the increase in urban sprawl (defined as the increase in areas covered by roads and buildings). Other factors, such as GDP and population growth, turned out to have had only a minor effect on the increase in transport greenhouse gas emissions.

IV. Why might the relations between factors that determine the level of car dependency of a city differ for developing cities?

The empirical work that has been conducted on the impact of urban density on car dependency mainly relies on U.S. data and, to a lesser extent, European data. Consequently, for developing cities very little is known about this relation. From a study by Newman and Kenworthy (1999) on six developing Asian cities, the factors that determine the level of car dependency seem to be different. First of all, developed Asian cities have lower densities than their less wealthy neighbors, but those developing cities are more dependent on cars and make less use of public transport, as can be seen from figure 4. Moreover, when looking at the public transit operating cost recovery and the percentage of the GRP spent on passenger transportation (figure 5 and 6), a different pattern emerges than for the developed cities. Probably most apparent is the difference in the effect of GRP on car dependency; for the developed cities there is no effect at all whereas for the developing cities GRP does seem to be of influence. The findings by Poumanyvong and Kaneko (2010) also reveal a difference in the impact of factors that affect the amount of energy use and CO_2 emissions of cities. They found a significant difference in the effects of more general measures of urbanization on the energy use and CO_2 emissions between low-income, middle-income and high-income groups in a global sample of 99 countries.

Hence, it might be the case that whereas for developed cities urban density is the factor that most influences the level of car dependency, for less wealthy cities this relation might be less strong and other factors might be more important. It is for example quite likely that GRP has a much larger effect on the level of car dependency in developing cities, since the share of GRP the city has to spend on operating a public transit system will be much higher. This might cause an under provision or poor working of the public transit system, which leads to higher levels of car dependency. Also factors such as preferences for suburbanization and for private car ownership and the cost of owning and running a car might affect car dependency differently in developing cities.

A better understanding of the factors that determine the level of car dependency could have important policy implications. Emerging economy megacities are currently urbanizing very quickly and will cause most of the growth in transport related energy consumption and related greenhouse gas emissions. Currently those cities are rapidly sprawling and are becoming increasingly car dependent. For developed cities there is a growing awareness for the need of compact city development to reduce the negative externalities that are caused by urban sprawl (Dieleman and Wegener 2004). In response, several smart growth initiatives have been put into action that aim for compact cities that would preserve open space, reduce the costs of providing public transport and reduce car dependency and its externalities (Bento et al. 2004). London's Greenbelt Act in 1938 and Seoul's and Portland's greenbelts in the 70's are examples of such policies. However, Angel (2011) argues that whereas these policies might be beneficial for developed cities, they might have counterproductive effects on cities that are less developed and rapidly urbanizing. A possible reason for this might be that in rapidly urbanizing cities, the density is often already high enough to sustain a viable public transport system and it is therefore unnecessary to make those cities even denser. Considering the threshold for urban intensity that has been estimated for developed cities, those rapidly urbanizing cities might still expand a lot before reaching this threshold.

V. Conclusion

There is a rich literature from the developed world that analyses the most important factor determining the car dependency of cities: urban density. Those findings have led to the conclusion that the density of a city is the main determinant of its transport related energy consumption, and that other factors are of much less influence. However, it remains the question if those relations also hold for less wealthy cities. From data collected by Newman and Kenworthy (1999) on six developing Asian cities, the factors that determine the level of car dependency seem to be different. There is clearly a lack of research on these determinants of car dependency in developing cities. Moreover, the large majority of research on this topic uses the dataset from Newman and Kenworthy (1999), which includes only six developing cities, all located in Asia. Research that would use a dataset including a wider range of cities around the world, with different levels of development and income, would be a great contribution to the existing literature and could possibly gain valuable insights into the dynamics of rapidly urbanizing developing cities, with important policy implications.

Such a research should first of all serve to get a better understanding of the main determining factors of car dependency in developing cities. Furthermore, it would be interesting to look into the development path of rapidly urbanizing megacities; are they currently approaching EU levels of car dependency? Or are they moving towards US levels? Those findings could then be translated into policy recommendations. Recently, in developing cities there has been a growing awareness for the need of compact city development that resulted into several ‘smart growth’ or ‘new urbanism’ initiatives. It is however questionable if these strategies are also beneficial for rapidly urbanizing developing cities, which usually already are very dense. It might be the case that other planning strategies are more suitable for those cities.

Following Poumanyvong and Kaneko (2010) the sample of cities in the proposed research could be divided up into low-income, middle-income and high-income cities. “Despite the relationship between urbanization, energy use and CO_2 emissions has been extensively studied in recent years, little attention has been paid to differences in development stages or income levels. Most previous studies have implicitly assumed that the impact of urbanization is homogeneous for all countries. This assumption can be questionable as there are many characteristic differences among countries of different levels of affluence.” (Poumanyvong and Kaneko 2010: 434). Furthermore, aggregate data on the vehicle kilometers of travel could be used as a measure of the car dependency of each city. The physical structure of the cities can in turn be determined using data collected by Huang et al. (2007) on 77 urban regions in Europe, Australia, the U.S., Asia and Latin America. With satellite images from the Global Land Cover Facility they precisely measured the urban built up area of each city and collected data on density as well as other measures of urban form such as the city shape, compactness and centrality. This comparative perspective could result in valuable insights that could help policymakers and city planners in developing countries to formulate policies on sustainable urban development, limiting transport related energy consumption.

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