SCENARIO ANALYSIS OF CHINESE PASSENGER VEHICLE GROWTH

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This article reports on a simulation and scenario analysis of Chinese passenger vehicle growth and resulting energy demand and CO_2 emissions. The model includes provincial level logistic growth functions with saturation levels representative of neighboring Asian economies, income growth measured in international dollars, and both estimated and literature-based income elasticities. Scenarios explore variation in key parameters, including income and population growth rates, elasticity income ranges, fuel economy, and vehicle saturation. Countrywide base case results estimate growth from 4.22 to 54.33 passenger vehicles per thousand people from 1995 to 2025. Resulting passenger vehicle oil demands and CO_2 emissions increase nearly 17-fold. (*JEL* R40, Q40, N70)

I. INTRODUCTION

As personal incomes rise, China is rapidly becoming more dependent on personal vehicle, highway-based, passenger transportation. Among current developing countries, China represents the largest potential modal shift for passenger transport from rail to highway. Figure 1 highlights an increase in personal transport by highway between 1990 and 1997 from 262 to 554 billion passenger-kilometers, based on data from the China Statistical Yearbook (CSY; 1998). Total distance traveled increased 93% (64% of which was by highway) between 1990 and 1997. Sinton (1996) reports per capita passenger-kilometers traveled by highway in 1992 were 272 in China, compared with 6985 in Japan, 10,645 in the United States, and 2230 in the former Soviet Union. Recent accession to the World Trade Organization is expected to magnify this trend. This modal shift of China's transport sector is similar to that experienced in Taiwan, Republic of Korea, and Japan, the key distinction being the path the latter countries took and the path China has yet to find. Resulting traffic congestion, regional air pollution, and dependence on foreign oil plague each of China's Asian neighbors.

Ownership of the vehicle fleet has also changed rapidly. Averaging 17.7% growth per year during the 10-year period from 1984 to 1993, much of this new vehicle ownership is private, compared to past growth primarily through state ownership (Sinton, 1996). In many of China's urban areas, the car has become a status symbol. Between 1990 and 1997, private ownership increased from

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ABBREVIATIONS

AAMA: American Automobile Manufacturers Association
CSY: *China Statistical Yearbook*
GDP: Gross Domestic Product
ICP: International Comparison Project
IPCC: Intergovernmental Panel on Climate Change
OECD: Organisation for Economic Co-operation and Development
PPP: Purchasing Power Parity

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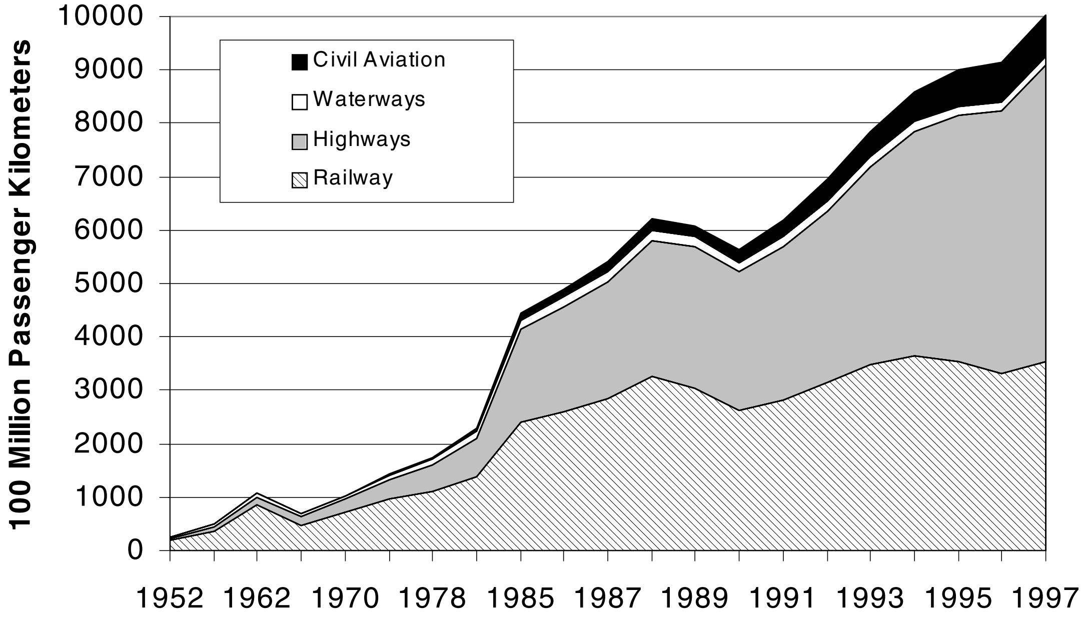
FIGURE 1
Increasing Passenger Travel by Highway



Source: China Statistical Yearbook, 1998.

14.8% to 32.9% of total ownership (CSY, 1991, 1998).

As with many Asian countries, more private vehicles on a capacity-filled road network presents a balancing act for space between bicycles, passenger vehicles, and public transportation (Greene and Santini, 1993). Passenger vehicles, defined here as small passenger cars and buses, already provide the majority of highway passenger kilometers in China compared to motorcycles and other motor vehicles.[1] Although the number of Chinese passenger vehicle sales is small relative to the world automobile market, the potential exists for rapid expansion driven by steady per capita income growth. As evidence, several large automobile manufacturers have located in China, including Peugeot, Volkswagen, Chrysler, and General Motors. General Motors alone recently invested $2 billion to open a factory in China (*Fortune*, 1999).

Growing passenger vehicle ownership raises three primary concerns for both China and the international community. First, increased car and bus stocks will exacerbate local air pollution problems. Chinese cities are already among the world's most polluted cities. The World Resources Institute (1998) reports that ambient concentrations of sulfur dioxide exceed the World Health Organization's recommended guidelines for more than half of the 88 Chinese cities monitored, and 85 of the cities exceed the guidelines for total suspended particulates. Second, as a net importer of oil since 1993, automobile growth will continue to increase China's oil import demand. A study by Sandia National Laboratories (see Conrad et al., 1998; Drennen and Erickson, 1998) forecasts that China's total oil import requirements could rival current U.S. imports, reaching as high as 7.1–8.1 million barrels per day (mbbls/day) by 2015. Lacking proven domestic reserves, the China National Petroleum Corporation has begun to secure oil concessions in Sudan,

1. Small passenger vehicles have an average of eight seats and are designated cars for this study. The majority of passenger vehicles owned by the state or individuals are minibuses. Passenger cars, as defined in Western countries, remain a small percentage of small passenger vehicles (see Sinton, 1996).

Venezuela, Iraq, and Kazakhstan and develop oil and gas pipelines from Russia and Central Asia to China (Rashid and Saywell, 1998). The potential magnitude of Chinese oil import requirements has serious implications for global geopolitics. Finally, increases in the vehicle fleet will contribute to ballooning carbon emissions. The per capita emissions for China are low relative to developed nations, but China emits about 14% of total world carbon dioxide, ranking China as the world's second largest emitter after the United States (Drennen, 2000). Even if developed nations in Europe and North America agree to greenhouse gas reduction strategies developed in the Kyoto Protocol, global emissions cannot stabilize or decline without the support from developing nations, such as China and India.

Stemming from these three related issues, the purpose of this article is to estimate passenger vehicle growth in China, along with corresponding oil requirements and carbon dioxide emissions.

II. CHINESE INCOME GROWTH AND PASSENGER VEHICLE DEMAND

Passenger vehicle stocks vary widely around the world and are indicative of several factors, including income levels, government policy toward car ownership, population density, fuel prices, and the availability of substitutes, such as bicycles and mass transit. The American Automobile Manufacturers Association (AAMA, 1995) last reported approximately 568 passenger vehicles per thousand people in the United States in 1993, compared to China's stock of roughly 4 passenger vehicles per thousand people in 1997 (a number that varies widely by province). Although it is unlikely that China could ever support the number of vehicles per capita in currently developed nations, it is possible that China will follow the path of other Asian countries. The AAMA (1994) reported that Japan, Taiwan, and the Republic of Korea had 314, 114, and 79 cars per thousand people, respectively, in 1992.

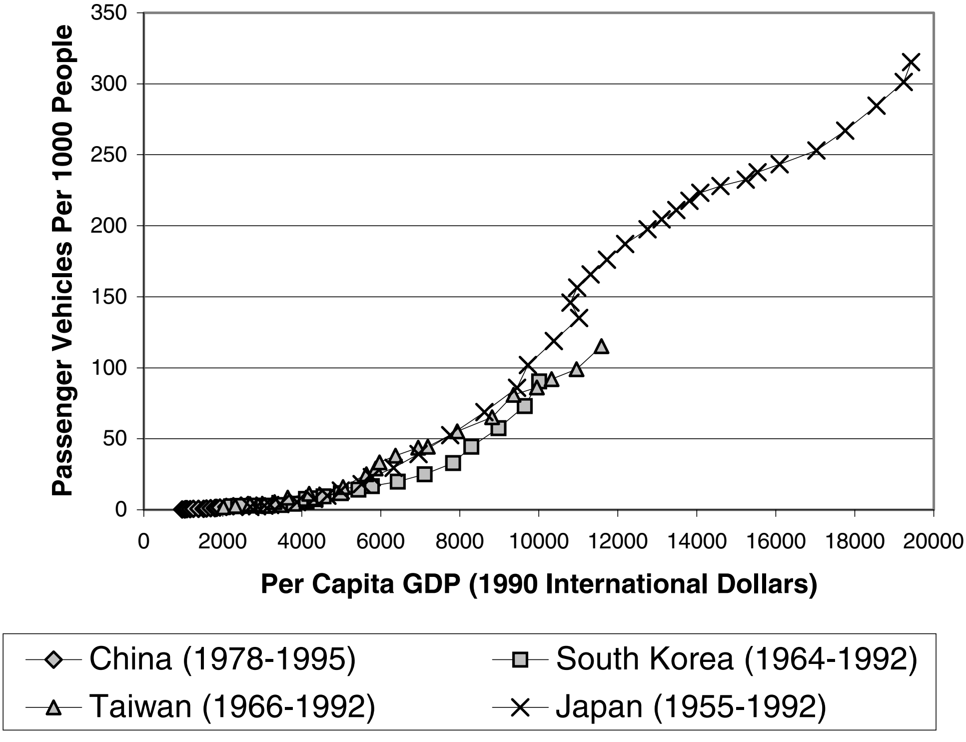
Each of these Asian countries is at a different level of development. Figure 2 plots their passenger vehicle ownership levels against average income purchasing power (measured in international dollars) using Organisation for Economic Co-operation and Development (OECD) estimates from Maddison (1995, 1998). China is still well below income levels required for vehicle ownership levels representative of Japan or Taiwan. The World Resources Institute (1998) reported the average Chinese per capita income of US$572 in 1995. The per capita income needed to purchase even lower-end car models in China has been estimated at US$4000 (*Asiaweek*, 1993). However, due to recent accession to the World Trade Organization, China is expected to reduce tariffs on imported autos and allow foreign car companies to offer car loans, making it far easier for the average Chinese citizen to consider car ownership. Furthermore, the dominantly state-owned automobile industry will likely open to greater foreign ownership (Liu and Woo, 2001), opening the door to productivity gains and price competitive domestic models.

This relationship between income and vehicle ownership has been the most reliable in previous passenger vehicle ownership studies. Past studies differ in how to measure income, with measures including disposable personal income (Dargay and Gately, 1999), household income (Button et al., 1980), and per capita income in constant prices (Tanner, 1978). Regardless of the measurement, a constant current year is used to account for domestic inflation, and a common currency unit (most often the U.S. dollar) is used when multiple countries are compared. However, a shortcoming of previous multiple country vehicle ownership models and a point of difference in the current study has been a neglect of any adjustment for purchasing power. For instance, often cited international transportation studies by Dargay and Gately (1997, 1999) and Button et al. (1993) adjust to a common currency but do not account for the purchasing power of that currency in the study countries.

This article builds from these past studies, utilizing international dollar units (also known as Geary-Khamis dollars) to calculate income elasticities and to capture vehicle ownership trends in Japan, Republic of Korea, Taiwan, and China. Conversion to international dollars is based on a multilateral comparison to account for both purchasing power parity (PPP) of currencies and international average prices of commodities, as compared to the bilateral approach

FIGURE 2

Passenger Vehicle Ownership and Income Growth over Time for China, Republic of Korea, Taiwan, and Japan



Source: Maddison, 1995, 1998.

(i.e., benchmarked to one country) of the World Bank's PPP estimates. The more current international dollar conversions form the basis of the International Comparison Project (ICP) of the United Nations, a process in which China has not yet fully participated, making conversion from yuan problematic (Keidel, 2001). The present conversion of Chinese yuan to international dollars (described in more detail later) builds on the ICP framework and from the most recent work of renowned economic growth historian Angus Maddison (1995, 1998) of the OECD.[2]

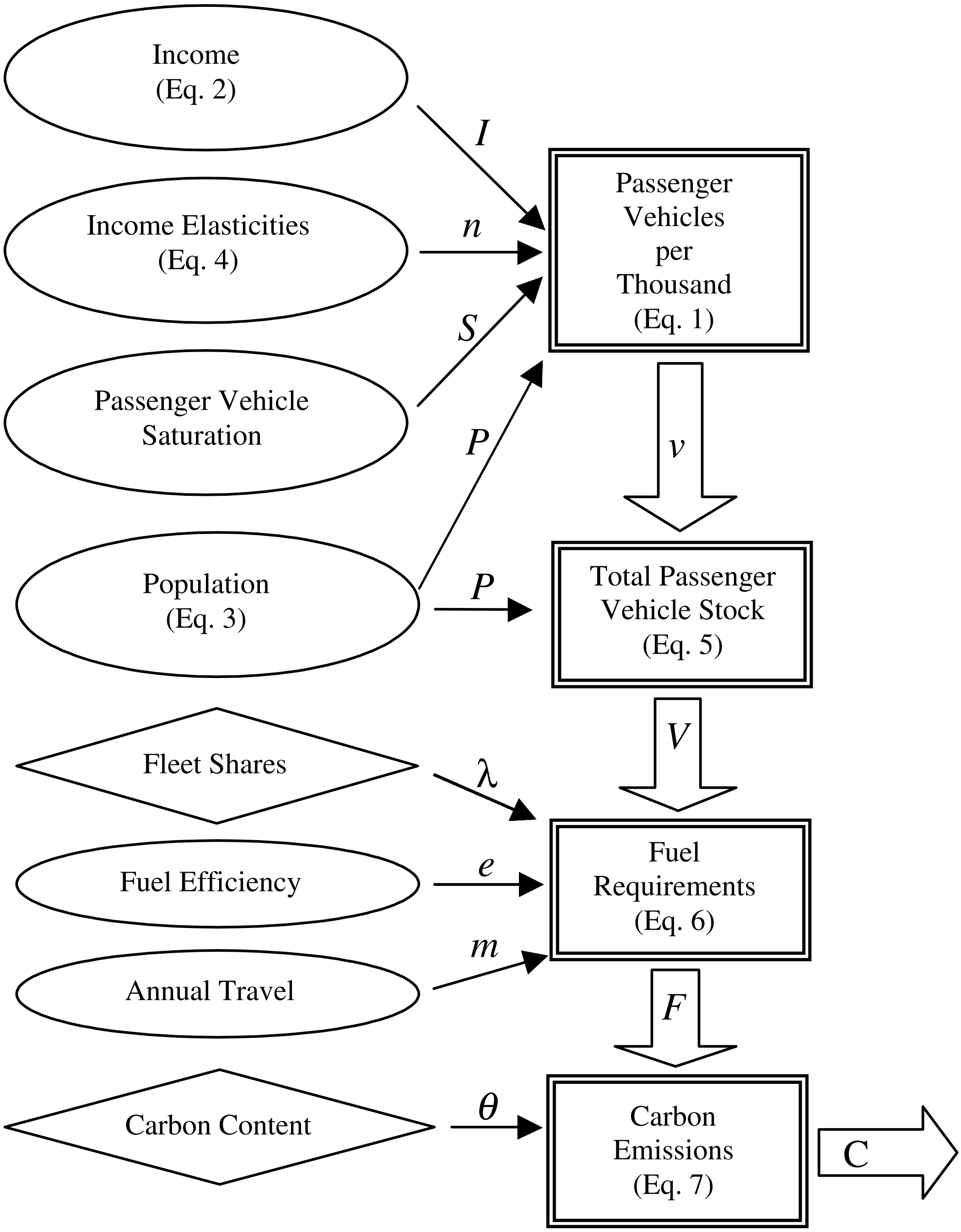
2. Maddison's (1998) recent effort specific to China builds on the work of Ren Ruoen, also of the OECD. Ruoen (1997) produced a binary currency conversion to compare Chinese and U.S. gross domestic product. By adapting Ruoen's binary estimates to a multilateral, ICP-type conversion, Maddison reestimated Chinese per capita GDP, providing an explicit yuan to international dollar conversion.

III. MODEL STRUCTURE AND ESTIMATION

Figure 3 outlines the structure of passenger vehicle growth simulation for Chinese provinces from 1995 to 2025.[3] Equation numbers refer to equations (1) through (7) detailed later. The model estimates values outlined in square boxes, including provincial passenger vehicles per thousand (v), total passenger vehicle stock (V), fuel requirements (F), and carbon emissions (C). The variables in ovals—including provincial income (I), income elasticities (n), passenger vehicle saturation (S), provincial population (P), fuel efficiency (e), and annual travel (m)—can each be varied in scenario analysis. Fleet shares of mini-buses and cars (λ) and carbon content (θ) are fixed (specified by diamonds) in all model runs. Data

3. Thirty provinces included; all except Chongqing due to insufficient data.

FIGURE 3
Schematic of Provincial Passenger Vehicle Growth Simulation Model



were compiled at the provincial level primarily from CSY (years 1990 through 1998) and the *China Energy Databook* (Sinton, 1996).

A. Passenger Vehicle Growth and Saturation

Several authors have effectively demonstrated the usefulness of the logistic function for simulating passenger vehicle growth and market saturation (e.g., Zhongyuan et al., 2002; Dargay and Gately, 1999; Button et al., 1993; Tanner, 1962). Accordingly, cars per thousand (v) at the provincial level ($i = 1, 2 \ldots 30$) for yearly time steps ($t = 0, 1, 2 \ldots 30$) are modeled as:

$$(1) \quad v_{i,t+1} = v_{i,t} + n_k(I_{i,t}/P_{i,t}) \times [[(I_{i,t+1}/P_{i,t+1}) - (I_{i,t}/P_{i,t})] / (I_{i,t}/P_{i,t})]\, v_{i,t}[1 - (v_{i,t}/S_a)].$$

The simulation runs from 1995 to 2025, with base year provincial vehicle ownership ($v_{i,0}$) based on the CSY. The growth function includes income elasticity (n_k) as a function of yearly provincial per capita income ($I_{i,t}/P_{i,t}$) in 1990 international dollars, where k equals the number of income ranges assumed (described later). Because this study is the first to estimate growth in passenger vehicle ownership at the provincial level, many challenges were faced in constructing a provincial level database of income, population, and other key variables. Unless otherwise noted, official data from the CSY (both country-wide and provincial yearbooks) was used as a primary source, often supplemented and cross-checked with data from various sources, including Maddison (1998).

A passenger vehicle saturation level (S_a) determines the horizontal asymptote of the logistic functional form, with the index a specifying which of three estimates are assumed. Button et al. (1993) specifically examined low-income countries and found a saturation level for developing Asian countries of 350 cars per thousand people. Dargay and Gately (1999) assume a saturation level of 850 motor vehicles (including cars, buses, and other motorized vehicles) and 620 cars per thousand people for each of the 26 study countries, including China.

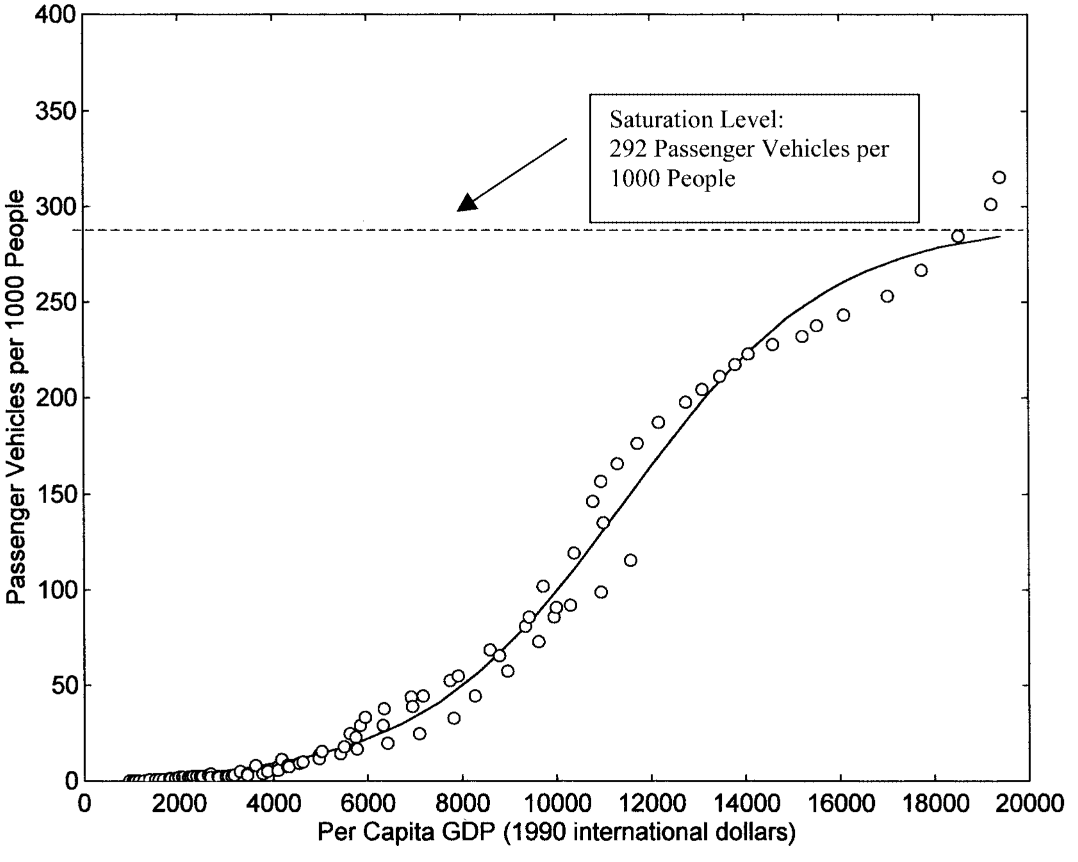
A common technique to develop a saturation level of ownership applies a linear regression on the percentage change of per capita (or per thousand people) vehicle ownership and the per capita (or per thousand people) vehicle ownership. The saturation level is then estimated at the x-axis intercept. This assumes that as the number of vehicles per capita increases toward a saturation point, the percentage increase in vehicle ownership decreases. This method has been used to model moderately to highly developed countries and their respective levels of vehicle ownership. In the context of developing nations, linear extrapolation may be misleading for countries on the portion of the S-shaped logistic curve between the origin and the inflection point. It is more intuitive to model low-income countries and their respective growth patterns on other countries of similar origins and access to resources. It is unlikely that China, India, or other highly populated countries with low per capita income will have the physical space and income for the necessary infrastructure expansion to support 850 vehicles per thousand people during this century.

To estimate the saturation level, this article fits a logistic growth curve to per capita income and vehicle ownership data for four Asian countries in different development stages. Using the Loglet Software from the Rockefeller Institute for the Environment (Yung et al., 1998), a saturation level of 292 passenger vehicles per thousand people was estimated with a 90% confidence interval of {281, 299}. Figure 4 represents the output of fitting the logistic growth curve to historic passenger vehicle data for Japan, Republic of Korea, Taiwan, and China. In scenario analysis, the default setting is the authors' estimate of 292, however, custom values and those for either the Button et al. or the Dargay and Gately study can be selected.

B. Real Income Growth

There is no shortage of forecasts for country-wide Chinese real income growth. The OECD estimates of Maddison (1998) assume China's gross domestic products (GDP) growth rate to slow to an annual average of 5.5%. Others include a 6.5% estimate from Ho et al. (1998), and a 7.5% assumption of Conrad et al. (1998). These pre-WTO estimates may be further magnified by China's

FIGURE 4
Estimated Saturation Level of Passenger Vehicle Ownership



Note: Data ranges are 1955–89 for Japan, 1970–92 for Republic of Korea, 1966–91 for Taiwan, and 1964–92 for China.

formal accession to the World Trade Organization in November 2001. Oxford Economic Forecasting (1999) predicts a World Trade Organization premium to GDP growth rates as high as 1.5–2.5% per year. Due to broad economic reform, Chow (2000) estimates the Chinese economy will continue to grow at 7% annually over the next two decades.

To capture this range of forecasts, real income growth (in 1990 international dollars) was modeled with four goals in mind. First, the average across all provinces should equal a country-wide average within the range of low to high projections of various international agencies. Second, this should be a weighted average based on the current income share of each province. Third, real income growth rate for each province should be based on the current distribution of growth, so that the current rank of provinces by real income growth is maintained throughout the simulation. Fourth, yearly growth rates should be distributed over the simulation period such that the 1995 base year has the highest rate, each subsequent year declines at a constant percentage, and the annual weighted average across all 30 provinces equals the specified country-wide average.

With these goals in mind, provincial income growth takes the form:

$$I_{i,t+1} = [1 + \alpha_{i,t}]I_{i,t}, \tag{2}$$

where provincial level annual growth rates ($\alpha_{i,t}$) were defined such that a country-wide average annual real income growth rate (A_g) would be maintained for the period 1996 to 2025 ($t = 1$ to 30) under one of three assumptions ($A_g = 5.5, 6.5$, or 7.5%).

To maintain a selected average, base-year provincial level real growth rates ($\alpha_{i,0}$) were calculated for each province based on 1990 to 1995 data. Yearly weights (w_t) were then calculated such that:

(2a) $$A_g = \left[\sum_{i=1}^{30}\sum_{t=1}^{30} w_t \alpha_{i,0}\right] \Big/ 30$$

and

(2b) $$w_t = [A_{t-1}(1-\Delta_g)]/A_0,$$

where A_t is the average annual provincial real income growth rate (i.e., a country-wide average), A_0 is the average of weighted provincial real income growth rates for 1990–95 (equal to 13.4%), and Δ_g is the fixed yearly percentage change in A_t (such that $A_g = \sum_{t=1}^{30} A_t/30$ for $A_g = 5.5, 6.5$, or 7.5%).

To develop the income data used in these income growth equations and income elasticity estimates (described later), provincial-level income data was converted to 1987 yuan using deflators from Maddison (1998). A conversion coefficient of 1.402 developed for this model by Kobos (2000) was then applied to convert 1987 yuan to 1990 international dollars. Although this conversion does not account for regional price disparities, it does reveal the general trends of regional real income growth and follows methodologies developed by Maddison (1995, 1998) and Ruoen (1997).

C. *Population Growth*

Population by province by year grows according to

(3) $$P_{i,t} = (1 + \Omega_z \beta_i) P_{i,t},$$

where initial provincial population levels ($P_{i,0}$) are based on official statistics in the CSY (1990 through 1998). To capture differences at the provincial level, 30 separate annual population growth rates (β_i) are set to their respective average of provincial annual growth rates over the base period 1990–97. However, these fixed averages do not account for preliminary evidence of a decreasing rate of population growth country-wide and in some provinces. The country-wide trend is most reflected in the 2000 CSY estimate of a 0.043 average percentage point decline per year in annual population growth rates during the base period.[4] However, according to CSY statistics, a country-wide rate of decrease was insignificant and provincial growth rates were in decline in only 13 of the 30 provinces while remaining statistically flat for the remaining 17. The provinces with declining rates of growth are predominately near Beijing, perhaps reflecting the influence of rural to urban migration. Beijing itself has the highest annual population growth rate over the base period at nearly 2%.

To investigate hypotheses of both an urban migration and a country-wide slowing of population growth, the i by t matrix Ω_z is used in scenario analysis. The base-case ($z = 1$) assumes population growth rates remain fixed at β_i. The urban migration case ($z = 2$) assumes the 13 provinces with significant downward trends in growth rates continue this linear trend through the simulation period, while the remaining 17 provincial growth rates remain fixed at base-case values. Finally, the scenario of country-wide slowing ($z = 3$) assumes all provincial growth rates linearly decline by 0.043 percentage points per year. This scenario eventually drives 17 provinces to negative annual population growth by 2020 and 20 provinces by 2025.

D. *Income Elasticity*

Various studies have estimated income elasticities associated with transportation, although not many focus specifically on car ownership. In a comparison of over 50 studies of income elasticities of various energy types in the developing world, Dahl (1994) notes that energy for transport is more income elastic than total energy demand, with a long-run average of 1.64. For auto registrations, the estimates of Dunkerly and Hoch (1987) range from 1.3 for industrialized countries and 1.5 for middle-income developing countries to 1.7 for low-income developing countries. Walls (1997) estimates a long run income elasticity for vehicle stock in Hong

4. This rate of decline is based on a reviewer's comments to an early draft, however, is much less and statistically insignificant in the nation-wide growth rates reported in the CSY.

Kong of 1.7. Stares and Zhi (1995) summarize income elasticities reported from various sources ranging from 1.09 to 1.95 for vehicle ownership in free-market and OECD countries. Specifically, they report income elasticities for cars or passenger cars ranging from 1.02 to 1.58 and lower elasticities for commercial and total motor vehicles. Dargay and Gately (1999) estimate short-run income elasticities for cars at 1.2 and a long-run income elasticity in China for 2015 of 2.34, numbers that seem to agree more with estimates for industrialized countries. For example, Johannson and Schipper (1997) estimate short-run income elasticities for vehicle stocks at 1.23 and long-run elasticities of 1.0 in OECD countries. Last, Button et al. (1993) estimate income elasticities for low-income countries in five categories ranging from 0.57 to 1.60.

The shortcoming of using a single value is that income elasticities are only likely to hold within a certain income range and are unlikely to be constant across all levels of income. For this article elasticity measures were estimated using point elasticities followed by an arc elasticity estimate to account for the endpoints of the income ranges. For the point elasticity estimates, data on passenger vehicle ownership in Japan, Republic of Korea, Taiwan, and China were regressed against international dollars per capita GDP levels. Table 1 reports regression results for both a two-income and four-income range model, with the natural log of passenger vehicles per 1000 people as the dependent variable and the natural log of per capita income in 1990 international dollars as the independent variable.

TABLE 1
Regression Results for Point Elasticity Estimates

Per Capita Income Range (1990 International Dollars)	Constant	Income Coefficient	Adjusted R^2
Two-income range model			
$I < 10{,}000$	−18.25 (−48.68)	2.46 (53.96)	0.96
$I \geq 10{,}000$	−10.11 (−7.25)	1.61 (10.99)	0.83
Four-income range model			
$I < 5{,}000$	−15.94 (−30.93)	2.15 (32.77)	0.96
$5{,}000 \leq I < 10{,}000$	−18.88 (−10.53)	2.53 (12.58)	0.86
$10{,}000 \leq I < 15{,}000$	−17.44 (−5.82)	2.40 (7.51)	0.78
$15{,}000 \leq I < 20{,}000$	−5.84 (−6.23)	1.17 (12.20)	0.95

Note: t-statistics shown in parentheses.

An arc elasticity method was then used to account for the endpoints of each income range. This method is based on the average income and vehicle ownership levels within the specified range.[5] The general intuition behind relying on arc elasticity estimates is the extreme sensitivity of point estimates over the critical low-income range of 1000 to 5000 international dollars per capita. At the beginning of the model's time frame in 1990, 29 of the 30 provinces in China lie within this range. By 2005 under the low growth assumption, 11 of the 30 provinces still remain within this range of per capita income. Income elasticity estimates will greatly affect the results of the model over this dominant range. Thus the more conservative approach is to use the arc elasticity method of calculation.

In scenario analysis, the model can use elasticity estimates for one income range based on Dargay and Gately (1999), or two or four income ranges based on the arc elasticity results. The one income range assumption ($k = 1$) assumes a gradual increase in elasticity from the base year value of 1.21 to a fixed level of 2.34 in 2015.

$$
\begin{aligned}
\text{(4a)}\quad n_1(I_{i,t}/P_{i,t}) &= 1.21 \qquad \text{for } t = 0,\\
&= n_t(I_{i,t}/P_{i,t})\\
&\quad + [n_{20}(I_{i,20}/P_{i,20})\\
&\quad - n_0(I_{i,0}/P_{i,0})]/20\\
&\quad \text{for } 0 < t < 20,\\
&= 2.34 \qquad \text{for } t \geq 20
\end{aligned}
$$

where provincial income ($I_{i,t}$) and population ($P_{i,t}$) grow according to equations (2) and (3), with trends specified in scenario analysis.

5. Using the arc elasticity method, the income elasticity (n) between any two income (I) and quantity (V) points is given by: $n = (\Delta V/[0.5(V_1 + V_2)])/(\Delta I/[0.5(I_1 + I_2)])$. For example, over the 1000–5000 international dollars per capita range: $n = 1.41 = (10.6025/[0.5(10.9448 + 0.3423)])/(4000/[0.5(5000 + 1000)])$. The quantities of passenger vehicles per thousand people were estimated using the regression equations.

A two-income range ($k = 2$) assumption, using arc elasticity estimates, assumes

$$\text{(4b)} \quad n_2(I_{i,t}/P_{i,t}) \begin{aligned} &= 1.21 \quad \text{for } I_{i,t}/P_{i,t} < 10{,}000, \\ &= 1.52 \quad \text{for } I_{i,t}/P_{i,t} \geq 10{,}000. \end{aligned}$$

A four-income range ($k = 4$) assumption, again using arc elasticity estimates, assumes

$$\text{(4c)} \quad n_4(I_{i,t}/P_{i,t}) \begin{aligned} &= 1.41 \quad \text{for } I_{i,t}/P_{i,t} < 5{,}000, \\ &= 2.12 \quad \text{for } 5{,}000 \leq I_{i,t}/P_{i,t} < 10{,}000, \\ &= 2.25 \quad \text{for } 10{,}000 \leq I_{i,t}/P_{i,t} < 15{,}000, \\ &= 1.17 \quad \text{for } I_{i,t}/P_{i,t} \geq 15{,}000. \end{aligned}$$

E. Total Passenger Vehicle Stock and Fuel Requirements

Total annual passenger vehicle stock (V_t) is calculated as

$$\text{(5)} \qquad V_t = \sum_{i=1}^{30} (v_{i,t} P_{i,t}/1000).$$

Total annual fuel requirements (F_t) in liters then follows as

$$\text{(6)} \qquad F_t = ([V_t m_c (1 - \lambda_{b,t})]/e_{c,t}) + (V_t m_b \lambda_{b,t}/e_b)$$

where $\lambda_{b,t}$ and $(1 - \lambda_{b,t})$ are annual percentages of mini-buses and cars, respectively, from the total passenger vehicle stock. Mini-buses comprised 20.5%, 18.5%, and 16.8% of all Chinese passenger vehicles in 1990, 1991, and 1992, respectively (Sinton, 1996). To reflect a near-term trend of a declining bus fleet share, the base case assumes $\lambda_{b,t}$ to fall one percentage point every two years from 16% in 1993–94 to 10% in 2005, and remains at 10% for the remainder of the simulation. Separating the stock allows for different fuel efficiency and average kilometers traveled assumptions. In the base case simulation, fuel efficiency for cars ($e_{c,t}$) grows from 8 km/L in 1995, based on a 1990 IPCC estimate (Michaelis et al., 1995), to 10.6 km/L by 2025, based on a constant increase of 0.9 km/L every 10 years beginning in 1995. Bus fuel efficiency (e_b) remains constant at 3.63 km/L, based on Sinton (1996). Annual vehicle kilometers driven by cars (m_c) are set at 15,000 km per year for cars according to Dargay and Gately (1999). Annual vehicle kilometers driven by buses (m_b) are based on an average between Chongqing and Hangzhou cities of 57,689 km per year according to Bushell (1994). Both efficiency and kilometers driven can be changed in scenario analysis.

F. Carbon Emissions

Carbon emissions (C) in million metric tons are calculated as

$$\text{(7)} \qquad C = (F_t * \theta)/(1.00 * 10^6),$$

where θ is a carbon factor of 0.647292 kg of carbon per liter of fuel based on a common IPCC assumption (Michaelis et al., 1995).

IV. MODEL RESULTS AND SCENARIO ANALYSIS

The dynamic simulation model allows policy analysts to explore a wide range of possible scenarios for Chinese passenger vehicle growth. Examples include variations in provincial income and population growth rates, income elasticities, vehicle saturation level, fuel efficiency of cars, and average annual distances driven per car or bus. The model was programmed with Powersim Constructor (see www.powersim.com), a dynamic simulation programming package. The following scenario analysis can help illuminate where policy may play a role in balancing vehicle ownership with local and international environmental and energy policy goals. Unless otherwise noted, model variables are set to their base-case levels outlined in Table 2.

A. Scenario Analysis: Income Growth

Table 3 summarizes the results for passenger vehicles per thousand people, oil requirements, and carbon emissions for three income scenarios. The scenarios are derived by changing the income growth assumptions, where low-, medium-, and high-income growth correspond to an average annual

TABLE 2
Base Case Variable Set

Variable	Notation	Base Case Assumption
Passenger vehicle saturation level	S_a	292 passenger vehicles ($a = 1$)
Country-wide income growth rate	A_g	6.5% ($g = 2$)
Income elasticity	n_k	Four-income range estimate ($k = 4$)
Scaling matrix for population growth rates	Ω_z	Provincial level population growth rates fixed at 1990–1997 average annual growth rates ($z = 1$)
Car fuel efficiency	$e_{c,t}$	Improvement of 0.9 km/L per decade
Bus fuel efficiency	e_b	3.63 km/L
Average yearly car travel	m_c	15,000 km
Average yearly bus travel	m_b	57,689 km

provincial-weighted income growth rate of either 5.5%, 6.5%, or 7.5% for the simulation period 1996 through 2025. Historical growth rates are used from 1990 to 1995.

For the selected cases, the estimated number of passenger vehicles grows from 1.6 million in 1990 to between 64 and 125 million in 2025. Given provincial-level population growth trends, the nationwide average vehicle ownership expands to between 39 and 73 passenger vehicles per thousand. Accompanying oil requirements and carbon emissions amount to just over 3 mbbls per day and nearly 119 million metric tons of carbon (MtC) for the low-growth case, and just over 6 mbbls/day and nearly 232 MtC for the high-growth case. When considering only cars for 2025 (i.e., factoring out buses), the model estimates range from about 58 to 112 million cars, requiring 1.4 to 2.7 mbbls of oil per day and emitting 53–103 MtC per year.

Figure 5 illustrates passenger vehicles per thousand people at the provincial level for the base case scenario. This scenario estimates an average of about 41 passenger vehicles per thousand people in 2015, increasing to 54 by 2025. Estimates range from just over 3 passenger vehicles per thousand people in Guizhou province to nearly 119 passenger vehicles per thousand people in Fujian. By 2025, the lowest and highest estimates are 3.4 and 159.9 passenger vehicles per thousand. The provinces with the highest numbers of vehicles are mostly located along the coast in the more industrialized, rapidly urbanizing areas of China.

TABLE 3
Income Growth Scenarios

Scenario	Year	Passenger Vehicles (Millions)	Passenger Vehicles per Thousand	Oil per Day (mbbls)	Carbon (MtC)
Low growth	2015	46.09	31.95	2.36	88.79
	2025	63.91	38.72	3.16	118.55
Medium growth	2015	59.63	40.63	3.06	114.86
	2025	91.55	54.33	4.52	169.8
High growth	2015	74.06	49.90	3.80	142.66
	2025	124.84	72.75	6.17	231.56

B. Scenario Analysis: Income Elasticity

The three types of income elasticities incorporated in the model include the estimated four- and two-income range elasticities and an extrapolation of Dargay and Gately (1999). Figure 6 illustrates the results for the three options while other variables are held at base case levels.

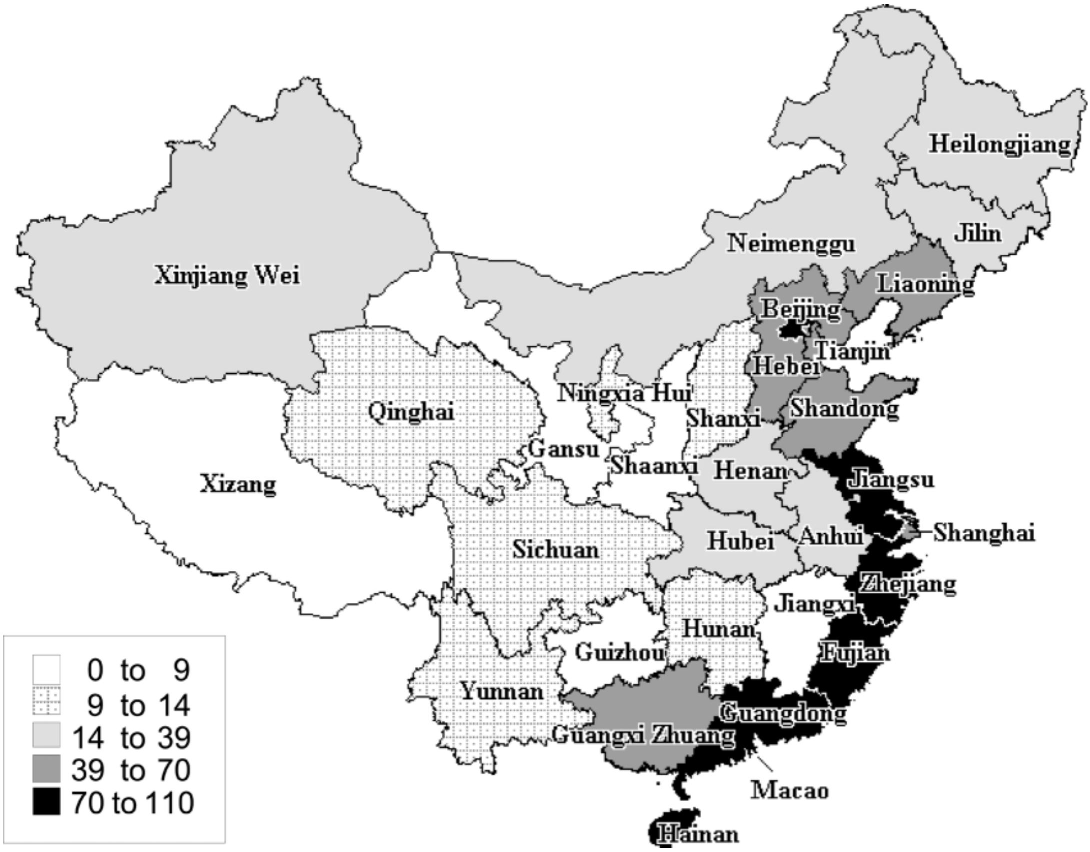
The importance of the income relationship with new vehicle ownership is reflected in the magnitude of difference resulting from varying the elasticity assumption. The four-income range scenario results in a 2025 estimate that is nearly twice the magnitude of the two-range option. By incorporating distinct income stages of vehicle demand, model results may more accurately reflect stages of growth in China's vehicle market.

C. Scenario Analysis: Vehicle Saturation Level

The default saturation level used for China is the authors' estimate of 292 passenger vehicles per thousand people. To illustrate the sensitivity of the model to other saturation levels, an estimate of 350 by Button et al. (1993) and 620 by Dargay and Gately (1999) are included in Figure 7. With other variables held at base case values, projections to

FIGURE 5

Passenger Vehicles per Thousand People by Chinese Province, 2015



Note: Base case scenario. Chongqing not included in model due to limited data; represented 1.4% of nationwide 1997 passenger vehicle stock (CSY, 1998).

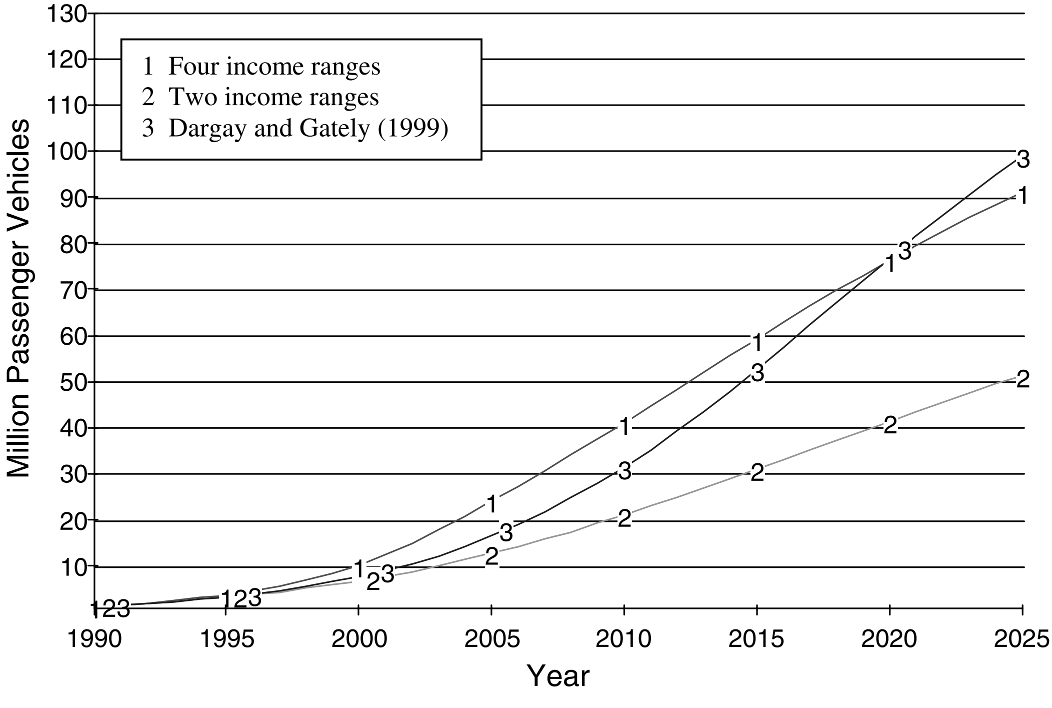
2025 differ by over 15 million passenger vehicles. Even during the next 30 years, China remains far below any of the saturation estimates. In fact, by 2025 some 27 of the 30 provinces remain below 146 passenger vehicles per thousand people, the midpoint of the logistic curve for a 292 saturation level.

D. Scenario Analysis: Population Growth

Growth in provincial populations indirectly affects passenger vehicle ownership by jointly determining provincial per capita income with provincial income growth. The base case ($z = 1$) assumes population growth rates fixed at their respective provincial 1990–97 average. Two scenarios investigate the impact of a declining rate of population growth, the first ($z = 2$) reflecting evidence of urban migration, and the second ($z = 3$) reflecting preliminary evidence of a nationwide slowing of population growth rates. Figure 8 plots total population (in millions) over the simulation period for each case.

The impact of lowering population growth rates is seen mostly through higher estimates of passenger vehicles per thousand. Compared to base case nationwide averages of 41 and 54 passenger vehicles per thousand in 2015 and 2025, the urban migration case results in 45 and 67, and the nationwide slowing case results in 44 and 68. At the provincial level, the differences are more revealing. By

FIGURE 6
Income Elasticity Scenarios



2025, the base case results in five coastal provinces (Jiangsu, Zhejiang, Fujian, Guangdong, Hainan) reaching over 100 passenger vehicles per thousand. In contrast, the migration case adds the coastal provinces of Tianjin and Guangxi to the over-100 club, with Tianjin (near Beijing) joining Fujian (north of Guangdong) as the two provinces with over 150 passenger vehicles per thousand. The nationwide slowing case results in eight provinces with over 100 passenger vehicles per thousand, replacing Tianjin with Beijing and adding the coastal province of Shandong. Under this case, Beijing and Fujian reach a dubious level of 179 and 189 passenger vehicles per thousand by 2025.

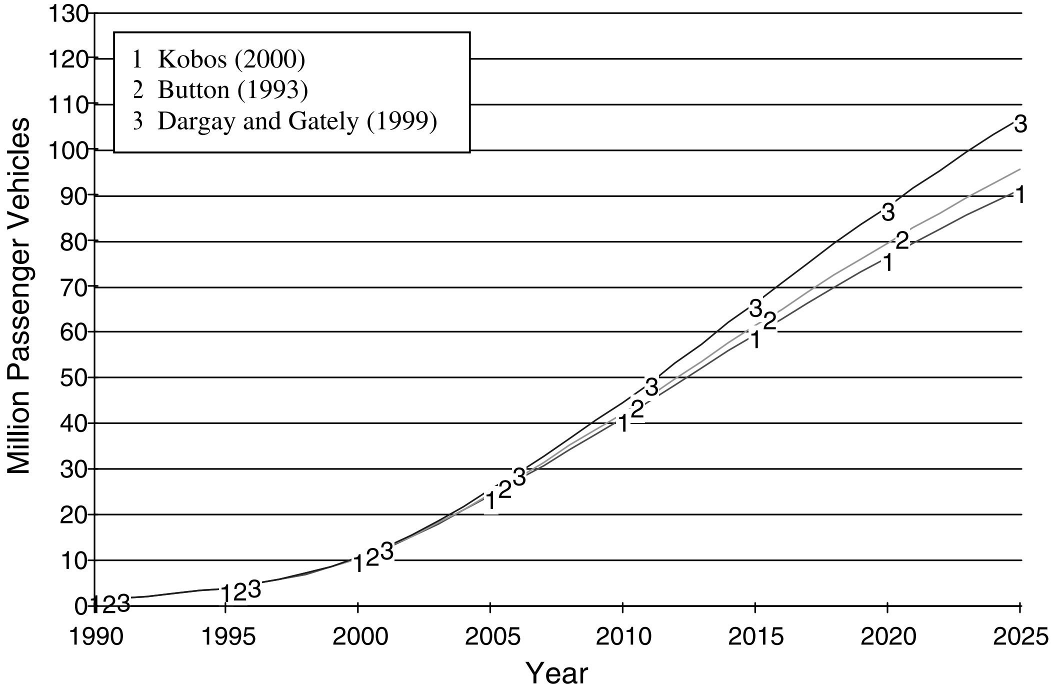
Despite clear implications at the provincial level, the overall impact on the total passenger vehicle stock (V_t) is negligible. This is due to the nearly canceling effects of the multiplication of higher passenger vehicles per thousand ($v_{i,t}$) and lower population ($P_{i,t}$) in equation (5).

E. Scenario Analysis: Fuel Efficiency and Annual Travel

Table 4 illustrates several fuel efficiency and annual distance driven scenarios. Results reflect the medium income growth scenario (6.5%), with 2025 values of 92 million passenger vehicles and 56 passenger vehicles per thousand. Efficiency and annual travel scenarios only apply to the car portion of the passenger vehicle fleet. Small buses make up the remainder of the fleet, and their share (10% for 2005–2025), annual travel (57,689 km), and fuel efficiency (3.63 km/L) remain constant throughout this simulation.

A policy aimed at a 33% improvement in car fuel efficiency by 2025 reduces oil use and carbon emissions by between 10% and 14%. Under a constant fuel efficiency scenario, oil use and carbon emissions drop by nearly 30% between the high and low annual travel scenarios. When increasing fuel efficiency is assumed, the percentage decrease is about 25%. The decrease in oil use and carbon emissions from the high travel/low

FIGURE 7
Saturation Level Scenarios



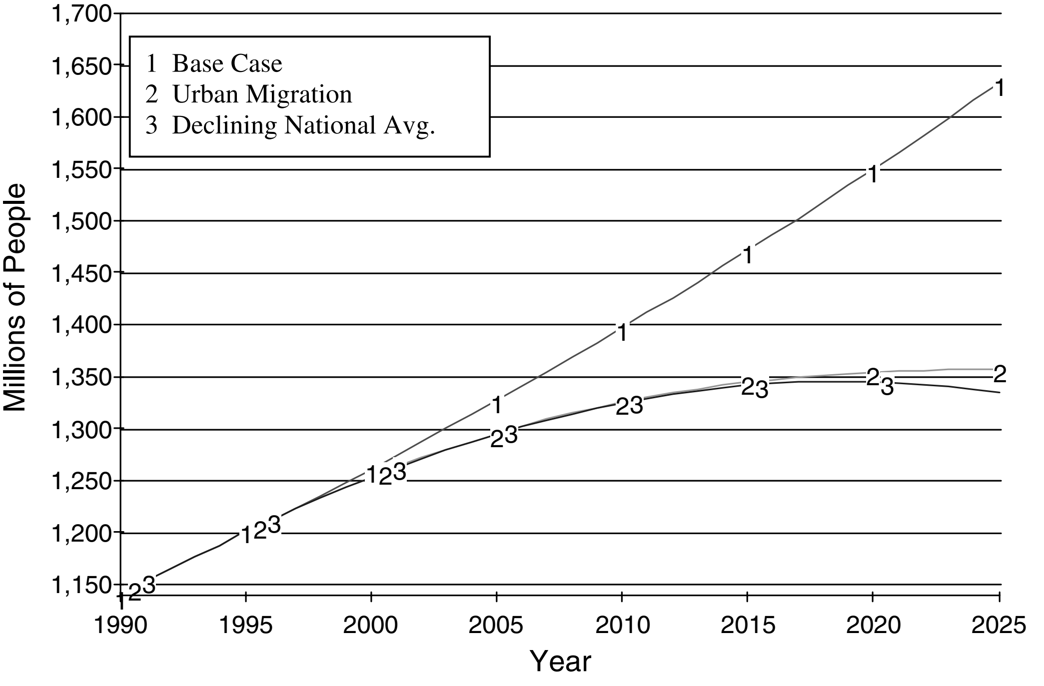
efficiency scenario (worst case) to the low travel/high efficiency scenario (best case) is roughly 36%.

V. DISCUSSION

Growth in passenger vehicle ownership has been modeled predominately on income, particularly in developing countries. This choice has both practical and theoretical significance. In theory, income is a major factor in the purchase of durable goods that occupy a large portion of consumer budgets. In practice, data on nonincome factors of vehicle demand are scarce in developing nations, particularly for China. However, factors such as traffic congestion, road infrastructure, and access to public transportation may not have as much of an influence on early stages of Chinese passenger vehicle demand. For instance, higher levels of vehicle ownership exist in China's city centers, contrary to developed country vehicle ownership trends. In 1993, China's national average for all types of motor vehicle ownership per thousand people was 7.4, whereas in Beijing, Shanghai, and Guangzhou it was 47.8, 24.3, and 41 motor vehicles per thousand people, respectively (Stares and Zhi, 1995). Demand for vehicles tends to mirror the high concentration of urban wealth in China.

However, other limiting factors could eventually overwhelm income effects, even in these early stages of market development. For example, roadway infrastructure development in China is one of the most restrictive parameters of the transportation network. Virtually every city in China has insufficient roadway networks to support Western-style car ownership levels. Bus, bicycle, and pedestrian lanes all support the day-to-day commuting. Road networks are growing, but disproportionately in urban over rural China, building on an urban income effect. The total length of urban roads increased from 29,485 km in 1980 to 104,897 km in 1993, representing 10.2% annual growth (Ganshi, 1995). In most provinces, rural roads are virtually nonexistent or are of very low quality. Provincial level simulation of passenger vehicle

FIGURE 8
Population Scenarios



ownership (highlighted in Figure 5) reflects these trends.

Given this backdrop, this article outlined a vehicle transportation model for China at the provincial level. Modifications over past studies included new estimates of saturation level, income elasticity, and purchasing power. In addition, according to the knowledge of the authors, this model was the first to evaluate vehicle ownership at the provincial level. The results are consistent with other country-wide estimates. Dargay and Gately (1999) estimated that by 2015 China will have 40 cars per thousand people, similar to the medium-growth scenario of Table 3. A report in the *Beijing Review* (1994) estimated that China could reach 40 cars per thousand people by 2010, faster growth than estimated by this study's high growth scenario of 33 cars per thousand people by 2010. A tangential

TABLE 4
Car Fuel Efficiency and Annual Travel Scenarios, 2025

	Fuel Efficiency Scenario			
	Constant		Increasing	
Average Annual Car Travel (km/year)	Oil per Day (mmbls)	Carbon Emissions (MtC)	Oil per Day (mmbls)	Carbon Emissions (MtC)
10,000	4.29	161.19	3.85	144.72
15,000	5.18	194.52	4.52	169.80
20,000	6.07	227.84	5.19	194.89

Note: Income growth, population growth, small bus fleet share, annual travel, and fuel efficiency held to base case levels.

analysis to our own by Zhongyuan et al. (2002) estimated that by 2020 China will have between 71.6 and 99.46 million cars (measured as "automobiles"). Conrad et al. (1998) assume that as a percentage of GDP, by 2025 the transport sector will increase only slightly, from 5.6% to 6%. However, based on assumptions about declining energy intensities and continued economic growth, their model estimates oil consumption for the transportation sector to increase from 0.53 mbbls/day in 1995 to 2.8 mbbls/day by 2015 and 4.8 mbbls/day by 2025. The present results suggest that economy-wide models (such as Conrad et al.'s) may actually underestimate future oil import requirements.

This study also picked up where others on Chinese vehicle ownership have left off. Rapid growth in passenger vehicles in China has implications for domestic air quality, oil import requirements, and international efforts to limit greenhouse gas emissions. The results of this model suggest a substantial increase in the number of passenger vehicles as Chinese income increases. However, vehicle and car ownership levels do not approach the levels experienced in other countries. The argument that China has the "right" to develop as others have is most often used in discussions over international environmental agreements. Table 5 summarizes 1995 oil consumption for China, Republic of Korea, Japan, Taiwan, and the United States for the transport sector. The Chinese consumed approximately 0.68 mbbls/day for transport (all types), compared with 7.7 mbbls/day in the United States. The average Japanese citizen consumed 11 times what the average Chinese citizen did in 1995; the average U.S. citizen consumed 54 times as much. The high-income growth scenario suggests that Chinese oil demand from increased vehicle ownership could reach 2.7 mbbls/day for cars and 6.2 mbbls/day for total passenger vehicles by 2025. Though it is a large number, it is still well below 1995 U.S. consumption for transportation.

TABLE 5
Select Asian Nations versus United States Oil Consumption in the Transport Sector, 1995

	Oil Consumption (1000 bbls/day)	Per Capita Oil Consumption (bbls/year)
China	680	0.2
Republic of Korea	163	1.3
Japan	765	2.2
Taiwan	137	2.3
United States	7,789	10.8

Source: Drennen and Kobos, 1998.

However, these dramatic differences between China and developed nations, such as the United States, do not negate the fact that small changes in per capita consumption in China can bring about large aggregate increases in terms of energy use and carbon emissions. Drennen (2000) estimates total carbon emissions in China as high as 2,677 MtC by 2020. The total carbon emissions from passenger vehicles under the high-growth scenario in this article reach nearly 189 MtC by 2020, or about 7% of total emissions. At the sectoral level, transportation in China for 1991 emitted only 24.5 MtC, or 3.7% of the national total carbon emissions from energy use (Lin and Polenske, 1998). For perspective, the emissions from the transportation sector in the United States for 1997 were 473 MtC, accounting for 32% of carbon emissions from all energy use (Energy Information Administration, 1999).

Clearly, China's growing contribution to global greenhouse gas emissions is not largely due to its transportation sector. In 1990, for example, due to the coal-dominant structure of energy consumption in China, 83.4% of total carbon emitted was from coal. Total oil use made up only 15% of 1990 carbon emissions (Zhang, 1998). However, alternative transportation development paths can have significant domestic benefits to a growing Chinese economy. Increases in passenger vehicle use in China will place serious strain on land use, urban air pollution (in particular ground-level ozone), and regional oil requirements. Urban air pollution, the most serious short-term problem, may reach monumental proportions with an expanding car fleet in China. In Guangzhou, the capital of the Guangdong province, ground-level air pollution from coal combustion has been surpassed by motor vehicle emissions. Already it is estimated that the "emissions from Chinese-made motor vehicles are at least ten times above the Japanese and U.S. standards for all pollutants" (Lin and Polenske, 1998).

Modest improvements in fuel efficiency (perhaps through technology transfer) can reduce oil requirements and carbon emissions, however, only by 12.7% over a no-improvement scenario. Annual travel reductions (perhaps through public transport expansion) have a larger and more immediate effect but would require a reversal in trends that higher personal incomes tend to strengthen. As is the case in neighboring Asian economies, the income effect on vehicle demand and use is perhaps the single most overwhelming variable. Lower income growth rates and weaker income elasticities have the most substantial effect on ameliorating growing personal vehicle ownership. However, to the contrary, with China's recent accession to the World Trade Organization will likely follow greater opportunities for personal income growth, more mass media pressure on consumer preferences for personal car ownership, reduced prices on foreign auto imports, and broader access to foreign capital for personal auto loans.

In conclusion, China's strong macroeconomic performance, increasing currency purchasing power, and rapidly evolving consumer tastes for automobiles all point toward a clear need for an integrated transportation policy with broad implications for domestic air quality, oil import requirements, and international efforts to limit greenhouse gas emissions. This article presents a model developed with the policy maker in mind. By allowing the user to change key assumptions about the Chinese market at the provincial level, it offers a tool for helping policy makers understand both the implications of increased car use and the opportunities for limiting the environmental and energy security problems associated with the personal transport sector.

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