The future mobility of the world population

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Abstract

On average a person spends 1.1 h per day traveling and devotes a predictable fraction of income to travel. We show that these time and money budgets are stable over space and time and can be used for projecting future levels of mobility and transport mode. The fixed travel money budget requires that mobility rises nearly in proportion with income. Covering greater distances within the same fixed travel time budget requires that travelers shift to faster modes of transport. The choice of future transport modes is also constrained by path dependence because transport infrastructures change only slowly. In addition, demand for low-speed public transport is partially determined by urban population densities and land-use characteristics. We present a model that incorporates these constraints, which we use for projecting traffic volume and the share of the major motorized modes of transport – automobiles, buses, trains and high speed transport (mainly aircraft) – for 11 regions and the world through 2050. We project that by 2050 the average world citizen will travel as many kilometers as the average West European in 1990. The average American’s mobility will rise by a factor of 2.6 by 2050, to 58,000 km/year. The average Indian travels 6000 km/year by 2050, comparable with West European levels in the early 1970s. Today, world citizens move 23 billion km in total; by 2050 that figure grows to 105 billion. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Mobility; Scenarios; Forecasting; Automobiles; Aircraft; Buses; Railroads

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1. Introduction

How much will people move around in the distant future? Which modes of transport will they use? In which parts of the world will traffic be most intense? Answers to these questions are critical to planning of long-lived transport infrastructures and to assessing the consequences of mobility, such as environmental pollution. These questions also lie at the center of efforts to estimate the size of future markets for transportation hardware and services. Here we describe a simple but radically new model, which we use to develop a scenario that offers plausible answers to these questions.

Answering these questions requires large-scale, long-term models of the transportation system. But that pressing need contrasts sharply with capabilities of existing modeling techniques. Regional and urban transport models, the most extensively developed transport planning tools, have been oriented to forecast local traffic demand, flows and costs (Button, 1993; Oppenheim, 1995). These tools optimize directed traffic flows by minimizing costs or maximizing the utility of consumers. They compute details of the transportation system, such as the number of cars using roads at different times, average speeds, and layout of transport infrastructures. An intrinsic consequence of detail is that such models are built on a large number of interrelated variables such as automobile ownership, loading and usage of vehicles, zonal or household trip rates, relative prices of transport modes, urban trip speeds, and income. Because the relationships among variables are known only poorly, these multi-variate methods degrade rapidly for projections far into the future. The original purposes of transport planning models make them poor tools for developing long-term scenarios.

All national, regional, and global projections have employed more aggregate models, but the methods chosen also have been inappropriate for long-term scenario-building. Most have been motivated by the desire to forecast future energy demand and related variables such as greenhouse gas emissions. Some estimate energy demand and emissions mainly by extrapolating past trends in energy demand (e.g. Environmental Protection Agency, 1990; Eads et al., 1998). However, using final energy as the dependent variable has obscured the factors that dictate demand for different transport modes that, in turn, define the combined demand for energy. Only one projection, by Walsh (1993a,b), estimates demand for global transportation services (i.e. mobility) and then subsequently computes energy demand and emissions. However, his scenario is an extrapolation of vehicle fleets based on growth rates for each mode of transport individually; it largely does not account for competition between modes, which determines the particular modes that people select to supply their demand for mobility. His scenario is not based on a model that explains why the particular values and trends he proposes will prevail. (The study also excludes railroads entirely, and some of air transport.) Similar criticisms apply to the many national forecasts, such as those for Germany (Eckerle et al., 1992) and the United Kingdom (Martin and Shock, 1989). All these projections offer some glimpses into the future, often in the form of multiple scenarios that bound a large range of possibilities, but offer little guidance about which futures are most likely. Most treat transport modes independently.

In addition to these transport sector studies, forecasters have given particular attention to some modes of transport, notably automobiles and aircraft (e.g. Deutsche Shell, 1995; Airbus Industrie, 1998; Boeing, 1998; Vedantham and Oppenheimer, 1998). Many such forecasts are typically sponsored by commercial vendors and are oriented to estimate potential demand for new equipment; the time horizon of such forecasts is typically no longer than two decades. A few studies have
been inspired by the special issues associated with a particular mode of transport, notably the personal freedom afforded by self-piloted automobiles (e.g. Roos and Altshuler, 1984).

Our model is designed especially to allow formulation of aggregate (regional and global) and long-term scenarios. It is fundamentally rooted in the tradition of transport planning and thus accounts for how travelers choose among transport modes when satisfying their demand for mobility. (Throughout, we use the term “mobility” to denote traffic volume, measured in passenger-kilometers, pkm.) However, our model requires only aggregate data. The aim is not to calculate detailed estimates of trip lengths and vehicle speeds, but rather to project total mobility and the share supplied by each mode (modal split) for aggregate world regions far into the future. An aggregate approach matches the large-scale concerns – such as global markets and globally mixed pollutants – to which we can apply our results. This unique approach was previously impossible because there was no set of comparable historical data on mobility and transport mode for all world regions. Here we also introduce a new data set that makes such an approach feasible.

First we describe the two budget constraints that are the core elements of our method. Next we estimate future demand for the service that the transportation system provides: total mobility. Then we estimate the share of mobility supplied by each of the four major motorized modes of transport: buses, trains, cars, and aircraft. We perform these estimations for 11 world regions and aggregate for the world. The regions, shown in Table 1, are identical to those adopted for use in the International Institute for Applied Systems Analysis (IIASA)/World Energy Council (WEC) scenarios (IIASA and WEC, 1995; Nakicenovic et al., 1998). Table 1 also defines the compact three-letter identifiers for each region, which we use throughout this paper. Finally, we present statistical analysis of all regressions, explore whether the results are internally consistent, and test the sensitivity of the scenario to changes in the most important or uncertain assumptions.

Table 1

<table>
<thead>
<tr>
<th>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). Shown are the names of the regions and main countries. The regions are classified within three meta-regions – industrialized, reforming and developing countries</th>
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<tr>
<td><strong>Industrialized Regions</strong></td>
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<tr>
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<td>Eastern Europe (EEU)</td>
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<td><strong>Developing Regions</strong></td>
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<td>South Asia (SAS)</td>
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<td>Other Pacific Asia (PAS)</td>
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2. The budget traveler

Our model is a tool for aggregate policy planning which builds on two core relationships from the urban transportation model of Yacov Zahavi. Zahavi (1981) built the inverse of conventional transportation models, beginning with a small number of driving variables and simple relationships from which he simulated traffic fluxes, modal splits, trip speeds, and other variables of interest to transportation planners. 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 (1993, 1994), have explored a wide range of such “anthropological invariants” and applied them to social and technological forecasting. Here, we discuss and validate these two Zahavi constraints.

2.1. Travel time budget

First, Zahavi proposed that, on average, humans spend a fixed amount of their daily time budget traveling – the travel time budget (TTB). Time-use and travel surveys from numerous cities and countries throughout the world suggest that TTB is approximately 1.1 h per person per day. Fig. 1 shows the stability of the travel time budget over a wide range of income levels, geographical and cultural settings: residents of African villages devote similar time for travel as those of Japan, Singapore, Western Europe or North America.

While the TTB is constant on average, many variations are evident when examining the behavior of small populations and individuals. Travel time budgets are higher in congested cities; Londoners, for example, spend 30% more time traveling than do people in spacious Scotland (UK Department of Transport, personal communication of unpublished data of the 1985/86 and 1989/91 National Travel Surveys). Fig. 1 shows that the magnitude and variance of the TTB in cities (open circles) are higher than average TTBs for whole countries (solid symbols). Travel times are generally highest for the largest cities (e.g. Paris). TTB also varies with sociodemographic group. A 1989 survey in West Germany (Kloas et al., 1993) illustrates the variability of travel habits by profession – the average person traveled 1.09 h per day, but university students and government employees spent much more time in motion (1.27 and 1.32 h, respectively). German pensioners were less mobile (0.94 h). Studies have shown that TTB per traveler is typically higher at lower incomes (Roth and Zahavi, 1981). (A “traveler” is defined in travel surveys as someone making at least one motorized trip on the day of the survey.) The poor face more constraints on their choice of living locations and transport modes and thus find it more difficult to optimize travel times. The share of travelers to total population is lower in low-income societies; thus the average per person TTB (as shown in Fig. 1) is similar to that of other, high-income societies. ²

² In addition to those discussed here, many other factors (including differences in survey methods) affect the measured TTB values. We have made extensive effort that the data discussed here and presented in Fig. 1 are based on comparable survey methods. For example, we have excluded survey data from several Chinese cities because they excluded short walking trips.
The cause of the empirically observed constant travel budget is not clear. Perhaps security of the home and family, the most durable unit of human organization, limits exposure to the risks of travel (Marchetti, 1993). Also, traveling is naturally limited by other time-consuming activities such as sleep, work and leisure. Even when other demands on time change, there is evidence that the TTB remains constant. For example, compared with other OECD nations (France, Germany, UK, and US), Japanese workers spend 25% more time at work (Maddison, 1991); yet travel time budgets are nearly identical (Fig. 1).

Our purpose is to project motorized mobility, but the stability of average TTB holds only for travel by all modes. Fig. 2 shows how the time spent in motorized modes ($TTB_{mot}$) rises with income and mobility as people shift from slow non-motorized modes to motorized travel. Data on $TTB_{mot}$ are sparse and must be estimated for low-income regions (see caption). Equation 1 describes the relationship between mobility and $TTB_{mot}$:

$$TTB_{mot} = a + \frac{b}{(TV - c)^{a}}.$$  \hspace{1cm} (1a)

Constraining the curve to pass through the zero-point and through a $TTB_{mot}$ of 1.1 h per capita per day at a traffic volume of 240,000 pkm/cap (see below for the logic), results in...
Manually iterating $d$ for the best fit yields $d = 20$ and $c = -176,083$ (Standard Error 5061); $R^2$ is 0.9896.

2.2. Travel money budget

A second constant proposed by Zahavi is that individuals devote a fixed proportion of income to traveling, the travel money budget (TMB). Fig. 3 presents TMB time series data for 13 industrialized countries (no other continuous time series surveys are available) and discrete points for three developing countries. We are interested in the aggregate, stable budget, but some well understood variations exist. As Zahavi (1981) observed, TMB rises with motorization (see also Zahavi and Talvitie, 1980). Households without a personal car devote only 3–5% of income to traveling, which is illustrated by the three developing countries shown in Fig. 3. The rising TMBs for Greece, Japan, Italy and Portugal in Fig. 3 illustrates the effect of increasing motorization. With increased ownership of cars the TMB rises until it stabilizes at 10–15% when motorization
rates exceed 200 cars per 1000 capita (e.g. 1980 in Italy). TMBs vary across countries with social and economic factors, such as the price level for travel services (high in Denmark and Portugal, lower in The Netherlands). However, within each society the TMB follows a predictable pattern. In the only exception, Japan, TMB has stabilized at only 7%, reflecting the atypically large share of public high-speed transport (e.g. Shinkansen, discussed below) and higher prices for non-transport goods and services.

Oil shocks in the 1970s, which overnight raised the cost of automobile transport, illustrate and test the stability of the travel money budget. Fig. 4 shows seven transport-related indicators for the United States, the country with the largest share of total mobility supplied by automobiles. In response to rising retail fuel prices (e.g. a 50% jump in 1979), travelers reduced other costs of transport, for example by demanding less expensive (and more fuel efficient) new vehicles. Despite these two rapid rises in fuel prices, multiple economic recessions, and fluctuations in new car prices, the travel money budget remained nearly unchanged between 1970 and 1990, oscillating between 7.9 and 9.0% of income (GDP/cap).

3. The model and scenario: total mobility

We begin with historical observations on total mobility. Next we use the historical data to constrain a scenario for future mobility.
3.1. Historical relationships

A predictable TMB allows us to posit a strong relationship between income and the total demand for mobility. As income rises, spending on travel must also increase – the proportion is defined by the TMB. In turn, higher transport spending allows greater mobility. This relationship between income and mobility can be quantified. For income (GDP) data we employ the widely used Penn World Tables, which report time-series estimates for all nations into constant 1985 US dollars (Summers et al., 1996). Appendix A provides more detail and caveats and compares the Penn World Tables with other available macroeconomic data. Mobility statistics are available from national and industry statistical yearbooks, which one of us has compiled into a unique global data set (Schafer, 1998). That complete historical (1960 to 1990) data set for all 11 regions

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3. This paper includes some minor improvements to the Schafer (1998) data set. Most important, air traffic data from non-scheduled flights between 1975 and 1990 are now derived from ICAO (1975–1991). We estimate data between 1960 and 1974 by assuming that the ratio of non scheduled traffic volumes was fix at the level observed between 1975 and 1990.
allows us to test the claim that the TMB defines a predictable quantified relationship between
growth in income and total mobility. 4 The data also make possible statistical regressions that are
the tool of our model.

Fig. 5 shows the relationship between income (independent variable) and mobility (dependent
variable). In all five of the regions with highest income – Eastern Europe (EEU), former Soviet
Union (FSU), North America (NAM), pacific OECD nations (PAO), Western Europe (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, others below
the central trajectory of slope = 1 (dashed line). For example, at 10,000 USD per capita, per capita
mobility in WEU was only 60% that of NAM, reflecting different infrastructures, population
densities, cultures, and unit costs of transport.

The six lower income regions show more variation, which reflects several factors. One factor is
that conversion of income statistics into common units is imperfect (see Appendix A). A second
factor is the substitution of motorized transport for other modes, notably non-motorized forms
(walking, bicycles, animal-drawn carts) and motorcycles – data for those other modes are poor
and not shown in Fig. 5. Such a substitution has been demonstrated in the replacement of horses
by automobiles in the US over a period of less than three decades beginning in the 1900s
(Nakicenovic, 1988). We interpret the curvature of the growth in mobility in Pacific Asia nations
(PAS) in Fig. 5, for example, as evidence of such substitution; 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 (see Appendix A). A third factor, deep economic re-
cession, applies especially to Middle East and North Africa (MEA) and Sub-Saharan Africa
(AFR). 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 economic recession
and demand for transport because earlier investments (the major share of transport costs) continue to enhance mobility in the early stages of recession. Latin America (LAM) experienced a
shorter deep recession in the 1980s, leading to similar but less pronounced results. The earlier
history of all three of these regions – MEA, AFR, and LAM – shows that during periods of
sustained growth, mobility rises with income.

3.2. Future mobility

Our projection of total mobility is a function of the stable TMB, which is the sum of two parts.
One is the fraction of income allocated to mobility (TMBM). The other is the share devoted to
quality of service – comfort, style, safety, engine power (TMBS).

4 In principle, the rise in TMB from 3–5 to 10–15% with increasing motorization might allow for more rapid growth in
mobility because a larger fraction of income is devoted to travel. In practice, it appears that rising travel money budgets
are offset completely by the rising unit cost of travel as travelers shift from public modes (bus, railroads) to private
automobile. 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 important, confirms the aggregate relationship that is crucial to our forecast). See Fig. 5 and discussion
below.
Time series data from both the United States (Fig. 4) and Germany (Deutsche Automobil Treuhand, 1994), for example, suggest that the two shares do not necessarily remain strictly constant over time. In both countries, the average real purchase price of new automobiles – which is a proxy for quality of service – rose with rising per-capita income. In the US, both new car prices and income grew 40% between 1970 and 1990. In Germany, however, new car prices doubled while income rose only 52%; German car-buyers have devoted a growing share of income to quality of service and taxes. Data that illustrate the constancy of the TMB (e.g. Figs. 3 and 4) are the sum of these two components; however, only $TMB_M$ is used to determine the relationship between income and mobility. The following simple equations describe the relationship.

Traffic volume ($TV$) per capita depends on (i) the money people spend on transport and (ii) the inverse unit cost of transport, $\chi$ (units: pkm/USD). The first of these factors can be expressed as the product of income ($GDP/cap$) and the travel money budget ($TMB_M$). The factor $\chi$ depends on several economic and technological parameters of the employed modes of transport, such as capital costs and fuel efficiency. In the general case:

$$\frac{TV}{cap} = \left( \frac{GDP}{cap} \cdot TMB_M \right) \cdot \chi. \quad (2)$$

If historical data for each of the three variables on the right hand side were available we could use Eq. (2) for estimating future levels of mobility. However time series data for travel money budget and $\chi$ are only available for a few countries. According to Fig. 5, the relationship between per capita mobility and per capita income can be approximated by:

![Fig. 5. Scenario for mobility and income for 11 regions, 1991–2050. A hypothetical “target point”, to which all trajectories converge, is shown. For comparison, historical data (1960–1990) are shown with symbols.](image)
\[
\log \frac{TV}{cap} = e \cdot \log \frac{GDP}{cap} + f
\]

where \( e \) is the slope and \( f \) the intercept. From Eq. (3) follows:

\[
\frac{TV}{cap} = \left( \frac{GDP}{cap} \right)^e \cdot f^*.
\]

A comparison with Eq. (2) reveals that factor \( f^* \) accounts for the travel money budget (\( TMB_M \)) and the inverse unit costs of transport.

Some of the world regional trajectories are slightly curved, especially in the low-income regions – e.g., centrally planned Asia (CPA) and south Asia (SAS) – where substitution of motorized for non-motorized modes of transport is evident. To account for this substitution, we added a dimension-less log factor to Eq. (4), yielding a better fit with convex curves:

\[
\frac{TV}{cap} = \log \left( \frac{GDP/cap}{g} - h \right) \cdot \left( \frac{GDP}{cap} \right)^e \cdot f^*.
\]

Eq. (5a) allows us to extend the relationship between income (GDP/capita) and mobility into the future through regression of historical data. However, the use of historical data alone when projecting future mobility would yield inconsistent results. This is especially true for low income regions where substitution of non-motorized transport is evident in historical statistics will not continue to play such a large role in the future at higher mobility levels when such substitution is complete. To perform a consistent projection of future levels of total mobility, we conduct the following thought experiment. Long-term data analysis shows that whole infrastructures can be eliminated (e.g. canals) or created (e.g. airways) over time periods of six or seven decades (Grübler and Nakicenovic, 1991). Indeed, such infrastructure substitution is necessary; rising mobility within a fixed travel time budget requires a shift to faster modes. Hypothetically, at very high levels of income and mobility the highest speed mode (aircraft) must supply all mobility. Since aircraft operate largely independent of geography, at such high incomes transport must also become largely decoupled from the land. When transport is fully decoupled from geography, and much transport is inter-regional, 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.

Such geographic decoupling allows us to estimate a hypothetical future point to which income and mobility in each region evolves. If all demand were supplied by aircraft at today’s gate-to-gate mean speed of 600 km/h, and the travel time budget is fixed at 1.1 h/cap/d, the total annual distance traveled would be 240,000 km/cap. Assuming that this point lies on the trajectory of slope \( = 1 \), as suggested by historical data, the corresponding income is 240,000 USD/cap. Thus, for each region we apply Eq. (5a) to the historical data and constrain it through the target point, by determining factor \( f^* \) to

\[
f^* = \frac{240,000^{1-e}}{\log \left( \frac{240,000}{g} - h \right)}.
\]
Inclusion of the historical data also helps to account for the many factors that determine the exact relationship between income and mobility, such as the unit costs of transport, the particular value of the TMB, and historical developments such as investments in transportation infrastructure. These factors change only slowly and thus each region’s history constrains the exact development of total mobility.

We used Eqs. (5a) and (5b) for all regions except LAM, MEA, and AFR, where prolonged recessions meant that historical growth in income has not been continuous. For those regions, we used Eq. (4) over the 1990 value and the target point. In CPA, this paper uses only the last two decades of historical data; earlier data show an irregular oscillation of modal shares and appear to be especially implausible. Parameter estimates, $R^2$, and standard errors of all regression equations are indicated in Appendix B.

We have no model of the world economy, and thus we used growth rates based on the widely used IS92a baseline scenario of the Intergovernmental Panel on Climate Change (IPCC/IS92a; Legget et al., 1992). However, that scenario employed growth rates in Asia that are below other authoritative scenarios (see review in Alcamo et al., 1995); thus, we used higher values (from IPCC/IS92e) for the three Asian developing regions (CPA, PAS, SAS). The values that we used for the “reference scenario” presented in this paper are summarized in Table 2. Below we illustrate the sensitivity of our results to this crucial parameter – income growth – with a “high scenario” that employs the even higher growth rates for Asia drawn from the World Bank (World Bank, 1996), also shown in Table 2.

Fig. 5 also shows the regional projections and the “target point”. Values for 1960, 1990, 2020 and 2050 are shown in Table 3. None of the regions approaches the income and mobility levels of the target point by the year 2050, which is consistent with its use as a concept rather than a strictly realistic statement about the future. The target point is sufficiently distant in the future that its specific location on the central trajectory does not matter much (see the section “Sensitivity of the Results”, below). NAM, the region where the projected income growth will be highest by 2050, would reach the target point only a century later (in 2160) if income kept growing at the same rates.

Calculating absolute levels of future mobility (Table 3) requires population estimates. We used the 1992 World Bank projections, which estimate an increase in world population to 10.1 billion in 2050 (Bos et al., 1992). In those projections, growth is strongest in developing countries, where population more than doubles during the period and accounts for 85% of world population in 2050. These values are similar to the 1992 UN medium forecast (United Nations, 1992).  

Based on Eqs. (5a) and (5b) and the assumed income growth rates we project that per capita traffic volume will increase by a factor between 2.6 and 3.8 in the three regions of industrialized countries; in developing regions the rise in mobility will be as much as nine-fold (CPA). Globally, in 2050, people will 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 largest absolute and relative growth in population. Hence, regional shares in

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5 More recent forecasts include the 1996 World Bank (9.2 billion) and 1996 UN (short-term) medium projection (9.4 billion). For a review and some recent projections, see Lutz (1996).
Table 2
Assumed income growth rates. In the “reference scenario”, which is used for all main results reported in this paper, we derived values from IPCC and transformed them into purchasing power parities (PPP) using the method summarized in Appendix A. Also shown is a “high” scenario, which we use only to for a sensitivity analysis. Values for the reference scenario and the high scenario are from the IPCC/IS92a “business as usual” scenario (Leggett et al., 1992). However, in the reference scenario we adopt more plausible (higher) growth rates for the Asian regions (CPA, SAS and PAS) from the IS92e scenario. In the high scenario we adopt even higher growth rates for the three Asian regions, based on short-term World Bank forecasts (World Bank, 1996). The regional groupings for IPCC do not match our groupings exactly. IPCC reports growth estimates for the “USA”, which we use for all of NAM; IPCC values for “OECD-W” and “OECD-A” are applied to WEU and PAO, respectively; we apply IPCC values for “Southeast Asia” to both PAS and SAS; we use IPCC values for “USSR & E. Europe” for both EEU and FSU; and we apply the reported growth rates for the two IPCC regions “Middle East” and “Africa” to MEA and AFR, respectively. IPCC values are reported in five-year steps, and this table shows three decade averages; however, our model employs ten-year steps.

<table>
<thead>
<tr>
<th>GDP/cap USS ('85) (1990)</th>
<th>Reference scenario</th>
<th>High scenario growth rates (%/yr)</th>
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<tbody>
<tr>
<td></td>
<td>Original IPCC IS'92 a/e growth rates (%/yr)</td>
<td>PPP-transformed growth rates (%/yr)</td>
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<tr>
<td></td>
<td>1990 2020 2050 2050</td>
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<td>5.1 4.2 4.6 2.2 2.7 2.4</td>
</tr>
<tr>
<td>South Asia (SAS)</td>
<td>1298</td>
<td>3.9 3.7 3.8 1.7 2.2 1.9</td>
</tr>
<tr>
<td>Other Pacific Asia (PAS)</td>
<td>2983</td>
<td>3.9 3.7 3.8 1.7 2.2 1.9</td>
</tr>
<tr>
<td>Latin America (LAM)</td>
<td>4083</td>
<td>1.7 2.3 2.0 1.0 1.6 1.3</td>
</tr>
<tr>
<td>Average</td>
<td>1890</td>
<td>3.0 3.1 3.0 1.5 2.0 1.8</td>
</tr>
<tr>
<td>World Average</td>
<td>4222</td>
<td>1.8 1.5 1.7 1.4 1.4 1.9</td>
</tr>
</tbody>
</table>
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.

4. The model and scenario: transport modes

Now we project the shares of the four transport modes – buses, rails, cars, and aircraft (including high speed trains) – which operate at different speeds. For the unique determination of four variables, we need four constraints. The main constraint is the fixed travel time budget (TTB), which requires that people shift to faster modes of transport as their total mobility rises. In addition, path dependence, land use patterns, and a balancing equation provide three other constraints. These four constraints are presented below.

---

Table 3

<table>
<thead>
<tr>
<th></th>
<th>1960 Absolute</th>
<th>1990 Absolute</th>
<th>2020 Absolute</th>
<th>2050 Absolute</th>
</tr>
</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>REF</td>
<td>1550</td>
<td>477</td>
<td>8.7</td>
<td>5672</td>
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<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>3.3</td>
<td>1614</td>
</tr>
<tr>
<td>CPA</td>
<td>152</td>
<td>109</td>
<td>2.0</td>
<td>637</td>
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<tr>
<td>SAS</td>
<td>349</td>
<td>200</td>
<td>3.7</td>
<td>1778</td>
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<tr>
<td>PAS</td>
<td>587</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>552</td>
<td>1191</td>
<td>21.7</td>
<td>2125</td>
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<tr>
<td>WOR</td>
<td>1814</td>
<td>5481</td>
<td>100.0</td>
<td>4382</td>
</tr>
</tbody>
</table>

6 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 compilation 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.
4.1. Path dependence and railways

Transport infrastructures, like many massive technologies and infrastructures, do not rise and fall rapidly (Grübler, 1990). Earlier choices and the level of mobility constrain possible future developments, limiting the rate at which one mode can substitute for another. Expensive and long-lived infrastructures lock-in the initial choices; substitution between infrastructures occurs only over several decades. Thus the future for some modes of transport may be strongly evident in their current 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 with a hyperbolic regression equation of past (declining) trajectory, reaching a zero-share at a traffic volume of 240,000 pkm/cap [Eq. (6)].

\[ S_R = i \left( \frac{1}{(TV - j)^k} - \frac{1}{(240,000 - j)^k} \right). \]  

The parameters \( i, j \) and \( k \) are determined by least-squares regression.

4.2. Urban land-use and low-speed public transport

Although we expect that all low-speed transport modes will decline to essentially zero share in the very distant future (at the “target point”), the transition from the present to their ultimate demise could take many paths. In WEU, for example, the share of mobility supplied by low-speed transport modes (buses and trains) has been significantly higher than that of NAM but lower than in PAO at similar levels of per capita traffic volume. Such differences in the share of low-speed public transport in these three regions reflect transport infrastructures built to accommodate particular patterns of urbanization, population density and land-use. North American cities are the least dense (14 people per ha) and people use the least amount of low-speed public transport (8% of total mobility at a traffic volume of 10,000 pkm/cap). Density in European cities is four-fold that of North America, and the modal share of low-speed public transport is correspondingly higher (19%). Asian cities are typically even more compact, with an average density 3 times that of Western Europe, and a 30% modal share of low-speed public transport.

The three experiences suggest constraints for the scenarios of growth in low-speed public transport in lower income regions that have similar urban, population and land-use characteristics. Ideally, land-use statistics would be used to compare the characteristics of particular regions and, in turn, constrain the range of possible scenarios for future shares of low-speed public transport modes. However, such statistics are only available for a few selected cities, mainly in OECD countries, and forecasts do not exist. Thus we make comparisons with the three industrialized regions – NAM, WEU, and PAO – which represent three typical urban land-use settings.

---

\[ ^7 \] Data from Newman and Kenworthy (1989), Table 3.4. The density of Asian cities (160 people per ha) is an average of three typical cities (Tokyo, Singapore and Hong Kong), only one of which is in PAO. Density in Australian cities (14 people per ha) is comparable with those of North America, but the high traffic volume in Japan results in PAO having modal shares characteristic of high-density Japan.
The three industrialized regions define an envelope for the trajectory of low-speed public transport in other regions with comparable urban land-use patterns. Fig. 6 shows the share of low-speed public transport for these three regions and the eight other world regions. We assume that the NAM trajectory is anomalous due to extremely low population density and high mobility. All eight other regions thus follow either the WEU (medium density) or PAO (high density) trajectory. We assume that the three Asian regions (CPA, PAS, SAS) follow the PAO trajectory – in each of those regions, motorized transport is especially concentrated in high density cities. We assume that all remaining regions (AFR, EEU, FSU, LAM, and MEA) will follow the trajectory of WEU.

Formally, this constraint can be expressed for the three OECD regions as:

\[
S_{LS} = l \left( \frac{1}{TV - m} - \frac{1}{240,000 - m} \right) .
\]

(7a)

The parameters \(l\) and \(m\) are determined by least-squares regression.

The trajectories of the eight other regions were determined with a segmented model. The first segment is based on historical data and was approximated with a four-degree polynomial function:

![Fig. 6. Relationship between mobility and share of low-speed public transport. The three industrialized regions (PAO, WEU and NAM) illustrate the shares of low speed public transport and mobility that are the result of three typical urban land-use patterns. In this scenario, those three regions are used to define an envelope for the trajectory of low speed public transport in other regions with comparable urban land-use patterns. For illustration, the projection for LAM is shown; note the transition to the medium density trajectory density.](image)
That first segment converges to the second segment, which is the trajectory based on the appropriate OECD “lead” region [i.e. Eq. (7a)]. To achieve this convergence, the coefficients \( n \) and \( o \) were determined by equating Eq. (7b) (first segment) to Eq. (7a) (second segment) at the point \( t v_0 \) where both the functional value and the first derivative of both equations are equal. Substituting the expressions for \( n \) and \( o \) in Eq. (7b) results in:

\[
S_{LS} = \frac{l}{tv_0 - m} \left( 1 + \frac{TV}{m - tv_0} \right) + p \cdot (TV - tv_0)^2 + q \cdot (TV^3 - 3tv_0^2TV + 2tv_0^3) + r \cdot (TV^4 - 4tv_0^3TV + 3tv_0^4).
\]  

The parameters \( p, q, r \) and the traffic volume at the point of convergence between the two segments \( (tv_0) \) were determined through least-squares regression. For illustration of the segmented model, Fig. 6 shows the computed transition paths for the LAM region, which follows the trajectory of medium density.

Because rail shares are already determined [Eq. (6)], the share for bus travel results from:

\[
S_B = S_{LS} - S_R
\]  

4.3. Travel time budget

A fixed travel time budget 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.

Formally, the sum of the daily motorized per capita travel time \( TT \) over all modes of transport \( (i) \) which move daily traffic volume \( (TV_i) \) at mean speed \( (V_i) \), must equal the travel time budget for motorized modes \( (TTB_{mot}) \):

\[
\sum_i TT_i = \sum_i \frac{TV_i}{V_i} = TTB_{mot}.
\]  

Applying the \( TTB \) constraint from Eq. (9) requires that we estimate the mean speed of each travel mode. Table 4 summarizes available travel survey data in three world regions – NAM, PAO and WEU – which we used to estimate future speeds in other regions. The table shows that the mean speed of buses, trains and aircraft are identical in the three regions; we assumed that the same speeds apply to all other regions as well. In contrast, the mean speed of car travel varies by region. We derive \( TTB_{mot} \) from Eqs. (1a)–(1c).

4.4. Balancing equation – total traffic volume

The fourth constraint is that the traffic volume of each motorized mode \( (i) \) must sum to the total projected traffic volume for each region:

\[
TV = \sum_i TV_i.
\]  

\[\text{(7b)}\]

\[\text{(7c)}\]
Equations for the modal shares for high speed transport (HST) in 2050 can be derived from Eqs. (9) and (10):

\[ S_{HST}^{2050} = \frac{1 - S_B(1 - V_C/V_B) - S_R(1 - V_C/V_R) - V_C \cdot TTB_{mot} \cdot 365/TV}{(1 - V_C/V_{HST})}. \]  

(11)

Especially the future mean speed of automobiles is difficult to estimate, and we have no relationship that describes how speeds may change with income and mobility. We are thus unable to make a continuous projection over the whole 1990–2050 time period using Eq. (11). Thus we apply Eq. (11) (with speed estimates in Table 4) to calculate the high-speed transport share in 2050. We then project the continuous share with a non-symmetric logistic (Gompertz) regression equation through the historical data of this mode:

\[ S_{HST} = s \cdot \exp \left( e^{-t(TV-u)} \right) + v \]  

(12a)

The parameters \( s \) and \( v \) were specified to force the trajectory through the projected 2050-value and the target point.

\[ s = \frac{S_{HST,2050} - 1}{\exp (e^{-t(HST_{2050}-u)}) - \exp (e^{-t(240,000-u)})} \]  

(12b)

\[ v = 1 - m \cdot \exp \left( e^{-t(240,000-u)} \right). \]  

(12c)

The parameters \( t \) and \( u \) are estimated with least-squares regression. ⁸

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Table 4
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, especially speeds for bus and rail can only be a rough estimate. Source: Department of Transport (1993), Dienst für Gesamterkehrsfragen (1992), Kloas et al. (1993), Stab für Gesamverkehrsfragen (1986), Vibe (1993), Ministry of Infrastructure (no date), US Department of Transportation (1992)

<table>
<thead>
<tr>
<th>Industrialized regions</th>
<th>Car</th>
<th>Bus</th>
<th>Rail</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<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>Other regions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFR, EEU, FSU LAM, MEA</td>
<td>45</td>
<td>20</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>CPA, PAS, SAS</td>
<td>35</td>
<td>20</td>
<td>30</td>
<td>600</td>
</tr>
</tbody>
</table>

---

⁸ The results from this regression allow us to calculate the mean automobile speeds that would be needed to have continuously projected the share of high-speed transport. That exercise yields a mean automobile speed that rises 0.8% per year, which is consistent with recent (1968–1988) US historical data (Levinson and Kumar, 1994). After year 2015, computed mean automobile speeds decline back to their 1990 value by 2050, which is the consequence of our exogenous assumption for vehicle speeds but is consistent with the expectation that most automobile travel will be shorter distance and in urban areas. Long distance trips will be substituted by higher speed modes (see below).
Finally, we can derive the share of automobile travel $S_C$:

$$S_C = 1 - S_{LS} - S_{HST}.$$  \hspace{1cm} (13)

4.5. High-speed niche markets

In principle, we could derive all regional projections for HST shares from Eq. (11). All terms in that equation are determined by exogenous speed assumptions or calculations, except the final term in the numerator. The value of that term depends on the value of $TTB_{mot}$; Fig. 2 shows that $TTB_{mot}$ is especially sensitive in regions with low income (low traffic volume). For example, reducing $TTB_{mot}$ in NAM in 2050 by 10% would only incur a 6% increase in the modal share of high-speed transportation, whereas the same change in SAS would result in a 56% increase. Moreover, data on modal speeds and $TTB_{mot}$ are practically non-existent in those regions and thus it would be inappropriate to use this method. Setting the first derivative of Eq. (11) (i.e. $dS_{HST,2050}/dTTB_{mot}$) to $-1$ allows us to calculate the threshold traffic volume at which a change in $TTB_{mot}$ by one unit results in an equal unit change in $S_{HST,2050}$. Mean car speed varies by region and thus the calculated threshold value also varies: 24,340 pkm/cap in NAM; 17,750 pkm/cap for WEU, AFR, EEU, FSU, LAM, MEA; and 13,560 pkm/cap for PAO, CPA, PAS, SAS. Only in the three OECD regions (NAM, PAO, and WEU) are the projected 2050 levels above that threshold (see Table 3); using this criterion, we can apply Eq. (11) only for these three regions.

For other regions, where Eq. (11) cannot be applied, we identified patterns in the historical development of high-speed niche markets in industrialized regions (Fig. 7), which we used to determine the share of high-speed transportation. Commercial air transport was developed in

![Fig. 7. Niche markets for high-speed transportation in NAM, PAO, and WEU, 1960–1990.](image-url)
North America; in that region, the rate of growth has been comparatively slow but will last over a long period. In regions where high-speed technology was introduced later, innovations pioneered in the lead regions were less costly and adopted more readily, which allowed more rapid growth in the niche market. Other factors that affect demand include the length of trips and policies that have altered market share, such as government subsidies. The data (Fig. 7) suggest two possibilities – in Western Europe the rate of adoption (expressed as share of high-speed transport as a function of total traffic volume) 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 riders. We applied these growth rates in the niche markets for the calculation of the 2050 share with the same regional correspondence as with the urban land-use constraint. Formally, the equation can be written as:

\[ S_{\text{HST,2050}} = S_{\text{HST,1990}} \cdot w^{(T_T_{2050} - T_T_{1990})}. \] (14)

The niche market approach [Eq. (14)] applies only in regions where the share of HST is typical of a niche market, which we assume is approximately 5% of the 1990 traffic volume. In addition to NAM, PAO and WEU, two other regions exceed that level: FSU (14.4%) and PAS (7.5%). For those regions, we apply Eq. (11). In the later section on “Sensitivity of Results” we vary the factors that affect Eq. (11) (transport speeds and TTB mot) to check the sensitivity of the 2050 HST share. That analysis confirms that for these five regions (FSU, NAM, PAO, PAS, and WEU) it is appropriate to use Eq. (11).

4.6. Results

Together, these constraints define unique values for each mode in each region. Fig. 8 presents each of the regional projections.

Fig. 8 also reports the results aggregated at the world level. 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 supply 42%. In all three industrialized countries, automobile shares decline sharply by 2050. Rising automobility in developing countries is unable to offset fully the automobile’s relative decline in other regions for several reasons: (a) income levels remain low in AFR and CPA, and thus automobility remains modest in these regions; (b) higher population densities lead to a lower saturation level for automobiles; and, (c) high shares of air travel supplant some of the potential share of automobiles.

Fig. 9 shows absolute mobility levels for each mode in 1960, 1990, 2020 and 2050. In light of the four fold rise in total mobility, the absolute mobility by each mode increases even for modes that are in relative decline. Absolute mobility by car increases 260%. High speed mobility rises to 28 times its 1990 level.

Such a strong increase in air travel may appear unrealistic because the airway network is already dense and congested in some regions. However, many technological possibilities are feasible and can easily find widespread application within six decades. Aircraft can be bigger – carriers with a capacity of 1000 people are technologically feasible before 2020 (e.g. Covert et al., 1992). In addition, our scenario for “aircraft” consists of all high-speed modes operating at an average speed of 600 km/h, which may include surface-bound high speed transport modes, such as wheel-on-rail and
Fig. 8. Share of total mobility supplied by cars, buses, conventional railways, and high speed transport (mainly aircraft), Eastern Europe (EEU) and Western Europe (WEU), Southeast Asia (SAS), Pacific Asia (PAS), Middle East and North Africa (MEA), Pacific industrialized countries (PAO), Former Soviet Union (FSU), Centrally Planned Asia (CPA), Latin America (LAM) and North America (NAM), Sub-Saharan Africa (AFR), the world (aggregated from the 11 regions). In each world region, conventional railroads are a (declining) hyperbolic regression of past trends.
magnetic levitation trains. Currently such trains provide a minor share (4%) of global high-speed mobility, but many plans are under way to build more extensive networks.

Fig. 8 also underlines the importance of regional projections. Since the share of traffic volume supplied by conventional railways and high-speed transport modes have a uniform development in all 11 world regions, such a trend is also evident in the aggregated world projection. However, no such uniform trend is evident in the world automobile and bus scenarios, although clear trends are evident for those modes in most of the regions. Thus even if the aim of a transport scenario is only to estimate world mobility and modal shares, results from our method underscore that it is essential to build such scenarios on estimates for a number of coherent regions.

Fig. 8 illustrates a consistent stepwise pattern – slow modes are replaced by ever-faster ones. At mobility levels below 5000–7000 pkm per capita, low-speed public transport modes predominate. As the economy of each region grows, so does the travel demand; a greater distance must be covered within the same fixed time budget and thus the share of faster automobiles rises. At approximately 10,000 pkm per capita, automobiles predominate. At still higher levels of mobility, the automobile share declines as faster modes of transport – aircraft – are needed to satisfy the rising demand for mobility within the fixed travel time budget. This relative decline must lead to an absolute decline in automobile traffic volume at a sufficiently high level of total mobility. Fig. 10 illustrates the rise and fall of per-capita automobile traffic volume in NAM, with absolute declines evident starting in 2010 at per capita automobile traffic volume of approximately 22,000 pkm/cap.

Despite the projected absolute decline of automobility in the OECD and the strong growth of air traffic, the automobile will still remain an essential mode of transport. In fact, travelers will continuously spend most of their travel time in the automobile. This result is shown in Fig. 11,
which compares the 1990 and estimated 2050 TTB allocation by mode of transport for the three industrialized regions NAM, WEU, PAO and two regions from the developing world (LAM, CPA).
5. Consistency of results

For the developing world our results imply rapid diffusion of the automobile. For all regions, especially in industrialized and reforming regions, our scenario envisions large increases in high speed mobility. Here we check whether those results are plausible – we compare the rise of automobility with historical patterns; and, we check that the predominance of high speed travel in the industrialized world is consistent with requirements for short distance travel (e.g. local shopping), where slow modes are likely to remain preferable.

5.1. Consistency with the historical motorization trends

Unlike conventional forecasting methods, where motorization rates (passenger cars per capita) are a model input variable, our method allows calculation of motorization rates as an output variable. That computation requires the per-capita traffic volume supplied by automobiles (calculated by the model) and two assumptions: a passenger load-factor and the annual distance driven per vehicle. The projected motorization rates for developing countries can then be compared with historical trends in industrialized countries as a test of the consistency of the model output. We apply this consistency check to CPA, PAS, and SAS – the three Asian developing regions which have the highest projected GDP growth and will have strong substitution of automobiles for other transport modes over the period of our projection.

We expect that load factors will decrease with rising incomes, as has been observed historically in nearly all countries. In 1990 the load factor was about 2.5 occupants per vehicle in SAS and CPA and 2.3 in PAS (Schafer, 1998). We estimate an exponentially decreasing curve defined by data series from the US (Federal Highway Administration, 1992), UK (Department of Transport, 1988, 1993), The Netherlands (Central Bureau voor de Statistiek, 1978–1993), New Zealand (Jollands, 1995), Switzerland (Dienst für Gesamtverkehrsfragen, 1992), Australia (FORS, 1988), and Germany (Deutsches Institut für Wirtschaftsforschung, 1991, 1993). Dividing the projected world-regional traffic volume of passenger cars by the load factor and then by the estimated distance traveled per vehicle (from Schafer, 1998) delivers estimates of motorization rates. Fig. 12 shows that the motorization rates of the three regions, which rise with income, are broadly consistent with those of industrialized regions. The difference in motorization rates (high in SAS, low in CPA) are a result of the different levels of mobility at a given income level (see Fig. 5) and, in turn, a consequence of the PPP-adjustments of the macroeconomic data set. However, we may underestimate motorization in CPA because the historical data set that we use does not extend beyond 1990 and thus excludes the marked increase in motorization evident in the early 1990s (SSB, 1996).

5.2. Short distance travel

If the hypothetical “target point” were reached, high speed transport modes would account for 100% market share. However, high speed modes are impractical for short trips, such as shopping and travel to high speed nodes. Thus even at very high mobility levels, low speed modes must retain some share of total mobility. We have checked that all projections are consistent with plausible estimates for such short distance niche markets, with particular attention to the industrialized
regions where the share of high speed transport accounts for two-thirds of total traffic volume by 2050. For example, in NAM the projected per capita automobile traffic volume is 16,000 km in 2050, which means that North Americans will still be driving as much in 2050 as they did in 1980 (see Fig. 10). In each industrialized region the share of travel time spent in low speed public transport modes (buses and rails) does not change significantly from 1990 levels (Fig. 11).

We underscore that our model does not explicitly account for trip length. A possible extension of our approach would entail separating the total demand for mobility into several markets defined by trip length and to model competition to supply mobility within each of these discrete markets. However, such an approach would require historical data for demand as a function of trip length. Such data exist for only a few countries.

6. Sensitivity of results

Our model is not fully deterministic and is obviously sensitive to its main assumptions. Here we examine four of the most important or uncertain assumptions: the stability of the target point, the assumed rate of income growth, mean vehicle speeds, and the $TTB_{mot}$.

6.1. Stability of the target point

The location of the target point depends on the mean speed of the fastest mode of transport – the high-speed modes which travel at 600 km/h. Changes in the location of the target point would
alter the development of the world-regional trajectories and thus the projected traffic volume. To
test the sensitivity of the projections of total mobility, we examined an extreme case: reducing the
mean speed of the high-speed transport modes by one-third, to 400 km/h. This reduction causes a
proportional shift in the target point from 240,000 to 160,000 pkm/cap. As a result, the projected
traffic volume in 2050 declines by merely 1.5% in North America. The sensitivity of the other 10
world regions is comparably low.

6.2. Income growth

The pattern of high speed transport modes replacing slower forms, and the dynamics that are
particular to each region, are robust derivations from the concepts of travel time budget and path
dependence. But the particular levels of mobility are mainly a function of income growth, which is
exogenous to our model. Here we illustrate the sensitivity using a set of higher growth rates for the
three Asian developing regions (CPA, PAS, SAS) derived from World Bank forecasts (Table 1).
These higher rates yield a global income in 2050 that is 34% higher than in our reference scenario.
World mobility increases by a factor of 5.8, only 29% higher than the reference scenario. The
difference between income and mobility reflects that although regional per capita mobility rises
almost directly with regional per capita income in 11 regions, both variables contribute with
different shares to the world economy and traffic volume. The sources of these differences include
PPP-adjustments of the macro-economic data set (see Appendix A), which both shift and influence
the shape of the projected total mobility curve. In 1990, the CPA region contributes 3.5% to
the global motorized traffic volume, but its share of world GDP is almost twice as high (6.7%).

Increasing the income growth rates also affects the mode of transport. With higher mobility and
a fixed travel time budget, travelers shift earlier to faster modes. In CPA and SAS automobiles
substitute for buses; in PAS, where income and mobility are comparatively higher, more rapid
growth in income leads to substantially greater use of high-speed transport. Globally, many of
these regional differences offset. With high income growth rates, automobiles and high-speed
transport account for 40% and bus travel declines to 14% of the traffic volume in 2050. Our
reference scenario envisions only slightly different shares for buses (18%), high-speed transport
(36%) and automobiles (42%).

6.3. Mean vehicle speeds and $TTB_{mot}$

Applying Eq. (11) has required assumptions about the mean speed and the time budget for
motorized travel ($TTB_{mot}$). Table 5 illustrates the sensitivity of the computed $S_{HST,2050}$ share to a
10% change in $TTB_{mot}$ or the same change in the velocity of the three low-speed modes. The results
show that our modal projections for the three industrialized regions are very stable. Projections
for FSU and PAS are also relatively stable. The least stable results are for the six regions where we
applied the niche-market concept [Eq. (14)]. For those regions, the results in Table 5 are purely
hypothetical – they illustrate the high sensitivity of the results if we had used Eq. (11), which
supports the use of the alternative niche market approach.

Many phenomena could cause actual travel speeds to differ from our assumptions, which would
also alter projections that employ the $TTB_{mot}$ [Eq. (11)]. For example, in regions where buses
account for a high share of total mobility they must also account for a large share of intercity
traffic and thus probably operate at speeds higher than the values we have assumed. For example, increasing the bus speeds by 50% (to 30 km/h, equal to that of railways) in PAS would reduce the HST share from 34 to 19% and increase the 2050 automobile share by nearly half, from 38 to 54%. Thus, for this region, we have probably underestimated the future share of automobile traffic and over-stated the share of high-speed transport. A priority for future research is to make more precise estimates of vehicle speeds for each world region.

Results could also be affected by the introduction of intelligent transportation systems (ITS), such as timed-entry freeways and on-board traffic directors that could reduce congestion and increase the mean speed of automobiles by up to 15% (e.g. Diebold Institute for Public Policy Studies, 1995). Consequently the share of automobiles would rise as this mode could, with ITS, better satisfy the demand for higher speed transport. Nonetheless, if automobile mean speeds increase by 15%, our results are not radically altered. In NAM, for example, ITS would increase the 2050 automobile traffic share from 28 to 32%. However, as high-speed modes are still one order of magnitude swifter, the decline of automobiles would be delayed by only approximately 4 years.

7. Conclusions

On average, people spend a constant share of money on traveling; rising income leads nearly directly to 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 modes to remain within the fixed travel time budget of 1.1 h per person per day. In addition to these constant budgets, travel behavior is also affected by the path dependence of infrastructures, land-use constraints, and the development of niche markets. We use these factors to develop a new technique for projecting future mobility and mode of transport in all 11 world regions from 1990
to 2050. This projection is made possible not only by the method presented in this paper but also by the availability of a new historical data set (1960–1990) for all major motorized travel modes.

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 largely reflect the historical legacy of infrastructures, which partially reflect population density, policies and tastes. Accounting for those differences, our technique suggests that transportation systems behave in deterministic patterns. Over the long term, 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.

The wealthiest regions are most mobile and thus have the highest share of high-speed modes, but even in these regions travelers will spend most of their travel time in automobiles. In North America the HST share of mobility will rise fourfold to 71% by 2050, but only 17% of the average person’s travel time budget (11 min) will be spent moving at high speeds; a little time goes a long way in aircraft.

A five-fold increase in per-capita mobility will make more common what is extreme traveler behavior today, such as living in Bombay or Boston and commuting daily to Delhi or Washington. Because extreme mobility depends on access to high speed modes, pockets of low-density living will persist where it is time-intensive to travel to nodes (airports and maglev train stations) in the high-speed transportation system – as likely in the outskirts of London as the Sahara.

Although powerful, our technique is highly simplified. Neither the model nor the historical data set distinguishes between urban and rural travel; nor do they compute trip rate or length. Thus we are unable to further constrain our scenario by matching modes to the particular types of transport services for which they are most appropriate. Refinement is also needed for projections that depend on the travel time budget. That constraint can be implemented more fully only with improved data and projections for vehicle speeds and motorized travel time budgets, especially in the non-OECD regions. This also suggests that distinguishing between urban and intercity travel in our model would be a logical next step.

Acknowledgements

The authors especially thank Harry Geerlings and Arnulf Grüber for detailed comments on earlier drafts, Thomas Stoker for invaluable econometric advice, Frank A. Haight for assistance and thoughtful comments throughout the review process, Nadejda Victor for comments and assistance with data, Jesse Ausubel, Jean-Pierre Orfeuil and three anonymous referees for comments. We are also grateful to Aviott John and Eddie Löser for help securing many data sources, Wiley Barbour for providing income assumptions used in the IPCC/IS92 scenarios, the UK Department of Transport for supplying unpublished travel time budget data, and Hans van Vliet for providing travel time budget data for The Netherlands.
Appendix A. Purchasing power parities

There is no well-established method for converting income statistics from different countries into common units. For low-income countries, especially, the use of market exchange rates is inappropriate because of barriers to free trading in local currencies; moreover, many local goods (e.g. food) do not trade at international prices. Hence, a comparison of low-income and high-income countries using market exchange rates would systematically under-state the purchasing power in low-income countries. Thus virtually all studies use some form of purchasing power parity (PPP) adjustment.

In this paper we use the Penn World Tables (PWT) of gross domestic product statistics, which is the most transparent global macroeconomic data set (Summers et al., 1996). PWT is also the most widely used PPP-adjusted income data set, which allows for easy comparison with other studies. However, data for some countries and time periods are missing (e.g. Libya all years and Saudi Arabia 1960–1979 and 1990). For these, all of which are small countries with low mobility, where possible we have estimated the missing values through interpolation or by comparison with data reported through the United Nations Macroeconomic Data System (MEDS; United Nations, 1993b).

The rate of PPP adjustment varies considerably by method. For example, Fig. 13 shows per-capita income for India (representing 74% of the population of SAS in 1990) using the three main income data sets: PWT, MEDS, and the World Bank. Both recent series of the PPP-adjusted PWT data are shown: version 5.5 (1993) and version 5.6a (1995). Values differ by more than a factor of 4; even within a single method (PWT), adjustment has been substantial (30% in

![Fig. 13. PPP adjustments for India, normalized to US$ (1985) as reported in four data sets: Penn World Tables versions 5.5 (1991) and 5.6 (1995), UN Macro-Economic Data Set (MEDS), and World Bank (World Bank, various years).]
Fig. 14. The share of total mobility supplied by motorized transport in three world regions – SAS, PAS, and MEA – as a function of income. Income statistics, expressed as GDP/cap in US$ (1980), are derived from the MEDS data base.

Fig. 15. PPP adjustments as a function of GNP/cap, expressed in US$ (1990), as derived from the IPCC IS92 scenario. PPP adjustments, defined by the ratio of PPP (PWT5.6) and GNP (IPCC IS92), were used to transform the economic growth rates from the IPCC scenario to growth rates that are appropriate for use with the PWT macroeconomic data set, which is PPP-adjusted. Data points correspond to the world regions as defined in the IPCC IS92 scenarios.
1990. The MEDS and World Bank series are based on market exchange rates and not PPP-adjusted.

For illustrative purposes, Fig. 14 shows the consequence of using MEDS income data instead of PWT for our projections in one cluster of regions – SAS, PAS, MEA (Schafer, 1998). The PPP adjustment in the MEDS database results in a smooth transition, from SAS to PAS to MEA, of all four modal split trajectories.

The prescribed growth rates used in this paper are derived from the IPCC/IS92 scenarios. Because the IPCC growth rates apply to macroeconomic data that are based on market exchange rates, we have had to transform them for use with the PPP-adjusted PWT data set used in this paper. This transformation was done as follows. First, the IPCC macroeconomic data for the base year (1990) and the IPCC projections were transformed into PPP data using a hyperbolic function. Fig. 15 shows the function, which was estimated using the relationship between GNP/cap for the nine IPCC regions and the world and the PPP data (from PWT) for those same regions in 1990. Second, we then estimated the growth rates that would be necessary in each region for income to rise from the transformed IPCC base year to the transformed IPCC projected values for each decade, 1990 to 2050. The resulting “transformed” growth rates are reported in Table 2.

Appendix B. Statistical analysis

Tables 6–9 summarize the estimated parameters, $R^2$, and standard errors for each of the equations used in the regression analysis.

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<th>Parameter estimates, standard errors (in parenthesis), and $R^2$ squared for Eq. (5a)</th>
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Table 8
Parameter estimates, standard errors (in parenthesis) and $R^2$ squared for Eq. (7a) (NAM, PAO, WEU) and Eq. (7c). The table also indicates the computed values for $n$ and $o$, determined by Eq. (7b).

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Resulting values

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Table 9
Parameter estimates, Standard Errors (in parenthesis), and $R^2$ squared for Eq. (12a). The table also indicates the computed values for $s$ and $v$, determined by Eqs. (12b) and (12c).

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Resulting values

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