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Urban Mobility Forecasts: Emissions Scenarios for Three Indian Cities

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ABSTRACT
The growth of motorization and travel activity associated with India's rapid urban development has serious implications for global climate change. Effective mitigation action requires comprehension of the scale of the problem. However, data limitations have thus far constrained efforts to understand how changes in demographics, travel behavior, and policy might affect future emissions of greenhouse gases. This study uses recently available data on city-level travel patterns to forecast emissions from passenger transport for three metropolitan areas: Mumbai, Ahmedabad, and Surat. The forecasts compare carbon dioxide emissions for three scenarios using various mode choice and trip length assumptions. The results predict dramatic increases in emissions under all circumstances. Travel in Surat is forecast to generate between 1.9 and 9.5 million tons of CO_2; in Mumbai it could generate 10.3 to 49 million tons. However, differences between scenarios suggest the potential positive effects of policy interventions. While the results help convey the magnitude of the emissions problem, further analysis requires more complete data on individual travel behavior.

INTRODUCTION

The rapid growth of urban India has attracted the world's attention to these cities' enormous potential, but also to the seriousness of the implications for climate change. In the transport sector, the challenge of mitigating climate change arises from the convergence of several trends: population growth, large-scale migration to cities, rapid economic development, and rising incomes, all of which lead to greater travel demand and motorization. The introduction of low-cost cars, affordable to a growing middle class, could hasten the trend toward greater automobility. At the same time, urbanization and the increased importance of urban areas has placed the spotlight on cities to manage greenhouse gas (GHG) emissions. India's cities now stand in a position to guide future mobility, but doing so requires an understanding of the probable consequences of various policy paths.

Although the scale of urban growth in India is widely recognized, data limitations have constrained efforts to understand how changes in demographics, travel activity, and transport policies might affect future emissions of GHGs. Previous analyses of vehicle emissions have been limited to the national level or the very largest cities. However, newly available city-level travel surveys enable projections of mobility scenarios to a greater degree of detail for a wider range of cities. The present analysis uses available data on demographic trends and travel behavior to forecast carbon dioxide emissions from passenger transport for three metropolitan areas: Mumbai, Ahmedabad, and Surat. The forecasts illustrate how alternative policy strategies designed to influence travel patterns could affect future emissions.

This paper describes the study's methodology and results. The first section identifies gaps in existing studies, discusses the selection of cities, and explains the approach to the problem. The second section describes the methodology, presenting details for the city of Surat. Analysis for the other two cities follows the same methodology, using similar data sources and assumptions. Final sections of this paper compare results from the three analyses, discuss policy implications, and recommend future directions for research.

Previous Studies

Several studies have attempted to quantify the impact of India's transport sector on GHG emissions, but few studies have considered city-specific travel behavior at a detailed level. In a study for Delhi, Bose and Nesamani (1) estimate emissions from urban transport under various scenarios. Their analysis predicts future passenger travel and vehicle ownership based on historical correlations with population and income growth. Focusing on Mumbai and Delhi, Das and Parikh (2) formulate a model of transport energy consumption and emissions using projected changes in vehicle numbers. In the only study to recognize the influence of urban form on travel behavior, Fabian and Gota (3) calculate emissions for 29 cities based on trends in travel demand, city density, and current mode share.

At the national level, Schipper et al (4) forecast emissions generated by travel under three different scenarios based on growth in vehicle ownership. In a study comparing energy efficiency scenarios, Singh (5) estimates per capita mobility as a function of GDP and calculates energy consumption and CO_2 emissions.

The results of these analyses point to the magnitude of the emissions problem, but all rely on scarce data and generous assumptions. With one exception, these studies derive from vehicle counts rather than city-specific observed travel behavior and consider only nation-wide emissions or the largest cities. Even with limited data, an analysis focused on city-level travel behavior can contribute to our knowledge of emissions from urban travel.

Choice of Cities

To enable a more generalizable analysis of city-level travel, we have selected cities at three distinct stages of development: Mumbai, Ahmedabad and Surat. Mumbai is representative of large metropolitan areas which have been established as major cities for some time, similar to Delhi or Chennai. Having experienced significant growth in the past two decades, Ahmedabad represents more recently emergent cities such as Bangalore and Pune. Surat belongs to a category of cities that are smaller but currently undergoing intense growth, making them important targets for sustainable policies.

Mumbai

With a population of 17.7 million, Mumbai is a city struggling to cope with tremendous numbers of people. Fueled by economic migration, the city maintains a high rate of growth—it added 4.3 million inhabitants between 1991 and 2001. Though the official Mumbai Metropolitan Region is large (435 km^2), most of the population lives within the 438 km^2 Greater Mumbai area at a density of 22.7 per hectare. South Mumbai is one of the most crowded districts in the world, with 491 residents per hectare. Given such high density in the existing city, future growth will necessarily spread outward to the north and east.

Travel in Mumbai is characterized by crowding and congestion. The barriers of Thane Creek and the Arabian Sea force new development to the north of the city and, despite attempts to encourage business growth in the eastern node of Navi Mumbai, the vast majority of employment still lies in the established commercial centers, forcing traffic into relatively few and narrow corridors. Compared with other Indian cities, usage of public transit in Mumbai is high (52% of all trips) and non-motorized mode share is relatively low, presumably due to the city's longer travel distances, relatively high incomes, and greater availability of transit (TABLE 1). Given its higher rate of motorized travel and the higher frequency of trips, we would expect Mumbai to have greater per capita emissions than other cities, a pattern that will probably continue for some time into the future. Even with higher capacity infrastructure and the development of new employment centers, it is likely that Mumbaikars will continue to face long and crowded commutes. On the other hand, use of private vehicles (including motorcycles) is relatively low and heavy congestion may prevent it from growing.

Ahmedabad

While not characterized by the extreme growth of Surat or the enormity of Mumbai, Ahmedabad represents challenges typical of large Indian cities. Its population of 5.4 million has grown 32% from 1991 to 2001, driven largely by rural-urban migration. Expansion has generally followed main corridors, which form the spines of a concentric road network. The population in the older inner city has largely stabilized at a relatively high density of 184 persons per hectare (6). The entire Ahmedabad Urban Agglomeration is populated at 20 per hectare, but is densifying as the city develops. Overall, the city is still relatively compact, but the availability of peripheral land presents a high potential for sprawl.

Travel in Ahmedabad is largely individual. Most trips are by foot (38%), motorcycle (25%), or bicycle (18%) (TABLE 1). The usage of motorcycles is increasing; this could lead to higher per capita emissions, especially if motorcycle users switch to automobiles. However, the recent introduction of bus rapid transit could be a step toward a signficant transit system that could moderate growth in emissions.

TABLE 1 Travel Behavior Characteristics for Three Cities, 2005

	Mumbai	Ahmedabad[e]	Surat[f]
Population (millions)	17.7	5.4	2.4
Trip rate (trips per person per day)	1.26[a]-1.67[b]	1.04	1.31
Average trip length - motorized (km)	12.4[c]	14.4	8.5
Average trip length - non-motorized (km)	2[b]	2.3	3.6
Mode split (% of total trips)			
Walk	27[d]	37.6	42
Bicycle	6	17.6	13.4
Auto-rickshaw	6	8.3	10.8
Bus	26	8.4	2.3
Train	20	0.3	0.1
Motorcycle	10	25.3	28.4
Private car	5	2.48	2.6

Sources: [a](9); [b](11); [c](10); [d]*Mode split data for Mumbai based on* (9) *and* (11); [e] (6); [f](8).

Surat

Smaller but rapidly growing cities like Surat attract less attention than their more superlative counterparts, but it is these "now exploding" cities that offer the greatest potential for intervention, as infrastructure and policies introduced now will have profound influence over the city's future. Driven mainly by rural-urban migration, Surat is one of the fastest growing cities in India. Between 1991 and 2000, its population rose from 1.5 to 2.4 million, an increase of 62%; compare this with a 32% increase in Mumbai during the same period. The city is relatively compact, with a density of 506 persons per hectare in the walled city and 194 per hectare in the wider central city area. The city has been expanding rapidly along the main radial corridors and, as in Ahmedabad, holds the potential for low density sprawl.

Surat's travel profile resembles that of Ahmedabad (TABLE 1). The average trip is somewhat shorter than in the other cities though, perhaps due to its smaller size. In both cities less than 3% of trips are currently made by car; in this context even a small increase in car use could mean visibly large rises in emissions. Like many other growing cities in India, Surat is developing a bus rapid transit system that could encourage more transit use in the future.

Emissions and Transport Policy

Four basic factors contribute to GHG emissions in transport: overall amount of travel, share of travel accorded to each mode, energy consumption of vehicles, and characteristics of fuel and vehicle technology (7). Urban transportation planning policies can potentially reduce emissions by influencing the first two factors: amount of travel and mode share. By focusing on these two aspects of travel behavior, this paper will address the magnitude of possible effects of transportation and spatial planning policies on emissions.

Overall travel, measured in vehicle kilometers traveled, is determined by population, trip length, and trip frequency. The driving forces behind trip frequency—namely household income and employment—are expected to increase in all Indian cities. Trip length is determined by relative travel cost, time constraints, and origin-destination locations—a combination of factors often summarized as accessibility. Transport policies to reduce overall amount of travel work by targeting travel cost, while planning polices might encourage shorter trips through their influence on urban form, particularly density and location of major population and employment centers.

Transport policy can also target mode choice, the determinants of which closely interact with those factors influencing travel activity. Generally speaking, mode choice is determined by relative travel cost, both monetary and temporal, which is in turn influenced by general accessibility. Travel distances and the design of streets and transport facilities can influence the relative attractiveness of each mode—making policies that affect urban form and transport infrastructure particularly important.

METHODOLOGY

Emissions forecasts are developed using a "bottom-up" model based on reported travel activity. More specifically, data on observed trip rates, combined with assumptions about travel distances, mode share and vehicle emissions, allow calculation of CO_2 emissions for three policy scenarios, each reflecting a different policy strategy.

Data Sources

The analysis for Surat uses travel data from household surveys conducted by the Central Road Research Institute (CRRI) in 1988 and 2004, as reported in the Surat Comprehensive Mobility Plan (8). Additional travel data for Surat comes from a 2005 survey by Consulting Engineering Services Pvt. Ltd. Unless otherwise noted, the CRRI data are used, as they provide greater consistency between the two time points.

Data for Ahmedabad come from a household travel survey conducted in 2000 and referenced in the Ahmedabad BRT Plan Report (6). Sources for Mumbai travel data include the Mumbai Comprehensive Development Plan (9), the Mumbai Metropolitan Regional Development Authority (10), and the World Bank-funded household survey conducted in 2003 and 2004 (11). All population figures come from the Indian Census.

Demographics

Growth in both overall population and in the number of workers drives much of the increase in vehicle emissions. In Surat, the growth rate is assumed to decline gradually (resulting from a lower birth rate and reduced migration), resulting in a population of 10.8 million in 2041 (see TABLE 2).

TABLE 2 Population Growth Assumptions for Surat

Year	Population	Decadal Growth Rate
1951	223,182	-
1961	288,026	29%
1971	471,656	64%
1981	776,583	65%
1991	1,498,817	93%
2001	2,433,785	62%
2011	3,967,070	63%
2021	5,950,604	50%
2031	8,330,846	40%
2041	10,830,100	30%

Travel Activity

Experience of more industrialized countries suggests that growth in per capita trip rates corresponds with rising income and employment, which is driven by economic growth and increasing numbers of working women (12). Evidence from Indian cities indicates steadily increasing trip rates, which will likely continue to rise along with economic development and greater women's employment (TABLE 3). If current trends continue, residents of Delhi and Surat (two cities for which historical data are available) will make an average of two trips per day in 2040. The trip rate in Mumbai has increased even more rapidly. If one accounts for the likely effect of many more women working outside the home, rises will be even steeper. The present analysis assumes that the per capita trip rate in each city increases from current levels to three trips per day in 2040. A trip rate of three is comparable to current rates in other developed countries, which have reached fairly stable levels (TABLE 3).

TABLE 3 Trip Rates for Selected Cities and Countries

Location	Year	Average Per Capita Daily Trips
India		
Delhi[a]	1969	0.49
Delhi[a]	1981	0.72
Mumbai[b]	1991	0.95
Mumbai[c]	2000	1.67
Surat[d]	1988	1.02
Surat[d]	2004	1.31
International		
U.S.[e]	1995	3.8
U.K.[e]	1997	2.9
Toronto[f]	1964	1.5
Toronto[f]	1996	2
Singapore[g]	1991	2
Norway[g]	1992	3
Netherlands[g]	1995	3.5

Sources: [a](13); [b](10); [c](11); [d](8); [e](14); [f](15); [g](16).

Policy Scenarios
The scenarios envision three different policy approaches to transport and land use policy: automobility ubiquity, two-wheeler promotion, and sustainable urban transport. Mode choice and trip length assumptions define the differences between scenarios.

Mode Share
Scenario 1: Automobility Ubiquity Under this scenario, increased household wealth and availability of affordable vehicles allow widespread automobile ownership, resulting in greater car travel at the expense of walking, cycling, and public transit. Since most families aspire to own a car rather than a motorcycle, 2-wheeler mode share declines. Public transport receives minimal investment, and road space gives preference to cars. Traffic congestion becomes a serious problem in all cities, but because public transport service is poor, those who can afford a car choose to drive. TABLE 4 shows mode share assumptions for each scenario.

TABLE 4 Assumed Mode Share Scenarios in Surat (% of total trips)

	Current	Automobility Ubiquity		Two-Wheeler World		Sustainable Urban Transport	
Mode	**2004**	**2020**	**2040**	**2020**	**2040**	**2020**	**2040**
Walk	42.0	36	22	30	18	30	20
Bicycle	13.4	11	6	9	2	14	15
Auto-rickshaw	10.8	8	8	8	5	6	5
Motorcycle	28.4	20	12	38	50	20	8
Bus	2.3	5	10	5	10	25	45
Train	0.1	0	0	0	0	0	0
Private car	2.6	20	42	10	15	5	7

Scenario 2: Two-wheeler World As in the first scenario, rising incomes enable greater vehicle ownership, but, fearing massive traffic congestion and air pollution, cities have enacted policies promoting smaller vehicles. As a result, larger vehicles are expensive and street design favors two-wheelers, making motorcycles the most popular choice. However, non-motorized modes and public transit remain a lower priority and shares for these modes remain relatively low.

Scenario 3: Sustainable Urban Transport In contrast to the previous two scenarios, policymakers promote energy-efficient modes of public transit, cycling, and walking. Auto rickshaws, shared taxis, and private vehicles are still important, but careful and proactive planning has resulted in the decoupling of economic growth and increased motorization. Well-integrated transit and non-motorized modes serve a substantial portion of travel demand, complemented by moderate use of motorized vehicles. Coordinated land use planning ensures that the transport system meets travel demand without requiring car dependency. As a result, the share of bus, rail, walking, and cycling rises relative to that of other modes.

Trip Length and City Density
Trip lengths in all cases are expected to increase as cities grow and travel becomes faster and/or cheaper. Evidence indicates that travel distances in Indian cities have been increasing; in Surat the average car trip lengthened from 3.8 km in 1988 to 9.7 km in 2004 (8). However, trip length data for these three cities include only two historical time points. Rather than rely solely on

extrapolation from such limited data, future trip lengths are estimated based on expected city size and density, then compared with estimates from extrapolation of current trends.

Each scenario assumes that urban development will take on a given density, which, given population forecasts, determines city area and influences travel distances. Since population densities for all three cities are already quite high, the scenarios envision either constant or somewhat lower densities. At present, the Surat Municipal Area holds 217 persons per hectare. Residents of Greater Mumbai live at 227 per hectare; the density of central Mumbai is 491 per ha. The three cities could reasonably be expected to continue development at current densities, but higher densities are assumed to be both improbable and undesirable. Thus the Automobility scenario supposes that easier car travel and weak policies permit the city to sprawl, reducing density by 50% in 2041. The Two-wheeler and Sustainable Transport scenarios assume that stronger planning and higher travel cost maintain density at constant levels.

The average trip length in each city is assumed to be a function of overall city size and shape, as determined by expected density. Surat and Ahmedabad are roughly circular in shape, so travel distances are measured asa ratio of the city radius. Mumbai commuting patterns are currently mostly linear, but additional commuting axes are expected as population expands to the east of the city, eventually approximating a quarter-circle. So, for example, to accommodate new population at current densities, Surat will have to grow to 500 km^2 in 2040, implying a trip from the periphery to the city center would be 13 km. Trip lengths for each mode are estimated assuming the current relationship between city radius and travel distance for each mode remains the same (TABLE 5). Of course, few people travel exactly from the city edge to the center, and these cities will likely become even more polycentric, but the assumption of a relationship between trip length and city size provides a rough approximation of travel distances. The trend shown by extrapolation of available trip length data predicts similar values, suggesting that these assumptions are reasonable. For example, the assumed trip length for a car under Sustainable Transport is 14.2 km, compared with 15.3 km according to the trend.

TABLE 5 Assumed Trip Lengths Compared with City Size - Surat

	Current	Automobility		Two-Wheeler		Sustainable Transport	
	2005	2021	2041	2021	2041	2021	2041
Trip lengths by mode (km)							
Auto-rickshaw	5.3	7.9	13.1	6.9	9.3	6.9	9.3
Motorcycle	5.8	8.7	14.3	7.5	10.1	7.5	10.1
Bus	12.4	16.2	26.7	14.0	18.9	14.0	18.9
Train	9.3	13.4	22.1	11.6	15.6	11.6	15.6
Private car	9.7	12.2	20.1	10.6	14.2	10.6	14.2
City Size							
Population[a] (millions)	2.43	5.95	10.83	5.95	10.83	5.95	10.83
Population Density (per ha)	217	163	109	217	217	217	217
City Area (km2)	112	366	999	275	500	275	500
Radius (km)	6.0	10.8	17.8	9.4	12.6	9.4	12.6

[a]*Population and area are for the Surat Municipal Area.*

Emission Factors

The emission factors for each vehicle and fuel type are based findings from three studies of vehicle emissions reported in Mittal & Sharma (17), Bose & Nesamani (1), and Iyer (18). Each of these studies estimates emissions of the current Indian fleet using basic combustion principles and appropriate Indian driving cycles. International Panel on Climate Change (IPCC) conversion factors for each fuel type allow translation from average energy consumption values to CO_2 amounts (see TABLE 6).

TABLE 6 Energy Consumption and Emission Factors for Current Indian Vehicles as Estimated in Various Studies

Vehicle Type	Bose & Nesamani[a] (MJ/km)	Mittal & Sharma[b] (MJ/km)	Iyer[c] (MJ/km)	Average (MJ/km)	Emission Factor (g CO2/km)
Motorcycle (2-stroke)	0.8	0.48	0.60	0.6	45.2
Motorcycle (4-stroke)	0.54	0.43	0.47	0.5	34.6
Auto-rickshaw (2-stroke)	1.6	0.97	1.06	1.2	87.2
Auto-rickshaw (4-stroke)	1.5	1.14	0.92	1.2	85.6
Petrol car	3.5	3.71	-	3.6	259.9
Diesel car	4	3.94	-	4.0	286.2
Diesel bus	11.25	8.3	-	9.8	704.8
Train (metro)	-	-	-	21.3	1541
Train (suburban rail)	-	-	-	14.7	1063

Sources: [a] (1); [b](17); [c](18).
Dashes indicate data not available.

Electricity generation for rail transit is assumed to derive 68% from coal and 15% from hydroelectric (19). Average energy demand for metro and suburban trains in major Asian cities, as reported in Kenworthy (20), form the basis for emission factor calculations. Energy consumption rates are expected to decline, with future Indian rail approximating the efficiency of today's trains in high-income Asian countries. Although these data account for delivered energy and not actual energy consumption, it is the best available data for the context of Indian cities. Since the contribution of rail travel to overall emissions is very small for all scenarios, the difference between energy demand and actual consumption is unlikely to significantly affect results. IPCC emission factors are used to convert from energy consumption per vehicle-kilometer to CO_2 emissions (TABLE 6).

Calculation of future fleet-wide emission factors assumes that fuel economy of new vehicles improves at a pace similar to that in other countries. Average emissions from new European passenger cars have fallen from about 180 grams CO_2/km in 1995 to 165 g CO_2/km in 2002 (21). In an agreement with the European Union, European, Japanese, and Korean automakers have committed to a further reductions, aiming for 120 g CO_2/km in 2012 (21). India does not currently regulate CO_2 emissions for vehicles, but standards for other pollutants follow European standards, with a five-year time lag. Assuming that vehicles generating 120 g CO_2/km are available in India in 2017, it is not unreasonable to expect the entire fleet to achieve 120 g CO_2/km by 2037, given that the approximate lifespan of Indian automobiles is twenty years (17). This would represent an annual improvement in fuel economy of about 2.1%. It is assumed that fuel economy for passenger cars and buses improves at the same rate (TABLE 7). Emissions for two- and three-wheelers, which are already relatively low, are expected to decrease by 1.5% each year.

TABLE 7 Projected Emission Factors for Vehicles in India (g CO_2/veh-km)

Vehicle Type	2000	2020	2040
Petrol motorcycle (2-stroke)	45	33	25
Petrol motorcycle (4-stroke)	35	26	19
Petrol auto-rickshaw (2-stroke)	87	65	48
Petrol auto-rickshaw (4-stroke)	86	63	47
CNG auto-rickshaw	67	50	37
Petrol car	260	170	111
Diesel car[a]	286	173	104
CNG car	212	139	91
Diesel bus	705	461	302
CNG bus	548	359	235
Train (metro)	1541	1008	659
Train (suburban rail)	1063	696	455

[a]The current data show that Indian diesel cars produce greater emissions than petrol cars, when, theoretically, diesel cars should achieve greater fuel economy that petrol vehicles. It is assumed that fuel economy for future diesel vehicles is similar to that in other countries.

Fuel Type

The scenarios assume modest increases in the use of diesel and compressed natural gas (CNG) in passenger cars. The Indian government has required three-wheelers and buses in Delhi to convert to CNG, prompting support for similar policies in other cities (22, 23). This analysis assumes that by 2040 all three-wheelers and 80% of buses run on CNG.

Vehicle Occupancy

Values for average vehicle occupancy are based on 2004 CRRI data and are shown in TABLE 8. In Surat, where shared auto-rickshaws are common, each vehicle carries an average of 3 passengers; whereas in Mumbai the average is 1.2. Mumbai trains are assumed to carry an average of 150 people in each of 10 cars per train. The occupancy values allow conversion of emission factors to g CO_2 per passenger-kilometer, as shown in TABLE 8.

TABLE 8 Vehicle Occupancy and Per Passenger-km Emissions for Surat

	Vehicle Occupancy	Emission Factor (g CO_2/passenger-km)		
Mode		2005	2020	2040
Auto-rickshaw	3	27.3	12.4	14.3
Motorcycle	1.1	36.3	27.2	20.4
Bus	40	15.7	14.1	13.1
Private car	1.25	210.0	188.3	170.3

RESULTS

Steep rises in GHG emissions are expected in all scenarios, yet the results suggest that different policy strategies could result in dramatically different levels of emissions. In all three cities, population growth, higher trip rates, and city expansion will contribute to increasing travel activity. In 2041, Surat will need to accommodate ten times as many trips as in 2005, which will produce between 1.9 and 9.5 million tons of CO_2 annually (TABLE 9). Yet these figures are dwarfed by comparison with Mumbai, where transport will generate 10 to 49 million tons of CO_2.

TABLE 9 Estimated Travel Activity and CO_2 Emissions

	Current	Automobility		Two-Wheeler		Sustainable Transport	
	2005	2021	2041	2021	2041	2021	2041
Total Daily Trips (millions)							
Mumbai	29.6	65.4	146.9	65.4	146.9	65.4	146.9
Ahmedabad	5.6	14.9	39.8	14.9	39.8	14.9	39.8
Surat	3.2	10.9	32.6	10.9	32.6	10.9	32.6
Total Emissions (million tons CO_2/year)							
Mumbai	2.33	14.89	49.12	6.08	15.20	5.36	10.26
Ahmedabad	0.33	3.49	12.32	1.56	4.19	0.93	1.97
Surat	0.15	1.56	9.52	0.93	3.62	0.60	1.92
Total Per Capita Emissions (kg CO_2/person/year)							
Mumbai	132	490	1011	200	313	176	211
Ahmedabad	61	397	933	178	317	106	149
Surat	63	262	879	156	334	101	177
Ratio to 2005 emissions							
Mumbai		6.4	21.1	2.6	6.5	2.3	4.4
Ahmedabad		10.6	37.4	4.8	12.7	2.8	6.0
Surat		10.2	62.3	6.1	23.6	3.9	12.6

Comparison between the three scenarios shows that the overall emissions from transport greatly depend on mode choice. In all cities, automobility ubiquity will mean dramatic increases in overall emissions (TABLE 9). On the other hand, emissions under the Sustainable Transport scenario increase "only" about twelve times. In all cities, the amount of CO_2 generated by each resident would increase by a factor of ten under the Automobility scenario, while the Sustainable Transport scenario predicts only a two- or three-fold increase in per capita emissions.

In all scenarios, automobiles contribute the greatest amount to emissions, even when they represent a very small proportion of trips. Under the Automobility scenario in Surat, cars make 42% of trips but are responsible for 90% of total emissions. Even in the Sustainable Transport scenario, when their mode share is only 7%, cars generate 50% of CO_2.

The predicted magnitude of increase in emissions is undeniably and perhaps surprisingly large, especially for the Automobility scenario. Yet the trends represented here are not unprecedented in the rest of the world. Even under the "worst-case" Automobility scenario, the average Surat resident in 2040 would travel 29 kilometers each day, comparable to the average German or Briton and substantially less than the typical American (16). The average trip length in Surat would be 9.5 km, slightly less than the average journey-to-work distance in Canada or Hong Kong (24). The corresponding level of vehicle ownership would be 337 cars per 1000 people, still below levels in European and American cities (25).

Uncertainty in Results

The scarcity of available data for this analysis introduces a considerable amount of uncertainty. By relying on travel activity information rather than vehicle ownership, this analysis has attempted to draw attention to the local context of urban travel, but substantial assumptions are still necessary. Lack of historical data on trip length and trip frequency mean that forecasts must be estimated indirectly based on demographic trends and physical city form. Current data from industrialized countries has been used to validate both trip length and frequency assumptions, but even these show a great degree of variability between countries and there is no guarantee that Indian cities will follow the same path. Trip lengths have been assumed to depend on city area, as influenced by the land use context envisioned in each scenario. The assumptions have been validated against historical travel trends in these cities, as well as against data from other countries, but it is conceivable that individuals' time constraints or changing land use patterns could slow growth in travel distances. These two sources of uncertainty have a fairly large effect on results. For example, the level of emissions is directly proportional to trip rate; if we assume a trip rate of 2 rather than three, resulting forecasts will be one third lower. If trip lengths for each mode increase only 20% over current levels, rather than growing as assumed, emissions levels would be approximately 40% lower under the Automobility scenario and 20% lower under the other two scenarios.

Information on emission factors for current vehicles, with the exception of rail transit, is more widely available than is travel data, but the accuracy of assumptions about future improvements in vehicle technology depends greatly on government action as well as the price of fuel. A gradual conversion to electric vehicles, for example, is one possible scenario that we did not consider here that would drastically change the emissions picture.

Finally, the rate of urban population growth is subject to a good deal of uncertainty, as it depends heavily on migration rates. Established migration trends may change if cities reach a point of population saturation—if crowding, strained infrastructure, and long commutes outweigh benefits of urbanization—but these conditions, which are already quite acute, have so far failed to act as major deterrents (13).

CONCLUSIONS

The results of this analysis highlight the magnitude of the GHG emissions problem facing Indian cities, while illustrating the potential of policies to influence the future situation. On the one hand, the dramatic differences between the three scenarios reflect the great uncertainty involved in forecasting; on the other hand, this uncertainty can be seen as opportunity. The aspects of this analysis that show the greatest uncertainty are also key points for policy influence. It will be important for cities to provide good public transit and promote use of more sustainable modes while discouraging automobile travel, whether through incentives, street design, or other measures. At the same time, land use strategies to maintain high density, limit sprawl, and promote local destinations can moderate growth in travel distances. The right combinations of these actions can help prevent the “worst case” emissions represented by Automobility Ubiquity. Future research should examine potential strategies for sustainable transport in a way that critically addresses the specific context of each city.

While this and other similar scenario forecasts help to define the scale of the emissions problem, further analysis of the issue requires much more complete data. Given that Indian cities are reaching a point at which planning for future growth is absolutely critical, further studies cannot rely on such thin data if they are to be serious about shaping policy. There is clearly an urgent need to gather detailed data on individual travel behavior in order to identify historical patterns, assess present conditions, and predict future needs. With better data, future research can more closely analyze how city development and transport provision may be expected to reduce emissions.

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