Modeling Dynamics of Car Ownership and Urban Density for Developing Cities

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Abstract: Restraining the increasing pace of car ownership rate in developing cities is a major policy concern. Car ownership modeling can potentially generate important policy insights for formulating urban transport strategies. The effectiveness of higher urban density to discourage car ownership has long been debated, but the established modeling streams rarely include urban density as possible policy leverage. This paper first discusses the cross-sectional patterns of car ownership and some common reinforcing feedback loops involving car ownership, and set a hypothesis on policy relevance of urban density. A modified model formulation that include urban density in a policy relevant way is proposed, and validated through estimation. Utilizing the estimated parameters, maximum income elasticity of car ownership is computed, which corresponds at a per capita income level of about US $ 4000 (in 1996 price). This figure may provide useful guidance to policy makers as “take-off” stage for motorization.

Key Words: Motorization, Car ownership model, urban density, developing cities,

1. BACKGROUND

Degrading condition of urban transport in developing countries is increasingly attracting attention from policy makers. Poor quality of public transport, increasing traffic congestion, traffic related environmental pollution and increasing number of traffic accident are common problems in most developing cities. Rapidly growing developing economies, in particular, are facing challenge of addressing such urban transport problems under the increasing trend of car ownership and usage primarily fueled by increasing income. It is a commonly accepted fact that one of the root causes of urban transport problems is such pattern of motorization. The future socio-economic scenario in many developing economy indicates accelerated car ownership, which may have serious implications for mobility and other associated socio-economic and environmental aspects.

Policy makers have realized that this trend is potentially threatening otherwise good prospect for achieving sustainable form of urban transport system in developing cities. Efforts have been made by implementing range of policy measures with expectations of restraining pace of motorization. However, such efforts are either grossly inadequate or ineffective to produce desirable results of intended significance.

There is a good stream of literature in car ownership mechanism and its impact on performance of overall urban transport system. Ever since the early motorization wave emerged after the World War II in western countries, researchers made attempts to understand the phenomenon. However, focus was limited only to forecasting car ownership mainly for
the purpose of road network planning. Such supply oriented policy approach did not last long particularly in urban transport policy domain. As early as 1980s, it was realized that road building alone can not solve the traffic congestion and associated problem and emphasis was shifted towards so called Transport Demand Management (TDM). However, focus is more on restraining car use rather than restraining car ownership apparently because of near-saturation level of car ownership in developed cities.

But car ownership not only makes the choice for private mode feasible but also induces behavioral changes in favor of private mode. Hence, restraining car ownership is most effective option for minimizing car use. In contrast with the case of developed cities, the car ownership in developing cities is still low and it can be restraint to a reasonable level by appropriate policies. Maintaining higher urbanized density is one of the effective strategies to keep car ownership level low since urban density in most developing cities is still higher. Unfortunately, the car ownership modeling approach is not responding to such relevant policy leverage and has ignored real prospect of restraining car ownership through urban density. The apparent reason for such omission is that urban density is not much of relevance in minimizing car use in developed cities as urban structure has been already stabilized in developed world.

With this background, this paper proposes a car modeling approach that explicitly includes urban density for its potential role as effective policy leverage for restraining car ownership. Section 2, first discusses the car ownership trend in developing cities and major underlying factors. This is followed by a broad discussion on urban transport dynamics highlighting the dynamic interaction of car ownership and urban density. Section 4 is on car modeling that includes review of existing modeling practice and formulation and estimation of new model, and policy implications of the results. Finally conclusion is drawn.

![Figure 1. Car ownership trend in selected cities (Source STREAM Study)](image)
2. CAR OWNERSHIP TREND IN DEVELOPING CITIES

Assuming a stable relationship between GDP per capita and car ownership rate, (Chamon 2008) examined the worldwide motorization trend and estimated that between 2005 and 2050, number of cars will increase by 2.3 billion of which 1.9 billion will be in emerging market and developing countries. Large share of this increase will occur in developing countries cities making their urban transport condition more degraded. Figure 1 shows car ownership trends in some selected Asian megacities. As compared with car ownership rate in Tokyo, all other cities are experiencing rapid increase in car ownership. Developing Asian megacities such as Bangkok and Jakarta recorded an unprecedented speed of motorization. As is obvious the case, the trend is basically driven by higher growth rate in income in these economies.

![Figure 2: Metropolitan income and car ownership rate (2002~04)](image)

However, just blaming the income growth for car ownership does not help much in devising effective policy responses. After all, there is no point to stop income growth on the ground that it encourages motorization. On the other hand, the international cross-sector pattern for car ownership at the city level shows interesting patterns. Figure 2 shows cross-sectional pattern of car ownership in selected metropolitan areas worldwide. As expected the figure shows a general trend of positive correlation between income level and car ownership rate. However, there is also a clear pattern that metropolitan areas with similar level of income have significantly different level of car ownership. There are distinct patterns among key regional groupings; such as American cities have max car ownership while developed Asian cities have much lower level of car ownership for corresponding level of income. The case of EU cities falls in between. Despite the high growth rate of car ownership in developing cities of Asia, the absolute car ownership is still at moderate or lower level as shown in Figure 2 (clustered at the lower left corner). The international patterns as depicted here offer developing cities alternative choices for different trajectory of car ownership rate. Unfortunately, under the business as usual scenario, most developing cities are likely to follow trajectory of US cities as cities like Bangkok and Jakarta have already shown such a tendency. The patterns, on the other hand, logically ask to further explore the underlying reasons.
Figure 3 plots metropolitan level car ownership rate and income, and shows strong negative correlation between them. The patterns clearly explain the key underlying reasons for great variation in car ownership rate for cities with similar level of income. High density cities maintained lower level of car ownership in the face of increasing income while in low density urbanization income growth accelerated car ownership level. Policy insights to be extracted from these patterns, which is the pivotal role of urban density in restraining car ownership rate, is very useful for developing cities since the urban density is still higher there and there is urgent need to restrain motorization trend. Newman and Kenworthy (1999) strongly advocated an urban form with high population density and promotion of public transport. However, there is an argument that the causal link between urban density and car ownership is not clearly understood. Some observers even pointed that car ownership rate has stronger impact on urban density than the other way round suggesting policy measures directed to restrain car ownership such as higher car related taxes or parking control (Ingram and Liu 1997).

3. Dynamics of Urban Transport in Developing Cities

As an attempt to highlight complexities of urban transport problems, it is often mentioned that the urban transport system is characterized by several vicious cycles and car ownership is one of the core elements driving such cycles (for example see Acharya 2005, Ortuzar and Willumson 2001, Kitamura, Nakayama et al. 1999). Figure 4 shows feedback diagrams detailing principle feedback loops commonly inherently in urban transport system. The diagram, in particular, elaborates the dynamic interaction of car ownership and use, and urban density to develop a hypothesis for car ownership modeling. In particular, the understanding
the nature of feedback may help to make judgment about effectiveness of urban density in restraining car ownership rate. The feedback loops diagram depicts part of the dynamics of urban transport system following feedback loop approach of System Dynamics (see Sterman 2000). Each element of system is presented as “neutral” that is without qualifier such as “increasing” or “decreasing”. Depending on the given situation, the elements can take any direction. For example, if urban density is low, then quality of public transport will also be low which lead to higher relative utility of car use. The polarity of causal link has not been shown as it is obvious from the relationship of the connecting elements. The dotted link between car ownership and use and urban density represents delayed causation as it takes considerable time to see the impact of increased car ownership on urban density. However, effect of urban density on the convenience of car use and thereby on car ownership and use is very quick.

All the three feedback loops, which are of reinforcing nature (or positive feedback loops), involve car ownership and use as the main driving element. As is obvious, for most developing cities, the increasing trend of car ownership and use are driving these reinforcing cycles as vicious cycle- that is producing undesirable consequences. For example, loop-1 is about direct competition between private mode and public transport mode, another service attributes due to direct impact on operation revenue. Loop-2 is about longer term dynamic effect of car ownership and use on urban density which then effect quality of public transport due to low-level urbanization. Finally, loop-3 shows that urban density also effects convenience of car use through its effect on provision of car related infrastructure such as
road and parking space. As seen in real world situation, low density urban area can offer greater land space to road and parking infrastructure making car use very convenient and further increases car ownership. The policy challenge is to turn all these vicious cycle into virtuous cycles by appropriate policy strategies and one of the key elements of such strategy should be to maintain high urban density.

The nature and intensity of above mentioned feedback loops for developed and developing cities show a clear contrast. As the overall urban transport system is near stabilization in developed cities, the feedback loops (vicious cycles) are now running at low intensity that is not bringing any significant changes in the system. Yet, there are attempts to improve the situation but not much scope in turning these loops as virtuous cycle except in some isolated cases. Most of the urban transport policies are therefore targeted in avoiding externalities of car use by imposing efficiency cost on users. However, in developing cities urban density is still higher and public transport mode dominant, and turning the vicious cycle into virtuous cycle does not require much effort if right policy lever is selected. Urban density is changing slowly while car ownership changes relatively fast. So, policy makers might be tempted to intervene directly to control car ownership and use through physical control and/or fiscal measures. However, without maintaining high urban density, the effectiveness of such measures may not last long as the system seeks it own goals of higher car ownership under lower urban density. In other words, car ownership control measures are effective so far as higher urban density is maintained but their effect does not transmit to the level of supporting higher urban density. Urban density requires policy measures of its own.

4. MODELING CAR OWNERSHIP FOR DEVELOPING CITIES

As discussed above, the mainstream literature on car ownership modeling appeared to be influenced by the context of developed cities, where urban density does not feature as potentially effective policy leverage. On the other hand, in principle, urban density influence long-term car ownership of an urban area through multiple channels as discussed in Section-3 above. In fact, developed cities seem to have already missed the opportunity to restrain car ownership by maintaining higher urban density when they were facing strong wave of motorization during early postwar decades. Unfortunately, the negative impacts of private car use then were not as much visible and appreciable as it is now. Rather private car was something to be celebrated for its contribution to flexible and high quality mobility with absolute freedom. Here, developing cities can learn important lessons to utilize urban density as an effective policy lever to restrain car ownership rate. In this section, existing modeling approach is discussed particularly highlighting how it misses to appreciate the potential role of urban density and propose a new modeling approach targeting policy needs in developing cities.

4.1 Policy Relevance of Existing Car Modeling Approach

Jong et al (2004) undertook a comprehensive review of car ownership models and discussed their characteristic features by grouping them into different types, namely aggregate time series model, aggregate cohort models, aggregate car market models, heuristics simulation models, indirect utility models, static disaggregate choice model pseudo-panel and dynamic models. It was pointed that only aggregate models are suited for application to developing countries since other models are more data demanding. However, the review is more focused on forecasting or prediction strength of models rather than their policy relevance. Likewise,
taking a broad review of modeling tradition for car ownership, Ortuzar and Willumsen (2001) summarized the underlying purpose of car ownership modeling as market research for automobile manufacturers, forecasting for highway planning, and formulation of transport strategies.

In terms of modeling approach, there are mainly two basic streams; first aggregate model based on national or regional level aggregate data, next disaggregate model based on micro-foundation that utilizes household level data with an emphasis that car ownership is mainly determined by individual household level decision rather than the decisions at the macro-level. For their obvious appeal for urban transport policy in developing cities, only aggregate models will be discussed here.

Most aggregate model assumed an S-shaped pattern of car ownership which is reasonable as there is some saturation level of car ownership inherent in the system. However, the choice of explanatory variables and model structure vary greatly in different models. Most simple modeling form adopts time-series extrapolation such as the model used by Tanner (1978). Equation (1) shows the generic form of such time series extrapolation.

\[
 CW_t = \frac{S}{1 + e^{a-bt}}
\]

Where,

\( CW \): car ownership rate

\( t \): time

\( S \): saturation level of car ownership

\( a, b \): parameters

The models with such forms assumed that the saturation level is constant and it is only matter of time to reach the saturation time. Model is driven only by time and does not include any policy relevant variable. Therefore, such models are not much useful for urban transport policy analysis. To make the aggregate models more policy relevant, efforts were made to include more explanatory variables adopting econometric frameworks. Dargey and Gately (1999) used Gompertz model (as shown in eq 2), a variant of S-shaped pattern, for international comparison of car ownership pattern covering developing countries like India and China. The only explanatory variable is income, and the model is for country level. Yet they have highlighted importance of model at the city level and need to include other explanatory variables including population density to make the model more policy relevant.

\[
 CW = Se^{ae^{bt}}
\]

Where,

\( I \): income level

Ingram and Liu (1997) attempted to include more policy relevant explanatory variables for both country level and city level car ownership model (eq 3). This model certainly offers more leverage in terms of gaining more policy relevant insights as demonstrated by estimation results and other analysis over the model. In the model for urban areas, urban density is one of the explanatory variables recording a statistically significant effect on car ownership level.
Where, \( x_i \): vector of explanatory variables

\[
CW = \frac{S}{1 + e^{-S_{x_i}}}
\]  

(3)

However, the models reviewed above (few more not listed here), which use S-shaped curve for car ownership pattern take saturation level of car ownership as constant. In models using cross sectional data (say of urban units), all cities have same level of situation for car ownership that is eventually they reach same level of car ownership. The explanatory variables effect is limited only in determining the speed of car ownership trend towards saturation level. For example, when such model is used for policy simulation, the effect of policy measures is to change the slope of the S-shaped curve shifting the curve right or left depending up on their effect on car ownership (Figure 5). Under such formulation, no policy measures will change the saturation level of car ownership as it is modeled as a constant parameter. But for long-term sustainability of urban transport system, what is important is not just to reduce the speed of car ownership but to reduce the saturation level of car ownership by having appropriate urban structure, such as high density urbanization as advocated by Newman and Kenworthy (1999). As mentioned such option of reducing saturation level of car ownership is more relevant for developing countries’ cities.

4.2 Modifying and Estimating Car Ownership Model

Modification of the model: The S-shaped model shown in equation (3) is modified to specify saturation level of car ownership as being dependent on urban density. The parameter \( S \) is resolved in to a new expression as function of urban density. The modified model is shown in equation (4)

\[
CW = \frac{e^{c-dD}}{1 + e^{a-bt}}
\]  

(4)

Figure 5 Change in curve slope versus change in saturation level
Where, \( D \): urban density; \( c, d \): parameters

In the new formulation, car ownership varies with income level and urban density. The effects of these two explanatory variables on car ownership rate are of different nature. The urbanized density fixes the saturation level (implying different S-shaped curves for different urbanized density), and income level then determine car ownership rate. This way, saturation level of car ownership can be influenced through urban density, which is broadly supported by real world patterns. In this model too, the main driving factor for car ownership is income increase. As the urban structure including urbanized density in developing cities is yet to be stabilized, this modified formulation could be of much relevance for policy modeling in developing cities since it offers important policy leverage in the form of urban density to restrain car ownership rate.

Table 1: Descriptive statistics of variables used in the model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Min</th>
<th>Max</th>
<th>No of observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car ownership (CW)</td>
<td>Number of cars per 1000 population</td>
<td>297</td>
<td>209</td>
<td>8</td>
<td>746</td>
<td>55</td>
</tr>
<tr>
<td>Income per capita (I)</td>
<td>US $ (1996 price)</td>
<td>1631</td>
<td>13012</td>
<td>396</td>
<td>45425</td>
<td>55</td>
</tr>
<tr>
<td>Urbanized Density (D)</td>
<td>Persons per hectare</td>
<td>96</td>
<td>88</td>
<td>6</td>
<td>356</td>
<td>55</td>
</tr>
</tbody>
</table>

Data and model estimation: Cross-sectional data for 55 cities worldwide (with population more than 2 million) that is available in the database compiled by UITP (2001) is utilized for the estimation of parameter in the model. Table 1 shows the descriptive statistics of variables used in the model. The data set reveals good variation in each variable reflecting coverage of developing and developed cities as well as high density and low density cities.

Table 2: Results of model estimation

<table>
<thead>
<tr>
<th>Models for car ownership (CW)</th>
<th>( CW = a + bI + cD )</th>
<th>( CW = \frac{S}{1 + e^{a-bI}} )</th>
<th>( CW = \frac{e^{c-dD}}{1 + e^{a-bI}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>496.0 (37.7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( a )</td>
<td>255.7 (39.1)</td>
<td>1.85 (0.38)</td>
<td>5.86 (2.91)</td>
</tr>
<tr>
<td>( b )</td>
<td>0.0087 (0.001)</td>
<td>0.00018 (0.00004)</td>
<td>0.0011 (0.0005)</td>
</tr>
<tr>
<td>( c )</td>
<td>-1.04 (0.202)</td>
<td>6.32 (0.61)</td>
<td></td>
</tr>
<tr>
<td>( d )</td>
<td></td>
<td>0.005 (0.001)</td>
<td></td>
</tr>
<tr>
<td>( Adj.R^2 )</td>
<td>0.70</td>
<td>0.66</td>
<td>0.72</td>
</tr>
</tbody>
</table>

1) Numbers in parenthesis are standard errors
2) All estimations are statistically significant at 95% confidence level

\( CW \): car ownership (cars/1000 population); \( I \): City income/capita (US$ 1996 price)
\( D \): urban density (persons/ha); \( S \): saturation level of car ownership
\( a, b, c, d \): parameters
For comparison, linear model, S-shaped with constant saturation level and S-shaped with variable saturation level are estimated. The linear model is estimated with ordinary least square estimator while nonlinear models are estimated with non-linear least square estimator. Table 2 shows estimation results.

Parameters for all models are statistically significant. And the modified model shows better explanatory power with highest $R^2$ value. Using the estimated parameter values, different trajectories of car ownership are obtained for different level of urban density. Figure 6 shows different trajectories for a hypothetical set of urban densities as 20, 80 and 140 persons per hectare. The computed patterns closely represent the real world situation and hence further validate relevance of the proposed model.

Income elasticity of car ownership:

One of the indicators of much interest to policy maker is the income elasticity of car ownership. As the relationship is non-linear, measure of elasticity provides useful information to the policy maker concerning the stage at which the car ownership is significantly influence by the income. At the stages when income elasticity of car ownership is higher, car ownership can be restrained by some measures which work through income effects, such as car related taxes. When the income level surpassed the stage corresponding to maximum elasticity, tax related measures have relatively weaker impact as is the case in high-income cities. The income elasticity of car ownership therefore provides valuable guidance to policy makers.

Income Elasticity of car ownership can be obtained from equation (4) as,

$$\frac{\partial CW}{\partial I} \frac{I}{CW} = \frac{bI}{1 + e^{-a+bl}}$$

(5)

Income elasticity of ownership is computed using the estimated parameters. Equation (5) shows derivation for income elasticity of car ownership. The elasticity is maximized, when income is at about US$ 4000 (1996 price) as shown in Figure 7. This can also be interpreted as the stage corresponding to car ownership “take-off”. The figure provides useful guidance.
for policy makers so that they can act before the “take-off” happens.

4.3 Policy Implications

The modified formulation for car ownership modeling provides important policy leverage for urban density. Even though the model is of aggregate nature, it can potentially offer important insights on the effectiveness of higher urban density in restraining car ownership and contribute to orient urban transport strategies towards long-term sustainability. The model may appear too simple, but its underlying message is stronger. Particularly, in the context of prevailing notion that urban density gets affected by car ownership rather than affects car ownership (for example see Ingram and Liu 1997), and therefore is not relevant policy instrument, the modified model make an attempt to introduce new perspective.

As hypothesized in section 3 above, urban density potentially influences car ownership through multiple channels and can therefore serve as important element in urban transport strategies especially in developing cities. The confirmation of statistical significance of all parameters and a reasonable degree of explanatory strength of the modified model (through estimation result) has provided empirical support to such hypothesis. As shown in figure 6, the characteristics car ownership curve varies significantly with urbanized density. For urban density of 140 persons per hectare, the maximum car ownership rate is below 300 cars per 1000 population while a density of 20 persons per hectare raises the saturation level over 500 cars per 1000 population. This pattern closely corresponds to the real world situation but not much formalized in the modeling practice. Another important aspects depicted by figure 6 is that for all density levels, the city achieved saturated level of car ownership at around the income level of US $ 10,000. That is once a city reaches this income level, income is not any more a constraint for car ownership. One may be tempted to refute this conclusion on the ground that cities have experienced growth in car ownership continuously even after reaching higher-income level. However, the model result suggests that the growth in car ownership in high-income cities is more due to change in city structure or decline in urbanized density rather than increase in income. Of course, there could be some other variables such as
provision of public transport that influence car ownership, but that is also somehow related with urbanized density. If a city can maintain higher urban density, public transport can be operated in a more competitive way which contributes towards restraining the growth in car ownership.

Further, the computed income elasticity of car ownership including max take-off point is of valuable indicator for practical policy making. In addition, the confirmation of effectiveness and relevance of urban density as effective policy instrument to calm down the growth of car ownership has practical value as well. One of the challenges in developing countries is lack of political support and willingness to introduce strict car control measures. As compared maintaining high density urbanization is relatively easier as urban planning and density control is traditionally under the public domain. Most importantly, if higher urban density could be maintained, the market forces may works towards discouraging motorization as price of urban land will be higher leading to higher cost of car use as the mode is space intensive.

5. CONCLUSION

Rapid motorization in developing countries, which is characterized as growth in car ownership rate, is creating multiple problems and threatening the prospect of achieving sustainable urban transport. There is an established tradition of car ownership modeling; however most of such modeling is either for market research for automobile makers or for road network planning. On the other hand, car ownership modeling could potentially generate important policy insights for formulating urban transport strategies. In particular, such model need to include effective policy leverage in policy relevant way. This paper first discussed the cross-sectional patterns of car ownership and some common reinforcing feedback loops involving car ownership, which led to a hypothesis that urban density is the most effective strategic element to restrain car ownership in the long-run. A brief review of car ownership models revealed that the existing model specification or modeling approach do not treat urban density as policy instruments for restraining car ownership. A modified model formulation is proposed, which explicitly links urban density with saturation level of car ownership. The model is estimated using metropolitan level cross-sectional data. Statistically significant parameters and reasonable degree of explanatory power of the model confirms the analytical validity and practical relevance of the model. Furthermore, utilizing the estimated parameters, maximum income elasticity of car ownership is computed, which is corresponds at a per capita income level of about US $ 4000 (in 1996 price). This figure may provide useful guidance to policy makers as it can be interpreted as “take-off” stage for motorization.

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