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THE RISE OF CHINA
AND ITS ENERGY IMPLICATIONS

Vehicle Stocks in China: Consequences for Oil Demand

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The Rise of China and Its Energy Implications is a major research initiative to investigate the implications of China's oil and natural gas policies and domestic energy market development on global energy markets. This study focuses on the influence of China's energy development on U.S. and Japanese energy security and global geopolitics. Utilizing geopolitical and economic modeling and scenario analysis, the study analyzes various possible outcomes for China's domestic energy production and its future import levels. The study considers how trends in China's energy use will influence U.S.-China relations and the level of involvement of the U.S. oil industry in China's domestic energy sector.

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Center for Democracy in the Americas, 2009); "The Militarization of Energy—The Russian Connection," with Amy Myers Jaffe in *Energy Security and Global Politics: The Militarization of Resource Management*, eds. Daniel Moran and James Russell (Routledge 2008); "Market Structure in the New Gas Economy: Is Cartelization Possible?" with Amy Myers Jaffe in *Natural Gas and Geopolitics: From 1970 to 2040* (Oxford University Press, 2006); "The Role of Inventories in Oil Market Stability," with Amy Myers Jaffe (*Quarterly Review of Economics and Finance*, 2002); "Automobile Ownership and Economic Development: Forecasting Passenger Vehicle Demand to the Year 2015," with Kenneth B. Medlock III (*Journal of Transport Economics and Policy*, May 2002); "The Economics of Pipeline Routes: The Conundrum of Oil Exports from the Caspian Basin," with Amy Myers Jaffe in *Energy in the Caspian Region: Present and Future*, eds. Amy Myers Jaffe, Yelena Kalyuzhnova, Dov Lynch, and Robin Sickles (Palgrave Macmillan, 2002); and "Potential Growth for U.S. Energy in Cuba," with Amy Myers Jaffe (*ASCE Volume 12 Proceedings*, Cuba in Transition website). Soligo is currently working on issues regarding energy security and the politicization of energy supplies. He holds a Ph.D. from Yale University.

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I. Introduction

In recent years there have been a number of studies aimed at estimating future motor vehicle stocks and motor fuel demand. Many of these studies have been motivated by a desire to estimate motor vehicle stocks and associated fuel use, particularly in China. China stands out due to its massive population and its persistently high growth rates over the last 30 years. A consequence of this growth has been, particularly in the last decade, very rapid growth in the ownership of automobiles and concomitant growth in the demand for oil—the latter of which has resulted in widespread concern about the future balance of global oil markets. Moreover, the geopolitical implications are far-reaching, as nations must deal with the implications of China's large and growing demand for oil. Within China, the growing stock of vehicles and associated vehicle use are presenting challenges related to road infrastructure, urban congestion, and the demand for oil, which increasingly must be imported. This, in turn, means that China must also grapple with its own concerns about energy security.

The growth of automobile stocks in China has been extremely rapid in recent years. The total vehicle stock in China, which includes cars, vans, buses, and trucks, has more than quadrupled in a decade, increasing from 14.5 million in 1999 to 62.9 million in 2009.[1] Growth in the stocks of personal cars has been even faster, rising to a total of 45.9 million by 2009,[2] with Chinese vehicle sales exceeding sales in the United States in both 2009 and 2010.[3]

The effect of this rapid growth has already shown up in China's energy demand, with oil consumption rising from 5.6 million barrels per day (b/d) in 2003 to 9.2 million b/d in 2010.[4] The growth in demand has outstripped increases in domestic production and resulted in rapidly rising net imports, which are up from 2.0 million b/d in 2003 to 4.9 million b/d in 2010. The composition of oil use has also changed, with the transport share of the total rising from 29 percent in 2003 to 36 percent in 2008.[5] In its *World Energy Outlook 2010 New Policies Scenario*, the International Energy Agency (IEA) forecasts that China will consume 14.3 million b/d in 2030, with the transport share of total oil demand rising to 61 percent,[6] meaning oil use in transportation could rise to over 8.7 million b/d. Accordingly, imports are forecast to rise to 11.2 million b/d.

This paper attempts to predict how quickly vehicle stocks will grow, while keeping in mind that the most important issue for energy security and world oil markets is not precisely how many vehicles will be on China's roads—but how much oil they will consume and what efficiency policies might be instituted. Using a dataset that includes 47 countries covering the time period from 1975 through 2009, we estimate a model based on the previous work of Medlock and Soligo (2002). Under a reference case scenario that involves real gross domestic product (GDP) growth through 2030 averaging 6.0 percent, we estimate total vehicle stocks in China could rise to 149 vehicles per thousand people in 2020, and approach 493 vehicles per thousand people in 2040. As a point of reference, the United States currently has about 825 vehicles per thousand people, with less than one-fourth the population of China.

We then use the forecast of vehicle stocks to project a range of possible outcomes regarding oil use in transportation in China. In the reference case, we assume that vehicle miles traveled (VMT) will be about the same as in France, which is used a proxy for major Western European countries. It is also higher than levels in Japan, which we use as the representative case for the low VMT scenario, and below levels in the United States, which we use for the high VMT scenario. We justify this assumption by comparing factors such as the density of cities and penetration of rail transportation in China with those of developed countries, but also provide estimates of projected oil use under alternative outcomes.

We also assume that vehicle efficiency standards are likely to continue to tighten in line with stated government targets. Again, however, we also provide estimates of projected oil use in transportation under alternative fuel efficiency outcomes, including allowing electric vehicles to play a varying but modest role longer term. These assumptions lead to reference case projections of oil consumption in transportation of 4.8 million barrels per day in 2020, rising to 13.4 million barrels per day in 2040.

There are many uncertainties present when projecting oil demand for transportation use. In the cases we considered herein, allowing for a reasonable range of outcomes regarding fuel efficiency standards and vehicle miles traveled around a reference economic growth scenario, we estimate a range of anywhere between 3.6 and 6.1 million b/d in 2020 and 8.2 to 22.6 million b/d in 2040. Other factors that could affect oil demand include fuel tax policy, the development of urban public transportation networks and rail, the density of cities undergoing urbanization,[7] and the adoption of new technologies and penetration of alternative fuel vehicles.

If we allow for very aggressive adoption of electric vehicles (EVs) relative to stated government targets, we see that the impacts of higher fuel efficiency standards and the promotion of lower VMT through perhaps the promotion of public transportation options are much more significant. Moreover, we see that a combination of high efficiency standards, low VMT, and rapid adoption of EVs has the greatest impact. This is telling because even if these goals are not fully met, by pursuing them all, the projected reference case demand for oil in transportation will be stemmed.

II. Models of Vehicle Demand

Generally speaking, countries undergo several shifts in the pattern of energy use in the course of economic development. In the early stages, energy intensity (defined as the amount of energy used per unit of GDP) of an economy grows as industrialization, urbanization, and heavy infrastructure development commence. With continued economic growth and wealth creation, the pattern of growth shifts toward services, which are generally much less energy intensive. The result is that the energy intensity of the economy declines. Total energy use continues to increase, but at a declining rate.[8]

The work of Medlock and Soligo (2001) indicates that the transportation sector tends to exhibit different patterns in energy intensity compared with other broadly defined economic sectors. Namely, energy intensity in the transportation sector is generally the last to rise significantly, and does not show signs of significant decline until very high levels of economic development are reached. In fact, transportation energy demand increases persistently with per capita income, a pattern that is consistent with observed patterns in growth of motor vehicle ownership. Gains in fuel efficiency tend to work in the opposite direction, but, historically at least, these have not been significant enough to offset the dominant effect of income growth.

There are distinct traits within the Chinese experience that distinguish it from the typical country. Energy demand in transport has historically been lower than what is usual in other countries at similar levels of per capita income, and energy demand in the industrial and other sector has been higher. This was characteristic of a command economy, which emphasized investment in heavy industry to the detriment of other sectors. Even during the early stages of its economic liberalization, China severely restricted the production of automobiles and development of transport infrastructure, emphasizing the utilization of bicycles as the primary mode of personal transportation. During the past decade, however, China has moved closer to average development trends witnessed in other countries. This is especially true in the case of private transportation, where domestic production of automobiles has increased rapidly and automobile ownership has followed suit, making China more comparable to countries with similar per capita incomes.

Over the last decade and a half, there have been a number of studies that attempt to forecast the effects of income growth on vehicle stocks. However, due to the rapid growth in China and the emergence of a middle class with real purchasing power, the predictions of many of these studies are made obsolete in rather short order.

In a relatively early paper, Dargay and Gately (1999) used data from a wide array of countries, both developed and underdeveloped, to model the growth in vehicle stocks and provide forecasts to 2015. They estimated that car stocks for China would be between 40 vehicles per thousand people and 60 vehicles per thousand people.[9] Their forecast was based on an assumption that per capita income growth would average 5.85 percent over the period 1992 to 2015. Obviously, these estimates turned out to be relatively conservative. For one, the growth in per capita income has defied historical precedent and has continued at an average rate of 8.6 percent per year since economic liberalization began in 1978. This has resulted in total vehicle stocks reaching 50 vehicles per thousand people in 2010, a full five years ahead of Dargay and Gately's estimates.[10]

Medlock and Soligo (2002)[11] used a different model specification aimed at forecasting *passenger* motor vehicles, which is a subset of total. They projected 24 passenger vehicles per thousand people in 2015 based on an overly conservative estimate of per capita income growth of 5 percent. Passenger vehicle stocks have, of course, already surpassed this estimate, totaling 37 vehicles per 1000 people in 2009.

An obvious limitation of these projections is the ability to forecast overall economic growth. With both Dargay and Gately (1999) and Medlock and Soligo (2002), projected economic growth turned out to be lower than what was realized. So, it is important to also understand the variable sensitivity that income growth itself has on projected vehicle stocks. We return to this point below.

One major problem in making comparisons is that different studies focus on different measures of vehicle stocks. Choices across studies generally include: passenger cars,[12] light-duty vehicles (which includes sport utility vehicles (SUVs), vans, and small trucks),[13] passenger vehicles (which excludes small trucks but adds buses and vans),[14] and highway vehicles (which includes all vehicles including medium and large trucks used for freight).[15]

There are a number of other factors that could exert an influence on motor vehicle stocks. Country-specific characteristics such as population density, the degree of urbanization, the state of public transport infrastructure, the extent of road infrastructure, and policies such as automobile ownership and/or fuel taxes that affect affordability of vehicle ownership will play some role in determining how extensive automobile ownership will become.

The distribution of income may also be an important variable. At low levels of per capita income, inequality is positively correlated with vehicle stocks. In a poor country, appreciable levels of vehicle ownership require, to an extent, some income inequality in order for there to be enough of the population with sufficient income to purchase a car. On the other hand, at higher levels of income, vehicle penetration is negatively related to inequality, as the number of persons whose income is larger than some minimum required value (or threshold) is smaller than in an otherwise similar country with a more equal distribution of income.

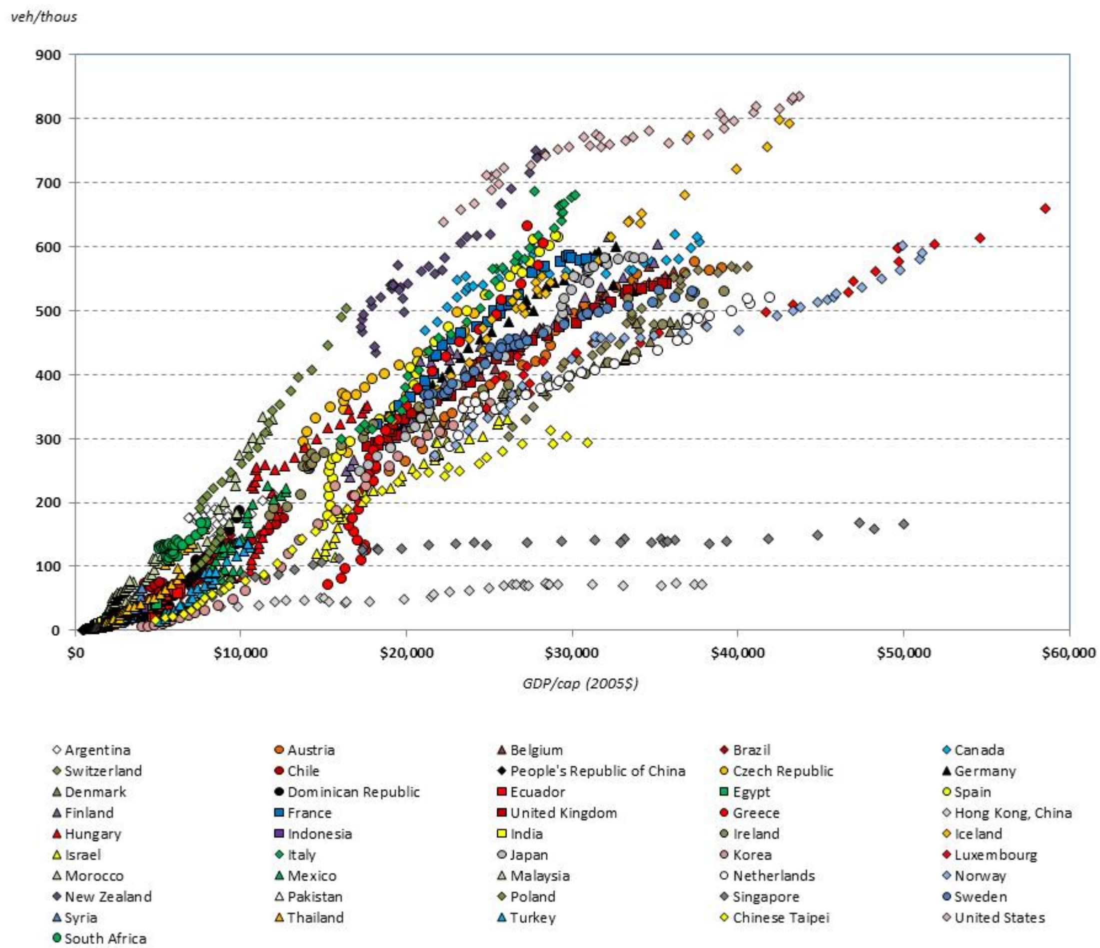
Many of these influences are not specifically accounted for in some analyses because they do not tend to vary through time in a substantial way. So, while the effects of these variables are interesting, if the goal is to generate income-dependent vehicle stock forecasts, these variable influences are often swept into some fixed, country-specific effect that allows for heterogeneity across countries—without a specific accounting of the nature of the heterogeneity. For the purpose of this paper, we account for income and fuel price (as a measure of utilization cost), as those variables do exhibit substantial temporal variation, but we assume any other country-level heterogeneity is subsumed in a country-specific, fixed effect.[16]

Perhaps the most critical issue to understand when considering the litany of models that have been developed to project vehicle stocks is the functional form specified in the empirical analysis. Several functions have been hypothesized to capture an observed S-shaped pattern in motor vehicle stocks revealed by the time series data. Interestingly, these functions tend to be the same as those used in population studies in the biological sciences, where populations approach some maximum carrying capacity of the environment. Some examples are the logistic function (Lescaroux and Rech [2008]) and the Gompertz function (Dargay and Gately [1999] and Dargay, Gately, and Sommer [2007]). Other non-linear specifications have also been suggested, such as a log-quadratic function (Medlock and Soligo [2002]).

Non-linear model specifications will determine how the income elasticity of demand for vehicles changes with income, and whether or not there is a pre-specified or econometrically estimated saturation level of motor vehicle stocks. For example, the Gompertz function implies that the income elasticity of demand increases over some range at the early stages of economic development, reaches a peak, and then declines. The log-quadratic function implies steadily declining income elasticity.

Indeed, when vehicle stocks are plotted against time, the resulting curve resembles an S-shape.[17] This observation has led to a choice of non-linear functional forms for analyzing vehicle stock evolution, normalized for population. The primary driver of growth in motor vehicle stocks per thousand people is per capita income. This provides a reasonable barometer of the manner in which the level of economic development influences vehicles per thousand people. Figure 1 depicts the relationship between per capita income and vehicle stocks per thousand people for the 47 countries used in the analysis in this paper.

Figure 1. Car Ownership and Real Per Capita Income in 47 Countries, 1975-2009



Of note in Figure 1 are Hong Kong and Singapore, both of which are virtual city-states that fall well below the rest of the sample. In contrast, at the top end of the sample lies the United States. The point being that although the general relationship between income and vehicle stocks is common to all countries (see analysis below), the exact path and saturation level—the level at which vehicle stocks per thousand people ceases to grow—will vary across countries. This result is a reflection of things such as transport policies and other country-specific characteristics.

Most models of vehicle stock evolution posit an optimal stock based on population and per capita income. Some studies have also included other variables such as fuel costs, the price of a typical automobile relative to per capita income, urbanization, population density, and the distribution of income. Most of these models, in particular the earlier work, also posit a saturation level rather than econometrically estimate it. In one case, the authors even propose a common saturation level toward which all countries would converge.[18]

Wang et al. (2006) specifies three saturation levels for China corresponding to the “Asian” and “European” experiences as well as a “low-growth” scenario with fewer vehicles than in the Asian scenario. Besides being motivated by patterns in the actual data, positing a saturation level is one way to model car ownership so as to capture the declining income elasticity of demand for vehicles as income increases. More recent data, however, suggest that vehicle ownership levels between Japan and major Western European countries may be narrowing.[19]

More recent literature posits a specification in which the saturation level is country-specific, often determined by estimation of the proposed variable relationship. In fact, that is the approach taken in this paper. Table 1 indicates the implied saturation levels for each country from the analysis performed herein. Note that the saturation level for China falls in a range comparable to the United States and, in fact, is the ninth largest in the sample.

Table 1. Saturation Levels of Motor Vehicle Stocks Per Thousand People

	Saturation Level			Saturation Level
Argentina	692		Italy	965
Australia	954		Japan	827
Austria	782		Korea	867
Belgium	841		Luxembourg	867
Brazil	626		Morocco	675
Canada	862		Mexico	905
Chile	596		Malaysia	1496
China	1050		Netherlands	760
Czech Republic	1134		Norway	789
Denmark	701		New Zealand	1342
Dominican Republic	1225		Pakistan	121
Ecuador	96		Poland	1952
Egypt	266		Singapore	233
Finland	1057		South Africa	712
France	822		Spain	1039
Germany	740		Sweden	775
Greece	1533		Switzerland	778
Hong Kong	102		Syria	613
Hungry	978		Thailand	841
Indonesia	349		Turkey	633
India	403		Taiwan	587
Ireland	885		United Kingdom	803
Iceland	1194		United States	1057
Israel	608			

The saturation level is important for long-term growth projections because it effectively caps the level that vehicle stocks can reach. In general, a higher saturation level will tend to result in extended periods of vehicle stock growth. This point is what makes the estimated saturation level for China so striking. It portends a rather substantial growth potential for vehicle stocks in the country, which has implications for long-term transportation fuel demand.

Despite the data presented in Table 1, the appropriate saturation level for any given country is open for discussion. This has tended to push more recent research into the realm of allowing the econometric analysis to determine the saturation level, effectively removing an element of subjectivity from the analysis. Nevertheless, in one recent paper, Chamon, Mauro, and Okawa (2008) argued that there is no sign that any country has yet reached a saturation level and they doubt that such a point even exists. As they point out, per capita vehicle ownership continues to increase even in high-income countries. However, a number of analyses have indicated that the income elasticity of demand for automobiles decreases as per capita income increases, which is the driving factor that yields a basic S-shaped curve—even if the elasticity never actually reaches zero.

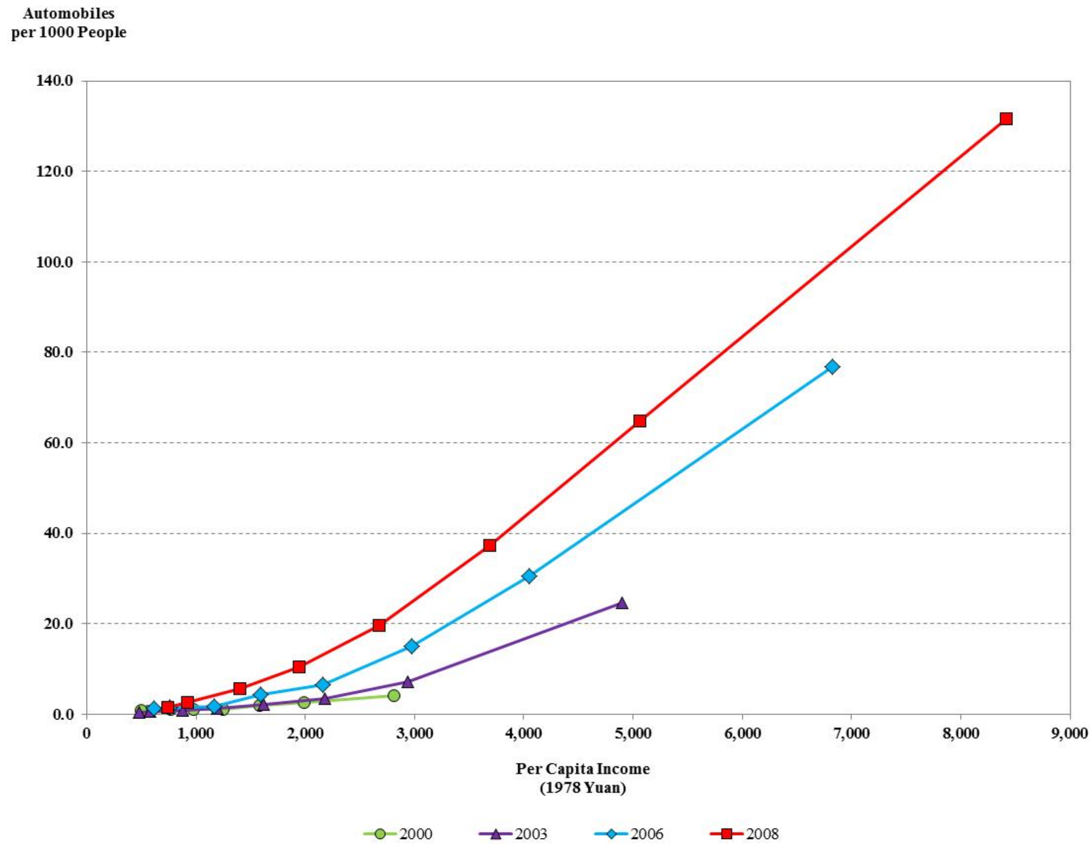
Forecasting Chinese motor vehicle stocks can be difficult at best. As noted above, recent forecasts have dramatically missed the mark, whether the cause is an underestimate of future economic growth or some other factor, the track record is not good. Wang, Teter, and Sperling (2011) have offered an interesting paper in which they propose a potential explanation as to why the forecasts of all of the other studies on Chinese vehicle stocks have underestimated future vehicle stocks. Those studies, they argue, pool data from a large number of countries at very different stages of development and observations are from a relatively short period of time due to data availability. As a result, these studies do not include observations from large countries that underwent "motorization" in earlier years. For example, these studies exclude the years in which the United States, Japan, and Korea experienced very rapid growth rates in vehicle stocks as their own domestic auto industries developed.

Wang, Teter, and Sperling (2011) argue that the behavior of a country in terms of the speed of acquisition of automobiles is substantially affected by simultaneous development of a large automobile manufacturing sector. They point out that, "… constituencies advocating for motorization tend to be far weaker in countries without an automotive industry and, not coincidentally, those countries tend to have low rates of vehicles per capita."[20]

Thus, for example, China should be compared with Japan and South Korea in the 1950s and 1960s, "a key motorization period," or the United States in the first two decades of the 20th century when motor vehicle penetration rose from seven vehicles per thousand in 1911 to 173 per thousand in 1925. Accordingly, Wang, Teter, and Sperling (2011) chose seven large countries that had major domestic vehicle producers and examined the growth rates of vehicle stocks after they had reached a vehicle density of 37-38 per thousand people, which was the level for China in 2008. Based on the growth rates of vehicle stocks experienced in several high-growth countries, they estimate stocks in 2022-2024 to be anywhere between 358 and 419 million, depending on what specific countries are used in the forecast.

It should be pointed out that Wang, Teter, and Sperling (2011) do not arrive at their estimates by using the same curve-fitting technique used by others. They simply argue by analogy that other countries experienced very high growth rates of vehicle stocks as they entered their own motorization period. Their estimates are then derived by applying those growth rates to China.

Figure 2. Automobile Ownership in China in Urban Households by Income Level



Source: NBS, *China Statistical Yearbook*, various years

However, there is compelling evidence, at least for China, that the relationship between vehicle ownership and per capita income may have been shifting upwards over time in the past decade or so. Figure 2 graphs the cross-sectional relationship for select years from 2000 to 2009. The wealthiest 10 percent of urban families in 2000 had per capita income of 2,811 Yuan (in 1978 Yuan) and owned only 4.5 automobiles per thousand persons. Yet by 2009, the second-poorest quintile, whose per capita income was lower at 2,210 Yuan (in 1978 Yuan), owned about three times as many automobiles, at 13.7 per thousand persons. This is consistent with the notion that adjustments to the desired (or optimal) level of motor vehicle stocks may be occurring more rapidly over the last decade in China as the domestic motor vehicle industry has become more vibrant, which is a point argued by Wang, Teter, and Sperling (2011).

More generally, the apparent upward shift in the cross-sectional relationship is consistent with the idea that actual stocks adjust to desired (or optimal) levels with a lag. With per capita income growing as rapidly as it has over the last decade in China, the observed current vehicle stock will reflect adjustments to past levels of income, as well as a portion of the initial response to the current income level.

In this paper, we posit a log-quadratic relationship between total motor vehicle stocks per thousand people and per capita income and price. Specifically, using panel data we estimate the following equation

$$veh_{i,t} = \alpha_i + \beta_1 y_{i,t} + \beta_2 y_{i,t}^2 + \beta_3 p_{i,t} + \beta_4 veh_{i,t-1} \quad (1)$$

where $veh_{i,t}$ denotes vehicle stocks per thousand people for country *i* at time *t*, $y_{i,t}$ denotes per capita income for country *i* at time *t*, denotes the price of fuel for country *i* at time *t*, $i \in [1, 47]$ denotes a specific country, and all variables are expressed as natural logarithms. Note that the countries included in the estimation are listed in Table 2. For more details regarding the estimation, please see the appendix.

Data on vehicle stocks were obtained from Dermot and Gately at New York University and verified and updated using data from the International Road Federation and Ward's Motor Vehicle Databook. Thus, the data we used in this analysis is directly comparable to that used in Dargay, Gately, and Sommer (2007). Data for GDP and population were obtained from the Penn World Tables and fuel price data were obtained from the IEA and U.S. Energy Information Administration (EIA).

The coefficients in equation (1) are the parameters used to determine the short-run elasticity of vehicle demand with respect to price and income. The long-run elasticities are determined by simply dividing the short-run elasticity by the term $1-\beta_4$, where β_4 is the coefficient that indicates the speed of adjustment to the desired, or optimal, stock of motor vehicles. Consistent with most other studies, we assume that country-specific heterogeneities are captured in a fixed effect, α_i, and all slope coefficients, $\beta_{i,j}$, are common across countries.[21]

The above functional form is consistent with the approach used in Medlock and Soligo (2002). However, the data span a greater number of years, 1975-2009, and use a larger sample of countries, 47 versus 28. The estimated coefficients imply a short-run income elasticity that is given as

$$\varepsilon_{veh,y} = \frac{\partial veh_{i,t}}{\partial y_{i,t}} = \beta_1 + 2\beta_2 y_{i,t}.$$

Notice $\varepsilon_{veh,y}$ will decline as income rises so long as $\beta_1 > 0$ and $\beta_2 < 0$, which is indeed the case. Moreover, we can evaluate the point at which the income elasticity reaches zero by simply setting $\varepsilon_{veh,y} = 0$ and solving for income. This yields a saturation level of per capita income at a value of $119,000, which is well above the observed income ranges for the countries in our sample.

III. Projecting Total Vehicle Fuel Use

In order to project total vehicle fuel use, we build up from three principle components. In particular, we make use of the identity

$$fuel\ use = \frac{VMT}{eff} \cdot \#veh$$

where VMT denotes average vehicle miles traveled (expressed as miles per vehicle), eff denotes fleet motor vehicle fuel efficiency (expressed in miles per gallon), and $\#veh$ denotes the number of motor vehicles in use. Thus, we must project vehicle stocks, vehicle miles traveled, and efficiency.

In what follows, we present the methods chosen for each of these projections so that they may be taken either piecewise or in sum. Then, we present a range of possible outcomes noting a high, reference, and low for all of the variables in the identity. This will, in turn, present a significant range of possible outcomes for oil demand in transportation. As a matter of policy recommendation, however, we will rely on the reference case outcomes as they represent what is deemed to be the most likely outcome, admittedly with a degree of subjectivity.

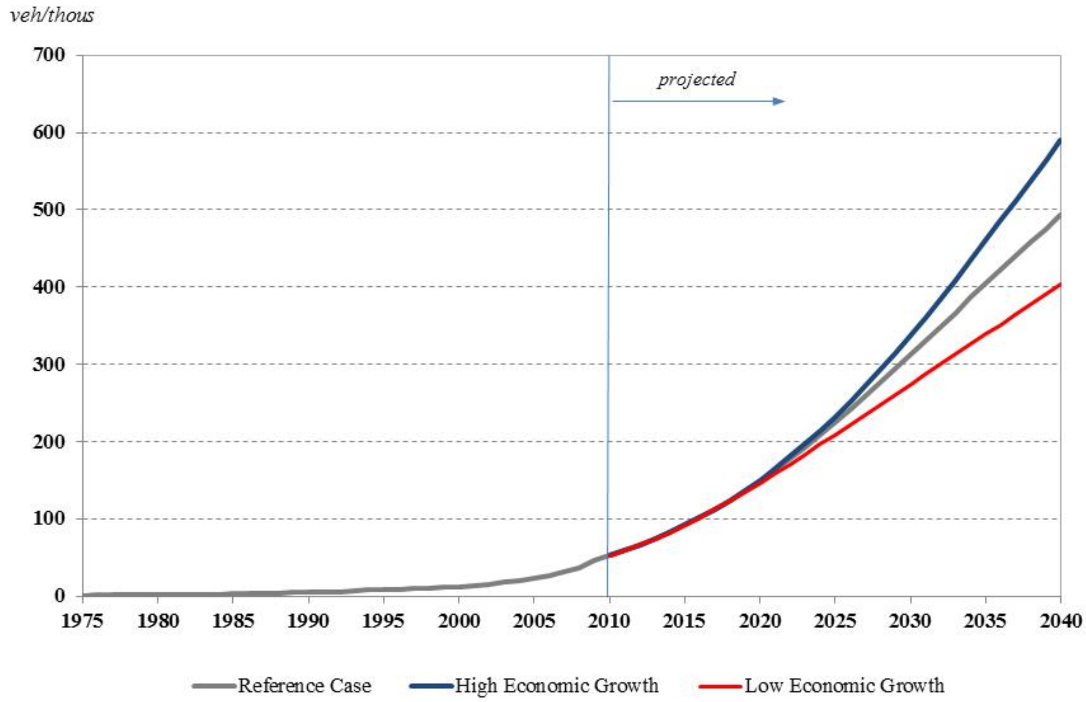
Vehicle Stock Projections

The model described by equation (1) above is used to generate projections of vehicle stocks per thousand people, given assumption about rates of per capita income growth and the future price of oil. We also require a population growth rate in order to project total vehicle stocks. For per capita income we use per capita income growth estimates from the International Monetary Fund (IMF) global economic outlook for the period up to and including 2015. Beyond 2015, we assume that per capita growth will begin a slow but persistent decline. For the reference growth scenario, we assume the decline through 2035 is consistent with an annual average growth rate of 6.0 percent, which is roughly consistent with the growth rate in the outlook of the International Energy Agency (IEA). In the high growth case, economic growth is increased to 8.0 percent, but it is lowered to 4.0 percent in the low growth case.

The fuel price index is based on the refinery acquisition cost of crude oil for U.S. firms. We rely on the projected oil price from the Energy Information Administration's Annual Energy Outlook 2011 (AEO2011). This yields a real oil price that steadily approaches $120 per barrel by 2030.

The forecast of motor vehicle stocks by year from the reference, high, and low growth paths are graphed in Figure 3. We do not vary the price of oil in this exercise, so the AEO2011 forecast is assumed to hold in all projections. History is also included to provide a point of reference.

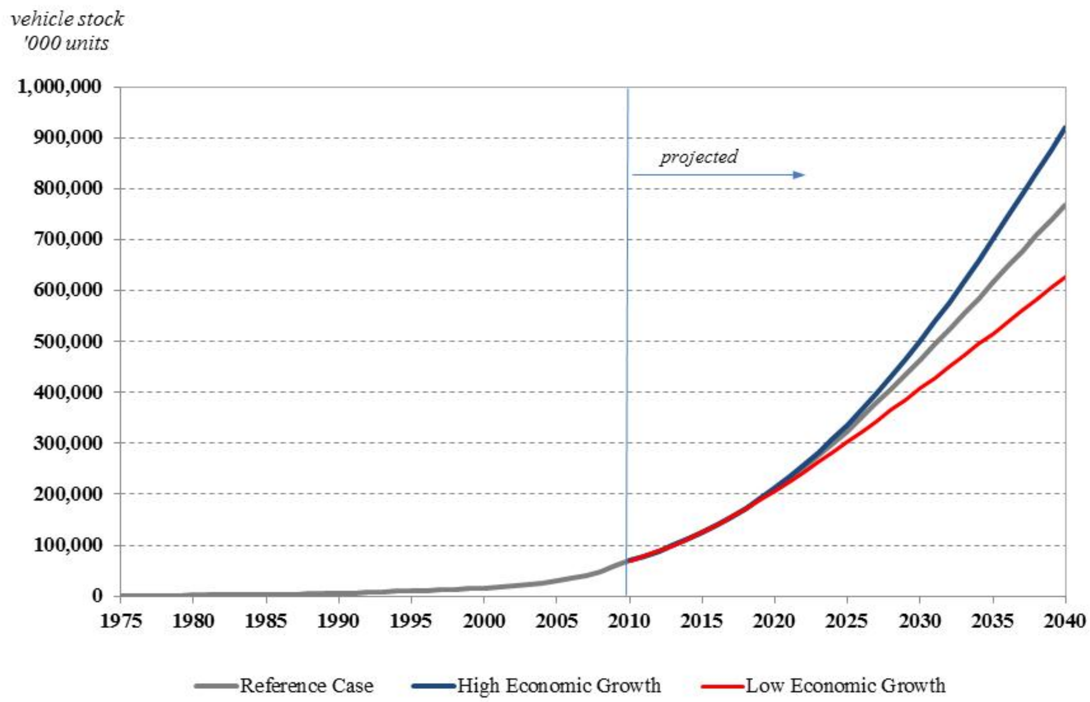
Figure 3. China Vehicle Stocks per Thousand People, 1975-2040



Notice that the range of outcomes widens as we move further into the future, which speaks to the uncertainty that is directly related to the rate of economic growth. In 2020, the model projects between 146 and 150 vehicles per thousand people, but this range expands to between 274 and 337 vehicles per thousand by 2030, and 403 and 590 vehicles per thousand by 2040.

To project total vehicle stocks once we have a projection of vehicles per thousand people, we use the median estimate of population growth from the United Nations. For China, this results in a forecasted population growth rate of 0.55 percent per annum. This in turn results in a forecast window between the high and low economic growth scenarios of between 628 and 921 million vehicles in 2040, with the reference forecast at 769 million vehicles.

Figure 4. China Total Vehicle Stocks, 1975-2040



It is interesting to compare projections from other modeling exercises and note significant differences. Table 2 contains a summary of comparisons to other works cited herein. Wang et al. (2006) forecast a much lower vehicle stock for 2030 than this study. In part this is due to their assumption of a decline in per capita income growth after 2020 to 4.7 percent. They also assume a lower population growth rate. The paper by Dargay et al. projects a 2030 stock of 390 million, which is somewhat lower than the reference case estimate in this paper of 463 million, but nearer to the low economic growth result. As shown in Table 2, other papers project lower vehicle estimates as well, except for Wang, Teter, and Sperling (2011), who estimate that if China follows the experience of Japan and South Korea its vehicle stocks would grow much more robustly than even our high economic growth case would suggest. However, if China follows the experience of the seven-country average, the estimates are much more similar to what our analysis suggests.[22]

Table 2. Projections of Vehicle Stocks

Paper	Vehicle Stocks in 2020 (millions)	Vehicle Stocks in 2030 (millions)	Economic Growth	Other Assumptions/ Results	Last Year of Actual Data	Other Notes
Medlock, Soligo, Coan (2011)	207-212 Reference, 211	407-503 Reference, 463	Reference Case projection of 6.0%	Saturation level of 1049	2009	All vehicles, not just passenger vehicles
Wang et al. (2006)	87-93 (midpoint 91)	186-217 (midpoint 203)	Average annual growth of 8.0% from '06-'10, 6.0% from '11-'20 and 4.7% from '21-'30	Saturation level of 400-600 vehicles per 1,000; Population 1.45 billion by '50	2004	
Dargay, Gately and Sommer (2007)		390 (All vehicles, not just passenger vehicles)	Average annual growth of 4.8% from '02 to '30	Saturation level of 807 vehicles per 1,000; Population 1.45 billion in '30	2002	Includes population density
Chamon, Mauro and Okawa (2008)	134	254 (but with other assumptions, 141-255)	Average annual growth of 5.3% from'05-'30			Relies on a survey of Chinese households
Lescaroux[23] (2010)		288.2	Average annual growth of 5.9% from '98-'30	Population at 1.46 billion in '30	1998	Interested in income inequality
Hao, Wang, and Yi (2011)	166	343	Average annual growth of 8.38% from'11-'20 and 7.11% from '20-'30	Population at 1.44 billion in '20 and 1.47 billion in '30, urbanization rate 63% in '20 and 70% in '30	2008	Uses ownership by income and vehicle prices
Wang, Teter, and Sperling (2011)	364 (Japan/S.Korea growth), 288 (7-country average growth)	Mid-500s (Japan/S.Korea growth), Mid-400s (7-country average growth)	Those of Japan/South Korea or 7-country average growth		2008	No economic model used

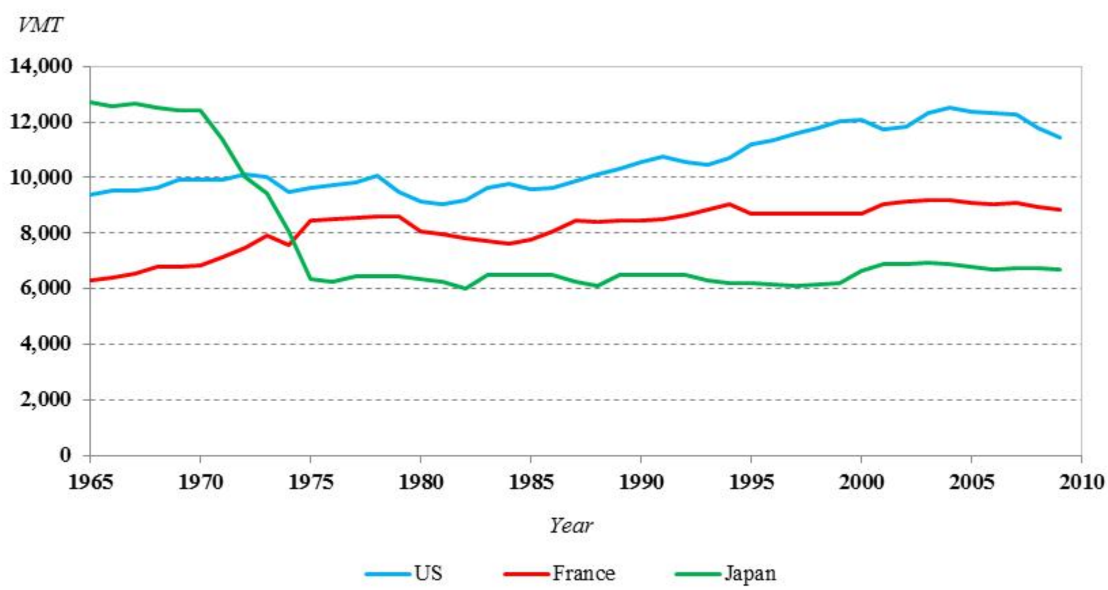
Estimating Vehicle Miles Traveled

Consistent data on miles driven per vehicle are not available and tend to be less reliable for many countries, so it is difficult to establish a robust relationship between distance driven and other variables for countries other than the most developed.[24] Millard-Ball and Schipper (2010) provide a recent compilation of historical light-duty vehicle ownership and use.[25] Their analysis is limited to eight developed countries,[26] to a large extent because of the difficulty in obtaining a long historical series of vehicle use in various countries.

To this point, data on vehicle miles traveled (VMT) for China are difficult to obtain, and given the approach taken in this paper to estimate transportation fuel use, VMT is a critical input. While other researchers (see Wang et al. [2006][27]) have opted to use simple analogs for China's VMT, we choose to estimate the annual evolution of VMT in China under three different possible pathways. IRF data on the United States, Japan, and France, where France is used as a European benchmark, demonstrate that countries tend to initially have declining levels of VMT at lower levels of income. These three countries were chosen because they represent the high, low, and median VMT for a large sample of countries examined in the IRF database.

The IRF data motivates the use of a nonlinear functional relationship between VMT and GDP per capita to estimate a small panel composed of the United States, Japan, and France spanning the years 1965 through 2009. The nonlinear specification accounts for the observation that at low levels of income (and vehicle ownership), VMT will tend to reflect commercial activities, such as taxis and freight, more than private activity, such as personal vehicle use. Thus, as private motor vehicle use increases relative to commercial use, VMT should decline for a period of time before eventually rising. Estimation of the specified model indicates a soft inflection that occurs at a per capita income level of $16,840. The VMT data used in the analysis are depicted in Figure 5, and the projected pathways for VMT are depicted in Figure 6.

Figure 5. VMT for the United States, Japan, and France (1965-2009)



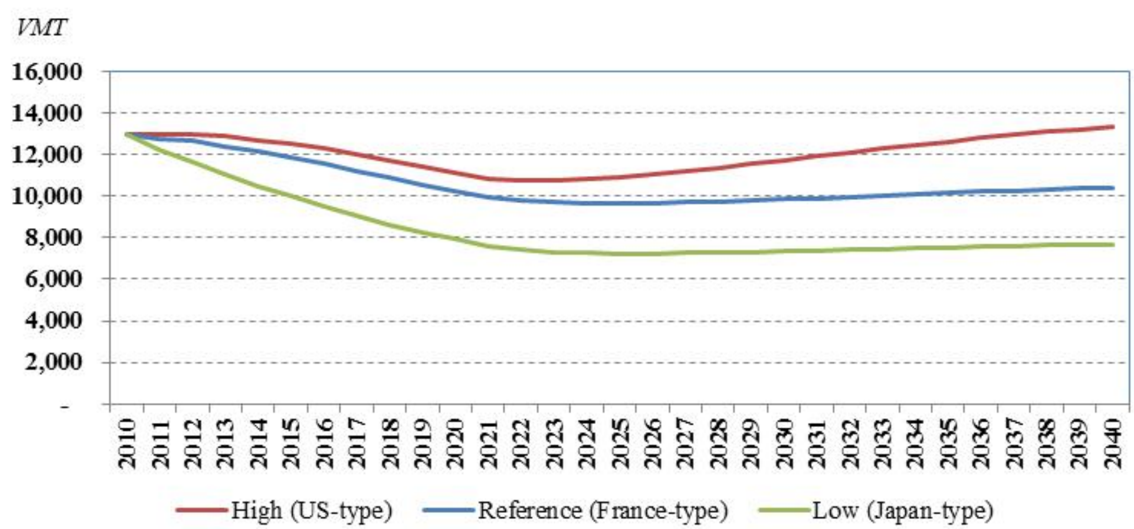
The three "type" curves constructed to represent the possible futures for VMT in China are based on the econometrically estimated experience of the United States, France, and Japan. The U.S.-type curve is constructed assuming the experience of the United States, according to the VMT model, will be followed by China. The France-type VMT path and the Japan-type VMT path are the two alternatives that China is postulated to follow.

The initial year VMT was constructed using data for total transportation energy use and estimated fuel efficiency. Specifically, we calculated VMT in 2010 as

$$VMT_{2010} = \frac{eff_{2010}}{\#veh_{2010}} \cdot fuel\ use_{2010}.$$

which yields a value of 13,317 miles per vehicle. In all three cases, VMT declines until the early 2020s, but begins to rise when per capita income in China reaches the estimated inflection point.

Figure 6. "Type" Curves for VMT in China



Given the uncertainty regarding the future path of VMT in China, we incorporate each of the above three possible scenarios for miles driven. The lower estimate is comparable to average miles driven in Japan, the medium estimate is comparable to European driving patterns, and the high estimate is consistent with the U.S. experience. Factors that could push China in certain directions include, but are not limited to, intra-city density, length of paved roads, population density, population distribution, and patterns of rail use. Policies that aggressively push for public transportation could also affect VMT, perhaps even pushing miles driven toward the Japan-type experience.

The median case, or the France-type VMT path, implies that total vehicle miles traveled in China will decline to 10,254 miles per vehicle in 2020, bottoming out in the mid-2020s at 9,640 miles per vehicle, then rising to 10,409 miles per vehicle by 2040. The values in the high case, or the U.S.-type VMT path, are 11,125 in 2020, falling to 10,734 in the mid-2020s, then rising to 13,363 by 2040. Finally, in the low case, which corresponds to the Japan-type VMT path, total vehicle miles travelled are 7,927 in 2020, bottoming at 7,242 in the mid-2020s, then rising to 7,685 in 2040. The difference between the low and high cases in 2040 is 5,678 vehicle miles traveled, which is evidence of the importance of the manner in which policies aimed at encouraging certain forms of public transportation, such as rail, rather than private transportation could influence VMT, and hence, oil use in transportation.

Efficiency Standards

Finally, we need to estimate the manner in which fuel efficiency could evolve over the next 30 years in China in order to project total oil use in transportation. The state of efficiency depends on the efficiency standards of new vehicles sold as well as the vintage effect of the efficiency of vehicles already in use. Thus, the diffusion of new vehicles into the existing stock is critically important when determining how rapidly on-road fuel efficiency will change. Historical data for on-road efficiency is also important as it establishes the baseline into which new vehicles with higher fuel efficiency can matriculate.

Less than 10 car models were produced in China before the mid-1990s.[28] Many of these vehicles used old technologies that were more than a decade behind their Japanese and European counterparts. Chinese experts noted that while these vehicle fleets had an average curb weight and engine displacement of almost 11 percent and 15 percent less than those counterparts, average fuel economy was still 10 percent worse.

Beginning in the summer of 2001, the former State Economic and Trade Commission (SETC) initiated the *Study on Fuel Economy Standards and Policies for Vehicles in China*.[29] This was in response to a 90 percent increase in oil imports during 2000. By 2004, the Chinese government set forth its goal of raising the average fuel economy of new vehicles by 15 percent in 2010 relative to a 2003 baseline. The first Chinese fuel consumption standards took effect in 2006, with a second phase in 2008.[30] The program divided vehicles in 16 weight classes, each with its own standard. While heavier vehicles had less strict standards in an absolute sense, they were relatively stricter as a way to try to encourage consumers to buy smaller, more efficient vehicles.

With the standards, sales-weighted average consumption dropped to 8.06 liters per 100 kilometers (L/100km) in 2006 from 9.11 L/100 km, which represents an increase from 25.8 miles per gallon (mpg) to 29.2 mpg. However, imported passenger vehicles were exempt from the standards, and because there was no corporate average standard, consumers began buying larger imported vehicles.

In December 2009, China issued a proposed Phase III standard designed to reduce consumption of new passenger vehicles to 7.0 L/100 km (33.6 mpg) by 2015. This standard is supposed to include a corporate average standard.[31] The Chinese government is currently considering tightening fuel economy standards for 2020 to 5.0 L/100 km, or about 53 mpg.[32] Actual on-road fuel use is expected to be roughly 19 percent higher than the standards would suggest, consistent with the European Driving Cycle used in China.[33]

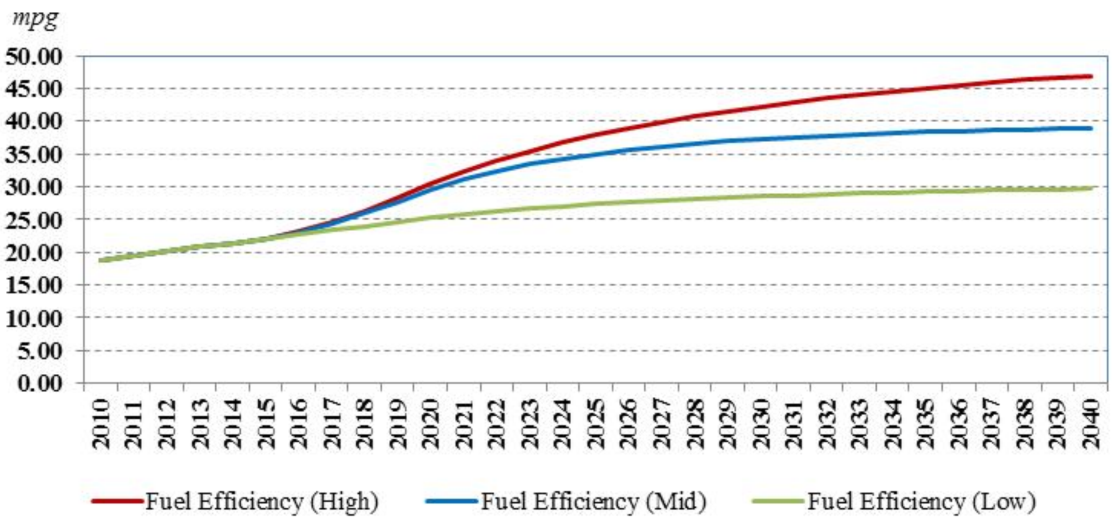
In addition to fuel economy standards, the adoption of new alternative technologies such as electric vehicles could also play a role in determining transportation oil demand. China has committed about $15 billion over the next five years to develop electric vehicle infrastructure and is exempting electric vehicles from the lottery system for license plates begun this year to limit the number of vehicles in Beijing.[34] There are various electric fleet vehicle programs in China.[35] China aims to produce 300,000 "new energy" vehicles each year by 2012, a category that includes hybrids, electrics, and fuel-cell vehicles, and Beijing itself aims to have 100,000 electric vehicles on the road by 2015.[36] A draft plan released in April 2011 jointly drafted by China's Ministry of Industry and Information Technology, the Ministry of Science and Technology, the Ministry of Finance, and the National Development and Reform commission calls for production and sales of 1 million "new energy" vehicles each year by 2015, 50 percent of which should be all-electric or plug-in electric. Moreover, the plan calls for global sales of 5 million units each year by 2020, with a goal of becoming the global leader in new energy vehicles.[37] Some Chinese automakers are introducing electric and plug-in vehicles, including

Build Your Dreams, often referred to as BYD, which was made famous when Warren Buffett invested in the company.[38]

Importantly, in none of the scenarios considered do we allow for a substantial impact from the adoption of electric vehicles. Even if China's plan to introduce electric automobiles is successful, the penetration rate will still remain very low relative to the total stock of motor vehicles. We do, however, consider a hypothetical in which Chinese domestic EV sales rise to 5 million vehicles by 2030. Even in this case, which is very aggressive relative to the stated goals, the impact on fuel use is not substantial. The results of this scenario are presented below.

For our purposes, we posit three alternatives for the future of on-road fuel efficiency in China. In the reference efficiency case, we posit that China will implement both the 7.0L/100km and 5.0L/100km new vehicle fuel efficiency standards, and diffusion will occur at roughly 5 percent per year—meaning on-road fuel efficiency will gradually improve though 2040, reaching about 40 mpg, which represents a near 100 percent improvement relative to 2010 (see Figure 7). The high fuel economy scenario is the same as the reference case with regard to the new vehicle fuel economy standards, but diffusion occurs more quickly, reaching about 7 percent per annum. In this case, on-road fuel economy improves to 50 mpg in 2040. The low fuel economy scenario sees much lower efficiency improvement as only the 2015 target for new vehicles is implemented, which results in on-road fuel efficiency only reaching 28 mpg in 2040.

Figure 7. On-Road Fuel Efficiency Projections



Oil Use in Transportation

The above projections of total vehicle stocks, VMT, and fuel efficiency facilitate projections of oil demand in transportation in China. Using the reference and median projections for each variable, we see that oil use in transportation rises from 3.15 million b/d in 2009 to 4.8 million b/d in 2020, 8.0 million b/d in 2030, and 13.4 million b/d in 2040 (see Figure 8). Based on these estimates, oil demand for transportation in China is projected to surpass the current demand for oil in transportation in the United States within the next 30 years. Given the fact that our economic growth assumptions put Chinese per capita income at just over $30,000 and its population is more than four times that of the United States, wealth and scale result in very strong demand for oil in transportation.

Figure 8. Median Path Transportation Oil Use in China (2010-2040)

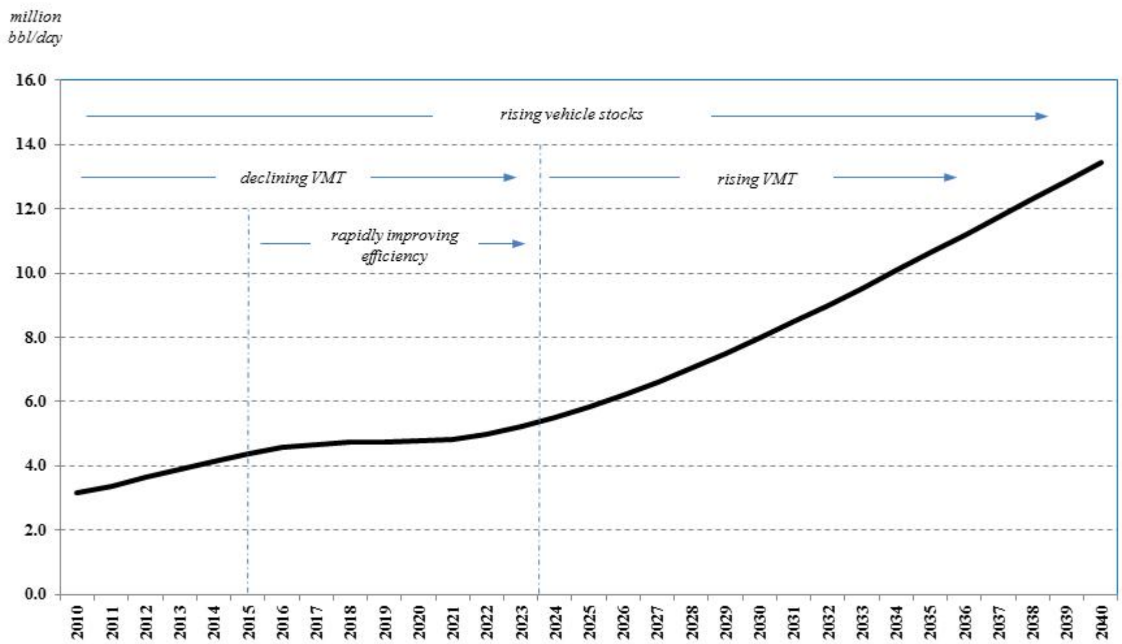
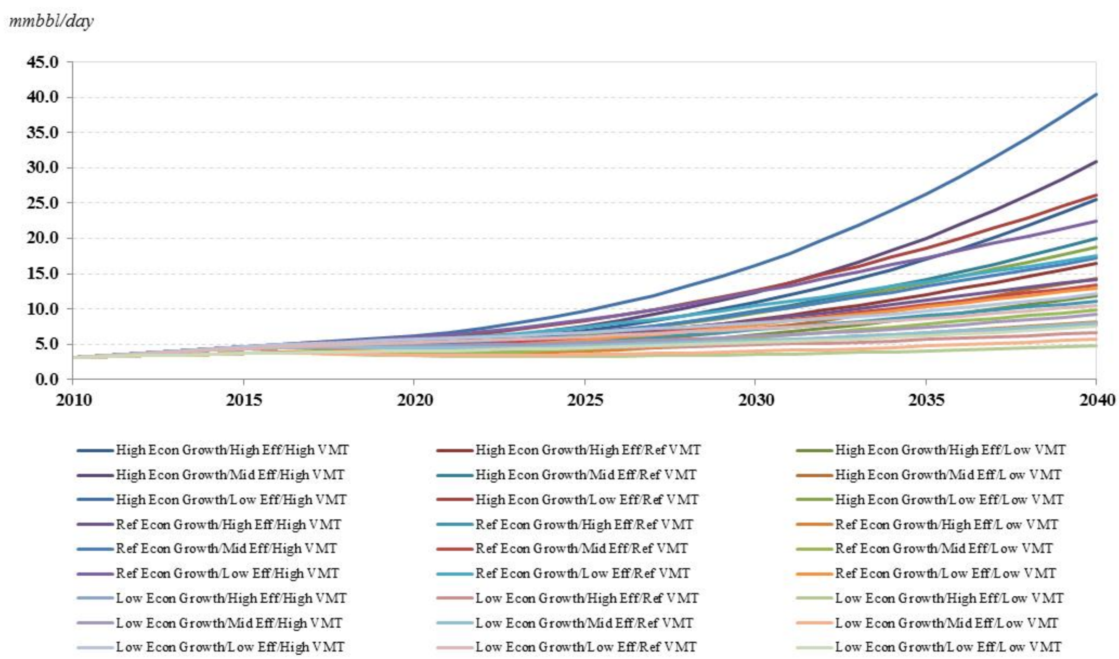


Figure 8 reveals the effects that trends in vehicle stocks, efficiency, and VMT have on total transportation fuel use. In particular, we see that fuel demand growth is slower from 2015 through the mid-2020s due to strong efficiency improvement *and* declining VMT. Once these trends abate, fuel demand growth increases, which signals the importance of both variables and the policies that influence them.

Low and high estimates of vehicle stocks, vehicle use, and efficiency provide a wide range of estimates for oil use in transportation, as shown in Figure 8, particularly when considered in various combinations with one another. These result in oil use estimates that range from 3.4 to 6.2 million b/d in 2020, 3.6 to 16.2 million b/d in 2030, and 4.8 to 40.5 million b/d in 2040.

Obviously, the boundaries of these ranges are quite extreme, and are in fact highly unlikely. In particular, the upper boundary is consistent with a case in which there is high economic growth, a U.S.-type VMT path, and low fuel efficiency improvements. If such an outcome were to eventuate, the impacts on future oil prices would be substantial, which would trigger a set of changes that are not accounted for in these projections. In other words, the endogeneity of price to any projected future path is simply ignored. Nevertheless, the outcomes are informative because they can help to identify the variables to which projected future oil demand are most sensitive. In turn, this can provide policymakers with reasonable targets to maximize the bang-for-buck. For example, with extensive programs to promote public transportation, as well as tax (or subsidy removal) policies that raise gasoline prices, VMT could ultimately more closely resemble Japan's rather than that of the United States or France. This would tend to push China into the lower end of the projected range in Figure 9.

Figure 9. Range of Transportation Oil Use (2010-2040)



Many other policies could alter the projected paths. For example, even assuming that economic growth continues at the levels predicted, authoritarian steps to limit vehicle ownership, as was seen in Shanghai and Beijing, could spread to other cities or even provinces. The policy in Shanghai has been very successful. In 2009, despite having a slightly higher per capita income than Beijing, there were only 140 automobiles per 1000 households in Shanghai compared with 29.5 in Beijing.[39] Beijing has also taken steps to restrict vehicle ownership, limiting the number of new license plates in 2011 to roughly one-third of sales in 2010.[40]

Finally, electric vehicles could become very popular, possibly through incentives, higher gasoline prices, and/or mandates that a certain percentage of new vehicles sold or produced be plug-in or fully electric.

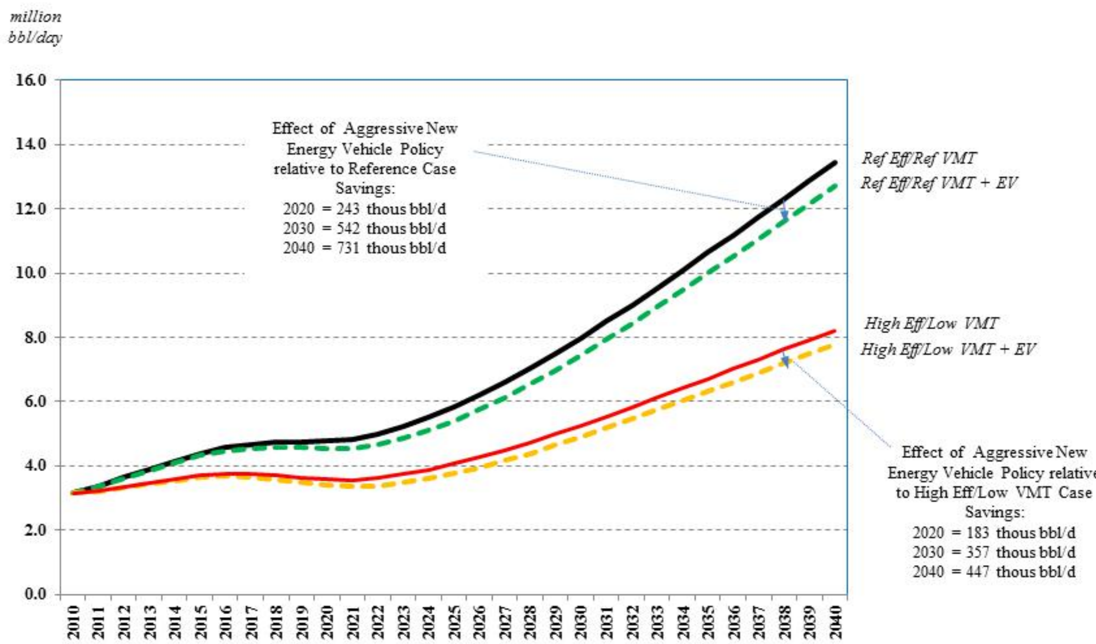
On the other hand, China's leaders have a history of implementing programs that promote vehicle ownership. In 2009, China halved the tax rate on vehicles with engine sizes less than 1.6 liters from 10 percent to 5 percent, and the tax rate was not returned to 10 percent until 2011.[41] There were also incentives for rural car buyers to purchase vehicles.[42] These types of policies act to raise, *ceteris paribus*, transportation fuel demand.

The Effect of Electric Vehicles

The question of "what if" is one that often enters the discussion when considering future energy demands. As such, we consider a case in which electric vehicles are adopted very aggressively. In particular, we allow electric vehicle sales to rise to 5 million per year by 2030. Sales are assumed reach 657 thousand units by 2015 and 3.28 million units by 2020, and EVs are assumed to have a 7 year life. Accordingly, the EV stock reaches 31.5 million vehicles by 2030 and 41.9 million vehicles by 2040. Note this is very aggressive relative to the goals stated by Chinese officials. Nevertheless, the scenario will provide a good barometer of the impact that EV policies, as currently outlined, could have on overall fuel use.

Figure 10 depicts the effect of aggressive EV adoption under two cases. Both cases indicated assume the Chinese economy averages 6 percent growth through 2030. But, one sensitivity case shows the effect relative to a scenario that follows the France-type VMT path and the median fuel efficiency path. The other case depicts the effect relative to the scenario that follows the Japan-type VMT path and the high fuel efficiency path.

Figure 10. The Impact of Electric Vehicles



As can be seen in Figure 10, the EV policy has a relatively minor initial impact that grows over time, which should be expected as EVs diffuse into the vehicle stock. Perhaps the most striking feature of Figure 10 is the fact that the shift from the France-type VMT path *plus* median fuel efficiency to the Japan-type VMT path *plus* high fuel efficiency lowers fuels use by much greater amounts than the aggressive EV scenarios. This reveals that policies targeting fuel efficiency improvements and VMT (and even EV adoption) could be much more effective than EV policies alone if the goal is to lower overall oil use.

VIII. Conclusions

China's rapid increase in oil consumption, oil imports, and automobile sales has been phenomenal. As of 2010, China was the second-largest consumer of oil in the world and imported over 53 percent of its requirement.[43] Moreover, there is little to suggest China's oil demands and import requirements will abate. Since 2009, China has been the largest vehicle market in the world. In 2010, more vehicles were sold in China (18.1 million) in one year than were present in the total stock of vehicles on China's roads nearly a decade earlier in 2001 (18.0 million).[44]

As shown in Medlock and Soligo (2001), as countries grow, an increasing percentage of oil consumption derives from the transportation sector. The manner in which oil demand and imports change over time as a result of increasing penetration of automobiles has geostrategic implications for the rest of the world. In particular, the Chinese will be forced to increasingly focus on energy security, which will have implications for a wide range of policies in the United States and other countries.

Using an analysis of a panel of 47 countries spanning 1975 through 2009, we project vehicle stocks in China will increase—in the reference case—to 210 million (or 149 per thousand people) by 2020, 464 million (or 312 per thousand people) by 2030, and 771 million (or 494 per thousand people) by 2040. On the basis of vehicles per thousand people, this is still substantially lower than what is currently the case in the United States and most developed economies. Given the absolute size of China's population, the data translate into potentially large increases in transportation fuel demand.

When combined with median estimates for vehicle miles traveled and fuel efficiency, the reference case estimate of oil use for transportation is 4.8 million b/d in 2020, 7.9 million b/d in 2030, and 13.4 million b/d in 2040. Even the reference case projections represent large increases from present levels, and the ranges presented above indicate there could be even larger increases on the horizon.

We do not estimate oil use from non-transportation sources, but the IEA projects non-transportation oil use in China will remain relatively steady at around 5.7 million b/d.[45] Thus, when added to the projections above, it is very possible that by 2040, Chinese oil use could match current U.S. oil use. While China has consistently defied expectations with its extremely rapid and steady growth for over three decades, it is obvious that continued strong economic growth will present challenges for both Chinese policymakers and policymakers internationally, in particular with regard to meeting projected transportation energy demands.

Appendix A: The Model of Vehicle Stocks

Using the specification derived in Medlock and Soligo (2002), we posit the demand for the stock of motor vehicles to be a function of consumer wealth and user cost. Using per capita income, y, as a proxy for wealth (this is also, for our purposes, an indicator of the level of economic development) and p as a measure of the user cost of motor vehicles, we can write a log-quadratic expression describing the demand for motor vehicle stocks in country i as

$$veh^*_{i,t} = a_i + b_1 y_{i,t} + b_2 y^2_{i,t} + b_3 p_{i,t}$$

where the star denotes optimality and all variables are expressed in natural logarithms. The income and vehicle stock variables are expressed in per capita terms and all monetary variables are expressed in real 2005$. The term a_i is an intercept term. As discussed in the text, the log-quadratic formulation has the advantage of allowing for a declining elasticity *and* allowing an estimate of the saturation level for motor vehicle stocks in each country.

We use the price of motor fuel as a proxy for user cost. As argued in Medlock and Soligo (2002), we recognize that this ignores the fixed cost component of the user cost of owning a motor vehicle, and that any changes that actually occurred in the fixed costs of ownership over the period spanning 1975-2009 may introduce some noise in the estimation. However, this simplification is not only reasonable, it is necessary because, to our knowledge, data to proxy fixed costs are not available for all of the countries in our sample.

For a variety of reasons (such as habit persistence, uncertainty about the continuation of current economic trends, or constraints on the rate at which vehicles can be produced or imported), individuals may not adjust fully to changes in the factors affecting their desired demand for vehicles when they occur. In order to account for such a possibility, we incorporate a standard stock adjustment mechanism given by

$$veh_{i,t} - veh_{i,t-1} = \gamma\left(veh^*_{i,t} - veh_{i,t-1}\right)$$

where $\gamma \in [0,1]$ is the speed of adjustment.[46]

If $\gamma = 1$ then the adjustment process is instantaneous, and the actual investment in new vehicles will be equal to the desired level, that is $veh_{i,t} = veh^*_{i,t}$.

We can use this adjustment mechanism to eliminate $veh^*_{i,t}$ from the long-run equation above describing the demand for vehicle stocks, which yields our equation to be estimated

$$veh_{i,t} = \alpha_i + \delta_j + \beta_1 y_{i,t} + \beta_2 y^2_{i,t} + \beta_3 p_{i,t} + \beta_4 veh_{i,t-1}$$

where α_i is a country-specific fixed effect. We also have that $\beta_k = b_k/(1-\beta_4)$ for $k = 1,2,3$, which are used to find the short-run elasticities, and $\beta_4 = 1-\gamma$. The terms b_k are, in turn, used to find the long-run elasticities of the demand for vehicle stocks with respect to income and price. The term δ_j is an additional dummy variable for country *j*, where $j \equiv [Arg_{1994-2006}, Aut_{2002-2009}, Chl_{1989-1993}, Ger_{2007-2009}, Lux_{1975-1978}]$, which takes a value of 1 in the indicated years and is 0 otherwise. It is included to control for specific anomalies in the data, such as the unexplained downward shift in the reported data for Argentina for the years 1994 through 2006 (see Figure A1).

As indicated in the text, the income elasticity is given as

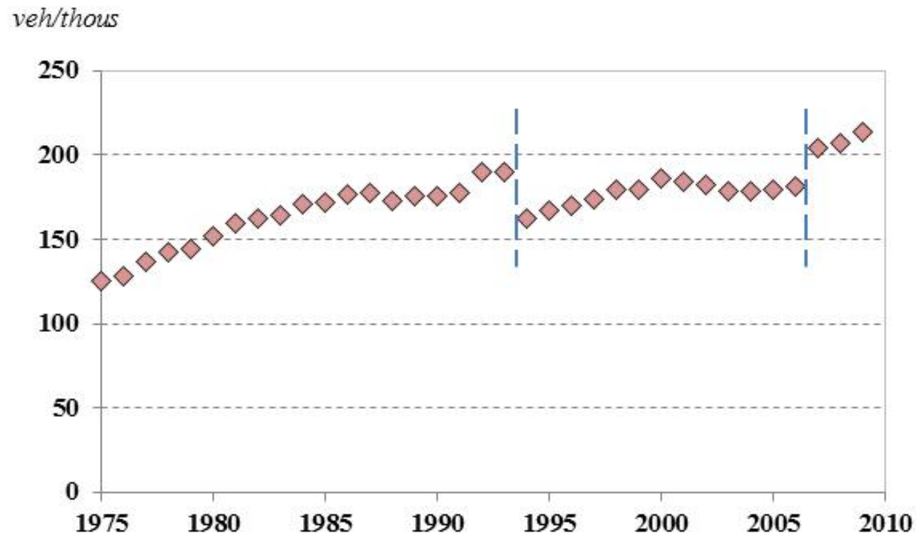
$$\varepsilon_{veh,y} = \frac{\partial \ln veh_{i,t}}{\partial \ln y_{i,t}} = \beta_1 + 2\beta_2 \ln y_{i,t}$$

which implies a saturation level of income that can be expressed as

$$y^{sat} = e^{-\frac{\beta_1}{2\beta_2}}.$$

For every point beyond the saturation level of income, it is assumed that stocks will no longer be influenced by income, meaning the income elasticity is zero. However, since saturation occurs at a relatively high level of income ($119,000), this is of no practical relevance.

Figure A1. Argentina Vehicle Stock Data, 1975-2009



The equation to be estimated is done so using the instrumental-variable (IV) estimation method suggested by Balestra and Nerlove (1966). The use of instrumental variables, which in this case are present and lagged values of the exogenous variables and population, is necessary due to the correlation that exists between the lagged endogenous variable and the error term. The technique is devised for estimating dynamic panel data models with individual country effects. This method is chosen because we are interested in sample characteristics, which reflect a common global development pattern, in order to make forecasts for each country. By imposing common slope parameters across countries, we are essentially mapping future paths of developing nations into the existing paths of industrialized nations.[47] The country effects are treated as fixed, not random, and account for the fact that countries have different levels of per capita passenger vehicle stocks at given levels of income.[48] The heterogeneity is attributed to things such as differences in fixed costs of vehicle ownership, as well as cultural and philosophical ideologies that dictate domestic transport policies. Testing also reveals that time effects are insignificant.

Estimation yields the following

$$veh_{i,t} = \alpha_i + \delta_j + \underset{(0.0368)}{0.3142}\, y_{i,t} - \underset{(0.0019)}{0.0134}\, y_{i,t}^2 - \underset{(0.0002)}{0.0011}\, p_{i,t} + \underset{(0.0051)}{0.9290}\, veh_{i,t-1}$$

The estimated coefficients and their standard errors (in parentheses) are of the expected sign and statistically significant, and the model fits the data rather well with an R^2 value of 0.998.

The estimated coefficient on the lagged endogenous variable suggests that adjustment to the optimal stock occurs at about 7 percent per year ($\beta_4 = 0.9290$, so that $\gamma = 0.071$), which is a rather sluggish movement and implies that price and income effects take significant time to be fully realized.

Figure A2 is generated using the estimated equation assuming the average of the country fixed effects. Figure A3 is constructed assuming the generic economic growth rate applied to develop Figure A2 occurs annually beginning from a generic year 1 through year 270. Notice this gives the S-shaped pattern that is typically observed in time series data.

Figure A2. Generic Country, Vehicles Per Thousand vs. GDP per Capita

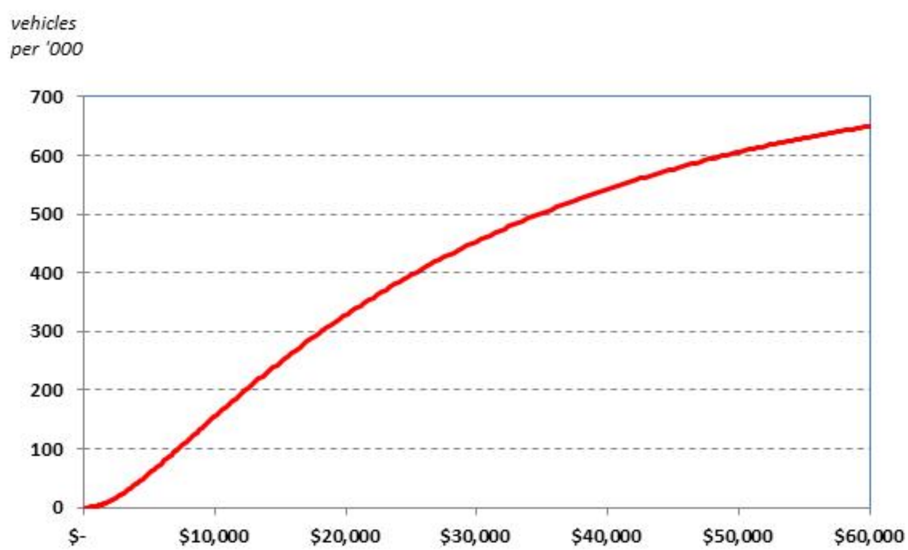
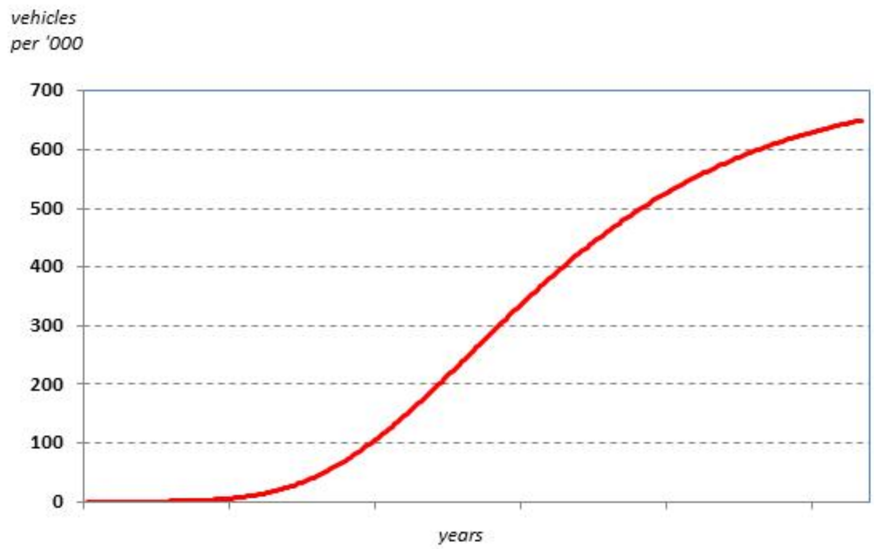


Figure A3. Generic Country, Vehicles Per Thousand People vs. Time



For the purpose of forecasting Chinese vehicle stocks, the terms δ_j are all equal to zero and only the Chinese fixed effect is considered. Then, it is a relatively simple matter to use forecasts of GDP per capita and price, as discussed in the text above, to recursively generate a forecast of vehicle stocks per thousand people.

Appendix B: The Model of VMT

Vehicle miles traveled (VMT) are assumed to be a function of per capita income. We use a small panel of data composed of three countries—the United States, France, and Japan—spanning the years 1965 through 2009. The estimated relationship is log-quadratic for incomes up to $16,840 and log-linear for incomes greater than $16,840. More specifically, we estimate

$$VMT_{i,t} = \sigma_i - \underset{(0.590)}{1.293}\, y_{i,t} + \underset{(0.029)}{0.066}\, y_{i,t}^2 + \underset{(0.136)}{0.441}\, ygr_{i,t-1} - \underset{(0.005)}{0.011}\, p_{i,t} + \underset{(0.021)}{0.874}\, VMT_{i,t-1}$$

where y denotes per capita income, ygr denotes per capita income growth, p denotes fuel price, and all variables are in natural logarithms. The standard errors on the estimated coefficients are in parentheses.

Higher growth rates tend to raise VMT, suggesting that robust economic activity may signal consumers to drive more. Increases in fuel prices tend to lower VMT, which follows from the notion that increased cost of driving will negatively influence driving itself, such that VMT is a normal good.

Finally, the estimated coefficients suggest that VMT will decline at low levels of income, reach a minimum, and then increase at higher-income levels. In fact, the estimated coefficients imply a specific income level at the point of inflection implied by the quadratic function, which is found to be $16,840. We use this point as a knot in a piecewise formulation at which the VMT transitions to a log-linear specification. For the linear estimation, however, we do not impose common slope coefficients. Rather, we allow them to be different for each of the three countries—the United States, France, and Japan. The result is

$$VMT_{US,t} = \underset{(0.422)}{1.399} + \underset{(0.034)}{0.133}\, y_{US,t} - \underset{(0.007)}{0.029}\, p_{US,t} + \underset{(0.076)}{0.711}\, VMT_{US,t-1}$$

$$VMT_{FRA,t} = \underset{(0.703)}{1.959} + \underset{(0.037)}{0.058}\, y_{FRA,t} - \underset{(0.008)}{0.023}\, p_{FRA,t} + \underset{(0.109)}{0.728}\, VMT_{FRA,t-1}$$

$$VMT_{JPN,t} = \underset{(0.789)}{2.145} + \underset{(0.032)}{0.051}\, y_{JPN,t} - \underset{(0.005)}{0.004}\, p_{JPN,t} + \underset{(0.068)}{0.699}\, VMT_{JPN,t-1}$$

with R^2 of 0.96, 0.85, and 0.78, respectively.

We focus on these three countries in order to construct three "type" pathways to describe VMT over the course of economic development. We do this because we do not know exactly what course China will take, and each of these countries has had a different experience with regard to public transportation options and policies that affect VMT.

In order to project VMT in China, we have three "type" pathways it can follow. For example, if we wish to simulate VMT in China assuming it follows the U.S.-type pathway, we have

$$VMT_{China,t} = \sigma_{US} + \mu_1 y_{China,t} + \mu_2 y^2_{China,t} + \mu_3 ygr_{China,t-1} + \mu_4 p_{China,t} + \mu_5 VMT_{China,t-1}$$

$$\text{if } y_{China,t} \leq \ln(16{,}840)$$

$$VMT_{China,t} = \rho_{US,0} + \rho_{US,1} y_{China,t} + \rho_{US,3} p_{China,t} + \rho_{US,3} VMT_{China,t-1}$$

$$\text{if } y_{China,t} > \ln(16{,}840).$$

The results of the exercise, when replicated for the France-type pathway and the Japan-type pathway for VMT, are graphically depicted in Figure 5.

We still need to estimate VMT in China in 2010 as an initial data point, in particular because the VMT specification given above is dynamic. To do this, we rely on

$$VMT_{2010} = \frac{eff_{2010}}{\#veh_{2010}} \cdot fuel\ use_{2010}$$

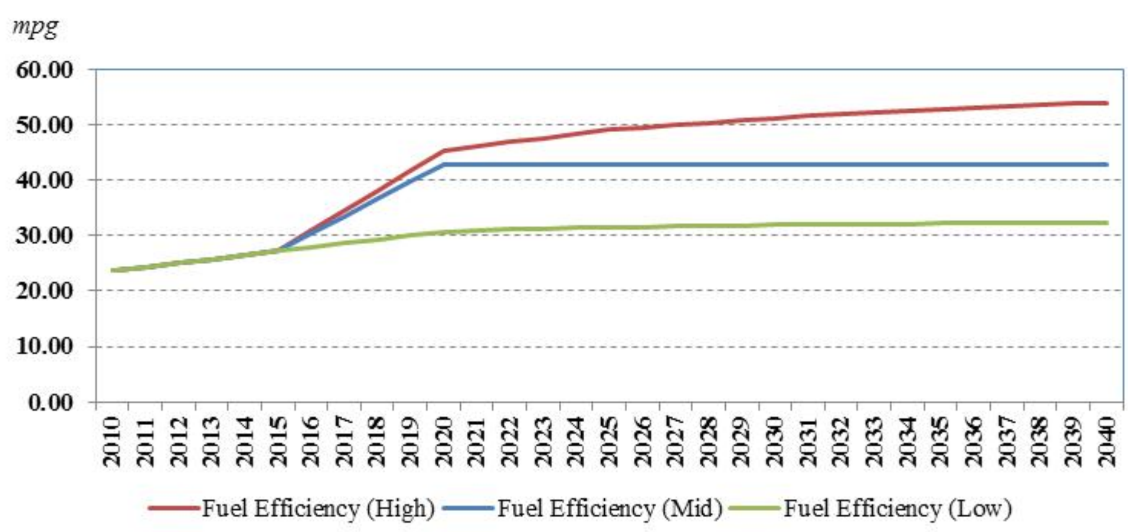
where fuel use is known, efficiency is estimated, as described in the next section, and the number of motor vehicles is known. This technique yields an estimate for VMT in 2010 of 13,317 miles per vehicle, which is then used to seed the forecast for VMT in each of the three type pathways for VMT.

Appendix C: On-Road Fuel Efficiency

On-road fuel efficiency is projected for all motor vehicles by accounting for (i) the fuel efficiency standards of light-duty vehicles, (ii) the fuel efficiency of medium- and heavy- duty vehicles, (iii) the composition of the vehicle stock (i.e., the fraction is light-duty vehicles) and (iv) the penetration rate of new vehicles.

Regarding points (i) and (iv), we use the government-announced fuel efficiency targets and the year in which those targets are specified to establish the fuel economy of new light-duty vehicles. Beyond 2020, there are no official policy targets for fuel efficiency, so, in the reference efficiency case, we hold the efficiency of new vehicles fixed beyond 2020. For the high-efficiency case, we allow new vehicle efficiency targets to continue to increase beyond 2020, ultimately rising to just shy of 55 miles per gallon by 2040. In the low-efficiency case, we assume only those targets announced for 2015 will be met, although there is very modest growth in fuel efficiency beyond 2015. The new vehicle fuel efficiencies, so modeled, are given in Figure C1.

Figure C1. New Vehicle Fuel Efficiency, 2010-2040



These targets are not met by all motor vehicles instantaneously. Rather, the new vehicle fuel-economy standards matriculate into the vehicle stock slowly, where the rate of penetration is dependent upon vehicle stock growth, retirements, and new vehicle sales. We model vehicle stock penetration such that the change in projected vehicle stocks, plus a 10 percent rate of retirements of existing vehicle stocks, result in a penetration rate that declines as the vehicle stock grows. Note that the 10 percent rate of vehicle retirement was established given knowledge of new vehicle sales in 2010 and the total vehicle stocks in 2009 and 2010, such that the retirement rate is given as

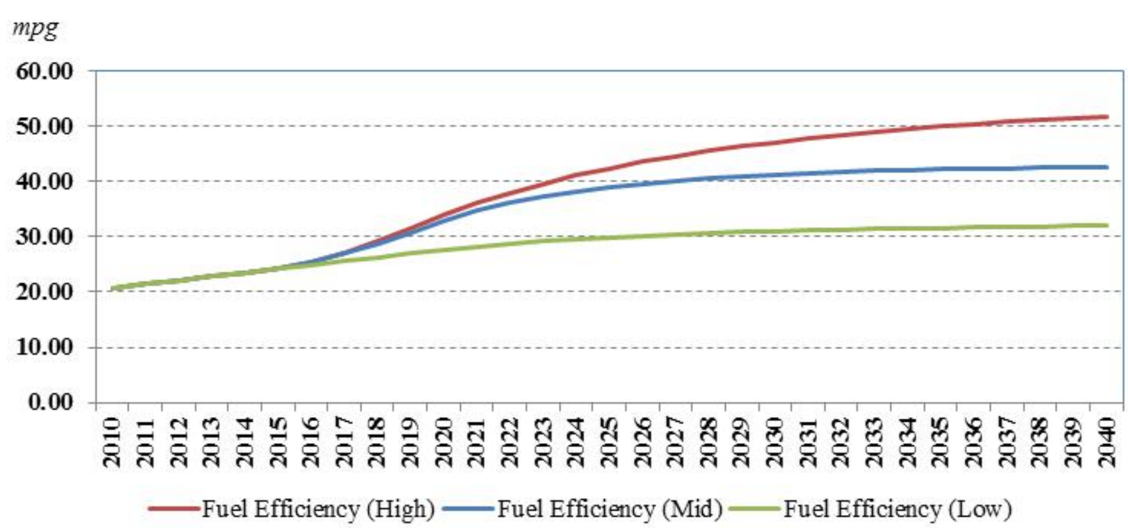
$$retire = \frac{sales_t + veh_t - veh_{t-1}}{veh_{t-1}}$$

so that the rate of diffusion of new vehicles is estimated as

$$diffusion_t = \frac{\left(veh_t - veh_{t-1} + retire \cdot veh_{t-1}\right)}{veh_t}$$

Taking this into account, we see that the on-road fuel efficiency of light-duty vehicles tends to lag the fuel economy targets.

Figure C2. Light-duty Vehicle On-Road Fuel Efficiency, 2010-2040



The final step to estimating future fuel efficiency for *all* motor vehicles involves a projection of medium and heavy vehicles fuel efficiency and the share of light-duty vehicles currently and projected. First, we assume the weighted average fuel efficiency of medium- and heavy-duty vehicles is 12.0 mpg in 2010, slowly rising to 14.6 mpg by 2040. Moreover, the share of medium- and heavy-duty vehicles in total was 23 percent in 2010. When combined with the average fuel economy of light-duty vehicles, this yields an overall on-road fuel efficiency of 18.5 mpg.

Using the experience of the United States as a benchmark for how the composition of vehicle stocks might change as vehicles stocks increase, we are able to project the share of light-duty vehicles in total. Specifically, U.S. data are used to estimate the following

$$\ln\left(-\ln\theta_t^{LV}\right) = \underset{(0.076)}{5.915} - \underset{(0.036)}{0.283}\ln veh_t$$

with an R^2 of 0.897. A double log formulation is used because it bounds the share of light-duty vehicles between zero and one, which is a fundamental requirement for generating projections.

The estimated relationship between light-duty vehicles and total vehicle stocks indicates that as vehicle stocks increase, the share of light-duty vehicles in total will also increase. The share of light -duty vehicles is projected to rise from 77 percent in 2010 to 87 percent in 2040. As a point of reference, the U.S. share of light-duty vehicles is over 93 percent.

Combining the projected composition of motor vehicle stocks with the projected on-road fuel efficiency for both light-duty vehicles and medium/heavy-duty vehicles, we can construct the weighted-average on-road fuel efficiency for all motor vehicles in China, which is depicted in Figure 6 in the main paper.

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Notes

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16. Hypothesis testing reveals the panel data set to be best characterized by a fixed effect model with common slope coefficients. See the appendix for more detail.

17. For example, see Joyce Dargay, Dermot Gately, and Martin Sommer, "Vehicle Ownership and Income Growth, Worldwide: 1960-2030," *The Energy Journal* 28, no. 4 (2007): 143-70.

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19. In addition to the issue of saturation levels, Wang, Teter, and Sperling (2011) in their article titled "China's Soaring" point out a number of other issues that make it difficult to compare saturation levels.

20. Wang, Teter, and Sperling, "China's Soaring."

21. Lescaroux and Rech argue that the adjustment may be much slower for developing countries since there are "cultural shifts" and "sociological evolutions" that must occur before vehicle stocks fully adjust to a new level of per capita income. In some sense, one could say that there are really two lags involved: The usual lag of actual to desired stock levels, but also a lag in the formation of a desired level in response to changes in per capita income. In some cases, people (e.g., older, more tradition-bound) may never adjust to the idea of owning a car. In this case, at any given level of per capita income, the desired stock will increase over time as older people are replaced with younger ones. See Francois Lescaroux and Olivier Rech. "The Impact of Automobile Diffusion on the Income Elasticity of Motor Fuel Demand," *Energy Journal* 29, no. 1 (2008): 41-60.

22. The seven-country average in Wang, Teter, and Sperling (2011) is based on the United States, Germany, Italy, Spain, and Brazil in addition to Japan and South Korea.

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25. Millard-Ball and Schipper, “Peak Travel.”

26. The countries in the paper were Japan, Germany, Sweden, the United Kingdom, France, Australia, Canada, and the United States.

27. They assumed China’s VMT for cars will ultimately be similar to Western Europe’s at 7,500 miles/year/vehicle by 2050. In the meantime, VMT for passenger vehicles in China is projected to fall from roughly 15,000 miles/year/vehicle in 2000 to 8,100 miles/year/vehicle in 2030. A major reason that per vehicle VMT was so high was the high proportion of taxis, which averaged 56,000-71,500 miles/year and represented 16.4 percent of the 2002 passenger vehicle fleet and 10.1 percent of the 2004 fleet, respectively. However, their data do not show that 7,500 miles/vehicle is average. The data they show for three countries in the late 1990s, Germany, France, and the UK, range from 7,500-10,500 miles/vehicle/year. However, the IEA notes that OECD Europe averaged 7,500 miles/vehicle/year in 2005 in the following publication: International Energy Agency, *Transport, Energy and CO2: Moving Toward Sustainability* (Paris: International Energy Agency, 2010).

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29. Ibid., 13.

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46. There are other adjustment mechanisms that could also be used; however, the above mechanism (introduced by Koyck (1954)) preserves simplicity while rendering both long- and short-run elasticities.

47. A Hausman-type test indicates that intercepts are not homogeneous. Moreover, following the test based on the work of Wooldridge (1990), we ascertain that imposing homogeneity among the slope parameters across is not overly restrictive, meaning pooling the data is acceptable.

48. A Hausman-type specification test indicates that the fixed effect approach is the suitable one.