Global passenger travel: implications for carbon dioxide emissions

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Abstract

Humans spend, on average, a constant fraction of their time and expenditure on travel. These and a few other constraints allow a new model for projecting regional and world travel, which we use to develop a scenario for carbon emissions from passenger transport. Globally, carbon emissions rise from 0.8 GtC in 1990 to 2.7 GtC in 2050. In every industrialized region aircraft and high-speed trains become the dominant mode; unable to satisfy the rising demand for mobility within a fixed travel time budget, automobile travel declines by 2050. Passenger transport carbon emissions stabilize by 2020 without any further policy intervention. But in developing countries automobile travel is still rising and becomes the dominant source of carbon dioxide from passenger transport. Fear of global warming may require stabilization of these emissions by mid-century. We show that without some action to accelerate an improvement in energy efficiency starting in the next decade, the goal of stabilization is a technically impossible task, unless zero-carbon technologies become available. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Vital to the modern economy, transportation also causes vexing environmental problems. Among those is global warming from carbon dioxide, 13% of which is the consequence of personal mobility. In past efforts to manage problems such as urban smog, transport effluents have proved difficult and costly to regulate; policy makers fear the same will hold when regulating
emissions of carbon dioxide. Yet remarkably few studies have tried to answer two basic questions that are fundamental to analyzing the future level and policy options for limiting carbon dioxide from transportation: how much will people move in the distant future, and by what mode? It is now possible to understand the underlying principles that determine travel demand, at regional and worldwide spatial scales, and to provide rough answers to these questions.

We show that only a few variables govern aggregate travel behavior. Among them is a constant travel time budget (1.1 hour per person per day), which requires that people shift to faster travel modes as their total mobility rises. Based on this and a few other constraints, we build a simple model that roughly predicts world travel demand over long time periods that are relevant for analysis of the global warming problem. In every industrialized region of the world, we project that by 2050 traffic volume from automobiles declines as they are replaced by faster modes—aircraft and high-speed trains—and that emissions of carbon dioxide from automobiles stabilize after 2020 without any policy intervention. But in developing countries, where mobility is lower and slower, automobility continues to rise; failure to begin regulation of these emissions in the near future could bequeath an impossible task of stabilizing carbon emissions in these countries later in the century, unless zero-carbon transportation fuels are rapidly and widely introduced into the market. Globally, although policy attention today is focused on automobiles, in the longer term emissions from aircraft will be more important.

Lack of appropriate methods partially explains the near absence of long-term projections for personal mobility. Regional and urban transport models are the most extensively developed transport planning tools [1,2] but they are highly disaggregated and too complex for analysis on a global level. All national, regional, and global projections employ more aggregated models, but in practice the methods used also make them inappropriate for long-term projections. Some analysts have estimated energy demand and carbon dioxide emissions from transport mainly by extrapolating past trends in energy demand [3]. However, using final energy as the dependent variable obscures the factors that dictate demand for different transport modes that, in turn, define the combined demand for energy and emissions of carbon dioxide. Only one projection, by Walsh [4,5], estimates demand for global transportation services (i.e., mobility) and then subsequently computes energy demand and emissions. But his scenario is an extrapolation of vehicle fleets based on growth rates for each mode of transport individually; he also excludes railroads entirely and some air transport. Similar criticisms apply to the many national forecasts (e.g. [6,7]), commercial vendor studies [8,9] and studies on single transport modes [10,11], which treat transport modes independently and thus are unable to account fully for the dynamic competition as different modes vie to supply the demand for passenger mobility. Moreover, studies by commercial equipment vendors are typically conducted for time scales no longer than several product cycles (typically two decades).

The lack of historical data needed for model calibration also explains the absence of rigorous long-term projections. Global data sets exist for the whole energy system and have been used to calibrate regional and global energy models, but not yet to projections of passenger transport (e.g. [12–14]). Here we not only apply a new method for long-term transport projections but also calibrate it with a unique new historical data set on mobility by each motorized mode—buses, trains, automobiles, and high-speed transport (mainly aircraft).
2. Fundamental travel behavior

We have presented our model in detail elsewhere [15]. Thus here we only survey the main elements of our approach. The model is a tool for aggregate policy planning which builds on two core relationships from the urban transportation model of Yacov Zahavi [16]. He found that the behavior of travelers was largely determined by two fundamental constraints: on average, fixed budgets of time and money are devoted to travel. Others, notably Marchetti [17], have explored a wide range of such anthropological invariants and applied them to social and technological forecasting. But until now efforts to develop regional and global mobility scenarios have not employed such fundamental properties.

First, Zahavi proposed that, on average, humans spend a fixed amount of their daily time budget traveling—the travel time budget (TTB). Zahavi posited a constant TTB for travelers—people, who make at least one motorized trip per day. We generalize the concept to a per-capita basis and find a similar constancy. Time-use and travel surveys from numerous cities and countries throughout the world strongly suggest that TTB is approximately 1.1 hours per person per day [Fig. 1(a)]. While the TTB is constant on average, many variations are evident when examining the behavior of small populations and individuals. For example, the TTB in large cities [open circles in Fig. 1(a)], where congestion slows travel speed, is generally higher than the average TTBs for countries (solid symbols). Studies have shown that TTB per traveler is typically higher at lower incomes [18]. The poor face more constraints on their choice of living locations and find it more difficult to optimize travel times and can afford fewer motorized trips. But the average per person TTB [as shown in Fig. 1(a)] is similar to that of other, high-income societies.

A second constant proposed by Zahavi is that individuals devote a fixed proportion of their income to traveling, the travel money budget (TMB). Fig. 1(b) presents TMB time series data (as a share of total expenditures) for 13 industrialized countries (no other continuous time series surveys are available) and discrete points for 3 developing countries. In nearly all industrialized countries, TMBs have stabilized at 10–15% of total expenditure. We are interested in the aggregate, stable budget, but some well-understood variations exist. As Zahavi observed, TMB rises with motorization. Households without a personal car devote only 3–5% of total expenditure to traveling (in the developing countries shown). With increased ownership of cars the TMB rises, stabilizing at 10–15% at motorization rates above 200 cars per 1000 capita\(^1\), as evident in the rising TMBs for Greece, Japan, Italy and Portugal. Only in Japan, where prices for non-transport goods and services are atypically high and so is the share of public high-speed transport (e.g., Shinkansen, discussed below), has the TMB stabilized at only 7%.

In addition to the two Zahavi constraints, our model is based on two additional characteristics. One is “path dependence” [19]. Transport infrastructures, like many massive technologies and

\(^1\) Our projection of total mobility relies on the stability of TMB, which means that there is a direct relationship between income growth and increased demand for (spending on) mobility. In principle, the rise in TMB from 3–5% to 10–15% might allow for more rapid growth in mobility because a larger fraction of income is devoted to travel. In practice, it appears that rising TMBs are offset completely by the rising unit cost of travel by private automobiles. Thus even at low mobility, there is a direct relationship between rising income and rising mobility. No data exist to test exactly this relationship, but the tight correlation between income growth and total mobility offers a partial test (and, most importantly, confirms the aggregate relationship that is crucial to our projection). See Fig. 2 and discussion.
infrastructures, do not rise and fall rapidly [20]. Initial choices become locked in, constraining possible future developments and limiting the rate at which one mode can substitute for another. Thus the future for some modes of transport may be strongly evident in their current patterns of development, especially for low-speed conventional railroads that depend on dedicated infrastructure.

The final characteristic is that population density and land-use also partially determine the share of public transportation systems. Fig. 1(c) shows the fraction of total mobility supplied by public transportation—low-speed buses and railroads (including urban light rail systems, which are part of the data set we use although often omitted from railroad statistics). North American cities are the least dense (14 people per hectare) and people spend the lowest fraction of their mobility in low-speed public transport (4.3%); density in European cities is four-fold that of North America, and the share of low-speed public transport is correspondingly higher (17%) [21]. Asian cities are typically even more compact, with an average density three times that of Western Europe, and a 28% share of motorized travel is supplied by low-speed public transport. We assume that these different structures will persist in the future although in each region the share of public transport in total mobility declines. The rate of decline offsets the growth in total mobility and thus the absolute level of low-speed public transport in each region remains roughly constant. (Low-speed modes are still used for short-distance commuting and travel to high-speed hubs.) In the absence of systematic land-use statistics, these three experiences—North America, Western Europe, and Pacific OECD (mainly Japan)—suggest an envelope that defines the rate of decline for the other regions.

3. Our model and scenario projection

We begin by applying some of these fundamental principles of travel behavior to a simple model and project the total level of service (mobility). Using the remaining principles we then examine how that service will be supplied (the four modes of transport). Later we use energy intensity and carbon emission factors to compute emissions of carbon dioxide.

3.1. Total mobility

A predictable TMB allows us to posit a strong relationship between consumption and the total demand for mobility. As consumption rises, spending on travel must also increase—the proportion
is defined by the TMB. In turn, higher transport spending allows greater mobility. Both of these variables—consumption and mobility—can be quantified. Because the availability of data on consumption is limited, we use statistics on income approximated as gross domestic product [GDP] per capita. We employ the widely used Penn World Tables, which report time-series estimates for all nations into constant 1985 US dollars. (For more detail and caveats, including comparisons with other available macroeconomic data see [15].) We derive data on mobility from a new data set especially constructed for long-term regional and global analysis [22]. Together, these data allow us to test the claim that the TMB defines a predictable quantified relationship between growth in income and total mobility.

Fig. 2 shows that the relationship between income (independent variable) and mobility (dependent variable) is nearly proportional for each of the 11 world regions we use for our projection. (The regions, defined in Table 1, are the same regions defined by the International Institute for Applied Systems Analysis (IIASA)/World Energy Council (WEC) energy scenarios.) In all five of the regions with the highest income (EEU, FSU, NAM, PAO, WEU), per-capita mobility and income have grown in essentially the same proportion, with slope = 1. This pattern exists despite a wide variety of different regional and cultural settings. However, there are significant differences in absolute mobility; some regional trajectories lie above and others are below the central trajectory of slope = 1 (dashed line). For example, at US$10,000 per capita, per capita mobility in WEU was only 60% that of NAM, reflecting different infrastructures, population densities, cultures, and unit costs of transport.

Fig. 2. Past and future of total mobility. Historical development of total mobility and income for 11 regions from 1960 to 1990 (symbols) and our scenario until 2050 (lines). A hypothetical “target point”, to which all trajectories converge, is shown. We compute through the target point and end our scenario in 2050. 2050 is sufficiently distant that it allows for turnover of the transportation infrastructure, which is necessary for examining the potential for significant reductions in carbon dioxide emissions. This is confirmed by other studies, which have shown that the mean lifetime of transport infrastructures is 60–70 years [51]. (Historical data from [22].)
Table 1

Eleven regions and their major countries. To facilitate comparison of results, we adopt the regional classification of the International Institute for Applied Systems Analysis (IIASA)/World Energy Council (WEC). The names of the regions and main countries are shown. The regions are classified within three meta-regions—industrialized, reforming and developing countries.

<table>
<thead>
<tr>
<th>Industrialized Regions</th>
<th>Canada, USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America (NAM)</td>
<td></td>
</tr>
<tr>
<td>Pacific OECD (PAO)</td>
<td>Australia, Japan, New Zealand</td>
</tr>
<tr>
<td>Western Europe (WEU)</td>
<td>European Community, Norway, Switzerland, Turkey</td>
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</tbody>
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<thead>
<tr>
<th>Reforming Regions</th>
<th>Russia, Ukraine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Former Soviet Union (FSU)</td>
<td></td>
</tr>
<tr>
<td>Eastern Europe (EEU)</td>
<td>Bulgaria, Hungary, Czech and Slovak Republics, former Yugoslavia, Poland, Romania</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Developing Regions</th>
<th>Argentina, Brazil, Chile, Mexico, Venezuela</th>
</tr>
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<tbody>
<tr>
<td>Latin America (LAM)</td>
<td></td>
</tr>
<tr>
<td>Middle East and North Africa (MEA)</td>
<td></td>
</tr>
<tr>
<td>Sub-Saharan Africa (AFR)</td>
<td>Kenya, Nigeria, South Africa, Zimbabwe</td>
</tr>
<tr>
<td>Centrally Planned Asia (CPA)</td>
<td></td>
</tr>
<tr>
<td>South Asia (SAS)</td>
<td>Bangladesh, India, Pakistan</td>
</tr>
<tr>
<td>Other Pacific Asia (PAS)</td>
<td>Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand</td>
</tr>
</tbody>
</table>

The six lower income regions show more variation, reflecting several factors. One factor, evident in the three developing Asian regions, is the substitution of motorized transport for other non-motorized modes (walking, bicycles, animal-drawn carts) and motorcycles—data for these modes are poor and not shown in Fig. 2 and thus the lines are convex. Such curvature is not evident in all low-income regions, probably because the extent of curvature also depends on the methods used for gathering and converting income data. Conversion of income statistics into common units is imperfect, especially for low-income countries where local and world prices are not comparable and currencies are often not openly traded. An additional factor, deep and sustained economic recession, applies especially to the Middle East & North Africa and Sub-Saharan Africa. In these regions, economies contracted sharply in the 1980s although aggregate mobility continued to rise, temporarily. As a result, the data show a hysteresis between income and demand for transport because earlier investments (the major share of transport costs) continue to raise mobility in the early stages of recession. Latin America experienced a shorter recession in the 1980s, leading to similar but less pronounced results. The earlier history of all three of these regions shows that during periods of sustained growth, mobility rises with income.

3.1.1. Future mobility

The stability of the TMB establishes a nearly direct relationship between income and mobility; historical data confirm that income and mobility rise approximately in proportion. Thus we estimate that the future demand for mobility grows roughly in proportion to income. We have no model of the world economy, and thus we use growth rates based on the widely used baseline scenario of the Intergovernmental Panel on Climate Change (IPCC/IS92a) [23]. That scenario
employed growth rates in Asia that are below other authoritative scenarios [24]; thus, we use higher values (from IPCC/IS92e) for the three Asian developing regions. Expressed in market exchange rates, the annual increase in GDP per capita between 1990 and 2050 corresponds to 1.9%/yr in the industrialized regions, 1.6%/yr in the reforming regions, and 3.0%/yr in the developing regions. At the global level the average annual increase is 1.7%. Expressed as purchasing power parities (Penn World Table method) the per-capita income growth rates are 1.8%/yr, 1.4%/yr and 1.8%/yr in the industrialized, reforming and developing regions, respectively, and 1.4%/yr averaged worldwide.

Although the near-term development of per capita traffic volume is determined by factors that are, in part, unique to each region, over the long term the regional trajectories must all converge. At very high income levels, theoretically, the fastest available mode (aircraft and high-speed trains) must satisfy the enormous demand for mobility within the fixed TTB2. Since aircraft operate largely independent of geography, at such high incomes transport must also become largely decoupled from the land. Once decoupled, travelers in all regions will largely face the same prices; thus, plausibly, the same relationship between income and mobility will prevail in all regions. (Already today, globalization of the world economy has caused convergence of prices and tastes.) This thought experiment allows us to posit a hypothetical “target point” of convergence. Based on aircraft’s gate-to-gate mean speed of 600 km/h, and the TTB of 1.1 h per capita per day, the total annual distance traveled would be 240 000 passenger-km (pkm) per capita. Assuming that this point lies on the trajectory of slope = 1, as suggested by historical data (Fig. 2), the corresponding income is US$240 000 per capita. Future levels of regional per capita mobility are projected with a logarithmic type of regression equation through the historical data; the equation is constrained to pass through the hypothetical target point. The regression equation and associated statistical results are reported elsewhere [15].

Fig. 2 shows this “target point” to which all regional trajectories converge (by logarithmic function) in our scenario. None of the regions approaches this level of income and mobility by the year 2050, which is consistent with the use of the point as a conceptual thought experiment. The target point is sufficiently distant in the future that its specific location on the central trajectory does not matter much. NAM, the region where the projected income growth will be highest by 2050, would reach the target point only a century later, after 2150.

Table 2 summarizes the results. Using the 1992 World Bank population projections, Table 2 also shows the absolute levels of future mobility [25]. The Bank projections envisage an increase in world population to 10.1 billion in 2050. Growth is strongest in developing countries, where population more than doubles during the period and will account for 85% of the world population in 2050. These values are similar to the 1992 UN medium forecast [26] and slightly higher than more recent population projections.

We project that per capita traffic volume will increase by a factor between 2.6 and 3.8 in the

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2 Because our forecast is only six decades long we omit the possibility that a new form of transport that is substantially faster than existing aircraft will supply a significant fraction of total mobility by 2050. If such a mode were to play such a role, its penetration into at least niche markets in the transport system would probably already be evident. Maglev trains are one possibility, but they operate at similar speeds as aircraft and are included with our aircraft projection. Supersonic transport (SSTs) aircraft are another possibility, but their passenger niche (i.e. Concorde) has not significantly grown nor are new SSTs soon poised to enter the market.
Table 2
Per-capita and total mobility for 11 regions (and share of global total) in 1960, 1990, 2020, and 2050 for the reference scenario. Bold figures are sums of groupings of nations: industrialized (IND), reforming (REF), developing (LDC)

<table>
<thead>
<tr>
<th></th>
<th>1960</th>
<th>1990</th>
<th>2020</th>
<th>2050</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>pkm/cap</td>
<td>bill.pkm</td>
<td>%world</td>
<td>pkm/cap</td>
</tr>
<tr>
<td>NAM</td>
<td>11 854</td>
<td>2384</td>
<td>43.5</td>
<td>22 078</td>
</tr>
<tr>
<td>WEU</td>
<td>3074</td>
<td>1106</td>
<td>20.2</td>
<td>10 622</td>
</tr>
<tr>
<td>PAO</td>
<td>3025</td>
<td>323</td>
<td>5.9</td>
<td>10 294</td>
</tr>
<tr>
<td>IND</td>
<td>4400</td>
<td>3813</td>
<td>69.6</td>
<td>14 276</td>
</tr>
<tr>
<td>EEU</td>
<td>1824</td>
<td>181</td>
<td>3.3</td>
<td>5389</td>
</tr>
<tr>
<td>FSU</td>
<td>1419</td>
<td>295</td>
<td>5.4</td>
<td>5796</td>
</tr>
<tr>
<td>MEA</td>
<td>1222</td>
<td>140</td>
<td>2.6</td>
<td>4546</td>
</tr>
<tr>
<td>AFR</td>
<td>898</td>
<td>193</td>
<td>3.5</td>
<td>1614</td>
</tr>
<tr>
<td>CPA</td>
<td>152</td>
<td>109</td>
<td>2.0</td>
<td>637</td>
</tr>
<tr>
<td>SAS</td>
<td>349</td>
<td>200</td>
<td>3.7</td>
<td>1778</td>
</tr>
<tr>
<td>PAS</td>
<td>878</td>
<td>125</td>
<td>2.3</td>
<td>3470</td>
</tr>
<tr>
<td>LAM</td>
<td>1980</td>
<td>424</td>
<td>7.7</td>
<td>5094</td>
</tr>
<tr>
<td>LDC</td>
<td>582</td>
<td>1191</td>
<td>21.7</td>
<td>2125</td>
</tr>
<tr>
<td>WOR</td>
<td>1814</td>
<td>5481</td>
<td>100.0</td>
<td>4382</td>
</tr>
</tbody>
</table>

three regions of industrialized countries; in developing regions the rise in mobility will be as much as seven-fold (CPA). Globally, in 2050, people average an annual traffic volume comparable to that of West European and PAO residents in 1990. The stronger growth in per capita mobility in the developing world is amplified by the strongest growth in population. Hence, regional shares in global traffic shift markedly. While the industrialized countries accounted for more than half of the global traffic volume in 1990, their share drops to 42% in 2050.

3.2. Future modes of transport

Now we project the shares of the four transport modes—buses, railways, cars, and aircraft. We include high-speed trains in the aircraft category; the two operate at similar door-to-door speeds for many services, and our method is based, in part, on travel speeds and is thus presently unable to distinguish between them. Four variables require four constraints to yield unique solutions,

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3 High-speed trains (e.g., Shinkansen) are part of the aircraft category. Already, such trains account for 5% of total mobility and 30% of mobility by all high-speed transport modes in Japan. The Shinkansen travels at 220 km/h, which is 37% of the average speed we assume for HST. Our model does not allow us to estimate the relative shares of aircraft and high-speed trains, and thus we do not here add the complication of lowering the average HST speed for the PAO region. This is the only region with a substantial fraction of HST supplied by such trains. The next generation of (maglev-) trains is intended to operate at speeds close to the assumed aircraft speeds of 600 km/h.
which we compute continuously through 2050. Equations and statistical information on regressions are reported elsewhere [15].

3.2.1. Path dependence

Because past choices lock in future developments, the future for some modes of transport may be strongly evident in their historical patterns of development. This is typically true for ordinary railways, which are declining systematically in all regions. Thus, for each region we project future railway shares as a hyperbolic type of regression that passes through zero share at 240,000 pkm per capita.

3.2.2. Urban land-use

Although we expect that all low-speed motorized transport modes will decline to essentially zero share in the very distant future (at the “target point” in 150 years or more), the transition from the present to their ultimate demise could take many paths. As shown in Fig. 1(c), we define an envelope based on the historical development of low-speed transport modes (buses and trains) that helps to define the particular path that will be followed. We assume that the North American trajectory is anomalous due to extremely low population density and high mobility. Thus the envelope defined for all other regions lies between that of a Western European (medium density) or PAO (high density) trajectory. The three Asian regions (CPA, PAS, SAS) follow the PAO trajectory—in each region, motorized transport is dominated by high density cities. All other regions (AFR, EEU, FSU, LAM, MEA) follow the trajectory of WEU. We project future shares of low-speed motorized transport modes in the three industrialized regions (North America, PAO, Western Europe) with a hyperbolic type of regression that passes through zero share at 240,000 pkm per capita. The trajectories of the other eight regions are projected with a segmented model, where the transition towards the industrialized trajectories corresponds to the first segment and the development along the industrialized trajectories to the second segment.

3.2.3. TTB and high-speed niche markets

A fixed TTB requires that the mean speed of travel increases in proportion to the projected rise in total per capita mobility. More distance must be covered within the same period of time. Since transport carriers only operate within a range of speeds, rising mean speed requires shifting to faster transport modes.

Applying the TTB constraint requires that we estimate the mean speed of each travel mode. Adequate travel survey data are available in industrialized nations, which are summarized in Table 3. While our model only applies to the four motorized modes of transport, the fixed TTB of 1.1 hours per capita consists of the time spent in all modes. Thus we have specified a function that allocates the TTB between motorized and non-motorized forms based on survey data for 1990 and estimates through 2050. (Obviously this travel time relationship between motorized and non-motorized modes has a strong influence on the computed model shares. This can be seen from the results of this paper and an earlier version of the model [27]).

A sensitivity analysis by the authors [15] shows that—at low levels of income—the projected modal shares of automobiles and aircraft are highly sensitive to the allocation of the TTB between motorized and non-motorized modes and the assumed mean vehicle speeds. However, in developing countries survey data that would allow estimation of motorized travel time or travel
Table 3
Mean travel speeds (km/h) by mode of transport, 1990. NAM data are based on the U.S. 1990 travel survey. WEU speeds are the weighted average from travel surveys in four countries—Germany, Norway, Switzerland, UK. PAO data are the weighted average of Australia, New Zealand and Japan. (New Zealand is assumed to have the same modal speeds as Australia.). Speeds for other regions are estimates based on these three industrialized regions (see main text). In these regions, speeds for bus and rail especially can only be a rough estimate. Data source: [15]

<table>
<thead>
<tr>
<th>Mode of Transport</th>
<th>Car</th>
<th>Bus</th>
<th>Rail</th>
<th>Air</th>
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<tbody>
<tr>
<td><strong>Industrialized Regions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAM</td>
<td>55</td>
<td>20</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>WEU</td>
<td>45</td>
<td>20</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>PAO</td>
<td>35</td>
<td>20</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td><strong>Other Regions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFR, EEU, FSU</td>
<td>45</td>
<td>20</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>LAM, MEA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPA, PAS, SAS</td>
<td>35</td>
<td>20</td>
<td>30</td>
<td>600</td>
</tr>
</tbody>
</table>

speeds are practically non existent. Thus, for six developing regions, we have introduced a constraint of high-speed niche markets.

In applying this niche market constraint, we adopt an approach that is similar to our application of the land-use constraint. In each of the industrialized regions, patterns of land-use affect not only low-speed modes [see above and Fig. 1(c)] but also the size of high-speed market shares. Commercial air transport was developed in North America; in that region, the rate of growth has been relatively slow but occurred over a long period. In regions where high-speed technology was introduced later, innovations pioneered in the lead regions were adopted later but more rapidly because they were available at lower cost. As in the case of the land-use constraint the historical data suggest two possibilities—in Western Europe the rate of adoption (slope of the line in Fig. 3) was similar to that of North America. In PAO high-speed modes grew more rapidly—dense human settlement impeded the use of road-based transportation for long-distance trips, and government subsidy of Shinkansen encouraged passengers. For each of these regions we apply these growth rates—with the same correspondence as with the urban land-use constraint—until high-speed transport grows beyond just a niche market and thus the model is less sensitive to possible errors in estimating motorized travel time and modal speeds.

3.2.4. Balancing equation

A fourth constraint is that in each region all four motorized modes must sum to the total motorized mobility. Fig. 4 indicates all model inputs and outputs.

3.2.5. Results

Fig. 5 presents the results for seven selected regions and the world aggregate. Globally, by 2050 only the share of aircraft is growing; all other modes are in relative decline. Aircraft provide 36% of global mobility in 2050; automobiles provide 42%.

In all three industrialized regions, automobile shares decline sharply by 2050. In developing countries the automobile share rises, but not enough to offset fully the automobiles decline in the high income regions for several reasons: income levels remain comparatively low in AFR and
CPA, and thus automobility remain modest in these regions; higher urban population densities lead to a lower saturation level for automobiles; and, high shares of air travel supplant some of the potential share of automobiles. In some developing regions (notably SAS) the model projects a rapid growth in per capita automobile traffic volume (6% rise in pkm per year in 2030); as a consequence we have verified that the increase in vehicle stock needed to achieve such growth is consistent with the rate of rising motorization rate observed historically in higher income regions at a given income level [15].

Fig. 5 illustrates a consistent stepwise pattern—fast modes replace the slow. At mobility levels below 5000–7000 km per capita, low-speed public transport modes predominate. At more elevated levels higher speed automobiles diffuse into widespread service; they supplement then partially
supplant lower-speed modes in providing total mobility. As travel demand in each region grows, the demand for automobility grows in a similar fashion; one follows the other to the peak and then declines. At mobility levels above 20 000 pkm per capita the automobile share declines as faster modes of transport—aircraft and high-speed trains—are needed to satisfy the rising demand for mobility within the fixed TTB. This relative decline ultimately leads to an absolute decline in automobile traffic volume at higher levels of total mobility. Fig. 6 illustrates the rise and fall of per-capita automobile traffic volume in each of the industrialized nations. In North America, absolute declines are evident starting in 2010 at per capita automobile traffic volume of approximately 22 000 pkm per capita. Despite the projected absolute decline of automobility in the industrialized regions and the strong growth of air traffic, the automobile still remains an essential mode of transport. In fact, our projection suggests that travelers will continuously spend most of their travel time in the automobile. In North America we estimate that (on average) 48 minutes per day will be spent in cars in 2050. Only 11 minutes will be devoted to air travel, but such a short time will go a long way—the 2.6-fold distance as covered in automobiles.

Fig. 7 shows the level of absolute mobility—for the world, and three aggregate regions (industrialized countries, reforming countries, and developing countries)—for each three decade interval from 1960 to 2050.

Elsewhere we have demonstrated the stability and consistency of our results with other data as well as the sensitivity of our model results to critical assumptions such as travel speeds and
Fig. 6. The peak and decline of automobility in industrialized nations. Historical and projected per-capita automobile traffic volume in North America, Pacific OECD, and Western Europe, 1960–2050.

Fig. 7. Absolute levels of mobility, 1960–2050. The results are shown for the four motorized modes which sum up to the world totals.
the TTB (see [15]). For example, the introduction of intelligent transportation systems (ITS) could increase mean automobile speed by 15%. In North America, ITS would delay by merely 4 years the decline in automobile traffic share. Speedy aircraft are a superior competitor, and thus the gains from ITS in low-speed modes are comparatively small.

4. Emissions of carbon dioxide

Here we use our projection to estimate future emissions of carbon dioxide from passenger transport in three groups of nations: industrialized countries, reforming economies, and developing countries. These groups correspond to the broad political coalitions that have been active in the UN Framework Convention on Climate Change (UNFCCC) and negotiations over stronger regulatory targets, which led to the December 1997 Kyoto Protocol. Both the Convention and the Protocol oblige industrialized countries to adopt regulatory policies, suggest that reforming countries should do the same but be given lenient treatment because of their special situation, and explicitly exempt developing countries from any obligation to limit emissions [28].

Carbon dioxide emissions depend on the energy intensity of a given mode (see below), the fuel carbon content (we use a standard value of 20 gC/MJ for light oil distillates and—based on ref. [29]—43.2 gC/MJ for the 1990 world electricity generation mix), and the degree of combustion (we assume to be complete).

4.1. Modal energy intensities

Energy intensity (MJ per pkm) consists of two factors: vehicle fuel efficiency (energy used per vehicle-km) and operational efficiency (passengers per vehicle, also known as passenger load factor). These factors vary by mode of transport and region, and are summarized in Table 4.

4.1.1. Automobiles

Regarding the industrialized countries, despite the introduction of new more fuel-efficient vehicles the average energy intensity of automobile travel has remained roughly constant since 1970 in nearly all 11 industrialized countries for which time series fuel consumption data are available [30]. Improved fuel efficiency was offset by declining load factors. Only the USA is an exception—after the first oil shock (1973) average fuel efficiency of new vehicles roughly doubled before 1990, perhaps spurred by mandatory fuel efficiency standards (CAFE). However, declining load factors offset some of the improved fuel efficiency and thus energy intensity declined by only 18%. Given the past developments, we assume that load factors continue to compensate improvements in fuel efficiency and thus energy intensity remains constant.

In the reforming economies, data are available for the Former Soviet Union [31], the EEU region [32] and for Poland [33]. Load factors are estimated at 2 occupants per car [22], higher than in industrialized countries. Combining these factors yields a base year intensity that we use for all reforming economies (EEU and FSU). We assume that the energy intensity converges versus that of the industrialized countries by 2050.

In the developing countries we have data that cover all six regions: 13 countries in five regions and one regional estimate for MEA [3,34–37]. In general, fleet efficiency is higher in Asia than
Table 4
Energy intensity (MJ/pkm) in 1990 and estimates for 2050 for industrialized, reforming, and developing countries. Projection for ground transport based on improved fuel efficiency of equipment largely offset by declining load factors, as strongly evident from historical data. High-speed modes are based on improved fuel efficiency of hardware and stable load factors.

<table>
<thead>
<tr>
<th>Region and mode</th>
<th>1990 (MJ/pkm)</th>
<th>2050 (MJ/pkm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Industrialized Countries</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Bus</td>
<td>1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Rail</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Electric</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>High speed</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Reforming Countries</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Bus</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Rail</td>
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<tr>
<td>Diesel</td>
<td>1.4</td>
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<tr>
<td>High speed</td>
<td>3.4</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Developing Countries</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Bus</td>
<td>0.6</td>
<td>0.6</td>
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<tr>
<td>Rail</td>
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</tr>
<tr>
<td>High speed</td>
<td>2.9</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Latin America and Africa. We adopt a mean fleet fuel efficiency of 13.2 l/100km. We expect that vehicle fuel efficiencies could improve significantly in regions such as Latin America while remaining constant in others (e.g., Asia). Low motorization rates in developing countries lead to high load factors. On average, we assume 2.2 persons per vehicle in 1990. As motorization rates increase, we expect load factors will decrease towards the levels in industrialized countries and offset improvements in vehicle fuel efficiency. On balance, we estimate that energy intensity will remain level.

4.1.2. Buses
Data on fuel consumption in fleets of buses are sparse. In industrialized countries we have data for Germany [38], Japan [39] and the USA [30,40] showing that for all bus services (intercity and urban), fleet efficiencies range from 9 to 15 MJ/km and load factors from 15 to 17 passengers per vehicle. We expect the energy intensity of bus transport to improve modestly at 0.5%/yr.

In reforming countries, we have data only for energy intensity of bus travel in the FSU [41]. In developing countries, data from Korea (all services) [42] suggest lower energy intensity of 0.8 MJ/pkm. Data from China (all services) [43] and New Delhi (urban only) [44] suggest much lower intensities (≈ 0.3 MJ/pkm), but these are based on unreliable surveys and estimates. We
assume a mean value of 0.6 MJ/pkm. For both these groups we assume that improvements in vehicle fuel efficiency will be offset by falling load factors, and thus energy intensity will remain unchanged.

4.1.3. High speed transport

For each region, we estimate current aircraft fuel efficiency from statistics reported by the International Air Transport Association [45] and the International Civil Aviation Organization [46], and energy consumption reported by the International Energy Agency [47]. Regarding future fuel efficiency, we assume that all regions will experience similar developments as there are few world suppliers of new aircraft, and most aircraft are operated by increasingly competitive airlines. Since 1960, fuel consumption per pkm of new aircraft decreased by 30%; further reductions in the order of 70% are possible by 2050 [48]. In light of the trend between 1974 and 1990, when fuel consumption of the global aircraft fleet decreased by 2–3%/yr [49], we assume fuel consumption will decline by 2%/yr, which corresponds to a 70% reduction by 2050. We assume that load factors will remain constant at their long-term historical rate of 62% [45]. All regions converge to the same energy intensity (1.0 MJ/pkm).

4.1.4. Railways

Although a huge potential exists for reducing railway fuel consumption, mainly through operational improvements, we assume that such vehicle efficiency improvements will be offset by continued decline in load factors. Due to the minor role of rail transport in most regions and the world, assumptions in rail energy intensity have little effect on our projections. In 1990, only 10% of world passenger-km were traveled by rail; by 2050 we project the share of railway traffic volume will decrease to 5%.

4.2. Computed carbon emissions

Fig. 8 shows our projected carbon dioxide emissions for each of these three groups of regions by mode of transport. Global emissions from passenger transport rise from 0.19 GtC in 1960 to 0.77 GtC in 1990, with 13% of global carbon dioxide caused by burning of fossil fuels due to passenger transport [50]. In 2050 we estimate that emissions will rise to 2.7 GtC which is 19% of carbon dioxide emissions from fossil fuel combustion in 2050 under the IPCC/IS92a median scenario. (Typically higher numbers, some 20% in 1990, are often quoted for transportation’s contribution to carbon emissions. Our numbers are lower because our model excludes freight transport, estimated to be 10% of total emissions in 1990.)

Many analysts see the goal of stabilizing carbon dioxide emissions at 1990 levels as challenging; absent new policies, nearly all industrialized countries project that their emissions will rise far beyond that goal in the near future [51]. The Kyoto Protocol requires an average 5% cut in emissions in the industrialized and reforming regions, although special provisions, notably regard-

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4 See [23]. We are mindful that our results are not directly comparable with those of IPCC/IS92a because our income growth rates are a hybrid of IS92e (for Asian regions) and IS92a (all other regions). If we had used IS92a growth rates for all regions, projected passenger transport emissions would be 2.5 GtC, or 17.2% of IS92a total emissions.
Fig. 8. World emissions of carbon dioxide. Past and projected carbon emissions for industrialized nations, reforming countries (Eastern Europe and Former Soviet Union), and developing countries. These three regions correspond to the political groupings in the international political efforts to slow global warming. Projections are made using mobility by each mode (calculated from our model), region-specific factors for the energy intensity of each mode, and standard carbon emission factors (see Table 4).

Surprisingly our scenario suggests that over the next four decades these countries are nearly on track to stabilize emissions from passenger transport, without further policy measures. In the industrialized countries, total carbon emissions stabilize at nearly 1.2 GtC by 2045. Carbon emissions from automobiles will decline from 2030, which reflects the projected decline in automobile traffic volume; aircraft emissions will grow steadily, despite our assumption of rapid (2% per year) improvement in efficiency. Total emissions from the reforming countries remain comparatively small, reaching only 0.2 GtC (8% of world passenger transport emissions, down from 9% in 1990).

Increasingly, politicians and analysts argue that a truly global effort must involve developing countries where emissions from nearly all sources are rising rapidly. We estimate that developing country emissions from passenger transport will rise nearly eightfold and exceed those of industrialized countries in 2046. (But on a per-capita basis, emissions are substantially lower than in the industrialized world throughout the period of our projection.) Yet today these countries are exempt from regulatory commitments. To illustrate some implications of current policies, which focus regulation almost exclusively outside the developing world, we imagine a plausible policy scenario: in 2035, one-quarter century after the Kyoto targets take full effect in the industrialized and reforming regions, developing countries also agree to stabilize emissions at that year’s level. Here we focus only on emissions from automobiles, which account for two-thirds of all passenger transport emissions in developing countries in 2035.
Achieving the 2035 stabilization target through efficiency improvements alone would require a “crash program” to reduce average fleet energy intensity by roughly 5.2% per year between 2035 and 2050. No such rapid fleet improvement has ever been observed in the history of the automobile. By 2050, sustaining the 2035 stabilization would require the average automobile on the road in developing countries to have a fuel consumption of 4.8 liters per 100 km, which is only achievable with today’s best available production diesel powered compact passenger cars with a mechanical drive train. In short, stabilizing emissions after waiting until 2035 is probably infeasible without zero carbon fuels and/or significant constraints on individual mobility.

For comparison, we compute the more gradual reductions in fuel intensity required to achieve identical cumulative emissions (1990 to 2050) as in the “crash program” but starting with emission controls in the year 2010. (Carbon dioxide is long-lived in the atmosphere; thus, cumulative emissions are, to first approximation, more important for global warming than the particular year when emissions are released to the atmosphere.) The result is a 0.9% annual improvement. This “rapid improvement” scenario is feasible though it might still prove difficult to sustain, especially in light of load factors that will probably decline as incomes rise. For comparison, average fuel consumption in the US declined by 2.3% per year from 1973 to 1990 (see [30]). However, automobile load factors in the US declined approximately 1% per year during that period, and thus the actual decline in energy intensity was merely 1.3% per year. If the goal is to stabilize automobile emissions from developing countries by 2050, efforts to start soon are probably warranted. Fig. 9 shows the changes in automobile energy intensity that comprise the “crash program” and “rapid improvement” scenarios.

We have not explored here lifestyle changes—such as not driving cars—which are also cited by policy advocates as a possible option. We doubt whether those will be implemented or effective. Resurgent automobile growth in Eastern Europe, after central planners had constrained automobile ownership for decades, should make policy makers who strive to deviate from the natural dynamics of the transportation system, pause for thought. Nor have we examined low- or zero-carbon automobile fuels here. Determining the most effective portfolio of actions to stabilize carbon emissions requires, in part, economic and technological analysis. Our model’s strength is in developing scenarios, not analyzing particular technological policy options. Research is under way at MIT to link this model with economic and energy system models to provide exactly such an analysis in the context of economy-wide carbon control.

5. Conclusions

On average, people spend a constant share of money on traveling; rising income leads nearly directly to a rising demand for mobility, which we demonstrate historically. A person also spends a constant share of time for travel on average; as total mobility rises, travelers shift to faster

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5 We make this calculation by computing the efficiency improvements that are needed, starting overnight in the year 2035, to keep emissions stable at 2035 levels.

6 These calculations are based on 1.8 occupants per vehicle. This estimate is based on our data sets from survey data. Most likely fuel consumption must decline even more rapidly because load factors will decrease with affluence, as they have in the industrialized world.
Fig. 9. Stabilizing carbon emissions in developing countries. The figure illustrates a plausible scenario requiring developing countries to stabilize emissions from automobiles (and other sectors of the economy) starting in 2035—a quarter century after the commitments in the Kyoto accord take full effect in industrialized countries. Waiting until 2035 to begin action requires a “crash program” of 5.2%/yr reduction in energy intensity to stabilize passenger transport sector emissions. The cumulative emissions (between 2010 and 2050) could be achieved at a significantly lower rate (0.9%/yr) in the “rapid improvement scenario”, in which reductions start 25 years earlier. Historical experience suggests that the latter is feasible but challenging, and the former is impossible.

modes to remain within the fixed TTB of 1.1 hours per person per day. We use the empirical facts of these constant budgets and other constraints based on path dependence and land-use patterns to develop a new model for estimating future mobility and mode of transport in all 11 world regions from 1990 to 2050.

All world regions illustrate the same phenomenon of shifting from slow to faster modes as income and the demand for mobility rise. Variations among regions reflect the historical legacy of infrastructures, which are in part the result of differences in population density, policies and tastes. At the high levels of aggregation examined here, transportation systems behave in deterministic patterns—modes are largely selected by the speed of their service, not (directly) according to policy. We project that in cases where policy has advanced or retarded the natural selection of modes—such as the premature rise of aircraft in the Soviet Union or the delayed rise of automobiles in Eastern Europe—over time the transport system will recover its natural dynamics.

We expect that emissions of carbon dioxide from passenger transport in industrialized countries will stabilize by 2020 even without policy intervention. In the developing countries, where growth in emissions will be strongest, transportation is technically poised between two options. If emissions from automobiles (which contribute most to rising carbon emissions) are stabilized in 2035—which is a plausible goal that policy makers might pursue—then the required efficiency improvements will probably exceed technical feasibility. Starting earlier can yield the same
environmental benefits and is technically feasible. Carbon-free fuels and lifestyle changes could also help meet that goal and thus reduce the need for near-term policy action to improve energy efficiency. Although we do not analyze the other options, the result suggesting that efficiency improvement must begin soon are strong. We have not addressed who might pay for such a scheme. Some form of technical assistance program will be demanded, and may be necessary, to overcome the developing countries’ wariness to adopting such commitments.

References


