Developments and Prospects for Land and Air Transportation in the Next Century

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Few long-term projections of the development of passenger transportation systems take account of current knowledge of innovation diffusion or the dynamics of technological change. I submit that, as a result, these projections are misleading. In particular, I believe that in the short term — the next 20 or 30 years — they significantly overestimate growth in air travel and the spread of cars, particularly in developing countries. In the longer term, they may underestimate further increases of mobility and diffusion of new transportation systems.

Most projections of changes in passenger transportation systems rely on econometric analysis and on straightforward extrapolations of trends in industrialized countries. In essence, they assume that if Chileans or Indonesians ever become as wealthy as Americans, each of them will buy about the same number of cars and take about as many airplane trips.

This assumption — that developing countries will, to the extent that they are able, mimic earlier patterns of development in developed countries — is not consistent with the historical record. History indicates that transportation systems spread differently in countries where a given technology is introduced late in the technology's "life cycle". New transportation technologies typically spread more quickly in follower countries, but ultimately achieve lower levels of diffusion. Late-comers do not mimic the countries that adopted the technology first.

The story of transportation is indeed a story of technological revolutions, from canals to railways to automobiles and aircraft. These revolutions, however, are anything but random. Technological systems evolve, spread, and are replaced in clear and consistent patterns. Their evolutionary trajectories can be analyzed mathematically by simple, biological growth and interspecies interaction models.

These conclusions are based on extensive work at IIASA on the diffusion of transportation technology and the dynamics of technological change. I believe that there was a time to build canals and railways, as there was a time to build more highways and cars. But expansion of technological systems is invariably followed by a structural discontinuity, a season of saturation: all booms eventually bust.

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It may be more creative to think about the opportunities generated by the transition to a new technological regime, rather than to develop scenarios assuming further development of well-established systems of technology and infrastructure — systems that are moving towards the saturation phase.

This article sketches out projections of growth in road and air travel, with a focus on passenger transportation, and the implications of these projections for energy demand, in particular for oil, and for emissions of CO_2. These two modes of transportation are critical in OECD countries: cars and buses account for roughly 80 per cent of passenger travel; aircraft account for another 1 per cent of domestic travel and six times as much on international routes.

The scenarios suggest a forthcoming saturation of automobiles in industrialized countries, and lower adoption levels in the developing countries. They further suggest lower levels of growth in air travel than are commonly predicted.

If automobile ownership is approaching saturation and productivity of aircraft is levelling off, then the question becomes, What technologies will succeed them? What will be the next transportation revolution?

New technologies are indeed emerging: high-productivity super- or hypersonic aircraft fuelled by methane or hydrogen, magnetic levitation trains (maglev) based on superconductivity, and electric and hydrogen powered automobiles.

Maglev or other high-speed train systems may become particularly important, largely replacing short-haul flights. Such systems would indeed be expensive, but the growth of cities, especially in the Third World, will provide the population density needed to support them. In this respect, the Bullet Train and Japan's Shinkansen Corridor point to the future: other urban conurbations will need comparable infrastructures. The expansion of such systems would reshape societies in regions that adopt them, just as the automobile has done in this century and the railroad did a century earlier.

Such thinking may seem unrealistic, given current institutions and levels of technology. But it is consistent with historical trends. Figure 1 shows the remarkable historical consistency of increases in personal mobility, expressed as the average daily travel range in France. Since 1800 mobility has increased from 20 meters to more than 30 kilometers per person per day — a factor of fifteen thousand.

There were hopes that the information revolution might curtail growth in passenger travel. New communication technologies may indeed substitute for some travel, but there are indications that improved communications spur demand for face-to-face meetings, and thus more travel. Demand for better and faster passenger travel seems insatiable.

Growth of Transport Infrastructures

When the first railways were built in the 1830s, they marked a leap forward in mobility, speed and productivity over turnpikes and canals. Elaborate railway networks gradually spread across North America and Europe.

By the 1930s the great railway era was over. The global railway network reached a length of about 1.3 million kilometres by 1930 and has remained at that level ever since. New construction in developing countries was offset by decommissioning of lines in Europe and North America. By 1930 almost 70 per cent of all railroad lines in existence today had been constructed. This implies that countries that missed the great 19th century railway bandwagon did not follow the same pattern of adoption.

The late adopters achieved faster diffusion rates with a pronounced catch-up effect. The process lasted about 100 years in the leading countries, but only a few decades in the late adopters.

This phenomenon is not unique to railways.

The British initiated the canal mania at the end of the 18th century. The development of canal networks in the Britain, France and the US peaked in the 1850s and 1860s. As with rail networks, follower countries caught up quickly. In both cases, however, the absolute level of adoption was much lower for late-comers. (Figure 2 illustrates the regular patterns of growth and decline of transportation technologies in the United States and the former Soviet Union.)

Diffusion of automobiles in different countries followed the same pattern as railroads. The diffusion rate was slowest in the United States and Canada, somewhat faster in most of the European countries, and faster yet in Japan. In developing countries the adoption rate has been even faster.

Figure 3 shows the diffusion rate of cars (given on the lower curve and labelled on the left vertical axis) as a function of the beginning of the innovation diffusion on the horizontal axis. The band at the top of the figure gives the estimated automobile adoption levels (plotted on the right vertical axis in number of cars per 1,000 people, with the associated statistical uncertainty bands), again as the function of the automobile introduction date. It shows a pronounced acceleration of the diffusion rates that is proportional to the time lag in adoption.

The Growth of Car Fleets

The advent of the automobile around the turn of the century signalled a new era. Increased personal mobility became the symbol of industrial development along with oil, petrochemicals, electricity, telephone, and (Fordist) manufacturing. The automobile became accepted as a precondition for modern industrial development.

Our scenario of the future growth in automobiles, shown in Figure 4, is based on two main assumptions. First, it portrays a typical S-shaped diffusion pattern that leads to saturation 20 to 30 years from now. Second, the diffusion process is separated into two phases, based on historical data. During the first phase, which lasted till about 1930, the automobile rapidly replaced horse-drawn carriages as the main means of highway transport — a classic case of one transportation technology succeeding another. During this phase average growth rates were about 30 per cent per year. The second phase, which is still in progress, is characterized by substantially lower growth rates: the number of cars registered worldwide increased typically by 5 per cent annually. Currently about 425 million cars and 133 million trucks and buses are registered worldwide.

The two phases are shown in Figure 4. They are especially visible on the logarithmic scale (left side), with the inflection point around 1930. The linear scale (right) extends the scenario to the year 2010. Saturation is still decades away: the scenario projects up to 500 million passenger cars by 2010.

The scenario suggests an increase between 1985 and 2010 in the global passenger car fleets of 21 to 38 per cent. The growth is higher in the developing regions both in absolute and in relative terms. In the high case the car fleet outside the OECD region doubles by 2010 to about 150 million cars.

But even this scenario is lower than other projections in the literature, especially for developing countries. This is because our calculations do not rely on the motorization trends of the industrialized countries as a guide. There is no reason to assume that pervasive adoption of the automobile — or any other technology, for that matter — in developed countries will lead to similar rates of adoption throughout the world.

The mathematical projections of slower growth of car fleets fit well with current trends. At a time when the public and policy makers are increasingly aware of environmental factors, the private car is perceived as one of the most environmentally offensive of all transportation options. Cars contribute significantly to local (ozone), regional (acid rain) and global (CO_2) pollution. Each day brings discussion of more and more measures that would directly or indirectly limit the use of cars, from local city ordinances to national carbon taxes — passenger cars account for 500 million tons of carbon annually, or about a tenth, of all CO_2 emissions from energy sources.

Newer engine technology might get around the pollution problem, but even environmentally benign cars would not solve the problem of traffic gridlock. Cities from London to Singapore are simply saturated with cars; more would only make things worse. The high population growth in Third World cities augurs for the construction of efficient mass transit systems for short-range level. For travel over longer distances, air transportation appears to offer more growth potential in these countries.

Our results suggest that car ownership rates will continue to vary widely from country to country.

Countries with similar per capita income show a remarkable range of car ownership rates. In the mid-1980s Argentina, Brazil, Mexico and South Korea had roughly similar GNP per capita — around US$2,000-2,500 per person — but their car densities ranged between 64 and 124 cars per 1,000 inhabitants in the Latin American countries to 16 cars per 1,000 in South Korea.

The Future of Air Transport

Our projections also suggest lower growth in air transport. The data suggest that the inflection point in the growth of air carrier operations worldwide occurred around 1980. The saturation level is estimated with 90 per cent probability between 240 and 340 billion ton-km (passenger plus freight traffic) per year, compared to some 200 billion ton-km in 1990. The upper value of this range appears more likely since growth has barely passed the estimated inflection point.

Contrary to the history of the automobile, the volume growth in air traffic has been sustained by significant productivity increases of the equipment, rather than by increases in the overall fleet. Over the last five decades the productivity of aircraft has increased by about two orders of magnitude. The DC-3, introduced in 1935, has a performance of about 7,400 passenger-km/hr (21 passengers at 350 km/hr); the Boeing 747 of 1969 has a performance of about 500,000 passenger-km/hr (500 passengers at 1,000 km/hr). Future versions of the B-747 could carry close to 700 passengers, making them about a hundred times as productive as a DC-3.

If we accept that speed and passenger load — passenger-km/hr — are the central criteria of productivity, then the B-747 may mark a watershed in aircraft technology. No airliners now in production or planned for production are significantly faster or larger. Given airport congestion and the inconveniences with an aircraft carrying say 2000 passengers, the likelihood of hyperjumbos is slim.

Accordingly, our projection of future growth in air travel is not as bullish as most aircraft manufacturers' forecasts (e.g. Boeing, see Steiner, 1989). This is partly because our scenario employs a non-linear model, and also because it takes into account the limits for further productivity improvements to aircraft. With productivity levelling off, future growth could be achieved only by an increase in the number of aircraft in operation. In view of the congestion of airspace and airports in most developed countries, this appears unlikely.

If the numbers of aircraft on major routes is near saturation and the size of aircraft is approaching practical limits, then the most obvious way out of this impasse would be a quantum leap in speed, similar to the introduction of the jet engine. Cruise supersonic and possibly air-breathing hypersonic aircraft connected to a new generation of ground transport systems such as maglevs might spark a new phase of expansion of global passenger travel and freight services.

Implications for Energy Demand and Carbon Emissions

At IIASA we have estimated the implications of our projections for final energy demand. We have developed three scenarios: one based on 1985 automobiles and aircraft efficiencies; the second on evolutionary efficiency improvements of about one per cent per year; and a third that additionally envisages technological changes in the fleet resulting from the diffusion of electric and hydrogen propelled vehicles. Each scenario envisages passenger car growth of 30 per cent and air travel growth of 70 per cent by the year 2010.

In the first case, no improvement in efficiency — the final energy demand would level off at about 0.9 billion tons of oil equivalent (40 GJ) per year. About 80 per cent of the fuel would be consumed by cars and the remainder by aircraft. Annual carbon emissions from these sources would also increase to eventually level off in the 2030s at around 750 million tons. Figure 5 projects CO_2 emissions under various scenarios.

This scenario appears unlikely. Historically, fuel efficiencies in the transport sector have improved at about one per cent per year, for aircraft, the rates have been up to two to three times higher.

Improvements of one per cent per year would offset our projections of growth in car fleets, leaving automotive final energy demand in 2010 about the same as in 1985. Demand for air transport fuel, however, would be some 30 per cent higher. Annual carbon emissions would start declining after 2010 to about 550 million tons by 2030.

The third alternative combines the evolutionary efficiency improvement with the introduction after the year 2000 of advanced hydrogen and/or electrically powered cars and hydrogen propelled aircraft. Such technologies combine significantly reduced fuel requirements with zero-carbon emissions. Our scenario assumes that liquid hydrogen aircraft and new-generation vehicles would be introduced first in OECD countries and would diffuse globally within three decades.

Under this scenario final energy demand by 2030 is only a third of the first alternative (frozen at 1985 efficiency). Overall, this alternative leads to a 2.5 per cent per year reduction in energy requirements per vehicle kilometer. Carbon emissions are even lower: by 2030 they would decline to less than 400 million tons per year, a level already exceeded during the early 1970s.

Figure 5 illustrates the CO_2 emissions of these three scenarios, together with the US EPA *Rapidly Changing World* scenario which assumes high population and economic growth leading to exponential increases in emissions. The IIASA '92 scenario gives lower emissions because it is based on historical rates of automotive efficiency improvements. By contrast, the three scenarios described above are not "business as usual", but assume an S-shaped growth curve for global car fleets, leading to eventual saturation; each results in substantially lower emissions.

Conclusion

Conventional projections of technology growth based on extrapolation of trends in developed countries are probably misleading. Scenarios based on knowledge of innovation diffusion and the dynamics of technological change paint a much different picture. In the case of passenger transportation systems, they point to much lower growth in air travel and cars fleets, especially in developing countries, than is commonly predicted.

Historically, small and incremental improvements to mature transportation technologies invariably yield to revolutionary changes. We are now in need of such revolutionary changes, if we are to lower environmental impacts and respond to the evolving demands for mobility of people and goods. Fulfilling such demands in an environmentally benign way will be perhaps the biggest technological challenge of our lifetimes. In the meantime, efforts must continue to make current transport technologies more efficient and productive.

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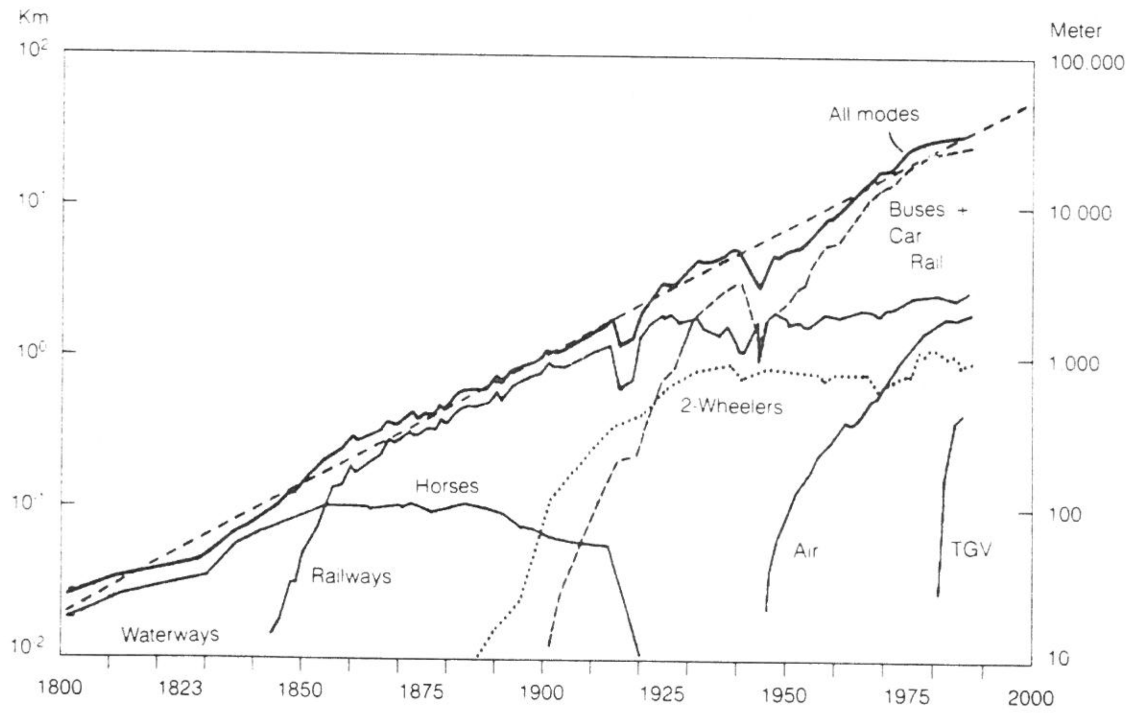

Fig. 1 Growth of mobility measured as distance travelled per day per person in France (Grübler, 1990). Mobility has increased the exponential rates since 1800 leading to a total growth by a factor of more than 10,000. Distances travelled on horseback averaged at most 100 meters per person per day. The introduction of railways increased at the average to more than 2 km per person per day. With the introduction of motor vehicles it now averages up to 30 kilometres per person per day.

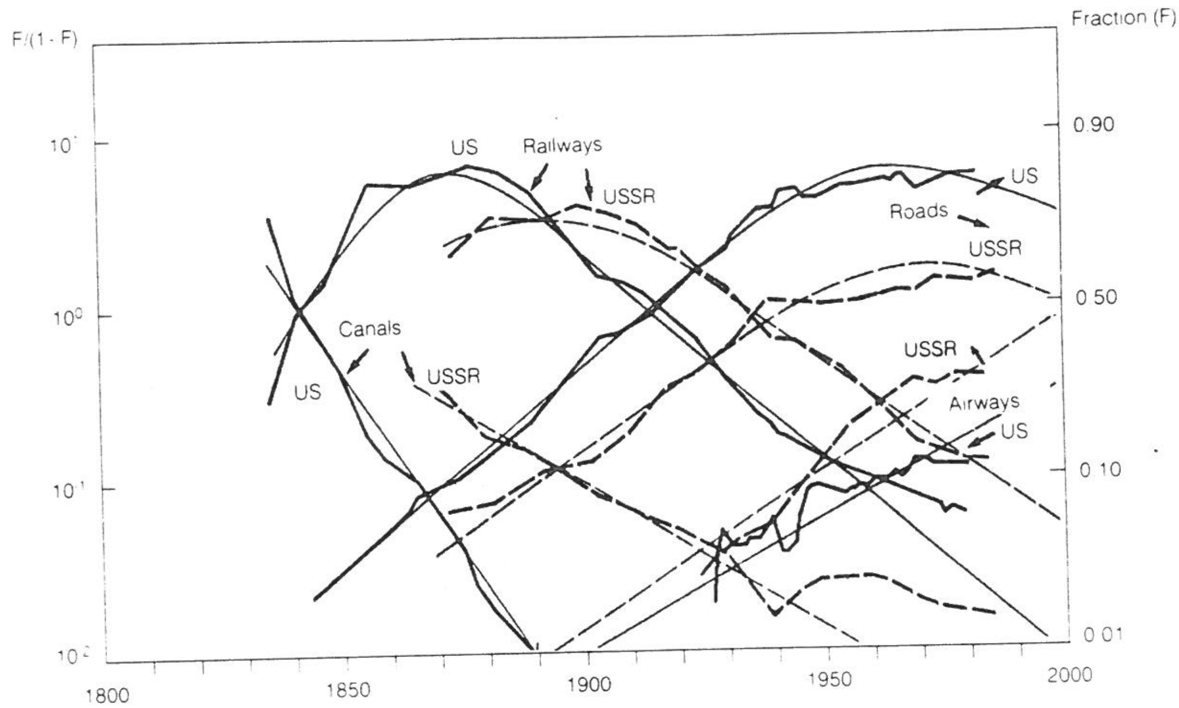

Fig. 2 Substitution of transport infrastructures in the USA and former USSR (Grübler and Nakićenović, 1991). The fractional shares, F, are plotted as the linear transformation of the logistic curve, i.e. F/(1-F), as the ratio of the market share taken by one infrastructure over the sum of the market shares of all other competing systems. Every competitor undergoes three distinct phases: growth, saturation, and decline. This is illustrated by the substitution path of railways (and later roads). There is a noticeable catch-up of former Soviet Union with reference to the United States.

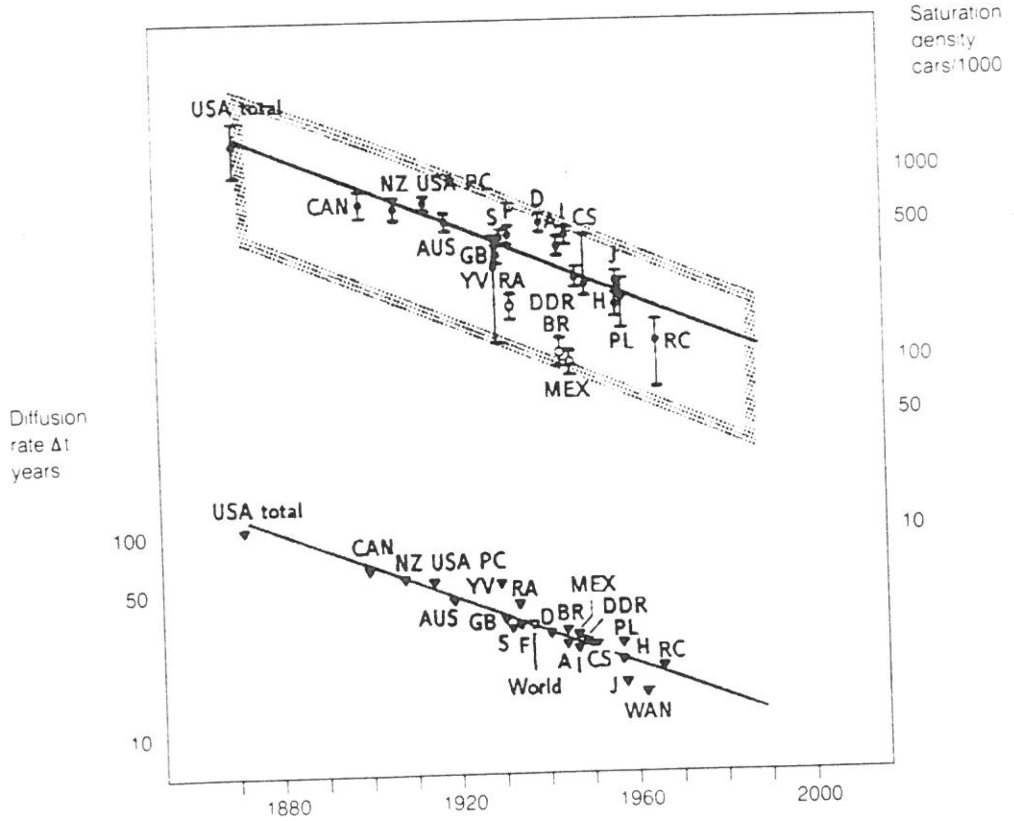

Fig. 3 Diffusion rates and ultimate ownership densities of passenger cars as a function of introduction dates (Grübler, 1990) The diffusion rate of cars is given on the lower curve and labelled on the left axis as Δt. Δt presents the time required for the automobile fleet to grow from 1 to 50 per cent of the ultimate saturation level. The band at the top of the figure gives the estimated automobile saturation level plotted on the right vertical axis in number of cars per thousand people together with the associated statistical uncertainty bands.

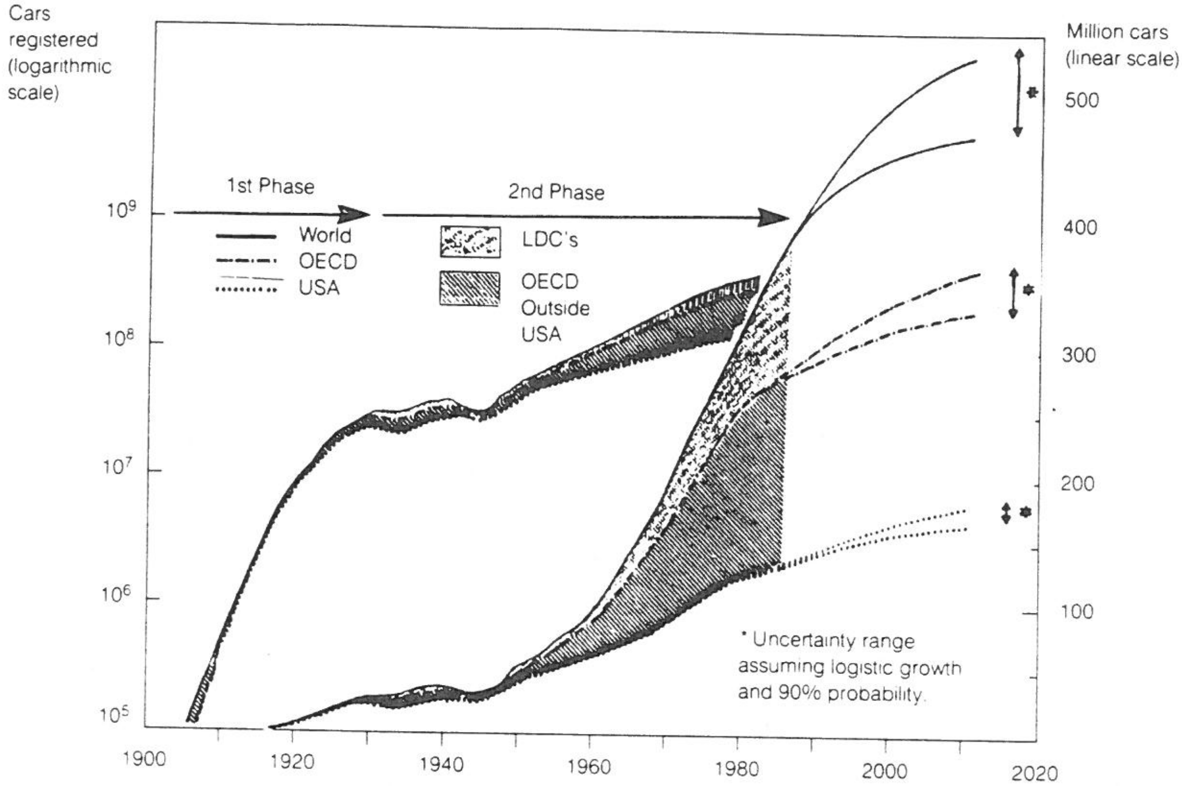

Fig. 4 Passenger car diffusion in the world and a scenario of future development. The global vehicle fleets are shown on a logarithmic scale on the left-hand axis and on a linear scale on the right-hand axis. About 80 per cent of all the passenger cars in the world are registered in the OECD countries, where more than half of the vehicle-kilometres are driven over short distances in urban conurbations and with a load factor frequently not exceeding one passenger per vehicle. The scenario of future developments shows the global vehicle fleet approaching 550 million passenger cars by the early 2020s compared to 425 million today.

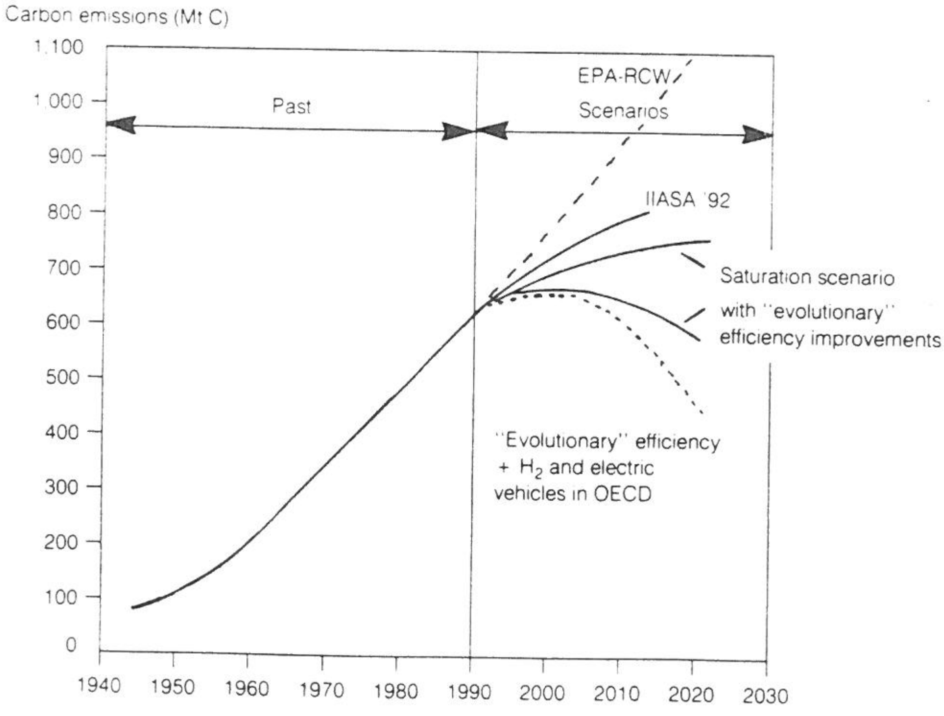

Fig. 5 Carbon dioxide emissions from passenger transport and scenarios of future development (Nakićenović *et al.*, 1992). Passenger car emissions account for more than 80 per cent of all passenger transport emissions. The EPA Rapidly Changing World (RCW) scenario assumes high population and economic growth leading to exponential increase of carbon dioxide emissions. The IIASA '92 scenario gives somewhat lower emissions because it is based on historical rates of efficiency improvements. The three alternative scenarios all incorporate saturations of the global car fleet, resulting in substantially lower emissions and eventual reversal.