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Projections of highway vehicle population, energy demand, and CO_2 emissions in India to 2040

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Abstract

This paper presents projections of motor vehicles, oil demand, and carbon dioxide (CO_2) emissions for India through the year 2040. The populations of highway vehicles and two-wheelers are projected under three different scenarios on the basis of economic growth and average household size in India. The results show that by 2040, the number of highway vehicles in India would be 206-309 million.

The oil demand projections for the Indian transportation sector are based on a set of nine scenarios arising out of three vehicle-growth and three fuel-economy scenarios. The combined effects of vehicle-growth and fuel-economy scenarios, together with the change in annual vehicle usage, result in a projected demand in 2040 by the transportation sector in India of 404-719 million metric tons (8.5-15.1 million barrels per day). The corresponding annual CO_2 emissions are projected to be 1.2-2.2 billion metric tons.

1. Introduction

Since its liberalization in 1991, the Indian economy has grown at an impressive average annual rate of 6.4% through 2008 (CSO, 2008). This rapid economic growth has led to significant growth in the motor vehicle population. The vehicle population (including two-wheelers, cars, commercial trucks, buses, three-wheelers, and tractors) has more than tripled, from roughly 20 million in 1991 to 67 million in 2004. The Indian economy is expected to grow at an annual rate of 4% or higher by 2040 (IMF, 2009; US EIA, 2008), and its population is projected to reach 1.51 billion by 2040 (UNDP, 2009). These factors and the past vehicle growth trend suggest a potentially substantial increase in the Indian motor vehicle population in the next three decades. The growth in the vehicle population will cause a substantial increase in petroleum use unless fuel economies of the future vehicles are enhanced. The Indian Government has assigned the Bureau of Energy Efficiency the task of formulating motor vehicle fuel efficiency standards for the future (Ghosh, 2009) in order to limit the increase in future oil demand.

The rapid economic and motor vehicle growth in India in the past two decades and forecasts of a continued high level of economic growth has led to several studies that project future vehicle ownership, oil demand, and CO_2 emissions (Fulton and Eads, 2004; ADB, 2006; Singh, 2006; Bouachera and Mazraati, 2007; Banerjee *et al*., 2009).

The main objective of the study presented here was to project future vehicle growth and the resulting energy demand and CO_2 emissions up to the year 2040 under alternative scenarios providing a range of future growth possibilities.

2. Background and past studies

Projections of oil demand and CO_2 emissions from the transportation sector have generally focused on determining the total vehicle stock, market share by vehicle type, vehicle usage, and fuel economy by vehicle type. Three studies, IEA/SMP (Fulton and Eads, 2004), ADB (2006), and Banerjee *et al*. (2009), followed the ASIF methodology (Marie-Lilliu and Schipper, 1999), which decomposes the energy demand and CO_2 emissions from the transportation sector to activity of personal travel or freight transport (A), share of different travel modes (S), energy intensity of each travel mode (I), and share of different fuels for each travel mode (F).

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The IEA/SMP model assumed similar fuel mix, vehicle activity, and fuel intensity for all developing economies, with limited data specific to the Indian road transport sector. It projected the light-duty vehicle (cars, utility vehicles) and two- and three-wheeler population by using the Gompertz function, linking personal vehicle growth to increase in GDP per capita. For commercial vehicles and buses, they assumed vehicle growth in developing countries to follow the past trends of developed economies, with limited growth in the bus population.

The ADB study projected vehicle populations in India and China up to the year 2035 but did not include buses and tractors (ADB, 2006). The study applied the ASIF methodology by using IEA/SMP model assumptions regarding fuel mix, fuel efficiency, and annual vehicle activity (Fulton and Eads, 2004). Vehicle projections were developed by applying a proprietary model to major Asian economies. The study's use of a proprietary model makes it difficult to compare its forecasts with other studies.

Singh (2006) projected passenger kilometers per capita to 2021 by using logistic and Gompertz functions and calculated energy demand and CO_2 emissions. The projections did not include commercial vehicles and tractors, which together account for roughly 55% of the current transportation oil demand in India.

Bouachera and Mazraati (2007) have modelled rates of car ownership in India by using logistic, quasi-logistic, and Gompertz functions and calculated fuel demand through 2030. This study assumed a high car-ownership saturation level of 850 vehicles per 1,000 persons, which, in combination with high vehicle usage (15,000 km annually) and high energy intensity (13 L of gasoline per 100 km), projected very high energy demand.

Banerjee *et al*. (2009) developed CO_2 emissions forecasts up to 2030 for Indian passenger vehicles and projected vehicle population. They assumed that, under the BAU scenario, Indian car ownership in 2030 would be the same as that of South Korea in the early 1990s.

The uncertainties in previous studies are further compounded by the lack of reliable data for the Indian road transportation sector. For example, all of the previous studies relied on vehicle registration data reported by the Ministry of Road Transport and Highways (MORTH) and assumed the data to represent the historical vehicle stock. However, MORTH's vehicle registration data represent the cumulative new vehicle registrations since the year 1951. Vehicles used for commercial purposes (commercial trucks, buses, three-wheelers and tractors) are required to be registered annually, thus their registration counts take into account out-of-service and scrapped vehicles. In contrast, the passenger vehicle (cars and two-wheelers) data refer to the total number of registered new vehicles since 1951. In the current study, the passenger-vehicle registration data are corrected by considering the vehicle age distribution of the current Indian fleet.

In the study reported here, a methodology was developed to project growth in the Indian vehicle population, related oil demand, and CO_2 emissions up to the year 2040. The methodology was applied to develop separate projections for highway vehicles and two-wheelers based on: (1) the historical vehicle stock and sales data for India; (2) vehicle growth trends worldwide; (3) factors affecting the market share of each vehicle type; (4) trends in fuel mix of Indian vehicle types; (5) change in annual vehicle usage commensurate with increases in per capita GDP; and (6) Government policies towards infrastructure development, personal vehicle growth and regulation of motor vehicle fuel consumption. This is a second such study conducted by Argonne National Laboratory, following a 2006 study that projected Chinese vehicle growth up to 2050 (Wang *et al*., 2006).

3. Indian vehicle classification

The vehicle registration data reported by MORTH (2009) include two-wheelers, cars (personal, taxis, and utility vehicles), buses, commercial vehicles, and other vehicles (agricultural tractors, three-wheeler passenger vehicles, and other miscellaneous vehicles). These data can be subdivided as personal vehicles (two-wheelers, cars, utility vehicles), public transport vehicles (buses and three-wheeler passenger vehicles), commercial vehicles (trucks, three-wheeler goods vehicles), and agricultural tractors. This classification is followed by the Society of Indian Automobile Manufacturers (SIAM), an organization representing Indian vehicle manufacturers that also reports annual vehicle sales data.

SIAM reports detailed vehicle sales data as follows. Cars, classified by length, include Mini (up to 3,400 mm), Compact (3,401-4,000 mm), Midsize (4,001-4,500 mm), Executive (4,501-4,700 mm), Premium (4,701-5,000 mm), and Luxury (>5,001 mm). Additionally, multi-utility vehicles (MUVs) and multipurpose vehicles (MPVs) are classified under the car segment on the basis of their gross vehicle weight (GVW) in metric tons (MT), with MUVs having a GVW < 5 MT and MPVs having a GVW < 3.5 MT. Three-wheelers are classified as either passenger carriers or goods carriers. The goods carriers are classified by their GVW. Trucks are classified on the basis of GVW either as light commercial vehicles (LCVs — GVW < 7.5 MT) or heavy commercial vehicles (HCVs — GVW ≥ 7.5 MT). They have subcategories: LCVs have two (<5 MT and > 5 MT) and HCVs have three (<12 MT, 12-16.2 MT, and > 16.2 MT). Buses are classified as light-duty buses (LDBs — GVW < 7.5) and heavy-duty buses (HDBs — GVW ≥ 7.5 MT) and have subcategories similar to trucks. Agricultural tractors are classified on the basis of their engine horsepower (hp). The wheel size determines the classification of two-wheelers as Scooters (≤30 cm), Mopeds (>30 cm and fixed transmission), and Motorcycles

(>30 cm). Additionally, engine displacement volume determines four motorcycle subcategories (<75 cc, 75-125 cc, 125-250 cc, and > 250 cc).

This study follows the SIAM classification with a few modifications. All vehicles except two-wheelers were classified as highway vehicles (HWVs). The projections of HWVs and two-wheelers were done separately because two-wheelers are very popular at present and are likely to follow a growth trajectory different than that for HWVs. Premium and Luxury car segments were merged with the Executive segment because of their low sales.

Additionally, each vehicle type was categorized by the fuel used: diesel, gasoline, compressed natural gas (CNG) or liquefied petroleum gas (LPG). All two-wheelers, however, are fueled with gasoline and all tractors with diesel. The use of gaseous fuels (CNG, LPG) is important in India, since their use can significantly reduce carbon monoxide (CO) and particulate matter (PM) emissions (Reynolds and Kandlikar, 2008).

4. Projection methodology

The change in vehicle ownership is directly related to per-capita GDP in a country. However, this relationship is not linear or log-linear, as evident from Figure 1. The figure shows the relationship between HWV ownership per 1,000 persons and GDP per capita on a purchasing power parity (PPP) basis (constant 2005 international dollars) for 19 countries for years 1991-2006 (World Bank, 2009; Davis *et al*., 2009). The relationship can be approximated graphically by a curve, in which vehicle ownership increases slowly at low-GDP levels, starts increasing rapidly (above US$ 5,000 GDP per capita), and then slows down as economies mature and vehicle ownership saturation levels are reached. Logistic, logarithmic logistic, cumulative normal, and Gompertz functions are among the methodologies used in the past to simulate vehicle ownership (Bouachera and Mazraati, 2007; Zachariadis *et al*., 1995; Dargay and Gately, 1999; Dargay *et al*., 2007).

Gompertz functions were used in this study to model HWV and two-wheeler ownership in relation to per-capita GDP in India. It can be specified as follows:

$$V_i = \gamma\theta e^{\alpha e^{\beta GDP_i}} + (1-\theta)V_{i-1} \quad (1)$$

Where:

V_i = vehicle ownership in year i (vehicles per 1,000 people);
V^* = equilibrium vehicle ownership level, defined as: $V^* = \gamma e^{\alpha e^{\beta GDP_i}}$;
γ = saturation level of vehicle ownership (vehicles per, 1,000 people);
GDP_i = GDP per capita in year i;
α and β = parameters that define the shape of the curve;
θ speed of adjustment for vehicle ownership, with respect to GDP growth ($0 < \theta < 1$).

Specification of a well-reasoned vehicle saturation level (V^*) is important for determining future vehicle ownership. Analysis of the historical HWV ownership data in Figure 1 reveals five different HWV saturation patterns. In the OECD North America pattern, the HWV population in the United States reaches a saturation level of 850 vehicles at

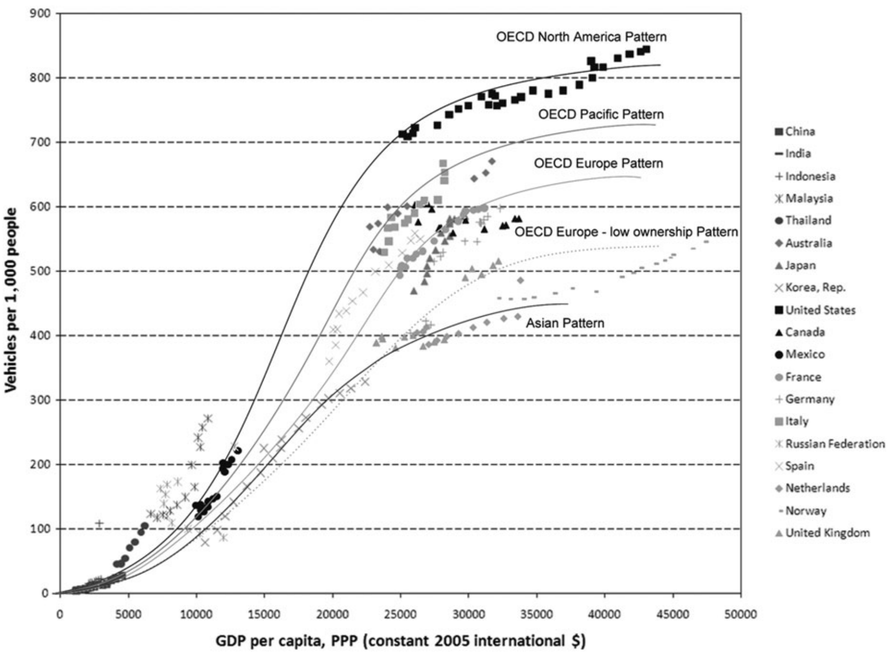

Figure 1. Highway vehicle ownership trends in various countries.
Source: HWV stock and GDP data for all countries from World Bank (2009), except US HWV stock data from Davis *et al*. (2009).

GDP per capita of US$ 43,000. In the OECD Pacific pattern, vehicle saturation is achieved at 700-750 vehicles. OECD Europe follows two different patterns: OECD Europe and OECD Europe-Low. In the OECD Europe pattern, countries such as France and Germany are expected to reach a saturation level of 650 vehicles. The OECD Europe-Low pattern, where the saturation level is 550 vehicles per 1,000 persons, seems to be followed by the United Kingdom, the Netherlands and Norway.

For the heavily populated developing Asian economies of China, India, and Indonesia, HWV ownership could saturate at 400-450 vehicles per 1,000 persons, assuming one car per household and the average household size reaches 3-3.5 persons (Jiang and O'Neill, 2009). However, actual HWV ownership is not expected to exceed 300 vehicles per 1,000 persons in the next 30 years, mainly because the GDP per capita will be in the range of 7,500-20,000 US$-PPP.

The average US household size was 2.59 persons in 2000 (US Census Bureau, 2009). The average Indian household size decreased slightly from 5.5 persons in 1991 to 5.3 in 2001 (CSO, 2009). Jiang and O'Neill (2009) project that with increased urbanization, reduced fertility rates, and a trend away from large households (>4 persons), average Indian household size by the year 2040 will be around 3.3 persons. Ignoring GDP per capita and assuming one car per household, this translates to 300 cars per 1,000 persons. Adding other types of HWVs (trucks, buses, three-wheelers, and tractors), a 400 HWVs per 1,000 persons ownership may be the upper limit. The projected 2040 Indian urban population share is 40% (Jiang and O'Neill, 2009). Considering lower ownership rates for rural households and the expected GDP per capita of 9,000-10,000 US$-PPP (IMF, 2009; US EIA, 2008), a saturation level of 250 HWVs per 1,000 persons is assumed in this study as the aggressive growth scenario, while saturation levels of 200 and 150 per 1,000 persons are selected as medium and conservative growth scenarios, respectively.

Two-wheeler ownership follows a different pattern compared to HWVs, rising rapidly at low per capita GDP, reaching saturation at middle-GDP levels, and then declining as higher GDP causes a shift away from two-wheelers to cars. The middle-GDP level at which two-wheeler saturation occurs has been approximated by ADB (2006) to be between 3,000 and 10,000 US$-PPP. The per capita GDP in India is expected to rise from 2,600 US$-PPP in 2007 (World Bank, 2009) to 9,100 US$-PPP in 2040. Consequently, two-wheeler ownership is expected to rise rapidly, but not reach the saturation level by 2040. Upper- and middle-income classes in India are shifting from two-wheelers to cars, and with the recent launch of ultra-low-cost cars (ULCC) like the TATA Nano, a similar shift is imminent for the lower-middle income class. Data necessary to reasonably estimate such a switch are not available for India. The two-wheeler projections presented here were developed by using per-capita GDP growth projections and assuming that the growth in two-wheeler demand from the lower-middle income class will be greater than the reduced demand from the middle- and upper-income classes.

On the basis of the 2004 Indian vehicle registration data (MORTH, 2009), two-wheeler ownership in 2004 was 47 per 1,000 persons. Since then, sales have risen rapidly, averaging 7.1 million annually during 2005-2009. To estimate the two-wheeler saturation level in India, we analyzed the ownership rates in other Asian economies during 1990-2003 (World Bank, 2006). For China, two-wheeler ownership increased from 3 to 46 per 1,000 persons, while GDP per capita increased from 1,099 to 3,393 US$-PPP (2005 US$). Indonesian two-wheeler ownership increased from 34 to 59 per 1,000 persons, with GDP per capita increasing from 2,077 to 2,959 US$-PPP (2005 US$). In Malaysia, two-wheeler ownership increased from 167 to 249 per 1,000 persons, while GDP per capita increased from 6,646 to 10,833 USD-PPP (2005 US$). Following these trends, and given the relatively high two-wheeler ownership at low-income level in India, three scenarios with saturation levels of 250, 300, and 350 two-wheelers per 1,000 persons were selected as conservative, medium, and aggressive growth scenarios, respectively.

The historical GDP and population data for vehicle projections were obtained from the Central Statistical Organisation of India (2008). The GDP data pertain to a financial year (i.e. April-March) and are reported in constant 2000 Indian Rupees. The historical vehicle registration data obtained from MORTH (2009) and supplemented with additional data from multiple editions of TERI Energy Data Directory and Yearbook (TERI) were corrected to account for scrapped vehicles. The commercial vehicle (trucks, buses, three-wheelers, and tractors) registrations were taken as vehicle population. As explained earlier, passenger vehicle (cars and two-wheelers) data from MORTH do not represent their population. On the basis of a report by the Central Road Research Institute (CRRI) (2002), which reported vehicle age distribution of all vehicle types in eight major metropolitan areas in India, the maximum age of cars and two-wheelers was determined as 20 years. The populations of cars and two-wheelers was corrected from the 2004 reported populations of 9.5 and 52 million to 8.2 and 48 million, respectively.

The Indian economy was assumed to grow at a rate that is in the range of 4.5-8.0% during 2009-2014 (IMF, 2009), and the assumed growth rate for the four subsequent periods of 2015-2020, 2021-2025, 2026-2030, and 2031-2040 was 5.4%, 4.3%, 3.9%, and 4.0%, respectively (US EIA, 2008). As per the medium-growth scenario in the United Nations Population Division database (2009), the Indian population would increase from 1.14 billion in 2008 to 1.51 billion by 2040. On the basis of the future GDP and population growth rates and assumed HWV and two-wheeler saturation levels, future HWV and two-wheeler stock values were estimated by using Equation 1.

4.1. Vehicle sales

The future vehicle population projected by using Equation 1 can also be expressed in terms of vehicle sales from previous years by vehicle type, as described in Equation 2.

$$VP_i = \sum_j \sum_{k=0}^{m} (Sales_{i-k} \times Market_{i-k,j} \times SR_{k,j}) \qquad (2)$$

Where:

k = vehicle again in years, $k = 0, 1, \ldots \ldots . m$; where m is the maximum age of vehicle;
VP_i = Vehicle population in year i;
$Sales_{i-k}$ = Total vehicle sales in year $i - k$;
$Market_{i-k,j}$ = Market share of vehicle type j in year $i - k$ (%);
$SR_{k,j}$ = Survival rate of vehicle type j at age k (%).

Equation 2 assumes that vehicle stock for a particular year is the sum of vehicles sold in previous years that are still operating in that year. Thus, given the vehicle stock in year i, vehicle sales from previous years, market share of each vehicle type in previous years, and survival rate for each vehicle type by vehicle age, the vehicle sales in year i can be calculated by using Equation 2.

Historical vehicle sales data for India (1985-2008) by each vehicle type were obtained from SIAM (2008) and market share (%) for each vehicle category was calculated. The sales data at the subcategory level (for cars, the subcategories are Mini, Compact, Midsize, Executive, MPVs, and MUVs) were available for 2002-2008 only. Shares for 1985-2001 were calculated on the basis of data collected through a literature review (Iyer and Badami, 2007) and information on general trends in the Indian automobile industry.

4.2. Future market shares

Market share trends for the Indian automobile industry were developed on the basis of the review of various government policy reports (TERI, 2006; Planning Commission, 2007; IASRI, 2006) and developing trends in the industry (Iyer and Badami, 2007; A.T. Kearney, 2008). Some of the notable future trends taken into consideration are as follows:

Cars: The share of cars from HWV sales will increase from the current 60% to around 67.5% by 2040. The Compact car segment will continue to be the most dominant segment, with a 40% share of car sales by 2040, declining from the current 55%. With the launch of such ULCCs as the TATA Nano, the mini-segment sales are projected to be over 5 million by 2020 (A.T. Kearney, 2008). By 2040, 30% of car sales are projected to be in the mini/ULCC segment. The share of Executive/Midsize segments will increase to 24% as a result of rising personal incomes, while the share of MUVs will stabilize at around 6% of the total car sales.

Commercial vehicles (CVs): Their share will increase from the current 16% to 17% of total HWV sales by 2040. Also, on the basis of India's eleventh five year plan (Planning Commission, 2007) and trends observed in developed countries, the LCV share of CVs will increase from 41% in 2007 to 58% by 2040.

Public Transportation: Sales shares of buses and three-wheelers were projected on the basis of a direct relationship with population, similar to that used in TERI (2006). Their market shares are projected to drop from 2.5% for buses and 15% for three-wheelers in 2008 to 1.5% and 11% of total HWV sales by 2040, respectively.

Tractors: Farm mechanization level in India is very low, with an average farm power availability of 1.35 kW/ha in 2001, compared to 7 kW/ha for South Korea and 14 kW/ha for Japan. On the basis of projections (IASRI, 2006) and trends in developed countries, tractor sales were assumed to rise at an average annual rate of 2.9%, with tractors' sales share declining from 12% of total HWV sales in 2007 to 3% by 2040.

Two-wheelers: Sales of two-wheelers in India have experienced significant changes during the past two decades, moving from a 50% share for scooters in 1990 to a nearly 80% share for motorcycles in 2008. The reasons for this shift are many — the better fuel economy of motorcycles, a demographic shift to younger drivers preferring motorcycles, and the stricter emission standards from the year 2000 (standards that motorcycles were better able to meet because they use four-stroke engines). Motorcycles were projected to have a 70% share of two-wheeler sales by 2040. Steady 20% and 10% shares were projected for scooters and mopeds because of their popularity among women and students (Iyer and Badami, 2007).

The projected market shares for HWVs and two-wheelers are presented in Table 1.

4.3. Fuel mix

The future fuel shares by each vehicle type were also projected, because the choice of fuel can have an impact on vehicular emissions of CO_2 and air pollutants such as CO, hydrocarbons (HC), nitrogen oxides (NO_x), and PM. Trends for diesel, gaseous fuels, and biofuels are presented below:

(a) Increased use of diesel: Because diesel is nearly 30% less expensive than gasoline on a per litre basis in India (MoPNG, 2008), the market share of diesel cars has increased from 5-10% in the 1990s to 35% in 2008 (Menon, 2007; Goodman, 2008). Assuming that the current fuel price differential is maintained, the sales share of diesel cars is projected to rise among larger car segments (Compact, Midsize, Executive, and MUVs) to reach 60% by 2040.

(b) Gaseous fuels: In the capital city of Delhi, public transport vehicles (buses, three-wheelers, and taxis) were required to use CNG beginning in 2001 to reduce vehicular air pollution. This programme has been a success, with

Table 1. Market share projections for highway vehicles (HWVs) and two-wheelers (%)

	1990	2000	2010	2020	2030	2040
HWV						
Cars	40.0	52.8	61.6	66.3	66.2	67.5
Mini	17.0	13.2	4.6	9.9	13.2	20.3
Compact	8.0	19.5	33.3	33.1	30.5	27.0
Midsize	1.2	5.8	9.1	10.9	11.6	12.5
Executive	0.2	0.4	1.8	2.7	3.1	3.5
MPV	6.0	4.9	4.1	2.0	1.0	0.3
MUV	7.6	9.0	8.6	7.6	6.8	3.9
CVs	18.8	10.8	16.4	19.1	16.7	17.2
LCV	4.2	3.9	8.2	9.0	8.8	9.9
HCV	14.6	6.9	8.2	10.1	8.0	7.3
Buses	3.7	1.3	3.1	1.7	2.1	1.5
LDB	1.5	0.6	1.4	0.7	0.7	0.5
HDB	2.2	0.7	1.7	1.0	1.4	1.1
Three-wheelers	15.7	15.2	13.9	10.0	12.0	10.9
Tractor	21.8	20.0	5.0	2.9	2.9	2.9
Two-wheelers						
Moped	26.4	18.8	6.0	7.3	8.7	10.0
Scooter	49.2	33.0	16.0	17.3	18.7	20.0
Motorcycle	24.4	48.2	78.0	75.3	72.7	70.0

Delhi having approximately 13,000 buses as of 2009 — the largest CNG-fueled city bus fleet in the world. On the basis of the Delhi experience, this programme has been implemented in six other states, with approximately 600,000 CNG vehicles operating as of 2009 (MoPNG, 2009). These include cars (237,000), three-wheelers (328,000), and nearly 35,000 LCVs. In addition to CNG, the Indian Government has encouraged the use of LPG. LPG is attractive in cities that lack access to natural gas pipelines. The fuel properties of LPG are similar to those of gasoline, making it suitable for light-duty vehicles (cars, three-wheelers, LCVs and LDBs). As of 2005, approximately 250,000 LPG-fueled vehicles were operating in India (Mathur, 2007). India has natural gas reserves of 1.06 trillion cubic metres, with a reserve-to-production ratio of 32.7. On the basis of the current trends in CNG use and significant reserves availability, the CNG fuel share in cars is projected to be 10% and in CVs, buses, and three-wheelers, it will be 15-20%. The LPG share is projected to be 5% for cars and 5-15% for LCVs, LDBs and three-wheelers by 2040.

(c) Biofuels: The Indian Government mandated a 5% ethanol blend in gasoline beginning in 2005 (MoNRE, 2009) and plans to introduce a 10% ethanol blend during the eleventh Five Year Plan (2007-2012). In India, ethanol is produced from the fermentation of molasses, a by-product of sugar production from sugarcane. Current ethanol levels are below the mandated 5% because of the low ethanol prices received by manufacturers who divert molasses to higher-value products (AIDA, 2007). A 2.5% ethanol blend was assumed for Bharat Stage II (BS II) gasoline (implemented in year 2005), a 5% ethanol blend for BS III

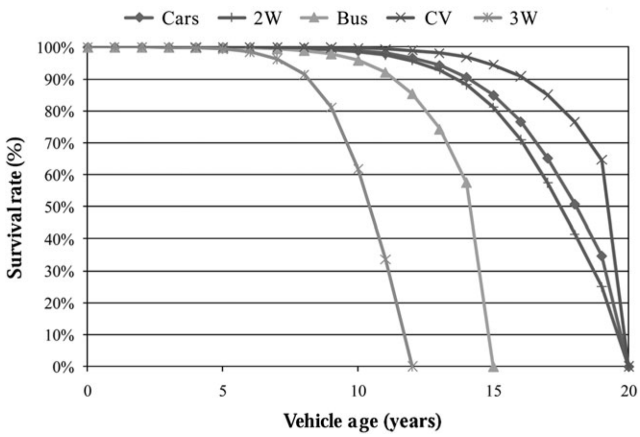

Figure 2. Survival rates of Indian vehicles.

gasoline (Euro III equivalent, 2010 implementation), and a 10% blend for BS IV gasoline (Euro IV equivalent, 2015 implementation). No commercial production of biodiesel has been reported yet in India. The government has plans for commercial biodiesel production from non-edible seeds like Jatropha and wants to introduce a 5% biodiesel blend in diesel by the end of the eleventh Five Year Plan (Planning Commission, 2003). Since land availability for the commercial production of biodiesel from Jatropha seeds remains unresolved at present, no biodiesel blending was considered in this study.

4.4. *Survival rates*

As described in Equation 2, survival rates for each vehicle type were to be determined for calculating vehicle sales. The survival rates for various vehicle types were calculated by following the methodology adopted by Yang *et al*. (2003) for calculating survival rates of light-duty vehicles in Beijing and using the vehicle age distribution data reported by CRRI (2002). Figure 2 shows the calculated survival rates by vehicle type.

4.5. *Vehicle utilization*

Vehicle kilometres travelled (VKT) by each vehicle type in India are not reported by any government organization. On the basis of estimates available from a few publications and reported trends in major world economies, (FHWA, 2003; Wang, M. *et al*., 2006; FHWA, 2010; Davis *et al*., 2010; Department for Transport, 2010) VKT by vehicle type in India have been projected, as shown in Table 2.

Cars and Taxis: A report by CPCB (2000) estimated cars and taxis VKT at 15,000 and 30,000 km/yr. This report assumed VKT per vehicle to remain constant. However, published trends in other major world economies indicate that the VKT of cars decrease as per capita income increases. These trends can be explained by the fact that as personal incomes rise, the ownership of private vehicles

Table 2. Indian annual VKT comparison with other major world economies (1,000 km)

Country	India[a]			United States[b]		China[b]		Japan[b]		Germany[b]		United Kingdom[b]	
Year	2000	2020	2040	2001	2008	2000	2006	2000	2006	1998	2005	1999	2007
Cars	10.9	9.4	8.0	19.0	19.0	24.0	14.1	10.2	5.2	12.5	12.4	16.7	14.9
LCVs	26.3	23.1	20.0	18.0	17.6	20.0	40.1	12.5	7.1	13.2	12.4	25.0	26.9
HCVs[c]	42.7	46.7	54.7	42.8	40.6	55.0						54.0	50.0
LDBs	30.8	27.9	25.0	15.0	13.5	35.0		27.9	28.8	43.7	41.9	59.5	30.9
HDBs	60.0	55.0	50.0			40.0							
Three-wheelers	30.8	27.9	25.0										
Tractors[d]	0.5	0.7	0.9										
Two-wheelers	10.0	8.0	6.0	3.1	3.1	9.0				3.4	3.3	6.7	4.4

[a] Indian data are from the sources mentioned in the text.
[b] VKT data for other countries from FHWA (2003), FHWA (2010); 2000 China data from Wang *et al*. (2006); 2006 China data from FHWA (2010); United Kingdom data from FHWA (2003), FHWA (2010), except HCV data, which were obtained from Department for Transport (2010).
[c] HCV data for United States include heavy single-unit trucks (2008 VKT ≈ 20,000 km) and combination trucks (2008 VKT ≈ 104,000 km), see Davis *et al*. (2010) for details. Only combined LCV and HCV data are available for China (year 2006), Japan and Germany, and these data do not include travel by combination trucks/articulated vehicles/semi-trailer truck, and such vehicles that have a high VKT. For United Kingdom, HCV VKT data are a combination of rigid vehicles (2007 VKT ≈ 34,000 km) and articulated vehicles (2007 VKT ≈ 94,000 km), see Department for Transport (2010) for details.
[d] Annual utilization for Tractors is reported in units of 1,000 hours.

increases, and these vehicles are driven fewer kilometers annually compared to taxis. A TERI (2006) study stated that from 21.4 km/day utilization of cars in 1980, VKT increased by 100 km every year. The TERI study also assumed VKT for taxis to increase from 60 km/day in 2001 to 80 km/day in 2036. On the basis of the TERI (2006) report, 91% of the current car population is assumed to be personal vehicles and 9% to be taxis. Following trends in other major world economies, it is assumed that future share of private vehicles will increase, and therefore, a gradual reduction in VKT is assumed for the car population by 2040.

CVs: The CPCB (2000) report stated annual VKT for LCVs and HCVs to be 30,000 and 40,000 km/year. A World Bank (2005) study reports annual utilization of light trucks to vary from 45,000 to 60,000 km and that of heavy trucks to vary from 80,000 to 108,000 km. However, these utilization rates assume trucks to last 10 years. Since trucks last for up to 20 years in India, the annual VKT values were calculated by averaging lifetime utilization over 20 years. For LCVs, it is assumed that annual VKT will gradually reduce by 2040. Considering the increased investment by the Indian Government in highway infrastructure, a 400 km/yr increase in HCV annual VKT is projected up to 2040.

Buses: The Indian bus sector has moved from 47% ownership by state governments in 1980 to 16% in 2003 (TERI, n.d.; World Bank, 2005). The Association of State Road Transport Undertakings (ASRTU), of which all public sector bus companies in India are members, reports the performance of the bus fleet owned by members at nearly 100,000 km/yr. (Ramaswamy, 2006). However, information regarding the utilization rates of the private sector bus fleet is not available. The CPCB (2000) report stated an annual utilization of 60,000 km for HDBs. The HDB VKT were calculated on the basis of CPCB estimates and the assumption that increased future investment in the bus sector will lower the utilization rate to 50,000 km/yr by 2040. For LDBs, the same utilization rates as for three-wheelers were assumed.

Three-wheelers: CPCB (2000) reported a high annual VKT for three-wheelers at 40,000 km. For this study, the TERI (2006) assumption that annual VKT would increase by 80 km/year from 29,200 km/yr in 1980 to 30,800 km/yr in 2000 was followed. For the future, a gradual reduction to 25,000 km/yr by the year 2040 was assumed.

Tractors: Annual utilization of tractors is measured in hours of use. The 1990-91 edition of TEDDY (TERI, n.d.) cites a 1985 study by the Advisory Board on Energy (Government of India) and reports annual use of 1,000 h and diesel consumption of 2.7 L/h for an average 30 hp tractor. A 2006 study (IASRI, 2006), based on a survey of farmers in the Indian state of Punjab, reports a much lower use of 397 h/yr in the early 1990s. In this study, the annual use of tractors was assumed to increase by 50 h every five years from 400 h/yr in 1990.

Two-wheelers: Annual VKT for two-wheelers were assumed at 10,000 km/year, as in the CPCB (2000) and the TERI (2006) report. The future annual VKT were assumed to decline gradually to 6,000 km/yr by 2040, following the trends in other major world economies.

4.6. *Fuel economy of the Indian vehicle fleet*

Since no government agency collects data related to vehicle fuel economy, fuel economy data for the Indian vehicle fleet are not publicly available (Roychowdhury *et al*., 2008). This situation may change with the recent appointment of the Bureau of Energy Efficiency as the agency to formulate fuel economy standards for the Indian vehicle fleet (Ghosh, 2009). The fuel economy of the current Indian fleet was

Table 3. Fuel economy of current Indian vehicles and comparison with Japanese phase 1 and 2 fuel economy standards (km/L)

Fuel Standard/ Scenario	Cars			CVs		Buses		Three-Wheelers	Tractors[a]	Two-Wheelers[b]
	Compact		UV	LCV	HCV	HDB				MCs_4S_75-125cc
	Diesel	Gasoline	Diesel	Diesel	Diesel	Diesel	CNG[c]	Gasoline	Diesel	Gasoline
BS II	13.5	13.3	8.2	5.2	2.8	3.6	2.8	20.5	3.25	53.1
Japan phase 1	14.3	13.9	9.0	9.0	2.8	3.6	2.8	19.9	3.25	51.1
Japan phase 2	15.5	15.5	9.2	10.0	3.8	4.0	3.1	20.0	2.41	53.9

[a] Fuel economy of tractors is presented as litres of diesel consumed/hr of operation; [b] fuel economy of 4-stroke motorcycles in the 75-125 cc category, which is the dominant category with the largest market share of two-wheeler sales in India; [c] Fuel economy of CNG vehicles expressed in km/kg.

calculated on the basis of a study by the Automotive Research Association of India (ARAI) (2007). ARAI tested and reported emission factors of 89 vehicles by using chassis dynamometer tests under an Indian driving cycle (IDC) and a modified Indian driving cycle (MIDC) for all vehicle types except CVs and buses, which were tested by using the overall bus driving cycle (OBDC). Tests were conducted for every vehicle type except tractors; for vehicles of various vintages, including 1991-1996, 1996-2000, 2000-2005, and post-2005; and for applicable conventional (gasoline and diesel) and alternatives fuels (CNG, LPG). The ARAI study measured tailpipe emissions of CO, HC, NO_x, CO_2 and PM, reporting emission rates in g/km.

On the basis of the emission factors obtained from the ARAI report, fuel economy can be calculated as described in Equation 3:

$$FE(km/L) = \frac{Density(g/L)}{\frac{[(CO_2 \times 12/44) + (HC \times 0.85) + (CO \times 12/28)]}{C - content}} \quad (3)$$

where:

FE = fuel economy of vehicle in km/L;
$C - content$ = carbon content (%) of fuel used.

The MIDC cycle is the same as the European NEDC (ECE15 + EUDC) cycle, except for the reduced maximum speed of 90 km/h. This cycle is not representative of real-world driving conditions because it does not accurately account for differences between cold start and hot emissions and fuel consumption, use of air-conditioning, reduced average speed in urban congestion, under-inflated tyres, and road quality. A recent European Union study (Smokers *et al*., 2006) compared the difference in fuel consumption between NEDC and real-world driving conditions and estimated the correction factor as 1.195. However, applying a single correction factor for different vehicle types is not appropriate because of lower variation between real-world and NEDC fuel economy for less fuel-efficient vehicles and higher variation between real-world and NEDC fuel economy for highly fuel-efficient vehicles. The US EPA has evaluated such variations while developing new adjusted fuel economy estimates for light-duty vehicles (US EPA, 2006). Additionally, the US EPA also developed correlations between new adjusted fuel economy and fuel economy obtained by using city and highway fuel economy tests.

Considering the low average speed under Indian driving conditions, the fuel economies of Indian vehicles (Equation 3) were adjusted on the basis of the relationship developed by the US EPA between new adjusted and city test fuel economies. This adjustment to calculate real world fuel economy is described in Equation 4:

$$\text{Real World FE (km/L)} = \frac{(2.352)^{-1}}{[0.003259 + (1.18053/(2.352 \times FE))]} \quad (4)$$

where:

FE = fuel economy of vehicle under standard driving conditions;
2.352 = conversion factor from miles/gal to km/L.

The fuel economy of two-wheelers was adjusted as 70% of the fuel economy calculated by using Equation 4. Selected fuel economy values are presented in Table 3.

To estimate a range of future fuel economy figures for the Indian fleet, three fuel-economy-improvement scenarios were developed:

4.6.1. Conservative scenario

A gradual improvement of 10% in fuel economy for the entire fleet was assumed to take place over a 25-year period, from 2015 to 2040, with two exceptions. A greater improvement of 40% was assumed for LCVs because of the expected future shift toward lighter LCVs. For already efficient two-wheelers, a fuel economy improvement of 5% was assumed.

4.6.2. Moderate scenario

India is assumed to follow the Japanese fuel economy standards (ECCJ and METI, 2008), with the introduction of Japan's phase 1 standards by 2015, followed by phase 2 in 2030. In the Japan phase 1 case (applicable in Japan as of

2005), significant improvements in the fuel economy of light-duty vehicles (cars, LCVs) are stipulated (Table 3). The Japan phase 2 (applicable in Japan in 2015) includes fuel economy standards for heavy vehicles and buses in addition to further improvements in light-duty fuel economy. In the Indian vehicle segments for which there are no equivalent Japanese fuel economy standards, we assumed fuel economy improvements similar to those of vehicles in other categories with a similar GVW. The fuel economy of the Indian two-wheeler fleet is high compared to fleets in other countries, and further improvements were assumed to follow the trends in Iyer and Badami (2007).

4.6.3. Aggressive scenario

The aggressive fuel economy improvement scenario assumed that Japan phase 1 standards are applicable in India by 2015, with the rapid introduction of Japan phase 2 standards in 2020.

4.7. Oil use and CO_2 emissions from Indian vehicle fleet

Oil use by the Indian vehicle fleet was calculated on the basis of the vehicle stock, VKT and average fuel economy by vehicle type. CO_2 emissions from vehicular use were calculated assuming the complete conversion of carbon in the fuel. Only the pump-to-wheels (PTW) results of oil use and CO_2 emissions are presented.

5. Results

5.1. Vehicle stock projections

Indian HWV and two-wheeler stock projections were done on the basis of Equation 1. By 2040, Indian HWV stock is projected to be between 206 and 309 million (Figure 3), and two-wheeler stock is projected to be between 301 and 359 million. Under the conservative growth scenario, the 2040 Indian HWV population will match the US HWV population in 1996 of 206.6 million, while under the moderate growth scenario, the 2040 Indian HWV population will edge the 2007 US HWV population of 247 million. In comparison, the United States is projected to have 330 million HWVs by 2030 (US EIA, 2006), and by 2040, China is projected to have 446 million HWVs (Wang *et al*., 2006). Thus, by 2040, India will have the third largest HWV stock in the world, and having not reached HWV ownership saturation, the Indian HWV population should continue to grow beyond 2040.

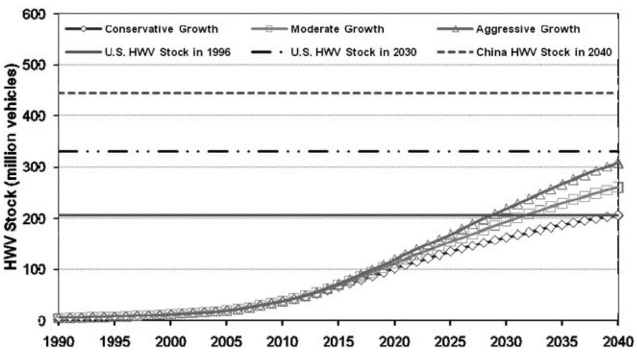

Figure 3. Projected Indian HWV stock by 2040.
Source: Authors' elaboration.

Projected HWVs stock by type and two-wheelers stock data are presented in Table 4. Under the conservative growth scenario, the 2040 Indian car stock of 144 million will exceed the 2007 US car stock of 136 million. However, a majority of Indian cars will be in the Compact and Mini segments, while the US car stock represents the Indian equivalent of Midsize and Executive segments, resulting in a lower average fleet fuel economy. The number of CVs is projected to be between 38 and 57 million, with a majority in the LCV segment (20-30 million). The Indian two-wheeler stock will continue to grow rapidly during the next 30 years, and the switch from two-wheelers to cars will have no significant impact on its growth because of the large population of young Indians and significant growth in lower middle class households. Between 2010 and 2020, the Indian two-wheeler population will exceed China's two-wheeler population; thereafter, India will have the largest two-wheeler stock in the world.

A comparison of our vehicle stock projection results with other recent studies is presented in Table 5. Fulton and Eads (2004), under the reference scenario, project low growth in car, CV and two-wheeler population and no growth in bus and three-wheeler population until 2040. Considering the average annual HWV and two-wheeler sales of 2.3 and 7.1 million vehicles during the past five years, their low growth projections do not seem to present a realistic scenario that matches with high economic and moderate population growth projections.

The ADB (2006) study, under the BAU scenario, projected the Indian car population to reach 80 million by 2035, with 43 million CVs and 236 million two-wheelers. However, the use of a proprietary model makes it difficult to compare their results with the projections in this study.

Dargay *et al*. (2007) projected Indian HWV stock of 156 million by 2030. The lower HWV stock projections in their study are due to the inclusion of population density and urbanization factors in the Gompertz model to estimate vehicle saturation level. Such an approach is suitable for a study that projects vehicle ownership for multiple countries. If the population density and urbanization factors are excluded, their HWV stock projections would be similar to the results in this study.

5.2. Annual vehicle sales projections

By 2040, annual sales of HWVs in India could reach 14-22 million; current annual sales are 2.6 million. By 2040,

Table 4. Indian vehicle stock by 2040 (million vehicles)

		2000	2005	2010	2020	2030	2040
Conservative Scenario	Total HWVs	13	20	38	101	163	206
	Cars	6	10	22	67	112	144
	CVs	2	3	6	19	31	38
	Buses	0.4	1	1	2	3	3
	Three-wheelers	2	3	5	10	13	16
	Tractors	3	3	4	4	4	5
	Total two-wheelers	35	55	87	170	245	301
	HWVs/1,000 persons	13	19	33	77	114	137
	Two-wheelers/1,000 persons	35	50	74	129	171	200
Aggressive Scenario	Total HWVs	13	20	39	119	219	309
	Cars	6	10	23	78	150	215
	CVs	2	3	6	22	41	57
	Buses	0.4	1	1	2	4	5
	Three-wheelers	2	3	5	11	18	24
	Tractors	3	3	4	5	6	8
	Total two-wheelers	36	55	89	183	279	359
	HWVs/1,000 persons	13	19	33	90	153	205
	Two-wheelers/1,000 persons	36	51	76	139	195	238

Source: Authors' elaboration.

Table 5. Comparison of vehicle stock projections (million vehicles)

	2000	2005	2010	2015	2020	2025	2030	2035	2040
Current Study — Moderate Growth Scenario									
HWV stock	13	20	39	70	111	154	194	230	260
Two-wheeler stock	35	55	88	130	177	222	264	301	333
Fulton and Eads (2004)									
HWV stock	15	19	25	32	43	53	67	85	109
Two-wheeler stock	33	37	45	54	64	75	88	97	107
ADB (2006)									
HWV stock		13		34		72		136	
Two-wheeler Stock		36		88		174		236	
Dargay *et al*. (2007)									
HWV stock							156		

Source: Authors' elaboration.

annual sales of two-wheelers could reach 19-24 million; current annual sales are 7.5 million. In 2007, 16 million light-duty vehicles (cars and light trucks) were sold in the United States (Davis *et al*., 2009) — in comparison, by 2040, annual sales of cars (including MUVs) in India could reach 9-15 million. The total annual HWV sales in India should at least reach 9 million by 2020 and 12 million by 2030.

5.3. Vehicle oil consumption and CO_2 emission projections

Projections of oil consumption by vehicles in India are shown in Figure 4, on the basis of nine different scenarios derived from a combination of three vehicle-growth and three fuel-economy-improvement scenarios. In 2008, Indian vehicles consumed 67.1 million metric tons of fuel (diesel, gasoline, CNG and LPG) or 1.4 million barrels per day of oil equivalent (Mbpd). By 2040, India's demand for fuel will rise to 404-719 million MT per year (8.5-15.1 Mbpd).

Oil consumption by Indian vehicles by 2030-2037 could match the oil consumption by road transportation in 2007 under four of the nine scenarios (Figure 4). However, under the most probable scenario of moderate vehicle growth and moderate fuel economy improvement, the demand by 2040 will be below the 2007 US oil use level at 530 million MT (11.1 Mbpd).

The aggressive vehicle growth and conservative fuel economy improvement combination yields the highest oil demand by 2040, 78% higher than the oil demand from the best combination of conservative vehicle growth and aggressive fuel economy improvement.

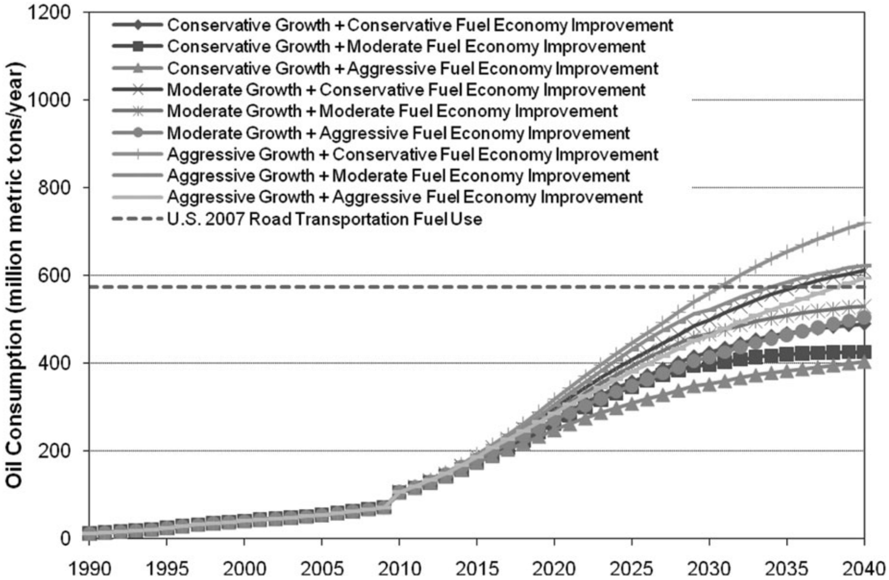

Figure 4. Oil demand projections for Indian vehicles.
Source: Authors' elaboration.

Because of increased use of diesel in cars and continued use of diesel in CVs and buses, diesel fuel demand will rise substantially. Diesel demand will rise from 48 million MT in 2008 to 268-501 MT in 2040. Gasoline demand will increase relatively slowly from 17 MT in 2008 to 65-94 MT in 2040.

The increased use of gaseous fuels in cars, buses and CVs will lead to higher demand for CNG and LPG fuels. By 2040, CNG demand will be 64-112 million MT per year, while LPG demand will be 7-12 million MT per year.

In 2008, oil consumption shares for cars, CVs, buses, three-wheelers, tractor and two-wheelers were 11.5%, 52.3%, 8.6%, 4.7%, 7.5% and 15.4%, respectively. By 2040, cars will account for 15-16%, and CVs will account for 64-69% of oil demand. The oil consumption share of two-wheelers will decline from 15.4% to 4.8-6.9 % by 2040.

By 2040, Indian vehicles are projected to emit 1.2-2.2 billion MT of CO_2 and these emissions will be 6-11 times more than the 2008 emissions of 0.21 billion MT.

6. Conclusions and discussion

In this study, projections of motor vehicles and related oil demand and CO_2 emissions for India up to 2040 were developed. To address the uncertainties of vehicle growth and fuel economy of vehicles, three scenarios for vehicle growth and three scenarios for fuel economy improvement were developed.

On the basis of these projections, by 2040, India could have the third largest fleet of vehicles in the world. The annual fuel demand from the transportation sector will be in the range of 404-719 million MT (8.5-15.1 Mbpd). Although the oil demand by the US and Chinese vehicle fleets will be higher than India's by 2040, the economic and resource related implications of this additional oil demand could be immense. Additionally, the annual CO_2 emissions from the Indian vehicle sector will be in the range of 1.2-2.2 billion MT, portending serious implications for the climate change debate.

The results cover nine different scenarios, encompassing a range of future vehicle growth and the extent to which fuel economy standards are stipulated. Because roughly two-thirds of oil demand will be from commercial vehicles by 2040, any future fuel-efficiency regulations in India should include CVs. The current Indian car fleet has high fuel-efficiency because it consists mainly of compact cars. However, with increased market share by Midsize and Executive car segments, future fuel-efficiency standards should aim for significant improvements by engine size.

At present, the fuel-efficiency of light-duty vehicles (cars, MUVs) is tested by using the MIDC cycle, buses and CVs are tested by using the OBDC cycle, and two-wheelers and three-wheelers are tested by using the IDC cycle. However, fuel efficiencies of vehicles in actual driving conditions are significantly lower than those measured by using these cycles. Government agencies worldwide have only recently started improving methods to accurately measure fuel efficiency and emissions under on-road conditions. The future fuel-efficiency standards in India should include research programmes to improve standard drive cycles, so that meaningful fuel-efficiency targets can be set.

These vehicle stock, oil demand and CO_2 emission projection results have a high degree of uncertainty, because of either a lack of reliable data or doubts regarding the accuracy of the data used. For example, data regarding survival/scrappage rates, annual utilization (VKT), and the fuel-efficiency of Indian vehicles were unavailable and were estimated from related publications. Although MORTH regularly reports vehicle registrations, these data do not account for scrapped and not-in-service passenger vehicles. In this study, this shortcoming was corrected through a few assumptions.

This study did not explore three important linkages in the Indian road transport sector: (1) shift from two-wheelers to cars; (2) impact of road-congestion on future vehicle growth and fuel-efficiency; and (3) the potential of biofuels (ethanol and biodiesel) and advanced vehicle technologies (hybrid electric vehicles, electric vehicles). The behavioural aspects of a shift from two-wheelers to cars were not explored because of the lack of necessary data regarding population distribution, rates of two-wheeler ownership by income level, and attributes of car buyers.

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References

A.T. Kearney, 2008. Mega market for ultra-low-cost cars, 4. Available at: http://www.atkearney.com/index.php/Publications/mega-market-for-ultra-low-cost-cars.html.

All India Distillers Association (AIDA), 2007. AIDA February 2007 Newsletter, 49 Pages. Available at: http://www.aidaindia.org/public/LatestNews.pdf.

Asian Development Bank (ADB), 2006. Energy efficiency and climate change considerations for on-road transport in Asia, ADB, 76 Pages. Available at: http://www.adb.org/Documents/Reports/Energy-Efficiency-Transport/.

Automotive Research Association of India (ARAI), 2007. Emission factor development for Indian vehicles, ARAI, 94 Pages. Available at: http://cpcb.nic.in/DRAFTREPORT-on-efdiv.pdf.

Banerjee, I., Schipper, L., and Ng, W.-S., 2009. CO_2 emissions from land transport in India: Scenarios of the uncertain. *Transportation Research Record: Journal of the Transportation Research Board*, 2114: 28–37. Available online at: http://dx.doi.org/10.3141/2114-04.

Bouachera, T., and Mazraati, M., 2007. Fuel demand and car ownership modelling in India. *OPEC Review*, 31(1): 27–51.

Central Road Research Institute (CRRI), 2002. Urban road traffic and air pollution in major cities. Report submitted to expert committee on auto fuel policy, New Delhi, India.

Central Pollution Control Board (CPCB), 2000. Transport fuel quality for year 2005. Ministry of Environment and Forests, New Delhi, India.

Central Statistical Organisation (CSO), 2008. National Accounts Statistics 2008, New Delhi, India. Available at: http://mospi.gov.in/mospi_cso_rept_pubn.htm.

Central Statistical Organisation (CSO), 2009. Selected socio-economic statistics India 2006, New Delhi, India. Available at: http://mospi.gov.in/mospi_cso_rept_pubn.htm.

Dargay, J. and Gately, D., 1999. Income's effect on car and vehicle ownership, worldwide: 1960–2015. *Transportation Research Part A: Policy and Practice*, 33(2): 101–138.

Dargay, J., Gately, D. and Sommer, M., 2007. Vehicle ownership and income growth, worldwide: 1960–2030. *Energy Journal*, 28(4): 143.

Davis, S.C., Diegel, S.W. and Boundy, R.G., 2009. *Transportation energy data book* 28 ed., Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Davis, S.C., Diegel, S.W. and Boundy, R.G., 2010. *Transportation energy data book* 29 ed., Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Department for Transport, 2010. *Road Freight Statistics 2009*, DoT, London. Available at: http://www.dft.gov.uk/pgr/statistics/datatablespublications/freight/goodsbyroad/roadfreightstatistics2009.

The Energy Conservation Center of Japan (ECCJ) and Ministry of Economy, Trade and Industry (METI), 2008. Top runner program: Developing the world's best energy-efficient appliances, ECCJ and METI, 68 Pages. Available at: http://www.eccj.or.jp/top_runner/img/32.pdf.

Federal Highway Administration (FHWA), 2003. Highway statistics 2002, FHWA, Washington, DC. Available at: http://www.fhwa.dot.gov/policy/ohim/hs02/index.htm.

Federal Highway Administration (FHWA), 2010. Highway statistics 2010, FHWA, Washington, DC. Available at: http://www.fhwa.dot.gov/policyinformation/statistics/2008/.

Fulton, L. and Eads, G., 2004. IEA/SMP transport model documentation and reference case projection, 92 pages. Available at: http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc.

Ghosh, P., 2009. Row ends; energy bureau will notify auto fuel efficiency norms. *Mint*. Available at: http://www.livemint.com/2009/06/02220620/Row-ends-energy-bureau-will-n.html.

Goodman, D., 2008. Diesel cars outperform petrol models. *Rediff.com*. Available at: http://in.rediff.com/money/2008/apr/28car.htm.

IMF, 2009. *World economic outlook database April 2009*, IMF, Washington, DC. Available at: http://www.imf.org/external/pubs/ft/weo/2009/01/weodata/index.aspx.

Indian Agricultural Statistics Research Institute (IASRI), 2006. Status of farm mechanization in New Delhi, India, IASRI, New Delhi. Available at: http://agricoop.nic.in/Farm%20Mech.%20PDF/contents.htm.

Iyer, N. and Badami, M., 2007. Two-wheeled motor vehicle technology in India: Evolution, prospects and issues. *Energy Policy*, 35(8): 4319–4331.

Jiang, L. and O'Neill, B., 2009. Household projections for rural and urban areas of major regions of the world. Interim Report, International Institute for Applied Systems Analysis. Available at: http://www.populationaction.org/Issues/Population_and_Climate_Change/IR-09-026.pdf.

Marie-Lilliu, C. and Schipper, L., 1999. Transportation and CO_2 emissions: Flexing the link — a path for the World Bank, Working paper. Available at: http://go.worldbank.org/3XQDYRJT80.

Mathur, S., 2007. *Auto LPG refuelling structure — the road ahead*, New Delhi, India. Available at: http://www.iac.org.in/downloads/Presentations/2007/004 Sunil Mathur.pdf.

Menon, N., 2007. Fuelling a diesel run. *Outlook Business*. Available at: http://business.outlookindia.com/inner.aspx?articleid=24&subcatgid=407&editionid=10&catgid=44.

Ministry of New and Renewable Energy (MoNRE), 2009. National policy on biofuels. MoNRE, New Delhi, India. Available at: http://www.mnre.gov.in/policy/biofuel-policy.pdf.

Ministry of Petroleum and Natural Gas (MoPNG), 2008. Petroleum statistics 2008, MoPNG, New Delhi, India. Available at: http://petroleum.nic.in/petstat.pdf.

Ministry of Petroleum and Natural Gas (MoPNG), 2009. Petroleum statistics 2009. MoPNG, New Delhi, India. Available at: http://petroleum.nic.in/petstat.pdf.

Ministry of Road Transport and Highways (MORTH), 2009, Motor transport statistics. MORTH, New Delhi, India. Available at: http://morth.nic.in/index2.asp?langid=2&sublinkid=202.

Planning Commission, 2003. Report of the committee on development of bio-fuel, Planning Commission of Govt of India, New Delhi, India. Available at: http://planningcommission.gov.in/reports/genrep/cmtt_bio.pdf.

Planning Commission, 2007. The working group report on road transport for the eleventh five year plan. Planning Commission of Govt of India, New Delhi, India. Available at: http://planningcommission.nic.in/plans/planrel/11thf.htm

Ramaswamy, N., 2006. A quick review of STUs (2005–06). *Indian Journal of Transport Management*, April–June Issue: 227–254. Available at: http://www.asrtu.org/performance.pdf.

Reynolds, C.C. and Kandlikar, M., 2008. Climate impacts of air quality policy: Switching to a natural gas-fueled public transportation system in New Delhi. *Environmental Science and Technology*, 42(16): 5860–5865.

Roychowdhury, A., Chattopadhyaya, V., Sen, J., and Chandola, P., 2008. *Avert the great guzzle — fuel economy regulations: Setting the principles right*. New Delhi, India. http://www.cseindia.org/userfiles/Monograph_Fuel Economy 2008.pdf.

SIAM, 2008. *The Indian Automobile Industry: Statistical Profile 2007–2008*, Society of Indian Automobile Manufacturers, New Delhi, India.

Singh, S.K., 2006. Future mobility in India: Implications for energy demand and CO_2 emission. *Transport Policy*, 13(5): 398–412.

Smokers, R., Vermeulen, R., Skinner, I., Fergusson, M., MacKay, E., Brink, P. Ten, Fontaras, G., and Samaras, Z., 2006. *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO_2 emissions from passenger cars*, European Commission, The Netherlands. Available at: http://ec.europa.eu/enterprise/automotive/projects/report_co2_reduction.pdf.

The Energy and Resources Institute (TERI), Multiple editions. *TERI Energy Data Directory and Yearbook: TEDDY*, Tata Energy Research Institute, New Delhi, India.

The Energy and Resources Institute (TERI), 2006. National energy map for India: Technology vision 2030. Tata Energy Research Institute, New Delhi, India. Available at: http://psa.gov.in/writereaddata/11913293531_NEMI2030.pdf.

US Census Bureau, 2009. Census 2000 demographic profile highlights, US Census Bureau, Washington, DC. Available at: http://factfinder.census.gov/servlet/SAFFFacts.

US Energy Information Administration (US EIA), 2006. *Annual Energy Outlook 2006*, US EIA, Washington, DC. Available at: http://www.eia.doe.gov/oiaf/archive/aeo06/index.html.

US Energy Information Administration (US EIA), 2008. *International Energy Outlook 2008*, US EIA, Washington, DC. Available at: http://www.eia.doe.gov/oiaf/archive/ieo08/index.html.

US Environmental Protection Agency (US EPA), 2006. Fuel economy labeling of motor vehicles: Revisions to improve calculation of fuel economy estimates, US EPA, Washington, DC. Available at: http://www.epa.gov/EPA-AIR/2006/December/Day-27/a9749.htm.

United Nations Population Division (UNDP), 2009. World population prospects: The 2008 revision population database. UNDP, New York. Available at: http://esa.un.org/unpp/.

Wang, M., Huo, H., Johnson, L., and He, D., 2006. *Projection of Chinese motor vehicle growth, oil demand, and CO_2 emissions through 2050*. Argonne, Illinois. Available at: http://www.ipd.anl.gov/anlpubs/2006/12/58260.pdf.

World Bank, 2005. India: Road transport efficiency study. World Bank, Washington, DC. Available at: http://go.worldbank.org/WLQBD1RM30.

World Bank, 2006. *World development indicators 2006*, World Bank, Washington, DC.

World Bank, 2009. *World development indicators 2009*. World Bank, Washington, DC. Available at: http://go.worldbank.org/U0FSM7AQ40.

Yang, F., Yu, L., Song, G., Wang, W., and Pei, W., 2003. Modeling dynamic vehicle age distribution in Beijing. *2003 IEEE Intelligent Transportation Systems, Proceedings*, 1: 574–579. Available at: http://dx.doi.org/10.1109/ITSC.2003.1252018.

Zachariadis, T., Samaras, Z. and Zierock, K., 1995. Dynamic modeling of vehicle populations: an engineering approach for emissions calculations. *Technological Forecasting and Social Change*, 50(2): 135–149.

Appendix

Acronyms and abbreviations

ADB	Asian Development Bank
AIDA	All India Distillers Association
ARAI	Automotive Research Association of India
BAU	Business As Usual
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
CRRI	Central Road Research Institute
CSO	Central Statistical Organisation
ECE	Economic Commission for Europe (United Nations)
EIA	Energy Information Administration (U.S. Department of Energy)
EUDC	Extra Urban Driving Cycle
FHWA	Federal Highway Administration (U.S. Department of Transportation)
GDP	Gross Domestic Product
GVW	Gross Vehicle Weight
HC	Hydrocarbons
HCV	Heavy Commercial Vehicles
HDB	Heavy-Duty Buses

HWV	Highway Vehicles
IASRI	Indian Agricultural Statistics Research Institute
IEA	International Energy Agency
IMF	International Monetary Fund
LCV	Light Commercial Vehicles
LDB	Light-Duty Buses
LPG	Liquefied Petroleum Gas
Mbpd	Million barrels per day
MIDC	Modified Indian Driving Cycle
MoNRE	Ministry of New and Renewable Energy
MoPNG	Ministry of Petroleum and Natural Gas
MORTH	Ministry of Road Transport and Highways
MPV	Multipurpose Vehicles
MT	Metric Ton
MUV	Multi-Utility Vehicles
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides
OBDC	Overall Bus Driving Cycle
OECD	Organisation for Economic Cooperation and Development
PM	Particulate Matter
PPP	Purchasing power parity
SIAM	Society of Indian Automobile Manufacturers
TEDDY	TERI Energy Data Directory and Yearbook
TERI	The Energy and Resources Institute (Formerly Tata Energy Research Institute)
ULCC	Ultra Low Cost Cars
UNDP	United Nations Development Programme
USD	U.S. Dollar
UV	Utility Vehicles
VKT	Vehicle Kilometers of Travel