Pergamon

Transpn Res.-A, Vol. 32, No. 6, pp. 455–477, 1998

Printed in Great Britain
0965-8564/98 $19.00 + 0.00

PII: S0965-8564(98)00004-4

THE GLOBAL DEMAND FOR MOTORIZED MOBILITY

ANDREAS SCHAFER*

Massachusetts Institute of Technology, Center for Technology, Policy and Industrial Development, and The MIT Joint Program on the Science and Policy of Global Change, Room E40-257, Cambridge, MA 02139, U.S.A.

(Received 26 December 1996; in revised form 10 December 1997)

Abstract—This paper provides a data set of global and regional passenger traffic volumes between 1960 and 1990 for the four major motorized modes of transport—cars, buses, railways, and aircraft—in eleven world regions. Based on these data, global long-term trends in motorized traffic volume and modal split are projected. The underlying constraints, originally employed in urban traffic planning and never before applied to global scenarios, assume that humans invest fixed budgets of money and time for travel on average. The paper also discusses implications of rising travel demand on world passenger transport energy use, on the global automobile motorization rate, and briefly deals with the long-term implications of unlimited mobility growth. © 1998 Elsevier Science Ltd. All rights reserved

Keywords: global mobility, passenger travel, travel budgets, transportation CO_2 emissions

1. INTRODUCTION

In 1960, world inhabitants traveled an average of 1820 km by car, bus, railway, or aircraft. Three decades later, the annual distance traveled has increased to 4390 km. In light of a 75% world population growth, absolute motorized mobility has risen by a factor greater than 4 (see Appendices for data descriptions). Perhaps most important, no saturation of traffic volume is evident; rather, demand for travel continues to rise, based on observed travel growth rates of 4% per year in the OECD, and rates almost twice as high in the developing world.

Such drastic rises in travel demand increase concerns over transport systems' impact on the environment. Already, transport sector emissions contribute significantly to major environmental challenges at local (e.g. deterioration of urban air quality), regional (e.g. acid rain), and global (e.g. stratospheric ozone depletion and the anthropogenic greenhouse effect) levels. This has led to a globally recognized need for implementing effective strategies to reduce transportation systems' environmental impact. Due to transportation infrastructures' long lifetimes, such strategies require a reliable projection of motorized mobility well into the future. This paper lays a foundation for such a project.

In recent years, analysts have followed essentially the same approach to projecting traffic volume on national, world regional, and global levels. Although the methods employed vary, scenarios are generally based on *independent* projections of traffic volume per mode of transport over time. Typically, each modal projection builds on a different method, and the total traffic volume becomes simply an aggregate of the independent estimates for the various modes (Martin and Shock, 1989; Eckerle *et al.*, 1992; Grübler *et al.*, 1993; Walsh, 1993a,b). Such an approach has several shortcomings: Independent estimates are inherently static, since no driving force creates direct competition between modes that provide transport services. In the absence of causal relationships, such methods fail to explain why one scenario is more likely than others to materialize. In addition, these methods build on variables subject to significant uncertainty themselves: while Grübler and Nakicenovic (1991) estimate that the world automobile fleet will become saturated at 500 million vehicles in 2010, Walsh (1993b) expects the vehicle count that year to be on the order of 700 million while continuing to increase. A further drawback of existing methods is that no data series has existed on which to base projections. In fact, no existing global projection takes into account the traffic volumes of all major modes of transport.

*Fax: 001 617 253 7140; e-mail: aschafer@mit.edu

This paper provides the empirical foundation for a new method based on money and time budgets that eliminates shortcomings of the traditional approach described above. The existence of causal relationships suggests reversing the traditional approach: motorized mobility (the aggregate traffic volume of cars, buses, railways, and aircraft) should be projected in a first step, and the related modal split computed thereafter. The resulting dynamic model would build on only two independent variables: population and GDP. This method, suited especially for high (world-regional) aggregation levels, roots on the first database ever compiled on world-regional, historical traffic volumes, by major mode of transport.

The paper is organized into the following sections. Section 2 presents historical data for global traffic volume by world region and mode from 1960 to 1990. Section 3 describes the two fundamental constraints on travel behavior that determine the dynamics of the model, the basic elements of which are described in Section 4. Section 5 describes three case studies: the effect of rising regional transportation demand on energy use and carbon dioxide (CO_2) emissions; the rate of global automobile motorization; and the factors contributing to unlimited growth in mobility. The paper's findings are summarized in Section 6.

2. GROWTH IN WORLD TRAVEL DURING THE PAST THREE DECADES

This paper presents an historical data set of global traffic volume for the first time (limited time-series data for traffic volume by mode of transport had, until now, been compiled for only a number of OECD countries; see, for example, Schipper, 1995). These data account for the four major motorized transport modes—cars, buses, railways, and aircraft—in 11 world regions. Although two- and three-wheelers represent an important mode of transport, especially in Asian regions, these were neglected because of poor data availability; however, this simplification does not significantly change the results of this research. Appendix A summarizes the data sources and estimation methods; Appendix B reports traffic volume and modal split for the years 1960, 1970, 1980, and 1990. The world-regional disaggregation is shown in Fig. 1.

Figure 2 illustrates per capita mobility by region and mode for the 11 world regions and the world average in 1960 and 1990. During that period, estimated global traffic volume rose from approx. 5.5 to 23.3 trillion passenger-km (pkm), due to a 2.4-fold increase in annual distance traveled (from 1820 to 4390 km) and a 75% rise in world population (from 3.03 to 5.29 billion). Although higher relative growth in per capita mobility occurred in the developing world [culminating in a factor of 10 in the Other Pacific Asia (PAS) region, four times the world average], reducing differences among all world regions, per capita mobility is still distributed unevenly throughout the world.

Generally, inhabitants of regions with the highest per capita income—the 'OECD regions' of North America (NAM), Western Europe (WEU), and the Pacific (PAO)—travel most.

Fig. 1. World regions as defined in this paper. NAM: North America; LAM: Latin America; WEU: Western Europe; EEU: Eastern Europe; FSU: Former Soviet Union; MEA: Middle East and North Africa; AFR: Sub-Saharan Africa; CPA: Centrally Planned Asia and China; SAS: South Asia; PAS: Other Pacific Asia; PAO: Other Pacific OECD.

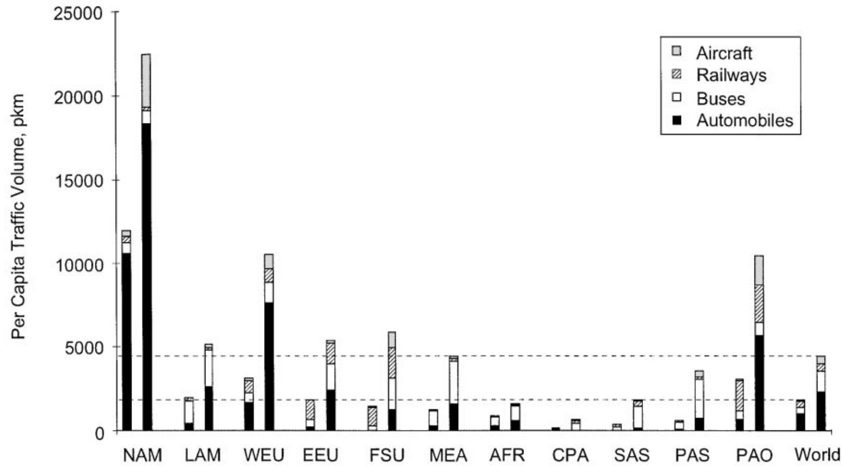

Fig. 2. Motorized mobility (pkm) per capita, by region and mode in 1960 and 1990. For data sources, see Appendix A.

Correspondingly, travel is lowest in regions having the lowest per capita incomes, such as Centrally Planned Asia (CPA), Sub-Saharan Africa (AFR), and South Asia (SAS). The three OECD regions, while accounting for only 16% of the world's population, produce more than half of the global motorized traffic volume. Most extreme, in 1990 NAM accounted for merely 5% of world population, but its motorized traffic volume accounted for 27% of global motorized pkm. The average North American traveled 22,440 km per year by motorized transport compared to only 630 km a year for someone in CPA (representing 24% of the world population)—a ratio of 36:1.

Similar disparities exist with respect to modal split. The modal split in highly mobile regions in 1990 was dominated by individual modes (automobiles) and high-speed mass transport systems (aircraft). By far most related traffic volume, i.e.—75% of global automobile and almost 70% of air traffic volume—occurred in the three OECD regions (NAM, PAO, and WEU). Less mobile regions relied heavily on slow surface mass transport modes, especially buses. (The developing world accounted for 76% of global bus traffic volume.) While world railway traffic volume was divided more equally among the OECD, the restructuring economies of Eastern Europe (EEU), the Former Soviet Union (FSU), and the developing regions (about one-third by each), its market segmentation differs substantially. In 1990 ordinary intercity trains accounted for only 26% of total railway traffic volume in the PAO region (basically Japan); the remaining share operated essentially in niche markets such as suburban railways (48%), urban light rail (7%), and high-speed trains (19%). By contrast, ordinary intercity trains represent more than 99% of the entire railway traffic volume in the CPA region and 80% of that in the FSU.

In 1990 some 90% of total world wide passenger travel occurred using surface modes, the remaining (almost) 10% having been by air travel. Roadways are the world's major travel infrastructure, accounting for 80% of global traffic volume. The most intensively used vehicle was the passenger car, which provided more than half of the global passenger traffic volume, followed by buses, accounting for almost 30%. Railways provided about the same volume as aircraft, i.e. almost 10%.

While the world regional per capita traffic volume shown in Fig. 2 only accounts for motorized means of transport, non-motorized modes can represent a significant share of total passenger traffic volume. This is especially true for developing countries, where the substitution of non-motorized modes of transport by motorized means has not yet taken place on a large scale. Trips satisfied by walking or bicycling account for more than half of all trips made in a number of Indian cities, and typically range from 60 to 90% of all trips in Chinese cities (TERI, 1993; Midgley, 1994). In rural areas, where per capita income is generally lower than in cities (thus, people can rarely afford motorized transport), the dominance of non-motorized transport is even stronger. This dominance of non-motorized travel also applies to the traffic volume as demonstrated by a simple estimate. In 1990, inhabitants of the CPA region traveled an average of 630 km yr^{-1} via motorized modes of transport (Table B1 in Appendix B). Assuming a daily travel time of one hour per capita, and a mean travel speed of 6 km h^{-1} for non-motorized and 20 km h^{-1} for motorized travel, the non-motorized traffic volume would account for 2000 km yr^{-1}, or 76%, of total travel.

In OECD countries, roughly one-third of all trips are made by walking. Since corresponding trip lengths are generally well below one kilometer, however, the resulting traffic volume is almost negligible. Travel surveys suggest that walking accounts for less than 5% of total km in Western European countries, and merely half a percent in the USA (USDOT, 1992; UKDOT, 1988, 1993; Kloas *et al.*, 1993).

3. TRAVEL CONSTRAINTS: MONEY AND TIME BUDGETS

J.C.Tanner is considered a pioneer in exploring travel behavior with regard to money and time budgets. Tanner (1961) suggested a constant budget of generalized costs (the aggregate of money and monetarized time expenditure on travel) per person, independent of residential density. In the 1970s, Zahavi argued for constant budgets of both money and time when analyzing US and European travel surveys. He proposed that urban travellers (people making at least one motorized trip on the census day) invest somewhat more than one hour per day for transportation, on average (travel time budget) and finance their travel through spending a constant share of household expenditures (travel money budget). The latter accounts for 3–5% of households relying on public transport services and 10% of those owning an automobile (Zahavi, 1981).

3.1. Travel money budget

Figure 3 illustrates the travel money budget (TMB) as a function of motorization rate for 12 OECD and three low-income countries. In the OECD, TMB increases from about 5% at a motorization rate of almost zero passenger cars per 1000 capita (US households without a car in 1909) to 10–15% at about 200 cars per 1000 capita, and remains approximately constant at higher ownership rates (TMB should remain at comparable levels when automobile fleets saturate, since an increasing share of travel expense is then dedicated to air travel). Seemingly, an ownership level of around 200 cars per 1000 capita corresponds to the threshold at which most households own an automobile (one car per household of five). Different saturation levels can be explained by relative price differences in the economy.

Due to the lack of a continuous time series, the TMBs of the three low-income countries Sri Lanka, Thailand, and Tunisia are shown only for individual years (lower data points: national average, higher data points: urban average). Their lower TMB compared to the OECD at a given

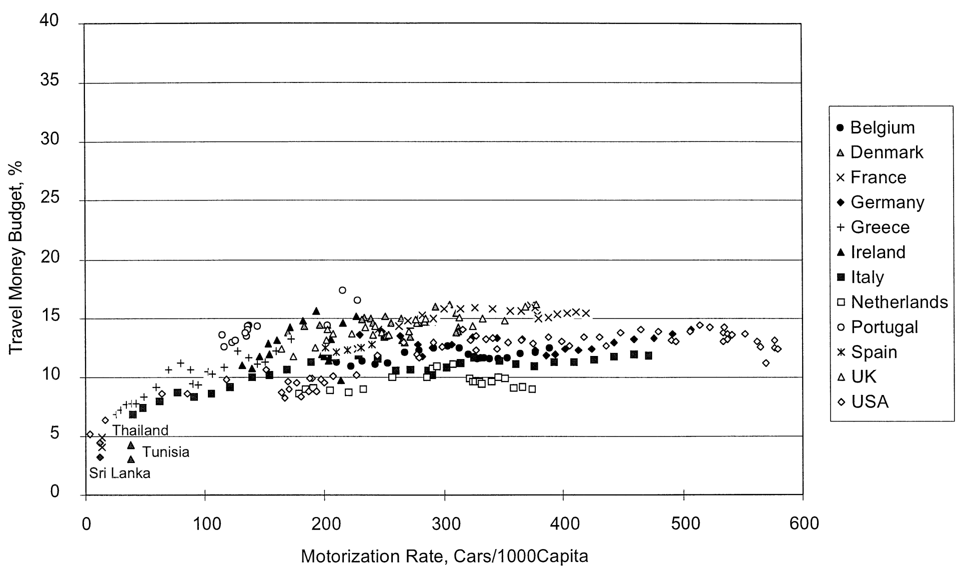

Fig. 3. Travel money budget (share of transport expenditures to total expenditures) vs car ownership rate for 12 OECD and three developing countries. The denominator of the TMB for the developing countries is total expenditure on nondurable goods and services—not total consumer expenditure, such as for the OECD data, which overrepresents the rich. Sources: Eurostat, (1994); Davis, (1994); SB, (1972, 1994); USDOC, (1975); UKCSO, (1994); UKDOT (1988); Deaton, (1985). Time period of country data: Belgium: 1970–92; France: 1970–92; Denmark: 1966–92; FRG, Greece: 1970–91; Ireland: 1970–89; Italy: 1960–92; Japan: 1970, 1975, 1979–1992; Netherlands: 1969–91; Portugal: 1977–89; Spain: 1980–85; UK: 1965–92; USA: 1909, 1914, 1919, 1921, 1923, 1925, 1927, 1929–40, 1948–92; Tunisia: 1979/80; Sri Lanka: 1980/81; and Thailand: 1975/76.

motorization rate results from both their high share of non-motorized trips especially in rural areas, and the concentration of automobiles in cities (see above). Correcting for the asymmetric distribution of the automobile fleet, Fig. 3 shows that the TMB of urban households develops close to the OECD trajectory (higher data points).

3.2. Travel time budget

People spend somewhat more than one hour per day travelling, on average (travel time budget), despite widely differing transportation infrastructures, geographies, cultures, and per capita income levels. Figure 4 shows the stability of the travel time budget (TTB) per person with regard to per capita income for numerous human settlements on all aggregation levels throughout the world: residents of African villages spend an amount of time travelling that is roughly comparable to travel times in Latin American metropolitan areas, Singapore, Japan, Australia, Western Europe, and the USA. Variation of the TTB, while due primarily to different aggregation levels, i.e. rural—urban—national (TTB rises with city size), is also due in part to different age groups, days considered, and survey methods.

The ultimate reason for TTB stability is unclear. It has been argued that a TTB of around 1 h cap^{-1} day^{-1} reflects a basic human instinct (Marchetti, 1993). In addition to possible anthropogenic roots, time spent travelling is naturally constrained by other time-consuming activities such as work, sleep, and leisure. If, however, TTB constancy results from time allocations to other activities, it could be argued that changes in the latter can alter the TTB. For instance, people who work less could spend more time travelling. Cross-country comparisons, however, show no evidence for such a hypothesis: despite significant differences in working time [Japanese spend around 25% more of their time on the job than workers in other OECD countries, such as Germany, France, the UK, and the US (Maddison, 1991)], the TTB remains approximately equal.

Roth and Zahavi (1981) have shown that TTB per *traveler* rises with declining income, probably because the poor have more difficulties adjusting to the TTB of about 1 h cap^{-1} day^{-1}, due to their constrained choices of both residence and transport mode. This observation is consistent with the income stability of TTB per *person*, shown in Fig. 4, since fewer low-income people take motorized trips.

It must be emphasized that both travel money budget and travel time budget are the mean of their respective distribution function, and thus represent the average of individual behaviors with often completely different preferences. Hence, disagreement remains among transport analysts concerning

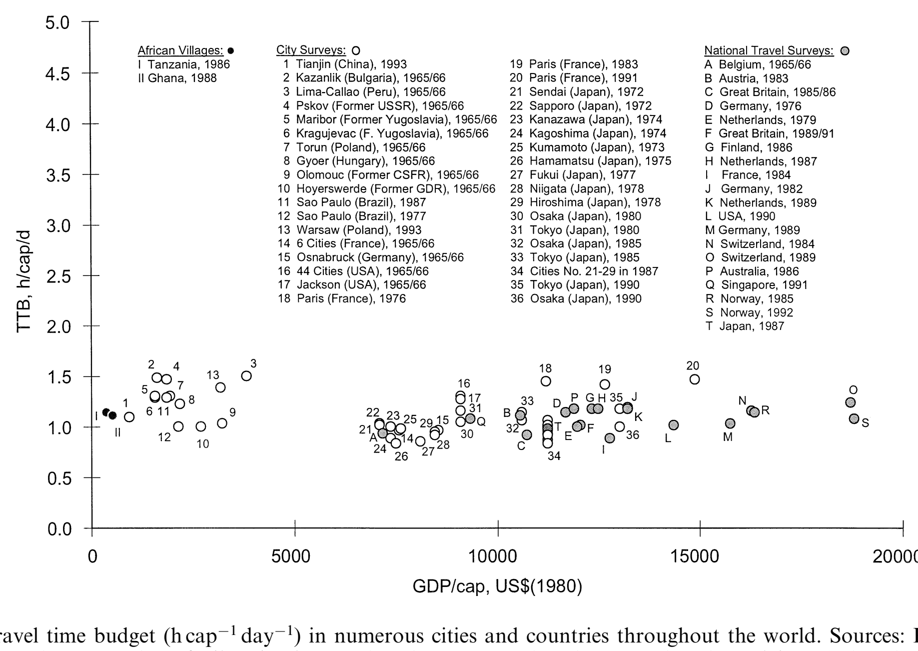

Fig. 4. Travel time budget ($h\,cap^{-1}\,day^{-1}$) in numerous cities and countries throughout the world. Sources: Kloas *et al.*, (1993); GFV, (1987, 1992); Orfeuil and Salomon, (1993); UKDOT, (1994); DMT, (1993); Szalai *et al.*, (1972); Katiyar and Ohta, (1993); USDOT, (1992); Malasek, (1995); Vibe, (1993); Riverson and Carapetis, (1991); EIDF, (1994); FORS, (1988); Metrõ, (1989); Olszewski *et al.*, (1994); Xiaojiang and Li, (1995).

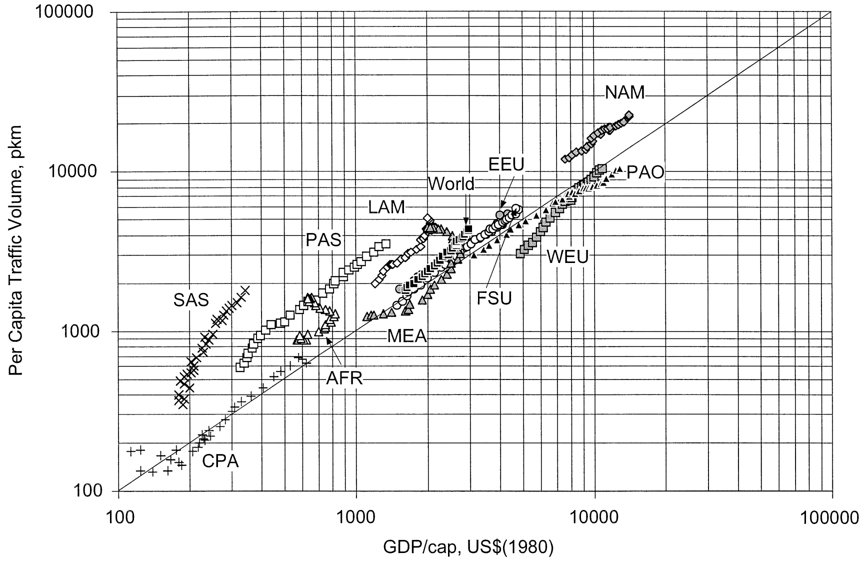

Fig. 5. Motorized mobility (car, bus, rail, and aircraft) per capita by world region vs GDP per capita between 1960 and 1990.

the validity of fixed budgets of travel time and money: while one group of researchers is seeking stability at very aggregate levels, the other group explores variability at highly disaggregate levels (Kirby, 1981). Since this paper relates to aggregate data levels, we follow the first group, relying on stability of both money and time budgets.

4. AGGREGATE TRAFFIC VOLUME AND MODAL SPLIT CHANGES

4.1. Aggregate traffic volume

We have seen that travel expenses are a fixed share of personal expenditures, the 'travel money budget.' Thus, growing income results in increasing travel expenditures, and consequently rising per capita mobility—assuming that the savings rate, i.e. the ratio of personal expenditures to personal income, remains constant.* Figure 5 shows the validity of this relationship for all 11 world regions and the world as a whole: all world regions follow one growth trajectory despite significant differences in culture, geography, and population density.

In the five world regions NAM, PAO, WEU, EEU, and FSU, per capita traffic volume has grown almost in proportion to per capita income. In the three world regions AFR, Middle East and North Africa (MEA) and Latin America (LAM), per capita GDP losses caused a decrease in aggregate traffic volume over the long term. The delayed response to decreasing per capita GDP can be explained by the fact that existing transport systems, in which investments had already been made, are used throughout their useful lifetime; part of such systems will not be replaced, due to lack of funds.

The trajectories of the two world regions SAS and PAS are curved because motorized two-wheelers and non-motorized forms of transport are excluded from the data set, and bus and car travel have grown at a high rate (in the CPA region, such development is also visible, albeit at a much slower rate). A similar substitution process of non-motorized modes by motorized means has been shown with regard to the replacement of horses by automobiles in the US in the early 20th century (Nakicenovic, 1987). In addition, inhabitants of the PAS and SAS regions experience a relatively high mobility compared to the world trajectory, given their per capita GDP, due to comparatively small purchasing power parity adjustments of raw GDP data in market exchange rates (UN, 1993). Other macroeconomic data sets (Heston *et al.*, 1993) suggest that per capita traffic volume of both regions is in line with the world trajectory.

*Note that only a part of the TMB is allocated to mobility; the other share refers to expenditures with regard to quality of service (travel comfort). Hence, a direct relationship between per capita traffic volume and per capita GDP also requires a constant share of TMB to be dedicated to mobility.

The quantitative relationship between per capita mobility and per capita income can be expressed by

$$\log\frac{\text{pkm}}{\text{cap}} = m\cdot\log\frac{\text{GDP}}{\text{cap}} + b \qquad (1)$$

with m being the slope and b the intercept. Hence,

$$\frac{\text{pkm}}{\text{cap}} = \left(\frac{\text{GDP}}{\text{cap}}\right)^{m}\cdot b^{*} \qquad (2)$$

In the simplest case, the linear form ($m = 1$), per capita mobility can be determined by

$$\frac{\text{pkm}}{\text{cap}} = \frac{\text{GDP}}{\text{cap}}\cdot\frac{\text{PCE}}{\text{GDP}}\cdot\text{TMB}\cdot\chi + C \qquad (3)$$

with PCE being personal consumption expenditure, χ the inverse unit costs of transport with unit pkm/$ (depending on a number of variables, such as modal split, cost and fuel efficiency of transport modes, and fuel prices), and C a constant, taking into account absolute differences in per capita traffic volume at a given per capita GDP. The latter result from original settings with regard to population density and settlement patterns, and travel behavior and variations of the product of the three factors forming b^* that may have occurred before 1960.

The close relationship between per capita income and per capita traffic volume can be used to project future levels of per capita mobility as a function of per capita GDP, if the value of the constant b^*, i.e. PCE/GDP·TMB·χ and C, are determined by means of a linear regression on the historical development ($m = 1$).* Given a global per capita GDP of US$(1980) 3000 in 1990 and an average annual growth rate of 2% (such as between 1960 and 1990), per capita GDP will be about $(1980) 5400 in 2020. Correspondingly, the 1990 global motorized mobility per capita will double by 2020 (the regression equation being pkm $\text{cap}^{-1} = -1248 + 1.83\cdot$ GDP cap^{-1}, $R^2 = 0.987$). In light of a world population increasing by 50% through 2020 [both the UN 'medium population' projection and the World Bank forecast a 50% increase from the 1990 world population by 2020 (UN, 1992; Bos *et al*., 1992)], absolute motorized traffic volume will increase by a factor of three. Most of this growth will occur in the developing world—especially in the Far East (SAS, PAS, and CPA), where high economic growth rates suggest a significant rise in mobility. Based on an average growth rate of per capita GDP of 5% per year, per capita mobility of a CPA resident will increase from 630 km in 1990 to 3075 km in 2020 (the regression equation being pkm $\text{cap}^{-1} = -31 + 1.16\cdot$ GDP cap^{-1}, $R^2 = 0.970$), a 4.9-fold increase; combined with the projected increase in population of 36% (Bos *et al*., 1992), aggregate motorized mobility will rise almost seven fold.

4.2. Modal split changes

As shown in Fig. 5, a constant TMB translates increasing per capita GDP into a (roughly predictable) growth in per capita motorized mobility. In addition to the TMB, the average person has a fixed travel time budget, spending somewhat more than one hour a day on travel (see Fig. 4). Consequently, more distance has to be covered per unit time, i.e. mean travel speeds have to rise. Since each transport mode operates within a range of speeds, increasing mobility changes the modal split toward more flexible, faster transport systems. Thus, the higher the per capita GDP, the faster and more flexible the transport infrastructure. This relationship is shown in Figs 6–10 for eight world regions and the world for a 31-yr time horizon starting in 1960.

*The underlying rationale for linear regression, i.e. $m = 1$ and a constant factor b^*, is based on the historical development of the used data set (UN, 1993). There, PCE/GDP decreased slightly with increasing economic development: in the OECD, from 67% in 1950 to 62% in 1990, and globally, from 63% in 1960 to 61% in 1990. The product TMB·χ is assumed to remain approximately constant as a result of two compensating effects: (1) TMB increases to motorization levels of about 200 cars per 1000 capita and levels off thereafter, and (2) χ decreases with increasing motorization rate, since pkm-specific consumer costs are higher for cars than for buses, and the inverse consumer costs thus result in lower values for pkm/$. At higher motorization rates, most traffic volume is covered by passenger cars, and thus lower fares of bus traffic weigh less; therefore the inverse unit costs can be expected to level off as well.

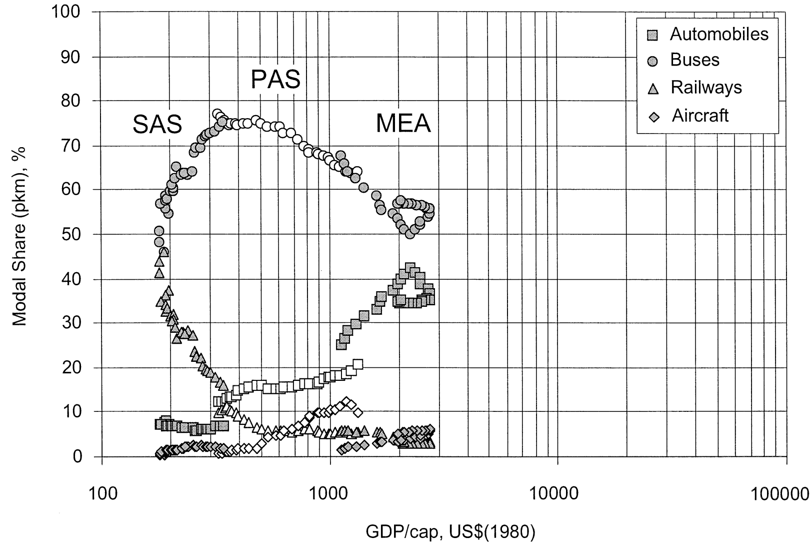

Fig. 6. Modal split vs GDP per capita between 1960 and 1990 for the three world regions SAS, PAS, and MEA.

Figure 6 illustrates the modal split trajectories for the SAS, PAS, and MEA regions. At low levels of economic development, low-speed collective vehicles account for virtually all transport services, as seen in the SAS region (railways and buses in 1960). As economic progress occurred, buses became the primary mode of transport due to their greater accessibility, flexibility, and hence lower travel time. In 1990, individual and high-speed means of transport still accounted for less than 10% of total pkm, and served only a small share of the population. The PAS region illustrates that as per capita GDP and hence per capita traffic volume grow, the share of bus pkm saturates, due to the more rapidly increasing traffic volume of higher-speed vehicles, i.e. passenger cars and aircraft. With further economic growth and rising per capita traffic volume, automobile traffic increasingly replaces that of buses (MEA).

A similar development occurred in the EEU region (Fig. 7). The share of bus and railway traffic volume continuously declined due to the rapidly rising share of automobile traffic, which occurred despite constrained access to individual modes of transport in the Socialist system; high-speed transport systems still have a negligible share. In WEU, the share of automobile traffic volume peaks at some 70%, due to increasing air traffic volume. Meanwhile, rail and bus services maintain a low share in special market niches (mainly high-density population areas). High-speed rail

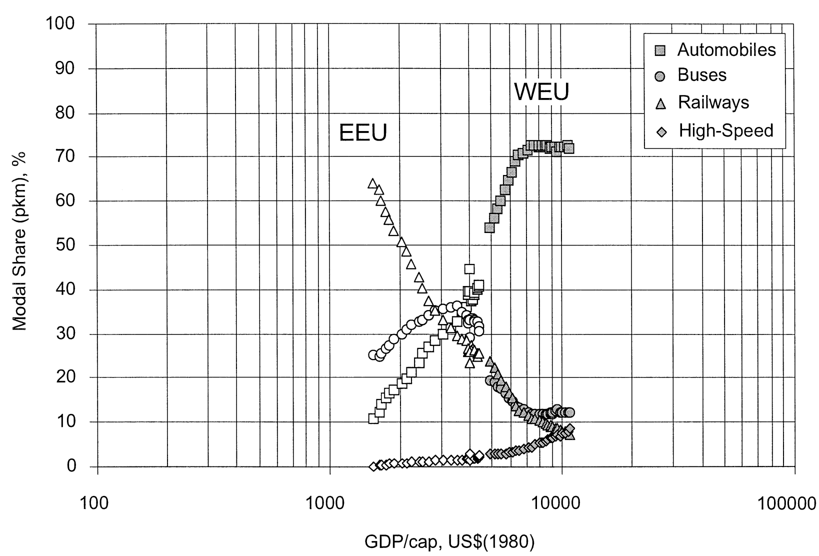

Fig. 7. Modal split vs GDP per capita between 1960 and 1990 for the two world regions EEU and WEU.

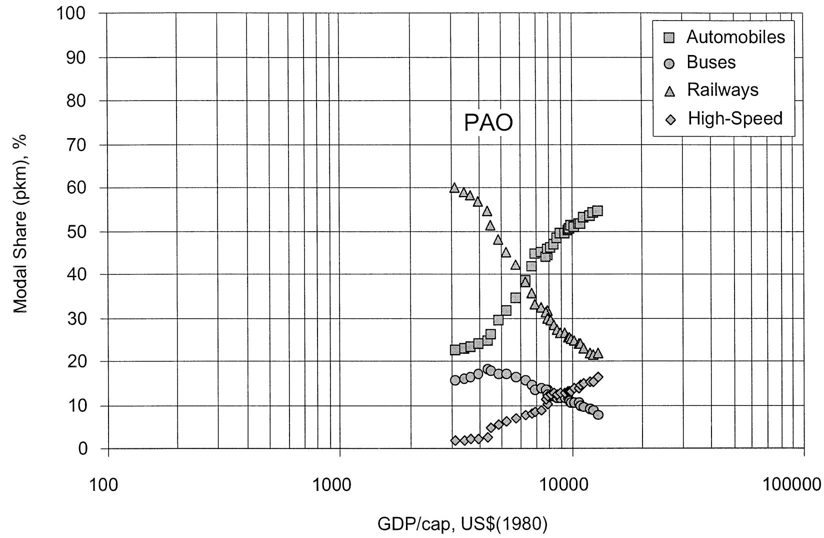

Fig. 8. Modal split vs GDP per capita between 1960 and 1990 for the world region PAO.

transport has been aggregated to air transport due to the similar service levels [in 1990, high-speed rail accounted for 4.2% of total high-speed transport in WEU (IATA, 1992; UN, 1990, 1991; CER, 1994)].

Figure 8 shows another similar development for the PAO region (mainly Japan). The modal share of railway traffic dropped from 60% in 1960 to some 20% in 1990 [high-speed rail transport has been aggregated with aircraft: in 1990, high-speed rail accounted for 30% of total high-speed transport in Japan (IATA, 1992; UN, 1990, 1991; SB, 1992)]. The traffic volume of high-speed transport modes has just exceeded that of buses. A further increase in the share of high-speed transport traffic volume (resulting from increased per capita traffic volume, which is in turn a result of per capita GDP growth) will saturate the share of passenger car traffic volume.

A more extreme picture exists in NAM, where virtually all passenger traffic is split between automobiles and aircraft (Fig. 9). Air traffic, offering still greater mobility through significantly higher speeds, is strongly increasing its market share at the expense of passenger cars. At one point, the declining share of automobile traffic volume will translate into an absolute decline. Such replacement of automobiles by aircraft and high-speed trains, obviously occurring for long-distance

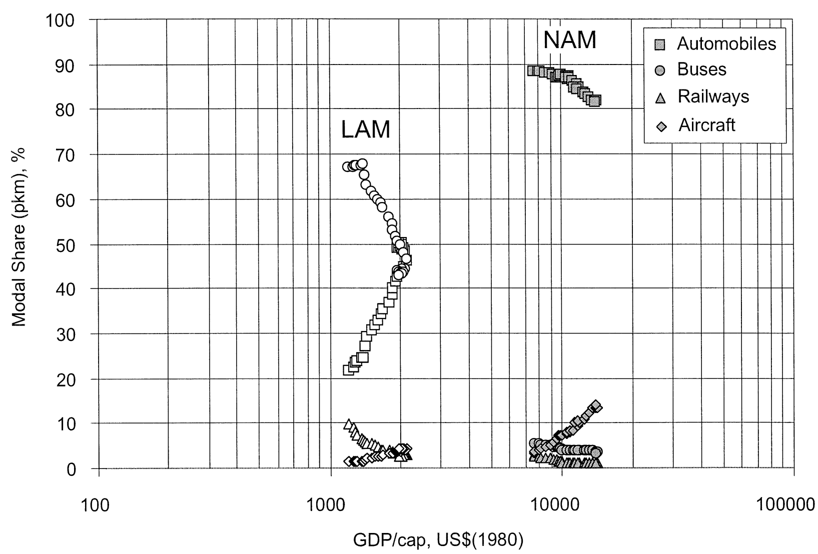

Fig. 9. Modal split vs GDP per capita between 1960 and 1990 for the two world regions LAM and NAM.

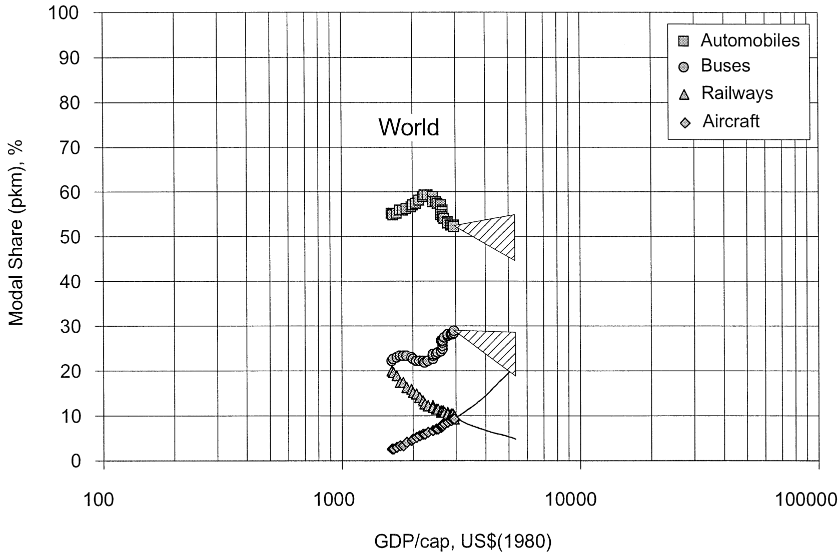

Fig. 10. World modal split vs GDP per capita between 1960 and 1990 and likely further development until 2020.

travel, results in the fact that the automobile of the 21st century will increasingly operate in niche markets (i.e. short-distance travel). The same figure shows that LAM may develop similarly to NAM.

While a constant TTB causes shifts towards faster modes of transport as income (and thus the demand) rises, the specific modal shares are also determined by urban land-use characteristics. In NAM, where population density is low, the share of automobile traffic volume became saturated at almost 90% in 1960 (Fig. 9). In the more densely populated WEU region, automobiles achieved only a 72% share of total traffic volume (Fig. 7). Correspondingly, in the PAO region which is dominated by Japan and its high population density, the relative importance of automobile traffic volume seems to peak below 60% (Fig. 8). Primarily as a consequence of different types of land-use, investments in transportation infrastructures also have been different across regions (a high share of railways in high density PAO and a low share low density in NAM).

Investments in transportation infrastructures also have been different because of the political system. For instance, in the formerly socialist countries of EEU improving access to public modes of transport and limiting ownership of private automobiles has allowed a higher share of buses and railways to accommodate the same per capita traffic volume as obtains in the automobile-dominated WEU.* Nevertheless, a similar trend towards faster modes of transport can also be observed there.

How do world regional modal splits compare to the world as a whole? At first glance, Fig. 10 seems counterintuitive, for two reasons. First, the share of bus traffic volume seemed to have replaced that of automobiles, although buses provide lower mobility levels. This contradiction is resolved if one takes into account the ‘phase-displacement’ among the region’s modal splits with respect to per capita GDP (and time), i.e. a currently stronger increase in global bus traffic volume (mainly in the two Asian regions CPA and SAS) compared to the traffic volume of passenger cars. This development was favored by the beginning saturation (PAO) and already declining share of passenger car traffic volume (WEU, NAM) in the OECD regions (Figs 7–9). Second, aircraft seem to replace conventional railways—despite the stepwise sequence of dominating modes observed in the world regional modal splits—because of the uniform increase in aircraft and decline in conventional railways across all world regions.

*In 1960, WEU inhabitants’ per capita traffic volume was 3090 pkm; the associated modal split was 54% cars, 20% buses, 23% railways, and 3% aircraft. Almost the same per capita traffic volume was achieved in EEU 11 years later, however, at half the share of passenger cars and a remarkably higher share of low-speed mass transport systems: 27% cars, 34% buses, 38% railways, and 1% aircraft.

Figure 10 further extends the likely future global modal split until 2020, based on an average annual growth rate in per capita GDP of 2%. Since the share of aircraft and railway pkm show the same development throughout all world regions, they are projected using a simple linear and hyperbolic fit, respectively. As a result, air traffic volume may account for 21% and rail traffic volume for merely 5% of world traffic in 2020. Due to the phase-displacement of automobile and bus traffic shares, a comprehensive estimate would have to be based on the modal split in each world region. Since this requires regional projections of per capita GDP growth rates and traffic volume, only a rough estimate is made here. An interregional comparison shows that the share of bus traffic may increase in CPA and SAS from some 60 and 75%, respectively, to about 80% of total pkm in 2020. In all other world regions, the share of bus pkm either saturates (including FSU, which, like AFR and CPA, is not shown in this paper) or declines. All this suggests that the global share of bus traffic volume will gradually decrease. As a first estimate, we assume the share of bus traffic to be within two limits, i.e. to remain at the 1990 level of 29% (bus/high) or to decrease by 10 percentage points (bus/low). Consequently, the share of car traffic will range from 45% (car/low) to 55% (car/high) of total pkm. Putting this into the perspective of a three-fold increase in aggregate motorized traffic volume, automobility will grow by a factor of 2.6–3.2, bus traffic by 3.0–2.0, railway traffic by 1.5, and high-speed traffic by a factor of 7—this last estimate substantially exceeding U.S. aircraft manufacturers' forecast of a four-fold increase in global commercial air traffic by 2020 (Covert *et al*., 1992).

5. IMPLICATIONS

5.1. Growth in world passenger transport energy use and CO_2 emissions

In 1990, world transport sector final energy use accounted for about 60 EJ (IEA, 1992); some 60% of that amount, i.e. 37 EJ, was consumed by passenger transport.* Any increase in energy use is determined by four factors: (a) rise in per capita traffic volume, (b) population growth, (c) change in modal split, and (d) alterations in energy intensity (MJ pkm^{-1}) of the four modes of transport considered.

5.1.1. Rise in per capita traffic volume and growth in population. In Section 4.1, global per capita traffic volume was projected to double through 2020, given a growth in per capita GDP of 2% per year. In combination with a 50% growth in world population, passenger transport energy use is expected to rise by a factor of three.

5.1.2. Changes in modal split. Table 1 reports the 1990 and projected 2020 modal splits. Based on the indicated modal split change and the (frozen) 1990 energy intensities alone, world passenger transport energy intensity is expected to increase by 11–20% over the 1990 level (from 1.61 MJ pkm^{-1} in 1990 to 1.79–1.93 MJ pkm^{-1} in 2020), depending on the projected modal shares of cars and buses. Note that this increase is significantly less than the rise in energy use associated with growing aggregate travel demand. In combination with the three-fold increase in aggregate travel demand, passenger transport energy use is expected to rise by a factor of 3.3–3.6.

5.1.3. Changes in modal energy intensity. Table 1 also summarizes the estimated 1990 modal energy intensities and their projected 2020 values.* The 2020 energy intensities of all ground transport modes are assumed to remain at 1990 levels—an optimistic assumption in light of historical development. In fact, in the case of automobiles, fuel efficiency of OECD countries' national fleets remained approximately constant during the past 20 yr (improvements occurred only in the US) (Davis, 1994). Since, in addition, passenger load factors continuously declined,

*1990 energy intensities by mode (in MJ pkm^{-1}) are derived from the world transport sector final energy use as published by IEA (1992) and the traffic volume data described in the appendices. Since IEA data on final energy use are aggregates (passenger and freight) for air, rail, road, and water traffic, respectively, modal disaggregation was done on the basis of energy use by mode of transport and major country of the 11 world regions, and a related passenger load factor described in Appendix A. Data sources were: Davis (1994); BFS (1992); Shlikhter (1990); Kolar (1993); IPCC (1990, 1995); EPA (1990); Moreira and Poole (1993); Sathaye and Walsh (1992); DIW (1991); EDMC (1994); APTA (1992a,b); KEEI (1993); SSB (1993); TERI (1993); IATA (1991).

Table 1. World modal shares and final energy intensities (FEI) of vehicle fleets in 1990 and projections for 2020. For data on energy intensities, see footnote on page 11 in text

	1990		2020	
	Modal share (%)	FEI ($MJ\,pkm^{-1}$)	Modal Share (%)	FEI ($MJ\,pkm^{-1}$)
Cars	52	2.10	45–55	2.10
Buses	29	0.65	29–19	0.65
Ordinary railways[a]	9.5	0.40	5	0.40
High-speed transport	9.5	3.00	21	1.65
Total/weighted averages	100	1.61	100	1.50–1.65

[a]includes both electricity- and diesel-fueled locomotives. Energy use by electricity-driven traction systems is expressed in fossil-fuel equivalents with a conversion efficiency of 35%.

energy intensity has increased. Similar patterns can be observed for buses and railways. Hence, a decline from the 1990 energy intensity to estimated 2020 values is only taken into account for high-speed transport (essentially aircraft); the assumed reduction of 2% yr^{-1} is in line with historical developments in aircraft fuel consumption at an approximately constant passenger load factor. Based on the 2020 modal split, projected energy intensities reduce the mean energy intensity resulting from the frozen 1990 numbers by about 15%. Combined with the growth in aggregate transport demand and the projected modal split change, overall world passenger transport sector energy use is projected to rise by a factor of 2.8–3.1 over the 1990 level.

In 1990, global passenger transport CO_2 emissions were about 0.75 billion of carbon (GtC), i.e. some 60% of total transport sector CO_2 emissions (which follows from the IEA energy balances (IEA, 1992) and the disaggregation of passenger and freight transports, as summarized in *, p. 465). Provided that refined oil will continuously fuel nearly the entire global transportation sector, CO_2 emissions will grow in proportion to final energy use, reaching 2.1–2.3 GtC in 2020.

Stabilization of projected 2020 emissions to the 1990 level can be approached through technological changes (fuel efficiency improvements and transportation fuels with lower carbon content), improved transportation system management, or some combination of these. Transportation system management improvements range from improving operational conditions (e.g. smoothing traffic flows) to reducing transport activity, i.e. vehicle-km traveled, through pricing policies, substitution of telecommunication for physical trips, etc.

Reducing vehicle fuel consumption solely through improvements in fuel efficiency would require passenger transport sector energy intensity to decline by two-thirds, on average. Even under the hypothetical assumption that the energy intensity of both buses and railways could decline at the rate assumed for high-speed transport, automobile energy intensity would have to be reduced by more than one order of magnitude (in light of the continuously declining vehicle occupancy rate) to achieve the 1990 emission level—an infeasible task, even in the industrialized world.

Transport system management strategies would provide multiple benefits in addition to the abatement of greenhouse gas emissions (e.g. relief of congestion and such associated impacts as toxic emissions, economic costs, and reduced noise), but their CO_2 reduction potential is comparatively limited, estimated to be 5–10% of the 1987 transport sector emissions in the US (OTA, 1991) and—due to the higher population density and the associated larger potential of such measures—5–16% of the 1990 transport sector emissions in West Germany (GEC, 1994). Based on a roughly 60% share of passenger transport CO_2 emissions to total transport sector CO_2 emissions, the two reduction potentials translate into 8–17% as well as 8–27% of *passenger* transport CO_2 emissions in the US and Germany, respectively. These potentials, however, are probably too high on a global scale, since both the use of public transport modes and vehicle occupancy rates will still be comparatively high in the developing world (where most of the projected demand will be generated) by 2020. A reduction of the projected 2020 level by a hypothetical 27%—the highest reported potential—would still result in emissions being a factor of 2.0–2.3 above the 1990 level. Thus, transport system management measures alone are far too weak to significantly abate CO_2 emissions.

A combination of both radical vehicle fuel-efficiency improvements and transport system management measures likewise could not reduce projected 2020 CO_2 emissions to the 1990 level. Even assuming extreme reductions in automobile, bus, and railway energy intensities by 2% yr^{-1} (such as observed for aircraft, but never achieved in fleets of surface-transport modes), 2020 global passenger transport CO_2 emissions would still rise by 71–100% over the 1990 level. That increase, which would have to be reduced by transportation system management measures to stabilize emissions to the 1990 level, far exceeds the above-indicated estimates of their CO_2 reduction potentials. Hence, achieving the 1990 emission level by 2020 requires the introduction of zero-carbon fuels (e.g. alcohols from biomass, hydrogen/electricity from renewable and/or nuclear energy sources) well before 2020, on a global scale.

5.2. *World motorization rate*

Conventional methods for projecting aggregate traffic volume typically build on independent estimates by mode of transport; automobile traffic volume, for example, is generally calculated by an extrapolated motorization rate (number of automobiles per 1000 capita) multiplied by the projected population, annual distance traveled, and mean vehicle occupancy rate. By contrast, the method advanced in this paper allows determination of the motorization rate from output variables. In the following, such an estimate will be given for the world.

For that purpose, we assume an average 2020 automobile traffic volume of 30,800 pkm per car, corresponding to the 1960 figure [as shown in Appendix B, the 1960 world automobile traffic volume was 3032 billion pkm; dividing by 98.3 million passenger cars (MVMA, 1992) leads to 30,800 pkm per automobile]. This number is higher than the 1990 figure of 25,700 pkm per car, being based on both higher load factors and vehicle-km per automobile; it is therefore consistent with developing countries' strong increase in automobile traffic volume. Based on the estimated per capita aggregate traffic volume of 68.4 trillion pkm in 2020, an automobile share of 45–55%, and the assumed traffic volume per automobile, the global automobile fleet would more than double, from 470 million vehicles in 1990 (including light trucks used for personal travel in the US) to 1.0–1.2 billion vehicles in 2020. In light of the projected world population growth of 50%, the motorization rate rises from 89 cars per 1000 capita in 1990 to 126–154 cars in 2020. Figure 11 shows this range to be in line with historical development.

5.3. *Toward unlimited mobility growth or saturation of demand*

A constant product of the three RHS factors forming the constant b^* in eqn (2) translates any growth in per capita income to an increase in per capita traffic volume (provided $m > 0$). Since a fixed travel time budget requires a proportional increase in mean speed, it induces a continuous shift toward increasingly rapid modes of transport. Over the longer term, therefore, automobiles will be unable to reach the mean speeds required: after an initial decrease in automobile traffic share, automobile *traffic volume* will decline due to strengthening demand for subsonic air traffic (while the automobile share declines, automobile traffic volume will not become insignificant). However, at a sufficiently high per capita travel demand, subsonic air traffic volume too will decline, due to large-scale needs for supersonic—and, later, hypersonic—transport. Such technologies must be available for further progress toward an unlimited per capita travel demand; without them, world regional demand curves will saturate.

If very high-speed transport systems are introduced, the world would essentially become a global city, the subcenters of which are connected by high-speed links. Given historical evidence that maximal city growth occurs in proportion to the fastest transport mode available to connect two endpoints of the city diameter within about one hour,* large-scale global commuting would require travel halfway around the Earth within one hour at a mean speed of 20,000 km h^{-1}. Although even higher speeds can be achieved in principle, considering basic technological limitations (e.g. via magnetically levitated trains running in vacuum insulated tunnels), their

*Strong evidence indicates that the mean speed of the dominating transport mode in combinations with the TTB of 1 h cap^{-1} day^{-1} determines an upper bound of a city's diameter and hence size (Marchetti, 1994). Hadrian's Rome, the city of Berlin during the early 19th century, and agricultural villages in Greece today have an area of about 20 km^2, corresponding to the area of a circle with a diameter of 5 km (the walking distance of which can be covered in an hour). Correspondingly, at the beginning of the 20th century, the diameter of the city of Berlin grew to 14 km—the distance a tramway can cover in an hour, on average. Due to automobiles' higher speed, Berlin's diameter grew to 40 km in the 1950's.

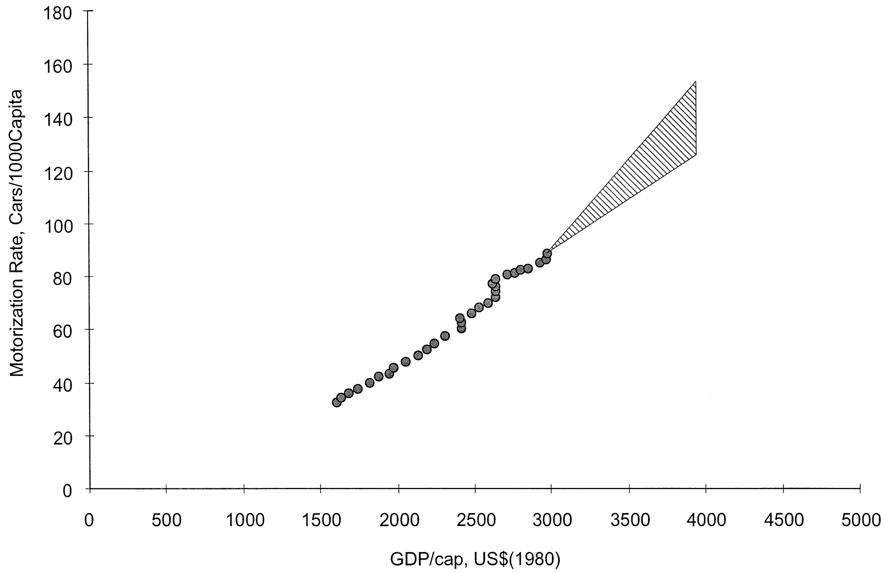

Fig. 11. Global motorization rate vs GDP per capita between 1960 and 1990, and the estimated range in 2020 as an output of this scenario.

practical application poses a variety of challenges—social, environmental, and engineering (e.g. to compensate losses in passenger comfort with regard to acceleration and zero-gravity conditions).*

Considerable time will be required, however, to realize large-scale global commuting. Assuming a world average growth rate in per capita GDP of 2% yr^{-1}, a hypothetical adjustment of income levels across all world regions, and a mean travel time budget of one hour per capita per day, large-scale global commuting would be possible in almost four centuries (around 390 yr) from 1990, based on the assumption that the world trajectory would converge to the straight line $m = 1$ in Fig. 4 over the very long term. On a world-regional basis, however, long-distance commuting could start much earlier across regions with the highest per capita income, and hence, highest per capita mobility. From today's viewpoint, this would occur within and between the three OECD regions NAM, PAO, and WEU. Of course, telecommunication might substitute for much travel long before then.

6. CONCLUSIONS

From a world-regional perspective, demand for motorized mobility follows deterministic patterns. On such high aggregation levels, the development of traffic volume and modal split can be described by essentially two travel budgets. Under certain conditions, a constant travel money budget establishes a direct relationship between economic development and motorized mobility: per capita traffic volume grows in proportion to per capita income. A limited travel time budget requires the rising per capita traffic volume to be provided by increasingly flexible and rapid modes of transport.

Both budgets further imply that—from a certain mobility level on—neither public surface modes nor automobiles can provide the required mean speed, and hence must be largely replaced by aircraft and high-speed trains (such a trend is already evident in the region NAM). At a sufficiently high per capita traffic volume, the mean speed of conventional passenger aircraft, in turn, will also be too low. Further growth in transportation demand therefore requires faster carriers, i.e. super- and then hypersonic transport. If these infrastructures are not supplied, the fixed travel time budget will force per capita traffic volume to saturate.

*Due to the curvature of the Earth's surface, such high mean speeds would temporarily result in zero-gravity conditions (determined by the balance of centrifugal and gravitational forces) in passenger cabins. At the Earth's surface, the mean speed resulting in zero gravity is 28,900 km h^{-1}. Depending on the acceleration/deceleration profile, this speed would even have to be exceeded in order to achieve a mean speed of 24,000 km h^{-1}.

Globally, per capita traffic volume is projected to double by 2020, given an annual increase in GDP per capita of 2%. In light of a world population growing by 50%, global mobility will rise by a factor of three. Most of that growth will occur in the developing world, especially in Far Eastern countries that experience the highest rates of economic growth. The total effect of threefold mobility and a more energy-intensive modal split (45–55% car, 29–19% bus, 5% rail, and 21% high-speed transport) will be increased final energy use in global passenger transport, by a factor of 2.8–3.1 over the 1990 level, given 2% yr^{-1} reductions in high-speed transport energy intensity. Stabilization of CO_2 emissions at the 1990 level by 2020 can be achieved only by the large-scale introduction of zero-carbon transportation fuels well before 2020.

Acknowledgements—This paper has benefited greatly from discussions with David Victor. The comments of Harry Geerlings, Leo Schrattenholzer, and Clas-Otto Wene on an earlier draft are highly appreciated. Many thanks go also to Aviott John and Eddy Löser from the library of the International Institute for Applied Systems Analysis (IIASA), for identifying many relevant transportation statistics. Manfred Kleemann provided road traffic measurement data from Java island (Indonesia), and Hans van Vliet and Steve Chapman furnished travel time budget data from the Netherlands and Great Britain, respectively.

REFERENCES

American Public Transit Association, APTA (1992a) *1991 Transit Fact Book*. Washington, DC.

American Public Transit Association, APTA (1992b) Transit data of earlier data books, personal communication, Washington, DC.

Asin, R. H. (1983) *Person Trip Characteristics—1977 NPTS*. U.S. Department of Transportation, Federal Highway Administration, Report No. 11, Washington, DC., U.S.A.

Australian Bureau of Statistics, ABS (1965, 1970, 1975, 1980, 1985, 1990, 1992) *Year Book Australia*. Canberra.

Biro Pusat Statistic, BPS (1986, 1993) *Statistical Yearbook of Indonesia*. Central Bureau of Statistics, Jakarta, Indonesia.

Bos, E., Vu, M. T., Levin, A. and Bulatao, R. A. (1992) *World Population Projections 1992–93 Edition*. Published for the World Bank, The Johns Hopkins University Press, Baltimore and London.

Bundesamt für Statistik, BFS (1992) *Schweizerische Verkehrsstatistik 1990*. Bern.

Central Bureau voor de Statistiek, CBS (1964) *Jaarcijfers voor Nederland 1961–1962*.

Central Bureau of Statistics, CBSI (1993) *Statistical Abstract of Israel 1993*, No. 44. Jerusalem.

Central Statistical Office, UKCSO (1994) *Annual Abstract of Statistics 1994*, No. 130. HMSO, London.

Central Statistical Office, CSOP (1967, 1975, 1980, 1983, 1992) *Statistical Yearbook of Poland*. Warsaw.

Covert, E. *et al.* (1992) *Aeronautical Technologies for the Twenty-first Century*. Aeronautics and Space Engineering Board, National Research Council, National Academy Press, Washington, DC.

Community of European Railroads, CER (1994) *High-speed Rail in Europe Gains New Momentum*. 3/1994. Paris.

Council for Economic Planning and Development, CEPD (1987) *Taiwan Statistical Data Book 1987*. Republic of China.

Davis, S. C. (1994) *Transportation Energy Data Book: Edition 14*. Oak Ridge National Laboratory, ORNL-6798, Oak Ridge, TN.

Deaton, A. (1985) The Demand for personal travel in developing countries: an empirical analysis. *Transportation Research Record* **1037**, 59–66.

Department of Statistics, DOS (1986, 1994) *Yearbook of Statistics Malaysia*. Kuala Lumpur, Malaysia.

Deutsches Institut für Wirtschaftsforschung, DIW (1991) *Verkehr in Zahlen*. Bundesminister für Verkehr, Bonn.

Dienst für Gesamtverkehrsfragen, GFV (1992) *Verkehrsverhalten in der Schweiz 1989*, GFV-Report 6/91. Bern.

Dutch Ministry of Transport, DMT (1993) Data related to National Travel Surveys, personal Communication with J.M.C. van Vliet, Rotterdam.

Eckerle, K., Hofer, P. and Masuhr, K. P. (1992) *Energiereport 2010—Die energiewirtschaftliche Entwicklung in Deutschland*, PROGNOS A.G.. Schäffer-Poeschel Verlag, Stuttgart.

Energy Data and Modeling Center, EDMC (1994) *Japanese Manufacturer Economic Statistical Overview*. The Institute of Energy Economics, Tokyo.

Eno Transportation Foundation (1992) *Transportation in America*, 10th ed. Washington, DC.

Environmental Protection Agency, EPA (1990) *Policy Options for Stabilizing Global Climate*. EPA, Washington, DC.

Equipment Ile De France, EIDF (1994) *Les Déplacements des Franciliens en 1991–1992.*, Enquête Globale de Transport, Direction Régionale de l'équipment, Paris.

Eurostat (1994) Consumer Expenditure Survey Data, personal Communication. Luxembourg.

European Conference of Ministers of Transport, ECMT (1989) *Statistical Trends in Transport*, 1965–1986. Paris.

Federal Office of Road Safety, FORS (1988) *Day-to-Day Travel in Australia 1985–86*. Department of Transport and Communications, Canberra.

Federal Office of Statistics, FOS (1987) *Annual Abstract of Statistics: 1985 Edition*. Lagos, Nigeria.

Federal Statistical Office, FSO (1965, 1970, 1975, 1977, 1982, 1980, 1985a, 1991) *Statistical Yearbook of Czechoslovakia*, SNTL/ALFA. Prague.

Federal Statistical Office, FSO (1985b) *Historical Statistical Yearbook of Czechoslovakia* 1945–1983, SNTL/ALFA. Prague.

Federal Statistical Office, FSOY (1993) *Statistical Yearbook of Yugoslavia*. Belgrade.

German Enquete Commission, GEC (1994) *Mobilität und Klima—Wege zu einer klimaver-träglichen Verkehrspolitik*. Enquete-Kommission 'Schutz der Erdatmosphäre' des Deutschen Bundestages, Economica Verlag, Bonn.

Grübler, A. and Nakicenovic, N. (1991) *The Evolution of Transport Systems: Past and Future*, IIASA Research Report RR-91-8, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Grübler A., Nakicenovic, N. and Schafer A. (1993) Dynamics of transport and energy systems—history of development and a scenario for the future. Reprint from a paper presented at the *15th Congress of the World Energy Council 'Energy and Life'*, Madrid, September 1992. IIASA, Laxenburg, Austria.

Heston, A., Summers, R., Nuxoll, D., Aten, B., Mercer, M. and Walsh, J. (1993) *Penn World Table 5.5*. revised and updated version of PWT 5, National Bureau of Economic Research, Cambridge, MA.

Hu, P. S. and Young, J. (1994) *Nationwide Personal Transportation Survey—1990 NPTS Data Book* Vol. II, U.S. Department of Transportation, Federal Highway Administration, FHWA-PL-94-010B, Washington, DC.

Hungarian Central Statistical Office, HCSO (1961, 1966, 1971, 1975, 1980, 1981, 1986, 1987, 1990), *Hungarian Statistical Yearbook*. Budapest.

Instituto Nacional de Estadistica, INEE (1961, 1971, 1981, 1991, 1993) *Annuario Estadistico de España*. Madrid.

Instituto Nacional de Estadıstica, Geografia e Informatica, INEGI (1993) *Annuario Estadıstico de los Estados Unidos Mexicanos*. Mexico.

Instituto Nacional de Estatistica, INEP (1981, 1991, 1993) *Statistical Yearbook of Portugal*. Portugal.

Institut National de Statistique, INS (1961, 1966, 1975, 1977, 1979, 1981, 1986, 1991) *Annuaire Statistique de la Belgique*. Brussells.

Institut National de la Statistique et de Etudes Economiques, INSEE (1981, 1991, 1993) *Annuaire Statistique de la France*. Paris.

International Air Transport Association, IATA (1950–1992) *World Air Transport Statistics*. Geneva.

International Energy Agency, IEA (1990), *Energy Statistics and Balances for the Former Soviet Union*. Ad-hoc group on international energy relations, IEA/IER(90)8, Paris.

International Energy Agency, IEA (1992) *Energy Statistics and Balances*. IEA/OECD, Paris.

Intergovernmental Panel on Climate Change, IPCC (1990) *Energy and Industry Subgroup Report*. Response Strategies Work Group, Energy and Industry Subgroup.

Intergovernmental Panel on Climate Change, IPCC (1995) *IPCC Second Assessment Report*, chap. II.C.3—mitigation options in the transportation sector. Response Strategies Work Group, Energy and Industry Subgroup.

International Road Federation, IRF (1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992) *World Road Statistics*. Geneva, Washington, DC.

International Union of Public Transport, UITP (1964, 1968, 1975, 1979, 1985/86) *Statistics of Urban Public Transport*. Brussels.

Katiyar, R. and Ohta, K. (1993) Concept of Daily Travel Time' (DTT) and its applicability to travel demand analysis. *Journal of the Faculty of Engineering* **XLII**(2), 109–121.

Kirby, H. R., (1981) Foreword to Conference Proceedings, Transportation Research-A. **15**(1–6) 0-00.

Klinger, D. and Kuzmyak, J.R. (1986) *Personal Travel in the US*,-Vol. II. 1983–1984 NPTS, U.S. Department of Transportation, Federal Highway Administration, Washington, DC.

Kloas, J., Kunert U. and Kuhfeld, H., (1993) *Vergleichende Auswertungen von Haushaltsbefragungen zum Personennahverkehr* (KONTIV 1976, 1982, 1989), Gutachten im Auftrage des Bundesministers für Verkehr, Deutsches Institut für Wirtschaftsforschung, DIW, Berlin.

Kolar, S. F. (1993) Carbon abatement in Central and Eastern Europe and the Commonwealth of Independent States. In: *The Global Greenhouse Regime, Who Plays*? eds. P. Hayes, K. Smith. United Nations University Press.

Korean Energy Economics Institute, KEEI (1993) *Report on Energy Census*. Ministry of Trade, Industry and Energy, Republic of Korea.

Korean Energy Economics Institute, KEEI (1995) Data on transportation in Korea, personal communication.

Maddison, A. (1991) *Dynamic Forces in Capitalist Development: A Long-Run Comparative View*. Oxford University Press, Oxford.

Malasek, J. (1995) Transport problems in Warsaw - possible solutions. In *Reconciling Transportation, Energy and Environmental Issues: The Role of Public Transport*. OECD, Paris.

Marchetti, C. (1993) *On Mobility*. Final Status Report, Contract No. 4672-92-03 ED ISP A, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Marchetti, C. (1994) Anthropological invariants in travel behavior. *Technological Forecasting and Social Change* **47**, 75–88.

Martin, D. J. and Shock, R. A. W. (1989) *Energy Use and Energy Efficiency in UK Transport up to the Year 2010*. Energy Efficiency Series, Energy Efficiency Office, Department of Energy, London.

Metrõ (1989) Pesquisa OD/87. Sıntese das Informações, São Paulo, Brazil.

Midgley, P. (1994) *Urban Transport in Asia, An Operational Agenda for the 1990s*. World Bank Technical Paper No.224, Asia Technical Department Series, The World Bank, Washington, DC.

Mitchell, B. R. (1982) *International Historical Statistics—Africa and Asia*. St Edmundsberry Press, Suffolk.

Mitchell, B. R. (1993) *International Historical Statistics—The Americas 1750–1988, 2nd edn. M Stocton Press, New York*.

Moreira, J. R. and Poole, A. D. (1993) Abatement of carbon dioxide emissions in Brazil. In *The Global Greenhouse Regime, Who Plays* P. Hayes, K. Smith. United Nations University Press.

Motor Vehicle Manufacturer's Association of the US, MVMA (1980, 1983, 1987, 1990, 1992) *World Motor Vehicle Data*. Detroit,IL.

Motor Vehicle Manufacturer's Association of the US, MVMA (1994) Personal communication.

Nakicenovic, N. (1987) *The Automobile Road to Technological Change*. IIASA Research Report RR-87-1, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

National Commission for Statistics, NCS (1976, 1994) *Romanian Statistical Yearbook*. Bucarest, Romania.

National Statistical Coordination Board, NSCB (1980, 1986, 1988, 1989, 1990, 1992) *Philippine Statistical Yearbook*. Republic of the Philippines.

National Statistical Institute, NSI (1974, 1991, 1993) *Statistical Yearbook*. Republic of Bulgaria.

National Statistical Office Korea, NSOK (1978, 1984, 1994) *Korea Statistical Yearbook*. Republic of Korea.

National Statistical Office Thailand, NSOT (1970–71, 1981–84, 1993) *Statistical Yearbook Thailand*. Office of the Prime Minister, Bangkok.

Newman, P. W. G. and Kenworthy J. R. (1991) *Cities and Automobile Dependence: A Sourcebook*. Avebury Technical, U.K.

Office of Technology Assessment, OTA (1991) *Changing by Degrees: Steps to Reduce Greenhouse Gases*. OTA-0-842, Congress of the United States, Washington, D.C., U.S. Government Printing Office, U.S.A.

Österreichisches Statistisches Zentralamt, ÖSZ (1961–91) *Statistisches Handbuch für die Republik Österreich.*, Wien, Austria.

Oficina Central de Estadıstica e Informática, OCEI (1992) *Annuario Estadıstico de Venezuela 1991*. Presidencia de la República, República de Venezuela.

Olszewski, P., Wong Y-D, Polak J. W. and Jones, P. M. (1994) *Analysis of Travel Behavior in Singapore*. Center for Transportation Studies, Nanyang Technological University, Singapore, NTU/CTS/94-02.

Orfeuil, J. P. and Salomon I. (1993) Travel patterns of the Europeans in everyday life. In *A Billion Trips a Day, Tradition and Transition in European Travel Patterns*, eds. I. Salomon, P. Bovy and J.P. Orfeuil. Kluwer Academic Publishers, Amsterdam.

Riverson, J. D. N. and Carapetis, S. (1991) *Intermediate Means of Transport in Sub-Saharan Africa—Its Potential for Improving Rural Travel and Transport*. World Bank Technical Paper Number 161, Technical Department Series, The World Bank, Washington, DC.

Roth, G. J. and Zahavi, Y. (1981) Travel time budgets in developing countries. *Transportation Research-A* **15**, 87–96.

Schipper, L. (1995) Determinants of automobile use and energy consumption in OECD countries. *Annual Review of Energy and the Environment* **20**, 325–386.

Sathaye, J. and Walsh, M. (1992) Transportation in developing nations: managing the institutional and technological transition to a low-emissions future, In *Confronting Climate Change, Risks, Implications and Responses*, eds. I.M. Mintzer *et al*.., Stockholm Environmental Institute, Cambridge University Press, Cambridge.

Shlikhter, E. B. (1990) *Energy Consumption in the Soviet Union Transport Sector*. Soviet Academy of Sciences, Moscow.

Stab für Gesamtverkehrsfragen, GFV (1986) *Verkehrsverhalten in der Schweiz 1984*, GFV-Report 2/86, Bern.

State Statistical Bureau of the People's Republic of China, SSB (1993) *China Statistical Yearbook 1993*. New York.

Statistisches Amt der DDR, SA (1977, 1990) *Statistisches Jahrbuch der Deutschen Demokratischen Republik*, Berlin.

Statistics Bureau, SB (1972–1994) *Japan Statistical Yearbook*. Management and Coordination Agency, Tokyo.

Statistisches Bundesamt Wiesbaden, SBW (various years) *Country Reports*, Algeria (1989a), Libya (1989b), Morocco (1990), Saudi Arabia (1993), South Africa (1968, 1974, 1981, 1985), Benin (1990a), Zaire (1990b), Angola (1991a), Madagascar (1991b), Namibia (1992a), Nigeria (1992b), SADC Countries (1993), Taiwan (1986), Cambodia (1991), Mongolia (1992), Vietnam (1993), Myanmar (1989), Peru (1990).

Szalai, A., Converse, P. E., Feldheim, P., Scheuch, E. K. and Stone, P. J. (1972) *The Use of Time: Daily Activities of Urban and Suburban Populations in 12 Countries*. The Hague, Mouton.

Tanner, J. C. (1961) *Factors Affecting the Amount of Travel*, Road Research Technical Paper No. 51. HMSO, London.

Tata Energy Research Institute, TERI (1993) *Impact of Road Transport Systems on Energy and Environment—An Analysis of Metropolitan Cities on India*. Final report, Energy Policy Group, New Delhi.

Tata Energy Research Institute, TERI (1994) *TERI Energy Data Directory and Yearbook*. New Delhi.

U.K. Department of Transport, UKDOT (1977) *Transport Statistics Great Britain 1966–1976*. HMSO, London.

U.K. Department of Transport, UKDOT (1983) *Transport Statistics Great Britain 1972–1982*. HMSO, London.

U.K. Department of Transport, UKDOT (1985) *Transport Statistics Great Britain 1974–1984. HMSO, London.*

U.K. Department of Transport, UKDOT (1988) *National Travel Survey: 1985/86 Report—Part 1: An Analysis of Personal Travel*. HMSO, London.

U.K. Department of Transport, UKDOT (1993) *National Travel Survey 1989/91*. HMSO, London.

U.K. Department of Transport, UKDOT (1994) Unpublished data of the 1985/86 and 1989/91 National Travel Surveys, personal Communication with S. Chapman, London.

United Nations, UN (1960–93) *Annual Bulletin of Transport Statistics for Europe*. United Nations, New York.

United Nations, UN (1966–1990/91) *Statistical Yearbook*. United Nations, New York.

United Nations, UN (1992) *Demographic Indicators 1950–2025* (the 1992 revision). New York.

United Nations, UN (1993) *Macroeconomic Data System*. Long-Term Socio-Economic Perspectives Branch, Department of Economic and Social Information and Policy Analysis, United Nations, New York.

U.S. Department of Commerce, USDOC (1975) *Historical Statistics of the US Colonial Times to 1970*. Part 2. Bureau of the Census, Washington, DC.

U.S. Department of Transportation, USDOT (1970–1991) *Highway Statistics*. Federal Highway Administration, U.S.A.

U.S. Department of Transportation, USDOT (1992) *Nationwide Personal Transportation Survey 1990*. Public user diskettes, U.S. Department of Transportation, Federal Highway Administration, U.S.A.

USSR State Committee on Statistics, SCS (1973, 1977, 1980, 1985, 1988, 1989) *USSR National Economy, Statistical Yearbook, Finance and Statistics*. Moscow.

Vibe, N. (1993) Våre deglige Reiser—Endringer i nordmenns reisevaner fra 1985 til 1992. Transportokonomisk Institutt, TOI Rapport 171/1993, Oslo.

VWS Karlsruhe (1992) *Environmental Impacts of Energy Strategies for Indonesia, Air Quality Model for the Traffic Sector*. Badan Pengkajian Dan Penerapan Teknologi, Forschungszentrum Jülich GmbH, Germany.

VWS Karlsruhe (1991) *Environmental Impacts of Energy Strategies for Indonesia, Assessment of the Emission Coefficients of the Traffic Sector in Jawa*. Badan Pengkajian Dan Penerapan Teknologi, Forschungszentrum Jülich GmbH, Germany.

Xiaojiang, L. and Li, Y. (1995) Land use and transport planning in China, In *China's Urban Transport Development Strategy, Proceedings of a Symposium in Beijing* eds. S. Stares, and L. Zhi. 8–10, November, 1995. World Bank discussion paper No.352, East Asia and Pacific Region Series.

Walsh, M. P. (1993a) Global transport scenario. In *Towards a Fossil Free Energy Future, The next Energy Transition*, ed. Lazarus *et al*., 1993. A Technical Analysis for Greenpeace International, Stockholm Environmental Institute, Boston Center, U.S.A.

Walsh, M. P. (1993b) Highway vehicle activity trends and their implications for global warming: the United States in an international context. In *Transportation and Global Climate Change*, eds. D.L. Greene and D.J. Santini. American Council for an Energy-Efficient Economy, Washington, DC. and Berkeley, CA.

Zahavi, Y. (1981) *The UMOT-Urban Interactions*, DOT-RSPA-DPB 10/7. U.S. Department of Transportation, Washington, DC.

APPENDIX A

A.1. Data descriptions

This Appendix summarizes the data sources and estimation procedures used in this paper. Data were confirmed with national statistical abstracts and other available sources wherever possible. Although excellent agreement was found in most cases, a few discrepancies remained, which were solved in all but a few cases. Minor data inconsistencies of less than 0.5% of world regional traffic volume (pkm) are not discussed.

A.1.1. Air Traffic While *scheduled* pkm were taken from ICAO statistics (UN, 1966, 1970, 1972, 1974, 1977, 1983, 1984, 1990, 1991), those from *charter* flights are based on IATA statistics (IATA, 1950–1992) and allocated to regions in proportion to scheduled traffic. For the FSU region country statistics were used (SCS, 1973, 1977, 1980, 1985, 1988, 1989).

A.1.2. Road Traffic Road traffic includes passenger cars and buses. Two- and three-wheelers are excluded from the analysis.

NAM Since data on Canadian road traffic volume were not available, all figures were derived from the US and extrapolated to Canada on a per capita basis. The error is small, since the US accounts for more than 90% of the NAM population during the entire historical time horizon, from 1960 to 1990. US automobile-km were taken from *Highway Statistics* (USDOT, 1970,1991) and USDOC (1975). Car occupancy rates were derived from the *Nationwide Personal Transportation Surveys* 1977, 1983, and 1990 (Hu and Young, 1994). Since no such figures exist before 1977, an occupancy rate of two people per car was estimated for 1960, as it was reported for Germany (DIW, 1991), a reasonable estimate in light of occupancy rates of 2.6, measured in Indian cities (TERI, 1993). Data from intermediate years were interpolated. The traffic volume of light trucks used for personal transportation was estimated from US travel surveys (Asin, 1983; Klinger and Kuzmyak, 1986; Hu and Young, 1994); data from intermediate years were interpolated. Bus traffic volume takes into account intercity buses (Eno, 1992), urban buses (APTA, 1992a,b), and school buses. Due to the lack of earlier data, pkm of urban buses before 1978 were estimated using the following equation (pkm = pkm, NoT = given number of trips, d = trip distance, δ = average distance):

$$pkm = \sum_i NoT_i \cdot di = \delta \sum_i NoT_i = \delta \cdot NoT \tag{A1}$$

δ was assumed to be the mean value of numbers between 1978 and 1990. Vehicle-km of school buses were derived from Highway Statistics (USDOT, 1970, 1991) and the *Transportation Energy Data Book* (Davis, 1994). Since the latter source reports only occupancy rates from 1990 on, they were assumed to be equal to the 1990 number, i.e. 19.4 passengers per bus (pkm bus-km^{-1}), during the study's whole historical time horizon.

WEU Car and bus pkm are based on the *Annual Bulletin of Transport Statistics for Europe* (UN, 1960, 1993), IRF Statistics (IRF, 1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992), and ECMT Statistics (ECMT, 1989). In addition, German, Swiss, and British transport data were taken from national statistics (DIW, 1991; BFS, 1992; UKDOT, 1977, 1983, 1985, 1993).

EEU Automobile pkm estimates were based on country-specific vehicle-km per car, the passenger car population, and an occupancy rate decreasing from 2.5 in 1960 to 2.0 in 1990 (the latter corresponding to the passenger load factor reported for West Germany at a comparable motorization rate). Hungarian and Polish vehicle-km data were available from UN (1960, 1993); IRF, (1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992); those of other EEU countries were estimated to be 10,000 km per car and year, such as in the FSU (see below). In the case of Former Yugoslavia, UN and IRF statistics could be used directly. Bus passenger-km were derived from the *Annual Bulletin of Transport Statistics for Europe* (UN, 1960, 1993); IRF (1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992); ECMT (1989). Data exclude Albania.

FSU Data for traffic of privately owned passenger cars were based on the number of private vehicles, an average annual distance traveled of 10,000 km (IEA, 1990), and a car occupancy rate decreasing from 2.5 to 2.0 people per car between 1960 and 1990. The passenger car population from 1970 on was taken from the statistical yearbook (SCS, 1973, 1977, 1980, 1985, 1988, 1989). For the prior decade, a linear increase from zero to the 1970 value was assumed. The SCS statistics also provided figures for pkm from taxis and company vehicles. Bus pkm were derived from the Annual Bulletin of Transport Statistics for Europe (UN, 1960, 1993).

CPA Due to lack of data, Chinese road traffic data were extrapolated on a per capita basis to the whole CPA region (China accounts for more than 90% of the CPA population during the 31-yr time horizon). All data were taken from the *Chinese Statistical Yearbook* (SSB, 1993). Figures for urban bus transport are based on the Chinese urban bus fleet between 1960 and 1990 and the number of passengers per bus in 1990. The automobile traffic volume results from the number of private automobiles, an annual distance traveled of 29,000 km per vehicle and an occupancy rate of 2.5 persons per car. Hong Kong data were treated separately (IRF, 1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992).

SAS As was done for CPA, Indian road transport data were extrapolated to the whole SAS region (India accounts for more than 75% of the SAS population during the 31-yr time horizon). The primary data source was the TERI *Energy Data Directory and Yearbook* (TERI, 1994). Data were available for the years 1961, 1970, 1975, and 1980-85; intermediate years were interpolated. 1960 and 1985-90 data were extrapolated, based on the number of transport means for each category, assuming constant vehicle-km and occupancy rate per car and bus, respectively.

PAO Australian and New Zealand road traffic data are based on IRF statistics (IRF, 1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992). While missing pkm for intermediate years were interpolated, those before or after a series of given data were estimated based on the number of registered vehicles. The vehicle population was taken from IRF (1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992); MVMA (1980, 1983, 1987, 1990, 1992, 1994). Japanese traffic data are taken from *Japanese Statistical Yearbooks* (SB, 1972, 1992).

LAM, MEA, and AFR Traffic volumes in these three regions were estimated based on the number of registered vehicles (IRF, 1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992; MVMA, 1980, 1983, 1987, 1990, 1992, 1994) Mitchell (1993), average vehicle occupancy rate, and the annual distance traveled per vehicle—the latter being a function of motorization rate. With increasing levels of passenger car ownership, annual vehicle-km per car decrease, saturating between 10,000 and 16,000 km. The decline results from the fact that the first cars entering a market are bought due to strong need; further vehicles represent also additional household cars that are driven less. Fig. A1 shows such a curve for Japan and Germany for ownership rates ranging from 1 to 150 cars per 1000 capita (SB, 1972, 1992; DIW, 1991);* saturation occurs at about 10,000 km per car in Japan and 13,000 km in Germany.

Due to a lower population density and a lack of competing rail infrastructure relative to Japan, the German curve was taken as the basis for estimating annual vehicle-km per car in the LAM, MEA, and AFR regions. This assumption is supported by data points for passenger cars operating in Israel, which fit well with German numbers at motorization rates between 100 and 200 cars per 1000 capita (CBSI, 1993). The average occupancy rate, selected to be 2.5 people per passenger car throughout the entire time horizon, is consistent with load factors measured in Indian urban traffic (TERI, 1993). Due to its higher motorization rate, the average automobile occupancy rate in LAM was assumed to decrease to 2 people per car during the 31-yr time horizon.

Table A1 indicates motorization rate and annual distance traveled per car as a result of the Fig. A1 curve in 1960 and 1990, for the three regions LAM, MEA, and AFR.

Similarly, the traffic volume of buses was estimated from the product of registered buses, annual distance traveled per bus, and an average occupancy rate. As with passenger car traffic volume, the number of registered buses was taken from IRF (1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992); MVMA (1980, 1983, 1987, 1990, 1992, 1994). The annual distance traveled per bus was derived from survey data published by the International Union of Public Transport (UITP, 1964, 1968, 1975, 1979, 1985, 1986). The same statistics served as the basis for estimating bus occupancy rates. In both cases, it was assumed that intercity buses show characteristics identical to urban buses. Table A2 illustrates the main figures used.

PAS The traffic volumes of both passenger cars and buses are based on individual traffic data series for the six countries Indonesia, South Korea, Malaysia, Philippines, Taiwan, and Thailand, representing 90% of the PAS population. The main sources for the number of registered vehicles are *Statistical Abstracts of Indonesia* (BPS, 1986, 1993), South Korea (NSOK, 1978, 1984, 1994), Malaysia (DOS, 1986, 1994), the Philippines (NSOP, 1980, 1986, 1988, 1989, 1990, 1992), Taiwan (CEPD, 1987; SBW, 1986), and Thailand (NSOT, 1970, 1971, 1981, 1984, 1993). In addition, IRF (1965, 1970, 1973, 1976, 1980, 1990, 1992); MVMA (1980, 1983, 1987, 1990, 1992, 1994) statistics were used. In contrast to the LAM, MEA, and AFR regions, the annual distance traveled per passenger car was derived from the Japanese development illustrated in Fig. A1, because Korean data essentially confirm lower mileage per automobile. Due to the low motorization rate between 1960 and 1990 (ranging from 2 to 27 cars per 1000 capita), the vehicle occupancy rate was estimated on a country basis to decrease from 2.7 to 2.3 people per car, comparable to Indian urban transport (TERI, 1993).

The bus traffic volumes in Korea and Taiwan were obtained from *Korean National Yearbooks* and the *Taiwanese Yearbooks* (both cited above). Special attention was given to the distinction between normal-sized buses and minibuses. The

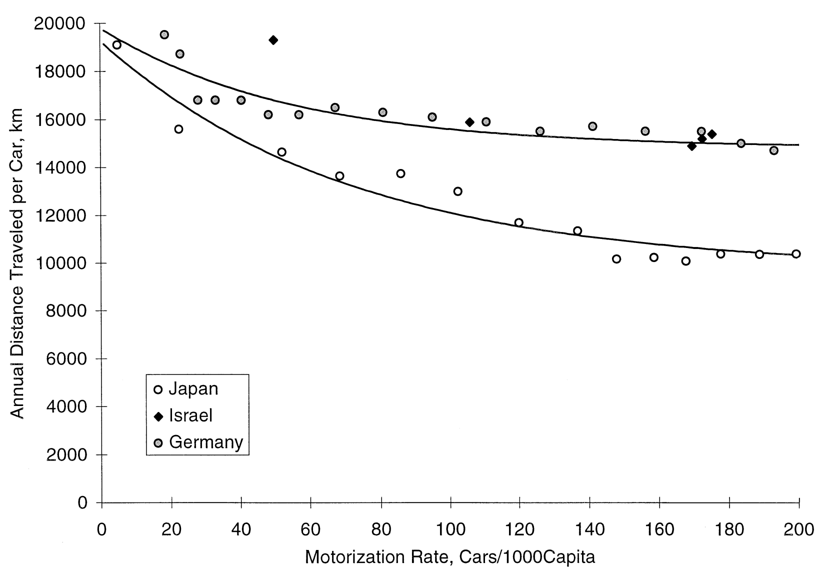

Fig. A1. Vehicle-km per car, depending on automobile motorization rate, in Japan, Germany, and Israel. The plotted curves ($R^2 = 0.947$ for Japan and 0.819 for Germany) are of the type $y = exp(-x) + C$.

Table A1. Motorization rate, occupancy rate, and annual distance traveled (ADT) per car in the LAM, MEA, and AFR regions in 1960 and 1990

	Motorization rate (Cars/1000cap)	Occupancy rate (pkm Car-km^{-1})	ADT (km)
Latin America (LAM)	11–86	2.5–2.0	18850–15850
Middle East and North Africa (MEA)	6–36	2.5	19300–17400
Sub-Saharan Africa (AFR)	6–13	2.5	19300–18800

*These were the only reliable data available. Corresponding US statistics date from 1936 (USDOC, 1975); at that time, however, the motorization rate was already 189 cars per 1000 capita.

Table A2. Estimates of occupancy rate and annual distance traveled (ADT) per bus in 1960 and 1990 in the LAM, MEA, and AFR regions

	Occupancy rate (pkm bus-km^{-1})	ADT (km)
Latin America (LAM)	35–30	60,000
Middle East and North Africa (MEA)	40	60,000
Sub-Saharan Africa (AFR)	40	60,000

Table A3. Estimates of occupancy rate and annual distance traveled (ADT) per vehicle in 1960 and 1990 in the PAS region

	Occupancy rate (pkm veh-km^{-1})	ADT (km)
Normal-sized bus	40	70,000
Minibus	10	25,000
Jeepney (Philippines)	10	15,000

latter continuously increased their market share until they currently account for about 85% of total registered buses. The distinction is significant: Due to the lower carrying capacity and annual distance traveled of minibuses, occupancy rate and average mileage per registered bus continuously decreased since 1960. The registered number of different bus sizes was merely reported in the Thai and—to some extent—Philippine statistical abstracts; thus, the annual shares of normal and minibuses in Indonesia and Malaysia were estimated based on the development in Thailand. The estimate of annual distance traveled per bus type and corresponding load factors are based on UITP statistics (1975, 1979, 1985/86). Again, it was assumed that intercity bus characteristics (in terms of annual distance traveled per bus and bus occupancy rate) are identical to urban buses. Table A3 summarizes the major parameters.

Estimates were confirmed with other sources. Traffic measurements for rural roads on Jawa (Indonesia) in 1989, as well as two travel surveys during 1972 and 1985 for Jakarta (VWS Karlsruhe, 1991, 1992), served as independent means for data checking; Korean data were checked with KEEI (1995).

A.1.3. Suburban and intercity railways The major information sources were UN *Statistical Yearbooks* (UN, 1972, 1974, 1977, 1983, 1984, 1990, 1991) and the *Annual Bulletin of Transport Statistics for Europe* (UN, 1960, 1993).

NAM US intercity railway pkm are based on ENO (1992), and commuter railway traffic is based on APTA (1992a,b). Canadian railway passenger-km were taken from UN *Statistical Yearbooks* (UN, 1972, 1974, 1977, 1983, 1984, 1990, 1991).

WEU, EEU, and FSU Railway pkm, which are based on UN (1960, 1993), include high-speed rail transport in the WEU regions. Since the traffic volume of high-speed-rail is not explicitly indicated, its share was calculated from CER (1994).

MEA Primary railway pkm sources are Mitchell (1982) and UN *Statistical Yearbooks* (UN, 1972, 1974, 1977, 1983, 1984, 1990, 1991). Compiled country statistics were also used (SBW, 1989a,b, 1990, 1993). The data contain one inconsistency: Pkm in Sudan were zero between 1960 and 1980, but the 1981 figure was 5.5% of regional pkm. Since no other data source was available, this inconsistency was left.

AFR Primary sources of railway pkm are Mitchell (1982), UN *Statistical Yearbooks* (UN, 1972, 1974, 1977, 1983, 1984, 1990, 1991) and FOS (1987). In addition, compiled country statistics were used (SBW, 1990a,b, 1991a,b, 1992a,b, 1993). More than half of all pkm in the AFR region relate to South Africa. Since the passenger traffic volume of South African railways was not available until 1984, it was estimated on the basis of eqn (A1). The number of trips was taken from SBW (1968, 1974, 1981, 1985); average distance traveled was assumed to be identical to the 1985 number of 35 km (by far, most of the pkm were related to commuting from suburbs to city centers). Some data inconsistencies could not be resolved, i.e. Swaziland: first reported pkm in 1981 (2.7% of total); Tanzania: first reported pkm in 1981 (1.7% of total); Uganda: first reported pkm in 1981 (0.6% of total). Moreover, no numbers were available for pkm in Mauritania.

CPA The primary sources for railway pkm were the *Chinese Statistical Yearbook* (SSB, 1993) and UN *Statistical Yearbooks* (UN, 1972, 1974, 1977, 1983, 1984, 1990, 1991). In addition, compiled country statistics were used (SBW, 1991, 1992, 1993).

LAM, SAS, and PAS The primary sources for railway pkm were Mitchell (1993) and UN *Statistical Yearbooks* (UN, 1972, 1974, 1977, 1983, 1984, 1990, 1991). In addition, compiled country statistics were used (SBW, 1989, 1990, 1991, 1992a,b,c).

PAO Australian railway passenger-km data were taken from IRF statistics (IRF, 1965, 1970, 1973, 1976, 1980, 1985, 1990, 1992) for the years 1963–1968 and 1988 after cross-checking with *Australian Statistical Yearbooks* (ABS, 1965, 1970, 1975, 1980, 1985, 1990, 1992). While railway pkm from intermediate years were interpolated, the 1989 and 1990 figures were assumed to be identical to the 1988 traffic volume. New Zealand's railway traffic volume was taken from UN *Statistical Yearbooks* (UN, 1972, 1974, 1977, 1983, 1984, 1990, 1991). Japan's railway pkm data were taken from *Japanese Statistical Yearbooks* (SB, 1972, 1992).

A.1.4. Urban Railways (light and heavy rail) Data on tramways and subways were generally derived from statistical abstracts, UITP *Handbooks of Public Transport* (UITP, 1964, 1968, 1975, 1979, 1985, 1986), and data collected by Newman and Kenworthy (1991). Since the latter two references merely publish data for individual years, data for missing years were interpolated. In a number of cases, no data were available between 1983 and 1990. In such cases, traffic volume was assumed to remain at the 1983 level through 1990, which may sometimes result in slight underestimations. Most travel data are published in terms of passengers carried. To obtain pkm, such data are multiplied by an average travel distance [see eqn (A1))]. Whereas mean travel distances are most often available for subways, they were assumed to be 3.5 km for tramways unless individual numbers were given. Due to the negligible traffic share of tramways, the error associated with the uncertainty of this default mean distance is negligible itself.

NAM. Data were taken from US APTA (1992a,b) and extrapolated to the NAM region on a per capita basis. Passenger-km were estimated from 1960 to 1978 according to eqn (A1).

LAM Urban rail primarily includes subways operating in Argentina, Brazil, Chile, Mexico, and Venezuela. Tramways operating in a few Mexican cities are also included. Besides statistical yearbooks of Mexico (INEGI, 1993) and Venezuela (OCEI, 1992), the major sources of information were the UITP *Handbooks of Public Transport* (UITP, 1975, 1979, 1985, 1986).

WEU. Statistical abstracts for the WEU region include those of Portugal (INEP, 1981, 1991, 1993), Spain (INEE, 1961, 1971, 1981, 1991, 1993), Belgium (INS, 1961, 1966, 1975, 1977, 1979, 1981, 1986, 1991), France (INSEE, 1981, 1991, 1993), the Netherlands (CBS, 1964), Austria (ÕSZ, 1961, 1991), and the German Democratic Republic (SA, 1977, 1990). In addition, national transport statistics were used from Switzerland (BFS, 1992), Germany (DIW, 1991), and Great Britain (UKDOT, 1977, 1983, 1985, 1993). Additional data sources were UITP (1964), 1968, 1975, 1979, 1985, 1986); Newman and Kenworthy (1991).

EEU Statistical abstracts for the EEU region include those of former Czechoslovakia (FSO, 1965, 1970, 1975, 1977, 1980, 1982, 1985a, 1991), Poland (CSOP, 1967, 1975, 1980, 1983, 1992), Hungary (HCSO, 1961, 1966, 1971, 1975, 1980, 1981, 1986, 1987, 1990), Bulgaria (NSI, 1974, 1991, 1993), Romania (NCS, 1976, 1994), and former Yugoslavia (FSOY, 1993). Additional data were derived from historical statistics of former Czechoslovakia (FSO, 1985b) and from UITP *Handbooks of Public Transport* (UITP, 1964, 1968, 1975, 1979, 1985, 1986).

FSU Urban tram and subway traffic were taken from SCS (1973, 1977, 1980, 1985, 1988, 1989). Traffic volume between 1960 and 1980 was estimated according to eqn (A1).

MEA, AFR, CPA, and SAS As suggested by UITP (1975, 1979, 1985, 1986), the traffic volume of urban rail measured during different years proved to be negligible compared to intercity and suburban railway traffic.

PAS The traffic volume of Korean subways was taken from NSOK (1978, 1984, 1994); that of Manila's elevated rail was taken from NCSB (1988, 1989, 1990, 1992).

PAO The traffic volume of urban railways was derived from *Japanese Statistical Yearbooks* (SB, 1972, 1992) and the UITP *Handbooks of Public Transport* (UITP, 1964, 1968, 1975, 1979, 1985, 1986).

APPENDIX B

Historical development of aggregate traffic volume and modal split

Tables B1 and B2 report the historical development of aggregate traffic volume and modal split for both the 11 world regions and the world.

(*Tables B1 and B2 overleaf*)

Table B1. Per-capita and total traffic volume for 11 regions and the world (and share of global total) in 1960, 1970, 1980, and 1990

	1960			1970			1980			1990		
		absolute			absolute			absolute			absolute	
	pkm cap^{-1}	bil.pkm	%wrld	pkm cap^{-1}	bil.pkm	%wrld	pkm cap^{-1}	bil.pkm	%wrld	pkm cap^{-1}	bil.pkm	%wrld
North America (NAM)	11,960	2402	43.7	16,080	3683	37.0	18370	4681	30.1	22,440	6270	27.0
Western Europe (WEU)	3090	1090	19.8	5890	2279	22.9	8130	3346	21.5	10,540	4529	19.5
Pacific OECD (PAO)	3030	324	5.9	6340	758	7.6	7890	1061	6.8	10,410	1495	6.4
Industrialized (OECD)	5770	3817	69.4	9130	6721	67.5	11,350	9089	58.4	14,420	12,294	52.9
Central and Eastern Europe (EEU)	1820	181	3.3	2930	318	3.2	4680	551	3.5	5370	666	2.9
Former Soviet Union (FSU)	1440	309	5.6	2750	667	6.7	4420	1174	7.5	5890	1697	7.3
Reforming countries (REF)	1560	490	8.9	2810	986	9.9	4500	1725	11.1	5740	2363	10.2
Middle East and North Africa (MEA)	1230	137	2.5	1840	268	2.7	3620	711	4.6	4450	1200	5.2
Sub-Saharan Africa (AFR)	900	200	3.6	1000	288	2.9	1390	531	3.4	1610	780	3.4
Centrally Planned Asia (CPA)	150	108	2.0	180	161	1.6	310	341	2.2	630	796	3.4
South Asia (SAS)	350	199	3.6	570	414	4.2	950	867	5.6	1780	2041	8.8
Other Pacific Asia (PAS)	590	129	2.3	1120	315	3.2	2060	726	4.7	3560	1514	6.5
Latin America (LAM)	1970	421	7.7	2890	810	8.1	4440	1584	10.2	5110	2262	9.7
Developing countries (LDC)	580	1194	21.7	860	2256	22.6	1450	4759	30.6	2130	8593	37.0
World	1820	5500	100.0	2680	9962	100.0	3490	15574	100.0	4390	23,251	100.0

Table B2. Modal shares in 11 world regions and the world in 1960, 1970, 1980, and 1990 for the four major modes of transport: cars, buses, railways, and aircraft (including high-speed trains). High-speed trains accounted for 27.9, 91.8, and 72.2 billion pkm in PAO (1970, 1980, 1990) and 16.3 billion pkm in WEU (1990), respectively (All numbers in %)

	1960				1970				1980				1990			
	Car	Bus	Rail	Air	Car	Bus	Rail	Air	Car	Bus	Rail	Air	Car	Bus	Rail	Air
North America (NAM)	88.5	5.4	2.8	3.3	87.3	4.2	1.3	7.2	84.4	4.1	1.1	10.4	81.7	3.4	0.9	13.9
Western Europe (WEU)	54.0	19.6	23.6	2.8	71.7	12.4	11.7	4.3	72.4	12.0	9.2	6.4	72.0	12.1	7.3	8.6
Pacific OECD (PAO)	22.6	15.7	60.0	1.8	41.8	14.5	35.7	8.0	49.3	11.6	26.6	12.6	54.5	7.6	21.7	16.2
Industrialized (OECD)	73.1	10.3	13.6	3.0	76.9	8.1	8.7	6.3	75.9	7.9	7.0	9.2	74.8	7.1	5.8	12.2
Central and Eastern Europe (EEU)	10.7	25.1	64.0	0.2	25.6	33.1	40.1	1.2	38.7	33.3	26.2	1.8	44.6	29.2	23.4	2.8
Former Soviet Union (FSU)	2.1	18.9	73.5	5.5	6.8	29.7	49.7	13.9	16.6	33.2	35.2	15.0	21.3	32.2	30.7	15.9
Reforming countries (REF)	5.3	21.2	70.0	3.5	12.8	30.8	46.6	9.8	23.7	33.2	32.3	10.8	27.8	31.3	28.6	12.2
Middle East and North Africa (MEA)	25.0	67.6	5.9	1.5	39.9	52.3	4.2	3.6	35.2	56.3	2.7	5.8	35.2	57.7	3.5	3.6
Sub-Saharan Africa (AFR)	30.9	61.5	6.8	0.8	35.6	54.2	7.5	2.7	36.4	53.6	5.9	4.1	36.5	55.5	4.2	3.8
Centrally Planned Asia (CPA)	0.3	36.7	62.9	0.1	0.6	53.8	45.0	0.6	1.3	55.3	42.2	1.2	2.4	60.7	33.6	3.3
South Asia (SAS)	7.4	46.2	46.1	0.3	6.9	59.7	31.8	1.6	6.4	64.1	27.1	2.4	7.0	75.4	15.9	1.8
Other Pacific Asia (PAS)	12.1	77.5	9.9	0.7	15.4	75.8	6.6	1.8	16.4	68.6	6.0	8.9	20.7	64.4	5.4	9.8
Latin America (LAM)	21.8	67.1	9.8	1.3	33.0	59.8	4.6	2.6	46.2	46.6	3.0	4.2	50.3	42.9	2.5	4.3
Developing countries (LDC)	18.3	61.1	19.8	0.9	24.5	60.0	13.1	2.3	28.5	56.0	10.9	4.6	26.9	59.3	9.3	4.4
World	55.1	22.3	20.0	2.6	58.7	22.1	13.4	5.7	55.6	25.4	11.0	8.0	52.3	28.9	9.4	9.4