DYNAMICS OF TRANSPORT AND ENERGY SYSTEMS:
History of Development and a Scenario for the Future

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Foreword

Scenarios of future energy developments and of their likely environmental impacts, particularly in the transport sector, face a number of challenging questions. For example, as societies develop will there be a global homogenization of lifestyles leading to higher demand for individual mobility and energy-intensive model activities as we see today in the industrialized countries? Are there alternatives that would challenge this conventional wisdom that envisages rapid growth in energy consumption and emissions? And finally, could we assess the importance of currently used technologies in the future, on the one hand, and the ultimate need for fundamentally new solutions, on the other?

This report analyzes the historical development of transport systems from canals to railroads, from horse-driven carriages to automobiles, and more recently to air transportation and new forms of high-speed ground transportation. The historically observed heterogeneity in the timing, duration, and adoption intensity of the diffusion of individual transport technologies is then used to sketch a scenario of energy demand, and resulting carbon emissions from the passenger transport sector.

In this scenario, automobile and air transport in the industrialized countries approaches saturation in the next two to three decades. For developing countries, however, the scenario suggests that despite their high growth potential, they may not necessarily mimic the high adoption intensity of individual transport modes prevailing in the industrialized countries. Combined with a continuation of historical rates of efficiency improvements, transportation energy demand and resulting carbon emissions could level off after the year 2000. Carbon emissions could be reduced significantly thereafter through the penetration of electric- and hydrogen-powered vehicles in the industrialized countries. Such a scenario illustrates a possible future pathway contrasting conventional wisdom and giving some indication of the direction and time scale of technology and transport policy actions required to reconcile growing mobility with global environmental concerns.

Peter E. de Jánosi
Director

Dynamics of Transport and Energy Systems:
History of Development and a Scenario for the Future

Systèmes de transport et de l'énergie:
histoire et scénario de leur évolution future

Dinámica de sistemas de transporte y de energía:
historia del desarrollo y escenario para el futuro

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1. Introduction
Introduction
Introducción

The history of transport systems is one of revolutions. *Technological changes* from the mail-coach to the airplane have transformed and extended the spatio-temporal range of human interaction patterns, leading to unprecedented levels of performance in terms of speed, quality of service, spatial division of activities, and integration of economic spaces. Similar dramatic changes in the energy system have accompanied (in fact made possible) the changes in transport technologies. In this report we provide a quantitative history of the transport system and draw some conclusions concerning possible future developments and implications for energy use. Evidence of long-term regularities in the evolution, diffusion, and replacement of several families of technologies that constitute our transport system emerges, thus facilitating a prospective look into the future.

The evolutionary envelopes analyzed reveal a process of gradual replacement of old by new systems along structured development trajectories that can be formalized mathematically by simple, biological growth and inter-species interaction models. Older systems are made obsolete through technological advance and economic development, and new ones are introduced that are better adapted to continuously changing social, economic, and

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environmental boundary conditions. Above all it is the advancement of *technology* that has denied or forestalled the original Malthusian resource depletion myth. Mankind has been able to modify and increase the size of its niche (including its spatial range) and to sustain a growing population at higher levels of economic well-being and mobility.

New transport technologies have been vital for economic development since the onset of the Industrial Revolution. In fact they have been so vital that economic historians have termed whole periods of economic development after various transport infrastructures, e.g., the "age of canals" in the first half of the 19th century, or the "railway and coal era", the expansion of which ended with the Great Depression in the 1930s. The oil and automobile alliance was the symbol, and one of the main contributing factors, to an expansion period unprecedented in the economic history of mankind, but this ultimately will also come to an end. The turbulence and volatility witnessed since the 1970s may be an indicator of a deeper structural transformation in the economy as a whole, and of the transport and energy sectors in particular.

Thus, the growth of individual transport systems is not a continuous process but time dependent. Based on historical analysis, we conclude that there was a time to build canals and railways, as there was a time to build highways and have increasing car ownership rates. However, despite the fact that the development of individual transport systems may be extremely successful over periods of several decades, any *boom* period will ultimately be followed by a structural discontinuity, a *season of saturations.* The expansion of a particular technological system reaches limits in terms of market saturation, social acceptability, and environmental constraints.

We suggest, again based on historical analogy, that 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 along the trajectories and intensity levels of the previous, by now saturating and ultimately vanishing, modes of economic and infrastructural development. Based on this working hypothesis we sketch out a scenario for the future evolution of the transport sector and illustrate the implications of this scenario for energy demand, in particular for oil. The scenario postulates a forthcoming saturation of automobile diffusion in industrialized countries with lower adoption levels in the developing countries. At the same time, we consider the possibility of further growth in passenger transportation, as well as the emergence of new transport modes, such as high-productivity super- or hypersonic aircraft fueled by methane or hydrogen, maglevs (magnetic levitation trains) based on superconductivity, or electric and hydrogen powered automobiles.

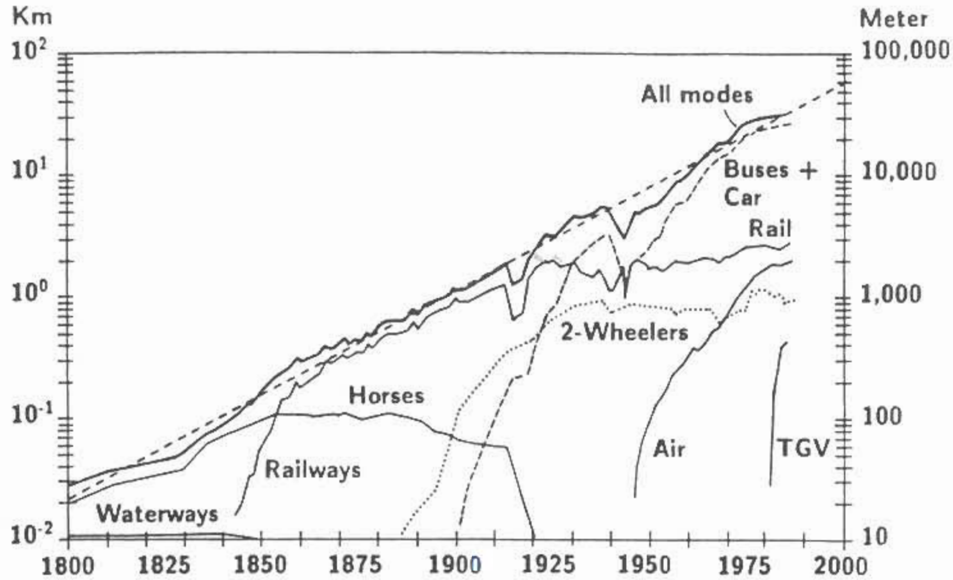

Figure 1. Growth of Mobility (Distance Traveled per Day per Capita), France (Grübler, 1990).
Croissance de la mobilité individuelle en France.
Crecimeinto de movilidad en Francia.

Such a scenario may appear unrealistic with current technologies and institutions, and in any case infeasible with a further intensification of traditional transport modes and no new breakthroughs in energy efficiency and reduction of emissions. It is however consistent with the historical trend towards greater spatial range and increasing mobility in the world. *Figure 1* shows that the increase in mobility, expressed as the average daily travel range, has been a pervasive historical development. Mobility increased *through four orders of magnitude (by a factor of ten thousand): For example*, the spatial range covered by the population of France appears to grow along a secular trend that increased from about 20 meters per day per capita in 1800 to more than 35 kilometers today. These increases in mobility were primarily achieved by the introduction and growth of new transport modes, railways in the 19th century and buses and cars in the 20th century. Although the increase in mobility may be sustained over several decades by growth in the output of the dominant transport system, as illustrated by the growth in railway traffic between 1860 and 1920 and by the growth of road traffic since WW II, there are obvious limits to the further expansion of traditional transport systems. Current transport modes will ultimately have to be replaced by more advanced (in terms of productivity and environmental compatibility) systems.

2. Growth of Transport Infrastructures
Croissance des infrastructures de transport
Crecimiento de la infraestructura de medios de transporte

The first railways were constructed in the 1830s and extended the range, speed, and productivity offered by previous transport infrastructures, in particular turnpikes and the elaborate system of canals constructed between the end of the 18th and beginning of the 19th century in a number of countries. In time, elaborate networks of railway systems were built in North America and Europe. Together with railways, a new era of coal, steam, steel, and telegraph began. The great railway era lasted until the 1930s.

Figure 2 shows the diffusion of railroads in Europe, the United States, and in the "rest of the world" illustrating the extent to which their development was synchronized internationally. While the processes differ both in rates of growth and duration, there is a high degree of congruence in their ultimate saturation in the industrialized countries towards the 1930s.

The diffusion cluster of railway networks in *Figure 2* that reached saturation by the 1930s accounts for almost 70 percent of all railroad lines constructed to date. This implies that the particular development trajectory (the "railway bandwagon") was not repeated by latecomers, i.e., by those countries that did not participate in the expansion pulse of the 19th century. In fact, the global railway network reached a length of about 1.3 million kilometers by the 1930s and has remained at that length ever since. Decommissioning of lines in the core regions (Europe and North America) was compensated for by new construction in the developing countries. In the core countries *the railway bandwagon focused as it evolved, converging toward the saturation period.* In other words, although the introduction of railroads occurred with great lags between the early and late adopters, such as between the UK and Scandinavia, the late adopters achieved faster diffusion rates with a pronounced catch-up effect converging towards saturation. This focusing of the expansion pulse of the railway era is most noteworthy when one considers that the whole development process lasted about 100 years in the leading countries and only a few decades in the late adopters. This phenomenon is not unique to railways. The development of canal networks (in the UK, France and the US) saturated between the 1850s and 1860s, with the follower countries catching up to the British "canal mania" initiated at the end of the 18th century.

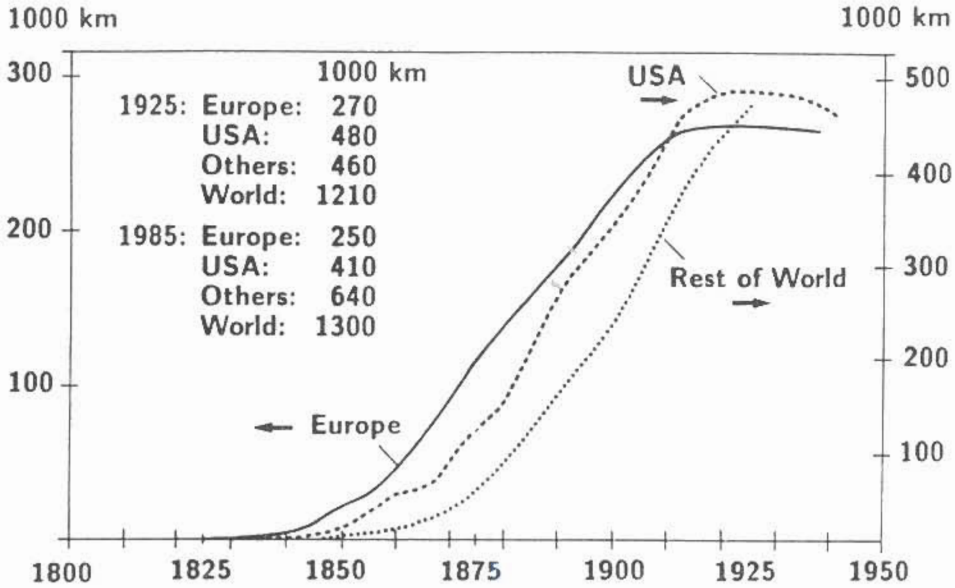

Figure 2. Growth of Railway Networks, in 1000 km.
Croissance des réseaux de chemin fer.
Crecimiento de redes ferroviarias.

The absolute level of adoption is however much lower for the late adopters compared to the early adopters. The ultimately achieved railroad density is in general higher the earlier the railroads are introduced; leaders achieve the highest diffusion levels. *Figure 3* shows this phenomenon. It demonstrates that the railway densities can be grouped within a declining "density envelope" as a function of the introduction date. This result shows that whereas the diffusion rate accelerates (i.e., the "catch-up" effect) for late adopters, the intensity of final adoption levels decreases. The intensity falls even further for those countries that introduced railways after the completion of the expansion pulse in the core countries. This identifies an "opportunity window" for the diffusion of pervasive systems like railways, which were the dominant transport system during the second half of the last century.

The advent of the automobile around the turn of the century initiated a new era in the development of transportation. Increased mobility became the symbol of industrial development along with oil, petrochemicals, electricity, telephone, and (Fordist) manufacturing. The flexibility offered by an

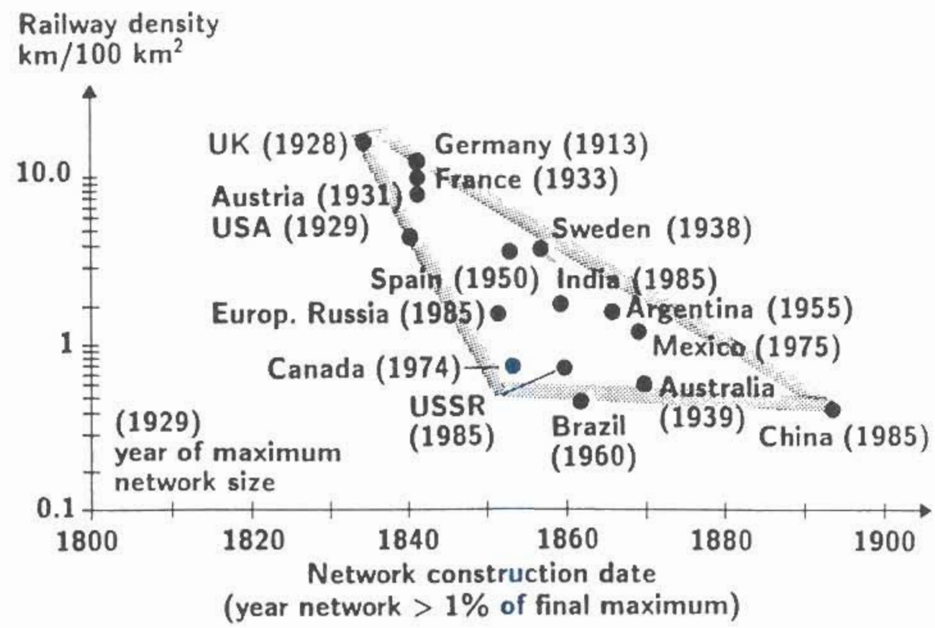

Figure 3. Railway Network Density as a Function of Introduction Date, World (Grübler and Nakićenović, 1991).
Densité des réseaux de chemin de fer en fonction de leur date d'introduction.
Densidad de redes ferroviarias dependiendo de la fecha de introducción.

individual mode of transport became affordable for a wider social strata, and only recently have the disadvantages of the automobile become socially transparent although they have been known for a long time. This perception lag illustrates the extent to which the automobile became accepted as one of the preconditions for modern industrial development.

The growth of the automobile to the present number of about 420 million passenger cars registered worldwide went through two distinct diffusion phases marked by different growth rates divided by a structural discontinuity in the 1930s. The first phase was initiated during the last century when horse-driven vehicles were the predominant form of road travel.

Figure 4 illustrates the first, rapid phase of automobile diffusion as it replaced horse-drawn vehicles in the United Kingdom, together with a similar substitution process in the railway transport system a few decades later

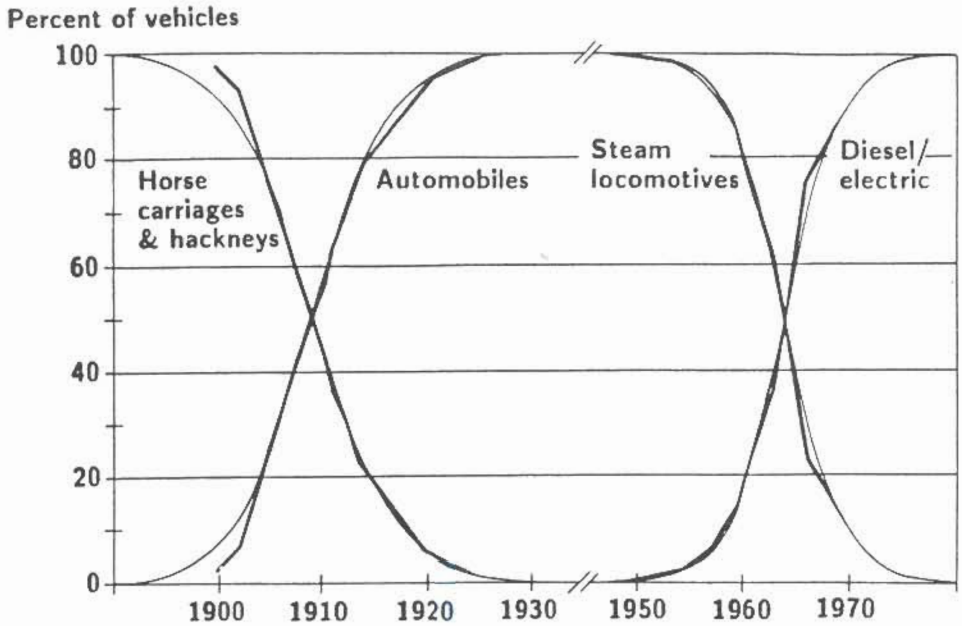

Figure 4. Substitution of Horse-drawn Vehicles by Automobiles and Steam by Diesel and Electric Locomotives, U.K., in Share in Total Number of Rolling Stock.
Remplacement des véhicules équestres par l'automobile et des locomotives à vapeur par cellés à diesel on électrique, Royaume-Uni.
Sustitución de vehículos (caballos por automóviles) y trenes (vapor por diesel y electricidad), Inglaterra.

when diesel and electric locks replaced steam propulsion in the rolling stock.[1] This example is typical of similar replacement processes throughout the world including the former centrally planned economies and developing countries. Technological change and substitution in road and railway vehicle fleets lasted in general between two to three decades.[2]

1 The fractional shares, F, are plotted as the share taken by the new competitor divided by the volume of the whole market or "niche", i.e., the share of the cars in the number of all cars and horse–drawn vehicles together. This form of presentation reveals S–shaped substitution paths of old by new technologies and systems as formulated by Fisher and Pry (1971). In most cases, this process can be described by logistic functions.

2 The duration of the diffusion process is measured as the time that elapses between the achievement of 1 percent and 50 percent (and from 50 to 99 percent) of the complete replacement of old by the new or the achievement of so–called market saturation. We call this measure Δt. Δt also approximates the time required to grow from 10 to 90 percent of the saturation level.

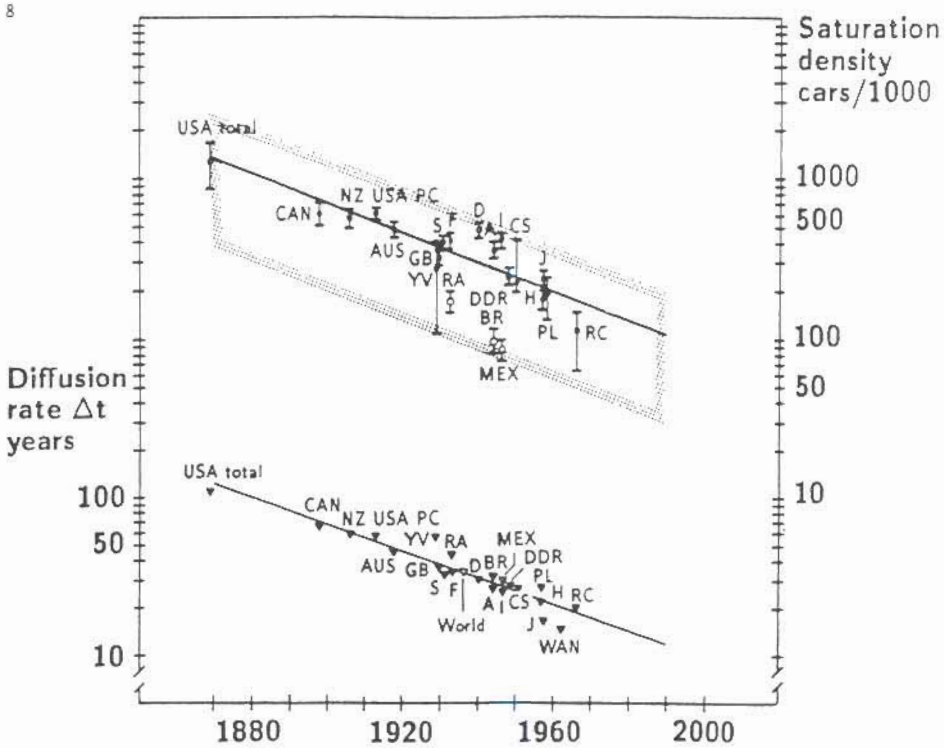

Figure 5. Diffusion Rates and Ultimate Ownership Densities of Passenger Cars as a Function of Introduction Date, World (Grübler, 1990).
Vitesse de diffusion et niveaux d'adoption ultérieure de l'automobile en fonction de sa date d'introduction.
Tasa de difusión y densidad de propiedad de automóviles dependiendo de la fecha de introducción.

The adoption level of the automobile in different countries follows the same pattern as the observed saturation levels of railroads. Of the industrialized countries, the diffusion rate was slowest in the United States and Canada, faster in most of the European countries, and fastest in Japan. The adoption of the automobile was even faster in developing countries, albeit that it started only recently and has led, at least for the time being, to relatively low levels of car ownership.

Figure 5 reports these results by showing the diffusion rate (Δt, given on the lower curve and labeled 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 capita with the associated statistical uncertainty bands), again as the function of the automobile introduction date. Thus, a pronounced *acceleration* of the diffusion rates can be observed that is proportional to the time lag in innovation adoption. Again, the ultimate adoption levels *decrease* with shorter diffusion time.

This result is consistent with spatial patterns of innovation diffusion. Originating from innovation centers that reach the highest adoption levels, the innovation generates additional gravity centers in space; however, the adoption levels remain lower in the peripheral regions compared with innovation centers. Early innovators achieve higher adoption levels and have the longest diffusion or "learning" times. Peripheral regions catch-up so that the diffusion process focuses toward the saturation period, but the adoption level in the periphery remains much lower than in the leading centers. Therefore whereas it is likely that road transport will continue to increase in the developing countries, any massive diffusion of car ownership, especially to levels anyway close to those of industrialized market economies, cannot happen "overnight". It is more likely to take several decades and extend well beyond the time horizon of the illustrative energy scenarios adopted here. In the meantime, additional growth in mobility outside the OECD region will have to rely to a large extent – as in the past – on buses, railways and aircraft.

3. Technological Substitution
Substitution technologique
Sustitución tecnológica

The evolution of transport infrastructures can also be seen as a substitution process. Infrastructures can be viewed as systems that replace each other in time. *Figure 6* shows the growth of transport infrastructure length in the United States as a substitution process[3] and for comparison the equivalent substitution process in the Soviet Union.

The pattern of temporal changes is marked by a high degree of regularity and a quest for higher speed and productivity. The phase transitions in the infrastructure substitution in the former USSR, however, are lagged by a few decades when compared with the United States. For example, the dominance of railways lasted until the 1940s while in the United States it ended two decades earlier. The decline of canals occurred much later as well, while the growth of national airways follows the same path as in the United States. During the last decades, development of transport infrastructures in

3 The fractional shares, F, are plotted as the linear transformation, 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 substitution phases: growth, saturation, and decline as shown by the substitution path of railways (and later roads), which curve through a maximum from increasing to declining market shares (see *Figure 6*). A detailed description of the model is given in Nakićenović, 1979.

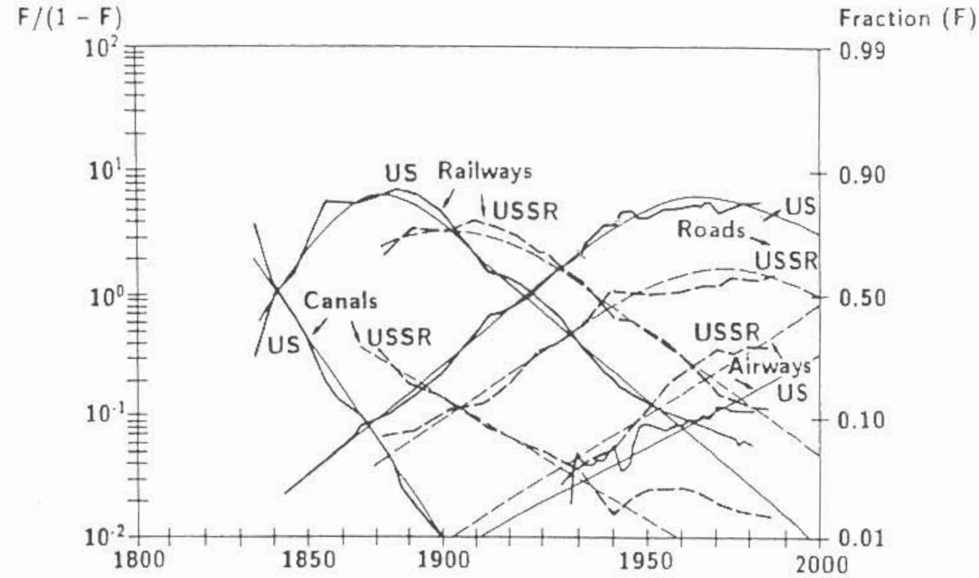

Figure 6. Substitution of Transport Infrastructures in the USA and the Former USSR, Fractional Shares in Length (Grübler and Nakićenović, 1991).
Substitution des infrastructures de transport aux Etas-Unis et en ancien Union Soviétique.
Sustitución de infraestructuras de transporte en EEUU y la antigua URSS.

the two countries has been converging. The rate of relative growth in the importance of road infrastructure and their saturation also appear synchronized. However, road infrastructures are used differently in the two countries: by individual road vehicles (cars) in the US and by collective ones (buses) in Russia. Thus, there is an increasing congruence and similarity in the structural and functional evolution of the transport system in the two countries. To a large extent this is also due to the fact that both countries have relatively low population densities and vast territories that modern transport systems must bridge in a matter of hours.

Figure 7 shows the actual usage of transport infrastructures. It gives the long-distance passenger modal split in the United States (top of *Figure 7*), the former Soviet Union and China (bottom of *Figure 7*). These examples are representative of the developments in most countries and illustrate a certain convergence in the development of transport systems.

Comparison of the three countries shows that in the past the intercity passenger transport development portrayed a phase-shift. Rail and bus are virtually extinct in the United States, while in the former Soviet Union and China they are still an important means of transport. Thus, while many characteristics of the former USSR's intercity modal split changes lag by several decades compared to the US (with the exception of air travel growth), China's lag of some 20 years behind the USSR (note the different time axes on the bottom of *Figure 7*) is even larger.

The above indicates that by the end of the century airways may become the dominant form of intercity travel in both the United States and the former Soviet Union. In both countries road transport currently has the largest share, albeit by automobile in one case and by bus in the other. The developments in the former USSR may serve as a guide for the modal split changes in China over the next decades. What is important is that the average choice of different modes of passenger travel changes consistently and favors faster and more productive systems.

The slower modes recede to service fewer people over shorter distances (fewer passenger-kilometers) and low-value segments of transport. Their shares in passenger transport decline, resulting in the rationalization of the respective infrastructures. The least productive links are decommissioned, and the infrastructure declines. The diffusion of more productive and faster means of transport leads to increased range and connects ever larger areas into single functional entities. During the last two centuries villages merged into towns, towns into cities, and cities into metropolitan areas. Large urban corridors have evolved throughout the world, some approaching a hundred million inhabitants requiring high productivity transport systems.

4. Transport and Energy Systems
Systèmes de transport et de l'énergie
Sistemas de transporte y de energía

The substitution of older transport infrastructures for new ones and the high degree of synchronization in the diffusion of transport systems are not coincidental. They reflect strong linkages and similar pervasive changes in the overall evolution of the social and economic system denoting major techno-economic paradigm shifts. The diffusion of railways is linked with the spread of steel, coal and many other related technologies throughout the world. The same can be said about cars, the internal combustion engine, oil, petrochemicals, etc. *Figure 8* shows the substitution pattern in primary energy sources in the United States. Similar paths of technological change

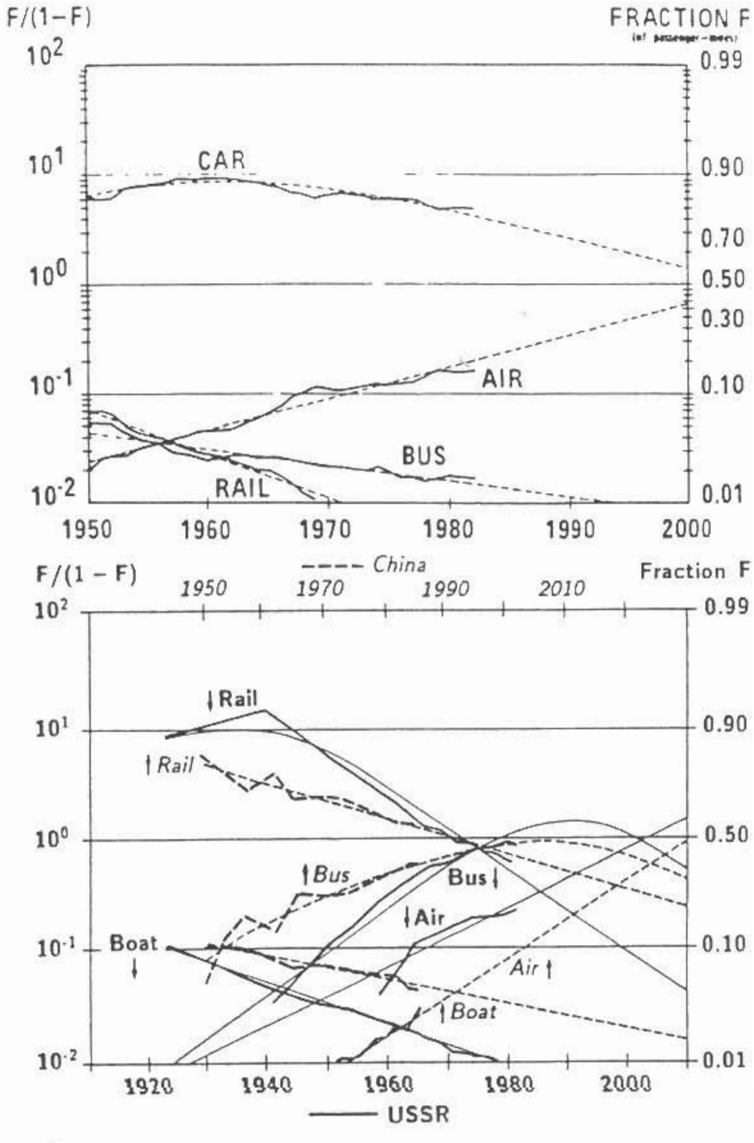

Figure 7. Substitution of Intercity Passenger Transport Modes in the USA (top) and the Former USSR and China (bottom, with shifted time axes), Fractional Shares in Inter-city Pass-km.

Substitution des modes de transport inter-urbain aux Etas-Unis, en ancien USSR et en Chine.

Sustitución de modos de transporte inter-urbano para pasajeros en EEUU y la antigua URSS y China.

can be found in other countries. Energy substitution is characterized by very long time constants (with Δts) of about one hundred years in the United States and even longer at the global level. The saturation periods of the market share of each consecutive primary energy source are separated by about five decades. The feed requirements for horses and working-animals saturate in the 1870s, coal around 1920, and oil around the time of the "energy crisis" of the early 1970s.[4]

Technological changes in transport and energy systems have been instrumental not only for raising productivity and providing new services but also for improving energy efficiency. The primary energy substitution of *Figure 8* can also be interpreted as a substitution process of energy end-use and

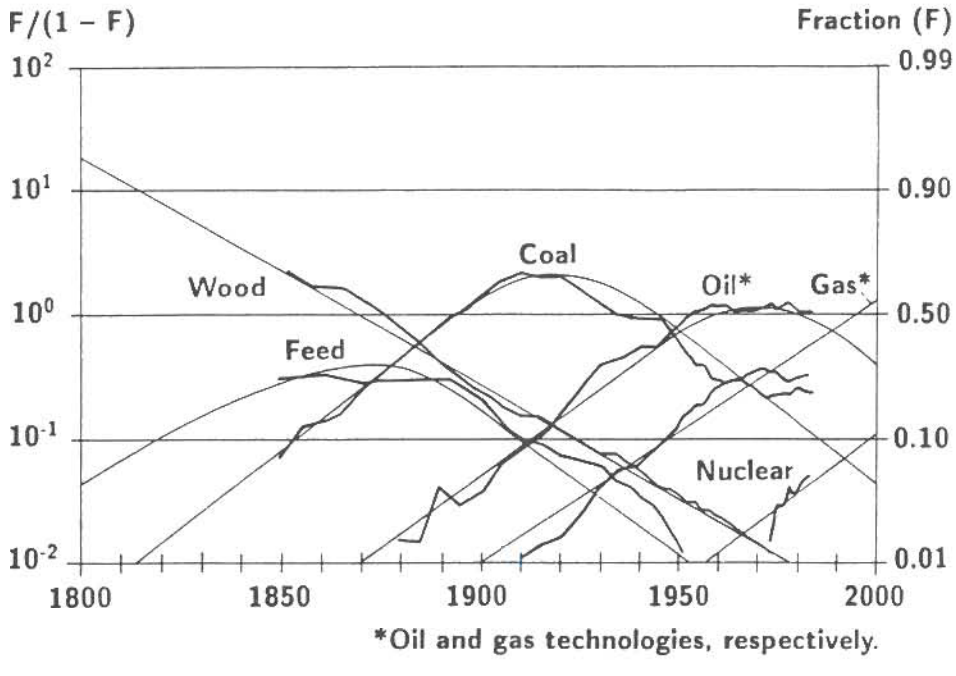

Figure 8. Primary Energy Substitution, USA (Nakićenović, 1987).
Substitution des sources d'énergie primaire, Etat-Unis.
Sustitución de energia primaria, EEUU.

4 "Oil technology" in *Figure 8* represents all primary energy consumption that is associated with oil production including associated natural gas. This is equivalent to the inclusion of town gas in the consumption of coal. "Gas technologies" exclude production of natural gas from oil wells.

conversion technologies, from the sailing to the steam ship, from stationary coal-fired steam engines to electric motors, from horses to internal combustion engine powered cars. The effect on improved energy efficiency of this technological change has been dramatic. A unit of value added in the US is produced today with only 20 percent of the primary energy requirements some 200 years ago (Nakićenović *et al.*, 1989). This corresponds to a long-term improvement rate in energy intensity of about one percent per year.

5. Scenario of Car Diffusion
Scénario de diffusion de l'automobile
Escenario de la difusión automovilística

Given that the replacement of transport and energy technologies follows broadly similar patterns both in space and time, our scenario of global mobility development assumes a similar co-evolution of transport and energy systems in the future. A new generation of automobiles and aircraft is assumed to be associated with a new generation of vehicle fuels, namely electricity and hydrogen. The scenario also assumes that the absolute diffusion level of these new technologies would be lower in the lagging regions of the world than in those that lead the innovation process.

The scenario of the future growth in automobile diffusion is based on two main assumptions. First, it portrays a S-shaped diffusion pattern that leads to a saturation after the end of this century. This is estimated from the historical growth of the world automobile fleet up to the present number of about 420 million passenger cars. Second, the diffusion process is separated into two phases, each corresponding to different market niches and driving forces of the growth of the automobile (see *Figure 4*, Nakićenović, 1986, and Grübler and Nakićenović, 1991). During the first phase, the automobile diffused rapidly into the market niches previously held by horse-drawn carriages, where its comparative advantage was particularly high and led to average growth rates of about 30 percent per year. The second phase, which started after the 1930s and is still in progress, is characterized by substantially lower growth rates: The number of cars registered worldwide increased typically by five percent annually.

The two phases of automobile diffusion are shown in *Figure 9*. They are especially visible on the logarithmic scale (left side) with the inflection point occurring around 1930. The scenario extends to the year 2010 and is shown on the linear scale (right) of *Figure 9*. Since the actual diffusion of the automobile in the world is still decades away from the estimated saturation level, the scenario is based on two alternative cases derived from the historical data - the "best fit" and "high" estimate. The two cases correspond to a range of 440 to 500 million passenger cars by the year 2010.

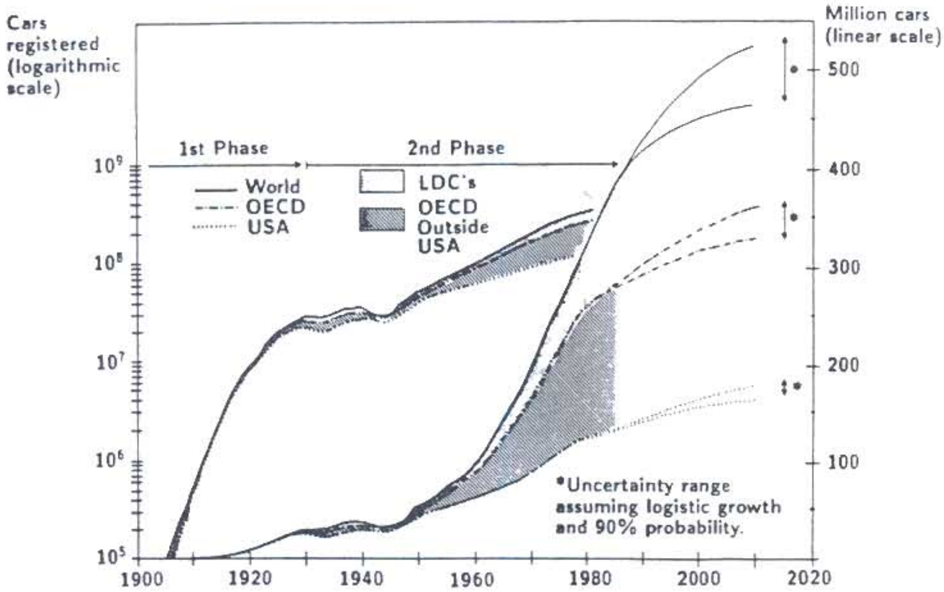

Figure 9. Passenger Car Diffusion and Scenario, World.
Histoire et scénario futur de la diffusion de l'automobile.
Difusión y escenario de automóviles.

5.1. Cars in the Year 2010 L'automobile dans l'an 2010 Automóviles en el año 2010

Table 1 summarizes the results by regrouping the 1985 values and scenario ranges (the best fit and high cases) for the year 2010 by broad geographical regions based on the selected sample of 21 countries. For a better comparison with other projections we have also aggregated 12 of the OECD countries (representing 98 percent of all passenger cars registered in the OECD) as a proxy for more developed countries, and the residual to the world total as a proxy for the sum of less developed (LDC) and (former) centrally planned economies (CPE). *Table 1* shows the high degree of heterogeneity in the ultimate adoption levels among different regions of the world. The differences are generally a function of the diffusion time. *Figure 5* illustrated that this is indeed the case and the scenario demonstrates the possible consequences of such a development in the future. The early adoption leads to higher diffusion levels and thus to higher and more pervasive automobile ownership. The scenario suggests an increase in the global passenger car fleets of between 21 and 38 percent compared with 1985 levels. The growth is higher in the developing regions both in absolute and in relative terms, and in the high case the car fleet actually doubles until the year 2010 outside the OECD region to a level of about 150 million cars.

Table 1. Scenario of Passenger Car Registration for the Year 2010.
Scénario du nombre de voitures immatriculées en l'an 2010.
Escenario de matrículas de automóviles para el año 2010.

	1985			2010		
Region	10^6 cars	10^6 pop.	Cars/ 1000	10^6 cars[a]	10^6 pop.	Cars/ 1000[a]
North America[b]	147.2	264.7	556	169.4–187.4	303.1	559–618
10 OECD Countries[c]	141.9	427.0	332	153.7–169.1	458.6	335–369
4 CPE[d]	11.7	80.5	145	16.5–21.5	85.7	193–251
5 NICs[e]	22.6	291.5	78	39.0–69.8	397.6	98–176
World	364.8	4838.5	75	439.5–501.6	7015.9	63–71
12 OECD Countries	289.1	691.7	418	323.1–356.5	761.7	424–468
% of world	79%	14%	–	71–73%	11%	–
LDCs and CPEs	75.7	4146.8	18	116.4–145.1	6254.2	19–23
% of world	21%	86%	–	27–29%	89%	–

[a]Range corresponds to best fit and high case respectively.
[b]USA and Canada.
[c]Australia, Austria, France, FRG, Italy, Japan, Spain, Sweden, New Zealand, and the UK.
[d]Czechoslovakia, former GDR, Hungary, and Poland.
[e]Argentina, Brazil, Mexico, Taiwan, and Venezuela.

This scenario is lower than other projections in the literature, especially for developing countries. Often, pervasive adoption of the automobile is thought to lead to similar ownership densities throughout the world. In contrast, the scenario does not rely on the motorization trends of the industrialized countries as a guide of what might occur in the developing regions. Instead, the rationale for the relatively low levels of automobile adoption in the world is based on the possible saturation of car densities in urban areas, an increase in air transport for longer journeys, the availability of new high-speed ground transportation systems, and perhaps also the increasing environmental problems associated with the further expansion of automobiles. The high urban population growth rates in developing countries calls for the construction of efficient mass transit systems for short-range travel. For long-distance travel, the growth potential for air transportation appears to be more consistent with the likely future developments in these countries than a linear extrapolation of the transportation trends of industrialized countries.

Today, different automobile ownership rates coexist at similar per capita income levels due to different initial conditions, diverse economic structures, varying degree of infrastructural development, etc. Countries like Argentina, Brazil, Mexico or South Korea have similar GNP per capita (of about 2,000 1982 US$ per capita in the Latin American Countries to about 2,500 1982 US$ per capita in South Korea) whereas in 1986 their car densities ranged between between 64 and 124 cars/1,000 inhabitants in the Latin American countries and 16 cars/1,000 in South Korea. According to the scenario, the diversity in automobile ownership would continue to be a characteristic feature of both developing and more developed countries.

5.2. Scenario of Air Transport
Scénario du transport aérien
Escenario del transporte aéreo

The long-term evolutionary changes in transport systems indicate that faster modes are favored in long-distance traffic. A logistic function fitted to the actual data suggests that the inflection point in the growth of air carrier operations worldwide occurred around 1980. *Figure 10* shows the statistical uncertainty bands associated with this estimate. The saturation level is estimated between 240 and 340 billion ton-km (passenger plus freight traffic) with 90 percent probability. The upper value of this range appears more likely since growth has barely proceeded beyond the estimated inflection point. The air transport scenario also includes the best fit and the high values as the possible volume of future global air transportation.

Contrary to individual automobile transport, the market volume growth in air traffic was sustained by the significant productivity increases of aircraft rather than by increases in the commercial aircraft fleet. Furthermore, much of the traffic is allocated to the most productive aircraft operating among the large hub airports, while other aircraft constitute the feeder and distribution systems for destinations with a lower volume of traffic. Over the last five decades the productivity of aircraft has increased by about two orders of magnitude. For instance, the DC-3 was introduced in 1935 with a performance of about 7,400 passenger-km/hr (21 passengers at 350 km/hr) whereas the Boeing 747 (B-747), introduced in 1969, has a performance of about 500,000 passenger-km/hr (500 passengers at 1,000 km/hr). The largest Jumbo will probably carry almost 700 passengers. The B-747 family is therefore about a hundred times as productive as the DC-3 was 50 years ago (Nakićenović, 1988). The volume of all airline operations has continued to increase since the introduction of the B-747 while its productivity increased only marginally through "stretching". Most of the subsequent technological development focused on gradual improvements such as noise reduction and

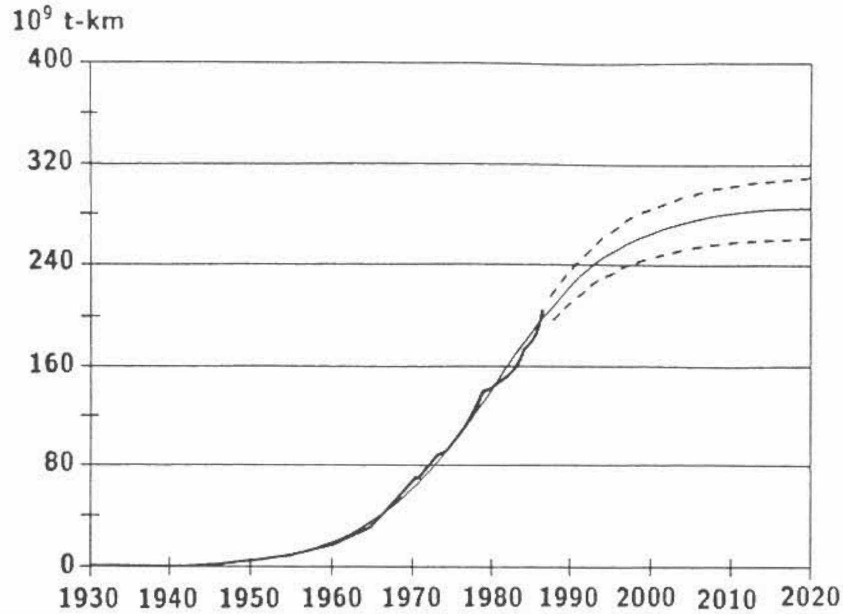

Figure 10. Air Transport Scenario, World.
Scénario du transport aérien.
Escenario del transporte aéreo.

increased fuel efficiency. Unavoidably, this leads to an impression of diminishing returns in the further advancement of airliners and, consequently, the possibility of an approaching performance saturation of the current generation of aircraft technologies. If we consider current airport overcongestion and the inconveniences associated with an increase in the size of an aircraft, the likelihood of developing hyperjumbos with capacity for a few thousand passengers is slim.

Accordingly our scenario of future air transport is lower than most aircraft manufacturers' forecasts (e.g., Boeing, see Steiner, 1989) not only because it employs a non-linear model but also because it takes into account the limits for further productivity improvements to the existing generation of aircraft. With aircraft productivity saturating, future growth in demand could only be achieved by an increase in the number of aircraft in operation. Again, this appears unlikely in view of the already overcongested airspaces and airports in most developed countries. A second possibility out of this impasse would be a quantum leap in technology, similar to the introduction of the jet engine.

This scenario of future air transport does not suggest permanent stagnation of market volume, but rather a transition to a possible new growth pulse in commercial aviation, as well as in ground transportation in about two decades. Cruise supersonic and possibly air-breathing hypersonic aircraft connected to high productivity ground transport systems such as maglevs might be the only technologies now on the horizon to provide the growth potential that could be required in the next expansion phase of worldwide passenger travel and freight services.

6. Implications on Energy Demand and Carbon Emissions Implications pour la demande d'énergie et les emissions CO_2 Consecuencias de la demanda de energía y emisiones de carbono

Saturation of passenger car and air transport would have repercussions for energy demand and associated emissions. The scenario envisages passenger car growth of 20 to 40 percent and air transport growth of 60 to 80 percent by the year 2010 compared with 1985 levels. *Figure 11* illustrates the energy demand of this scenario. Estimates are based on the medians between the best fit and high cases, i.e., passenger car growth of about 30 percent and air transport of about 70 percent. Three alternatives are shown: one based on 1985 automobiles and aircraft efficiencies; the second on "evolutionary" efficiency improvements of about one percent per year; and a third that additionally envisages technological changes in the fleet resulting from the diffusion of electric and hydrogen propelled vehicles.

The final energy demand would level off at about 0.9 billion toe (40 10^9 GJ) per year if the 1985 vehicle efficiency remains unchanged until 2010 (*Figure 11*). About 80 percent of the fuel would be consumed by cars and the remainder by aircraft. Carbon emissions from passenger cars and aircraft would also increase to eventually level off at a value of around 750 million tons carbon. This appears to be quite unlikely however as fuel efficiencies are certainly going to improve. Historically, fuel efficiencies in the transport sector have improved at a rate of about one percent per year, although in some cases like aircraft they are two to three times higher.

A value of about one percent per year improvement is adopted in the "evolutionary" efficiency alternative. The resulting automotive final energy demand by 2010 would basically be the same as in 1985, whereas air transport fuel demand would be some 30 percent higher (*Figure 11*). After 2010, fuel demand would decrease due to the projected saturation combined with a continuation of fuel efficiency improvement trends. Under such assumptions, energy requirements (and carbon emissions) by 2030 would drop to the levels that prevailed in the late 1970s.

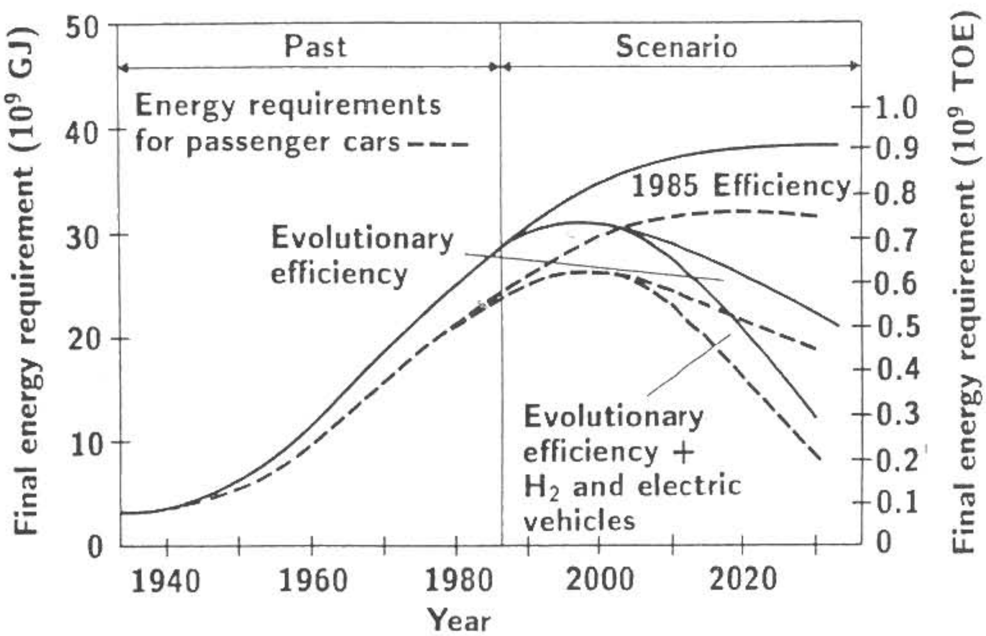

Figure 11. Final Energy Demand for Transport, and Scenario, World.
Scénario de la demande en énergie finale des transport.
Demanda final de energía para transporte y escenario.

The third alternative investigated combines the "evolutionary" efficiency improvement trends with the introduction of advanced hydrogen and/or electricity powered ground vehicles and hydrogen propelled aircraft. The industrialized countries are foreseen to take the lead in the development and diffusion of such a new generation of transport vehicles which combine significantly reduced fuel requirements and zero-carbon energy vectors. The replacement of conventional vehicles by electric cars or by cars equipped with hydrogen fuel cells, and of conventional jet–fuel aircraft by hydrogen powered ones offers a large potential for reducing final energy demand and, even more, carbon emissions.[5]

5 We only discuss final energy demand due to the uncertainties of the future fuel mix and efficiency of electricity and hydrogen production. Moreover, primary energy requirements (e.g. calculated via substitution equivalents of fossil energy inputs) are a rather problematic indicator in the context of renewable (solar or biomass) and carbon-free (hydro and nuclear) energy options.

It is assumed that liquid hydrogen aircraft would be introduced after the year 2000 – and for reasons of infrastructure compatibility – that they would diffuse globally within three decades. The diffusion of electric and/or hydrogen powered passenger vehicles is also assumed to start within technologically advanced and affluent countries with high passenger car densities (i.e., the OECD region) due *inter alia* to policies for limiting local (ozone), regional (acidic precipitation) and global (CO_2) environmental impacts from the transport sector. Based on the historical replacement dynamics of the vehicle fleets, this new generation of vehicles is assumed to diffuse throughout the world within three decades. Due to the much higher end-use efficiency, final energy demand (by 2030) of this scenario is only a third compared with the first alternative (frozen at 1985 efficiency). Overall, this alternative leads to 2.5 percent per year reduction in energy requirements per vehicle kilometer. Carbon emissions are even lower with some 150 million tons of carbon and are eliminated altogether in the OECD region.

These illustrative cases indicate that scenarios based on diffusion theory and the dynamics of technological change result in future development of individual transport with lower energy requirements and emissions. Market saturation and increasing awareness of the negative social and environmental externalities associated with further intensification of the dominant technological regime start to block further adoption. At the same time, incremental technological change concentrates on improving the performance of existing technologies via efficiency improvements and environmental "add-on" technologies. As such, *Figure 11* provides a clear illustration of the significant impacts on oil demand of scenarios combining a forthcoming saturation in the diffusion of automobiles and air transport with continued efficiency improvements.

Ultimately, however, small and incremental improvements have to yield to revolutionary changes in transport systems in order to lower environmental impacts and to respond to the evolving demands for mobility of people and goods. Perhaps the current "information revolution" bears witness to the almost unsatiable demand for improved interaction between human beings. It is likely that communication technologies may substitute for some passenger travel. However, there are many indications that improved communication, in turn, also translates into a demand for significant additional face-to-face communication and thus more travel. Fulfilling such potential demands in an environmentally compatible manner will perhaps be the biggest technological challenge in the decades to come. In the meantime, efforts have to continue to make the current generation of transport technologies more efficient and productive.

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Summary

This paper analyzes the development of transport systems from canals, railroads and horse-driven road vehicles, to automobiles and air transport, and outlines some important determinants of future development. The overall evolutionary envelope is analyzed as a process of the gradual replacement of old by new systems leading to improvements in performance and quality of services that increased range and speed, and connected ever expanding territories into a single functional system. Great leaps in the advancement of transport systems have allowed to cover greater distances in a unit of time, from traditional villages and preindustrial cities connected in one day by walking, to almost the whole world being connected in one day by aircraft.

New technologies are not adopted instantaneously, their diffusion takes time, in many cases several decades. There is great diversity in the timing, duration and ultimate application density levels of technologies among countries, economic sectors or different social strata. These patterns can also be observed in the way that new technologies succeed old ones. In those countries that introduce new systems early, diffusion is often pervasive and characterized by a long, sustained period of development. In other countries where diffusion is either blocked or occurs later, it can be significantly faster, "catching-up" with the leading countries. However, as the development time is shorter, the ultimate diffusion levels are also lower. Consequently, railroad networks are smaller in those countries where they were introduced later; similarly, automobile ownership is also lower compared with the leading countries. Thus, ultimate diffusion (saturation) levels are frequently lower in the follower countries.

The above forms the basis for a scenario of the further diffusion of current, and the introduction of new, transport systems. It explicitly considers heterogeneity in economic, social and spatial structures and in varying development stages. Consequently, the ultimate diffusion levels of current technologies in the scenario differ widely between countries as a result of their differences in initial conditions, degree of economic development, spatial structures, etc. For example, automobile ownership and car fleets are seen to be rather close to saturation in the industrialized countries. The growth potential in follower countries is high, yet ultimate car ownership levels will probably remain significantly below those achieved in the leading countries. Thereafter, the diffusion of a number of new technologies might lead to a renewed growth phase: Maglevs and hypersonic aircraft are possible candidates. This, however, would represent a revolutionary change. In the meantime, incremental and cumulative innovations will make the future derivatives of current automobiles and aircraft much more efficient and more productive.