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Low carbon urban transport scenarios for China and India: A comparative assessment

Shivika Mittal [a], Hancheng Dai [a,*], P.R. Shukla [b]

[a] National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Japan
[b] Indian Institute of Management Ahmedabad, Vastrapur, Ahmedabad, Gujarat 380015, India

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ABSTRACT

This paper assesses comparable urban transport scenarios for China and India. The assessment methodology uses AIM/End-use model with a detailed characterization of technologies to analyze two scenarios for India and China till the year 2050. The first scenario assumes continuation and enhancement, in both countries, of policies under a typical business-as-usual dynamics, like constructing metros, implementing national fuel economy standards, promoting alternate fuel vehicles and implementing national air quality standards. The alternative, low carbon scenario assumes application, in both countries, of globally envisaged measures like fuel economy standards as well as imposition of carbon price derived from a global integrated assessment modeling exercise aiming to achieve global 2 °C temperature stabilization target. The modeling results for both countries show that decarbonizing transport sector shall need a wide array of measures including fuel economy, low carbon fuel mix including low carbon electricity supply. The comparison of China and India results provides important insights and lessons from their similarities and differences in the choice of urban transport options. India can benefit from China's experiences as it lags China in urbanization and income. Modeling assessments show that both nations can contribute to, as well as benefit by aligning their transport plans with global climate stabilization regime.

Introduction

Transport accounts for 50% of the total global oil consumption, of which 40% is consumed in urban transport (IEA, 2013a). Global oil consumption in the urban transport sector is expected to get doubled by 2050. Majority of the increase is expected to come from developing countries where rising urbanization and incomes result in a rapid rise in private motorized transport (Li, 2011; Yan and Crookes, 2009). China and India account for nearly a third of global urban population. Evidently, the form and scale of urban transport sector has adversely impacted the three key sustainability indicators – energy security, urban air pollution and greenhouse gas emissions in both countries (Guttikunda & Goel, 2013; Creutzig and He, 2009; Pucher et al., 2005; Woodcock et al., 2009; Rao et al., 2013). The Chinese trends of these development indicators have grown with alacrity, and under the business-as-usual future, India is expected to follow similar trends. Given the large size of these two economies, their future development pathways will also decisively influence the global trends of these sustainability indicators.

* Corresponding author at: 16-2 Onogawa, Tsukuba-City, Ibaraki 305-8506, Japan. Tel.: +81 29 850 2355.
E-mail addresses: mittal.shivika@nies.go.jp (S. Mittal), dai.hancheng@nies.go.jp (H. Dai), shukla@iimahd.ernet.in (P.R. Shukla).

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There are three reasons for urgency to alter the energy and emissions trends from urban transport. First, the energy and emissions trends from transport have high path dependence vis-à-vis infrastructures and urban design (Schwanen et al., 2011). Second, efficient urban infrastructures, such as mass transit systems, have high upfront costs. Third, the policies to adapt to cleaner and efficient technologies, e.g. electric cars, have delayed effects on the overall transport system due to slow turnover time to replace old vehicle stocks and build new infrastructures. These reasons notwithstanding, there has been quick turnover in transport systems during the past decade, e.g. rapid expansion of inter-city high speed rail network and intra-city urban metro rail network in China (Ollivier et al., 2014). India may follow suit in a similar transformation of urban transport system.

Several studies have investigated the transport, energy and environment nexus at the national level (Baidya and Borken-Kleefeld, 2009; Creutzig and He, 2009; Dhar and Shukla, 2014; Guttikunda and Mohan, 2014; Li, 2011). They estimated historical emission trends in different countries at the sectoral level (Ramachandra and Shwetmala, 2009; Singh, 2006; Yan and Crookes, 2009; Huo and Wang, 2012). Singh (2006) estimated the future mobility demand and assessed CO_2 emission and energy demand from the passenger transport sector in India, assuming 1% reduction in energy and carbon intensity per year. Several studies have also done detailed analysis for metropolitan cities like Delhi, Mumbai, Beijing and Shanghai (Das and Parikh, 2004; Jalihal et al., 2005; Kejun and Songli, 2007; Songli and Kejun, 2004). Jalihal et al. (2005) analyzed the travel patterns in four metropolitan cities in India and found out that there is a shift towards private vehicles like two wheelers and cars from non-motorized modes. Zhang et al. (2011) analyzed the situation of carbon emission and energy consumption of the China's urban transport from 2000 to 2011 and identified factors like insufficient public transport and growing motorized transport impeding the low carbon transformation of China's urban transport.

The literature, however, is short of comparative studies that examine future urban transport scenarios for China and India. Pucher et al. (2007) has provided the overview of urban transport situation and critically evaluated the government policies in India and China. But it does not focus on the future implications of technological and infrastructural transformations that are likely to happen in urban transport sector in these two countries. Therefore, it is necessary to address elicited questions, i.e., what will be the implications of techno-economic transformations for the urban transport-related emissions in India and China in the long term? What are the similarities and differences in the two countries in the choice of urban transport options required achieve the global low carbon objective? As the city size and numbers are growing in India, there is a need to build physical infrastructure in order to manage the increasing travel demand. As China is ahead of India in terms of urbanization rate, GDP per capita and physical infrastructure, India has an opportunity to learn from China's experiences and direct the development towards a sustainable low carbon pathway. In this paper, we analyze Business-as-Usual (BAU) scenario and Low Carbon scenario (LCS) pegged with global 2-degree stabilization target using the bottom-up AIM End-use model. Cities are classified in different categories based on population and then travel demand is projected for each category. The technology options vary across city categories. For instance, option like Metro rail is considered for cities in high population category.

The remaining of the paper is divided into four sections. Section "Method and data" describes the methodology including a description of AIM/Enduse model, estimation of future service demand, model scenarios. Section "Results and discussion" presents the results of scenarios analysis showing the implications of different policy interventions considered in alternate scenarios on passenger travel demand, energy and emissions. Next section focuses on the lessons that India can learn from China's urban transportation pattern and followed by the conclusions.

Method and data

General model description

Bottom-up energy-economic-environment models have been used in several transport related studies primarily focusing on the vehicle technologies (Brand et al., 2012; McCollum and Yang, 2009; Yan and Crookes, 2009; Yang et al., 2009). In this study, AIM/Enduse model, bottom-up, partial equilibrium energy systems model is used for assessment. It is a technology rich, recursive optimization model which determines the optimal set of technologies to meet the projected future energy service demand subject to several constraints (emission, service demand, device share ratio, energy supply, etc.) using the "least cost" approach (Kainuma et al., 2003; Hanaoka and Kainuma, 2012). A detailed description of the model is provided in Kainuma et al. (2003). Modeling assessment is carried out for both countries separately. The model architecture includes the entire national energy system, but the scenarios and modeling assessment focuses on urban transport system. The time horizon of the study spans from 2010 to 2050. End-use demand for urban road passenger demand is divided into four categories, i.e., buses, two wheelers, car and metro. The service demand for all the transport modes is exogenously provided to the AIM/Enduse model and endogenous service demand shift between modes is not allowed in this model framework. The technology details like vehicle capital cost and vehicle efficiency for India are taken from GoI (2006) and for China, it is taken from the study done by Ou et al. (2010) (Supplementary material Tables S-1–S-3).

Scenario description

Two scenarios are assessed: (i) Business-as-Usual (BAU) scenario that assumes conventional development pathways, and (ii) Low Carbon Scenario (LCS) that assumes the application of global instruments like carbon tax in line with global 2 °C stabilization target as well as fuel economy standards consistent with global fuel economy initiative.

Business-as-Usual Scenario: In the business-as-usual scenario or base case scenario, the continuation of current economic energy sector trends and policies without any major interventions is assumed. The baseline scenario assumes that annual GDP of India will grow at the rate of 5.1% for next 40 years (2010–2050) similar to the rate assumed in SSP2 (Shared Socioeconomic Pathways) (Moss et al., 2010). The projections related to city population growth rate and level of urbanization closely follow the medium-variant of the demographics projections made by the UN for India (UN, 2014). The projections related to China's GDP, urbanization and city population are taken from the study conducted by Energy Research Institute (ERI) (Jiang and Hu, 2009). Advanced vehicle technologies like hybrid, plug-in hybrid cars and e-bikes are offered technological push by governments through various policies.

Low carbon Scenario: The "low carbon" scenario, assumes the government recognizes the need to achieve the stabilization target of 450 ppmv CO_2 eq-concentration target. The market-based instrument like carbon tax is used to achieve this target. Strict constraint on carbon emissions thereby provides an impetus for earlier adoption of advanced low-carbon technologies like electric and hybrid vehicles. Climate centric scenario also envisages high investment in R& D and strong coordination with developed countries and transfer of technologies to developing countries as a part of an international agreement. The socio-economic assumptions related to GDP, urbanization and population are similar to the business-as-usual scenario. In this scenario, efficiency improvement rate is aligned with the global fuel economy initiative target (Cuenot and Fulton, 2011) (Supplementary material: Table S-4). Carbon price path is taken from the study done by Rao et al. (2009) derived using IMAGE and MESSAGE models. Carbon price increases from US$ 46/t of CO_2 in 2020 to US$ 200/t of CO_2 in 2050 (Supplementary material: Table S-5).

Service demand estimation

The total urban transport demand can be calculated either using the bottom up or top down approach. As the travel characteristics like average trip length and trip rate vary across different cities, therefore, the cities are categorized based on their population size to calculate the total urban passenger transport demand. The cities in India and China are classified into four and five categories respectively based on their population as shown in Fig. 1.

Estimation method for India

The total intra-city urban passenger transport demand is estimated by multiplying the population in different city categories with corresponding trip length, per capita trip rate of motorized modes that is similar to Dhar and Shukla (2014) demand estimation methodology. The trip length and per capita trip rate of motorized modes for different city categories in the base year are taken from the various studies conducted at the city level (MOUD, 2008; EMBARQ, 2012; Das and Parikh, 2004).

Total urban transport demand

$$UTD = \sum TL_{tj} * PCTR_{tj} * Population_{tj} * 365 \tag{1}$$

where *UTD* Total urban transport demand, *TL* Trip length in km in category *j* in the year *t*, *PCTR* Trip rate per capita in category *j* in the year *t*, *POP* Population in category *j* in the year *t*.

In the study conducted by Wilbur Smith in 30 Indian cities, it was shown that the trip rate per capita by motorized modes and trip length increased gradually with city sprawl between the year 1994 and 2007. Based on the past trends, it is considered that trip length and trip rate per capita will continue to increase gradually with city sprawl in future.

The mode wise transport demand is estimated by calculating the demand for car, two wheeler and metro individually and the remaining unmet demand is assigned to bus transport. The private vehicle passenger demand is calculated by multiplying the vehicle population in year *t* with an average occupancy and average annual distance traveled by car in year *t* (Eq. (2)).

Travel demand by car and motorcycle

$$\text{Transport Demand}_{t,m,r} = OW_{t,m,r} * POP_{t,r} * AADT_{t,r} * \text{Occupancy}_{t,r} \tag{2}$$

where *OW* No of vehicles/1000 person in time *t* in each mode *m* in region *r*, *POP* Population in year *t* in region *r*, *ADDT* Average annual distance traveled in region *r*.

Ownership level

Several studies have found that car ownership per 1000 people follows *S* shaped curve. This curve indicates that ownership remains low in the initial slow growth period but increases rapidly with increase in per capita income and stabilizes in the saturated growth phase (Dargay et al., 2007; Metz, 2010; Wu et al., 2012). It can be represented using a logistic curve or Gompertz function. In this paper car ownership/1000 people for India is projected using the logistic curve (Eq. (3)).

Car ownership in India

$$V = V^*/(1 + \alpha * \exp(-\beta(t)) \tag{3}$$

where *V* car/1000 people in year *t*, V^* saturation value of car ownership, α and β two coefficients that determine the slope of the curve.

The saturation value (V^*) is key parameter to project the future car ownership level which also depends upon countries population density and share of mass transportation system (Huo and Wang, 2012; Dargay et al., 2007; Button et al., 1993).

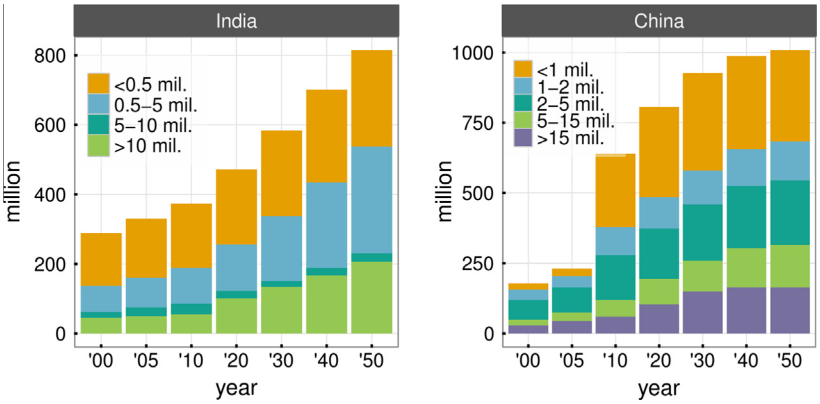

Fig. 1. Urban population in different city classes.

Dargay and Gately (1999) projected total vehicle stock for 26 countries (including India and China) using a logistic curve assuming 620 cars per 1000 persons as the saturation value in this study. Kobos et al. (2003) argued that highly populated country is unlikely to attain very high saturation level of car ownership. Button et al. (1993) modeled the vehicle ownership in low-income countries and assumed the range of 300–450 cars per 1000 people in the study. Three different car ownership patterns with different saturation levels can be observed by plotting car ownership/1000 people over GDP per capita (Huo and Wang, 2012). In this study, the saturation value is taken as 500 cars per 1000 people benchmarking with the Asian pattern as mentioned by Huo and Wang (2012).

In case of two wheeler category, the ownership per 1000 people follows inverted U-shaped curve that signifies two wheeler ownership level increases with increase in per capita income but it declines in the saturated growth phase (Nishitateno and Burke, 2014). In this paper, two wheeler ownership/1000 people was projected using the quadratic equation curve (as mentioned below) using GDP per capita as an explanatory variable.

Two wheeler ownership level in India

$$\mathrm{Log}(MC_t) = \alpha + \beta_1 * \mathrm{Log}(Y_t) + \beta_2 * \mathrm{Log}(Y_t) \wedge 2 + \varepsilon_i \tag{4}$$

where *MC* Two wheeler/1000 people, *Y* GDP per capita in US dollars (2005 Constant).

Occupancy and average distance traveled

The average car occupancy in India ranges from 1.8 to 3.18 as reported in the literature (Singh, 2006; IEA, 2009; Reddy and Balachandra, 2010). The average value of car occupancy is taken for the base year which is assumed to reach around 1.55 which is the current level in developed countries like U.S. and several European countries (Kenworthy and Laube, 1999). The average distance traveled by car per year ranges from 14,600 to 8000 as per various Indian studies (Ramachandra and Shwetmala, 2009; Singh, 2006; IEA, 2009). Huo and Wang (2012) shows the decline in average distance traveled by private light duty passenger vehicle in China based on surveys conducted in several Chinese cities like Beijing, Shanghai, Tianjin, Yichang during 2004–2010. Wang et al. (2006) also argues that as car fleet becomes saturated, there will be a decline in annual vehicle miles traveled by car in China. Based the above mentioned studies, it is considered that the average distance traveled by car will decline and then reach the saturation level of 8000 km per year with increase in private car ownership Based on values given in the literature, the average value is taken for the base year that reduces gradually to 8000 km in future. The occupancy and average distance traveled by two wheeler are taken as 1.6 and 8100 km respectively (IEA, 2009; Singh, 2006).

Travel demand by Metro

In order to manage the increasing transport demand in the growing cities, India has to increase the metros and subway network. The Ministry of Urban Development has already proposed the plan of building metros of around 1411.47 km length in various India's tier-II cities (population between 1 million and 4 million) for intra-city travel. It is expected that proposed metro network length will be completed by 2025 lagging by 15 years compared to China and will follow the logistic curve in the future (Fig. 2). The length of the metro is first projected and then multiplied by the average trip length, and average passenger traveled per km based on the past years data.

Estimation method for China

The demand for different modes has been estimated separately and then aggregated to estimate the total urban passenger transport demand. The values related to car and motorcycle ownership per household and household size in the urban area are taken from Jiang and Hu (2009) which are further used to calculate the total urban car and two wheeler population using the Eq. (2). The bus population is calculated by multiplying the population in different city categories with the corresponding bus density (Caerc and Da xue, 2013). The average occupancy and annual distance traveled by car, two wheeler and bus for different years is taken from Huo and Wang (2012).

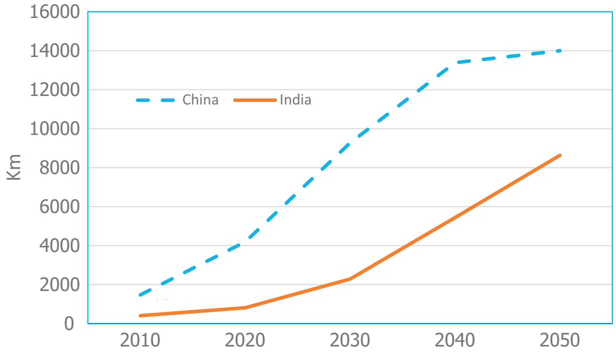

Fig. 2. Length of the metro network in two countries.

The central government of China has issued strict criteria for building metros in the cities having population over three million and GDP over $16 billion. The length of the metro network was 2058 km carrying around 872 thousand passenger in 2012 which is projected to increase to 14,000 km by 2050, assuming the same growth rate as taken in Jiang and Hu (2009).

Results and discussion

Transport demand

The total urban passenger transport demand increases by 3.4% and 5% per year from 2010 to 2050 in China and India respectively driven primarily by rising urban population and economic growth. The share of urban population has increased from 23.3% in 1980–81 to 31.1% in 2010–11, which is further expected to increase to 50% by 2050 (UN, Population Division). However, in case of China, the urbanization level has increased at a higher rate from 19.7% in 1980–81 (lower compared to India) to 49.5% in 2010–11. It is expected to reach 79% by 2050 which is 1.6 times more than that of India. Higher urbanization level accompanied with economic growth results in the higher mobility demand in case of China compared to India. Car ownership level is also higher in China compared to India due to higher income level in China.

Fig. 3 compares the urban transport modal spilt in both countries. As shown in Fig. 3, that there will be a shift from public transport towards the fastest and personalized mode of transport with income growth. The share of car transport will increase from 17% in 2010 to 51% by 2050 in India. Similar trend can also be seen in China also but the share of car in the overall urban transport is higher in China compared to India in 2050.The percentage share of 2 wheeler transport would be still higher in India compared to China due to lower GDP per capita and shorter trip distance within cities.

Energy consumption by technology

Energy consumption and emissions in China and India from urban road transport sector would be largely dependent on technology change in this sector. In the BaU scenario, the total energy consumed by China's urban road transport sector over 2010–2050 will increase by 3.6 times from 47 to 167 Mtoe whereas in case of India, the demand for energy increases at a higher growth rate from 7 Mtoe in 2010 to 51 Mtoe in 2050 (Fig. 4). The energy demand in urban transport sector in China is higher due to higher total passenger volume and car usage compared to India.

A closer look into energy consumption by technology reveals that in the case of China, the majority energy was consumed by gasoline car (43%), followed by diesel bus (39%) and diesel car (8%) in 2010 (Fig. 4). The technology mix will undergo changes by 2050 in the BaU scenario. Although internal combustion engine drivetrain technology will still be dominating the technology mix but due to consistent political support and technology progress, advanced technology car like hybrid, plug-in cars, and battery-operated electric vehicles will also penetrate in the market by 2050 under the business-as-usual scenario. The share of energy consumed by hybrid car, plug-in gasoline, and electric car would be 15%, 7% and 2.3%, respectively. The factors like climate change, air pollution, energy security and indigenous technology innovation have compelled the Chinese government to support the deployment of advanced electric vehicles (Chan and Yao, 2008; Zhang et al., 2010; Kan et al., 2010). The government of China has already set the target of deploying 5 million electric vehicles on the road by 2020 (IEA, 2013b). The government provided the subsidy of $10 thousand for electric car $8.3 thousand for advanced hybrid car in 2010 to achieve the target. Besides providing subsidies, the government also initiated the program named "Ten Cities Thousand Cars" in 2008. The program primarily focuses on the deployment of electric vehicles for public use in 10 cities which was further expanded to 25 cities in 2012 (Marquis et al., 2013).

The penetration of e-bikes in China has also increased drastically due to various policy interventions like banning motorcycles, limiting the number of issued licenses, restricting the entrance of motorcycles in particular lanes and allowing e-bikes in the bicycle lanes (Chen and Zhao, 2013; Hao et al., 2011; Suwei & Qiang, 2013; Yang et al, 2014). The share of electric two

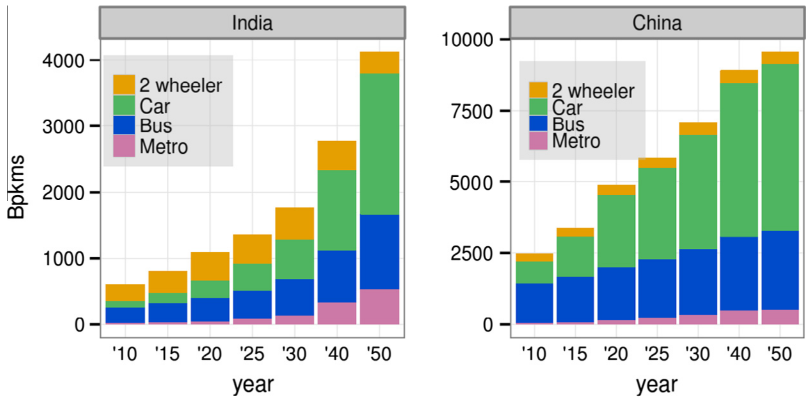

Fig. 3. Mode share in both the countries.

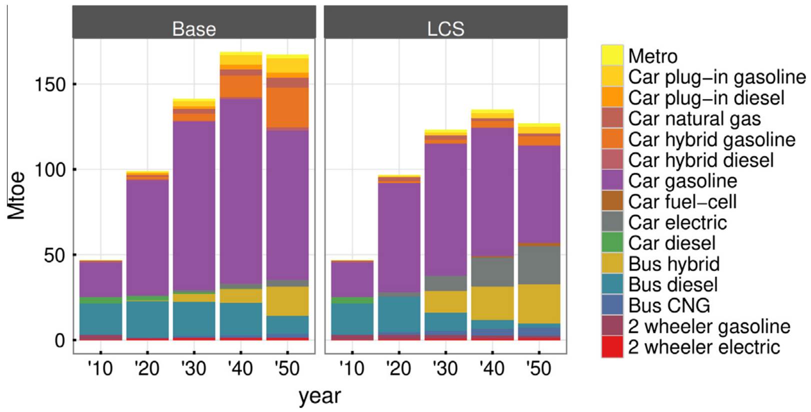

Fig. 4. Energy by technology in China.

wheelers will further increase in two wheeler market in China due to availability of low-cost vehicles and the introduction of large varieties of product in the market in the business as usual scenario.

In the low-carbon scenario (LCS), energy consumption in 2050 would change drastically that can be attributed to higher penetration of advanced vehicles and efficiency improvement. The costs of the advanced technologies like hybrid, plug-in, electric vehicles are assessed to decline in low carbon scenarios due to international cooperation and investment in R& D (Becker, 2009; Bruce et al., 2012). Vehicle stock has a shorter lifetime that provide flexibility for efficiency improvement that enable the decoupling between energy and demand growth. The decoupling happens between energy and transport demand in the LCS in China. Energy consumption grows at 2.5% compounded average growth rate (CAGR) during 2010–2050 compared to transport demand that increases at 3.4% CAGR during the same period. In the low carbon scenario, the penetration of electric vehicles like electric cars and hybrid buses is higher compared to BaU scenario due to strict carbon emission constraint, higher technology push towards clean technology and declining cost of battery.

In the case of India also, internal combustion engine drivetrain technology has dominated the technology mix in 2010 (Fig. 5). In two wheeler category, the electric two wheeler is still very minimal but it is expected the e-bikes sales will increase in the future due to the availability of low-cost electric bikes by Chinese producers. Similarly, like China, the Indian government has announced several initiatives to increase the diffusion of clean and advanced technologies. The Ministry of New and Renewable Energy (MNRE) has initiated Alternate Fuel for Surface Transportation Program (AFSTP) for supporting R& D activities related to advanced high energy density battery development and other components for electric vehicles. They have also laid out National Electric Mobility Plan expecting to increase the number of electric vehicles to around 6–7 million by 2020 by providing the incentives for faster diffusion of electric vehicles (SIAM, 2010). Owing to government's current policies, advanced technology cars like hybrid, plug-in cars, and battery-operated electric vehicles will also penetrate into the Indian market by 2050 in BaU scenario, but the share will be lower compared to China.

Similar to China, energy consumption in 2050 would reduce in India due to higher penetration of advanced vehicles and efficiency improvement. In the low carbon scenario, the energy demand would reduce to 32 Mtoe in 2050 from 51 Mtoe in BaU scenario. Furthermore, the energy intensity measured in terms of toe per passenger kilometer would reduce from 12 to

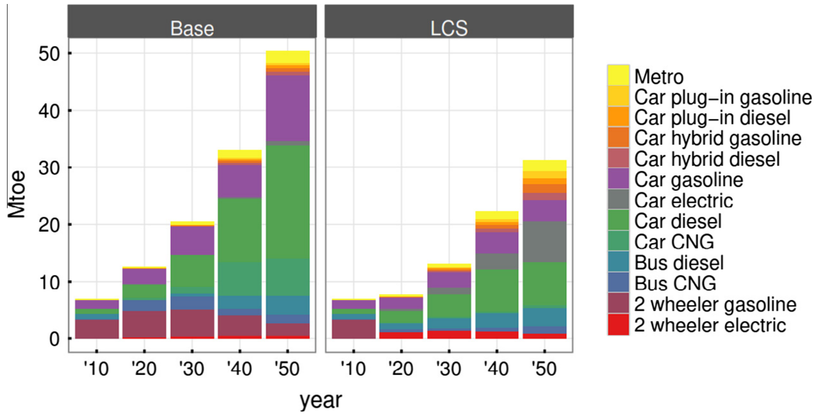

Fig. 5. Energy by technology in India.

7 toe/pkm in 2050 in low carbon scenario. The share of energy consumed by battery-operated electric vehicles increases to 22% in LCS compared to 1% in the business as usual scenario.

Fuel mix

As a result of technology mix change, the energy mix in LCS would differ significantly from the baseline scenario in both countries. As shown in Fig. 6, oil has dominated the fuel mix in urban road transport sector while the share of natural gas (1%) and electricity (3%) is marginal in 2010 in China. The situation does not change significantly in the baseline scenario in 2050. The slight diversification can be observed towards electricity, natural gas and biofuel in the BaU scenario. The share of electricity increases to 8% in 2050 due to more use of hybrid and electric vehicles in BaU scenario. On the contrary, a significant amount of fossil energy will be substituted by electricity and biofuel in 2050 in the LCS due to high penetration of electric and hybrid vehicles and fuel shift caused by carbon tax.

In India also, the energy mix is dominated by gasoline and diesel in the BaU scenario, but it diversifies in the low carbon scenario, and we can observe the presence of CNG and biofuel in the primary energy supply (Fig. 7). The share of electricity increases to 34% in the LCS from 7% in BaU scenario due to the penetration of advanced efficient technologies in 2050.

CO_2 emissions

As a result of the increased travel volume, the CO_2 emissions from urban transport sector would increase in both countries. In India, it would increase from 22 Mt CO_2 in 2010 to 157 Mt CO_2 in 2050 under the baseline scenario. The India's grid is highly carbon intensive with 950 gCO_2/KW h compared to other countries in the world (CEA, 2014) due to their high dependence on coal. The use of the electric vehicles and hybrid vehicles reduces the tailpipe emissions, but this reduction gets offset by increased emissions at the coal power plants in the BaU scenario. Similarly in the case of China, introduction of electric cars and e-bikes could not help in providing the deep CO_2 reduction due to high coal dependency in the electricity generation sector. The CO_2 emissions increase from 143 Mt CO_2 in 2010 to 475 Mt CO_2 in 2050 under baseline scenario.

However, as a result of cost reduction of advanced technologies like electric vehicles, efficiency improvement and carbon tax in low carbon scenario, CO_2 emissions would reduce to 55 Mt CO_2 and 239 Mt CO_2 in India and China respectively (Fig. 8). The CO_2 emissions in China would peak in 2030 and then start declining in the low carbon scenario. Due to the carbon tax, the carbon intensity of power sector will also decrease in the low carbon scenario in both countries which help in achieving the CO_2 reduction.

Comparative lessons and conclusions

Since China is ahead of India in terms of urbanization and per capita income, China's urban transport development pattern has important lessons for India. In the coming decades, India's cities shall grow in size and numbers and nearly 0.8 billion people will be living in urban areas (UN, 2014). This will pose challenges as well as offer opportunities for transforming the urban transport.

India can learn from China's positive and negative experiences. First lesson is to recognize that in an emerging economy that is rapidly transiting from low to medium income, the business-as-usual urban transport policies shall cause multiple negative externalities from congestion, local air pollution and CO_2 emissions. In China, the external costs from urban transport systems have been rising during the past two decades despite rapid implementation of measures like vehicles fuel economy, progressively improved emissions standards, constructing bicycle lanes, walkways and pedestrian bridges and

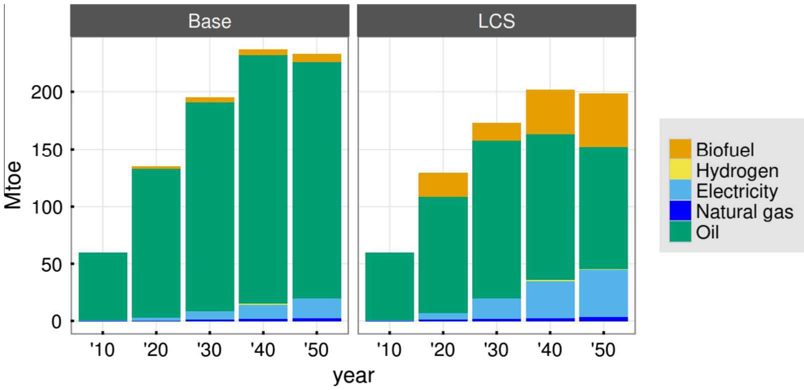

Fig. 6. Fuel Mix in China in different scenarios.

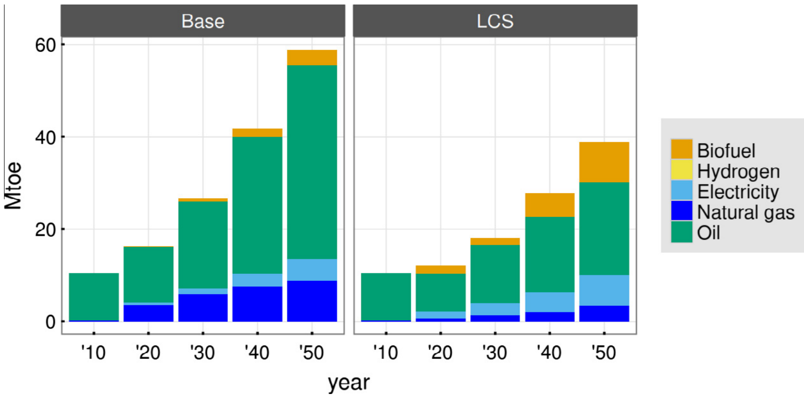

Fig. 7. Fuel Mix in India in different scenarios.

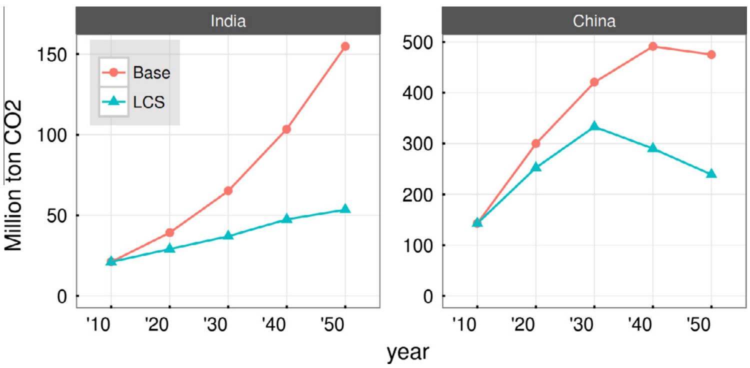

Fig. 8. CO_2 emissions from urban transport sector in India and China ($MtCO_2$).

major investments in public urban transport infrastructures. Since India's economic growth story is trailing China; the lesson, therefore, is obvious that even the stupendous efforts, such as made by China, would be inadequate to stem the rising external costs from urban transport. In India's case, the time lag has a disadvantage vis-a-vis the need for low-carbon transition. India's high economic growth shall overlap the period when the future global carbon budget (IPCC, 2014) to achieve the global 2OC temperature stabilization has become stringent and hence lead to higher carbon price expectations (Lucas et al., 2013). India therefore, besides learning from China, shall require implementing even more innovative urban low carbon transport solutions.

Another important lesson from China is that despite huge push to the public transport by the city governments, the urban transport demand in past decades kept outstripping the supply of public transport, thereby leading to rapid rise in private motorized transport. The modeling results show that such trend in China shall sustain under a business-as-usual future thereby making city transport a major contributor to local air pollution and CO_2 emissions. The sizable penetration of electric two wheelers in the Chinese cities have marginally mitigated the in-situ emissions of local pollutants, but there is little impact on CO_2 emissions due to high carbon content of electricity in China. Electric vehicles just transfer the emissions to the electricity system that powers these vehicles. Policies of shifting power plants away from cities and making mandatory use of end-of-the-pipe clean air technologies like flue gas desulfurization and denitrification do help mitigate local air pollution (Lin and Elder, 2014), but not the CO_2 emissions. The modeling results also show that under a business-as-usual future, urban transport demand in China and India shall continues to rise at a pace that is much quicker than the rate of improvement in vehicles fuel economy. The modeling assessment shows that the low carbon fuel-mix including the change in fuel-mix to decarbonize electricity is the key option for deep decarbonization of transport sector in both the nations under the low carbon scenario.

Income is an important driver of quantum and type of travel demand. In India, income and urbanization are expected to grow at a rapid rate over the coming decades while China's growth rate would subside. Under a business-as-usual trend, the car ownership levels (per thousand population) in India may follow the pattern of the developed nations such as in the number of cars per thousand population; e.g. U.S (423), Germany (517) and Japan (453).[1] The urban sprawl, diversity of activities, their scale and locations would depend on the design of the urban form. Evidently, the underplanned development in India, shaped largely by organic forces such as in the business-as-usual scenario, would result in lock-ins into longer trip distances and more motorized trips. In China, such structural and behavioral lock-ins are already evident; from the high rate of motorization, long trip lengths, trip numbers and energy inefficient fossil fuel dependent vehicles.

The immediate task in India is to prevent such lock-ins thereby circumvent; *first*, the health and other impacts from worsening air quality-; and *second*, the loss of time and increased stress due to congestion. Besides, high car ownership levels shall drive the oil demand which shall increase the risk to energy security as India imports overwhelming fraction of its oil consumption. India, has the opportunity to avoid the lock-ins through proactively shaping the transport supply and demand through the choice of urban forms, transport modes, vehicles and fuels standards, and pricing policies for public transport.

Another lesson for India, from China's trends, is the rapid transition from gasoline-powered two wheelers to electric two wheelers. The low vehicle price and operating cost, improved battery performance, dedicated two wheeler lanes and favorable government policies have made e-bike as an economic and convenient mode of transportation in China. To increase the penetration of e-bikes, the government has also taken several steps like banning the sale of gasoline-powered scooters and allowing them to use the bike lanes. Taking into consideration the short trip distance in small cities, e-bikes are convenient alternative to gasoline powered vehicles. As India has high two wheeler use, supply-deficit of public transport and rising urban transport demand, substituting gasoline-powered two wheelers with e-bikes can mitigate local air pollution in the near-term and also create charging infrastructure. This can pave the way for higher penetration of electric vehicles, as the electricity sector gets decarbonized under the global low carbon scenario.

In the coming decades, India will witness rising population, urbanization and income. These multiple transitions offer varied opportunities to gain multiple co-benefits by creating a sustainable urban mobility architecture that integrates land-use, infrastructures, finance and citizen behaviors. In addition to the conventional finance, the low carbon transport investments can receive incremental finance from the carbon finance instruments.

The key conclusions from the analysis in this paper are that vehicle fleet, driven by economic growth, rising population and urbanization, will continue to grow for the next several decades. The modeling results show that the emissions can be decoupled at two levels. First decoupling happens between energy and urban transport demand through efficiency improvement. However, improving fuel economy alone is inadequate to achieve the deep decarbonization needed to achieve the global 2 °C temperature stabilization target. Strong decoupling between energy and emission is essential for deep decarbonization that can be achieved through shift towards low carbon fuels like electricity generated from low-carbon sources and biofuel In other words, the results highlight the fact that there is no silver bullet which can reduce transport related greenhouse emissions radically.

India's approach to mitigate carbon emissions from the urban transport is to align the carbon mitigation policies with other development objectives to gain multiple co-benefits. With this aim, India has instituted 'Sustainable Habitat Mission (GoI, 2008). The analysis in this paper show that India's urban transport roadmap should focus, in the near-term on avoiding lock-ins into private motorized transport and in the medium-term include urban transport as an element of and for sustainable urban design. In the long-term, both China and India face enormous challenge to transform their transport systems that is geared to contribute to national development goals as well as global climate change target. This will require using a spectrum of measures like *avoiding* trips that are substitutable by design of urban forms or information technology; *shift*ing to lower energy using and emissions causing transport modes and adapting to *improved* vehicle technologies that use hydrogen or electricity generated by low carbon sources.

The comparative modeling assessments show that both China and India can contribute to as well as benefit by aligning their transport plans with global climate stabilization regime. Carbon finance as well as international co-operation and co-ordination for innovation and deployment of low carbon transport technologies and infrastructures, if well planned deployed, shall make low carbon transport transition a win–win–win strategic opportunity for China, India and the world.

[1] http://data.worldbank.org/indicator/IS.VEH.PCAR.P3/countries.

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Appendix A. Supplementary material

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